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Rolling horizon control framework for driver assistance systems. Part I: Mathematical formulation and non-cooperative systems

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ABSTRACT

In this contribution, we put forward a novel rolling horizon control framework for driver assistance systems. Under this framework, accelerations of equipped vehicles are controlled to optimise a cost function reflecting different control objectives, taking into account the predicted behaviour of other vehicles. A new numerical solution based on Pontryagin's Principle is proposed to solve the optimal control problem. The control framework is generic such that a large variety of objective functions can be optimised and it allows us to control not only one vehicle but a platoon of heterogeneous vehicles as well. The linear constant time gap algorithm widely used for Adaptive Cruise Control (ACC) systems can be derived under the framework.

The framework is applied to derive algorithm for a non-linear model predictive ACC controller. Simulation results for several representative scenarios demonstrate the desired performance of the proposed ACC controller and the sensitivity of control parameters on controller characteristics. The resultant flow capacity is largely determined by the desired time gap setting. To show the flexibility of the framework, it is also applied to controller design for Ecological ACC (EcoACC) systems, where the controlled vehicle minimises fuel consumption in addition to the objectives of the ACC systems. Compared to ACC systems, EcoACC systems lead to smoother following behaviour and a 18% reduction of consumed fuels in the accelerating phase of the simulation.

Part II of this research is devoted to controller design of cooperative driving systems, where controlled vehicles communicate and collaborate with each other.

1. Introduction

Advanced Driver Assistance Systems (ADASs) support drivers or take over driving tasks to operate vehicles in a safe, comfortable and efficient way (Varaiya and Shladover, 1991). More advanced ADAS are cooperative systems, where equipped vehicles are connected with each other via vehicle-to-vehicle (V2V) communications or with infrastructure via vehicle-to-infrastructure (V2I) communications. ADAS influence the individual vehicle behaviour and thus induce changes in aggregate flow as well. It is important to examine the performance of ADAS equipped vehicles to understand the potential impact on traffic operations and to support road operators in making relevant policy at strategic levels.

The Adaptive Cruise Control (ACC) system is the earliest ADAS that has been introduced by the automotive industry, which specifically aims at enhancing driving comfort (Darbha and Rajagopal, 1999; VanderWerf et al., 2001; Rajamani

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and Shladover, 2001; Van Arem et al., 2006). The most extensively studied ACC model is a linear feedback controller, where the vehicle acceleration is proportional to the (distance) gap and the derivative of the gap (relative speed with respect to the preceding vehicle) at car-following conditions:

$$a_i = K_s(s_i - t^* \cdot v_i - s_0) + K_v \dot{s}_i \tag{1}$$

where a_i is the acceleration of the ACC vehicle i. v_i and s_i are the speed and (distance) gap of vehicle i respectively. $\dot{s}_i = v_{i-1} - v_i = \Delta v_i$ is the derivative of the gap, which equals the relative speed Δv with respect to the preceding vehicle $i-1$. t^* is a user-defined desired time gap and s_0 is the minimum gap at standstill conditions. K_s and K_v are constant feedback gains for the gap error and speed error. This type of controller has been extensively studied (Darbha and Rajagopal, 1999; Rajamani and Shladover, 2001; VanderWerf et al., 2001; Van Arem et al., 2006). The resultant car-following behaviour of this controller is that ACC vehicles maintain a *constant time gap* t^* at equilibrium conditions. Hence the control strategy is referred to as Constant Time Headway policy (Ioannou and Chien, 1993; Darbha and Rajagopal, 1999). In fact, the term *Constant Time Headway (CTH)* is misleading, since t^* is the time gap, while the time headway $t_h = t^* + \frac{L}{v_i}$ varies vehicle speed v_i. In the ensuing, we will refer this type of controller as Constant Time Gap (CTG) controller. This controller is essentially a Helly-type car-following model (Helly, 1959). Extensions of the constant time gap controller have been reported to include the acceleration of the predecessor (VanderWerf et al., 2001; Van Arem et al., 2006) or multi-anticipation behaviour (Wilmink et al., 2007). However, there is no safety mechanism in this model. Under critical conditions, ACC systems have to be overruled by drivers and hard braking has to be performed to avoid a collision (Godbole et al., 1999).

Another controller for ACC systems in literature is called constant spacing policy (Darbha and Rajagopal, 1999). Instead of keeping a constant time headway, the constant spacing policy regulates the ACC vehicle to maintain a fixed gap to the predecessor with the following algorithm:

$$a_i = K_s(s_i - s^*) + K_v \dot{s}_i \tag{2}$$

where s^* is a fixed distance for ACC vehicles. This controller places demanding requirements on the quality of data to guarantee controller performance such as stability, which is difficult for ACC systems relying solely on on-board sensors. Some researchers (Hasebe et al., 2003) use the Optimal Velocity Model (OVM) to describe the ACC vehicle behaviour. The OVM regulates the speed of the controlled vehicle towards an optimal speed, which is a function of the following gap. Unfortunately, the optimal velocity model is not collision free under realistic parameters (Treiber et al., 2000). The Intelligent Driver Model (IDM) is also used to design ACC controllers, with a driving strategy that varies parameters according to traffic situations to mitigate congestion at bottlenecks (Kesting et al., 2008; Treiber and Kesting, 2013). Although benefits on capacity are gained through the IDM controller, physical limits such as minimum allowed deceleration and limited sensor detection range are not explicitly included in the model.

The aforementioned problems of existing ACC controllers call for a new approach to design ADAS. Furthermore, the increasing public concerns on traffic congestion and environment stimulate the need for the development of driver assistance systems that can fulfil multiple control objectives, capture V2V/V2I cooperation and operate vehicles in an optimal way. It is however difficult to use the existing ADAS controllers to achieve all these objectives.

This contribution generalises previous work on driver behaviour modelling (Hoogendoorn and Bovy, 2009; Hoogendoorn et al., 2012) to a model predictive control framework for driver assistance systems. The main control methodology entails that ADAS equipped vehicles predict the behaviours of other vehicles in the neighbourhood over a time horizon and choose accelerations to minimise a cost function. The cost function to be minimised is generic and flexible in such a way that it allows us to optimise different criteria representing safety, efficiency, comfort and sustainability. A numerical solution based on necessary conditions stemming from Pontryagin's Minimum Principle is proposed to solve this optimal control problem. The framework generates, among other things, the CTG model widely used for Adaptive Cruise Control (ACC) systems. The proposed solution algorithm leads to same solutions to the linear quadratic control problem as other two well-known approaches, while it allows sophisticated format of the cost function and gives insights into the optimal control input.

To show the functionality of the framework, it is applied to controller design for non-cooperative driving systems, where the controlled vehicle only optimises the situation within its autonomy, using information regarding the direct predecessor from its own on-board sensors. A model predictive ACC controller with an explicit safety mechanism is proposed, which prevents collisions from occurring with admissible deceleration. The performance of the proposed ACC controller is examined with simulation and analytic approach. Simulation results for several representative scenarios show that the proposed ACC controller generate desired performance. Sensitivity analyses provide insights into the influences of the control parameters on controller performance. Analytical results show that the desired time gaps of the ACC controller influences the maximum flow (capacity) most.

To show the generic characteristics of the framework, and the objective function in particular, the framework is then applied to model Ecological ACC (EcoACC) systems, where the controlled vehicle minimises fuel consumption in addition to the control objectives of ACC systems. Compared to ACC systems, EcoACC systems lead to smoother following behaviour and a substantial reduction of consumed energy in the accelerating phase.

The remaining of the paper is structured as follows. Section 2 presents the control framework with an example of deriving the CTG model under the framework, while Section 3 shows the solution approach and validity of the numerical solution. The application of the framework and the solution approach to a new ACC controller is described in Section 4 and verification