Modelling and Simulation of a Public Transport System with Battery-Trolleybuses for an Efficient E-Mobility Integration

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***Abstract*— This paper introduces the simulation of a public transport system with battery-trolleybuses. Today, the considered trolleybuses are equipped with a combustion engine in order to overcome the line free sections of the DC overhead grid. The goal of this paper is to present how the simulation model was built up. A constructive simulation model is developed based on the technical and physical limits which are given by both the trolleybuses and the grid. The model in question is supposed to provide a detailed insight of the load flow within the DC overhead grid. The hereby provided information is of crucial importance to handle the future work which will be the development of a regulated smart charging infrastructure for advanced trolleybuses with a battery instead of a combustion engine.**

Keywords: Trolleybus, Bus Power Profile, Topology, Slope Angle, Traffic Situations, DC Grid, DC Load Flow

I. Introduction

The city of Solingen owns one of three existing trolleybus systems in Germany which has nearly 100 km overhead line with 50 electric powered trolleybuses containing auxiliary diesel engines and 50 conventional diesel buses serving the public transport services. The project "BOB Solingen" is supposed to provide an entire public transport system which is solely powered by electrical energy. The acronym BOB stands for the German word "Batterie-Oberleitungsbus", which means battery-trolleybus. This can be reached through the replacement of both the conventional trolleybuses and the normal combustion engine buses with the new battery-trolleybuses (BOB). The BOB will combine proven trolleybus technology with the latest battery technology to create the next generation of buses. These are able to perform emission free operating even on lines with partly uncovered power supply, due to the fact that the combustion engine was replaced by a respectively dimensioned battery that can and will be charged in favorable situations.

Furthermore, the project includes the integration of decentral renewable power generation such as local PV systems. In addition, a high number of charging stations for electric vehicles and bikes are planned to be built and connected to the DC overhead line to make use of the remained grid power. A stationary power storage unit will integrate obsolete bus batteries in order to decrease the ongoing expenses and increase the total use efficiency of the battery.

The entire DC system will be efficiently linked to the energy sector to take part on balancing markets. Furthermore, the whole grid will be developed into a full "smart grid" which allows an intelligent control and management of the energy flow in the overall system.

The Chair of Power System Engineering of the University of Wuppertal will develop and implement an automation system for the DC grid to use its existing overhead infrastructure as effective and efficient as possible, avoiding the conventional grid expansion measures. To take part on balancing markets an intelligent coupling of the upstream distribution grid and the DC grid is necessary. Finally, a transferability analysis will be made to other cities, to find out the transferable project parts to other means of transportation, e.g. the tram system.

In order to realize an intelligent control of the grid, the load flow of the current grid including the trolleybuses as well as of the future grid including the battery-trolleybus has to be modeled and simulated. By means of the simulation critical grid situations and load peaks can be detected.

Aim of the present paper is to provide a structural insight of how the simulation model was gradually built up. In a first step all the relevant basics and general information regarding the bus will be presented which are necessary to build the simulation environment. Afterwards, the different operating modes of the bus will be explained since there are huge differences in power consumption up to power refeed in the range of driving uphill to breaking downhill. These specialized modes will be analyzed and formulated by means of all affecting physical forces and resistances. The resulting model will be presented in a flow chart in order to illustrate the conceptual proceeding of the bus power profile in our simulation model.

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The next section outlines how the real-life DC grid will be build up in order to observe the grids load flow. The total view on the DC grids load flow is of major importance since it provides indispensable information regarding the grid state and local burdens. The reliable detection of less loaded and overloaded branches or sections is the basis for a regulated intelligent charging infrastructure.

II. Bus Power Profile

Modelling a realistic bus profile requires detailed information regarding both the physical and technical properties of the bus. The following subsections are supposed to provide a slight overview of the basic knowledge in order to extend the before mentioned power profile subsequently.

A. *General bus information*

The specific properties which are taken into consideration are mostly

- Curb weight,
- Maximum speed,
- Front surface,
- Maximum passenger capacity,
- Engine power,
- And efficiency.

All of them depend on the respective bus type since there are three different bus types in use. Due to the fact that all three bus types will be considered in the simulation, Table I only shows the overall values which are not affected by choosing a different bus type. Otherwise, this would go beyond the scope of this publication.

TABLE I. Simulation Parameters

Parameter	*Value*
Acceleration	0.5 m/s² [1]
Braking deceleration	- 0.5 m/s² [1]
Rolling resistance coefficient	0.015 [1]
Aerodynamic drag coefficient	0.60 [1]
Air density	1.225 kg/m³ [1]

B. *Bus power profile*

In order to generate a realistic bus profile, four different driving modes [1] must be considered, as shown in Figure 1. At the outset, the bus accelerates (I) until it reaches a constant speed (II). Then, it passes into the coasting mode (III) before braking (IV) to reach the standstill.

I) Acceleration: The bus accelerates from zero to a specific speed which depends on the length of the route and the respective speed limits. In this step, the corresponding bus power had to be calculated which is why Newton's laws of motion were used [2]. The tractive force (F_T) depends on the mass (m), the acceleration (a) and the resistance force (F_R).

$$F_T = m \cdot a + F_R \tag{1}$$

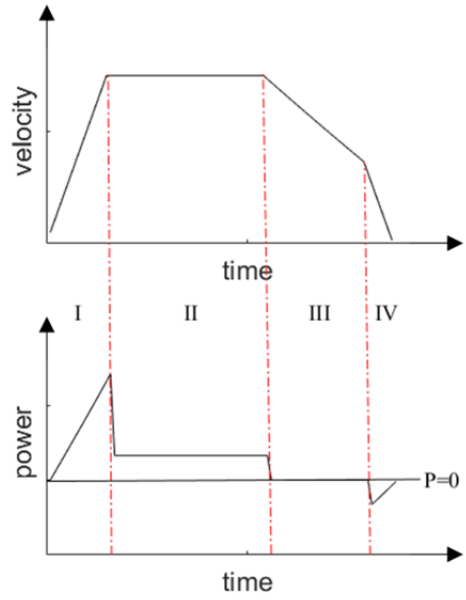

Figure 1. Bus speed and power profile

The resistance force consists of several forces namely the rolling resistance force (F_{RR}), the gravitational (gradient) force (F_{Grad}) and the aerodynamic drag force (F_{Drag}).

$$F_R = F_{RR} + F_{Grad} + F_{Drag} \tag{2}$$

The rolling resistance can be traced back to the deformation and abrasion of the tires [3]. Considering the rolling resistance coefficient (μ) and the wheel load (W), the rolling resistance force equals, as follows:

$$F_{RR} = \mu \cdot W \tag{3}$$

The gravitational (gradient) force had to be taken into account as well, since the slope angle of the road is frequently unequal to 0°. Arithmetically, it can be described by means of the mass (m), the gravitational acceleration (g) and the current angle (θ), as follows:

$$F_{Grad} = m \cdot g \cdot \sin(\theta) \tag{4}$$

The drag force is mainly caused by turbulent air flows. As a matter of fact, the value of the drag force increases by the square of the speed which is why the drag force had to be considered even though the maximum speed is roughly 50 km/h. It comprises of the density of the fluid which is air in our case (ρ_{air}), the dimensionless drag coefficient (c_d), the cross sectional area (A_f) and the speed of the object relative to the fluid (v_{air}).

$$F_{Drag} = 0.5 \cdot \rho_{air} \cdot c_d \cdot A_f \cdot v_{air}^2 \tag{5}$$

Finally, both the mechanical (P_M) and the electrical power (P_E) of the trolleybuses can be calculated from the resulting tractive force and considering the efficiency η.

$$P_M = F_T \cdot v \tag{6}$$

$$P_E = \frac{P_M}{\eta} \tag{7}$$

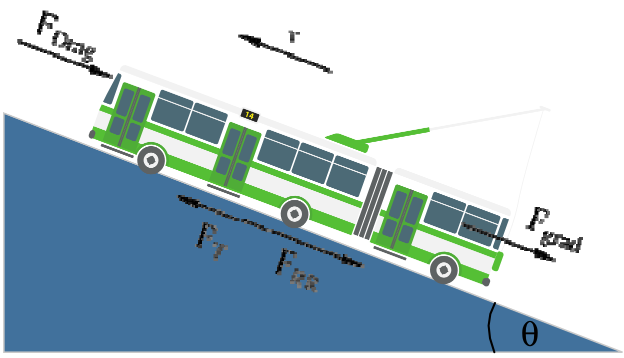

Figure 2. Occurring forces when driving uphill [1,2]

II) Constant Speed: When the bus reaches its maximum speed, the following relation results:

$$a = 0 \Rightarrow F_T = F_R \quad (8)$$

The bus power will decrease since the acceleration equals zero. Thus, the bus only needs to overcome the resistance forces to maintain the speed.

III) Coasting: In coasting mode the tractive force is zero, because the bus moves by its own momentum. As a result, the speed decreases and the acceleration turns negative, unless there is a large slope.

$$F_T = 0 \Rightarrow a = -\frac{F_R}{m} \quad (8)$$

IV) Braking: While braking, the bus decelerates until v = 0 is reached at the standstill. The bus can operate both in power drain or power refeed mode which is why the powers sign switches between negative and positive, respectively. This depends on the circumstances, such as the slope angle of the road.

C. Extended dependance for the bus power profile

In order to implement adequate points of interest within the simulation model, different types of nodes were defined. These can be seen in Table II. Every bus route basically consists of a high number of nodes and intermediate branches. Starting and ending points represent the respective fixed terminal stations of each bus line. Traffic lights, bus stops and junctions are all sharing similar properties since they can cause a delay due to the speed reduction and a standstill as well. The former depends on the daytime and the respective traffic mode which can be seen in Table III. The latter is generated by node-specific probability functions. The time zone and respective traffic mode varies depending on the location which is why Table III only illustrates one possible combination of "time zone" and "traffic mode".

TABLE II. TIME ZONES

Time zone	*Starting Time*	*Ending Time*	*Traffic Mode (example)*
1	10 p.m.	6 a.m.	0
2	6 a.m	11 a.m.	3
3	11 a.m.	3 p.m.	2
4	3 p.m.	7 p.m	3
5	7 p.m.	10 p.m.	1

In order to consider the traffic, a rudimentary function has been added up so far. Depending on the traffic situation, the maximum speed is reduced. The higher the traffic mode, the greater the speed reduction. By taking this into account, the time delay that occurs during high traffic is mentioned in the simulation. The traffic modes are namely:

- No traffic (0)
- Low traffic (1)
- Medium traffic (2)
- High traffic (3)

TABLE III. NODE TYPES

Node Type	*Speed reduction*	*Standstill*	*Dependence*
Start/End	Yes	Yes	Fixed Points
Traffic Light	Yes	Yes/No	Timezone and Probability Profile
Bus Stop	Yes	Yes/No	Timezone and Probability Profile
Junction	Yes	Yes/No	Timezone and Probability Profile
Passthrough	No	No	Reference points for topographical accuracy
Bend	Yes	No	Angle

Figure 3 is intended to illustrate how the program proceeds to calculate the bus power. First of all, the time is initialized and the following input parameters are read in:

- Node type
- Length of the branch
- Speed
- Total weight

Then the mode is determined to calculate the bus power. In order to capture the right mode, the distance that takes to get the bus to a standstill must be known. This distance is calculated, whereby the slope angle plays a decisive role. The distance, which is travelled in coasting mode as well as the distance required for braking mode varies and is subject to the slope angle.

It should be noted, that the coasting mode was renounced while driving downhill as well as driving on short branches. The current mode can be determined based on the recent position and the calculated distance to a standstill.

Subsequently, the bus power is calculated by the information of the mode and the above-mentioned equations. Among other things, the new distance is also determined. If the bus power (P_{bus}) is above the limited maximum bus power ($P_{bus,max}$), the acceleration will be adjusted. The acceleration will be reduced by a while loop until the newly calculated bus power is not greater than the maximum bus power.

Finally, the data will be saved. This process is carried out until the length of the branch (branch length) has been reached and the bus has come to a standstill.

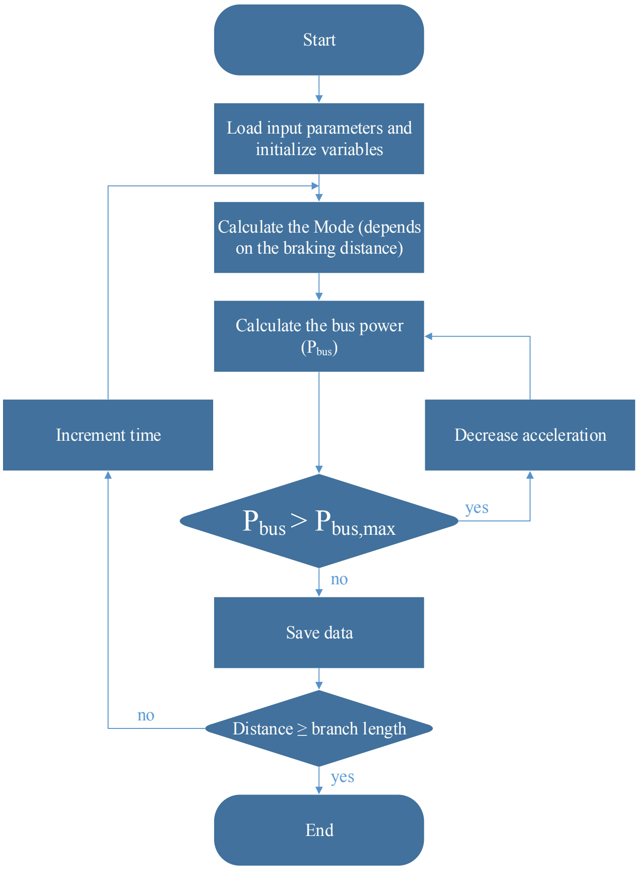

Figure 3. Flow chart of the simulation programm

III. Overhead Line

The trolleybus system of Solingen operates under a DC overhead grid. This grid is part of the investigation for the promising intelligent behaving and reacting with new electrical decentralized power generators, electrical vehicles charging station, power storage unit and on-board batteries charging system of the new trolleybuses (BOB) integration.

A. DC Grid

The existing DC grid covers most of the operating path of the mentioned buses, except for some parts where these buses are operating line free with an included combustion engine. Two DC parallel lines operate for each side of the streets flow direction, each couple of these lines is positive and negative with furthermore connected through specific points together, positive with positive and negative with negative.

Overhead DC lines, switches, lines crossings, dead-end disconnections and direct current connections (infeed and fixed outfeed) represent the points of interest to form the trolleybus DC grid topology. The operating mode and the maximum speed for the operating trolleybus will be affected as well by the position of the switches, lines crossings and the dead end of the DC overhead lines. The direct current connections are the access points to infeed the DC grid from the DC supply which are in this case the rectifier stations, the decentralized renewable energy sources or the battery storage station which is operating as a power supply here, on the other hand, these points can also be outfeed to supply the electric vehicles charging station or the battery storage station which is acting as a load in this case. The overhead DC lines are connecting all of these points together allowing the direct current to flow in between them and providing the trolleybuses with the required power to operate within their grid.

B. Load Flow

Voltage values across the DC grid parts as well as the amount of current flowing through the overhead line conductors represent the important critical parts for the required new enhanced battery-trolleybuses and the trolleybus DC grid. In order to get the direction and amount of power flowing from each DC power source within the grid towards the loads consuming this energy, a power flow (PF) method needs to be implemented. DC power flow problems are nonlinear. The Newton-Raphson and Gauss-Seidel methods [4,5] have proven to be reliable methods for solving nonlinear PF problems, Newton-trust region method [6] is proposed to solve PF equations in the DC grid.

The DC trolleybus grid could be divided into three parts: power sources, overhead distribution grid, and loads. Power sources are one of three counted types. They are DC generators (PV), AC/DC rectifier converters and batteries. Both DC generator and AC/DC converters can be modelled as a constant voltage source, the battery voltage behavior depends on the amount of energy which is stored in it [7]. Conductors of the overhead DC grid are to be considered as resistance branches with in the PF process, e.g. the DC grid is presented by its conductance matrix.

The last part are the loads, which are in this case of two types. The first one is the fixed position load e.g. the charging stations and the battery storage stations when operating in charging mode. The trolleybuses are the second type of the loads in this grid, with the mobility behavior of them, they will change the grid branches size, i.e. every bus movement will result in a new conductance matrix, and the PF will be performed for each bus movement, which is triggered on each time step, showing the grid voltages and flowing current at each time.

IV. Simulation Results

The results of the simulation with regard to the bus power are shown. The various circumstances are analyzed individually:

- Topology
- Total weight
- Limited engine power
- Traffic

Most of the work deals with the topology. The topologies of the bus routes are obtained by collecting the information of collaborative projects and preparing them in a geographic information system. As the last step, a complete bus route is simulated.

A. Topology

The topology has a big influence on the bus power, as shown in Figure 4. Even small changes of the angle (θ) lead to highly varying performance profiles. The required maximum power decreases enormously with smaller slope angles. With a sufficiently low slope angle, the bus can maintain the speed without consuming power. If the slope is large enough, the bus can also refeed power even though the bus accelerates.

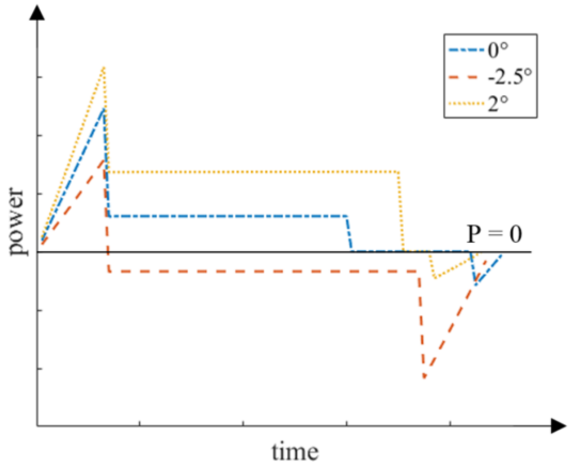

Figure 4. Bus power profile depending on the slope angle

This case also depends on the maximum speed that the bus can reach within the branch. On the basis of the results it can also be seen that the coasting mode was removed, when the bus drives downhill.

B. Mass

In addition, different bus weights lead to different power profiles. Figure 5 shows the power profiles of two buses. One bus is empty while the other one is fully loaded. As expected, the fully loaded bus requires more power and can also refeed more power when the bus brakes which can be traced back to the higher mass-related kinetic energy. Nevertheless, both buses reach the standstill at the same time, because the speed profiles of both buses are identical. Only the fully loaded bus needs more power to reach or maintain the speed. The bus power is approximately proportional to the mass.

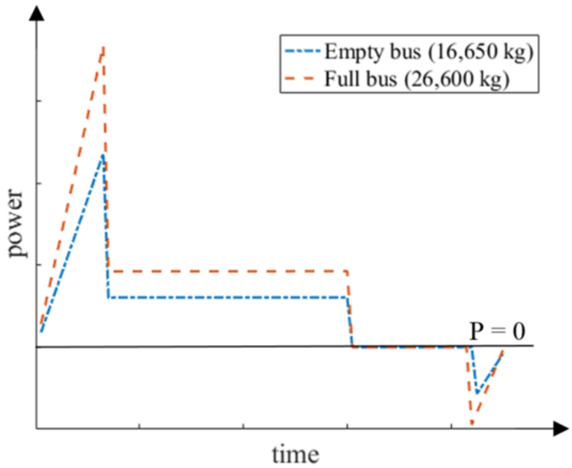

Figure 5. Bus power profile depending on the mass

C. Limited engine power

The results obtained so far do not consider the maximum engine power of the buses. The bus requires a lot of power when e.g. driving uphill. However, the maximum power consumption is limited. Figure 6 illustrates that the bus cannot continuously accelerate with the already mentioned 0.5 m/s², in case that the required power exceeds the limit ($P_{bus,max}$). In this case the acceleration will be reduced within the engines power range. As a result, the time that takes the bus to accelerate to the aimed velocity increases. This means the bus with the non-limited engine power is ahead of the other. So this bus can start decelerating earlier. Finally, the bus with the limited engine power reaches the standstill point later. The power-time diagram illustrates this situation. However, the same work is done over the whole distance.

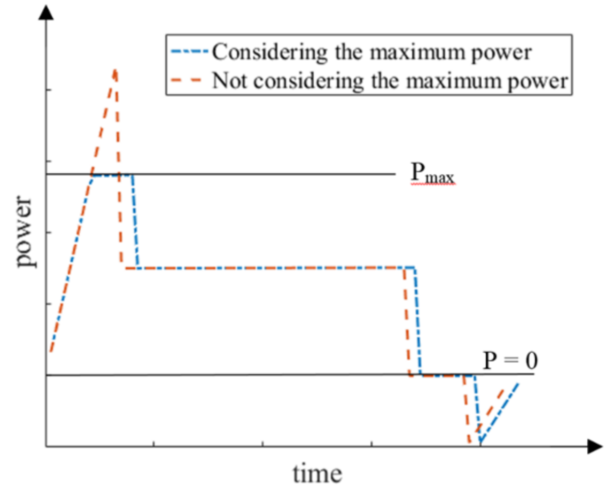

Figure 6. Bus power profile depending on the limited engine power

When taking a look from the theoretical point of view, it may also occur that the maximum engine power is not sufficient to reach the maximum permitted speed. Figure 7 illustrates this case. The maximum speed remains below the permitted speed, which is why the stopping point can only be reached with a delay. In both cases the same work is done again. Whether this case occurs or not depends among other things on the angle and the speed limit of the road as well as the maximum engine power and the weight of the bus.

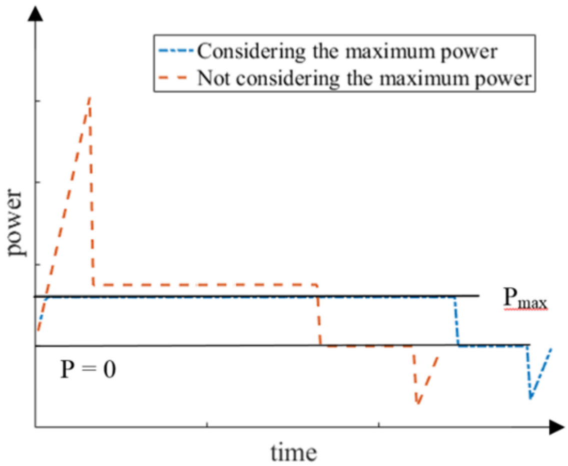

Figure 7. Bus power profile depending on the reduced limited engine power

D. Traffic

In Section II time zones and traffic modes were presented. As a result of the included modes, the time required to reach the stopping point is increased depending on the traffic mode, i.e. the top speed will be limited to the respective traffic situation. Thus, the bus which is subject to the heaviest traffic mode needs the longest time to reach the target point.

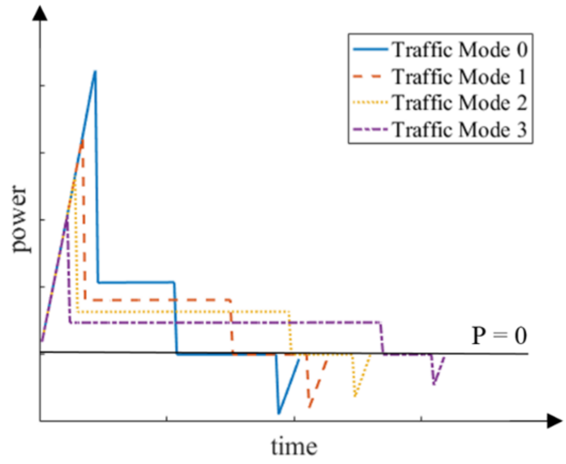

Figure 8. Bus power profile depending on the traffic

E. Bus operation line power consumption

Finally, a test of an entire bus route is simulated. The selected bus has a maximum power consumption of 172 kW. This corresponds to the oldest of the three existing buses. As mentioned above, the bus line was prepared in a geographic information system and all the relevant data were exported accordingly. The exported height profile of the bus route is shown in Figure 9 b). Before importing the profile into the simulation program, further geographic reference nodes are automatically added to capture local minima and maxima. This allows considering all relevant gradients of the route. During the digitization of the bus line, only the interesting nodes (e.g. traffic lights or bus stops) are added up. As a result, not all gradients were detected. Adding geographic reference nodes solved this problem. It can be seen from the figure that the bus drives the majority of the route uphill. Subsequently, the data (e.g. node type and length of the branch) are read in and processed by the simulation program. The program calculates for each time step, among other things, the power of the bus. In addition, the bus stops in this simulation at each traffic light as well as at every bus stop. For the entire route, the bus takes about 26 minutes to complete the route in the simulation, which can be seen in Figure 9 a). According to the timetable, the bus should only take 21 minutes. The difference is due to several circumstances. The bus which only takes 21 minutes for the route actually does not stop at each traffic light as well as at every bus stop. A function with a selected probability stops the bus at these points to ensure a realistic driving behavior. In addition, the various traffic scenarios play a role. The acceleration can also be varied in order to obtain more realistic simulations.

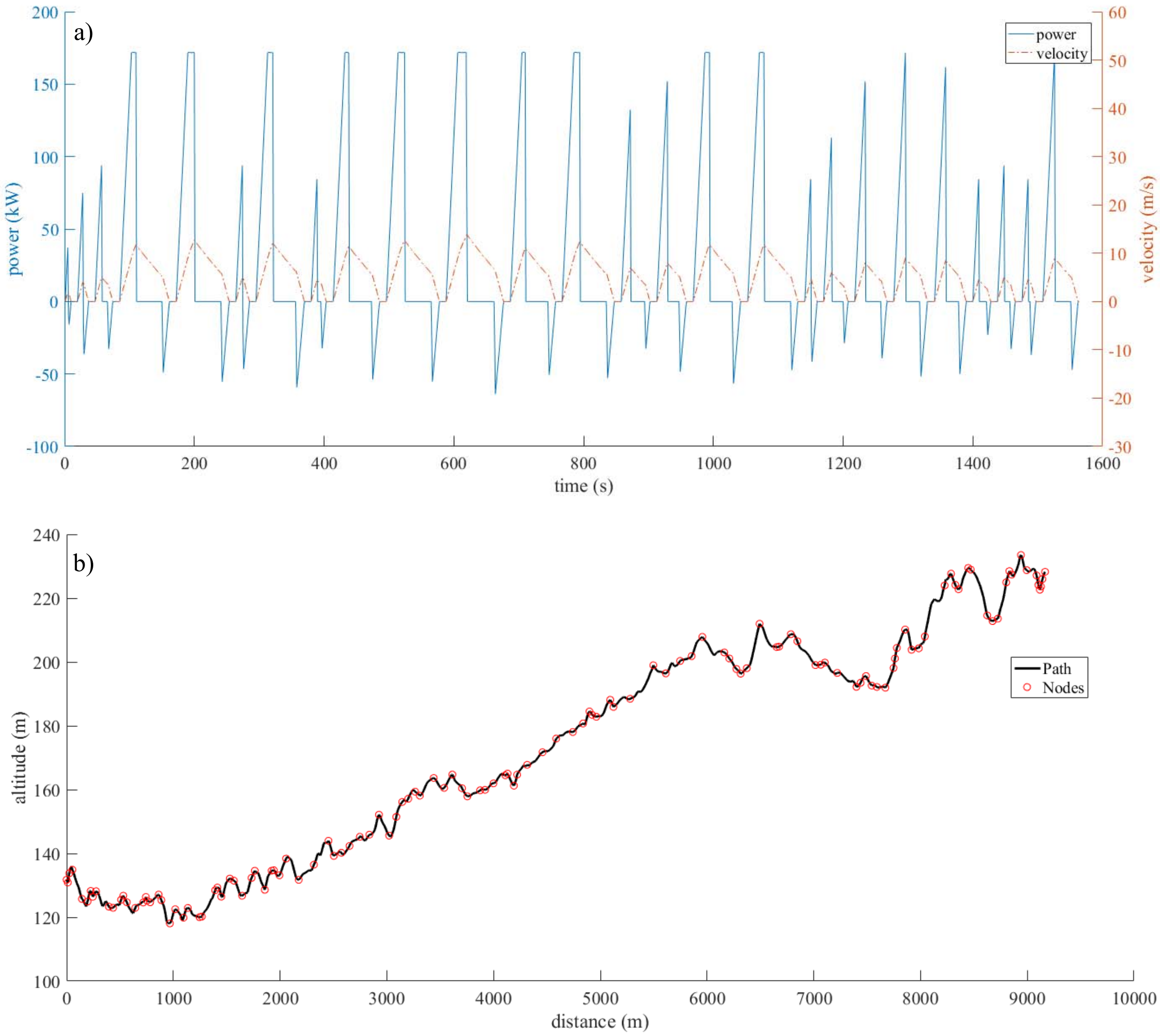

Figure 9. Bus operation line a) power consumption and b) altitude profile

V. Conclusion and Future Work

Within this paper a methodical approach of modelling a public transport system with trolleybuses was introduced. Starting with the collection and import of all the relevant technical and physical boundary conditions, the bus power profile was built up. The DC overhead grid mainly consists of numerous nodes and branches, whereby the nodes are not only fixed points of interests but also the moving buses leading to a dynamic system which is to be observed. Load flow calculations enable a reliable view on the DC overhead line in terms of overloads since this achievement is the basis for the aimed future work. This will be the implementation of a battery-trolleybus to finally develop an intelligent charging infrastructure for future application.

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