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Predictive Optimization Strategies by On-The-Edge Computing with Focus on Heavy Duty Trailers

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Executive Summary

With modern processors enabling powerful edge computing, real-time data processing in vehicles reduces reliance on cloud solutions with connectivity issues. This study explores predictive optimization using edge computing and digital twin technology to enhance energy efficiency in heavy-duty transport. Key functionalities include:

1. **Energy-based route selection** – optimizing routes via real-time vehicle data.
2. **Driving style adaptation** – dynamically adjusting driving behaviour.

Unlike traditional cloud-dependent models, the **Model Predictive Energy Optimizer (MPEO)** operates largely offline, leveraging a dynamic digital twin to analyse real-time parameters, optimize routes, and provide driving recommendations.
Initially tested through simulations, MPEO was validated in real-world conditions.
This research underscores the potential of edge computing and digital twins in improving energy efficiency for heavy-duty transport, reducing reliance on external connectivity and enabling real-time decision-making within the vehicle.

Keywords: Electric Vehicles, Heavy Duty electric Vehicles & Buses, Energy management, Climate change, Advanced control of EVs

1 Introduction

Energy efficiency is a key challenge in heavy-duty transport, particularly for electric and hybrid vehicles where optimizing energy usage directly impacts operational costs and range as well as CO2 emissions.

Current estimates suggest that 26% of CO_2 emissions from the transport sector in Germany are caused by heavy-duty vehicles [1]. Additionally, fuel costs are one of the main cost driver in the transport sector, therefore the overall transport cost depends highly on the fuel price [2].

Edge computing offers an alternative by enabling real-time data processing directly within the vehicle. This is particularly relevant for applications requiring fast feedback loops, such as predictive energy optimization.

This work introduces the MPEO tool, which integrates edge computing with a digital twin approach to optimize energy consumption. The tool provides two primary functions:

1. **Route Optimization** – Selection of the most energy-efficient route based on real-time vehicle parameters.
2. **Driving Style Adaptation** – Continuous monitoring and adjustment of driving strategies (including driver advice) based on real-time conditions and upcoming route profiles.

Previous approaches to energy consumption prediction for electric vehicles have largely focused on data-driven methods and machine learning. These methods use historical driving and consumption data to identify patterns and develop predictive models. One example is shown in the article "A Data-Driven Method for Energy Consumption Prediction and Energy-Efficient Routing of Electric Vehicles in Real-World Conditions" [3], which employs deep learning and historical telemetry data to provide accurate energy forecasts for urban delivery vehicles, taking into account traffic and weather. In another work [4] a quite similar approach was used to predict the consumption of electric vehicles. In this work measurement data of taxis were used as a database.
Another research direction involves the use of digital twins - virtual representations of real vehicles synchronized with live data. In the work "Energy Consumption Prediction of Electric Vehicles Based on Digital Twin Technology" [5] such a model that simulates consumption and vehicle behaviour in real time, allowing for the calculation of optimal energy paths, was developed.
For searching the most energy-optimal route, in another work [6] a high-fidelity consumption model was used to predict the energy consumption for several routes, to determine the most energy saving option.
Both studies highlight the great potential of digital twin technologies, though they are typically cloud-based, which introduces limitations regarding connectivity and real-time responsiveness - challenges that MPEO explicitly aims to overcome through its edge-computing architecture.

2 Methodology

2.1 Development of the MPEO Tool

The optimization process works as shown in the following figure.

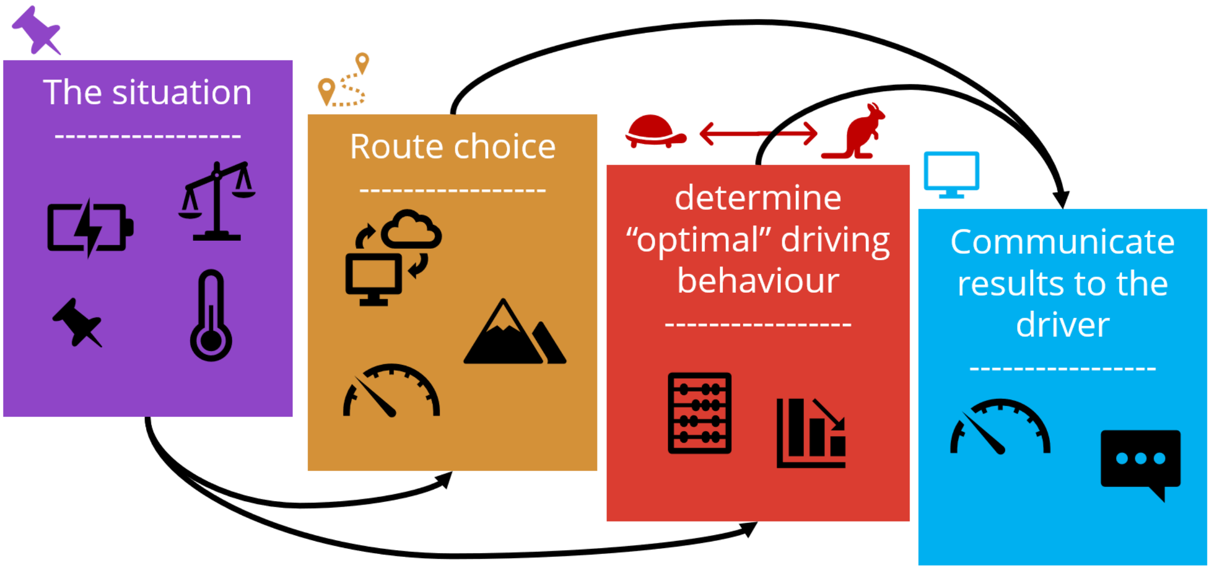

Figure 1: Process Flowchart

Before the optimization procedure starts, the current situation is detected. Therefore, it is possible to read in multiple sensor data, which can improve the simulation output of the digital twin, by adapting several parameters of the simulation to the real time measured data. With this improved digital twin (as described in section 2.1.2) two optimization steps are executed.

2.1.1 Communication to the driver

An intuitive user interface facilitates driver interaction and feedback delivery. During the ride, the driver gets informed about the optimal route. On top of that, MPEO gives advice to reduce energy consumption by adapting the driving style.

2.1.2 Digital Twin-Based Edge Computing

A digital twin is a virtual representation of a physical system that updates dynamically based on real-world data. In the context of heavy-duty transport, the digital twin can integrate information from multiple sensors or other sources, including:

- Battery state of charge (SOC)
- Vehicle mass (determined with onboard sensors)
- Ambient conditions (temperature, terrain, etc.)

By continuously synchronizing with real-world vehicle data, the digital twin allows the MPEO tool to predict energy consumption for multiple route options and recommend the most efficient one. On top of that, it is also used to create real-time recommendations for the driver based on the simulation outputs of the selected route. The consumption calculations of the digital twin are based on the following equations [7]:

- Rolling resistance F_R depends on the rolling resistance coefficient k_R and the normal force $F_{W,Z}$. Therefore, the mass of vehicles has a large impact on this resistance.

$$F_R = k_R * F_{W,Z} \tag{1}$$

- Air resistance F_L depends on the Air density ϱ_L, the drag coefficient c_W, the cross-sectional area A_V and the velocity v.

$$F_L = \frac{1}{2} * \varrho_L * c_W * A_V * v^2 \quad (2)$$

- Road grade resistance depends on the vehicle mass m and the inclination angle of the road α. g is the gravitational acceleration constant. As we see again, the vehicle mass has a large impact on this resistance

$$F_q = m * g * sin(\alpha) \quad (3)$$

- Acceleration resistance is calculated from the vehicle mass m, the inertial mass correction factor k_m and the acceleration a_x. Also, in this equation the vehicle mass takes a major role.

$$F_a = k_m * m * a_x \quad (4)$$

What currently is not considered is the effect of the cornering resistance. With this resistance the needed power is calculated. To calculate the needed power, an efficiency map of the installed powertrain is useful. Such an efficiency map can be defined for the whole powertrain or separately for single components.

- The total resistance F_W is the sum of the single resistance [8].

$$F_W = F_R + F_L + F_q + F_a \quad (5)$$

- The needed power, without considering efficiency losses, is calculated as follows [9].

$$P_W = F_W * v \quad (6)$$

- The needed power output of the battery can be calculated according to [10], η_G stands for the efficiency of the gearbox, η_{Mot} for the efficiency of the motor, η_{FU} for the converter and η_{Bat} for the efficiency of the battery.

$$P_{Batt} = \frac{P_W}{\eta_G \eta_{Mot} \eta_{FU} \eta_{Bat}} \quad (7)$$

- The needed energy from the battery over the time is calculated as [11].

$$dW_{Batt} = P_{Batt} * dt \quad (8)$$

2.1.3 Route Generation

To predict energy consumption for a route, the simulation needs a route profile as input. This profile is calculated based on information, which is loaded via an application programming interface (API) from **Open Route Service**. For this request the coordinates of the start point co_{start} and the end point co_{end} are needed. Based on this information, MPEO calculates different profiles such as the velocity $RoPr_v$, the pitch angle $RoPr_{alpha}$ and the curvature $RoPr_{curv}$ along the route. To consider the traffic, a traffic factor is defined for each road section. Currently the factor is set manually. Optimal would be to integrate the value as a real time value coming from an API. Events such as stopping on inner city roads for traffic lights or braking on highways are implemented as random happenings. The probability of those variables is based on the road type and the traffic factor ϵ_{trafic}. Also, other effects such as braking and accelerating due to curve drives, are considered during the profile generation. On top of that a factor for the adaptation of the driving behaviour $\epsilon_{behavior}$ is implemented. Based on this factor and the type of vehicle - which influence the moved mass $m_{vehicle}$ and the vehicle-specific speed limit v_{maxveh} -

both speed and acceleration are adjusted.
The profile generation is divided into five consecutive steps:

- Loading data from API and preprocessing of the data
- Adapting of the leading speed to the actual traffic situation
- Adding transient behaviour (low frequency acceleration with a high amplitude)
- Adapting the velocity behaviour caused by curves
- Adding high frequency transient behaviour

The dependence of the final velocity profile $RoPr_{curv}$ can be described as follows:

$$RoPr_{v,alpha,curv,\dots} = f(\epsilon_{trafic}, \epsilon_{behavior}, m_{vehicle}, v_{\max veh}, co_{\text{start}}, co_{\text{end}})$$

This tool is called **Route Profile Generator (RPG).**

2.1.4 Route choice

With the tools from 2.1.2 and 2.1.3 (the digital twin and route generation) different routing options are considered. Because MPEO works in real time in the car, the different routes considered cannot start directly from the actual position. The reason is that the car is moving during the calculations. Therefore, the starting point for the calculation 2 km ahead is taken. Afterwards different routes and their profiles are generated. The digital twin is then used to calculate the energy needed for the different routes. The route with the lowest energy consumption is selected.

2.1.5 Optimization of the driving behaviour

The selected route is precalculated with the digital twin. Based on the outcome the driving behaviour $\epsilon_{behavior}$ gets adapted. If the range is too limited to reach the desired destination, the driving behaviour is adjusted to extend the range until the destination becomes reachable. In case this is not possible in a realistic way, MPEO gives feedback to the driver, that the destination is not reachable under current conditions.

2.2 Test and Evaluation

As part of the development and evaluation of the prediction tool, various testing methods were applied to ensure both its functionality and accuracy. These included initial simulation-based testing in the office, followed by validation and real-world testing using measurement data and actual vehicles.

2.2.1 Simulation-Based Testing

First the tool is tested in the office by simulating the real vehicle with a digital twin in the background. The purpose is to estimate the potential of energy solving.

2.2.2 Validation of the prediction tool and the digital twin with measurement data as well as testing the tool itself on road

The route generation tool RPG, especially the generation of the velocity profile is validated with real world measured profiles between two points. Throughout the project a measurement campaign was made with a truck – trailer combination. Additionally, the profile generation tool was also validated with data from a passenger car. To validate the digital twins of the truck and the passenger car, the output of the digital twin is also compared with the measurement data, which at the same time serves as the validation of the entire prediction tool.
The tool was also tested in real world to validate the reliability of the MPEO. Because it is not possible to drive the same route under exact same conditions twice, it was not possible to validate impact of the driver advice regarding the driving behaviour. If the driver drives exactly how MPEO suggests, trivially the consumption would decrease as predicted, provided, the prediction is correct. To validate the impact of the driving behaviour advice on the consumption, a large-scale study would be necessary.

3 Results and Discussion

3.1 User Interface

The User Interface is available in two different versions:

- User Version – Provides real-time navigation and energy consumption insights.
- Developer Version – Includes additional technical data and debugging functionalities for system integration and testing.

In each version it can be selected, if MPEO gets used in real world or in office just for testing. If the “office – version” is chosen, a knob in the middle of the user interface pops up enabling the user to control the model in background. So, the knob emulates the gas and brake pedal.

3.1.1 User Version

- Left-Side: Destination input and consumption data visualization.
- Center: Vehicle status (SOC, range, speed, and recommended adjustments).
- Right-Side: Navigation and route recommendations.

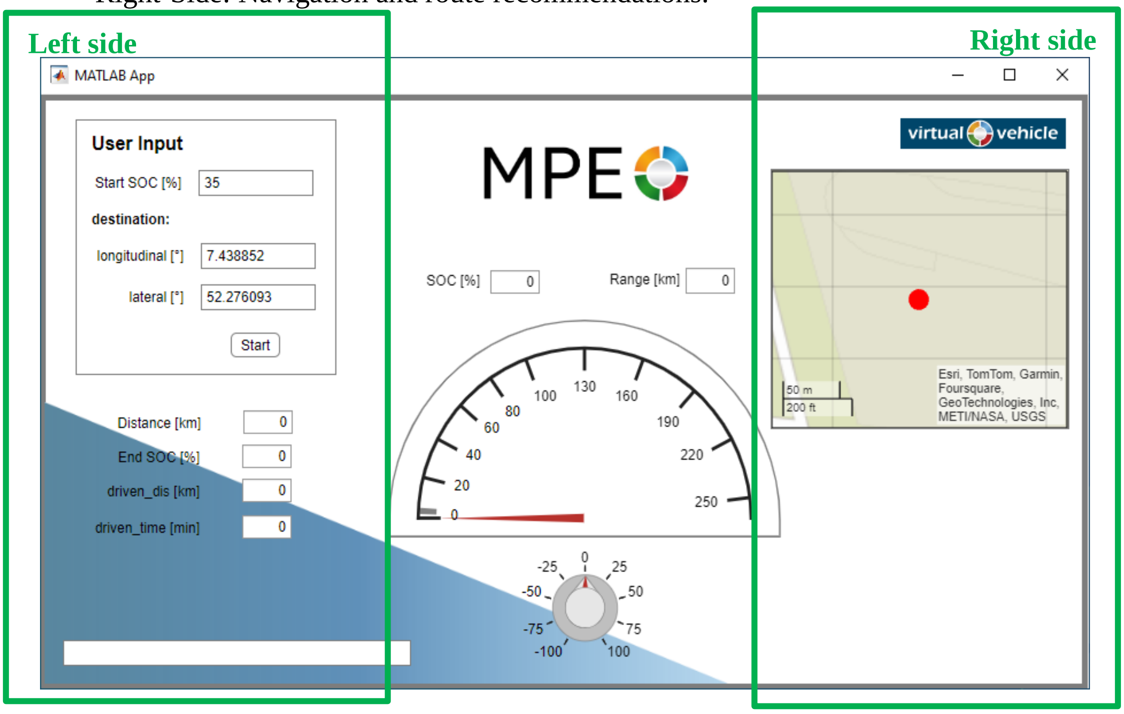

Figure 2: User Version of the UI

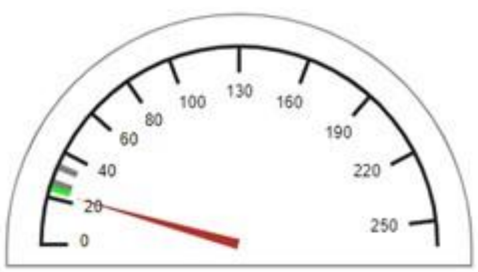

Figure 3: Feedback to the user

To give feedback and advice to the driver regarding the optimized velocity and acceleration behaviour, in the gauge appears a column in green or red colour. The green and red columns indicate energy-saving and energy-wasting driving styles, respectively. The column size describes the amount of energy saved or wasted.

3.1.2 Developer version

- Extended Data View: Displays additional vehicle parameters and system logs.
- Debugging Tools: Allows real-time inspection of energy models and algorithm outputs.

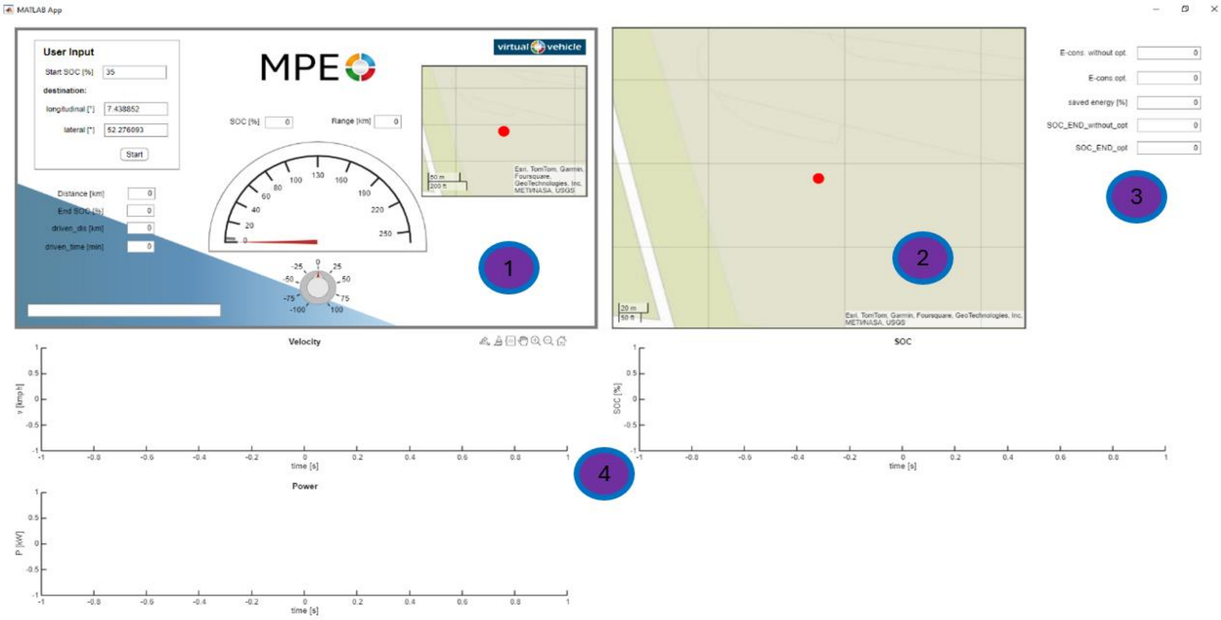

Figure 4: Developer version of the UI

Description:

- 1: general user interface
- 2: map including the whole route
- 3: overall route information – such as overall energy consumption and energy saving potential
- 4: overall route profiles

3.2 Simulation results

For simulation, a knob emulating the pedal position of a virtual vehicle appears in the user interface. With this knob the velocity of the simulation, which runs in background can be controlled.

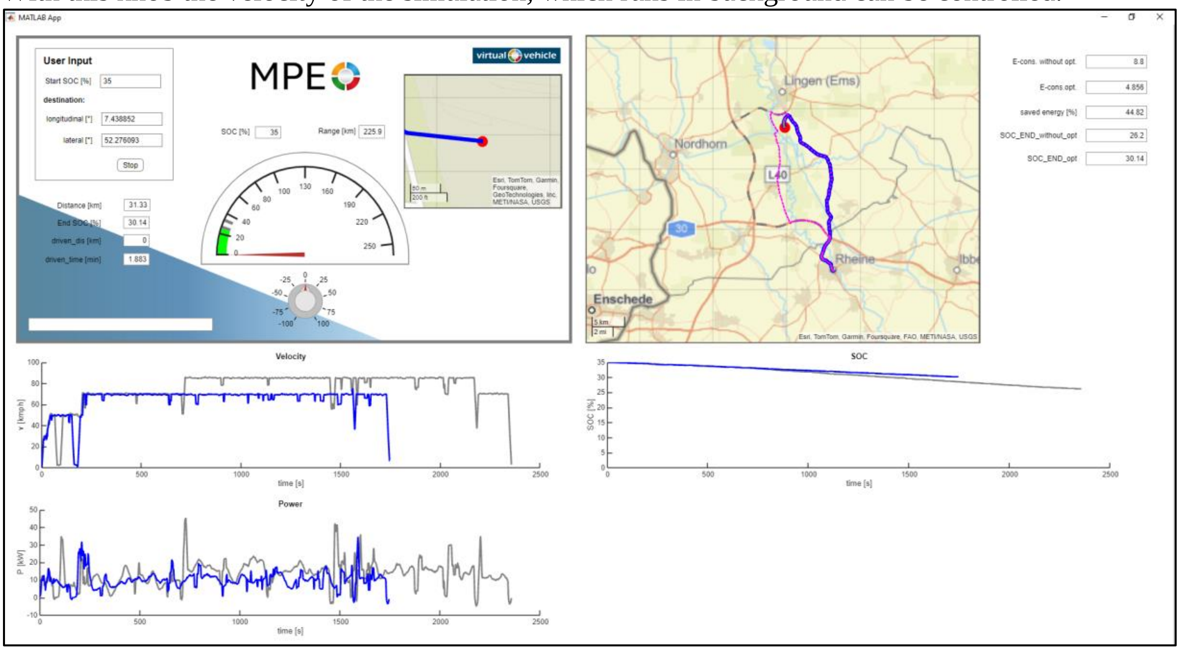

Figure 5: Simulation case 1: Lingen - Rheine

As known from the digital twin and RPG validation (see section 3.3), the results out of those tools match well with measurement data and therefore with real consumption. That means that the predicted saved energy matches reality. To get a feeling for energy saving potential, different routes were simulated in the office. The figure above shows the route from Lingen - Rheine, were the energy saving potential compared to the main chosen route is 44 %. That's a real exception, in general the potential is much smaller.

Table 1: Simulation results

Route	SOC_start [%]	SOC_end [%]	Consumption without optimization [kWh]	Consumption with optimization [kWh]	Difference [%]	Comments
Lingen - Rheine	35	30,1	8,8	4,8	44,8	Reduction because of new route
Graz - Wien	50	8,5	41,4	41,4	0	No decrease – SOC sufficient
Graz - Wien	35	3,61	41,4	31,6	23	Decrease due to efficient driving

3.3 Validation with real world measurements

3.3.1 Case1: Heavy Duty Truck

<u>Route generation:</u>

Figure 6 shows RPG results for the route from KRONE Future Lab in Lingen to Rheine.

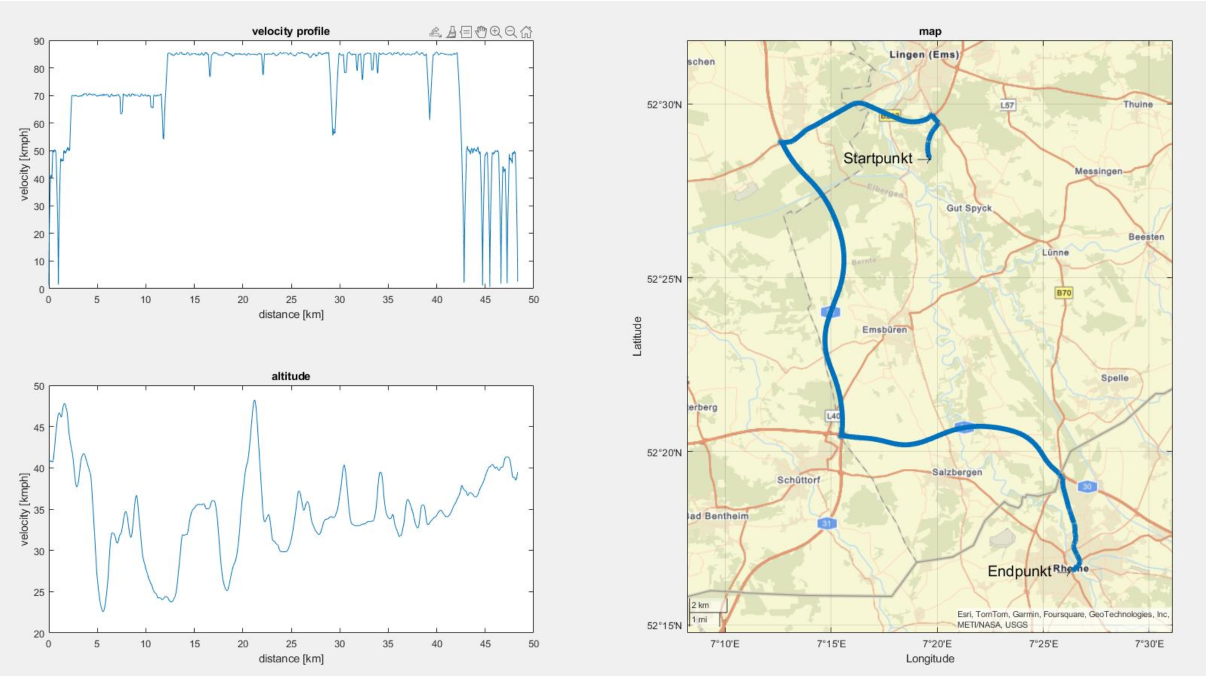

Figure 6: RPG results - Route, Lingen-Rheine

The route consists of different route types and therefore different traffic situations. The comparison of the calculated profile and the measured profile is shown in Figure 7. The ride starts on a small country road. The first crossing (number 1 in the figure) shows a junction from the first country road to another one. The second transition shows a highway entrance. The third significant turning point shows a highway intersection between two highways. The drop of the velocity plateau on point 4 represents a highway exit and the change to a country road again. As the validation shows, the profile generation works well. Of course, it does not fit exactly the measurement data because of unexpected events. Table 2 shows the accumulated data of the overall route, comparing measurement with calculation data. The deviation of the values is below 5%.

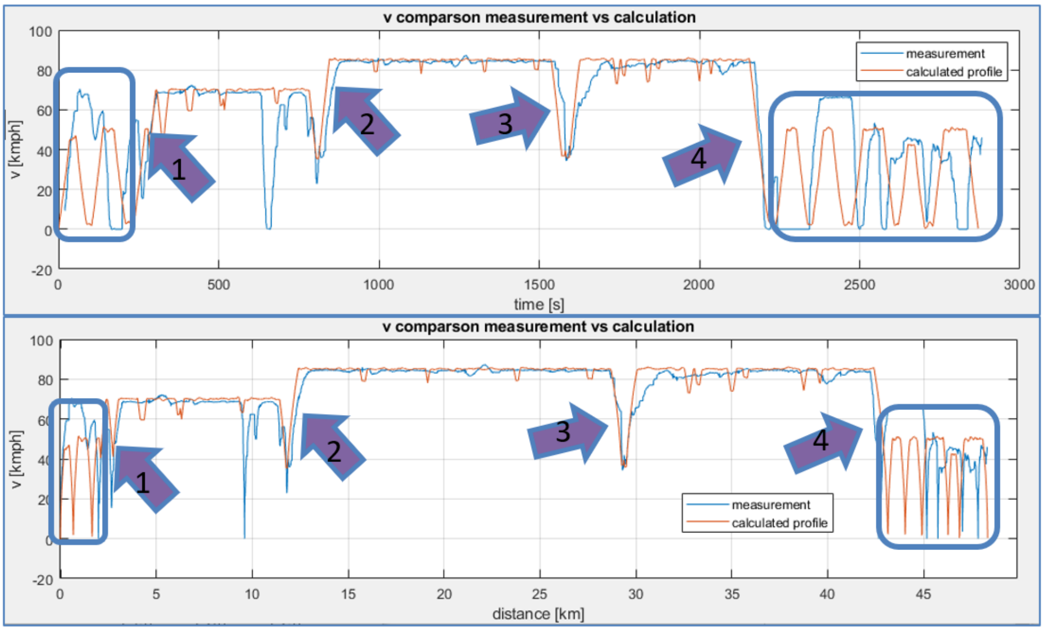

Figure 7: Comparison of the calculated and measured velocity profiles

<u>Overall predictive results:</u>

The generated velocity profile is used as input for the digital twin, which provides information about the consumption.

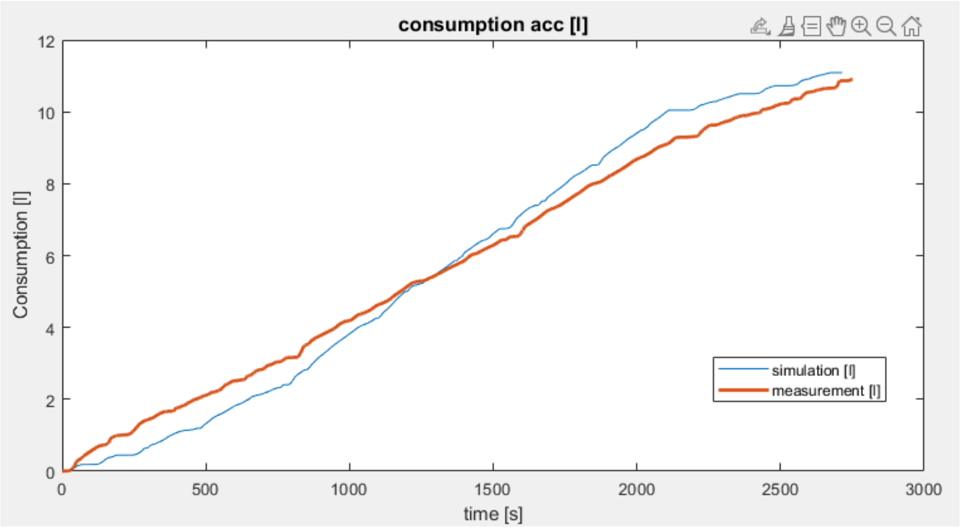

Figure 8: Comparison, simulated and measured consumption

Figure 8 shows the course of the consumption. In some points measurement and simulation differs a bit. That has several reasons. Thirst, the from the RPG generated velocity profile has events, which bases on random variables. Events as stopping for traffic lights doesn't match exactly with the measured profile, but the RPG tries to capture the real velocity profile over time. Second, the measurement of the Consumption in total is quite accurate, the measurement in small time intervals is less accurate. While the simulation is based on continuous models, the measurement relies on discrete data points. Minor discrepancies in short intervals are largely compensated during temporal integration. Table 2 shows the accumulated results of the simulation compared with the measurement.

Table 2: Validation of route generation: overall route information

	Ø-V [km/h]	time [h]	distance [km]	consumption [l]
measurement	63,1	0,77	48,5	11,0
simulation	60,6	0,8	48,3	10,9

3.3.2 Case2: Passenger Car

Route generation:

The route leads from Premstätten to the Merkur Arena in Graz (14,16 km) with a SOC at the start of 30%.

Figure 9: RPG results - Route, Premstätten - Graz, Merkur Arena

The route consists of living roads, land roads, highways and an intercity highway. The test was made with an electric vehicle (Renault C zero).

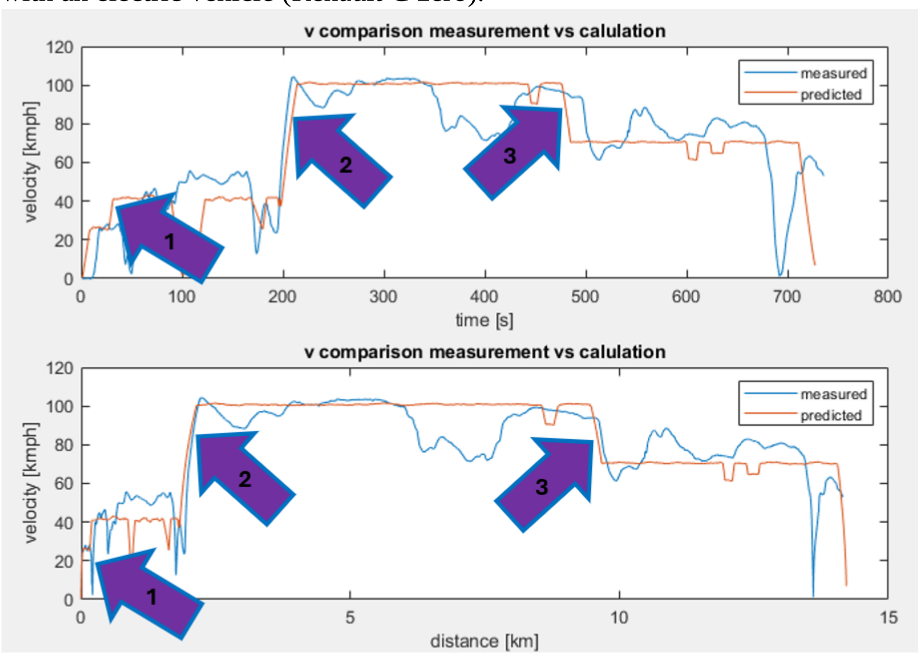

Figure 10: Comparison of the calculated and measured velocity profiles

The comparison of the calculated profile and the measured profile is shown in Figure 1.The ride starts on a small living road. The first crossing (number 1 in the figure) shows a junction from the living road to a country road. The second transition shows a highway entrance. The third significant turning point shows a highway intersection between the highway and the inner-city highway. Since the endpoint was set on a road, the calculated profile comes to a stop at the end, whereas the test driver had to continue driving through. That makes a small deviation in comparability of the two datasets.

In this case the deviation of the two profiles is much higher as in the first case. The reason for that are unpredictable events. 350 seconds after the start a construction area on the highway decreased the velocity. Shortly before the end a red traffic light caused and standstill, which was not predicted from the RPG.

Overall predictive results:

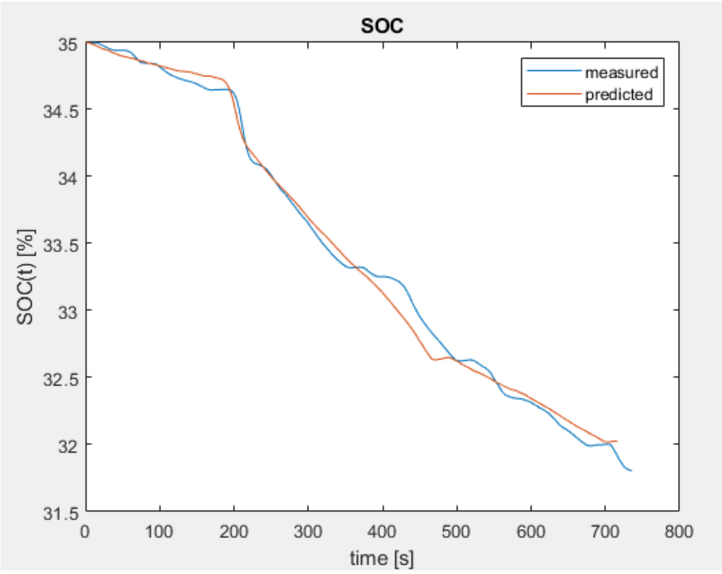

Figure 11: Comparison, simulated and measured consumption

In this case the predicted profile fits extremely well with the measured profile. Where differences can be seen around the 400ts second, where the construction area on the highway braked the vehicle down as well as differences at the end, which were described previously.

4 Conclusion and Future Work

This work demonstrates the potential of edge computing and digital twin technology for real-time energy optimization in heavy-duty transport. The MPEO tool provides an almost cloud-independent solution, enabling predictive energy management without requiring external data transmission.

Future research will focus on:

- Further refining the digital twin model with additional sensor data
- Further refining the information sources
- implementation of charging strategies for longer rides
- implementation of other target values, like desired arriving time
- Expanding real-world testing across various terrains and environmental conditions
- Using the potential of predictive calculations to control vehicle internal processes
- Potential assessment for integration in logistic related software environments

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Presenter Biography

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