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Universitet/högskola/företag Chalmers tekniska högskola	Avdelning/institution Mekanik och Maritima vetenskaper
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Nyckelord: 5-7 st Trip prediction, ML models, LSTM, energy optimization, electric vehicle fleet	

Preface

This project was financed by the energy agency and by CEVT AB (China Europe Vehicle Technology). The project has had a reference group consisting of Jonas Sjöblom (project manager, Chalmers), Morteza Haghir Chehreghani (Chalmers), Nikolce Murgovski (Chalmers), Niklas Legnedal (CEVT) and Shafiq Urréhman (CEVT). The manager from the energy agency has been Peter Kasche.

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Energimyndigheten

Sammanfattning

För att realisera energibesparingspotentialen med hjälp av elektrifierade framdrivningssystem måste många delsystem interagera effektivt. Energiledningssystemet (EMS) för framtida drivlinor kommer att behöva ta hänsyn till inte bara framdrivningssystemet (elmotor och förbränningsmotor), utan även hjälpsystem (t.ex. klimatsystem) samt andra krav (t.ex. utsläppskontroll). Genom att inkludera mer data än endast fordonsdata (såsom GPS-data, användarbeteendedata, etc) kan ett optimerat EMS uppnås. Ett ytterligare problem är att få förutsägelser om framtida körbeteende och detta har hanterats i detta projekt.

Projekt är ett samarbete mellan Chalmers tekniska högskola (Chalmers) och China Europe Vehicle Technology (CEVT) där CEVT levererade input och data till projektet och uppdaterade, optimerade strategier levererades från projektet till CEVT och samtidigt genererades kunskap som publicerades i vetenskapliga tidskrifter. Dessutom fungerade detta projekt som en möjliggörare för ökat samarbete mellan tre olika avdelningar på Chalmers och banade därmed väg för ännu starkare forskning inom energieffektiva transporter.

Projektet startade i januari 2020 med rekrytering av en doktorand. På grund av olika anledningar (inklusive pandemin) engagerades olika doktorander och postdoktorer, och projektet avslutades i April 2025. De flesta av resultaten nåddes och viktiga insikter uppnåddes samt publiceringen av flera tidskriftsartiklar.

Summary

To realize the energy saving potential using electrified propulsion systems, many sub-systems need to interact efficiently. The Energy Management System (EMS) for future powertrains will need to consider not only the propulsion system (electric motor and internal combustion engine), but also auxiliary systems (e.g. climate systems) as well as other requirements (e.g. emissions control). By including more available data than vehicle data (such as GPS data, user-behavior data, etc) an optimized EMS is achievable. One additional problem is to obtain predictions of future driving behavior, and this was be addressed in this project.

This project is a collaboration between Chalmers university of technology (Chalmers) and China Europe Vehicle Technology (CEVT) where CEVT delivered input and data to the project and updated, optimized strategies was delivered from the project to CEVT and at the same time generated knowledge was published in scientific journal papers. Moreover, this project acted as an enabler for increased collaboration between three different departments at Chalmers, thereby paving the way for even stronger research within energy efficient transportation.

The project started in January 2020 with the recruitment of a PhD student. Due to different reasons (including the pandemic), different PhD students and postdocs were engaged, and the project ended in April 2025. Most of the deliverables was reached and important insights were achieved as well as the publication of several journal papers.

Background

In recent years, the development of new Electric Vehicles (EV) has made a great contribution to reducing energy consumption and pollutant emission in transportation. One of the biggest challenges for EV is the design of the energy management system (EMS), which controls the power split between the ICE and the electric machine during a driving mission (trip). A lot of research has been done regarding EMS in many different areas also including machine learning and AI methods. One of biggest challenges is to find the optimal strategy for an ongoing trip, given partial knowledge on future events and disturbances. This becomes even more challenging when different forms of look-ahead data become available. Except standard GPS data, novel vehicles are expected to receive information on dynamic events, weather conditions, proximity to low- or zero-emission zones they will be able to communicate to other vehicles and infrastructures (V2X), etc.

These challenges cannot be met by one single technology only, but by interdisciplinary and long-term collaborations. This project will have the potential to significantly contribute to future EMS calibration by involving three different research areas as well as an OEM.

The project objectives included:

- Develop AI models that predict future driving patterns based on available (historical) data
- Develop AI models that predicts the reminder of a trip based on historical and present driving data
- Demonstrate energy reduction of 20% for a known trip

Project description

The project is divided into four work packages (WP) including:

- WP1 Collection of data and enabling of data transfer from vehicles to the simulations at Chalmers
- WP2 Generation of simulation results and combine this with available auxiliary data to develop various AI models that can predict future driving patterns.
- WP3 Development of EMS strategies to minimize energy usage given boundary constraints
- WP4 Evaluation and assessment of the EMS strategies on test vehicles that will run on test tracks, in traffic as well as in rest rig

Results

Results WP1 (Data collection and transfer)

To validate the models for real life applications and be able to ensure that they are leading to the end goal of improved energy efficiency with the knowledge of the upcoming journey(s), a new way of collecting the relevant data was needed. This resulted in that we created a GCP based cloud solution where the validation data from the demo vehicle was automatically uploaded as soon as the vehicle had Wi-Fi connection. The cloud data is arranged and sorted so that it is accessible for further evaluation afterwards. This data is not going to assist in the learning of the model since it is not going to be sufficient in size. Instead, a bigger database of driving data with 12 company cars that are recorded on a daily basis will be the basis for that. This will not be fully sufficient to train the models but will be the basis for validation of the model with known and many times repetitive journeys, but this is what can be achieved in the scope of the project.

The demo vehicle was equipped with a special version of energy planner and execution functionality that calculated the most energy efficient speed along the already known route and recorded it during the execution phase, in the end this is therefor already the solution that utilize the predicted route that is the outcome of the project as such. The identified journey in this version is calendar based or as a manual entry, this is the part that was to be updated with the predicted journeys that could add the new time and route of the next journey as an outcome of the project.

The energy efficient speed optimizer is a DP-based optimization done in MATLAB using the dpm.m function by ETH Zurich. The integration is done using RK4 in the spatial domain. Inputs are elevation and speed limit, and the states are speed, gear and "time offset" which is the relative time to the ideal duration on the route. The speed limit is based on the road speed limit but reduced to account for max speed due to road curvature, comfortability, road-friction, and speed bumps.

The cost function consists of minimizing change in speed, HV battery consumption and over-speeding penalty.

The energy savings compared to the ACC was in the range of 2-4%, however there are much higher potential in several of the tested use cases, proven by human driving with a learning-based behavior.

Results WP2 (development of AI models for trip predictions)

In this work package, we first developed a unified framework for trip destination prediction in an online setting, which is suitable for both online training and online prediction. For this purpose, we developed two clustering algorithms and integrated them within two online prediction models. We investigated the different configurations of clustering algorithms and prediction models on a real-world dataset. Our results show that both the clustering and the entire framework yield consistent results compared to the offline setting. Finally, we proposed a novel regret metric for evaluating the entire online framework in comparison to its offline counterpart. Using this metric, we showed that the proposed methods converge to a probability distribution resembling the true underlying distribution with a lower regret than all of the baselines. The results of this study were published in Machine Learning Journal [1].

In the following, we studied predicting future trip times and distances a vehicle will travel. For this purpose, we developed four methods: (i) an LSTM-based model for handling historical trip data, (ii) an attention-enhanced LSTM (At-LSTM) for improved prediction accuracy, (iii) a parallel LSTM framework for separate time and distance forecasts, and (iv) a parallel At-LSTM setup offering the highest precision with a significant error reduction. Our results show that the parallel At-LSTM model outperforms the basic LSTM model by 23.89 %with a 3.99 % error margin. Additionally, we adapted TimeSHAP to our framework, an explainability method used to analyze the learning and data sequencing processes of our models. These results have been published in an open archive (ArXiv) [2] and also submitted to the Journal of Engineering Applications of Artificial Intelligence [3].

Results WP3 (optimization of EMS strategies)

The work undertaken in WP3 resulted in the development of optimal energy management strategies for electrified vehicles. We developed two nonlinear model predictive controllers (MPC) for integrated propulsion and cabin-cooling management of electrified vehicles [4]. The MPCs were set to solve an optimal control problem, with the goal to minimize battery energy consumption while maintaining cabin-cooling comfort. A centralized MPC was developed to simultaneously address eco-driving and thermal management. It was set to achieve the theoretically optimal solution, in the expense of high computational load. To achieve computationally efficient and real-time implementable solution, a decentralized MPC was proposed where one control layer manages optimal eco-driving by planning vehicle speed in a hilly terrain, and another control layer manages cabin cooling and propulsion power.

The proposed methods have been showcased through two case studies, using an air-conditioning model that has previously been validated on a real system. The results show that both the centralized and decentralized MPC produce significant energy benefits while maintaining driving and thermal comfort. Compared to regular constant-speed cruise control that is equipped with a proportional-integral air-conditioning controller, the benefits to the battery energy earned by the centralized and decentralized MPC are in the order of 2.72% and 2.09%, respectively. Furthermore, compared with the centralized MPC, the decentralized MPC can achieve comparable performance in energy consumption and temperature regulation but with significantly lower computation effort.

Results WP4 (Implementation and assessment)

The verification with self-improving models in the vehicle was unfortunately not possible to perform due to the timeframe of the project which suffered some delays. At the time of the specific models being ready to implement the vehicle was no longer available for development purposes. However, the models were integrated in the iACC (Intelligent Adaptive Cruise Control) concept in a Zeekr 001 and verified in a vehicle test bed at Chalmers

It was already in WP1 development tests discovered that there is large potential for energy savings with a self-improving strategy. The energy efficient speed algorithm has been throughout the project been updated to make the implementation of it easier. The energy efficiency was only slightly improved; however, the computational effort was reduced to make it more suitable for real life applications. Focus was to find factors that can be used to optimize the difference between the theoretical and practical optimized speed. Two specific use cases with different challenges, “Albatross route” and “Bollebygd route” and multiple “drivers” concludes that there are both static optimization incorrectness as well as more subjective “driver” based learnings to identify and adapt for. The most important for the setup is to have identified a speed that will not be corrected by the driver since that causes the long-term plan to be less accurate. The “Albatross route” has a regulated speed that will be hard to follow even for someone experienced with the route as well as it has a lot of hidden corners and hills. The “Bollebygd route” is mainly wide hilly country road with good visibility and it will for many drivers feel safe to not compensate much at all for curves.

The first conclusion is that a “visibility in the curve” factor should be possible to add with a learning-based model since this where the “drivers” all compensate the speed when the visibility is poor, if the visibility is poor the curvature factor is not enough to compensate for the speed reduction that is desired.

The other observation in the use cases is that the compensation will need to be adapted for the different drivers individually and specially focus on to avoid a feeling of acceleration when the expectation is deceleration and vice versa. This “feeling” is very subjective and will be a challenge for a learning-based model to solve.

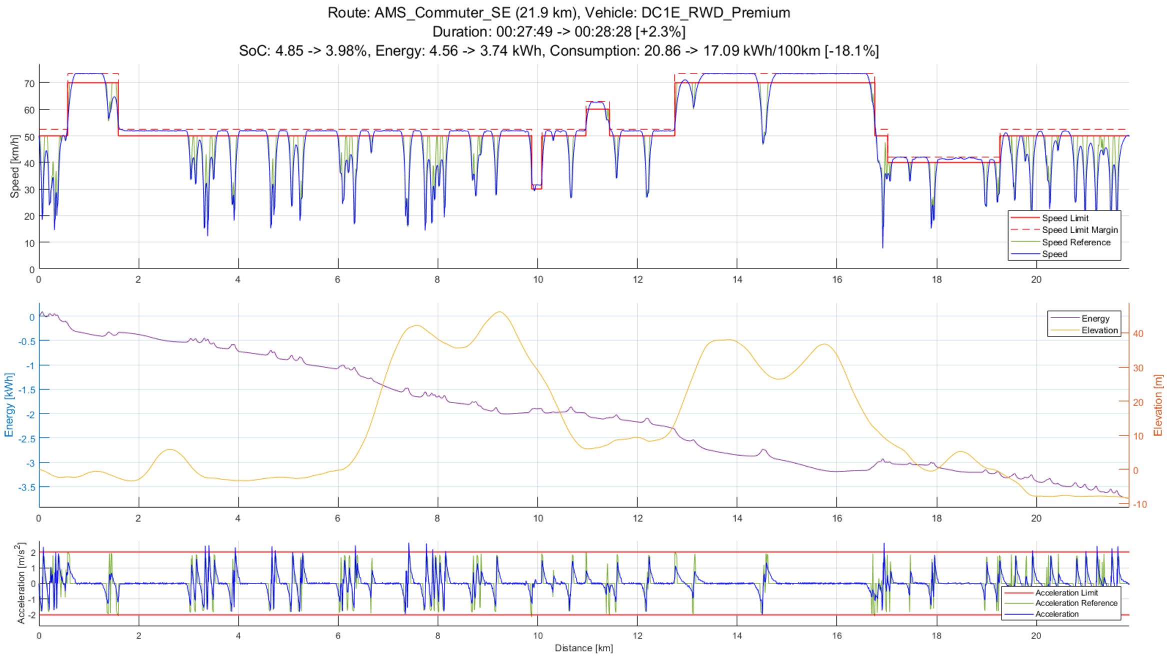
Results from the assessment tests

The purpose of the assessment test was to Validate proposed driving behavior and energy consumption in the vehicle in static conditions. The energy consumption was both estimated (modelled energy consumption in a simulated environment) and measured (actual measured energy consumption in a dyno rig at Chalmers).

The energy consumption was compared with and without the iACC[1] according to the table below.

Speed Profile	Speed Limits	Road Slope	Road Curvature
Without iACC	Close tracking	Ignored	Close tracking
With iACC	Tracking with margin	Considered	Smart tracking

Four different test routes were evaluated, and one example is displayed in the figure below.



The figure shows how the speed (and consequently the accelerations) is adjusted (green line) compared to the reference case (blue line). The trip duration is slightly increased, but the energy savings are significant. The results for the four different routes are shown in the table below.

[1] iACC (Intelligent Adaptive Cruise Control) is a feature found in Zeekr vehicles. It uses sensors and cameras to maintain a safe distance from the vehicle in front, automatically adjusting speed and accelerating or braking as needed, and is a core component of the "Intelligent Driving System" in Zeekr vehicles.

<table>
<tr><th rowspan="3">Route</th><th rowspan="3">Distance [km]</th><th rowspan="2">Duration</th><th colspan="3">Energy</th><th colspan="2">Difference</th></tr>
<tr><th colspan="2">Estimated</th><th>Measured</th><th rowspan="2">Time [%]</th><th rowspan="2">Efficiency [%]</th></tr>
<tr><th>With iACC</th><th>Without iACC [kWh]</th><th>With iACC [kWh]</th><th>With iACC [kWh]</th></tr>
<tr><td>AMS Commuter DE</td><td>21,7</td><td>00:26:57</td><td>6,1</td><td>5,2</td><td>5,1</td><td>+1,5</td><td>-14,8</td></tr>
<tr><td>AMS Eco DE</td><td>137,2</td><td>01:35:24</td><td>60,2</td><td>40,5</td><td>39,4</td><td>+0,8</td><td>-32,7</td></tr>
<tr><td>AMS Commuter SE</td><td>21,9</td><td>00:28:28</td><td>4,6</td><td>3,7</td><td>3,4</td><td>+2,3</td><td>-18,1</td></tr>
<tr><td>AMS Eco SE</td><td>110,5</td><td>01:34:27</td><td>29,6</td><td>23,0</td><td>24,1</td><td>+0,7</td><td>-22,3</td></tr>
</table>

The results show energy savings in the order of 20% (15% - 33%).

Discussion

The results from the different work packages have shown great potential for energy savings, in line with the project objectives. Many of the practical challenges have been solved, e.g. data acquisition, cloud solutions and data handling for large ML models. The final validation and system model assessment demonstrated energy savings for a pre-defined cycle in the order of 20%.

Different challenges also affected the project

- Personal resources: Due to the pandemic and other reasons, the project had to change researchers both at Chalmers and at CEVT.
- CEVT went through (unforeseen) both project changes and organizational changes and a new company Zeeker is now formed.

Publications

1. Eberstein, V., et al., *A unified framework for online trip destination prediction.* Machine Learning, 2022. 10.1007/s10994-022-06175-y DOI: 10.1007/s10994-022-06175-y.
2. Balouji, E., et al., *Prediction of Time and Distance of Trips Using Explainable Attention-based LSTMs*, in *arXiv:2303.15087*. 2023, arXiv.https://doi.org/10.48550/arXiv.2303.15087: https://doi.org/10.48550/arXiv.2303.15087
3. Balouji, E., et al., *Prediction of Time and Distance of Vehicle Trips Using Explainable Deep Learning*, Chalmers, Editor. 2024: Preprint submitted to Journal of Engineering Applications of Artificial IntelligenceMarch 9, 2024,
4. Ju, F., et al., *Integrated Propulsion and Cabin-Cooling Management for Electric Vehicles.* Actuators, 2022. **11**(12): p. 356, https://www.mdpi.com/2076-0825/11/12/356.

Appendix

- Administrative appendix ("Administrativ bilaga")