Optimal bus temperature for thermal comfort during a cool day

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A challenge for electric buses is to minimize heating and cooling power to maximally extend the driving range, but still provide sufficient thermal comfort for the driver and passengers. Therefore, we investigated the thermal sensation (TS) and thermal comfort (TC) of passengers in buses during a cool day (temperature 13.4 ± 0.5 °C, relative humidity (RH) 60 ± 5.8%) typical for the Dutch temperate maritime climate. 28 Males and 72 females rated TS and TC and gave information on age, stature, body weight and worn garments. The temperature in the bus of 22.5 ± 1.1 °C and RH of 59.9 ± 5.8% corresponded to a slightly warm feeling (TS = 0.85 ± 1.06) and TC of 0.39 ± 0.65. TS related significantly to bus temperature, clothing insulation and age. Linear regression based on these parameters showed that the temperature in the bus corresponding to TC = 0 and TS = 0 would have been 20.9 ± 0.6 °C. In conclusion, a 1.6 °C lower bus temperature during the investigated cool day probably would have led to less thermal discomfort and energy savings of electrical buses. The methodology to relate climatic measurements to subjective assessments is currently employed in a wider climatic range and may prove to be useful to find a better balance between thermal comfort and energy savings of the bus.

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1. Introduction

The Dutch public transport companies intend to make all public transport buses emission free before the year 2026. The driving range of electrical buses, however, is limited as compared to diesel buses. The problem of limited driving range becomes even more pronounced in hot or cold environments, when cooling or heating systems absorb a considerable part of the power meant for transportation. It has been estimated for instance that lowering the temperature in the bus by 6 °C on a cool day, may save 8% energy in an electrical bus (Vermeulen et al., 2015). It is the purpose of this study to investigate how power use by heating and cooling systems can be minimized without compromising thermal comfort or thermal sensation of the passengers for a specific temperate maritime climate.

A person can interpret the experienced temperature, hot or cold, in different ways. The main distinction is made between thermal sensation (TS) and thermal comfort (TC). TS is an indication of how warm or how cold the person feels, generally assessed using a 7-point scale (+3 hot, −3 cold) (ISO7730, 2005) or 9-point scale (+4 very hot, −4 very cold) (ISO9886, 2004). TC is defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation using a 5-point scale (0 comfortable, +4 extremely uncomfortable). TC can be partially influenced by different contextual and cultural factors but it is primarily an effect of the heat exchange between the body and the environment (Olesen and Brager, 2004). TC is an important factor for passengers of the public buses and for the bus companies. A passenger expects a comfortable environment when entering a bus. With regard to the bus companies, thermal comfort is part of high quality service (Walgama et al., 2006) provided by Heating, Ventilation and Air Conditioning systems (HVAC systems) (Jones, 2002). Since TS and TC are not similar in perception, both variables are included in this study.

Most field studies on thermal comfort in buses are performed in Asia (e.g. Lin et al., 2010; Shek and Chan, 2008; Zhang et al., 2014) in which hot temperatures dominate. Zhang et al. (2014) performed a study in public transport buses in Nanjing (China) in which overall bus comfort was measured as a combination of noise, thermal comfort, vibration and acceleration. They assessed thermal comfort...
by calculating the predicted percentage of dissatisfied (PPD) based on Fanger’s predicted mean vote (PMV). According to their calculations, passengers experienced the bus as comfortable when PPD \( \leq 23\% \). Lin et al. (2010) evaluated thermal comfort in short- and long haul vehicles by interviewing passengers concerning thermal sensation, thermal preference and thermal acceptance regarding the temperature, humidity, air movement and solar radiation. They observed that in short haul vehicles the optimal temperature range lies between 22.4 and 28.9 °C, with slightly higher optimal temperatures for long haul vehicles ranging between 22.4 and 30.1 °C.

Shek and Chan (2008) examined the indoor bus quality by measuring thermal comfort and air quality in public transport buses in Hong Kong. They interviewed bus passengers and used correlation analyses to construct a combined comfort model that can predict the PPD value based on thermal comfort and air quality. They found that thermal sensation is dominant over air quality in predicting the PPD. The influence of air quality was dependent on the presence or absence of air-conditioning in the bus. In non-air-conditioned buses air quality was more important than in air-conditioned buses. However, thermal sensation was still the main factor in predicting comfort. In the examined buses, mean bus temperature was 23 °C in summer and 19 °C in winter. According to their results, bus passengers did not experience these temperatures as thermally comfortable.

Mansour et al. (2008) introduced a new type of roof top bus air conditioning system for hot humid countries. Because in hot humid countries the air conditioning system has to work at maximum capacity between 10:00 h and 15:00 h it is important that the systems use as little energy as possible. They calculated Fanger’s PMV and PPD to guarantee passenger’s comfort. Using the new system at a set point temperature of 21 °C could have saved 31.6% of energy. Alahmer et al. (2012) evaluated thermal sensation and thermal comfort using a thermal manikin (based on the Berkeley model) in different vehicle environments. Fanger’s PMV and PDD were used to evaluate thermal sensation and thermal comfort. They concluded that relative humidity inside vehicles is important for thermal comfort, in both heating and cooling the vehicle. When the relative humidity was controlled while changing the thermal environment, the comfort zone was reached faster.

Pala and Oz (2015) designed a model to assess thermal comfort of a bus HVAC strategy and to compare the effect on thermal comfort when the parameters were changed. They installed a bus in a climatic chamber at −20 °C and left it there for 7 h. Next they performed a warm up experiment from −20 °C to +20 °C in 90 min. According to their developed model, thermal sensation and discomfort started at ‘a little cold’. Even though it was a warm up experiment, at the end of the warm up (20 °C) the simulated thermal sensation decreased to between ‘cold’ and ‘very cold’ because of the cold environment (−20 °C) at the beginning of the experiment. The simulated skin temperature also decreased during the experiment.

The studies described above are either performed in the heat or during thermal transients. Data is lacking on thermal comfort and thermal sensation in a stable cool day for a maritime climate. Therefore, the aim of the current study was to investigate the thermal sensation (TS) and thermal comfort (TC) of passengers in buses on a typical cool day in The Netherlands. The bus drivers in The Netherlands have the freedom to set the climate in their busses; no information is publically available about the actual settings that they employ.

## 2. Material and methods

### 2.1. Subjects

100 passengers in a city bus participated in this study. They travelled in a public bus in the city Utrecht, the Netherlands on November 9 or 11 in the year 2015 from 7:40 to 12:20. The participants were fully informed about the goals and protocol before giving a verbal consent to participate in the experiment. The study was approved by the Ethics Committee of TNO (Soesterberg, The Netherlands).

### 2.2. Experimental design

The experiments were scheduled in two morning sessions. Two sessions were conducted in a city bus. When a passenger entered the bus, he or she was asked for permission to participate in a small experiment on thermal sensation and thermal comfort in city buses. When the passenger approved, they were asked to supply their age, height and weight. Gender was assessed by the experimenter. Hereafter, the subjects rated thermal sensation, thermal comfort and mentioned the clothing items they were wearing. Finally, the skin temperatures of the hand and face were measured. Since the passengers were on a city bus and could leave the bus on the next stop, an effort was made to perform the measurements and assessment as quickly as possible, generally within 2 min.

### 2.3. Measurements and methods

The measurements took place in two different buses: a Mercedes-Benz Citaro diesel bus (Mercedes-Benz, Stuttgart, Germany) during the first day and an Optare Solo EV electrical bus (Optare, Leeds, United Kingdom) during the second day. One iButton with humidity sensor (DS1923, Maxim Integrated Products Inc. Sunnyvale, CA, USA) was located 10 cm from the ceiling in the front of the bus and a second one in the rear of the bus to measure temperature and relative humidity.

Thermal sensation was determined using a 9-point scale (from −4 = very cold to +4 = very hot) and thermal comfort was determined using a 5-point scale (from 0 = comfortable to +4 = extremely uncomfortable) (ISO10551, 2001).

The hand and face temperatures were measured using a Volo-craft IR-230 infrared thermometer (Conrad Electronic, Hirschau, Germany) to assess the thermal status of the passenger. The sensor was positioned about 3 cm from the skin back of the hand and the cheek so that no direct contact with the skin was made. In a pilot study in which 11 subjects were exposed to a 10–30 °C environment, hand and face temperatures were measured as well as rectal temperature and four skin temperatures according to ISO 9886 (Velt and Daanen, submitted). The mean weighed body temperature could be assessed from the average of hand and skin temperature using formula (1) with 52% explained variance.

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\text{Mean body temperature} = 31.154 + 0.152 \times \text{(mean face/hand temperature)}
\] (1)
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