

Electrical Bus Performance Modeling for Urban Environments

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ABSTRACT

Electric vehicles are seen as a key driver to address the issue of global warming, mainly through their zero tailpipe emissions operation and energy efficiency improvements. However, this does not solve the problem of urban chaos, related to traffic congestion and parking space cluttering, which contribute to increase human stress and overall economic productivity decrease. To address all these issues, electric urban buses come as an obvious solution, and they also have the advantages of being quieter than regular buses and of promoting a better travel experience to passengers.

Nowadays there are already electric buses operating in some parts of the world and one of the main concerns is their high weight, which is mainly due to the amount of batteries they carry in order to have an adequate range. Several strategies are possible and are being tested to provide buses with adequate operability in terms of range: battery swapping at central stations, battery charging at central stations on slow or fast charge rates and sizing the battery pack to the route of the electric bus using fast charge on bus stops.

This paper intends to provide a mathematical model for the electric bus powertrain and its routes, based on a created driving cycle that simulates an acceleration and deceleration period between two stops of a bus. The main objective is to verify how much of the energy recovered from regenerative braking can be absorbed by lithium-ion batteries and to verify whether the supercapacitors can excel the batteries for this purpose. The intent is to reduce the amount of batteries carried, in the attempt to increase the bus efficiency by optimizing regenerative braking capabilities and possibly reduce overall system weight.

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INTRODUCTION

Urban and suburban centers rely upon their transportation infrastructure for the well-being of their population, assuring their mobility. This mobility can be directly related to a sustainable urban development, due to the economic, social and environmental impacts that it has over the population. [1].

Many analyses on the social, economic and environmental costs and impacts of urban expansion have concentrated on the "invasive" nature of the automobile, consequence of their high flexibility on providing access to the increasingly dispersed urban functions. There is a persuasive picture in the urban lifestyle mindset in which the car is an essential element, thus contributing towards increase of traffic

congestion and mobility reduction [2]. These factors lead to an increasingly high amount of circulating cars, as expressed in Figure 1 for the European Union, which is detrimental to a sustainable urban development.

Based on what was presented, public transportation represents a solution for both a sustainable urban development and a reduction of traffic congestion, as it means a decrease on the number of circulating cars, once those people change of attitude will make them leave their cars at home. This change of attitude is somehow expected. People are becoming more environmentally aware and providing a clean mean of public transportation will persuade people to use it more often and thus contributing to an overall traffic reduction and consequently to a cleaner environment within cities and an overall energy consumption reduction.



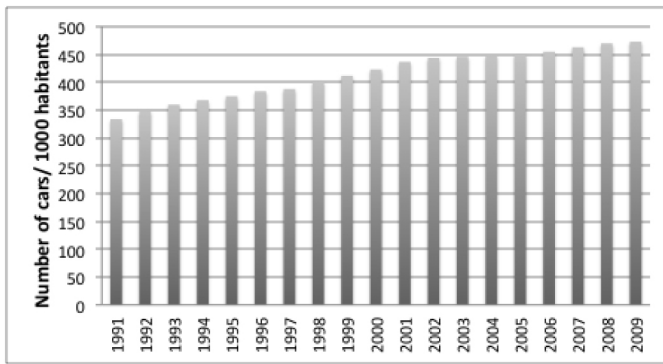


Figure 1. Number of cars per thousand inhabitants along time for the European Union Source: Eurostat [3]

Another well-known disadvantage associated with the large spread of automobiles relates with Green House Gas (GHG) emissions. According to NASA, motor vehicles are the largest net contributor to global warming pollution, followed by the burning of household biofuels (i.e. wood and animal dung) and raising livestock [4]. Besides, GHG emissions have negative effects on the earth's ecosystems as a whole, studies prove that by reducing the air pollution (namely fine-particulate) in $10 \mu\text{g}$ per cubic meter, an overall increase in life expectancy of 15% is observed [5].

In this sense, sole incentives and investment on conventional city buses - equipped with internal combustion engine - do not seem an adequate attempt towards solving all previous issues. On the other hand, electric buses emerge as a more comprehensive solution to solve both the air pollution issue - due to the absence of tailpipe emissions - as well as the "urban chaos" problem.

Electric buses also have a plenty of other positive aspects. The electric engine causes far less vibration throughout the vehicle, making for a more comfortable journey for those on board without the 'rattling' often experienced when a bus is at lights or a stop. A reduction in vibration also increases the life and reduces maintenance requirements of the bus, making it a cost-effective option for operators [6].

Another quality associated with electric buses is their reduced noise. They are noticeably quiet, lowering noise pollution and increasing comfort for those onboard. Although the initial introduction of an electric transport system and fleet can be costly, as a long-term mode of public transport they are surprisingly cost-effective in terms of lifespan and upkeep [6].

Nowadays there are already some electric buses in operation around the world. The Portuguese company *CaetanoBus* has launched its electric bus powered by lithium-ion batteries in 2011 for a 3-month test phase in Portugal. This company will also supply one of these models for Offenbach, a German city where it will operate under regular service. Moreover, *Sinautec Automobile Technologies* [7], and its Chinese partner, *Shanghai Aowei Technology Development Company*, have spent the past three years

demonstrating their supercapacitor bus model in China without any incident or failure. Another company that has developed its own electric bus using lithium-titanate *Altairnano* [8] batteries is *Proterra* [9], which launched its newest model *EcoRide BE35™* at California in 2010 for a testing phase.

In a general way, one of the main concerns regarding electric buses is their weight, which is significant due to the amount of batteries they have to carry in order to have an equivalent operational range as regular internal combustion engine buses. It is also important to mention that batteries represent the highest investment when considering the whole electric bus. Therefore, the main challenge for electric buses is to increase their efficiency and reduce costs. Reducing the battery size and weight is a natural strategy to be followed. One of the ways to do that is by implementing the use of supercapacitors, which has a much higher power density - quick storage and release of energy [10]- and thus are capable of absorbing a higher amount of the regenerative braking energy, which is generated at a rate (power) level that is not supported by conventional batteries [11]. This advantage could also be used for the acceleration of the vehicle which is worthy analyzing. The direct impact of implementing supercapacitors would be the possible reduction of the weight of the bus as the battery pack can be reduced. At the same time battery life is enlarged due to the reduction of energy transfer rate from and to the battery, since the energy for acceleration and from regenerative braking is transferred mainly between the super-capacitors and the motor [11].

In order to better study the possibility of reducing the battery pack, a mathematical model was developed to simulate the behavior of an electric bus on an urban environment, namely on a driving cycle representing the distance between two bus stops. The main idea is to investigate the amount of required energy to complete this cycle and the amount that can be recovered by the regenerative braking. With these results, the possibility of replacing part of the battery pack by a supercapacitors bank is approached.

SYSTEM MODELING STRUCTURE

A mathematical model of the electric bus performance was implemented in *MATLAB Simulink*. This model has several subsystems, which are used to calculate specific parameters. One of these subsystems represents the vehicle powertrain, taking into account the forces that work against its movement and the gear ratios involved. An output of this subsystem computes the amount of required energy for a driving cycle to be completed. There is a third subsystem that calculates the amount of energy that may be possibly recovered from the regenerative braking, taking into account the kinetic energy of the vehicle. The two other subsystems are related to the batteries and the supercapacitors, evaluating whether they are capable of absorbing the energy from the braking.

The calculation starts with the choice of the driving cycle, specified as an array of vehicle velocity versus time (at intervals of one second) [12]. This information is used to calculate the torque needed to operate the vehicle at each moment, considering aerodynamic drag, tire rolling resistance, climbing grade and vehicle inertia effects. The required total torque needed to drive the wheels at each moment is converted to power after calculating the speed of the motor (in rpm), taking into consideration the motor and the controller efficiencies. The time integral of power for the driving cycle gives the total needed energy or a specified route. Furthermore, the kinetic energy is calculated as a way of, after discounting the resistances' energy, finding out how much energy can be recovered from the regenerative braking. Then the batteries and supercapacitors were modeled to find out how much of the regenerative braking energy can be absorbed by them. The high-level scheme for this model structure can be observed in Figure 2.

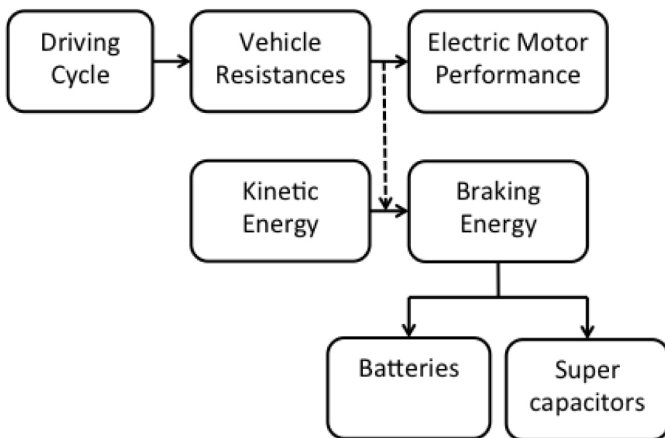


Figure 2. High-level model structure

SYSTEM MODELING DESIGN

DRIVING CYCLE

One critical component of the simulation is the driving cycle on which all the vehicle calculations are based [12]. For this study, a driving cycle was developed that simulates a stop-and-go part of a bus route. This part has a 10-second accelerating period, then 33-second period of constant speed and a 7-second period of deceleration. The acceleration rates are based on the simulated performance of the bus considering the specifications of its electric motor and the gear ratios involved, respecting the speed limits for buses in urban areas of 50 km/h [13]. The cycle corresponds to approximately 514 meters, which represents an average distance between bus stops in Europe [14]. This cycle can be observed in Figure 3.

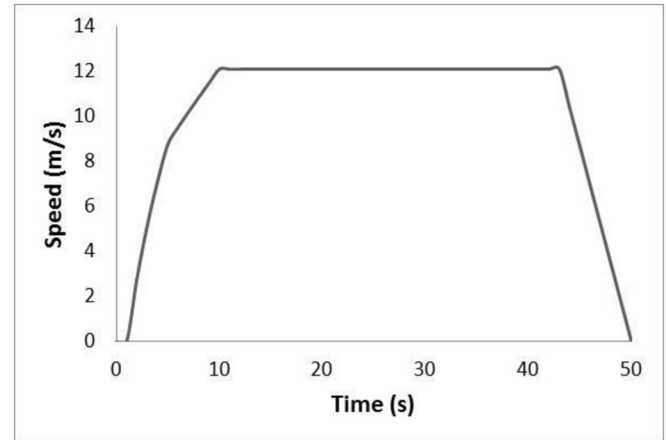


Figure 3. Driving cycle

TRACTIVE FORCE

This is the force propelling the vehicle forward, transmitted to the wheels. This force must overcome the vehicle resistance to the movement, which is composed by the sum of the different forces that act against its movement, such as the friction between the tires and the road (rolling resistance force), the resistance of air (aerodynamic drag force), the climbing grade (hill climbing force), and the inertia [15, 16].

Rolling Resistance

The rolling resistance force, F_{ro} , is primarily due to the friction of the vehicle tire on the road, but friction in bearings and on the gearing system must also be considered. The rolling resistance depends on vehicle speed and can be calculated by using an equation as a function of speed. The rolling resistance is also proportional to vehicle weight [12], [15], [16].

$$F_{ro} = f \cdot m \cdot g \quad (1)$$

For the rolling resistance coefficient, the following expression was used [17]:

$$f = (0.0041 + 0.000041 \cdot v \cdot 2.24) \cdot C_h \quad (2)$$

Where:

f = rolling resistance coefficient

m = mass of the vehicle (kg)

g = gravitational acceleration (m/s^2)

v = linear speed (m/s)

C_h = road surface coefficient

Aerodynamic Drag

The aerodynamic force F_l is due to the friction of the vehicle body moving through the air. It depends on the frontal area, shape, protrusions (such as side mirrors), ducts and air passages, spoilers, and many other factors [12, 15, 16].

$$F_l = 0.5 \cdot \xi \cdot C_w \cdot A \cdot (v^2) \quad (3)$$

Where:

ξ = air density (kg/m^3)

C_w = aerodynamic drag coefficient

A = vehicle frontal area (m^2)

v = vehicle speed (m/s)

Hill Climbing Force

The hill climbing force F_{st} is the force needed to drive the vehicle up a slope. It is simply the component of the vehicle weight that acts along the slope. It may have a negative impact on the movement of the vehicle, acting indeed as a resistance force but also a positive impact, if the vehicle is going down a hill. In this case, this force helps the movement [12, 15, 16].

$$F_{st} = m \cdot g \cdot \sin \alpha \quad (4)$$

Where:

α = grade angle

Acceleration Force

A force has to be applied in addition to the forces already mentioned if the velocity of the vehicle is changing. The acceleration force F_{ta} will provide the linear acceleration of the vehicle [15, 16].

$$F_{ta} = m \cdot a \quad (5)$$

Therefore, after the deduction and presentation of all the equations above, the total tractive force is their sum:

$$F_{te} = F_{ro} + F_l + F_{st} + F_{ta} \quad (6)$$

The torque can be expressed by $F_{te} \cdot r$, where r is the radius of the tire, and F_{te} is the tractive effort delivered by the powertrain. Assuming G as the gear ratio of the transmission system connecting the motor to the axle, and T the motor torque [16]:

$$T = \frac{F_{te} \cdot r}{G} \quad (7)$$

After calculating the tractive force, it is necessary to know the amount of power required for each instant of the driving cycle. This power can be calculated as a function of the vehicle torque and motor speed, according to the equation below. In order to know the amount of required energy to complete the driving cycle, one must make the integration of the power required for each instant [15].

$$P = \frac{T \cdot v_m \cdot 2 \cdot \pi}{60000 \cdot \eta_m \cdot \eta_c} \quad (8)$$

Where:

P = Power (kW)

T = Torque ($\text{N} \cdot \text{m}$)

v_m = Motor speed (rpm)

η_c = Controller efficiency

η_m = Motor efficiency

The motor speed v_m in revolutions per minute, can be calculated taking into account the linear speed, the perimeter of the wheel and the transmission gear ratio.

$$v_m = \frac{v \cdot 60 \cdot G}{2 \cdot \pi \cdot r} \quad (9)$$

KINETIC ENERGY

The effect of the vehicle mass when accelerating and stopping in town and city conditions is another area where the mass of the electric vehicle will have considerable influence on vehicle performance [16]. Basically when a vehicle of mass m (in kg) is travelling at velocity v (in m/s) its kinetic energy is given by:

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \quad (10)$$

If the vehicle brakes, this kinetic energy is converted into heat at the braking disks. When regenerative braking is used a certain amount of the energy is recovered. The kinetic energy is being used in this model for calculating the amount of energy dissipated in braking, considering the tires and air resistance and the climbing grade, which can contribute positively or negatively to the regenerative braking.