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# Modelling supported driving as an optimal control cycle: Framework and model characteristics ☆

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ABSTRACT

Driver assistance systems support drivers in operating vehicles in a safe, comfortable and efficient way, and thus may induce changes in traffic flow characteristics. This paper puts forward a receding horizon control framework to model driver assistance and cooperative systems. The accelerations of automated vehicles are controlled to optimise a cost function, assuming other vehicles driving at stationary conditions over a prediction horizon. The flexibility of the framework is demonstrated with controller design of Adaptive Cruise Control (ACC) and Cooperative ACC (C-ACC) systems. The proposed ACC and C-ACC model characteristics are investigated analytically, with focus on equilibrium solutions and stability properties. The proposed ACC model produces plausible human car-following behaviour and is unconditionally locally stable. By careful tuning of parameters, the ACC model generates similar stability characteristics as human driver models. The proposed C-ACC model results in convective downstream and absolute string instability, but not convective upstream string instability observed in human-driven traffic and in the ACC model. The control framework and analytical results provide insights into the influences of ACC and C-ACC systems on traffic flow operations.



## 1. Introduction

Advanced Driver Assistance Systems (ADAS) aim to support drivers or take over the driving tasks to operate vehicles in a safe, comfortable and efficient way (Varaiya and Shladover, 1991). This includes cooperative systems, where equipped vehicles are connected to and collaborate with each other through Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communications (Williams, 1992). Considerable efforts have been dedicated to ADAS control design and investigation of the resulting traffic flow properties. Among them, Adaptive Cruise Control (ACC) systems attract most of the attention due to the early availability in the market. The most widely reported ACC model is a proportional derivative (PD) controller, where the vehicle acceleration is proportional to the gap (net distance headway) and relative speed with respect to the preceding vehicle (derivative of gap) at car-following conditions. This controller has been well examined (Swaroop, 1994; Godbole et al., 1999; VanderWerf et al., 2002), and is essentially a Helly car-following model (Helly, 1959). Extensions of this controller class have been reported to include acceleration of the predecessor (VanderWerf et al., 2002; van Arem et al., 2006) or multi-anticipative behaviour (Wilmink et al., 2007) in the controller. 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

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collision (Godbole et al., 1999). Some researchers (Hasebe et al., 2003) used the Optimal Velocity Model (OVM) to describe the controlled vehicle behaviour and proposed a cooperative driving system under which the desired speed is determined not only by the gap to the vehicle in front but also by the gap to the vehicle behind. Unfortunately, the optimal velocity model is not collision free under realistic parameters (Treiber et al., 2000). The Intelligent Driver Model (IDM) is 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, 2010). Other controllers are reported by Swaroop (1994) and Ioannou and Chien (1993). The resulting traffic flow characteristics of ADAS differ among the controller and parameter settings. The increase of capacity is mainly a result of shorter time headways compared to human drivers (Rao and Varaiya, 1993; Kesting et al., 2008), while choosing a larger time headway could cause negative impacts on capacity (Minderhoud and Bovy, 1999; VanderWerf et al., 2002). Regarding the stability, some authors provide evidence that ACC/CACC systems improve flow stability (Hasebe et al., 2003; Davis, 2004; van Arem et al., 2006; Naus et al., 2010), while others (Marsden et al., 2001) are more conservative on the stabilisation effects of ACC systems.

ADAS and cooperative systems have a direct influence on the vehicular behaviour and consequently on flow operations. The lack of clarity on aggregated impacts of ADAS in literature calls for new insights into the model properties of ADAS and cooperative systems. Furthermore, the increasing public concerns on traffic congestion and environment stimulate the need for development of driver assistance systems that can fulfil multiple objectives, cooperate with each other and operate vehicles in an optimal way. It is however difficult to use the existing phenomenological ADAS controllers to achieve all these objectives.

This contribution generalises previous work on driver behaviour (Hoogendoorn and Bovy, 2009) to a control framework for driver assistance and cooperative systems. The framework is generic in such a way that different control objectives, i.e. safety, comfort, efficiency and sustainability, can be optimised. It is assumed that accelerations of ADAS vehicles are controlled to optimise a cost function reflecting multiple control objectives. Under the framework, we propose a complete ACC controller, which produces plausible human car-following behaviour at both microscopic and macroscopic level. The controller can be applied to all traffic situations, i.e. not only car-following and free driving conditions, but also safety-critical conditions such as approaching standstill vehicles with high speeds. The flexibility in the system and cost specification allows modelling a Cooperative ACC (C-ACC) controller, where an equipped vehicle exhibits cooperative behaviour by optimising the joint cost of both itself and its follower.

The aggregated flow characteristics of the ACC/C-ACC models are investigated analytically, with a focus on equilibrium solutions and (linear) stability analysis. Analytical criteria to quantify the influence on the model stability due to cooperative behaviour are derived.

The rest of the paper is structured as follows. Section 2 presents the modelling framework and solution approach, with several examples showing the application of the framework. Section 3 gives the analytical solutions at equilibrium conditions, criteria for string stability and the method for classification of string instability types. Section 4 gives insights into the model characteristics of the example controllers. Conclusions and future work are discussed in Section 5.

## 2. Control framework for supported driving

In this section, we first present the underlying assumptions and mathematical formulation of the control framework. The optimal control problem is solved using the dynamic programming approach, and the framework is applied to design ACC and cooperative ACC controllers.

### 2.1. Design assumptions and control objectives

The controller framework is based on the following assumptions:

1. A controlled vehicle adapts its speed or changes lanes to minimise a certain cost function, reflecting the control objectives.
2. A controlled vehicle has all information regarding (relative) positions and speeds of other vehicles influencing its control decisions.
3. Other vehicles influencing the control decisions are driving at stationary conditions within the prediction horizon, i.e. accelerations equal zero.
4. Control decisions are updated at regular time intervals.
5. Longitudinal manoeuvres of ADAS equipped vehicles are under automated control.

For the sake of analytical tractability, we only consider deterministic cases without time delay in this contribution, i.e. there is no noise in the information regarding other vehicles and the control decisions can be executed immediately. The control framework is generic in that it allows one to include stochastic processes and time lags in the controller (Wang et al., 2013).

Control decisions are made to fulfil some control objectives, which can be a subset of the following: