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Doctoral Dissertation
Doctoral Program in Mechanical Engineering (37th Cycle)

Energy Management Strategies for Hybrid and Battery Electric Vehicles Exploiting Driver Assistance Systems

A systematic assessment on the energy efficiency enhancement of ADAS at powertrain level

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Thesis Summary

The transition towards vehicle electrification and automation has become a significant discussion area in the modern automotive industry, encompassing substantial research efforts in academia and investments from industry stakeholders. Energy management for hybrid and electric vehicles is crucial for improving fuel economy, reducing emissions, and meeting more stringent environmental regulations. Various approaches, including rule-based, optimization-based, and AI-assisted methods, have shown promise in enhancing vehicle performance and efficiency, being adopted on many production vehicles nowadays. Other power management and energy optimization techniques have been explored to address environmental concerns by impacting the usage of the vehicle during its operation. Additionally, vehicle automation and connectivity have been studied for their potential impact on energy consumption, with research focusing on areas such as eco-driving, platooning, and intersection management.

However, the wide variation in study designs and implementation methods has led to differing predictions, highlighting the need for more comprehensive and application-specific research to accurately assess the energy efficiency benefits of advanced driver assistance systems (ADAS) on electrified powertrains. On this end, laboratory testing represents a powerful tool to implement a systematic performance assessment of integrated controllers that leverage ADAS to improve the effectiveness of energy management at the vehicle level.

The first aim of this work is to address the challenge of establishing a testing setup to evaluate the performance of ADAS-aided energy management. The contributions of this work on the topic are represented by the setup of a Vehicle-in-the-Loop (ViL) test on a state-of-the-art Powertrain Testbed and the definition of a testing methodology to obtain repeatable results on energy efficiency for a battery electric vehicle (BEV) and a light-duty commercial vehicle. Considering the vehicle as a whole in the testing loop is nowadays considered a standard procedure for ADAS validation, especially during the final calibration steps performed on track tests. This type of testing campaigns are costly and lack the coverage of the entire range of operational scenarios; thus, ViL testing has gained traction as a viable approach to support the vehicle-level testing of ADAS functionalities. This approach is traditionally combined with Chassis Dynamometer test rigs, which are well-suited to perform functional verification of safety and comfort but lack the powertrain dynamics testing

opportunities opened up by modern Powertrain Testbeds. The proposed testing method, which aims to fill the gap highlighted in literature, is a ViL setup to evaluate ADAS features for energy-efficiency on a Powertrain Testbed. This novel method consists of a stage of powertrain efficiency mapping, enabled by the high-dynamics road load emulators, where a baseline for energy and fuel consumption of the vehicle-under-testing is established in a repeatable manner. Then, the vehicle mounted on the testbed is equipped with sensors' stimulators coupled with a complete virtual environment running in the backend. This combines the testbed vehicle model with a full-scale simulation of the operational scenarios (i.e., vehicle-following for ACC testing, lane departure for LKA, etc.), where the powertrain response comes directly from the real hardware on the testbed.

The second objective is to propose novel integrated controllers to implement energy management and ADAS functions on real prototypes to be tested in the ViL setup. From this point of view, this work has aimed to contribute to the research effort of providing more integrated solutions to control electrified powertrains, integrating vehicle automation and driving assistance technologies. This scope has been approached from the control engineering point of view by proposing controllers that can perform the integration between the two domains of powertrain control and ADAS. The analysis of the rich state-of-the-art on the topic highlighted that the problem has been solved with two different approaches: eco-driving and automated eco-control. The former has the advantage of being easily integrated with normal production vehicles through Human-Machine Interfaces (HMI) and mostly relies on Vehicle-to-Everything (V2X) infrastructures. The main drawback is the user acceptance, which also impacts the energy-efficiency performance obtained. Nevertheless, the eco-driving solutions are an important technology to support mid-term integration of energy-efficient assistance systems on vehicles already on the road. The second approach, which is based on automated control, is the one adopted for the development of the proposed solutions. The possibility of controlling the vehicle with a model-based controller that features a combined description of the vehicle's surroundings, and its powertrain dynamics has been recognized as the most effective solution to implement energy-efficient ADAS. It has been demonstrated that this approach holds the best performance in energy optimization when the solution is obtained in a predictive control framework. Accordingly, Model Predictive Control (MPC) was selected as the technique to develop the two proposed adaptive cruise control (ACC) strategies, namely the MPC-ACC and the Energy-Efficient Predictive ACC (EEPACC).

The work resulted in the deployment of the controllers developed on rapid prototyping ECUs for vehicle-level testing on two vehicle prototypes, a light-duty commercial ICEV and an M-class BEV. The prototypes have been integrated with ADAS sensors to solve the environment perception problem and rapid prototyping ECUs to implement the assisted driving functions. The combination of the MPC-ACC proposed, and the Vehicle-in-the-Loop (ViL) testing setup on a Powertrain Testbed allowed to showcase the full potential of energy consumption reduction achieved by the predictive controller on the BEV. The results of the experimental campaign showed an energy reduction capability of up to 10% in common urban scenarios by adopting a spacing policy in the MPC routine with a headway time of 2.5 seconds. The value of headway time is chosen to constrain the maximum spacing allowed in an urban scenario, which is kept under 50 meters not to negatively impact the traffic flow. The outcome of this work is to have verified in a controlled laboratory environment the energy improvement introduced when vehicle automation is integrated with powertrain control, which represents a novel contribution in the field.

Keywords: *Energy Management, ADAS, Testing, Powertrain Testbed, Energy-Efficiency*