Data Driven Techniques for On-board Performance Estimation and Prediction in Vehicular Applications

Summary

The primary objective of this doctoral dissertation is to devise data-driven models for the purpose of performance evaluation within the domain of terrestrial transportation. The contemporary automotive industry is witnessing an increasing need for precise estimation methodologies, and data-driven models have surfaced as a viable solution. This dissertation puts forth three significant contributions to fulfil this requirement.

Initially, a virtual sensor is suggested for the purpose of promptly forecasting and supervising NOx discharges in diesel engine contexts, particularly during variable on-road driving conditions. The utilization of AI algorithms, specifically the XGBoost machine learning model, has demonstrated exceptional suitability and reliability in the execution of this task. The model has exhibited remarkable flexibility, robustness, and outstanding performance in predicting NOx engine-out. The implementation of this virtual sensor can be carried out on the engine control unit (ECU), thereby facilitating the uninterrupted monitoring and regulation of emissions. Subsequently, a simulated environment has been created to emulate the functioning of electric vehicles, with a specific focus on evaluating the performance of a two-wheeled electric vehicles. The global model employs the battery discharge current as an input variable and forecasts the instantaneous velocity of the vehicle. The battery model and vehicle dynamic model parameters were established via a calibration procedure utilizing data obtained from on-road experimental measurements. Through the integration of a battery model and a dynamic vehicle model, this environment facilitates a thorough evaluation of the overall performance, thereby assisting in the optimization and design decisions. Finally, a tool for estimating the optimal state-of-health (SOH) is presented for the purpose of managing battery systems (BMS). The development of the estimator involved the utilization of multiple Bi-LSTM neural networks. These networks were employed to leverage various datasets that contained time series of charge data with varying lengths across the entire SOC domain, creating a predictive tool that might be

smoothly incorporated into the Battery Management System (BMS). This tool accurately predicts battery cell lifetime by determining the optimal state of charge (SOC) window, thereby enhancing battery management efficiency and reliability.

The utilization of data-driven models presents notable benefits and enhancements within the realm of land vehicles. The provision of precise and up-to-date evaluations of diverse automobile parameters facilitates the implementation of improved control strategies and optimization methodologies. Moreover, these models serve to facilitate the practice of predictive maintenance, thereby enabling the timely identification of potential faults or degradation. In addition, they assume an essential role in the advancement of eco-friendly and energy-efficient vehicles through the facilitation of emission monitoring and the optimization of battery performance. To summarize, this dissertation presents innovative data-driven models for evaluating the performance of land-based vehicles. These models provide valuable insights and advancements in emission prediction, electric vehicle performance analysis, and battery health estimation. The applications of these models are crucial for enhancing vehicle efficiency, reducing emissions, and improving overall performance and reliability in the realm of land vehicles.

Review 1

Overall Rating of Thesis

Overall Rating: Based on your experience as a thesis evaluator, how would you rank this thesis among all theses you have evaluated so far?: B (between 10% and 20%).

Comments

The research work presented in the Thesis revolves around the application of data-driven modeling techniques to automotive estimation and prediction problems. This is an important topic that has been gaining a lot of attention in recent years and is contributing to advancing vehicle technology towards more efficient, safe, and sustainable solutions.

Best practices for data processing have been rigorously applied throughout the work, and the training and validation of the machine learning algorithms are clearly presented, which gives credibility to the results. Overall, this is a good Thesis with minor reviews needed regarding the contents. However, regarding the formatting and presentation there is room for significant improvement.

One of the research questions that is asked in the introduction is “What are the advantages of utilizing data-driven models over physics-based models?”. Answering this question is of course not a simple task, however, the reader would think that the presented work would provide new elements to help comparing the two approaches. Unfortunately, the question is not really addressed anywhere else in the Thesis. After an historical digression in Section 1.2 (that could probably be omitted in favor of a review of modern technology), Section 1.3 shortly describes physics-based models and data-driven models, without clearly comparing the two approaches. The literature review presented in the introduction is also quite scarce to formulate any answer to the aforementioned question. Comparing the results of the ML models to those of physics-based models (also taken from the literature), whenever possible, would help formulating an answer to the proposed question.

The author apologizes for any misunderstanding that may have arisen regarding the topic of matter addressed in this work. The formulation of the research question in this thesis was found to be inaccurate, as it failed to accurately depict the true objective of the study. The primary aim of this thesis is not to establish a comparison between the two modelling approaches (physics-based and data-driven techniques), but rather to employ data-driven models within the existing body of literature to investigate performance in the vehicular domain in the form of a papers collection.
Indeed, as shown in the following comment, the main research topic is the one stated in the title "Data Driven Techniques" through the development of advanced technologies and better in the automotive field through the exploitation of data-driven techniques.
For the sake of clarity, the research question posed has been modified, making the intent of the thesis work clearer.

In general, the structure of the work and the train of thought should be thoroughly reviewed to avoid digressions and repetitions, keeping the focus of the manuscript on the main research topic,

which is stated in the title “Data Driven Techniques” and again in Section 1.4 “contribute to the development of advanced technologies and improvements in the automotive sector by exploiting data-driven techniques”. In this regard, Chapter 3 could be completely removed without affecting the value of the work. It is not clear in what sense the model discussed in Chapter 3 is “a data-driven model for a lithium-ion battery-powered two-wheeler vehicle”, as it is in fact an empirical equivalent circuit model.

The author acknowledges the reviewer's intent in revising the structure of the thesis. However, the outline of the work consists of a paper collection, where each single research work is treated individually and requires a general framework.

The author acknowledges the debate presented in Chapter 3. The model of the electrically powered two-wheeled vehicle, utilising a lithium-ion battery, is based on an equivalent electrical circuit model. Nevertheless, the methodology to identify the structure and parameters of the model is based on a data-driven approach rather than relying on any predetermined knowledge of the battery system. The determination of the model's structure and parameters relies on the exploitation of measured input current and output voltage signals, hence offering significant benefits to battery researchers and engineers. Differently, the parameterization of physical models requires a corresponding background in chemical-physical experiments and skill. For the sake of clarity, the manuscript has been modified to take into account these elements.

It would be a good practice to clearly state the objectives and motivations only once (in the introduction, avoiding repetitions in the other chapters as much as possible) and collect all the relevant literature review in the introduction. A “Materials and Methods” Section dedicated to data processing, machine-learning models, and feature importance analysis, with particular reference to those used in the work, could also be included in the introduction. The more specific literature could still remain in each chapter, as appropriate.

The author acknowledges the value and efficacy of incorporating a specific part inside the introduction chapter that focuses on the materials and methods employed. Nevertheless, as explained in the preceding observations, this paper arrangement does not align with the appropriate structure of a paper collection structure. Indeed, the decision was made to maintain the existing structure, as this thesis opens up to a series of applications within the realm of vehicle performance investigation.

In Chapter 2, XGBoost is introduced without providing sufficient information about what kind of ML model it is. The reasons for choosing this particular ML model should be discussed in more detail. While the results prove the efficacy of XGBoost, it is still possible that other models would provide similar or better results. It is typically a good practice to test multiple ML models and provide a comparison, whenever possible.

The research objective is to assess and identify a predictive virtual sensing tool in the field of engines for automotive applications, therefore emphasizing the phenomenological side of the problem above the mathematical one. Diesel engines were chosen because there are more engine calibration parameters, and they offered a more reliable case study of the algorithm's predictive capabilities. Therefore, a single algorithm was chosen to validate the feasibility of the virtual sensor solution in connection to the engine control unit's real-time application. The authors express gratitude to the reviewer, and the research will continue to examine more algorithms.

In Chapter 4, a short technical review of SOH estimation methods with mathematical definitions would be very useful and the current state-of-the-art should be presented. Some more space should be dedicated to describing the tools that have been used for the implementation. It is only mentioned at the end of the Chapter that Matlab was used.

A short technical review of SOH estimation methods with mathematical formulations has been added to the introductive section of the relative chapter. Moreover, the literature has been extended with the current state-of-the-art concerning data-driven models for SOH estimation.

Finally, the English of the manuscript should be reviewed for some errors and typos. The attached document contains some suggestions for modifications.

The manuscript has been reviewed, and the attached document is taken as a reference. The author acknowledges several improvements has been reached thanks to the reviewer's suggestions. As far as the reviewer comments are concerned, for the sake of clarity and to facilitate a more straightforward presentation, table 4.3 has not been modified. However, references to the involved hyperparameters have been provided.

Review 2

Overall Rating of Thesis

Overall Rating: Based on your experience as a thesis evaluator, how would you rank this thesis among all theses you have evaluated so far?: A (between 5% and 10%).

Comments

The thesis presents the elaboration and development of data-driven models for the purpose of performance evaluation within the domain of terrestrial transportation: firstly, a virtual sensor is proposed of promptly forecasting and supervising NOx emissions in diesel engines; secondly, a tool for estimating the optimal state-of-health (SOH) is presented for the purpose of managing battery systems (BMS).
The manuscript, in an original way, deals with a very topical theme, using a rigorous methodology. The results are interesting and they open scenarios of on-board applicability.
The thesis's focus on data-driven techniques for performance estimation and prediction in vehicular applications is commendable, as it offers valuable insights into optimizing vehicle efficiency and reducing emissions. The integration of virtual sensors, electric vehicle performance models, and AI-driven SOH estimators presents promising solutions for enhancing vehicle management and sustainability. Additionally, the future work suggestions provide a clear roadmap for further advancements in the field. In fact, the future work section provides a comprehensive overview of potential research directions and improvements for each topic covered in the thesis. It is commendable that the future work suggestions are aligned with addressing real-world challenges in the automotive industry, such as fluctuating temperatures, battery behaviour, and the estimation of state-of-health (SOH). Overall, it is an impressive contribution to the automotive research domain.
The thesis is well written and the candidate, as far as I'm concerned, is admitted to publicly defend the doctoral thesis, subject to minor changes to be implemented by the candidate in the final version of the dissertation presented to the Examination Board.
Minor revisions:

1. In the thesis, it is essential to provide proper attribution for any equations used from external references and to explain the logic and proof behind the equations developed by the author. When incorporating equations sourced from external references, it is crucial to cite the appropriate sources and provide clear references for each equation. For equations developed by the author, it is necessary to provide a comprehensive explanation of the logic, derivation, and proof behind each equation.

   The author acknowledges the reviewer comment and the references to equations from external sources have been added.

2. In the first topic related to the development of a virtual sensor for estimating and monitoring NOx emissions, it is suggested to conduct a comprehensive experimental study involving varied controlled ambient temperatures. While this recommendation could enhance the estimator's precision, are there any specific challenges or considerations that may arise when conducting experiments in varied temperature conditions? Moreover, even if there are bibliographic references, I would like to suggest to add more details about the experimental campaign for NOx emissions, on test bench and on the road. In particular, an experimental set-up scheme, the sensors used, especially for

NOx, a scheme where is highlighted the position of the NOx sensor and characteristics of the engine analyzed could be added.

The exploration of various ambient temperatures during experimental trials has the potential to enhance the accuracy of the NOx estimation by the virtual sensor, thereby encompassing a broader range of operating conditions than those typically encountered by a vehicle during its routine on-road operation. Indeed, empirical evidence has demonstrated that lower ambient temperatures, specifically those below 10°C, have been associated with a notable rise in the emission of nitrogen oxides (NOx). This trend, however, diminishes as the temperature rises. The reliance on ambient temperature not only yields advantages in terms of the reliability and robustness of virtual sensor forecasting. Indeed, the performance of lean NOx traps and selective catalytic reduction (SCR) systems is influenced by ambient variables. Consequently, possessing sufficient understanding of these conditions can facilitate the creation of effective post-treatment controls. Conducting testing at various controlled room temperatures does not present any significant challenges, aside from the requirement of utilising air-conditioned equipment to establish the desired temperature conditions. Nevertheless, it is advisable to encompass the range of low temperature fields spanning from 0 to 10°C and extend it to higher temperature ranges, specifically from 20° to 30°C.
The experimental campaign is described in detail in the research paper https://doi.org/10.3390/en10121978, which is cited in the Material and Methods section 2.2. The authors have deliberately omitted this information to prevent plagiarism and to avoid burdening the physical treatment of the problem. However, a general outline of the conducted experimental campaign has been reported in the same section.

3. Pag.21 two times: “Kg” to be corrected in “kg”.

   Modified.

4. The suggestions for improving the estimation of state-of-charge (SOC) include the utilization of recursive estimation methods like the Kalman filter and data-driven methodologies such as artificial neural networks. While these techniques can enhance SOC estimation accuracy, have the potential challenges in implementing these methods in on-board Battery Management Systems (BMS) been addressed? How might the reliability and real-time adaptability of these methods be ensured in practical vehicular applications?

   In order to improve the accuracy of state of charge (SOC) estimation in battery management systems (BMS) for vehicular applications, advanced techniques such as the Kalman filter and artificial neural networks have been explored. However, the successful integration of these techniques necessitates a comprehensive approach that encompasses various factors including measurement accuracy, model complexity, adaptability, safety, and compliance to industry standards. The implementation of continuous improvement and adaptation strategies, informed by empirical data, plays a crucial role in guaranteeing the reliability and real-time adaptability of automotive systems in real-world situations. In order to tackle these challenges, it is sometimes necessary to foster collaboration among professionals specialising in battery technology, control system engineering, and data science. The enhancement of reliability and flexibility can be achieved through the continuous monitoring, feedback, and updating of SOC estimate algorithms, which are informed by real-world performance data.

In the Conclusion section, a comprehensive analysis of the on-board implementation challenges associated with BMS-related algorithms has been included.

5. Check the sentence at pag. 127: “Specifically, the proposed approach involves the development of virtual software that models the behavior of vehicle systems in both stationary and dynamic conditions, with the aim of achieving cost savings, performance improvements, and enhanced monitoring capabilities.”. In particular, the expression “virtual software”; is it right?

   The reviewer’s highlight points out a possible change for the “virtual software” definition among the proposed approach. The author intent was to comprehend all research works and contributions of the thesis in a single statement from a vehicular performance point of view. However, the “virtual software” might correspond to a commercial product which has been put on the market. In this case, it could be more appropriate talking about research approach and developed algorithms for predicting performance, achieving cost savings, and enhancing performance and monitoring improvements.
   The expression has been modified in favor of an appropriate definition of the developed tools.