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A framework for user- and system-oriented optimisation of fuel efficiency and traffic flow in Adaptive Cruise Control☆

Mohammad Mamouei[a,*], Ioannis Kaparias[b], George Halikias[c]

[a] Collaborative Transport Hub, City, University of London, United Kingdom
[b] University of Southampton, United Kingdom
[c] City University London, United Kingdom

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ABSTRACT

Fully automated vehicles could have a significant share of the road network traffic in the near future. Several commercial vehicles with full-range Adaptive Cruise Control (ACC) systems or semi-autonomous functionalities are already available on the market. Many research studies aim at leveraging the potential of automated driving in order to improve the fuel efficiency of vehicles. However, in the vast majority of those, fuel efficiency is isolated to the driving dynamics between a single follower-leader pair, hence overlooking the complex nature of traffic. Consequently fuel efficiency and the efficient use of the roadway capacity are framed as conflicting objectives, leading to fuel-economy control models that adopt highly conservative driving styles.

This formulation of the problem could be seen as a user-optimal approach, where in spite of delivering savings for individual vehicles, there is the side-effect of the deterioration of traffic flow. An important point that is overlooked is that the inefficient use of roadway capacity gives rise to congested traffic and traffic breakdowns, which in return increases energy costs within the system. The optimisation methods used in these studies entail high computational costs and, therefore, impose a strict constraint on the scope of problem.

In this study, the use of car-following models and the limitation of the search space of optimal strategies to the parameter space of these is proposed. The proposed framework enables performing much more comprehensive optimisations and conducting more extensive tests on the collective impacts of fuel-economy driving strategies. The results show that, as conjectured, a "short-sighted" user-optimal approach is unable to deliver overall fuel efficiency. Conversely, a system-optimal formulation for fuel efficient driving is presented, and it is shown that the objectives of fuel efficiency and traffic flow are in fact not only non-conflicting, but also that they could be viewed as one when the global benefits to the network are considered.

1. Introduction

During the past decade, environmental concerns have placed the energy efficiency of vehicles at the centre of researchers' efforts. Great leaps have been made in this area by employing a wide range of technologies that improve fuel efficiency, such as the use of lighter materials in car manufacturing, the adoption of more aerodynamic designs, and the introduction of techniques such as pulse

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* Corresponding author.
E-mail address: mohammad.mamouei.1@city.ac.uk (M. Mamouei).

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and gliding. However, an important factor that is somewhat overlooked is the impact of the behaviour of drivers and of driving strategies on fuel consumption. A search of the relevant literature reveals that this could be due to the difficulties associated with the formulation of energy efficiency in the car following regime. The algorithms proposed in this area are sometimes based on simplistic assumptions and usually lack comprehensive investigations on their collective impacts and stability features. This is due to the fact that the proposed models often rely on complex and computationally demanding machine learning and optimal control theory-based methods, which make their use in large-scale simulations impractical.

In this study, a new approach is proposed which makes use of car-following models in optimisation. The use of car-following models as the basis of control has already been addressed in the literature (Kesting et al., 2010). The incorporation of car-following models in simulation-based optimisation significantly reduces the complexity of the latter, which then allows its application to much more comprehensive scenarios. Additionally, the provision of control on the basis of car-following models benefits from the remarkable advantage of the extensive knowledge that exists on the collective properties of these models through the numerous studies that are available in the literature on aspects such as stability features and traffic flow characteristics.

Two distinct approaches to the question of fuel efficiency are investigated in the present study; (1) individual vehicles are considered and their fuel consumptions are minimised, and (2) fuel efficiency is considered from a broader, network-level perspective. While much of the studies in the literature revolve around the former, the latter is somewhat overlooked. A comprehensive analysis of the results sheds light on the important and fundamental differences between the driving strategies produced by the two approaches.

In Section 2 a literature review is presented and subsequently the gap in the literature is identified. In Section 3 two new approaches for optimisation of fuel consumption are formulated to cope with the shortcomings of the existing approaches. In Section 4 the results are presented. Finally, conclusions and future work are presented in Section 5.

2. Literature review

Wu et al. (2011) developed an advisory system that minimised fuel consumption in the acceleration phase before reaching desired velocities and the deceleration phase before coming to a standstill. The system was shown to deliver reductions of 12–31% in fuel consumption and the objective was defined as the minimisation of the cumulative fuel consumption, given by the VT-micro instantaneous fuel consumption model (Ahn, 1998), within the time interval of interest (deceleration/acceleration period). For this purpose the objective function was discretised and the resulting optimisation problem was then solved using the Lagrange Multiplier Method (LMM).

Themann et al. (2015) proposed a control model for Adaptive Cruise Control systems (ACC) that relied on the optimisation of the velocity profile with respect to fuel consumption. This study used Dijkstra's algorithm to find the optimal velocity profile for known road topography. Porsche's Innodrive ACC has also adopted a similar approach, resulting in about 10% reduction in fuel consumption (Markschläger et al., 2012). Hellström et al. (2010) developed a fuel-optimal control model for trucks. In this study, prior knowledge of road topography was used in order to optimise fuel consumption and gear-shifting, and the problem was formulated as a dynamic programming optimisation. In all these studies, fuel economy is obtained by producing a smooth velocity performance and avoiding unnecessary accelerations. Kohut et al. (2009) achieve the same objective by adopting a Model Predictive Control (MPC) framework. This study highlights the trade-off between fuel savings and trip time.

The development of optimal fuel economy control models in the car-following regime of driving is a more challenging task due to the highly unpredictable nature of drivers' behaviours. In the study by Li et al. (2008), cars' tracking capabilities and fuel efficiency were considered in the development of ACC, and in order to ensure fuel efficiency, accelerations were penalised in the objective function. The problem was then formulated as an MPC optimisation, and the testing of the control model was carried out by considering its performance in an urban driving scenario and a highway driving scenario; fuel savings of 8.8% and 2% were obtained in each scenario respectively. Kamal et al. (2013) developed an MPC-based controller for the car-following regime that saved an average of 13% in fuel consumption in urban driving scenarios. Similar approaches can be found in other studies (Luo et al., 2015; Zhao et al., 2017).

Zhang and Ioannou (2006) designed a Proportional-Integral-Derivative (PID) controller for the car-following regime for trucks. The proposed method reduced fuel consumption by avoiding unnecessary accelerations and braking, and the objective of the controller was set to track the velocity of the preceding vehicle while maintaining a specified range of spacing. A different approach in tackling the problem of fuel efficiency is based on the use of new technologies. The potential of technologies such as hybrid electric powertrains and telematics, providing traffic-related information (Manzie et al., 2007) and techniques such as pulse and gliding (Li et al., 2012) in the reduction of fuel consumption has been investigated in the literature.

Considering studies seeking more fuel-efficient driving behaviour, two categories can be defined. The first category includes studies seeking to optimise fuel consumption for simple scenarios, where there are no additional complexities caused by interactions between vehicles. In this case information about roadway topography or the position of traffic signals is used in order to formulate an optimisation problem and obtain the optimal velocity profile (Wu et al., 2011; Themann et al., 2015; Markschläger et al., 2012; Hellström et al., 2010; Kohut et al., 2009). The second category, on the other hand, consists of studies targeting driving conditions, where interaction between vehicles is the defining factor in driving behaviour. In these studies often simplistic assumptions are made about the relationship between fuel consumption and acceleration or driving dynamics in order to reduce the complexity of problem. More importantly, due to the computational cost of the methods used and the natural complexity of the car-following regime of driving, these studies often narrow down the scope of the problem to a single pair of follower-leader and, therefore, overlook the potentially negative impacts of their proposed control strategies on traffic flow and fuel consumption within the network (Li et al., 2008; Kamal et al., 2013; Luo et al., 2015; Zhao et al., 2017).