

Design of a hybrid powertrain model and optimization by a sensitivity analysis

B.Eng. Markus Schmidt, M.Eng. Roman Schaal, Prof. Dr.-Ing. Martin Cichon
Technische Hochschule Nürnberg, Institute for Vehicle Technologies Nuremberg, Germany

M.Eng. Stefan Marth
Dynardo GmbH, Weimar, Germany

Kurzfassung

Im Rahmen eines Projektes am Institut für Fahrzeugtechnik Nürnberg, welches innovative Antriebskonzepte für dieselelektrische Schienenfahrzeuge untersucht und bewertet, wurde ein Antriebsstrangmodell einer Hybridrangierlokomotive in der Simulationsumgebung SimulationX erstellt. Nach der Realisierung des Aufbaus und der Funktionsweise des Antriebsstrangmodells auf Basis der Rangierlokomotive Alstom H3 Hybrid, erfolgt eine Betrachtung der verwendeten Komponentenparameter in Bezug auf deren Sensitivitäten. Die Durchführung dieser Untersuchung wird durch die CAE-Software optiSLang mittels einer Sensitivitätsanalyse verwirklicht. Basierend auf den Ergebnissen der Sensitivitätsanalyse erfolgt abschließend eine Optimierung des Antriebsstrangmodells hinsichtlich des vom Verbrennungsmotor verursachten Kraftstoffverbrauches.

Abstract

As part of a project at the Institut of Vehicle Technologies Nuremberg, which examines and evaluates innovative drive concepts for diesel-electric rail vehicles, a powertrain model of a hybrid shunting locomotive was created in the simulation environment SimulationX. After the structure and functionality of the powertrain model, which is based on the shunting locomotive Alstom H3 Hybrid, was realized, there is a consideration of the sensitivities of the used component parameters. The implementation of this study is realized by the CAE software optiSLang using a sensitivity analysis. Based on the results of the sensitivity analysis a final optimization of the powertrain model with regard to fuel consumption caused by the combustion engine is done.

1. Motivation

The diesel traction has to reduce their emission, because of tighter environmental requirements. Nevertheless it is no solution to renounce the diesel traction in rail transport, because there are still gaps in the rail network electrification and there will be no change in foreseeable future. This is the reason for the special attention on the reduction of all pollutants emissions. A special attention is directed to fuel consumption respectively CO₂ emissions. To reach a reduction of the emissions, operational strategies of the powertrain and the ancillary units are unavoidable.

For an improved and targeted design of new powertrain configurations, simulation models can be dispensed with. The Institute of Vehicle Technologies Nuremberg inspects and rates with the project ‘Energieschonende Antriebe für dieselektrische Schienenfahrzeuge’ innovative powertrain concepts with regard to their saving potentials. In the course of this project a powertrain model, based on the hybrid shunting locomotive H3 from Alstom, is designed and parameterized with SimulationX.

2. Simulation

2.1 Components

The simulation model describes the whole powertrain (engine to wheel) and consider the forces being opposed to the vehicle. The hybrid toolbox of SimulationX was mainly used for the hybrid powertrain modelling. The system was structured based on the schematic layout of a serial hybrid, as it is used in the H3 shunting locomotive. There are some additional components:

- driving cycle
- driver
- control unit
- trailer load
- movement resistance
- braking resistance
- auxiliary consumption
- mechanical brake

The power losses of the DC/DC and DC/AC converter aren't included in the simulation model at first.

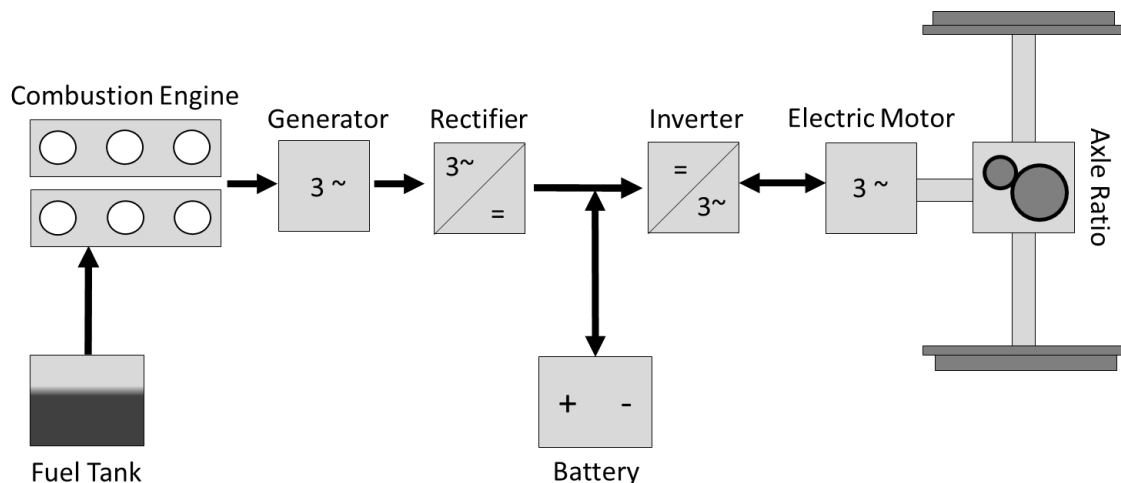


Figure 1: Schematic layout of a serial hybrid powertrain

2.2 Description of simulation model

The control unit defines torques for the engine, generator, electric motor and mechanical brake. Furthermore the control unit affected, depending on the operation mode, the behavior of these components. Besides the usual automatic mode, there is the possibility to choose a battery mode or to run the locomotive by the engine exclusively. The operation mode has to select before each simulation.

Automatic mode

If the locomotive drives with the automatic mode, the system takes the required energy from the tractive accumulator as long as possible. This can only be affected, if the current State of Charge (SOC) is between the minimal and maximal SOC. When the minimal SOC is reached, the start-stop-system switches the engine on. The engine works in his “best point” and generated a constant power, so that a high efficiency can be achieved. The generator converts the released mechanical power of the engine, into electrical energy and feed it in the intermediate circuit. The excess energy, that is neither be used from the electric motor than from any other auxiliary, can used to charge the tractive accumulator.

Battery mode

If the shunting locomotive drives with the battery mode, the engine stops for the whole simulation duration and no energy can apply to the system. The power supply occurs in this mode only with the tractive accumulator. With the expansion of 40 % of the minimal SOC, the usable energy of the tractive accumulator is increased.

Generator mode

In this mode only the generator arrange for a sufficient energy supply for the whole locomotive. The supply of the tractive energy can be effected with the control lever by the driver. The control lever affects the speed of the combustion engine (n).

$$n = n_{ll} + x * (n_{max} - n_{ll})$$

n_{ll} = Idle speed of the combustion engine

x = Position of the control lever

n_{max} = Maximum speed of the combustion engine

Depending on the current speed of the combustion engine, it creates a torque that relates to the power.

2.3 driving cycle

So that a comparison between simulation and reality is possible, real driving cycles will be specified. With the help of a GPS modul, velocities, gradients and curve radii of many shunting tracks, for example main station Nuremberg, were recorded. Furthermore trailer load, number of vehicles and the total length were logged. Based on the measurements and the protocols, real driving cycles can be given to the simulation program. This driving cycle include the resistance depending on the route and also the opposing forces caused by the vehicle.

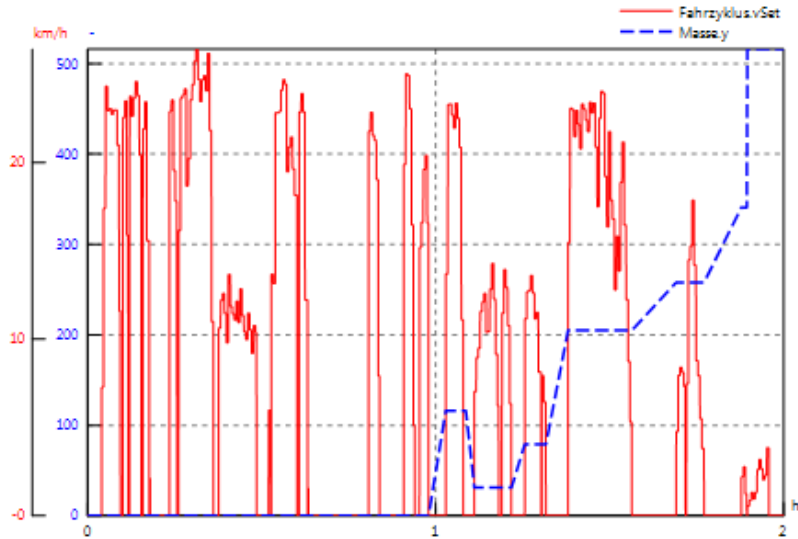


Figure 2: Velocity and the variable trailer load (shown dashed) over simulation time

The picture above shows the set velocity and the default trailer load. The trailer load varies during the stops of the locomotive.

3. Sensitivity analysis

As the powertrain model was designed not all parameters from the manufacturer were available. In this way an approximately assumption of some parameters is unavoidable. In order to investigate the influence of parameters on the system a sensitivity analysis is realized. Additional to the unknown parameters of the powertrain the sensitivity of some input values, which could be interesting for optimization, will be investigated. A suitable CAE-software for this analysis is optiSLang from Dynardo.

The regarded input values vary between a minimal and a maximal limit in a defined space. For the consideration battery parameters such as energy content and charge level limits are used. Also the consumer power of the auxiliary, axle ratio, combustion engine speed and all rotational inertia of the components (electric motor, axle ratio, driving shafts and combustion engine) are examined. Target of the analysis is to examine the influence of the enumerated parameters on fuel consumption. This study is based on a segment of a real shunting movement.

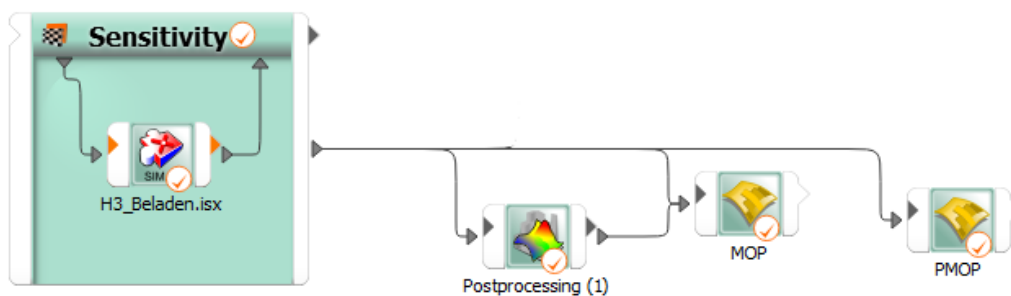


Figure 3: optiSLang workflow of a sensitivity analysis

For the sensitivity analysis 100 parameter combinations of the input values are regarded. These combinations results from the stochastic distribution of the parameters in the defined

space. In this case, the parameters in the Advanced Latin Hypercube Sampling (ALHS) are used for the random distribution. Based on the calculations of the 100 parameter combinations optiSLang create a Metamodel of Optimal Prognosis (MOP), which describes the relationship between the input values and the result size. The prognosis ability is expressed by a Coefficient of Prognosis (CoP). This coefficient provides the compliance of the prognosis model and the calculated results. [1]

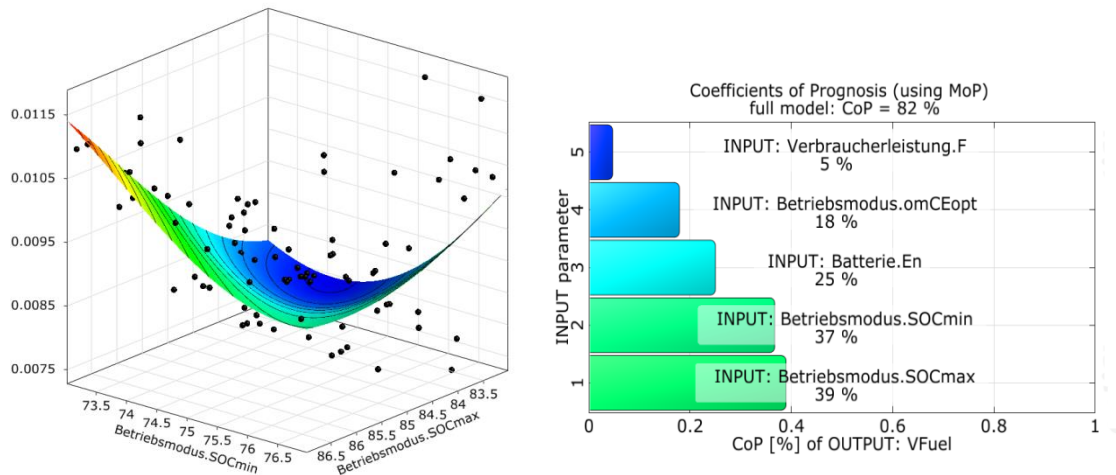


Figure 4: MOP of the fuel consumption with a CoP = 82 % (left) and the relevance of the input parameters on the fuel consumption (right)

From the MOP in the figure above (left) the most important input parameter (right) will be determined. As the results shows, the battery parameters influence the fuel consumption of the internal combustion engine most. These include the limits of the battery charge (“SOCmax“ and “SOCmin“) and the energy content “En” of the traction battery. Also the figure above shows, that the variation of the combustion engine speed “omCEopt” influence the overall fuel consumption with 18 %. The smallest influence on the system has the electrical load “F” with 8 %. Unimportant input parameters (< 1 %), which are not related by their sensitivities to the variation of the fuel consumption, will be automatically filtered out and ignored.

The following figure visualizes the inequalities of the fuel consumption based on the 100 combinations of parameters of the sensitivity analysis. This can be recognized in addition to the different curve in the differences of the overall fuel consumption.

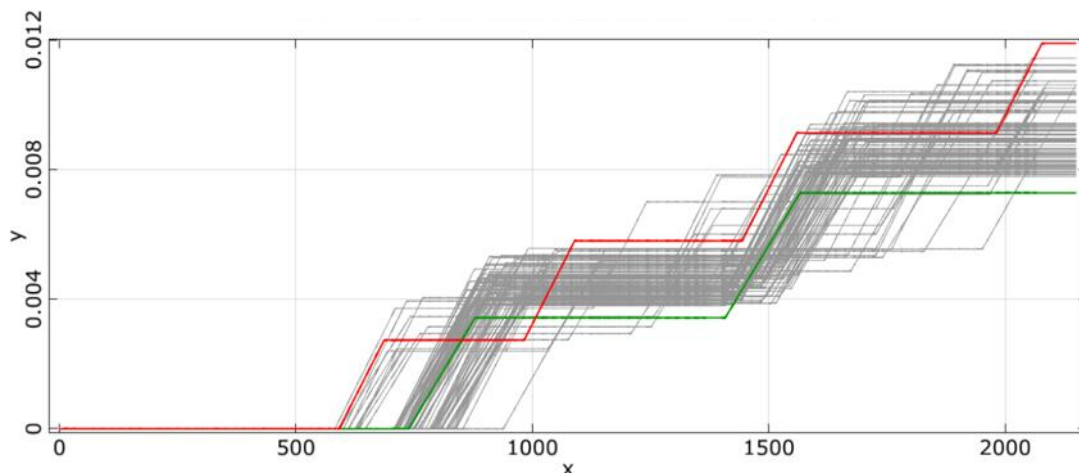


Figure 5: Differences in the fuel consumption over simulation time

4. Optimization

The model with the initial parameter set (design) used to start an analysis with optiSLang shows a final fuel usage of 8.44 liters. During the last step of sensitivity analysis additional 100 designs created by Latin Hypercube Sampling were calculated. Concerning the last values of their fuel consumption in Figure 5 a range of 4.61 liters can be determined between worst (11.89 liters, highest line) and best design (7.28 liters, lowest line). To achieve the initial goal of reducing emissions a subsequent optimization task occurs. optiSLang provides the possibility to run a pre-optimization on the existing metamodel. Using this option with the Evolutionary Algorithm [1] (EA) obtains a design consuming 7.11 liters and its validation a small deviation (7.19 liter) but also an improvement against the best design from sensitivity. To find the real minimum fuel limit a second optimization with the SimulationX model was done. In this case optiSLang automatically suggests the Adaptive Response Surface Method [1] (ARSM) as suitable optimization algorithm. Using this method required 180 designs to find the optimum parameter combination with a minimum fuel consumption of 6.83 liters. An overview of all analysis steps is shown in Table 1. In comparison to the initial design the optimized one saves more than 19 % of fuel.

Table 1: Overview of analysis steps and results

Step	Method	SimulationX variants	Fuel [liters]
1	Initial	1	8.44
2	Sensitivity analysis	100	7.28
3	EA on MOP (Validation)	0 (1)	7.11 (7.19)
4	ARSM on SimX	180	6.83

Summary and outlook

This paper described the structure and the functionality of a hybrid shunting locomotive with the simulation program SimulationX. Furthermore, the importance of the component parameters on the system has been shown in a sensitivity analysis with regard to the fuel consumption. With a final optimization of the model, the minimum fuel consumption for the given driving cycle could be determined.

For a closer examination of the powertrain, with regard to its saving potentials, a validation of the model by test runs should be done. Similarly, some components of the model need to be improved. For this consumer power and strategies of the auxiliaries such as compressor and cooling should be described in greater detail in the model.

References

- [1] Dynardo GmbH, „Methods for multi-disciplinary optimization and robustness analysis,“ Weimar, 2015.