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Thermal Management Strategy of Electric Buses towards ECO Comfort

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Abstract

Energy Management System (EMS) is a critical aspect in electric vehicles to increase driving range, minimize costs, and extend battery life. In E-bus drivetrains, EMS can be utilized to optimize thermal management of associated auxiliaries and en-route charging. A bus cabin environment is a dynamic environment contending with varying levels of passengers and ambient conditions. Buses use the Heating Ventilation and Air Conditioning (HVAC) system to maintain the internal cabin climate. In E-buses, the HVAC system draws electrical energy from the main battery; therefore, a suitable strategy is required to minimize the power utilization. The "comfort" aspect should ensure regulation of both temperature and humidity in the cabin. The controlling mechanism should provide proper comfort to the passengers, utilize the least energy, and respect the constraints of the HVAC system. In this paper, a dynamic thermal cabin model is developed to investigate the ECO-comfort strategy of E-bus and their impact on the energy consumption. Results show that HVAC power usage is inversely proportional to passenger load when ambient temperature is less than reference setpoint and vice versa, and the ECO-comfort offers substantial energy savings over contemporary climate control algorithms when the HVAC system is operated in moderated weathers.

Keywords: ECO-comfort; E-Bus: HVAC; Cabin climate; EMS; Thermal management system

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THERMAL MANAGEMENT STRATEGY OF ELECTRIC BUSES TOWARDS ECO COMFORT

1. Introduction

Energy Management System (EMS), which is a tool used to optimize performance and achieve energy efficiency, is one of the key elements in electric heavy-duty vehicles (such as buses and trucks), as the required energy should be supplied from the Energy Storage System (ESS). Proper EMS strategy is critical in Electric Vehicle (EV) applications to maximize the driving range of the vehicle from a fully charged battery. Although the energy density of Lithium metal is comparable to that of fossil fuels, such as gasoline and diesel, the energy density of lithium-ion battery packs used in electric vehicles are an order of magnitude lower. This is because the actual lithium content is less than 5% percent of the total weight of the battery according to Martin (2017), with the rest being taken up by the electrode materials, electrolyte, casing, and protection electronics. Moreover, in a battery pack this proportion decreases even further, as extra weight needs to be devoted to the cooling system and the packaging. This results in typical energy densities of only 0.25~0.70 kWh/l or 0.10~0.27 kWh/kg in commercial Li-ion batteries, costing in the range of 170~225 €/kWh according to Bayes et al (2018). To provide the same range as gasoline, the battery pack needs to be much heavier and voluminous, thus making it expensive. To put it in perspective, a 2019 Hyundai IONIQ Electric would require a battery costing at least €18k, weigh at least half a ton, and require at least 200 liters of space to get the 725 kms of driving range we expect from a full tank of gasoline (60 liters, 42 kg) according to five cycle test data from the US Environmental Protection Agency and Department of Energy (EPA, DoE).

One way to overcome this limitation in range is to optimize the energy utilization in electric vehicles through proper energy management strategies (EMS) in order to increase the driving range, minimize costs, and extend battery life. Electric motors are more efficient than a typical Internal Combustion Engine (ICE) by a factor of three to four according to Carney (2018). Furthermore, considering the transmission of power from engine to wheels, the electric powertrain is much more efficient than the mechanical drivetrain, which endures mechanical losses in the gearbox and transmission, thus helping to mitigate the disparity in the energy density between batteries and gasoline as a fuel source. Finally, the energy supplied to the electric motor for traction is partially recovered during regenerative braking, thus the net energy usage is smaller. With an electric motor, the energy flow between it and the ESS is bidirectional, which makes it simple to optimize the energy utilization given a specific driving profile, including for urban, suburban, and highways. In an electric bus, there can be a variety of EMSs that can be utilized considering the battery State of Health (SoH), battery State of Function (SoF), charging power level, charging location, auxiliary loads, charging time, and traveling time. These include various "ECO" features such as ECO-driving, ECO-charging and ECO-comfort strategies. "ECO" features on vehicles are typically those that employ strategies that favor fuel economy at the expense of driving performance.

The aim of the ASSURED project is to boost the electrification of urban commercial heavy-duty vehicles, like trucks and buses. Within the context of ASSURED, this paper will discuss the ECO-comfort model, in terms of the thermal management of the associated auxiliaries. The auxiliary system, such as the Heating, Ventilation, and Air Conditioning (HVAC) unit, in an electric vehicle is a constant drain on the battery. While the HVAC systems have good Coefficient of Performance (COP) of 3.2 to 4.5 for Air Source Heat-Pumps (ASHP) according to Fisher and Madani (2017), bus cabins are not the best insulated structures, which negates the efficiency of the HVAC system. Furthermore, unlike passenger vehicles, the bus cabin is constantly exposed to the outside environment since its doors frequently open to allow passengers to enter and exit the bus. And finally, unlike passenger vehicles, the passenger load inside a bus is more chaotic and random, thus leading to wide fluctuations in the internal cabin environment. This requires the HVAC system to work continuously to maintain and regulate the internal environment. The idea behind ECO-comfort is to optimize the thermal management of the HVAC system, and provide the maximum comfort to the passengers inside a bus, while respecting the constraints of the HVAC system.

2. Thermal Modeling for Buses

One of the key aspects for electric transport is the energy consumption and the range of the vehicles as well as the charging infrastructure. Recent developments within electrified transport is focused on these aspects to close the gap with the conventional type of transportation. To decrease the energy consumption and to increase the range of the vehicles, a range of measures is applied such as aerodynamic, weight and powertrain efficiency improvements, with aerodynamics being the feature that can be least improvement upon for a bus, while the powertrain is the feature that can be the most improved upon. In addition, an important factor for electric vehicles is the cabin climate. Especially for buses, controlling the cabin climate requires a significant part of energy because of the large volume and surface area. Compared to conventional vehicles, where at least part of the heating is done with excess heat from the engine, the energy consumption and range are much more affected by the climate system for electric vehicles. Within the ASSURED project, it is also investigated what kind of optimization can be done to the climate system and how this affects the energy consumption and range of the vehicle.

2.1. Cabin Climate Model

The Climate Model is a shell that provides the Thermal Management System (TMS) of an E-Bus with the environment inside which its HVAC system will operate. The climate model aims to simulate, as accurately as possible, what a typical bus will face as it goes along its intended route. There are two main factors that the HVAC system in the bus needs to contend with, including the number of passengers and the weather. The weather could include daylight, temperature, humidity, air pressure, wind speed, and cloud cover. Typically, weather data are taken from historical climate surveys for a given region, given as mean values for a calendar month. Passenger data are taken from traffic surveys. Passenger loads inside buses show patterns that are dependent on the time of the day (peak vs off-peak hours), and these patterns remain constant throughout the year. Taken together, these two factors will present the HVAC system with a variable environment which it needs to adapt and overcome to regulate the internal climate of the cabin. Climate survey for any city or region data can be found from Climate-data.org or directly from Google.

The generation of the climate data relies heavily on random variations within a given statistical range provided by climate surveys. The following data are considered:

1. Daylight hour: The current algorithm models' light intensity as a binary; therefore, it is assumed to be at full intensity during daylight hours, and fully dark at night. In future, the light intensity will be modeled as a variable depending on the time of the day.
2. Maximum and minimum daily temperature levels: The maximum and the minimum daily temperature is tied to the daylight. During daytime the temperature will increase from the minimum to the maximum following a certain time constant, and during night time, the temperature will decrease from the maximum to the minimum. The temperature is also subject to random variations throughout the day, and is also affected by cloud cover, with the temperature dipping slightly when the sky is overcast.
3. Cloud coverage: The cloud coverage will block sunlight during daylight hours. Currently, it is modeled as binary light intensity, so having clouds will be modeled as darkness. However, in future it will be modeled as a dip in intensity corresponding to the thickness of the cloud cover.
4. Humidity: The humidity is tied to rainfall statistics, therefore rainy days should have high humidity, and dry days having low humidity. However, to simplify simulation, daily variations of humidity for a calendar month are not modeled; instead, the average of the entire month is considered, and the value varies randomly around that point.
5. Wind speed and air pressure are not being considered in the present climate model.

3. HVAC System

Within the ASSURED project, a simulation framework is developed that includes the thermal part of the cabin of the vehicle. Fig. 1 shows a schematic representation of the influences on the cabin climate.

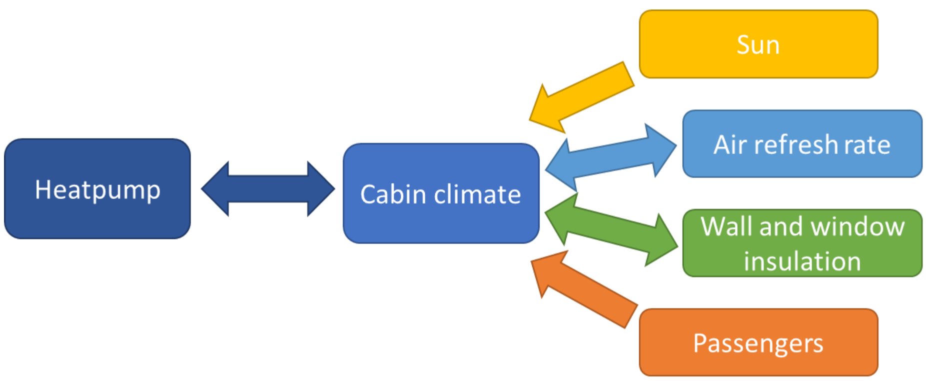

Fig. 1. Influences on the cabin climate

There are 4 effects that are considered:

1. The sun that radiates heat through the windows of the bus. It is dependent on the radiation power of the sun (including cloud effects) and the "sun catching factor". This latter factor is dependent on the transmission factor of the glass, the area of the windows and the angle between the sunlight and surface of the glass.
2. Air refresh rate. This term is a lumped value of fresh air flowing into the cabin. In this case, it is dominated by the airflow through the doors. This factor depends on whether the doors are opened and the temperature difference between the inside and outside air.
3. Wall and window insulation. Heat energy is also flowing through the walls and windows of the bus. A better insulated cabin enclosure will result in a reduced heat transfer between ambient conditions and the cabin climate. This factor depends on the temperature difference between inside and outside air and the insulation factor of the bus walls.
4. Passengers that generate heat inside the bus. Passengers generate heat through their metabolism system. The total heat energy that is generated inside the bus is equal to the energy generated per passenger multiplied by the number of passengers. Moreover, passengers are also a significant source of humidity increase inside the cabin. This also affects the passenger comfort.

To keep the temperature at the desired level, a heat-pump is responsible for the heat balance to compensate for the combined four effects described above. The heat-pump removes heat energy from the cabin air in case cooling is required and adds heat energy to the cabin air in case heating power is required to maintain a set temperature. This is done by means of the Mollier diagram as shown in Dixon and Hall (2014). This diagram defines the energy needed to heat-up or cool-down the air. In case of cooling the air, this diagram also takes the humidity of the air into account. Saturated air requires more energy to be cooled down because the water vapor inside the air needs to be condensed. To avoid complexity, it will be assumed that the temperature variation inside the bus cabin (i.e. from the front to the back) is minimal as the passenger distribution is uniform throughout the bus. Therefore, the control algorithm assumes a uniform cabin temperature based on sensor measurements from the center of the bus.

4. Comfort

The previous sections explain the different aspects of the thermal model that is developed within the simulation framework in terms of energy balance. An important input parameter for this model is the setpoint temperature within the bus cabin. Usually, the setpoint is kept at a constant temperature that is comfortable for the passengers inside the bus. This seems trivial, but the "comfort-aspect" is a very complex one. What a person perceives as a comfortable temperature depends on many parameters, such as:

1. Air humidity: humidity causes the temperature that is perceived by a person to be amplified. Cold humid air feels colder than cold dry air of the same temperature. Also, warm humid air feels warmer than warm dry air.
2. Air velocity: if there is an air flow around the person, the heat energy transfer between the person and the ambient air increases. Cold air feels colder, and warm air feels warmer in airflows caused by, for example, sitting next to the doors or the ventilation output.
3. Radiation: besides the cabin air being heated up by the sun, a person could also feel the direct effect of the radiating sun. When sitting close to a window, the radiation is directly felt and might cause that person to feel much warmer than someone sitting in the middle of the bus.
4. Seasonal effects: comfort is also closely related to temperature differences. If the outside temperature in the winter is 0°C, an inside temperature of 15°C might already feel very warm. Instead, in the summer, this setpoint might be too low. Furthermore, clothing differences in the winter and summer also play an important role here.
5. Metabolism: differences between persons in metabolism cause differences in the perceived comfort in temperature. Examples of these differences are body weight, gender and age.

Because of these combined effects, it is not possible to have one temperature setpoint that will cause all passengers to feel comfortable. The comfort of a group of people is generally expressed in terms of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). They are described in ISO standard 7730. PMV predicts the average value a group of people would rate their comfort. A value of -3 indicates a "very cold" sensation, a value of +3 indicates a "very hot" sensation and a value of 0 describes a neutral temperature feeling. PPD describes the percentage of a group that is dissatisfied with the temperature because it is too low or too high for them too feel comfortable. There is a relation between these 2 aspects that is displayed in Fig. 2. Interesting to note is that at a value of PMV of 0, the PPD is not equal to 0%. This indicates that it is not possible to satisfy everyone. Furthermore, this curve is symmetrical. A cold feeling has the same effect on the satisfaction of a group of people as a hot feeling.

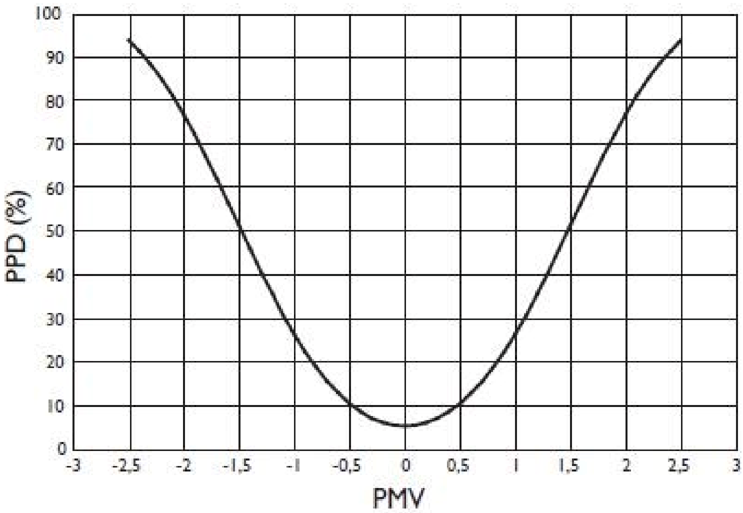

Fig. 2. Relation between Predicted Mean Vote and Predicted Percentage Dissatisfied (source: ISO 7730)

4.1. ECO-Comfort

Within the ASSURED project, attention is given to the optimization of the thermal system of electric vehicles. This is defined as the ECO-comfort functionality. This functionality can be summarized in two topics:

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. Similarly, the same method can be applied between summer and winter conditions. In the winter, lower setpoints can be accepted as comfortable than in the summer. This results in a lower energy consumption of the HVAC system. Finally, a consideration for transport companies may also be to reduce the comfort of passengers slightly to improve energy consumption. The difference between a PMV value of 0 and 0.5 is only 5% in PPD. The decrease of 5% in satisfaction might be acceptable in some cases if the benefit in energy consumption is high enough.
2. Pre-conditioning: The energy that is required for the heat-pump 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, also pre-conditioning can be applied to improve the 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 in route at terminal stops. This way, the initial required energy peak to control the temperature is taken directly from the grid rather than from the battery. This improves also the driving range of the vehicle.

The ASSURED simulation framework takes these 2 functionalities into account. The framework will help in calculating the optimal solution in terms of thermal comfort and energy consumption.

5. Results

Fig. 3 shows the simulation of the HVAC system for a period of 24 hours; Fig. 3a is the sunlight incident on the bus, Fig. 3b row reflects the passenger load within the bus, Fig. 3c depicts the ambient temperature and setpoint temperature, Fig 3d shows the ambient humidity, and Fig. 3e expresses the power consumption of the HVAC system. The results are for a 12m E-bus with a maximum passenger capacity of 75, a heat conductance of 350 W/K, and a HVAC system with a fan with an air refresh rate of 120L/s and heat-pump with a COP of 2.5. The model is simulated for the month of October in the city of Brussels, where the climate conditions are 11 hours of daylight, maximum temperature of 15ºC and minimum of 8ºC, a 29% cloud coverage, and a 88% humidity level. The bus is driven for a maximum of 20 hours a day, so part of the driving cycle falls during night time. Finally, the target cabin temperature is set to 20ºC. Results show a baseline power utilization of 2.4 kW, and a lower power utilization during the daytime compared to night time. Results also show that during the day the power usage of the HVAC is proportional to the passenger load in the bus, but during the night, the HVAC power utilization is inversely proportional to the passenger load.

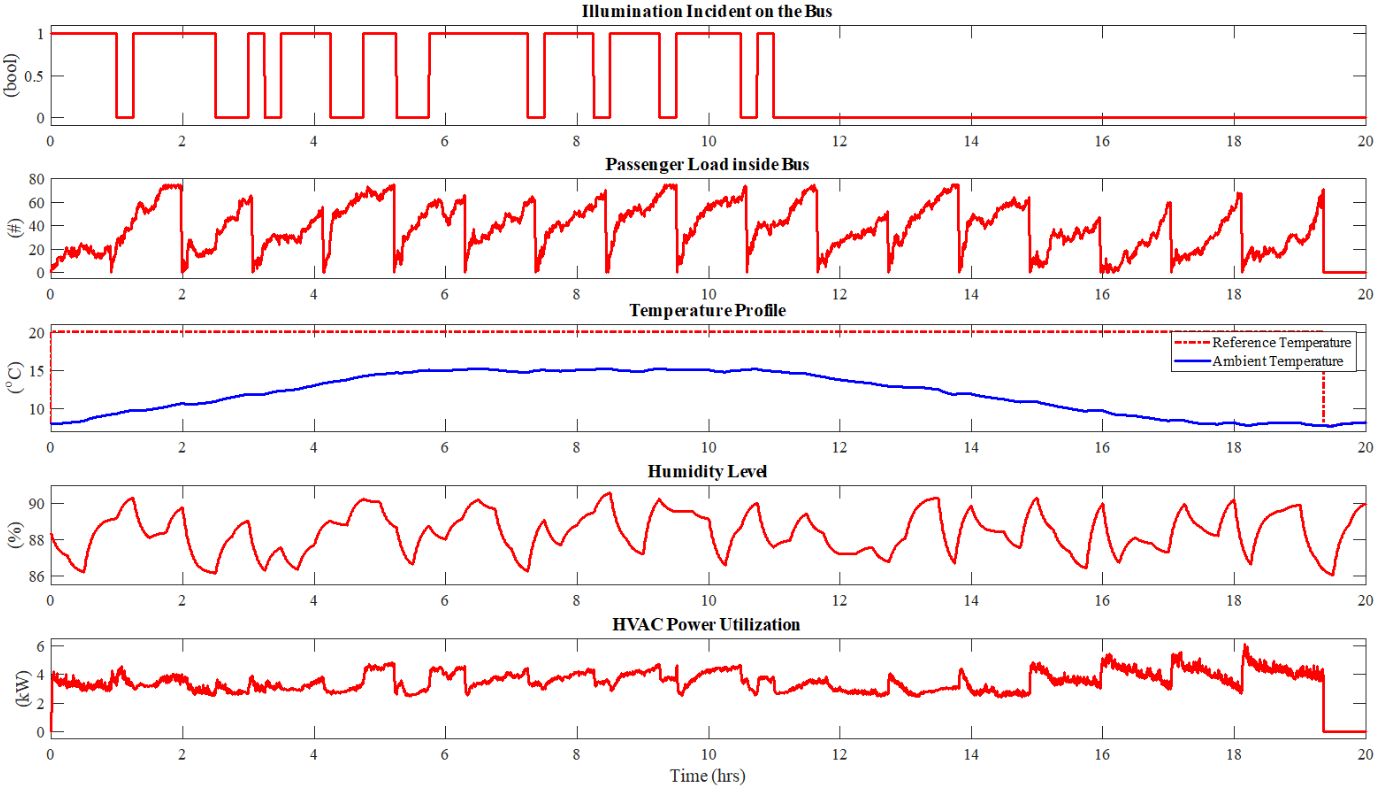

Fig. 3. Simulation of the thermal management based on ECO-comfort

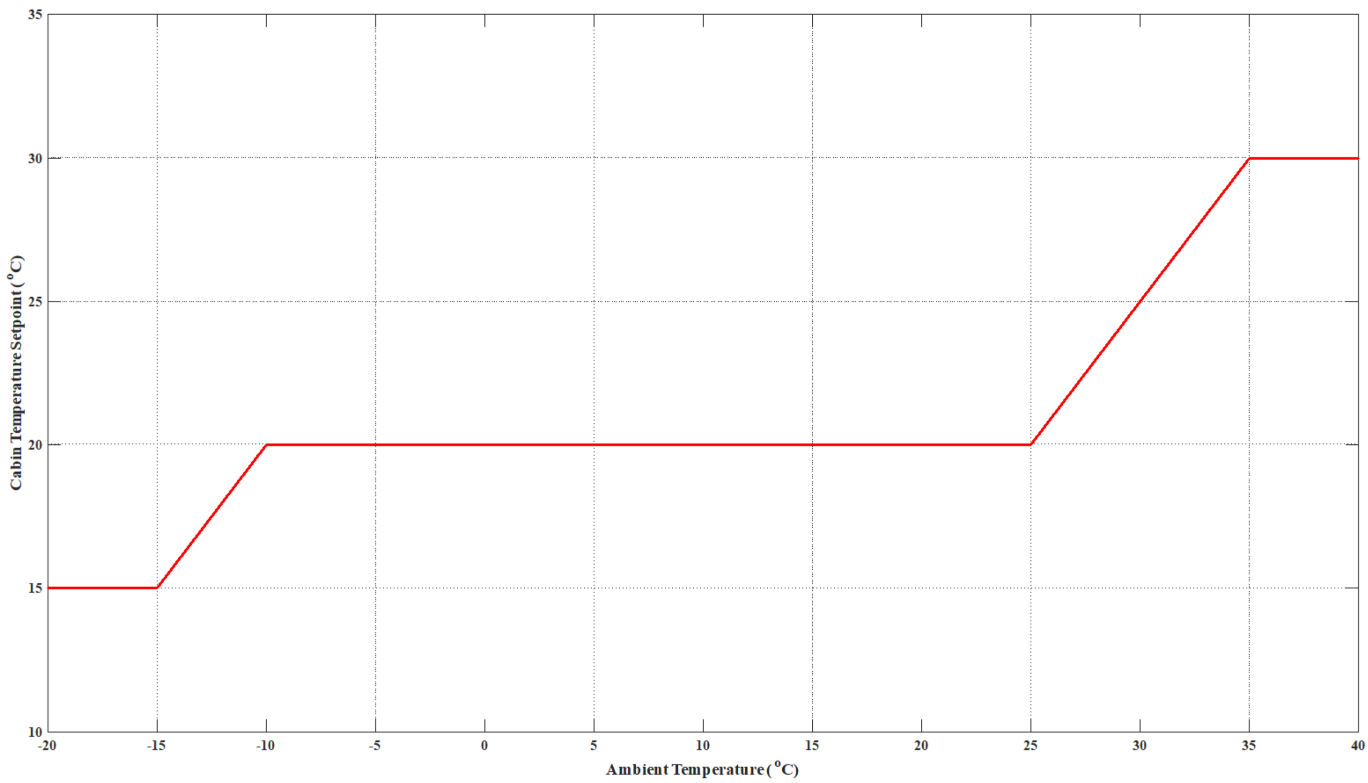

Fig. 4. Cabin setpoint temperature as a function of ambient temperature to provide comfort (source: VDV, 2015)

To determine the energy saving accomplished due to the ECO comfort algorithm, three cities with widely varying climates will be used to compare HVAC system operated according to ECO comfort with the performance of a typical HVAC system of a 12m bus depicted in Gohlich et al (2018); the average power utilization of such an HVAC system taken over the entire year was 8kW. Fig. 4 shows the internal cabin temperature regulated to provide the passengers with a modicum of comfort for a wide range of ambient temperatures; the data has been slightly modified from the standard defined by the Association of German Transport Companies (VDV, 2015). Finally, Table 1 illustrates three different climate types including Mediterranean, Warm Temperate and Cold Temperate, showing the average monthly temperatures, humidity, and daylight, which will be used to simulate the performance of the ECO comfort algorithm. The results of the simulation, illustrated in Fig. 5, shows that in all the cases the proposed HVAC system operated using ECO comfort outperformed contemporary HVAC systems. The results are promising since the climate conditions analyzed reflect the climate conditions of many cities within continental Europe, except for those in Scandinavian countries afflicted with polar or arctic climate. The results show that if the weather was hot or cold, the energy savings were minimal, as seen during summers in Barcelona or winters in Jaworzno, but for moderate weathers, the energy savings were substantial.

Table I. Climate conditions of three European cities to test the performance of the HVAC system with ECO comfort

City	**Barcelona, Spain**				**Brussels, Belgium**				**Jaworzno, Poland**			
Climate Type	**Mediterranean**				**Warm Temperature**				**Cold Temperate**			
	Hi (ºC)	**Lo** (ºC)	**Hum** (%)	**Day** (hr)	**Hi** (ºC)	**Lo** (ºC)	**Hum** (%)	**Day** (hr)	**Hi** (ºC)	**Lo** (ºC)	**Hum** (%)	**Day** (hr)
January	15	9	69	9.5	6	1	88	8.5	1	-5	88	8.5
February	15	8	66	10.5	7	1	86	10	3	-4	82	10
March	17	10	73	12	11	4	80	12	8	-1	79	12
April	20	13	69	13.5	14	6	78	14	14	3	74	13.5
May	23	16	68	14.5	19	10	77	15.5	19	7	73	15.5
June	27	20	67	15	21	12	78	16.5	22	11	76	16.5
July	29	23	67	15	23	14	80	16	24	12	76	16
August	29	23	72	14	23	14	82	14.5	24	12	78	14.5
September	26	20	74	12.5	20	12	84	12.5	19	8	81	12.5
October	23	17	74	11	15	8	88	11	13	4	83	11
November	18	12	72	10	10	5	90	9	7	0	86	9
December	15	9	70	9.5	7	2	90	8	3	-3	87	8

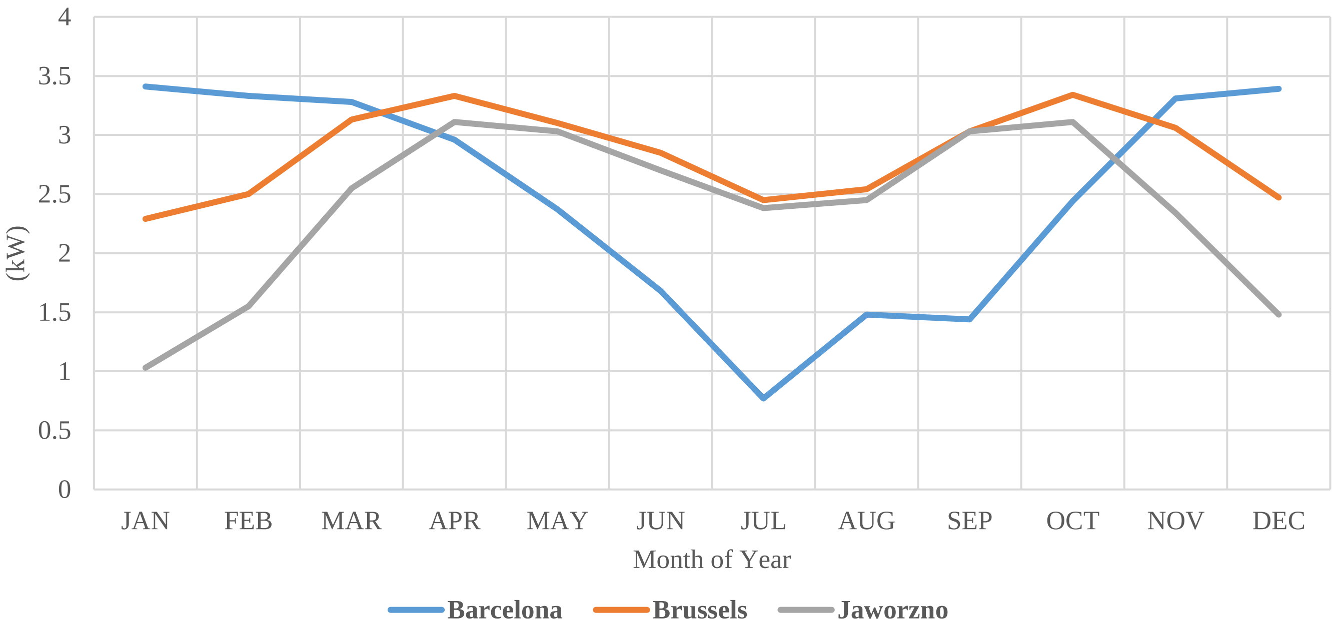

Fig 5. Average power saving of HVAC system using ECO Comfort compared to typical HVAC utilization

On average, operating over the whole year, the ECO comfort achieved a savings of 2.4kW for Barcelona, 2.5kW for Jaworzno, and 2.85kW for Brussels. Therefore, if a bus is operated for 20hrs a day, it translates of an energy saving of 17.5 MWh to 20.8 MWh per year per bus, causing the city bus operators to make substantial financial gain, and resulting in a lot less carbon dioxide emissions.

6. Conclusion

A simple EMS that handles thermal management using auxiliaries was described in this paper. The basic algorithm and the parameters affecting the model has been presented and an initial simulation of the model has been carried out. The results validate the HVAC performance as a higher passenger load, which indicate more heat and humidity, acts against the cooling system during the daytime, but acts in favor of the heating system at night. Results also indicate that more moderate or temperate weather found in most cities in continental Europe, the ECO comfort will offer substantial energy savings to the city bus operators, resulting in less greenhouse emissions. More refinement is necessary in future research to ensure that the HVAC system constraints are properly handled, the Illumination will be accurately modeled as radiated energy over an area, and the ECO feature will be properly tuned. Furthermore, research is needed to redefine ECO comfort for extreme climates found in Scandinavian countries that would allow energy savings. Finally, a rigorous life cycle cost analysis needs to be performed to determine the time required for the city to recoup the investments on electric buses and related infrastructure through the energy savings due to ECO comfort.

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