Transportation Research Part C 93 (2018) 148–160

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Globally energy-optimal speed planning for road vehicles on a given route

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ARTICLE INFO

Keywords:
Optimal vehicle speed control
Dynamic programming
Electric vehicles
Energy management
Traffic light

ABSTRACT

This paper provides a globally optimal solution to an important problem: given a real-world route, what is the most energy-efficient way to drive a vehicle from the origin to the destination within a certain period of time. Along the route, there may be multiple stop signs, traffic lights, turns and curved segments, roads with different grades and speed limits, and even leading vehicles with pre-known speed profiles. Most of such route information and features are actually constraints to the optimal vehicle speed control problem, but these constraints are described in two different domains. The most important concept in solving this problem is to convert the distance-domain route constraints to some time-domain state and input constraints that can be handled by optimization methods such as dynamic programming (DP). Multiple techniques including cost-to-go function interpolation and parallel computing are used to reduce the computation of DP and make the problem solvable within a reasonable amount of time on a personal computer.

1. Introduction

Improving the energy efficiency of road vehicles is one of the most important tasks for automotive powertrain control. Researchers have found that on the same route, different speed profiles caused by different driving styles can result in significant energy consumption differences (Ericsson, 2001; Van Mierlo et al., 2004). There are potentials in saving energy by adjusting the vehicle speed without too much sacrifice in comfort, drivability, and travel time. This motivates the concept of eco-driving (Alam and McNabola, 2014; Barkenbus, 2010; Berry, 2010), where initially the drivers were suggested to follow some driving rules and patterns, e.g., avoiding fast accelerations and hard brakes, to achieve lower energy consumption. There are also approaches trying to design a reference speed in real-time and provide it as guidance to the driver (Daun et al., 2013; Xiang et al., 2015). In the context of automated vehicles and semi-automated vehicles, the speed planning and control methods also need to consider the energy efficiency (Eben Li et al., 2013). All kinds of information related to the future trip, including the traffic condition, traffic light schedules, and road maps, can be utilized to design the best speed trajectory.

Many researchers have been working on figuring out optimal or sub-optimal speed trajectories for vehicles running in various situations, both on-line and off-line. Road grade information is utilized in some literatures. Ozatay et al. (2014a, 2014b) and Zeng and Wang (2015) propose the solution to minimize the energy consumption for vehicles running on roads with variable grades. Hellström et al. (2009) develop a look-ahead vehicle control considering road grade. Hu et al. (2017) optimize the vehicle acceleration and gear simultaneously on roads with dynamic speed limit and road grade. The optimal speed planning problem with a single traffic light is

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https://doi.org/10.1016/j.trc.2018.05.027

solved in several literatures. Dynamic programming (DP) is used to solve a single traffic light speed control problem (Kamalanathsharma and Rakha, 2013). Optimal vehicle speed trajectory for a traffic light arterial with consideration of a queue is presented by He et al. (2015). Stebbins et al. (2017) propose platoon vehicle optimal speed advisory system near a traffic light. Under the situation of multiple traffic lights, many existing approaches can find a sub-optimal solution, which first tries to avoid red lights, then optimizes the vehicle speed (Ozatay et al., 2013). Asadi and Vahidi (2011) design a predictive control utilizing multiple traffic light signals to improve fuel economy. Wu et al. (2015) propose a multi-stage energy-optimal speed control for multiple traffic lights. Wan et al. (2016) propose a sub-optimal speed advisory system. Luo et al. (2017) design optimal traffic light passing speed with sub-optimal stop logic for a hybrid electric vehicle. Huang and Peng (2017) propose a sub-optimal solution for vehicle speed trajectory over multiple traffic lights. HomCHaudhuri et al. (2017) use model predictive control for a group of vehicles to reduce stopping at red light. Miao et al. (2018) optimize the vehicle route and speed simultaneously with a traffic light penalty model. Describing the vehicle speed planning problem in distance domain instead of time domain may bring some advantages, especially when dealing with stop signs, which is not easy to describe in time domain. Distance domain methods for energy management with road grade terrain preview are proposed by Chen et al. (2014). Optimal velocity profile without considering the traffic light schedule is calculated using DP by Ozatay et al. (2014a, 2014b). A similar approach considering traffic lights is also proposed (Wiet, 2014), where it focuses on finding a speed trajectory that avoids red lights. When the vehicle encounters a red light, the speed profile will be adjusted iteratively until it avoids the red light, therefore no global optimality is guaranteed.

To the best of the authors' knowledge, there is not yet a good way to find the global optimal speed planning solution on a route with multiple traffic lights, stop signs, and different road grades. The main difficulty is that the constraints of this optimal control problem are described in two different domains. The traffic light locations, stop sign locations and speed limits are described in the distance domain, while the traffic light schedules are described in the time domain. If the problem is formulated in time domain, as discussion in Section 3 will show that, the distance domain constraints are not in a standard form and they cannot be handled directly by DP or Pontryagin's Minimum Principle. If the problem is formulated in the distance domain, the time-domain traffic light schedule information cannot be taken into consideration unless the time is added as an additional state, which may increase the system order and complexity.

In this paper, the global optimal speed planning solution for vehicles on a given route is presented. The route may include multiple stop signs, traffic lights, turns and curved segments, roads with different grades and speed limits, and even leading vehicles with known speed profiles. As a major innovation of this work, the non-standard-form distance-domain constraints are converted to state and input constraints in the standard form in time domain. In order to obtain the global optimal result, this comprehensive speed planning problem is solved via DP. Multiple techniques are used to reduce the computational load of DP and the algorithm can run on a personal desktop computer within a reasonable amount of time. An 8-km route is used in the simulation study as an example. The results show that comparing to a nominal speed profile with constant acceleration and deceleration, the optimal speed trajectory may consume significantly less energy.

The major contribution in this paper is that, the global optimal vehicle speed trajectory is calculated without formulating the idea of "avoiding red lights as much as possible" into the algorithm. Instead, only the traffic rules about red and green lights are formulated. This is achieved by reformulating the constraints into new forms that DP can handle. The algorithm will decide whether to adjust the speed to go through or stop at the lights based on the total energy consumption. Existing methods (Asadi and Vahidi, 2011; HomChaudhuri et al., 2017; Huang and Peng, 2017; Miao et al., 2018; Wu et al., 2015; Wan et al., 2016; Wiet, 2014) which embed the "avoiding red lights" idea within the algorithms can only provide sub-optimal results, especially in complicated situations with multiple traffic lights close to each other along the route. Many of those methods cannot be applied to trips with stop signs. The proposed method in this paper provides globally optimal results and works under both traffic light and stop sign constraints.

Obviously, the method proposed in this paper is not a real-time method. It requires a considerable computational resource and it does not consider any uncertain factors along the route. The purpose of this paper is not to design a real-time controller for the speed planning problem. It is not intended to replace other faster sub-optimal methods for this same problem. However, this paper provides a very useful tool that can calculate the *posteriori* global optimal speed trajectory and global optimal energy consumption. The *posteriori* global optimal results can be used to evaluate and compare the performances of other speed planning methods, either in eco-driving guidance applications or automated/semi-automated vehicle controls, just like in hybrid electric vehicle energy management study, the *posteriori* DP results can be used to evaluate other real-time control strategies. By comparing the energy consumption results from a certain speed planning method with the *posteriori* global optimal results, the potential room for improvement and performance consistency in different routes can be analyzed. The optimal trajectory calculated from this method can also be used to extract better rule-based speed control strategies, or combined with modern machine learning technologies to design artificial-intelligent-based speed automated control methods. The concept of the constraint conversion is also important and may inspire some future real-time-capable algorithms. It should also be noted that the advantage of this speed planning method cannot be shown in any driving cycle tests because it tries to change the speed profile itself.

The rest of this paper is structured as follows. Section 2 is the formulation of the optimal control problem for vehicles running on a given route. Section 3 describes how the constraints are converted and handled in DP. Several techniques to accelerate DP implementation are provided in Section 4. Section 5 shows an example of this method in simulation. Section 6 concludes the paper.

2. Problem formulation

In this section, the vehicle model will be introduced first. Then the optimal control problem of a vehicle running on a given route is formulated.