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GEOMETRY DESIGN AND ANALYSIS OF AN ELECTRIC BUS FOR THE INTERIOR THER-MAL MODELLING

DIZAJNIRANJE IN ANALIZA TERMIČNEGA MODELIRANJA NOTRANJOSTI ELEKTRIČ-NEGA AVTOBUSA

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Abstract

The heating, ventilation and air-conditioning (HVAC) system represents the main auxiliary load for any type of bus. Being the most significant energy-consuming auxiliary load for the electric bus, it must be given special attention in an electric bus system design. To study the heat transfer and thermal optimization for passenger comfort in the electric bus computer-aided design (CAD) is used. The geometry of an electric bus interior is designed considering the main components of the vehicle: passenger cabin, driver's cabin, windows, walls, and seats. Materials of the same type as those used in the real bus are considered for the geometry model. Based on the heat transfer theory, a thermal model and simulations are made for the heat transfer inside the electric bus. The simulated data are compared with measurement data, and based on these, it can be concluded that the thermal model of the electric bus can be validated and used further for a wide variety of thermal simulation types.

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Povzetek

Sistem ogrevanja, prezračevanja in klimatizacije (HVAC) predstavlja glavno dodatno obremenitev za vse vrste avtobusov. Ker gre za sistem z največjo porabo energije pri električnem avtobusu, mu moramo posvetiti posebno pozornost pri dizajniranju električnega avtobusa. Pri študiji prenosa toplote in optimizaciji v smislu udobja potnikov smo uporabili računalniško podprto dizajniranje (CAD). Postavitev notranjosti električnega avtobusa je zasnovana glede na glavne komponente vozila: prostor za potnike, prostor za voznika, okna, stene in sedeže. V oblikovanem modelu so uporabljeni materiali iste vrste kot v realnih avtobusih. Na podlagi teorije o prenosu toplote smo naredili model in simulacije prenosa toplote znotraj električnega avtobusa, nakar smo primerjali podatke iz simulacije s podatki iz meritev. Iz izvlečkov omenjene primerjave lahko zaključimo, da je termični model električnega avtobusa mogoče validirati in nadalje uporabiti za najrazličnejše termične simulacije.

1 INTRODUCTION

Energy consumption per trip for an urban vehicle is a major design factor, which is influenced by the driving pattern, the topology, the climate conditions and the payload. The energy required by the auxiliaries is not negligible, so that the efficiency enhancement of the auxiliaries could lead to an improvement of global energy use in the vehicle, which is particularly important for innovative means of transport which are characterised by a limited range, such as that of an electric bus.

The importance of energy consumption for non-traction needs is revealed when considering the percentage distribution of energy consumption in annual scales for a bus system *[1]*: traction needs represent about 52%, non-traction needs on stopping about 13% and non-traction needs for route operation about 35%.

A key parameter affecting the auxiliary energy consumption is the external temperature. A rise of 10 ^{o}C can lead to an energy consumption increase of about 0.75kWh/km *[2]*.

An important input parameter is the setpoint temperature within the electric bus cabin. Usually, the setpoint is kept at a constant temperature that is comfortable for the passengers inside the bus, but the “comfort aspect” is a relative aspect concept. What a person perceives as a comfortable temperature depends on many parameters, such as *[3]* air humidity, air velocity, radiation, seasonal effects, and metabolism.

Attention is given to the optimization of the thermal system of electric vehicles. This functionality can be synthesized as:

1. Dynamic temperature setpoint: By considering the different aspects of comfort, an energy-optimized temperature setpoint control can be implemented. For example, a temperature setpoint can vary over the day to account for ambient temperature changes. This results in lower energy consumption of the HVAC system *[3]*.

2. Pre-conditioning: The energy that is required for the heat to control the cabin climate is taken from the battery. Therefore, this might affect the driving range of the vehicle. Besides minimizing the energy consumption of the HVAC system, pre-conditioning can also be applied to improve the vehicle’s driving range of the vehicle. Pre-conditioning means that the cabin

climate is already controlled towards the desired temperature while the vehicle is still connected to the charger, either in the depot or en route at terminal stops.

Heat transfer theory, heat balance method and U-Value definition are the foundations used in calculations and modelling *[4]*. Based on the heat transfer theory, there are three mechanisms for transferring heat: conduction, convection and radiation.

The Heat Balance Method is a common method for calculation of heating and cooling loads in a space or zone *[4]*. The total heat released into the cabin is given by:

- Ambient load, as the thermal load caused by the temperature gradient between inside air and the ambient temperature,
- Radiation loads,
- Metabolic load, generated by human body,
- Ventilation load, as the flow of fresh air,
- Engine/Motor load, due to the bus motors,
- AC load, for keeping the internal temperature in the comfort zone by heating or cooling.

The heating, ventilation and air-conditioning (HVAC) system represents the main auxiliary load for any type of bus. Being the most significant energy-consuming auxiliary load for the electric bus, it must be given special attention in an electric bus system design. The HVAC systems usually implemented in electric buses is composed from a rooftop unit comprising a compression refrigeration machine and several heat exchangers for air cooling and heating. Heating can be also performed by heaters placed at the floor level and supplied from the main power supply, or from an auxiliary supply system (such as a battery), *[5-8]*.

Energy needs for resistance heating can significantly increase the vehicle's energy consumption. From measurements on a 12 m electric bus *[9]*, it is estimated the average electric power necessary to keep the interior of the vehicle at 17 °C on a cold winter day with ambient temperature of approximately -10 °C is around 24 kW. Assuming a specific energy demand for traction and non-HVAC auxiliaries of 1.2 kWh/km, a plausible value according to measurements, a constant 24 kW load for heating will increase vehicle consumption by 1.3 kWh/km at an average velocity of 18 km/h and 2 kWh/km at an average velocity of 12 km/h.

Possible measures to reduce energy consumption of the HVAC system include improved thermal insulation, double-glazed windows, door air curtains and using improved control systems. Differently from the conventional HVAC system on current buses, *[10]* an integrated air-conditioning and heating system specifically for an electric bus are proposed. For an i-HVAC (integrated HVAC) system, an electrical heat pump type should be considered.

2 HEAT TRANSFER MODEL

Thermal conduction is estimated considering Fourier's Law, with heat flux given by:

$$q=-k\cdot dT/dx \ [W/m2] \tag{2.1}$$

where:

q is the heat flux,

k is the thermal conductivity, $[W/m^2K]$,

T is temperature, [^oC],

x direction of the heat flux, [m].

Thermal convection is considered for the heat transfer between the air and the solid structure of the bus. Newton's formula is considered in this case for the heat flux estimation:

$$q=-h\cdot(T_s-T_f) \ [W/m2] \tag{2.2}$$

where:

q is the heat flux,

h heat transfer coefficient, $[W/m^2K]$,

T_s is the temperature of the solid, [^oC],

T_f is the temperature of the fluid, [^oC].

3 DESIGNING THE INTERIOR GEOMETRY MODEL OF THE ELECTRIC BUS

To study the heat transfer and thermal optimization for passenger comfort in the electric bus, computer-aided design (CAD) is used, COMSOL Multiphysics, which has a special application for thermal aspects, the Heat Transfer Module. In order to simulate the heat process inside the bus, the following steps are to be followed: geometry modelling, physics settings, solving, and results.

The geometry of the electric bus is constructed as a basic geometry and is composed from: passenger cabin; driver's cabin; bus walls; windshield; windows; floor; roof; doors; wheels; passengers seats; electric air heat units inside the passenger cabin; heating block inside the driver's cabin.

The dimensions of the electric bus are designed in the geometry model according to the actual dimensions of the real vehicle, an E321 electric bus used currently in public transportation in Chisinau, Republic of Moldova *[11, 12]*. This is a low-floor compartment vehicle with a capacity of about 100 passengers, with a 150kW electric motor, with four heating units inside the passenger cabin. The components of the vehicle described above are also designed on the geometry model considering their actual dimensions on the electric bus. Thus, the model and the simulation results will be close to reality.

The first step to build the geometry model of the electric bus was to design the passengers' cabin and the driver's cabin. For the modelling and simulations these areas will be considered to be filled with air.

The second step in designing the geometry model is to design the exterior components, such as the front wall, rear wall, lateral walls, front windows (windshield), rear window, lateral windows and the doors. For this, a 2D representation was used (Figure 1), as a work plane design and plane geometry design. For each of these components, coordinates for the size, shape and position are transferred into the geometry model.

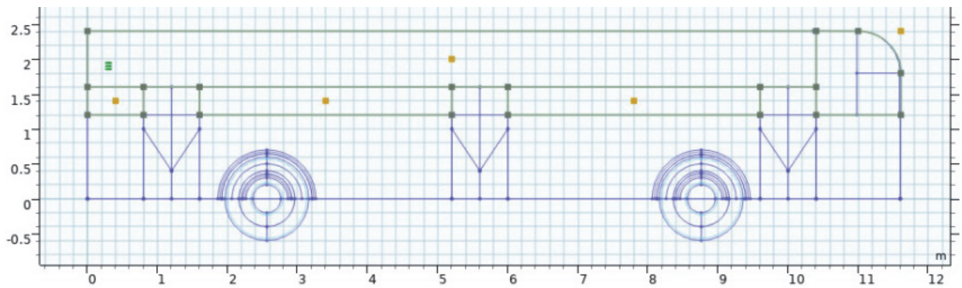

***Figure 1:** 2D design of the bus*

Having the main structure of the geometry model, the heaters can be designed inside the cabins. The passenger cabin is designed with four heaters and the driver's cabin with one heater (Figure 2). Thus, in the passenger cabin, the first heater is placed on the right side of the vehicle, next to the third door, a second heater is placed on the left side of the vehicle, in the middle area, the third heater is placed on the right side, after the second door, and the fourth heater is placed in front of the cabin, next to the glazed partition which separates the driver's cabin from the passenger compartment (Figure 2).

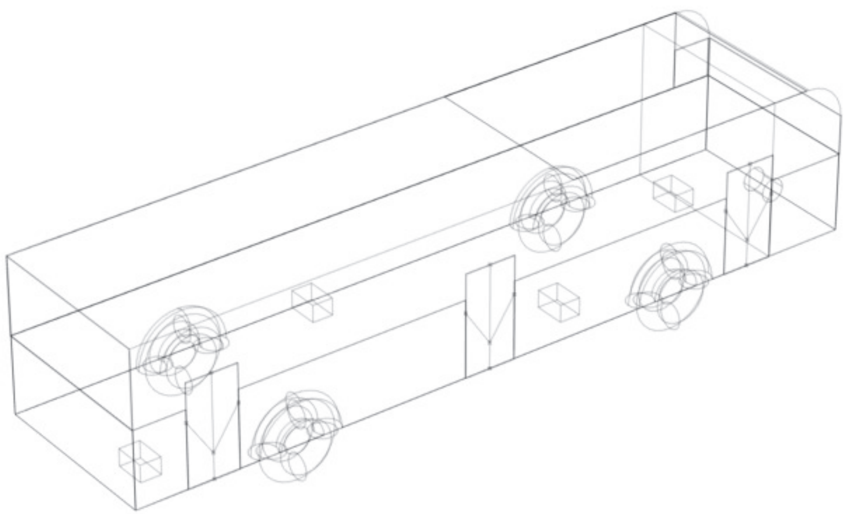

***Figure 2:** Heater positions inside the electric bus*

A non-transparent view can be used for a better identification of some of the components, as in Figure 3, where the front door is selected to accentuate its position, dimensions, and properties. A 3D grid can be also displayed in order to estimate the spatial distribution of the components.

The last main component of the geometry model is the current collecting system of the electric bus. This system is placed on the vehicle roof and consists of two skates placed on two core bars, which assure the vehicle's energy supply when it operates in a non-autonomous way, like a trolley-bus (Figure 4).

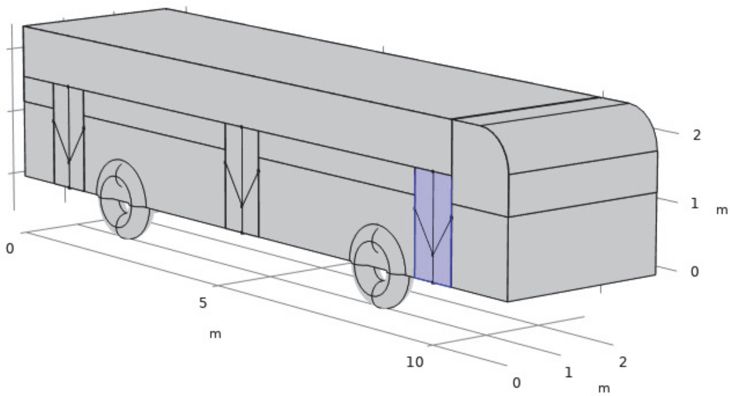

Figure 3: *Non-transparent view of the geometry model*

The finalized geometry has 87 domains, 676 boundaries, 1351 edges, and 773 vertices. This results in the basic geometry model of the electric bus, which will be used for the simulations.

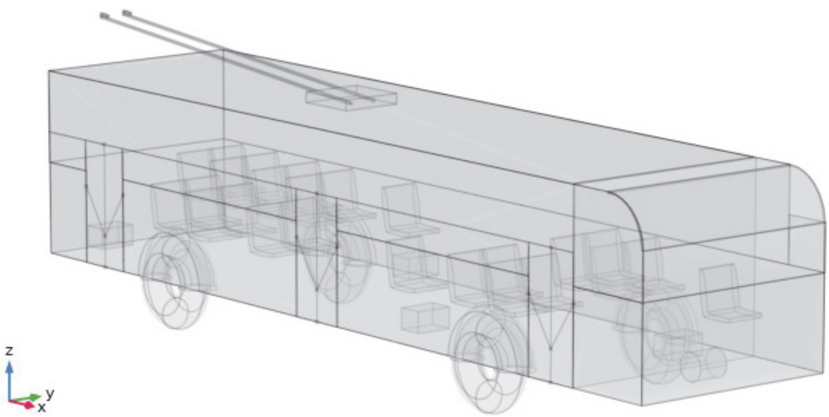

Figure 4: *The basic geometry model of the electric bus; transparent view*

The materials considered for the components of the bus for the model are iron, glass, acrylic plastic, fibreglass and PMMA – polymethyl methacrylate. The interior volume of the bus is modelled as filled with air.

4 SIMULATION RESULTS AND ANALYSIS

The main results of the simulations based on the thermal model are shown in Figure 5. Figure 5 shows the temperature distribution inside the electric bus with a view from the right side of the vehicle. The temperatures are estimated at the surfaces of the bus components. It can be observed that the highest temperature, as expected, is at the heaters (40 ^{o}C), and the lowest temperature is at the exterior surface of the roof, next to the power collecting box system where the trolleys are attached (17.3 ^{o}C).

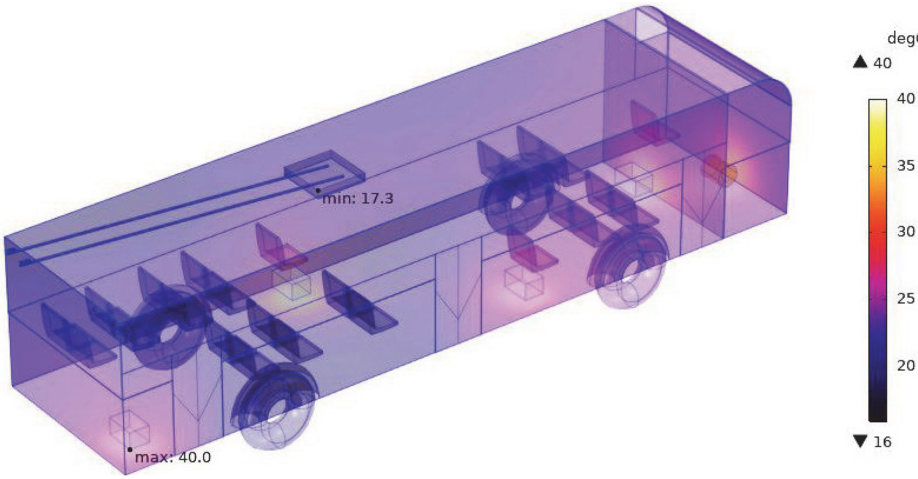

Figure 5: *Simulation results for the temperature distribution in the bus*

For a better visualization of the temperature distribution, it can be seen from the temperature variation along the electric bus that the higher temperatures are measured around the area where the heaters are placed and the lower temperature (between 17 ^{o}C and about 25 ^{o}C) in the area farthest from the heaters. For the validation of the thermal model, some experimental measurements of temperatures were taken at the various points in the interior of the electric bus. The results of the simulations were compared with the measured temperatures.

The temperatures were measured in different areas inside the electric bus with a point-and-shoot infrared camera (FLIR thermal-imaging camera). The temperature measured in the driver's cabin is 27.8 ^{o}C, quite comfortable for the driver. The temperature measured inside the electric bus, next to a heater, is 41.3 ^{o}C. These measurements are compared with the values resulting from the thermal simulation presented above. As seen in Figure 5, the simulated maximum temperatures inside the driver's cabin are between 25.2 ^{o}C and 27.9 ^{o}C, which are quite close to the measured temperature of 27.8 ^{o}C (Figure 6). As for the heaters, the simulated temperature is 40 ^{o}C, which is close to the measured one of 41.3 ^{o}C. Comparing the simulated and measured temperatures, it can be concluded that the thermal model of the electric bus can be validated as correct and be used further for a wide variety of simulation types in order to estimate the optimal solution to improve heat transfer inside the electric bus.

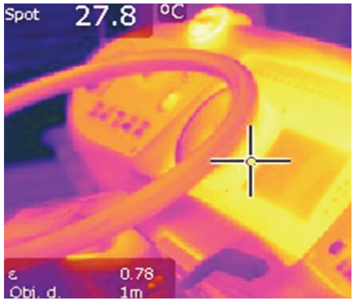

Figure 6: *Temperature measured with a thermal-imaging camera on the driver's cabin*

5 CONCLUSIONS

The geometry of an electric bus interior is designed considering the main components of the vehicle: passenger cabin, driver's cabin, windows, walls, seats and the main materials in accordance with a real bus. To study the heat transfer into the electric bus, a computer-aided design is used based on the heat transfer theory. A thermal model and simulations are made for the heat transfer inside the electric bus. The simulated data are compared with measurement data, and based on these data, it can be concluded that the thermal model of the electric bus can be validated and used further for various thermal simulations.

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Nomenclature

(Symbols)	(Symbol meaning)
h	heat transfer coefficient, [W/m^{2}K]
k	thermal conductivity, [W/mK]
q	heat flux
T	temperature, [^{o}C]
T_s	temperature of the solid, [^{o}C]
T_f	temperature of the fluid, [^{o}C]
x	direction of the heat flux, [m]