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eBUS - Electric bus test platform in Finland

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Abstract

Electrification of buses will revolutionize bus operations. Diesel buses are highly autonomous and interchangeable, whereas electric buses must be seen as a part of a smart city system. To introduce electric buses, several actors have to be brought together in public-private partnerships: state and public transport authorities, municipalities, bus operators, utilities, technology companies and research institutes.

The eBUS project, set up as a public-private partnership, establishes a world class electric bus test platform and generates experiences from electric bus technologies and their real-life performances. The buses will be tested in the field by actually running a bus line in Espoo (Line 11) in harsh climatic conditions. In addition, laboratory testing for determining e.g., efficiencies and driving cycle dependence, will be carried out. A special full-size electric vehicle will be built to serve as a platform for component testing and setting references. Computational tools to support route and operation planning for battery electric buses will be developed.

The test platform makes comparison of different electric buses and their subsystems possible. It also enables unbiased comparison to other alternative technology options for city buses. The project also will establish a new EV reference database, which can be used as reference for future development projects.

This paper presents the setup and fundamentals of the electric bus test platform in Finland, including the methodology for testing, and in addition it presents the first results for the prototype electric bus "test mule". At the time of writing, the first commercial buses are starting daily operation on Line 11. The plan is to have 4 – 6 battery electric buses of different brands running in parallel. At a later stage, results from these buses will also be presented. Parallel projects on charging and systemic issues are under way.

Keywords: Electric, city bus, efficiency, losses, testing, platform

1 Introduction

Just a few years ago, electric buses were not seen economically or technically competitive in comparison with the diesel and some other alternative technologies. The use of electric buses was usually limited to smaller vehicles and short-distance special operations. Recently the availability of full-size electric buses has been boosted by public funding for battery development, improved battery performance and increased battery production capacity all over the world. During the past years, there has been growing interest towards this technology [1-3]. Also emission reduction targets and political decisions to promote clean and efficient vehicles have made electric buses interesting.

Changing diesel buses to electric ones may sound simple, but there are plenty of challenges that need to be sorted out before public transport authorities or bus operators can make the decision to go for the electric route. Diesel buses are highly autonomous and interchangeable, whereas electric buses must be seen as a part of a smart city transport system. To introduce electric buses, several actors have to be brought together in public-private partnerships: state and public transport authorities, municipalities, bus operators, utilities, technology companies and research institutes.

There are several open questions related to electric bus systems as a whole, charging vehicles, and on the vehicle level feasibility of various electric bus technologies, their overall performance and economic impacts. The eBUS public-private partnership was started in the fall of 2011 to answer part of these questions by testing several electric bus models and gaining practical experiences [4]. The electric bus project consists of several blocks:

System level:

- tools for planning battery electric bus operations, support for decision making by life cycle analysis
- options for charging electric buses and impacts on infrastructure

Vehicle level:

- field testing on actual bus line in Espoo (Line 11), harsh climate conditions
- laboratory testing for determining e.g., efficiencies and driving cycle dependence
- full-size electric bus test vehicle “test mule” for component testing and references
- evaluation of the energy efficiency by modelling and simulation

The vehicle test platform makes it possible to compare different electric buses and their subsystems to each other. It also enables unbiased comparison to other alternative technology options for city buses. The project also will establish a new EV reference database which can be used as reference for future development projects.

This paper focuses on the vehicle testing part, presenting the setup and fundamentals of the electric bus test platform in Finland, including the methodology for testing. In addition, it presents the analysis of the design requirements and the first results for the prototype electric bus “test mule”. At the time of writing (summer 2013), the first commercial buses are starting daily operation on Line 11. The plan is to have 4 – 6 battery electric buses of different brands in parallel. At a later stage, results from these buses will also be presented.

2 Test Platform

2.1 eBUS as a part of Electric Commercial Vehicle project

Electric Commercial Vehicles - ECV is a part of the national electric vehicle programme EVE by Tekes, the Finnish Funding Agency for Technology and Innovation [5]. ECV creates a comprehensive and versatile research and test infrastructure for electric commercial vehicles. ECV brings together major Finnish technology companies, the public sector as well as the research community active in the field. The project combines the competencies of the most prominent national players working in this area, with a coverage starting from single components via subsystems all the way to vehicles and vehicle fleets. The main research topics of ECV are electric buses, mobile working machinery, electric power trains, electrochemical energy storages and other e-components for power transmission. Some activities are supplemented by modelling. The extensive R&D infrastructure and co-operation within ECV give a positive momentum to the Finnish electric vehicle and component industries. Finland has no major passenger car industry, but several world-class manufacturers of, e.g., heavy-duty mobile machinery and cargo handling equipment.

2.2 eBUS-project

In a public-private partnership, the eBUS project brings together all the relevant stakeholders needed to create an electrified bus system:

Authorities:
- Ministry of Transport and Communications
- The Finnish Transport Safety Agency
- Helsinki region public transport authority (Helsinki Region Transport, HRT)

Municipality:
- City of Espoo

Bus operator:
- Veolia Transport Finland

Electric utility:
- Fortum

Technology companies:
- Kabus (bus manufacturer)
- European Batteries (battery manufacturer)
- Vacon (manufacturer of power electronics)

Research community:
- Aalto University
    - Metropolia University of Applied Sciences
- VTT Technical Research Centre of Finland

The objective is to create a world-class test bed for electric buses in Metropolitan Helsinki. The uniqueness of the test bed arises from involving all key stakeholders, the exceptionally good co-operation between the public sector, industry, fleet operators and the research community and the challenging climatic conditions. The test bed is physically located in the so-called T3 area in Espoo, home of Aalto University and VTT, known as an innovation hub and famous for its many high-tech companies.

Espoo is an excellent site for demonstrating electric buses. A new westward metro line from Helsinki to Espoo will be completed in 2015. This will significantly change bus operations in southern Espoo. The regional bus routes from southern Espoo to Helsinki will end, and will be replaced by feeder-type bus services to the metro stations. The vision of both City of Espoo and Helsinki Region Transport is that at least part of this feeder traffic should be electrified. Therefore, charing of electric buses has to be taken into account in the construction of the new public transport terminals, now already under way.

As for the vehicle research part, eBUS is a combination of field and laboratory testing of electric buses. The buses are operated by Veolia Transport Finland in everyday service, in real conditions and in real operations. The research partners will study different charging technologies and new traffic planning methodologies to optimize the use of EV buses. VTT's tasks include chassis dynamometer measurements and data acquisition from the buses in service. The target of the project is to have a maximum of six (6) PHEV/EV buses in service from 2012 to 2015. In parallel to field testing there will be R&D activities carried out by using the eBUS test mule (a full-size battery electric bus engineered by Metropolia and VTT): power electronics, battery packs, charging, motors, powertrain, etc. This R&D platform offers services to bus and component manufacturers.

By today eBUS project has shown that there is a need for such testing and demonstration platform due to our severe climate conditions. Finnish tough climate with very cold nights has already shown its harshness to the electric buses during winter 2012. Biggest problems have occurred when temperature drops below -10 degrees Celsius. Even though Veolia Transport Finland has done only some thousands kilometres with two different electric buses in the toughest winter times, it is clear that heating of the bus and batteries is an important topic. As normally all buses are parked outside in the cold, electric buses require careful planning of thermal management. How to keep the batteries warm during charging and driving? How to heat up the passenger area in the most efficient way?

Second major learning phase has been fault diagnostic and repairs at the workshop level. Diesel buses have been as a "standard" for Finnish bus operators and workshops for decades. However, this new technology brings completely new faults and requires different kind of mental approach (also safety requirements are very demanding). Therefore, it has been essential to put efforts also on training of the mechanics in theory, but also in practice. As these early stage electric buses have been demanding to operate, they have also been a good concourse for education of mechanics.

Overall it still seems that all problems can be solved and for sure there will come more of these technical challenges that the project has not faced yet. Therefore, it has been good that electric buses have been introduced gradually to the bus operations in Espoo. There are two new electric buses in the production pipeline in China and further negotiations are on-going with several other manufacturers.

In parallel to electric bus testing, there is a need in the society for further debate of charging infrastructure. This debate should have two sub-headlines: technology and future standards and business models for ownership and financing of the opportunity charging. Before reaching these topics, one major decision has to be done before: Will there be opportunity charging with less flexibility on charging timing or overnight charging with higher flexibility? Also it is important to recognise the operational timeline and daily mileage: Does the system need 24h operations (+300km) or only max. 200km/per day divided to peak hour times in morning and afternoons with possibility for some charging at depot? As these topics require same stakeholders as the electric bus test platform, it has been natural to expand the on-going e-mobility discussion to charging infrastructure in Espoo.

2.3 Field testing

All electric buses will run in the city of Espoo on line 11. This relatively short line mimics future feeder-type bus service that could be provided by battery electric buses. Line 11 has 24 bus stops in 9,1km or 26 bus stops in 10,1km depending on the direction. First bus starts at 5:42 and last departure is 23:47. Travel time one way is about 25 minutes, so the commercial speed is around 20-25km/h depending on traffic. It is essential to test different kind of electric buses and related systems in normal daily operations before launching full scale operations. The main focus of the field test for Veolia Transport Finland is to evaluate how the buses perform in very tough winter conditions (lot of snow in the road and melting of snow inside the bus), and in spring/autumn time when temperature swings above and below freezing. The electric buses, always parked outside, have to survive from -30 to +30 degrees. Temperatures of -10 degrees and below are foreseen to be the most challenging conditions. The buses are equipped with data logging systems and related sensors to monitor real life energy consumption and effects of weather conditions on the operation of vehicle and subsystems. The performance of the buses will be followed-up with yearly laboratory measurements.

3 Laboratory testing

VTT has a rather unique chassis dynamometer test facility for heavy-duty vehicles. During the past 10 years, VTT has, in cooperation with Helsinki Region Transport, created one of the most comprehensive data bases on the performance of buses (energy consumption, exhaust emissions).

Testing of electric vehicles on a chassis dynamometer requires some special arrangements. The laboratory should have possibility for charging batteries while the vehicle is positioned on the test bed, and there should also be possibilities to feed the vehicle from an external energy source. Also several preparation and conditioning steps are needed to get comparable results.

VTT has already developed energy consumption measurements for electric passenger cars, and this methodology will be used as starting point for bus measurements, as well. In the passenger car study, the energy taken from grid was split up and allocated for all consumers inside the vehicle. This methodology, in addition to proving an overall value for energy consumption or efficiency, also provides subsystem level efficiencies. The principle remains the same for buses although the scales may change [6].

The basic chassis dynamometer test procedures, e.g., driving cycles, dynamometer settings and tyre selection can be directly adopted from VTT's normal test procedures for conventional vehicles [7].

4 Modelling and simulation

The modelling and simulation of the electric bus in the eBUS project was done by Aalto University. The preliminary design requirements for the test mule were evaluated and verified by vehicle simulations. An electric bus model was developed on the basis of ADVISOR vehicle and component models [8]. The modelling and simulation work focused on defining the performance requirements for the main powertrain components including the battery system, inverter, traction motor and final drive. In this case, the powertrain performance is defined by the traditional characteristics of the vehicle performance, such as acceleration, maximum speed, and gradeability. The energy efficiency of different powertrain topologies of electric buses was also evaluated with simulations in different types of city bus driving cycles [9].

The simulation model of the electric bus consists of parametric models of the powertrain components, auxiliary devices and vehicle control system. The parameters for the component models were acquired from the component specifications which were well known in the eBUS project. The energy efficiency of the powertrain is calculated based on the component specific efficiency maps.

In the first phase of the simulations, the design requirements of the powertrain were evaluated based on the performance requirements in the typical city bus driving cycles. In this case, the powertrain performance is defined as the power and torque capacity at the driven wheels. The powertrain performance was calculated on the basis of the specifications of the components which all have their own limitations impacting on the overall performance. The most limiting factor in the eBUS powertrain was the current acceptance of the inverters and current limitations of the battery in discharging mode. Figures 1 and 2 show the performance requirements in terms of power and torque for city buses in different driving cycles (BR = Braunschweig, MAN = Manhattan, NYC = New York Bus, and OCC = Orange County Cycle). The power and torque requirement is calculated at the driven wheel. In this case, the reference bus has the total weight of 12000kg. The calculated eBUS performance is also presented in Figures 1 and 2.

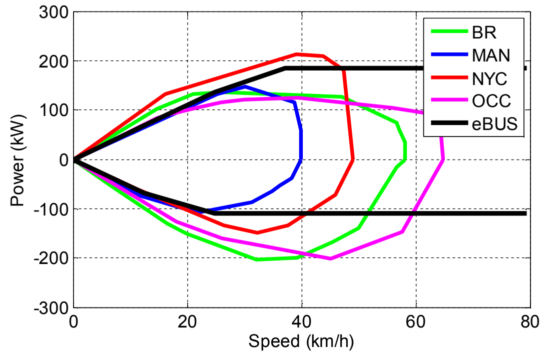

Figure 1: Power requirement

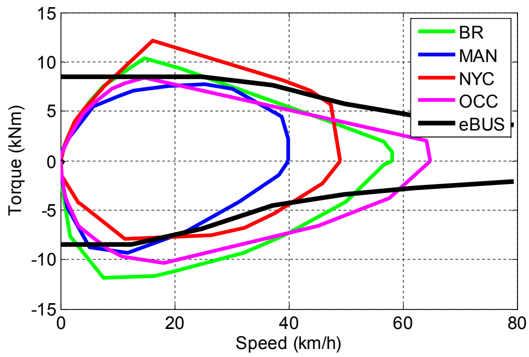

Figure 2: Torque requirement

The simulation results of the developed simulation model were compared with the measured results from the dynamometer tests. Overall, the simulation results corresponded well to the measured results in terms of component efficiency and total energy consumption. There was only 2-3% difference in the battery energy consumption. As the full dynamic behavior of the battery was not taken into account in the simulation model, the battery system voltage did not completely correspond to the measurements being a little bit higher in the discharge phases. Figure 3 and 4 shows the comparison of the battery and inverter currents in a portion of the Braunschweig driving cycle.

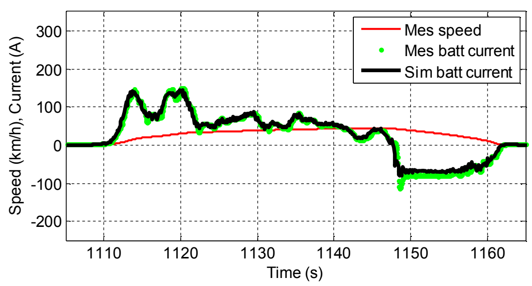

Figure 3: Measured and simulated battery current

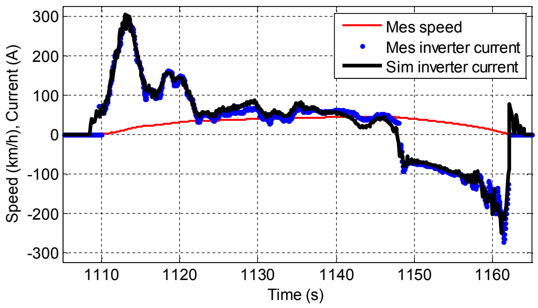

Figure 4: Measured and simulated inverter current

5 Test vehicle, the test mule

One part of the eBUS-project was to build a full size test vehicle. This vehicle called test mule was needed 1) to enable energy consumption measurement and analysis methodology, 2) to establish a solid reference for evaluating the various commercial vehicles on the test field and 3) to enable participating companies to test their components and provide a reference application for them.

Due to the modest specific energy of today's Lithium-ion batteries and the importance of the overall vehicle weight reduction to energy consumption, a lightweight body structure is highly desirable for any electric vehicle. Therefore a self-supporting full aluminium body from the Finnish bus and coach manufacturer Kabus was selected as the base of the test vehicle platform. This vehicle is originally designed for traditional but downsized diesel powertrain, which is placed behind the driven rear axle. In the diesel version, the curb weight is 8400 kg, which is some 3000 kg lower than for conventional vehicles. (Picture 1)

Picture 1: The test mule

Vehicle modelling and simulation were used for defining the preliminary design requirements for the test mule. The work focused on defining the performance requirements for the powertrain components (battery, inverter, traction motor and final drive). The powertrain performance is defined by the traditional characteristics of the vehicle performance, such as acceleration, maximum speed, and gradeability. Simulation studies also allowed evaluating the energy efficiency of different powertrain topologies of electric buses.

The test mule is built using mainly Finnish components. Visedo delivered a permanent magnet synchronous electric machine for propulsion. The motor is placed in lieu of the transmission of the original powertrain and it is driven by two parallel connected inverters manufactured by Vacon, which are directly connected to the battery DC link. The original rear axle was retained. Currently the vehicle is equipped with 56 kWh and 615 V nominal LiFePO battery system produced by European Batteries in Varkaus, Finland. This is sufficient for testing purposes, but commercial operation would require bigger energy storage.

In addition to the propulsion system, the vehicle is equipped with the necessary DC-DC converter to provide 24 V system power, electro-hydraulic power steering and direct electric drive air compressor. Both the hydraulic pump and air compressor are driven by small industrial asynchronous motors. Each individual electric load is equipped with sensors allowing accurate tracking of energy consumed during drive cycle and road testing.

The vehicle has been operated on road only limited number of miles at the moment, but instead is has been subject to several different dynamometer drive cycle tests.

6 Example results

By the date VTT has finalized and tested measurement procedures with two electric buses. The results for these commercial electric buses will be published later, when the database allows calculating average, minimum and maximum results without revealing in detail the underlying products and models. If the number of buses are growing as expected, that should be possible during 2014.

This paper presents preliminary results measured from the test mule. During the measurement campaign, the power train of the test mule was functional but not finished or fully optimized. Also the heating and the ventilation system was under construction, thus not included on the results.

6.1 Energy consumption in different driving cycles

Driving cycles have major impact on energy consumption. Therefore, those must be taken in account when choosing battery capacity and/or charging strategies. To represent the effect, five common city bus cycles were driven on chassis dynamometer. The basic characteristics of each cycle are collected on Table 1. The Espoo cycle (line 11) has highest average speed, least stops and lowest idle percentage. The cycle represents metro feeding traffic in Espoo area. All the other cycles are representing bus operation on centres of different size of cities. The buses on New York cycle stand still on idle most of the time, thus the average speed goes really low. This is the most demanding cycle for any exhaust emission after treatment systems.

Table 1: Characteristics of different driving cycles

Driving Cycle	Time (sec)	Av. speed (km/h)	Dist. (km)	Idle (%)	Stops per km
Espoo	1372	23.7	9.0	20	2.10
Braun-schweig	1750	10.9	22.6	26	2.65
London	2281	14.1	9.0	33	5.35
Paris	1897	5.68	10.7	33	7.52
New York	600	0.98	5.94	66	12.4

Figure 5 shows the energy consumption per driven kilometre on the chosen driving cycles with two different load levels. The total weight of 10400 kg means 2000 kg of payload and the 12 400 kg corresponds to 4000 kg.

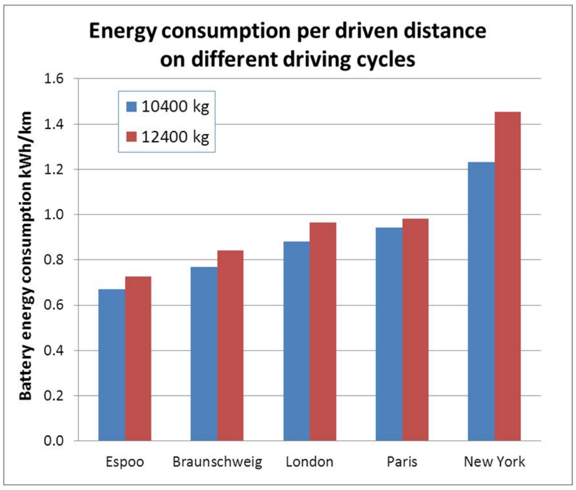

Figure 5: Battery energy consumption per kilometer

The cycles with lowest average speeds are showing the highest energy consumption readings per kilometre, but as the average speed will have effect on the driven distances per day, the consumption per time is more usable value for dimensioning components and systems. Figure 6 shows the energy consumption on time basis.

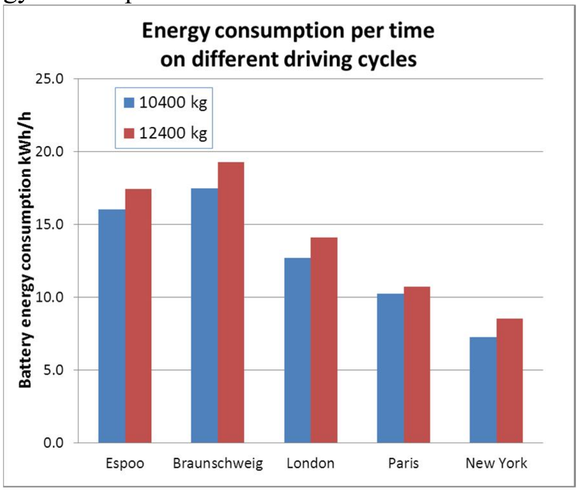

Figure 6: Battery energy consumption per hour

The Figure clarifies the fact that battery energy demand for 10 hours of operation would be only 70-90 kWh on New York cycle, but the Braunschweig cycle would need 170-200 kWh for the same operation time in this case.

On the other hand, if the bus in New York has climate control system, as they do in practice, the energy need for controlling the temperature may be higher than the energy needed for moving and for other vehicle functions itself. Same applies to heating needs during the winter time. These subjects will be further investigated during the project.

6.2 Energy distribution for consumers

The optimization of energy consumption becomes more essential in the case of battery-driven vehicles, as it will have an effect also on battery capacity, besides the energy costs itself. To understand the full reduction potential, one needs first to understand, where all the energy is used. Then it’s time to look into individual consumers, and consider their development potentials. Benchmarking the energy efficiencies will help to understand, what other manufacturers have been achieved in general.

Figure 7 presents how the energy from grid divides for different consumers in the case of test mule (still on development phase). The driving cycle used for testing was commonly used Braunschweig city bus cycle (Figure 8). The bus was tested in relatively high payload of 4000 kg representing about 40 to 50 passengers.

Driving resistances consisting of rolling resistance and air drag correspond with 34.0 % of the total usage. The driving resistance for the bus type was determined by coast down tests in earlier projects. The losses in inverter, electric motor and driveline were 18.6 %, in total. This loss is relatively high in bus driving cycle as the energy flow is fluctuating back and forth all the time in continuous acceleration and braking. To further clarify the nature of the driving cycle, the energy flows in and out of the battery can be reviewed, and they were 14.0 kWh out (discharge) and the 5.5 kWh in (regeneration/recharging). This behaviour also has an effect on battery losses during the driving cycle (6.2 %), which was calculated using constant 96 % charge/discharge efficiency for the battery. The actual efficiency measurements will be performed later using battery tester and the actual battery load cycle.

The power steering pump and air compressor were used only in partially as the steering is not used on chassis dynamometer and the doors were not used on the bus stops, as they are used on the actual bus line. This part will be studied more in details on test bus line.

In this case 3.4 % of the total energy went on brakes. The regeneration capability during braking may be limited by various reasons, like basic dimensioning of the system or battery state of charge.

Besides of the consumption on cycle driving, also some losses are present during the charging. In this example 25.6 % of the total energy from the grid was spent on losses on the battery charger, battery itself, and on battery management system. Battery management includes example battery cell balancing and controlling the temperature of the batteries (fluid).

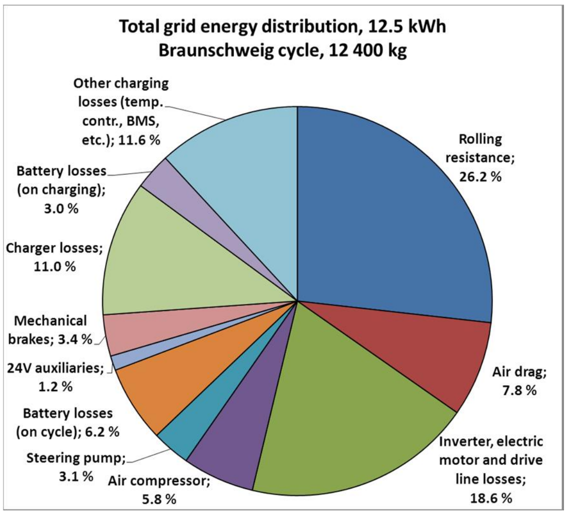

Figure 7: Distribution of total grid energy

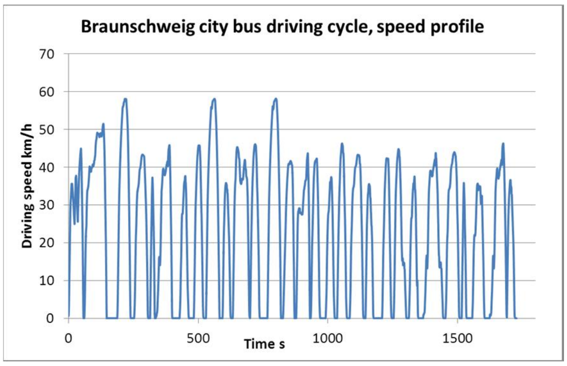

Figure 8: Speed profile of Braunschweig city bus cycle

The energy consumption from the grid is typically interesting from the view point of the operator, as they usually pay from electricity based on measurements on this point. Vehicle developer might be also interested on taking closer look inside the vehicle. The Figure 9 represents how the proportion of the consumption is changing when using battery energy as comparison point. Almost half of the energy is used on the driving resistances and other half is lost inside the vehicle.

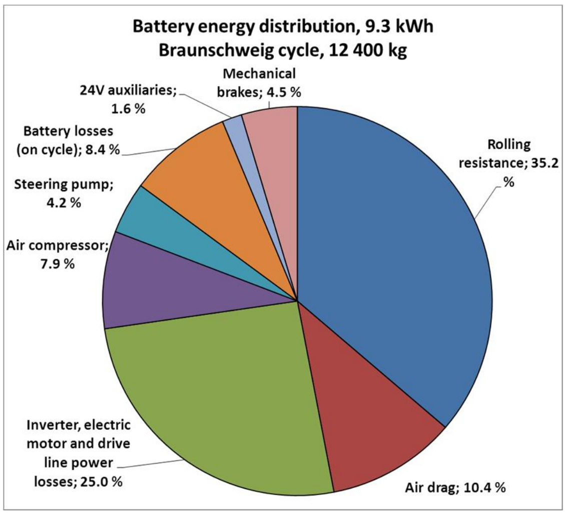

Figure 9: Distribution of total battery energy

Furthermore, temperature control and ventilation of the passenger compartment will play important role in total energy consumption, but not presented yet in this paper.

7 Conclusions

The Finnish test platform for electric buses is a unique combination of field testing, in-depth performance measurements in a heavy-duty chassis dynamometer and a test mule for benchmarking and development of HD electric vehicle components and subsystems. The test platform makes comparison of different electric buses and their subsystems possible.

First results were presented showing effects of driving cycles and energy consumption distribution for different consumers using electric test bus the "test mule" as an example vehicle.

Project will continue and the plan is to get 4-6 different electric buses running on the test line during the 2014-2015. The reference database for energy consumption will be established for vehicle and component level.

Acknowledgments

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