EVERLASTING

Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

# D8.12 – White Paper 09

August 2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 713771

Public

| PROJECT SHEET | |
|---|---|
| Project Acronym | **EVERLASTING** |
| Project Full Title | Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management |
| Grant Agreement | **713771** |
| Call Identifier | H2020-GV8-2015 |
| Topic | GV-8-2015: Electric vehicles' enhanced performance and integration into the transport system and the grid |
| Type of Action | Research and Innovation action |
| Project Duration | 48 months (01/09/2016 – 31/08/2020) |
| Coordinator | VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK NV<br>(BE) - *VITO* |
| Consortium Partners | COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES<br>(FR) - *CEA*<br><br>SIEMENS INDUSTRY SOFTWARE SAS<br>(FR) - *Siemens PLM*<br><br>TECHNISCHE UNIVERSITAET MUENCHEN<br>(DE) - *TUM*<br><br>TUV SUD BATTERY TESTING GMBH<br>(DE) - *TUV SUD*<br><br>ALGOLION LTD<br>(IL) - *ALGOLION LTD*<br><br>RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN<br>(DE) - *RWTH AACHEN*<br><br>LION SMART GMBH<br>(DE) - *LION SMART*<br><br>TECHNISCHE UNIVERSITEIT EINDHOVEN<br>(NL) - *TU/E*<br><br>VOLTIA AS<br>(SK) - *VOLTIA*<br><br>VDL ENABLING TRANSPORT SOLUTIONS<br>(NL) – *VDL ETS* |
| Website | www.everlasting-project.eu |

| DELIVERABLE SHEET | |
|---|---|
| Title | **D8.12 – White Paper 09 - Energy Management for Electromobility** |
| Related WP | WP8 (Dissemination and Exploitation) |
| Lead Beneficiary | TU/E |
| Author(s) | G.P. Padilla Cazar (*TU/E*)<br>M.C.F Donkers (*TU/E*) |
| Reviewer(s) | All partners |
| Type | Report |
| Dissemination level | PUBLIC |
| Due Date | M36 |
| Submission date | August 31, 2019 |
| Status and Version | Final, version 1.0 |

| REVISION HISTORY | | | |
|---|---|---|---|
| Version | Date | Author/Reviewer | Notes |
| V0.1 | 12/08/2019 | Paul Padilla (TU/E) | Main author |
| V0.2 | 12/08/2019 | Tijs Donkers (TU/E) | Review |
| V0.3 | 19/08/2019 | Sebastian Ludwig (TUM),<br>Matthieu Ponchant (Siemens)<br>Dominik Jöst (RWTH)<br>Didier Buzon (CEA)<br>Klaas de Kramer (VITO) | Review |
| V0.4 | 22/08/2019 | Tijs Donkers (TU/E) | Final version |
| V1.0 | 31/08/2019 | Carlo Mol (VITO)<br>Coordinator | Submission to the EC |

**DISCLAIMER**

The opinion stated in this report reflects the opinion of the authors and not the opinion of the European Commission.



The commercial use of any information contained in this document may require a license from the owner of that information.

All EVERLASTING consortium members are committed to publish accurate information and take the greatest care to do so. However, the EVERLASTING consortium members cannot accept liability for any inaccuracies or omissions nor do they accept liability for any direct, indirect, special, consequential or other losses or damages of any kind arising out of the use of this information.

**ACKNOWLEDGEMENT**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 713771

# TABLE OF CONTENTS

# LIST OF FIGURES

# Introduction

The EVERLASTING project (http://everlasting-project.eu/) will develop innovative technologies to improve the reliability, lifetime and safety of lithium-ion batteries by developing more accurate and standardized battery monitoring and management systems. This allows predicting the battery behavior in all circumstances and over its full lifetime and enables pro-active and effective management of the battery. This leads to more reliability and safety by preventing issues rather than mitigating them. To raise the awareness of the vital and positive role of battery management systems, a three-monthly white paper will be written on different BMS topics, aimed at a general technical public. These white papers are a few pages long and will be distributed via the EVERLASTING website and through the partners.

The first white papers focused on typical battery topics, such as BMS functions, the definition of State-of-Charge and State-of-Health and how to evaluate them. This white paper focusses on the need for energy management on the vehicle level so as to mitigate range anxiety, which is present when batteries are used in electric vehicles.

# 1 Electromobility

In the last years, the electrification of transport systems has raised as a promising approach to mitigate effects caused by the environmental role of transportation and to face the imminent depletion of fossil fuels. If the electricity consumed by electric transportation systems is produced from renewable energy sources, the impact on the reduction of CO2 emissions is direct. Under the same assumption, it is expected that electric transportation drastically reduces the high oil dependency of the modern society [1].

## 1.1 Definition

The electrification in automotive sector has been studied as electromobility in [2], which can be defined as vehicles that are propelled by electricity. This is a simple yet broad definition due to the fact that not only encircles (hybrid) electric vehicles (EV), this definition also includes vehicles that obtain energy form the grid or converts other energy sources to electricity, such as biomass and hydrogen. Hence, the term electromobility allows for flexibility of the electrified vehicles to have different energy sources [2].

## 1.2 Adoption

The evolution of the EV market in the recent years have opened the door for optimistic predictions about the future market for electromobility. For instance, in 2016. the EV made up 29% of the market in Norway, while in China, the number of EV units increased from 100.000 in 2014 to 650.000 in 2016 [2]. This tendency indicates that by 2030 electromobility might reach a stage of mass market adoption. This global optimism is also supported by the novel research announcements related to batteries, charging infrastructure and energy efficiency in vehicles.

## 1.3 Challenges: Mitigation of Range Anxiety

The goal of a complete acceptance of electromobility in the market is still far and several problems need to be solved. It has been identified that one of the main reasons that limits the penetration rate of EV in the market is range anxiety [3,4]; which is defined as the concern (experienced by users) that the vehicle has insufficient energy to reach the next charging station [2]. There are several factors that influence range anxiety, e.g., limited capacity of batteries to store energy, weather and traffic conditions that affects drastically the prediction of the remaining driving range [5], limited number of charging stations and the time- consuming charge process [6]. As a response to these factors, the mitigation of the anxiety range can be achieved by a combination of the next approaches:

- Lightweight and energy dense batteries.
- Fast charging.
- Extended charging infrastructure.
- Energy management strategies (EMS).

The use of lightweight and energy dense batteries is the most logical choice to reduce the energy anxiety effect by extending the driving range of the EV. Similarly, the extension of charging infrastructure and the development of fast charging technologies aim to reduce the range anxiety by offering the user the possibility to always have a reachable charging station where the charging process is performed in a reduced time, which is resembles the functionality of the current gas stations.

Vehicle energy management complements the other approaches to mitigate range anxiety. Vehicle energy management aims at extending the driving range of the vehicle by maximizing the energy efficiency during its operation. For instance, by using regenerative braking energy directly for the climate system, instead of storing the energy it inside the battery first and use it later, energy can be used in a more efficient way, as the energy is not dissipated in the battery (due to ohmic losses). For most of the cases, these strategies can be applied directly as software in the vehicle. Hence, the implementation cost is marginal. For this reason, energy management strategies have been a topic of intensive research in the last years and defines the global scope of the contents treated in this white paper.

# 2 Energy Management Strategies

Energy efficient operation of vehicles can be described as the solution to an optimal control problem that aims to obtain the optimal conversion of energy between the energy consumers in the power network of the vehicle. As previously stated, the main advantage for these strategies is that in principle they could be easily implemented in vehicles. In the following sections we will provide a description of the state of the art in term of the different kind of EMS.

## 2.1 Classic EMS

Traditionally, energy management problems are focused on controlling the power split between the combustion engine and the electric machine of a hybrid electric vehicle. By storing regenerative braking energy and shifting the operating points of the combustion engine, a significant amount of fuel can be saved. In [7], [14, Ch. 4] optimization techniques for energy control on hybrid vehicles are summarized. Furthermore, the books [9,10] present a complete introduction of this research area.

Classic EMS literature can be classified in an ad hoc solutions and optimal control approaches. Additionally, the optimal control approaches can be subdivided into off-line and on-line control problems.

### 2.1.1 Ad-hoc solutions

The set of EMSs that are included in this classification are normally characterised to be computationally fast, which make them suitable candidates for on-line implementations. Historically, this type of approaches was the first to appear in EMS literature [17,18]. Fuzzy logic [11] and neuron networks [12] are popular strategies among this classification. The disadvantage of these strategies is that the performance of the systems is sensitive to changes in operation, and the global optimality of the solution cannot be guaranteed. Nevertheless, some authors are currently proposing solutions to properly recalibrate these strategies using dynamic programming (DP) [13], thus obtaining an acceptable approximation of the global solutions.

### 2.1.2 Off-line optimal control problems

The EMSs under this category are normally used as benchmark solutions for specific applications or configurations of the optimal control problem since that global optimal solutions are typically achieved.

A representative optimization technique in this category is Dynamic Programming (DP) [14]; for instance, in [15], applying DP forces the convergence to the global optimum of the energy management problem proposed. However, DP has the inherent disadvantage that the computational burden increases with the number of states.

Optimization methods based on the Pontryagin's Maximum Principle (PMP), see, e.g., [16,17] can handle computational complexity of multi-state energy management problems. In PMP, the problem is reduced to solving a two- point boundary value problem, which can be difficult to solve in the presence of state constraints. Moreover, the global optimality of the solutions obtained can only be guaranteed if the formulation of the optimal control problem is convex. Similarly, static optimization methods can guarantee a global optimality only for convex approximations of the energy management problems, e.g., see [18] and the references therein.

Finally, it is important to remark that the EMS that belong to this classification need to have a priori complete information related to driving cycle. This is the main reason that limits the use of this EMS approach for on-line implementation. On-line implementation require modifications and are often based on estimates or predictions of the driving cycle.

### 2.1.3 On-line optimal control problems

In this case, algorithms that requires a low computational effort are described. Furthermore, the requirement of a priori information related to the velocity and road profile is relaxed, which normally leads to suboptimal solutions.

In [19,20] stochastic DP is used to performance an off-line calculation of the optimal EMS, which is given by a stochastic policy that is implemented as a look-up table in a low computational power embedded system. A fast-computational approach that uses PMP is known as the equivalent consumption minimization strategy (ECMS) [21]. In this strategy, the energy consumption in the battery is transformed into an equivalent fuel consumption, which is represented by a co-state function related to the battery energy. The co-state can be estimated at every time instant, thus eliminating the necessity for the complete driving profile information in advance. Consequently, ECMS can be implemented on-line. However, updating the co-state is a delicate task that often produce to suboptimal solutions. Model predictive control (MPC) is also used to implement on-line EMS [22,23]. A finite-time horizon prediction of the future the energy consumption is used to calculate optimal control strategy, from which only the first control decision is implemented. A successive execution of this procedure obtains a suboptimal energy management policy that depending on the quality of the predictions can be very approximated to the optimal solution.

## 2.2 Complete Vehicle Energy Management (CVEM)

In general, the classic EMS approaches consider only a reduced set of subsystems, i.e., the power interaction between the internal combustion engine, electric machine and batteries. This motivated the emergence of the CVEM concept. CEVM aims to extend classic EMS approaches to incorporate more subsystems in the optimal control problem. The extra degrees of freedom added to the problem, makes CVEM appealing to be used in fully electric vehicles, where the power split between the electric machine and the combustion engine has disappeared.

CVEM was first proposed in [9] and a deep discussion about the difficulties using classic EMS techniques to solve the CVEM problem was also presented. For instance, DP can provide global optimal solutions to CVEM problems, however, scalability becomes an issue due to the curse of dimensionality observed in this technique. Similarly, the inherit set of state constraints presented in the CVEM problem makes PMP approaches difficult to be used for this application. As a consequence, centralized [10] and distributed optimization approaches have been proposed to satisfy the requirements imposed by the CVEM concept [11,12].

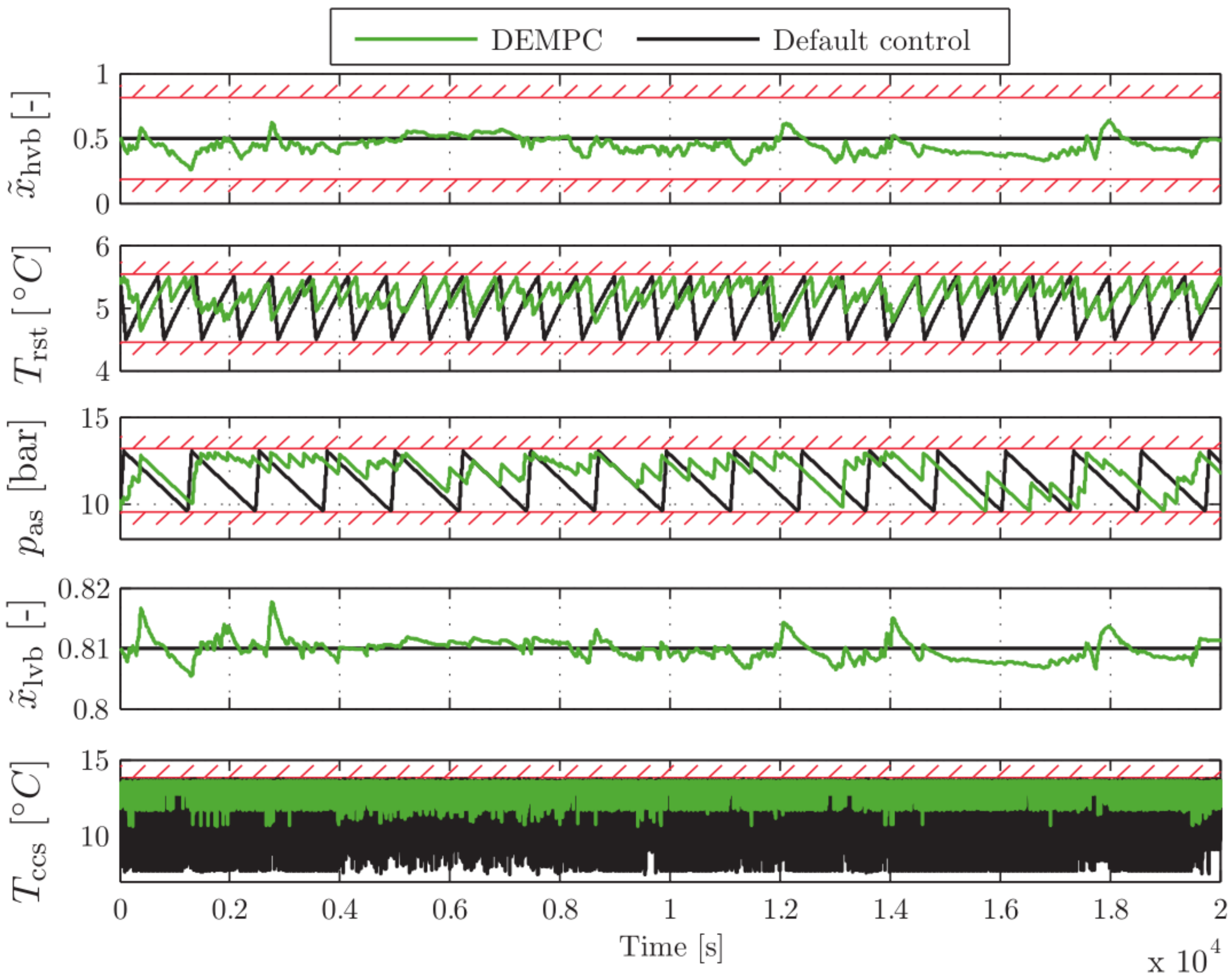


**Figure 1: CVEM strategy for a hybrid truck presented in [39].**

In [38], a case study of CVEM was presented on a hybrid truck with a low-voltage and a high-voltage battery, a climate control system, a refrigerated semitrailer and air-pressure system. The results of applying a distributed CVEM strategy are presented in Figure 1. The results reported shows that depending of the case the energy savings can go from 6% to 10%.

## 2.3 Eco-driving

In the approaches mentioned above, the vehicle velocity (and thereby the power needed to propel the vehicle) is often assumed to be completely given. Still, the vehicle inertia, which is the largest energy buffer in the vehicle can have a large impact in energy savings and consequently in the extension of the driving range. For instance, in [24] it has been reported that changes in driving behavior could improve the energetic performance of the vehicle more than 30%. These promising improvements in energy efficiency have contributed to the emergence of the eco-driving concept, which aims to increase the energy efficiency of a vehicle by means of a convenient selection of driving strategies; i.e. laws, technological implementations or simply changes in the driver's behavior. Hence, it is clear that eco-driving is a broad definition where government, manufacturers and users participate [25]. The problem of optimizing the velocity profile (in isolation form the other subsystems in the vehicle) to achieve optimal energy consumption has been considered for conventional vehicles in [26]–[28], for hybrid electric vehicles by [29], [30], and for electric vehicles by [31]–[35].

Eco-driving solutions have been widely implemented in Eco-Driving Assistance Systems (EDAS). Depending on the method used to influence the driving profile, the implementation of eco-driving solutions can be seen as an advisory system, where the driver receives suggestion to adjust the driving style to save energy consumption [36] or as adaptive cruise control (ACC) system, where the vehicle takes control on the velocity profile [37].

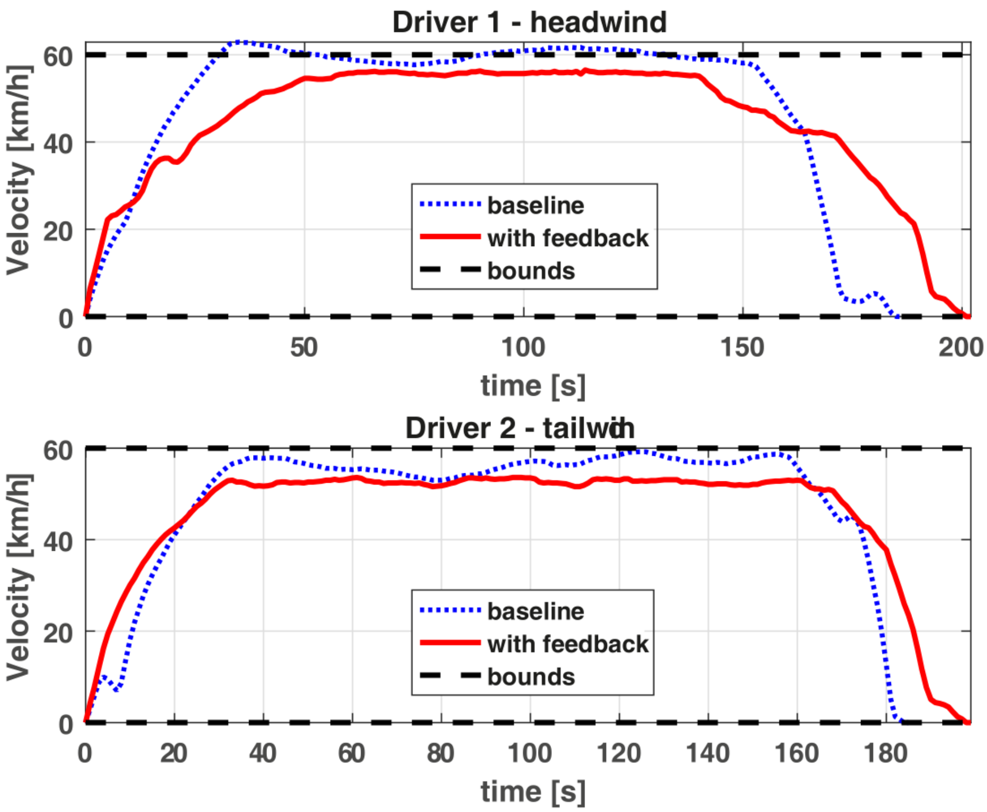


**Figure 2: Eco-driving implementation for an Electric City bus presented in [40].**

In [39], and online implementation of eco-driving for an electric city bus is presented. In this case study the bus driver received visual assistance to drive close to the optimal velocity profile. The energy consumption of the bus where the driver was compared to a base line where the driver did not receive any visual feedback is presented in Figure 2. It can be observed that the velocity profiles of obtained in the cases where the driver was being assisted by the eco-driving algorithm are smother. In fact, in those cases the average energy savings reported are approximately 11%.

# CONCLUSIONS

In this white paper we have highlighted the role of EMSs to mitigate range anxiety in electric vehicles. Two specific cases mentioned in this paper have shown that EMSs could let to energy savings up to 11% which can be directly mapped to range extension of the vehicles. Additionally, we have introduced a complete survey that classifies and describes the state of the art in EMSs that can be currently found in literature.

# REFERENCES

[1] "Global EV Outlook 2017," International Energy Agency, Tech. Rep., 2017.
[2] A. Grauers, S. Sarasini, and M. Karlstrom, "Why electromobility and what is it?" in Systems perspective on Electromobility, B. Sanden and P. Wallgren, Eds., 2012.
[3] "Electric vehicles in Europe," European Environment Agency, Tech. Rep., 2016.
[4] "Electric vehicles in Europe: Gearing up for a new phase?" McKinsey & Company, Tech. Rep., 2017.
[5] A. Editors, "Electric vehicles and range anxiety," Access Science, 2014.
[6] D. Watzenig and B. Brandstatter, Eds., Comprehensive Energy Management – Eco Routing & Velocity Profiles, ser. Springer Briefs in Applied Sciences and Technology. Springer International Publishing, 2017.
[7] A. Sciarretta and L. Guzzella, "Control of hybrid electric vehicles," Control Systems Magazine, 2007.
[8] "Model-Based Supervisory Control for Energy Optimization of Hybrid-Electric Vehicles," in Control System Applications, L. Guzzella and A. Sciarretta, Eds., 2009.
[9] B. d. Jager, T. v. Keulen, and J. Kessels, Optimal Control of Hybrid Vehicles, ser. Advances in Industrial Control, 2013.
[10] L. Guzzella and A. Sciarretta, Vehicle Propulsion Systems. Berlin, Heidelberg: Springer, 2013.
[11] H. Hannoun, D. Diallo, and C. Marchand, "Energy management strategy for a parallel hybrid electric vehicle using fuzzy logic," in Proc. International Symposium on Power Electronics, Electrical Drives, Automation and Motion., 2006.
[12] Z. Chen, C. C. Mi, J. Xu, X. Gong, and C. You, "Energy Management for a Power-Split Plug-in Hybrid Electric Vehicle Based on Dynamic Programming and Neural Networks," IEEE Transactions on Vehicular Technology, 2014.
[13] J. Peng, H. He, and R. Xiong, "Rule based energy management strategy for a series–parallel plug-in hybrid electric bus optimized by dynamic programming," Applied Energy, 2017.
[14] D. P. Bertsekas, Dynamic programming and optimal control. Athena Scientific Belmont, 1995, vol. 1.
[15] R. Wang and S. M. Lukic, "Dynamic programming technique in hybrid electric vehicle optimization," in Proc. of IEEE International Electric Vehicle Conference, 2012.
[16] T. H. Pham, J. T. B. A. Kessels, P. P. J. v. d. Bosch, R. G. M. Huisman, and R. M. P. A. Nevels, "On-line energy and Battery Thermal Management for hybrid electric heavy-duty truck," in American Control Conference, 2013.
[17] S. Ebbesen, P. Elbert, and L. Guzzella, "Battery State-of-Health Perceptive Energy Management for Hybrid Electric Vehicles," IEEE Transactions on Vehicular Technology, 2012.
[18] B. Egardt, N. Murgovski, M. Pourabdollah, and L. J. Mardh, "Electro- mobility Studies Based on Convex Optimization: Design and Control Issues Regarding Vehicle Electrification," Control Systems Magazine, Apr. 2014.
[19] T. Leroy, F. Vidal-Naquet, and P. Tona, "Stochastic Dynamic Programming based Energy Management of HEV's: An Experimental Validation," Proc. IFAC World Congress, 2014.
[20] P. Elbert, M. Widmer, H.-J. Gisler, and C. Onder, "Stochastic dynamic programming for the energy management of a serial hybrid electric bus," International Journal of Vehicle Design, 2015.
[21] G. Paganelli, S. Delprat, T. M. Guerra, J. Rimaux, and J. J. Santin, "Equivalent consumption minimization strategy for parallel hybrid powertrains," in Proc. IEEE Vehicular Technology Conference.
[22] H. Borhan, A. Vahidi, A. M. Phillips, M. L. Kuang, I. V. Kolmanovsky, and S. D. Cairano, "MPC-Based Energy Management of a Power- Split Hybrid Electric Vehicle," IEEE Transactions on Control Systems Technology, 2012.
[23] R. S. Vadamalu and C. Beidl, "Online MPC based PHEV Energy Management using conic interior-point methods," in Proc. of IEEE Intelligent Vehicles Symposium, 2016.
[24] C. Bingham, C. Walsh, and S. Carroll, "Impact of driving characteristics on electric vehicle energy consumption and range," IET ITS, 2012.

[25] B. Seraens, "Optimal Control Based Eco-Driving: Theoretical Approach and Practical Applications," Ph.D. dissertation, Katholieke Universiteit Leuven, 2012.
[26] D. Maamria, K. Gillet, G. Colin, Y. Chamaillard, and C. Nouillant, "Optimal eco-driving for conventional vehicles: Simulation and experiment," in IFAC World Congress, 2017.
[27] F. Mensing, R. Trigui, and E. Bideaux, "Vehicle trajectory optimization for application in ECO-driving," in IEEE VPP Conference, 2011.
[28] N. J. Kohut, J. K. Hedrick, and F. Borrelli, "Integrating traffic data and model predictive control to improve fuel economy," IFAC Proceedings, 2009.
[29] N. Murgovski, L. Johannesson, X. Hu, B. Egardt, and J. Sjoberg, "Convex relaxations in the optimal control of electrified vehicles," in American Control Conference (ACC), 2015. IEEE.
[30] L. Johannesson, N. Murgovski, E. Jonasson, J. Hellgren, and B. Egardt, "Predictive energy management of hybrid long-haul trucks," Control Engineering Practice, 2015.
[31] N. Petit and A. Sciarretta, "Optimal drive of electric vehicles using an inversion-based trajectory generation approach," IFAC Proceedings, 2011.
[32] W. Dib, A. Chasse, P. Moulin, A. Sciarretta, and G. Corde, "Optimal energy management for an electric vehicle in eco-driving applications," Control Engineering Practice, 2014.
[33] J. Rios-Torres, P. Sauras-Perez, R. Alfaro, J. Taiber, and P. Pisu, "Eco-Driving System for Energy Efficient Driving of an Electric Bus," SAE International Journal of Passenger Cars - Electronic and Electrical Systems, 2015.
[34] A. Lajunen, "Energy-optimal velocity profiles for electric city buses," in IEEE CASE, 2013.
[35] Z. L. Tan, T. Wilhelem, H. Okuda, B. Levedahl, and T. Suzuki, "Computation of energy-optimal velocity profile for electric vehicle considering slope of route," in IEEE/SICE ISSI, 2015.
[36] Q. Cheng, L. Nouvelie`re, and O. Orfila, "A new eco-driving assistance system for a light vehicle: Energy management and speed optimization," in Proc. of IEEE Intelligent Vehicles Symposium (IV), 2013.
[37] A. Weissmann, D. Gorges, and X. Lin, "Energy-Optimal Adaptive Cruise Control based on Model Predictive Control," in Proc. of IFAC World Congress, 2017.
[38] T.C.J. Romijn, "A distributed optimization approach to complete vehicle energy management," Ph.D. dissertation, Technische Universiteit Eindhoven, 2017.
[39] J.C. Flores, G.P. Padilla, M.C.F. Donkers, "A Shrinking Horizon Approach to Eco-driving for Electric City Buses: Implementation and Experimental Results", in IFAC International Symposium on Advances on Automotive Control, 2019.