9 Implementation of an Energy Model and a Charging Infrastructure in SUMO

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9.1 Abstract

Future traffic that will be accompanied by higher alternative drive concepts will pose as a challenge when it comes to corresponding energy systems, coordination of operations, and communication interfaces, such as needed for data acquisition and billing. On one hand, the increasing attractiveness of electric vehicles will inevitably lead to the development and testing of compatible technologies; on the other, these will need to be conformed to existing systems, when integrating them into the prevailing infrastructure and traffic. Funded by the German Federal Ministry of Transport, Building and Urban Development, an inductive vehicle charging system and a compatible prototype bus fleet shall be integrated into Braunschweig's traffic infrastructure in the scope of the project emil (Elektromobilität mittels induktiver Ladung – electric mobility via inductive charging). This paper describes the functional implementations in SUMO that are required by the methodic approach for the evaluation of novel charging infrastructures by means of traffic simulation.

Keywords: Traffic simulation, urban traffic, inductive energy transfer, public transportation, vehicle model.

9.2 Introduction

The prospective post-oil era and rising fuel prices have lately resulted in several global trends towards alternative drive technologies. The main advantage of gasoline fuel over other energy carriers is its high specific energy of up to 44.0 MJ/kg. Current projections for the development of equally convenient alternative energy storages go far beyond 2030. Thus, the utilization of alternative energy sources, such as the electrochemical energy stored in Lithium-Ion batteries (0.5 MJ/kg), will result in high vehicle masses and/or low ranges for the coming decades [1][2].

Measures that aim to counter these deficits include the application of light-weight materials, energy/time-optimal routing, intelligent control of traffic light-signal systems, and government regulations that introduce (operational, financial and/or infrastructural) incentives for buyers of vehicles with alternative drive concepts.

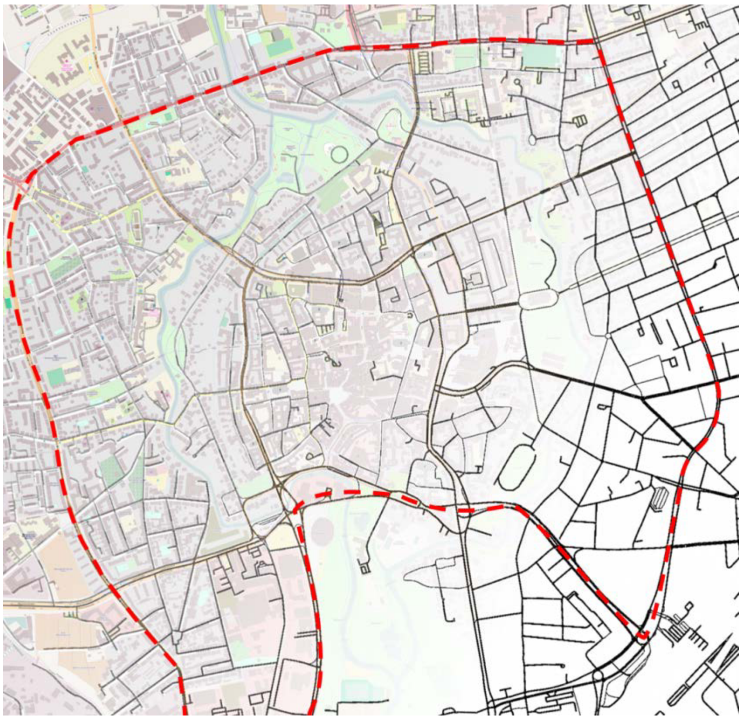

Figure 9-1: Braunschweig's urban road network with the route of bus lines M19 and M29 (red)
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The German Federal Ministry of Transport, Building and Urban Development (BMVBS) has therefore granted the funding of the project *emil* (Elektromobilität mittels induktiver Ladung – electric mobility via inductive charging). It includes the evaluative implementation of an inductive energy transfer system for public transportation and a compatible prototype bus fleet in the city of Braunschweig. The bus lines in question are the M29 and M19 that circle the city center counter-clockwise and clockwise, respectively. They carry the highest percentage of Braunschweig's publicly transported passengers with a high frequency from and to major traffic nodes and landmarks such as the central train station and the university. Figure 9-1 illustrates Braunschweig's urban road network.

The goal of the project *emil* is to analyze and optimize the operation and economic feasibility of an inductive electric charging system and to develop suitable operating strategies. One focus of research lies in the analysis of integrative aspects that allow for the common utilization of the charging and road transport infrastructure by public and private transport with minimum obstruction of public and total traffic. After outlining the methodic approach for these analyses, the implementations in SUMO shall be described that allow for its utilization in urban traffic optimization.

9.3 Methodic Approach

The goal of possible optimization measures (e.g. via genetic algorithms) lies in finding an optimum of the considered system in regard of the energy consumed. This evaluation requires a suitable simulation tool that allows the implementation of custom traffic scenarios, including traffic demand, a charging infrastructure, customized vehicles, prioritization, and different light-signal schedules. Additionally, it needs to generate an output of the required energy of individual road traffic participants and the entire system as the desired optimization criterion.

Since no simulation tools exist that allow all the mentioned requirement to be modeled, the best choice for this task is the traffic simulation tool SUMO (Simulation of Urban MObility), due to its open source character and high compatibility with numerous data sources, including many commercially available traffic simulation tools [3][4]. Its development was initiated by the Institute of Transportation Systems of the German Aerospace Center (DLR), in 2001. It has evolved into a simulation tool, high in features, functionality and interfaces. Even though instantiated vehicles follow a simplified behavior, traffic simulation tools like SUMO allow the realistic replication of prevailing traffic in arbitrary road networks.

The intended approach in the scope of this project is to model current representative traffic scenarios that take into account the existing infrastructure, a time-varying traffic demand model (differentiating between representative peak and nonbusy periods), and light-signal schedules [5]. Meanwhile, the implementation of new functionalities in SUMO on the system-function level will allow for the instantiation of inductive charging stations and compatible vehicles. Operation parameters will have to be identified and/or set for the inductive charging system and traffic demand, to create a representative scenario for Braunschweig's urban traffic. Figure 9-2 depicts the above described method, highlighting interfaces between SUMO's current functionalities, required additional functionalities, and an external optimization framework.

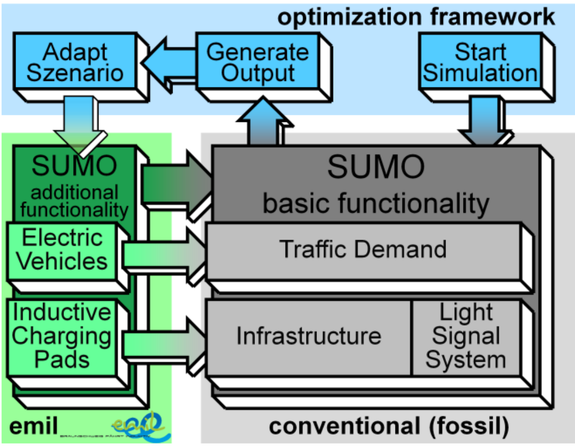

Figure 9-2: Project structure with interfaces between basic functionalities (gray), additional functionalities (green), and an optimization framework (blue)

9.4 State of the Art and Implementation

In order to generate an output about the consumed energy, an energy model will have to be implemented for instantiated vehicle objects. Numerous methods, functions and approaches exist that perform traffic quality assessment calculations, giving feedback about its characteristics. Implemented functionalities in SUMO include the vehicle- and lane-based HBEFA-emission [6] and HARMONOISE-noise [7] calculation and the corresponding generation of a suitable output.

In order to allow energy assessments and subsequent optimization, an additional framework has also been developed by Maia et. al. [8]. The work is based on a sophisticated vehicle model that takes into account mechanic and electric vehicle parameters and calculates the variation of the depth of discharge between discrete time steps. If a vehicle's movement requires a higher torque than its defined maximum, recalculations of the vehicle speed and acceleration take place in order to comply with the constraints of its components. The depth of discharge is subsequently calculated using an electrical traction model.

With the aim to enhance computation time, this paper presents the implementation of a similar vehicle model, which merely focuses on energy as the simulation output and reduces the complexity of required calculations. Additionally, this model evaluates the energetic state and calculates variations in energy content of corresponding vehicles without affecting their driving behavior. Additional benefits of this model include fewer required input arguments for instantiating vehicle objects.

9.4.1 Vehicle Energy Model

The change of one vehicle's energy content can be calculated by summing its kinetic, potential, and rotational energy gain components from one discrete time step to the following, and subtracting the losses caused by different resistance components [9]. The vehicle's energy $E_{\text{veh}}[k]$ at the discrete time step k can thus be calculated by equation 1, with the known variables vehicle mass m, time variant vehicle speed $v[k]$, gravity acceleration g, time variant vehicle altitude $h[k]$, and moment of inertia of internal rotating elements J_{int}.

$$\begin{aligned} E_{\text{veh}}[k] &= E_{\text{kin}}[k] + E_{\text{pot}}[k] + E_{\text{rot,int}}[k] \\ &= \frac{m}{2} \cdot v^2[k] + m \cdot g \cdot h[k] + \frac{J_{\text{int}}}{2} \cdot v^2[k] \end{aligned} \tag{1}$$

In consideration of energy losses $\Delta E_{\text{loss}}[k]$ caused by air, rolling, and curve resistance and constant consumers (e.g. air conditioning), the energy gain between time steps k and k+1 can be calculated by equation 2.

$$\Delta E_{\text{gain}}[k] = E_{\text{veh}}[k+1] - E_{\text{veh}}[k] - \Delta E_{\text{loss}}[k] \tag{2}$$

The energy loss is made up of the components in equation 3, with the variables air density ρ_{air}, vehicle front surface area A_{veh}, air drag coefficient c_{w}, covered distance $s[k]$, rolling resistance coefficient c_{roll}, centripetal force F_{rad}, curve resistance coefficient c_{rad}, and the (average) power of constant consumers P_{const} [9].

$$\begin{aligned} \Delta E_{\text{loss}}[k] &= \Delta E_{\text{air}}[k] + \Delta E_{\text{roll}}[k] + \Delta E_{\text{curve}}[k] + \Delta E_{\text{const}}[k] \\ \Delta E_{\text{air}}[k] &= \frac{1}{2} \rho_{\text{air}} \cdot A_{\text{veh}} \cdot c_{\text{w}} \cdot v^2[k] \cdot |\Delta s[k]| \\ \Delta E_{\text{roll}}[k] &= c_{\text{roll}} \cdot m \cdot g \cdot |\Delta s[k]| \\ \Delta E_{\text{curve}}[k] &= c_{\text{rad}} \cdot \frac{m \cdot v^2[k]}{r[k]} \cdot |\Delta s[k]| \\ \Delta E_{\text{const}}[k] &= P_{\text{const}} \cdot \Delta t \end{aligned} \tag{3}$$

Depending on its sign, $\Delta E_{\text{gain}}[k]$ is the amount of energy the vehicle has consumed or regained resulting from its movement. The variation of the energy contained in the vehicle's battery can further be calculated by equations 4 and 5 by introducing constant efficiency factors for recuperation η_{recup} ($\Delta E_{\text{gain}}[k] > 0$) and propulsion η_{prop} ($\Delta E_{\text{gain}}[k] < 0$).

$$E_{\text{Bat}}[k+1] = E_{\text{Bat}}[k] + \Delta E_{\text{gain}}[k] \cdot \eta_{\text{recup}} \tag{4}$$

$$E_{\text{Bat}}[k+1] = E_{\text{Bat}}[k] + \Delta E_{\text{gain}}[k] \cdot \eta_{\text{prop}}^{-1} \tag{5}$$

9.4.2 Vehicle Charging Model

For the purpose of evaluating a charging infrastructure, a new object will have to be implemented into SUMO that supplies compatible vehicles (or their batteries) with energy for their operation. The location of charging stations as well as their charging power and efficiency needs to be specifiable by the user. If a vehicle moves or stops above or within a system-specific proximity of such an infrastructure element, the energy content of its battery is charged according to equation 6, with charging power P_{chrg}, charging efficiency η_{chrg}, and duration between two discrete time steps Δt.

$$E_{\mathrm{Bat}}[k+1] = E_{\mathrm{Bat}}[k] + P_{\mathrm{chrg}} \cdot \eta_{\mathrm{chrg}} \cdot \Delta t \qquad (6)$$

Following the calculations of the energy variation between two discrete time steps, the battery's energy content is limited to the user-specifiable range

$$0 \leq E_{\mathrm{Bat}} \leq E_{\mathrm{Bat,max}} \,. \qquad (7)$$

Calculations of this energy model can be restricted to vehicles with $E_{\mathrm{Bat,max}}>0$, further reducing computing times.

9.4.3 Simulation and Results

For the correct dimensioning of components and layout, the technology provider Bombardier Transportation GmbH has developed a sophisticated simulation model for the battery's charge and discharge. Since the vehicles, which are to be used in this project, are still in development, this output of this sophisticated model is the only reference for a representative parameterization. In order to show that the simplistic vehicle model presented above is capable of calculating the trend of a vehicle's energy content with adequate accuracy, it has been given the same route as input, as Bombardier's sophisticated model (Solaris Urbino 12). Figure 9-3 shows the vehicle's route and its topographic profile.

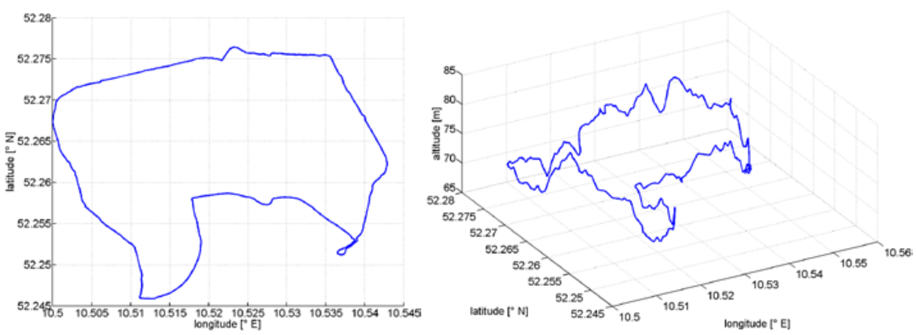

Figure 9-3: Designated bus route (left) and its topographic profile (right)

In a subsequent step, parameters for the newly developed vehicle model in SUMO have been determined that represent the reference behavior optimally, in the sense of least-squares. The reference (blue) and parameterized (red) simulation outputs for the same route as the model input are shown in Figure 9-4. The cumulated (Δt=1s) deviation of the two simulation outputs add up to E_{Error}=3.3998 kWh².

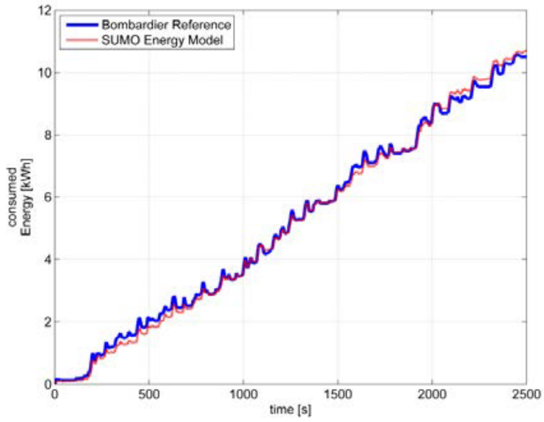

Figure 9-4: Simulation outputs of Bombardier's reference simulation and the newly implemented energy model with an optimal parameter set

9.5 Conclusion and Outlook

The identified parameter set can be used in the resulting function package of SUMO for the instantiation of a new traffic demand model with (representative) objects of the new vehicle class, including different vehicle types. This will allow for the development of different scenarios for Braunschweig’s traffic (including forecasts for electric vehicles) that can be further analyzed and optimized in regard of the new inductive charging infrastructure and its participants.

The development of an optimization framework with underlying algorithms will require an additional output of the specific simulation states by producing a feedback on the energy content of relevant participants. This output could be implemented in form of a custom device or detector. Potentials for optimization lie in the optimal positioning of the charging stations along the defined bus route. The optimization criteria can not only include a desired long battery life, but also travel time by synchronizing required charging times and the predictable waiting times for the entry and exit of passengers, light-signal systems, and remaining traffic. For the identification of optimal parameter sets, the utilization of genetic algorithms is intended in the further course of the project.

Simulation results can also include the evaluation of occupancy rates at different positions within the road network. This data can be used for the design and alignment of inductive charging pads that maximize their duty cycle and thus efficiency.

By implementing different scenarios for the amount of compatible vehicles in the future, it will also be possible to determine saturation points for the amount of participating vehicles, where operational interferences and obstructions among public transportation and between public and private vehicles can be expected.

9.6 Acknowledgements

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