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PRESENTATION OF A GENERAL PURPOSE SIMULATION APPROACH FOR ENABLING THE REALIZATION OF ELECTROMOBILITY CONCEPTS FOR THE TRANSPORTATION SECTOR

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ABSTRACT

The following paper describes an overall simulation method for the design of eMobility concepts for rail, road and coastal waters. The presented workflow enables the user to execute the realization process under the usage of real world elevation data and driving profiles. This is essential for the choice of a fitting battery and motorization. Additionally the charging infrastructure has to be chosen without changing anything on the existing driving schedule for electric buses. Taking a look at innovative and sustainable drive concepts completes the overview and indicates the direction for the implementation of eMobility in the near future without the need for big investments. With the shown software approach it is possible to answer the consumers cost questions and reduce their range anxiety for electric vehicles.

1 INTRODUCTION

Mobility, especially public transport on rail, road and in coastal waters is an essential factor in a modern society. It is absolutely necessary, that this happens resource saving and sustainable.

For the eMobility, in different applications, there are highly efficient drive-systems available, but none of them complies with one of the previously named aspects. Why? These systems are based on magnetic materials, like rare earth metals, which are causing a significant toxic impairment like radioactive waste during the mining process (often in developing countries). For judging the sustainability of a system, it is necessary to take a look at the whole production process with respect to the sum of used energy. This implies that a zero-emission and sustainable mobility has to be fitted to the needs of the raw materials producing countries, too. Sustainability is involving everything and everyone.

The described problem can be solved by a paradigm shift in drive technology and thus in the eMobility. Simple materials, like ferrite, which in fact have a smaller energy density and new drive concepts with much less material involved will lead to this goal. In combination with a flexible simulation tool it is possible to involve these strategies in concepts for a comprehensive realization of the future eMobility.

2 SIMULATION APPROCH

These days there are two main questions if you are asking people about eMobility:

- How far can I drive with my electric car?
- What does it cost in comparison to a combustion engine car?

Both questions can be broken down to one, if you have a look at the battery. Nowadays this is the bottleneck which limits the range of electric vehicles and drives the costs. So it is hardly surprising that private customers, but above service providers for the public transport, are currently not in the position to take the risk.

To minimize this risk it would be great to have a fast simulation tool for an assessment of the needed energy for a defined vehicle and a track from point A to point B. By knowing the needed energy for an application it is possible to design the needed drive system, battery size and after that determine the necessary charging infrastructure needed to fulfill the existing schedule. With such a tool it is for example possible to carry out eMobility Concepts for bus operators.

eMobility Concept *An eMobility concept is a workflow for public transport operators how they can electrify their fleet by offering energetic range analysis and point out the best positions for charging in respect to economic aspects.*

2.1 Physical Background

Independent of the used vehicle the total driving resistance forces $F_{r\,total}$ can be calculated by using Equation (1), which represents the sum of all single driving resistances $F_{r\,i}$ (Spiess 2005).

$$F_{r\,total} = \sum_{i=1}^{n} F_{r\,i} \tag{1}$$

A typical driving resistance for example is the grade resistance $F_{rg} = m \cdot g \cdot \sin(\gamma(s))$, which indicates how much of the weight of an object is accelerating it down a hill. Due to the fact that this force is depending on the actual angle of elevation $\gamma(s)$ of a corresponding position s, a longitudinal drive dynamic model is needed for calculation (Heißing 2011).

With a given accelerating driving force F_a, provided by a motor and the vehicles mass m, the acceleration $a = (F_a - F_{r\,total})/(m \cdot e_i)$ can be evaluated. The vehicle mass is multiplied with a mass factor $e_i \geq 1$ which represents the contribution of all rotating vehicle parts for acceleration and deceleration (Hoepke 2008). It can be neglected for vehicles with a low gear ratio for a first estimation.

The current position s and the velocity v can be calculated by a double integration of the current acceleration. These dynamic quantities can now be used in equation (1) for individually calculating all single driving resistances (Spiess 2005).

For a drive and battery design it isn't that interesting how fast you can drive with a vehicle, but it is necessary to know the needed power and energy from the battery. The kinematic drive input power $P_a = F_a \cdot v$ depends on the driving force F_a and the current speed v. During the acceleration period the power P_a is larger than zero. Instead of braking mechanically it is possible to slow down the vehicle by using the electric motor which acts as a generator in this case. Equation (2) provides the battery power by using the total drive train efficiency $\eta_{total\,xxx}$ (containing gearbox, electric motor, inverter and battery) for both cases.

$$P_{bat} = \begin{cases} P_a / \eta_{total\,acc} & for\ P_a > 0 \\ P_a \cdot \eta_{total\,rec} & for\ P_a \leq 0 \end{cases} \tag{2}$$

The consumed energy from the battery E_{bat} can now be calculated due to the fact that it is equal to the integral of the current needed battery power P_{bat}.

Figure (1) shows a transformation of the described physical correlation in a block diagram.

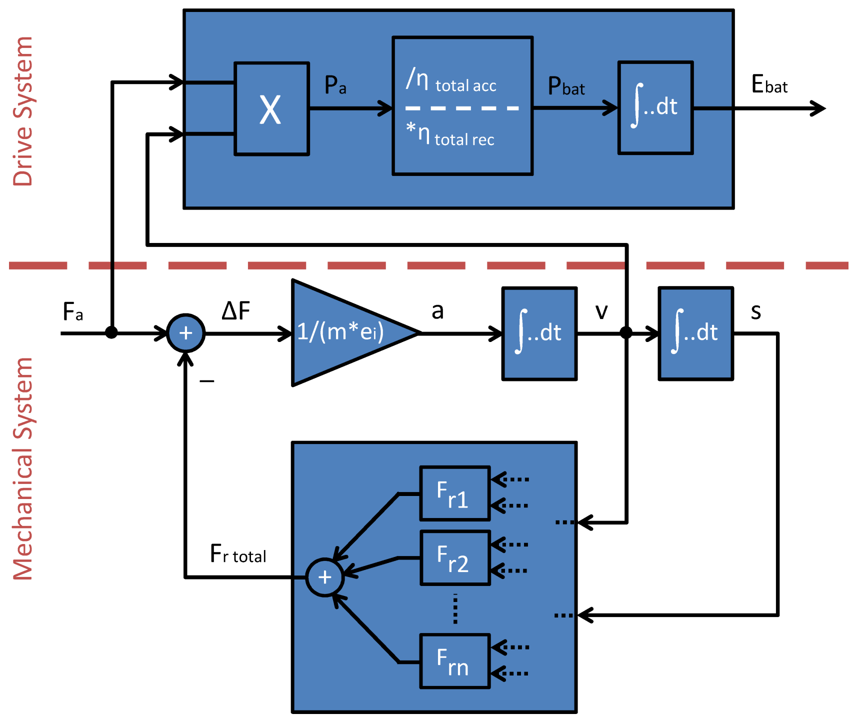

Figure 1: Load model structure.

With this consumed energy E_{bat} it is now possible to determine the current state of charge SOC of the battery by using the total battery energy amount $E_{bat\ total}$ in Equation (3).

$$SOC = \frac{E_{bat\ total} - E_{bat}}{E_{bat\ total}} \cdot 100\% \tag{3}$$

2.2 Required Parts

For the implementation of such a model there are several essential parts necessary. Some additional parts are required to replace the driver and let the model behave like a real vehicle.

2.2.1 Driving Load

In this part the kinematic equations are solved with respect to the total driving resistances. Like mentioned before the calculation of some driving resistances depends on the inclination data and so on the angle profile $\gamma(s)$ at the current position s of a vehicle.

Figure (2) shows an example elevation profile of a typical bus track. This profile has to be measured or generated, for example by a GPS device. Due to the fact that the measured data can be very noisy it has to be filtered before the calculation of the inclination profile.

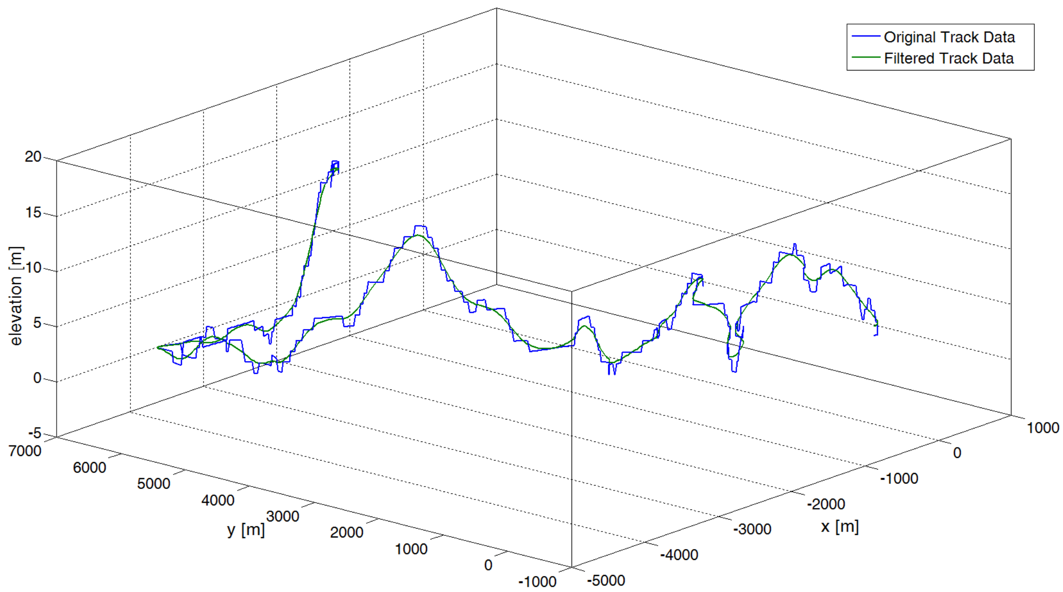

Figure 2: Elevation profile 3d.

For the calculation of the grade resistance it is necessary to convert this three dimensional track data into a two dimensional elevation profile like shown in Figure (3).

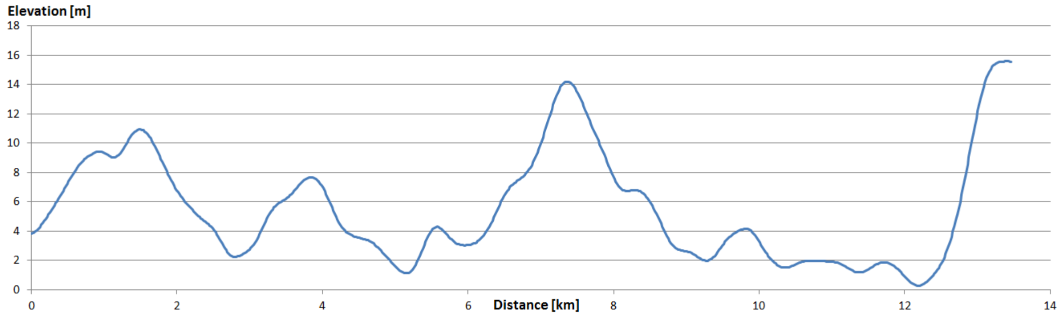

Figure 3: Elevation profile 2d.

With this elevation data the current inclination and so the angle $\gamma(s)$ can be calculated for every position s. For the previous example the corresponding inclination profile is shown in Figure (4). This data can be used in simulation as a lookup table for calculating the grade resistance.

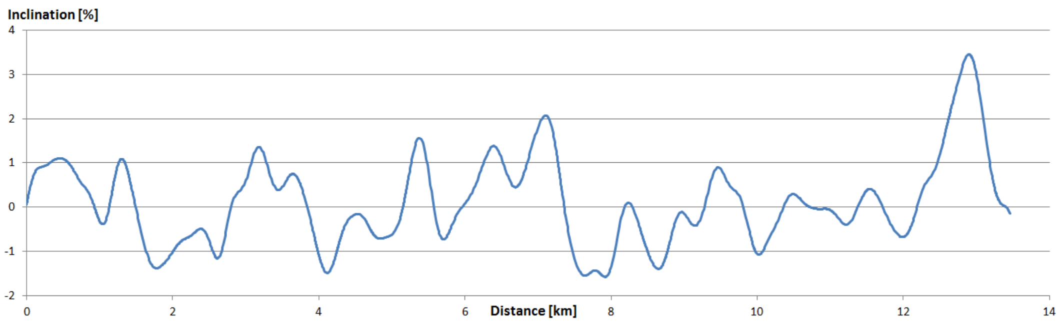

Figure 4: Inclination profile.

2.2.2 Battery

The battery is responsible for calculating the consumed energy. If the vehicle is accelerating the state of charge (SOC) of the battery is decreasing. When the virtual driver starts a braking maneuver, the energy flow reverses and the SOC starts increasing, which is called recuperation.

2.2.3 Motor

For driving with the virtual vehicle at a defined speed, a specific torque is required from the motor. The torque is transmitted into a force by the vehicles gearbox and tires, which results in an acceleration of the vehicle. By reversing the torque the motor acts as a generator and starts the recuperation process until standing still. The easiest possible simulated motor is a simple proportional block with torque limitations.

2.2.4 Driving Profile and Controller

The driving profile inherits the whole intelligence of a real driver. Therefore speed limits and expected stops at a given position are integrated into the driving profile. With this information the model is able to calculate at which position and with which torque value the vehicle has to accelerate or decelerate, for the best fit according to the made input specifications.

To achieve and hold the desired values, provided by the driving profile, the controller observes the current acceleration.

2.3 Simulation Model

According to the previously defined parts a simulation model can now be constructed. Figure (5) shows the overview mask where all required parameter settings can be done. The input parameters are for example the driving profile, the elevation profile and further driving resistance parameters.

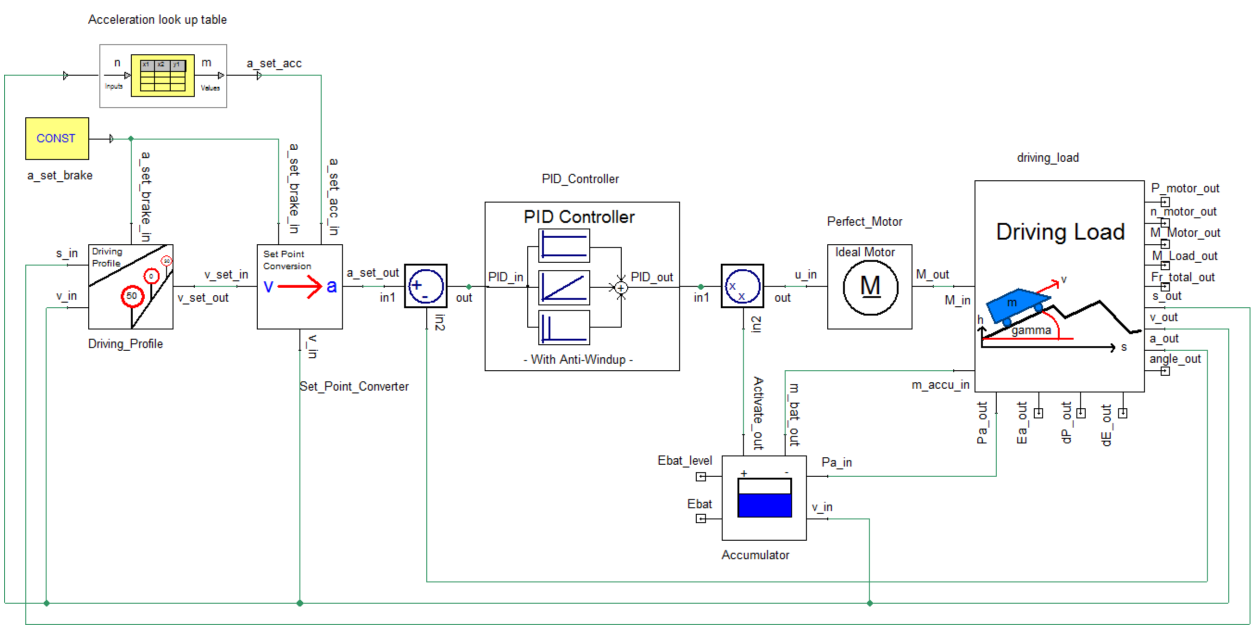

Figure 5: Simulation model overview.

2.4 Simulation Output

Every quantity which is calculated during one simulation can be used for post processing, but there are only a few which are needed for designing the drive train of a vehicle.

By having a look at the desired and actual speed of the vehicle in Figure (6) it is possible to check if the requirements made by the driving profile were achieved. On the contrary to a combustion engine an electric motor is able to recuperate kinetic energy during decelerating. This advantage makes often performed stops with an electric vehicle obviously less harmful.

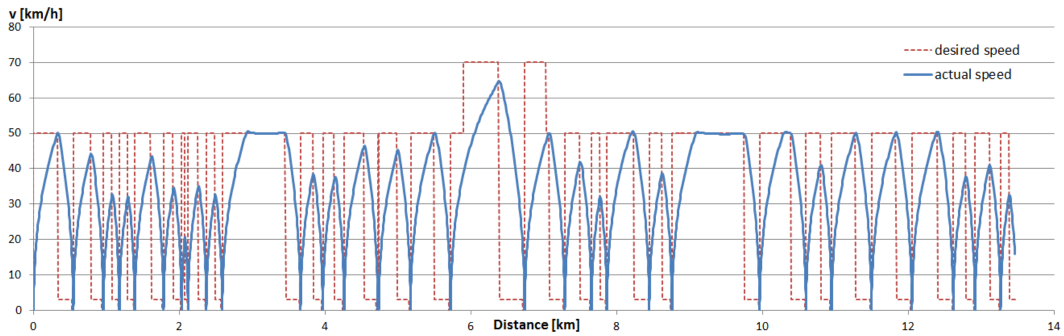

Figure 6: Vehicle speed.

Figure (7) shows the required power from the electric motor. Together with the speed characteristics from Figure (6) it is possible to design the drive train including the gearbox and electric motor for normal and overload operation.

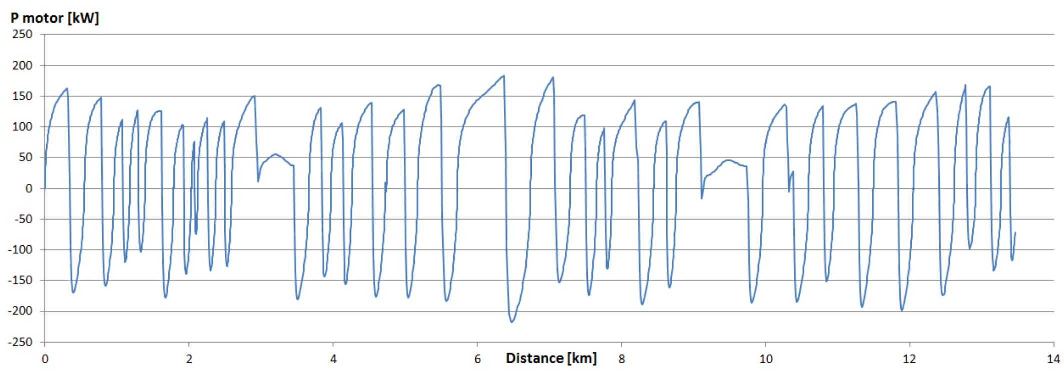

Figure 7: Required power.

After determining the required motor and gearbox size for a given vehicle it is very interesting to have a look at the consumed energy from the battery in Figure (8). It can clearly been seen that this energy curve has its most positive gradient during the acceleration periods by referencing to Figure (6). When the vehicle reaches its speed limit the gradient gets smaller, because no further acceleration is needed. During deceleration the energy curve has a negative gradient due to the fact that the negative power, shown in Figure (7), can be used for recuperation.

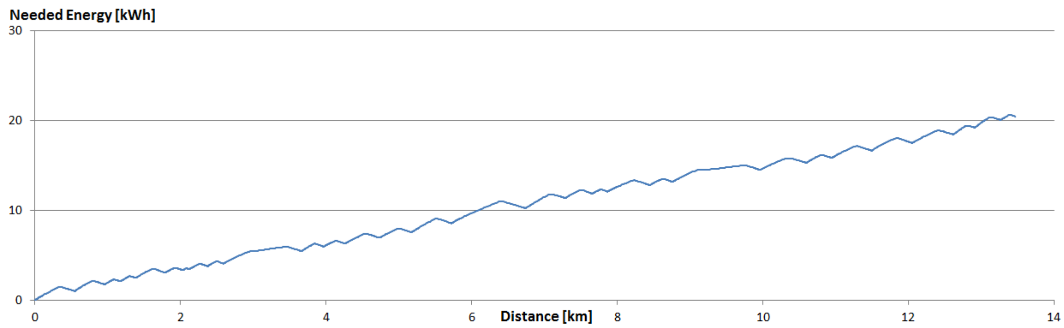

Figure 8: Needed energy.

With this energy it is possible to calculate the size and costs for a battery. Typical parameters and prices of lithium-ion batteries are noted in Table (1) according to (Oswal et al. 2012), (Albright et al. 2012), (Kleine-Möllhoff et al. 2012) or (VDI 2014). For the previous simulation example this would result in an lithium cobalt oxide battery with a weight of $110\ kg$ for the needed energy of $20.9\ kWh$. In respect to the required maximum power of $200\ kW$ you have to select a bigger battery with a weight of $500\ kg$ and a stored energy of $95\ kWh$. This leads to battery costs of $66500\ \$$ and a total possible vehicle range of $62\ km$.

Table 1: Typical parameters and prices of lithium-ion batteries.

	Lithium Cobalt Oxide	Lithium Iron Phosphate
Specific energy	$0.19\ kWh/kg$	$0.11\ kWh/kg$
Power density	$0.4\ kW/kg$	$3.3\ kW/kg$
Price	$700\ \$/kWh$	$700\ \$/kWh$

3 REAL WORLD

The example from the previous chapter demonstrated the strong interaction between the vehicle, motor and battery.

In a real world you have to take a more detailed look into those interactions because you won't only drive one single track with an electric vehicle and are able to do a full recharge reaching the end. This leads to the necessity of a detailed planning for the needed charging infrastructure, which itself depends on the topography, power grid and stop times. So it is necessary to consider the driving profile of one vehicle over a day. Due to the fact that the transportation sector is very time-critical you can't change everything of the existing driving schedule. The following workflow shows an example of the involved planning cycle.

1. Creating track data, driving profile and determination of the model parameters
2. Determine the necessary motorization (Simulation)
3. Calculate the needed energy (Simulation)
4. Dimensioning of the battery
5. Localization and dimensioning of the charging infrastructure for 24/7 operation
6. Calculation of the required investment costs / savings

Steps 3. to 6. have to be executed with multiple iterations until a given stop criterion is reached. Figure (9) represents the flowchart for the whole optimization process.

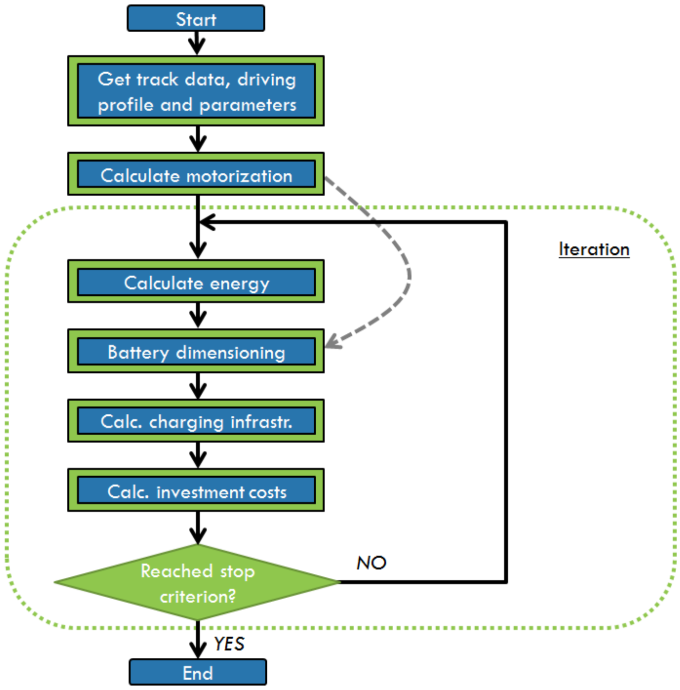

Figure 9: Optimization process.

One possible optimization sub step could be to vary the charging power. As shown in Figure (10) the localization and charging power of the charging infrastructure has a very big influence for planning and implementation of the eMobility in the transportation sector. In the shown scenario only the $150\ kW$ charging station is a possible option out of the depicted three because the battery state of charge mustn't drop under $20\ \%$ and shouldn't go above $80\ \%$ during fast charging (Eckroad 2007) (Brill 2008).

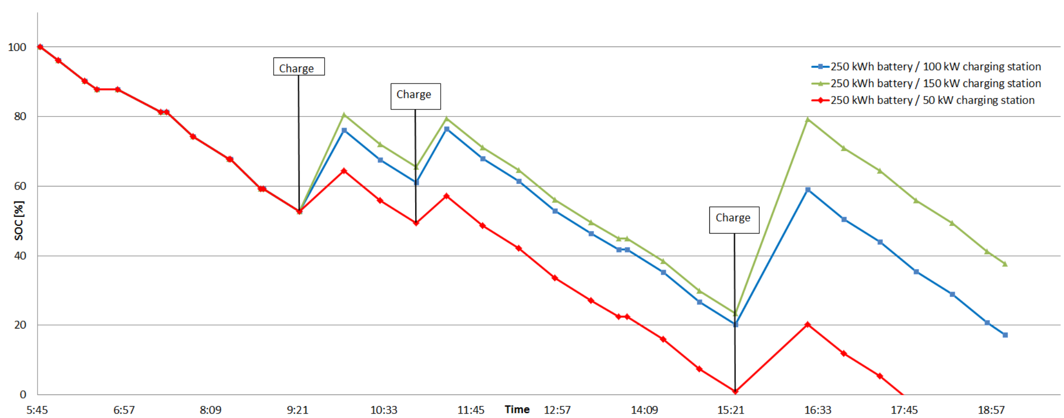

Figure 10: Influence of different charging stations.

4 APPLICATIONS AND MOTOR DESIGN

Like described before the model is flexible in reference to the investigated vehicle. By adding new driving resistance forces to Equation (1) it is possible to simulate electric bikes, cars, busses, trains, ships or even planes. Beside the energetic design of a vehicle it is important to have a look at the actual available components.

For fitting the claimed high efficiency in a battery driven electric application it is necessary to use the best motor technology available. Figure (11) shows an outer rotor motor design which is capable to meet these requirements and provides a higher torque density than usual electric motors. This enables the usage of cheap and environment-friendly ferrite magnets instead of neodymium magnets, which extremely harm the environment during mining process (Panorama 2011).

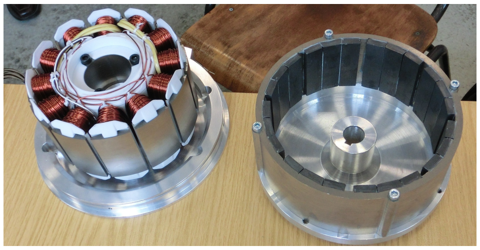

Figure 11: Outer rotor motor with concentrated windings and ferrite magnets (94 % Efficiency).

Such a motor is very resource saving because of its relative small dimensions, copper saving needle winding and the previously mentioned ferrite magnets which can be made of discarded metal. Additionally by integrating the motor into the drive application it doesn't need a bearing anymore. Like shown in Figure (12) the motor can be directly mounted on the gearbox shaft.

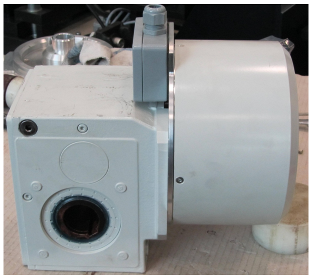

Figure 12: Outer rotor motor and gearbox.

Such a compact combination can be used in all electric drive applications. One possibility could be to equip each wheel of a railway wagon with the needed drive technology for carrying itself. Like shown in Figure (13) this smart solution results in very small motors. Because of the expensive electrification of railway tracks it would also be possible to put batteries in each wagon. This way the system becomes relatively immune to defectives.

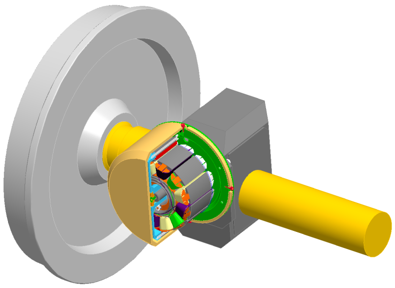

Figure 13: Railway application.

The calculation of the required size of one motor and the needed battery energy can be done by using the previously presented simulation tool. After that the described optimization process can be started with respect to the actual schedule of the railway, to calculate the best combination of drive train, charging infrastructure and investment costs.

5 CONCLUSION

With the described tool it is possible to design a complete drive train in eMobility applications like electric bikes, cars, busses, trains, ships or planes. By using real track data and driving profiles a very good forecast can be provided without having to pay dearly for the wrong technology. The optimization process which surrounds the simulation is able to deliver the best concept and the needed investment costs for the implementation of eMobility in the local transport sector.

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