E-Pico Master's Thesis

Energy management control strategies for connected hybrid electric vehicles

Following the progress of electrification in the automotive area, the technology of hybrid electric vehicles (HEVs) has quickly upgraded since HEVs have benefits of fuel economy improvement and emission reduction versus conventional internal combustion engine (ICE) powered vehicles. There is additional energy storage used for propelling the vehicle in HEVs. Given a power demand from a driver, there are different power supply ways through the engine and battery. Furthermore, fuel economy improvement could be achieved by driving the engine to work in the high efficiency zone, and the lacking power compared to the demanded power is provided by the motor. A promising approach to deal with this kind of problem is a real-time energy consumption optimization strategy, which includes making decisions on the power distribution between the engine and motor at the current time without the need for knowledge of further information along the route to the destination. With the capacity for obtaining vehicle-to-vehicle (V2V) and vehicle-to infrastructure (V2I) information in the connected environment, the vehicles with connectivity technology provide increasing potential in achieving energy consumption reduction. By means of V2V and V2I traffic data, the future behaviour can be predicted, and a control system can be designed based on the estimated information. See [1], [2] and [3].

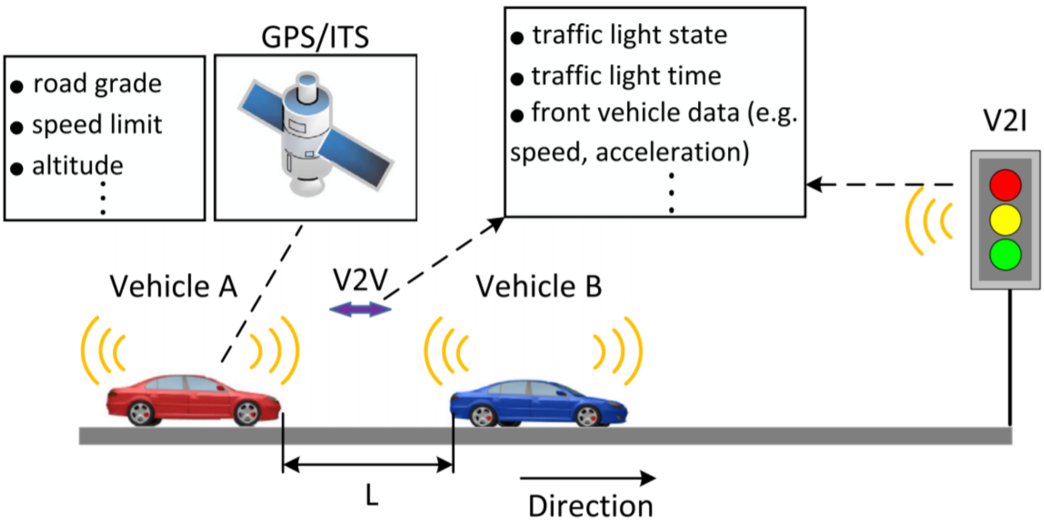

Figure 1: The scenario of two-vehicle energy management.

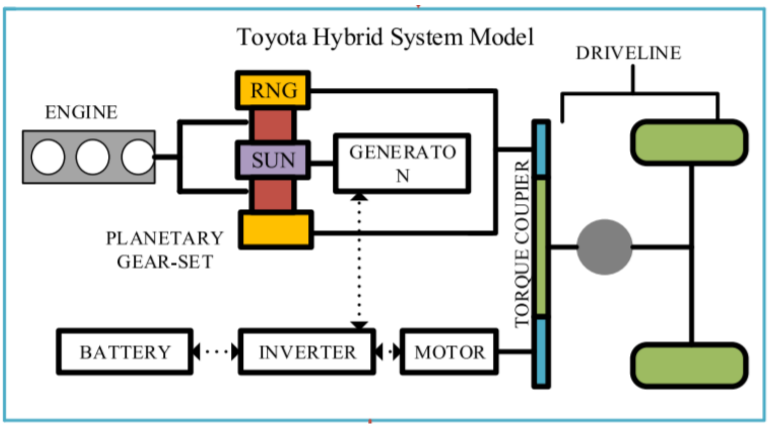

Figure 2: HEV model

Goals

1. **Energy management strategies (EMSs) of connected and automated HEVs/PHEVs**: Currently, the single-vehicle situation is mainly concerned in EMSs rather than a cooperative optimization for multiple connected HEVs. But, the increasing interactions among human behavior, vehicle, and road conditions in the Connected and Automated (CAV) setup will become increasingly critical. It is very important to take in these in the context of safety, comfort, fuel economy, and driving performance. Hence, how to plan an EMS for each HEV in a cooperative and intelligent manner while considering the coupling influence of multivehicles is essential to enhance the overall performance involving safety, system mobility, and energy efficiency for alternative automotive powertrains. Furthermore, heterogeneous dynamics and stability create another issue due to the presence of different dynamic characteristics for connected multiple vehicles. A heterogeneous platoon is composed of multiple vehicles with different longitudinal dynamics (see [a]). The connected HEVs/PHEVs may also present heterogeneous features. Consequently, it is necessary to include the heterogeneity in optimizing the velocity and EMSs to enhance fuel efficiency and maintain enough driving safety.

   [a] Li SE, Zhang X, Li R, Wang Z, Chen H, Xin Z. Optimal periodic control of connected multiple vehicles with heterogeneous dynamics and guaranteed bounded stability. IEEE Intelligent Transportation Systems,1–15, may 2018.

2. **Driver-in-the loop EMSs of HEVs/PHEVs**: Driver plays an important role in energy-efficient driving. Most of the literature presently ignores the human driver error in ecodriving, leading to limitation of tracking suggested speed profiles. Indeed, the driver may not track the optimal velocity exactly. As preliminary work for this purpose, the driver-vehicle-infrastructure cooperative framework for eco-driving is proposed considering the possible human driver errors in [b] for conventional vehicles. Equally for connected HEVs/PHEVs, the performance of EMSs is closely related to the velocity profile, which mostly does not take into account the human driver behavior in optimizing the velocity control and power split. It is always assumed that the optimal velocity in the higher level can be followed accurately and then the corresponding power split is determined. However, the uncertainty of driver behavior (e.g. lane changing, disposition) may affect the velocity tracking performance and further contribute to fuel consumption. Even if the subject vehicle may not "see" the preceding vehicles, the driver information for the preceding vehicles may be acquired through connectivity in the connected environment. Therefore, incorporating the human driver behavior into EMSs for connected HEVs/PHEVs (so called driver-in-the-loop EMSs) is an interesting topic, which contributes to achieving better tracking performance and potential fuel savings.

   [b] Qi X, Wang P, Wu G, Boriboonsomsin K, Barth MJ. Connected cooperative ecodriving system considering human driver error. IEEE Trans Intelligent Transportation Systems, 19(8), pp. 2721–33, 2018.

3. **Multi-objective optimization EMSs of HEVs/PHEVs**: HEVs are complex mechatronic systems with strongly connection, nonlinear characteristic, and multiple variables. In order to make it easier the optimal control problem, in the literature fuel economy is usually highlighted in optimizing the power split with many assumptions. This can satisfy the basic requirement of EMS but is not optimal. For example, the battery cycle life degradation that is inevitable for PHEVs would affect energy efficiency or predefined gear shift schedule is generally adopted for HEVs without adaptability. Specially in connected EMSs for HEVs/PHEVs, utilizing the future information can determine the optimal gear shift schedule. Normally, the comfort and fuel economy conflict with each other. Additionally, the safety should also be included for car-following and multi-vehicle scenarios. Thus, it is significant to

investigate an efficient optimal EMS to gain a trade-off among these performance measures considering the future information.

4. **Learning-based EMSs of HEVs/PHEVs**: The concept of learning-based EMSs is presented in [c], which tries to improve the robustness of EMSs with an integrated use of machine learning and the optimal EMS. A reinforcement learning technique is studied to develop a predictive energy management strategy for a parallel HEV. Analogous work can be found in [d] as well. This idea can also be extended to EMSs of connected HEVs/PHEVs. Conventional EMSs mainly focus on a specific driving condition with an assumption of steady operations, leading to less robustness and adaptability in the presence of the stochastic nature of driver behavior and traffic conditions. Intelligent transportation systems can enable vehicles to access numerous external information (e.g. traffic information, presence of surrounding vehicles, and their operating variables) through connectivity. This data can be fed back into EMSs based on cloud computing and then utilized to update the control parameters in a periodical or continuous manner to respond to the external environment. Motivated by the real-time data, assimilating such data that represent the external stochastic information precisely can improve adaptability of EMSs. Meanwhile, the EMS of each HEV can be devised considering the interaction between the agent and the environment based on multi-agent techniques. This is beneficial to larger scale EMSs for multiple connected HEVs/PHEVs.

[c] Liu T., Hu X., Li SE., Cao D., Reinforcement learning optimized look-ahead energy management of a parallel hybrid electric vehicle, IEEE/ASME Transaction Mechatronic;22(4):1497–507, 2017.
[d] Bin Xu FM, Rathod Dhruvang, Filipi Zoran, Real-time reinforcement learning optimized energy management for a 48V mild hybrid electric vehicle, In: SAE Technical Paper; 2019.

5. **CACC-based EMSs of HEVs/PHEVs**: Cooperative adaptive cruise control (CACC) that can improve the safety goals to coordinate the velocity for multiple vehicles with prediction of preceding-vehicle velocity utilizing the surrounding vehicles information via V2V/V2I communication. A CACC based on machine-learning algorithms is developed in [e] to reduce time gaps and improve string stability by employing the preceding dynamic information via V2V and V2I communication. In [f], the CACC for autonomous vehicles is proposed to obtain predictive gear schedule and reduce energy consumption in a cooperative manner. However, these endeavours are mainly conducted for conventional vehicles. In recent years, with the development of advanced V2V and V2I communication, such a CACC system provides a possibility for optimizing EMSs of HEVs with respect to system mobility, safety, and fuel economy from different levels, such as vehicle level and powertrain level. Therefore, developing CACC-based EMSs for a platoon of HEVs is a significant trend from local and global perspectives, which is advantageous for improving the traffic efficiency and energy benefits.

[e] Desjardins C., Chaib-draa B., Cooperative Adaptive cruise control: a reinforcement learning approach. IEEE Trans Intelligent Transportation Systems;12(4):1248–60, 2011.
[f] Murgovski N., Egardt B., Nilsson M. Cooperative energy management of automated vehicles. Control Engineering Practice; 57:84–98, 2016.

[1] Fengqi Zhanga, Xiaosong Hub, Reza Langari, Dongpu Cao, *Energy management strategies of connected HEVs and PHEVs: Recent progress and outlook, Progress in Energy and Combustion Science*, Vol. 73, pp. 235-256, July 2019.
[2] Fuguo Xu and Tielong Shen, *Look-Ahead Prediction-Based Real-Time Optimal Energy Management for Connected HEVs*, IEEE Transactions on Vehicular Technology, Vol. 69, No. 3, pp. 2537-2551, March 2020.
[3] Nikolce Murgovskia, Bo Egardta, Magnus Nilsson, *Cooperative energy management of automated vehicles*, Control Engineering Practice, Vol. 57, pp. 84-98, December 2016.

■ Requirements

You should have a good understanding of *Hybrid Electric Vehicles models, Vehcile dynamics, Automatic Control Theory*, *Connected Vehicles, MATLAB-SIMULINK*.

Contact:
Stefano Di Gennaro: stefano.digennaro@univaq.it
Domenico Bianchi: domebianchi@gmail.com

Website:
www.univaq.it