Int J Biometeorol (2010) 54:221–230
DOI 10.1007/s00484-009-0273-9

ORIGINAL PAPER

Passenger thermal perceptions, thermal comfort requirements, and adaptations in short- and long-haul vehicles

Tzu-Ping Lin · Ruey-Lung Hwang · Kuo-Tsang Huang · Chen-Yi Sun · Ying-Che Huang

Received: 27 March 2009 / Revised: 17 August 2009 / Accepted: 28 September 2009 / Published online: 23 October 2009

Abstract While thermal comfort in mass transportation vehicles is relevant to service quality and energy consumption, benchmarks for such comfort that reflect the thermal adaptations of passengers are currently lacking. This study reports a field experiment involving simultaneous physical measurements and a questionnaire survey, collecting data from 2,129 respondents, that evaluated thermal comfort in short- and long-haul buses and trains. Experimental results indicate that high air temperature, strong solar radiation, and low air movement explain why passengers feel thermally uncomfortable. The overall insulation of clothing worn by passengers and thermal adaptive behaviour in vehicles differ from those in their living and working spaces. Passengers in short-haul vehicles habitually adjust the air outlets to increase thermal comfort, while passengers in long-haul vehicles prefer to draw the drapes to reduce discomfort from extended exposure to solar radiation. The neutral temperatures for short- and long-haul vehicles are 26.2°C and 27.4°C, while the comfort zones are 22.4–28.9°C and 22.4–30.1°C, respectively. The results of this study provide a valuable reference for practitioners involved in determining the adequate control and management of in-vehicle thermal environments, as well as facilitating design of buses and trains, ultimately contributing to efforts to achieve a balance between the thermal comfort satisfaction of passengers and energy conserving measures for air-conditioning in mass transportation vehicles.

Keywords Thermal comfort · Thermal adaptation · Vehicles · Field study · Energy conservation

T.-P. Lin · Y.-C. Huang
Department of Leisure Planning, National Formosa University,
64 Wen-hua Rd,
Huwei, Yunlin 632, Taiwan

R.-L. Hwang (✉)
Department of Architecture, National United University,
1 Lien Da,
Miaoli 360, Taiwan
e-mail: rueylung@nuu.edu.tw

K.-T. Huang
Department of Landscape Architecture,
National Chiayi University,
300 Syuefu Rd,
Chiayi 600, Taiwan

C.-Y. Sun
Department of Land Economics, National Chengchi University,
64 Sec.2, Zhi-Nan Rd,
Taipei 116, Taiwan

Introduction

The thermal comfort of passengers is a priority concern in mass transportation (Bhatti 1999a, b) owing to its relevance to service quality and energy consumption (Walgama et al. 2006). Thus, ensuring thermal comfort inside mass transportation vehicles involves either defining the optimal temperature and acceptable thermal comfort zone, as perceived by passengers, or estimating the thermal sensations of passengers under certain conditions. Several studies have examined the thermal comfort of passengers from the perspective of heat equilibrium models of the human body (Farrington et al. 1997; Taniguchi 2001; Martinho et al. 2004; Mezrhab and Bouzidi 2006). However, as mentioned in ISO 14505-3 (ISO 2006b), under the heading *Ergonomics of the thermal environment—evaluation of thermal environments in vehicles*: "although mathematical and physical models and thermal indices can provide repeatable, reliable methods of assessment, vehicle environments are often complex, dynamic, and influenced by many factors. Models and indices are therefore often limited in validity. Human subjects are required to provide a direct means of measuring thermal comfort, and to validate other techniques."

Studies on thermal comfort in vehicles can be classified into two types. The first approach is to conduct tests in laboratory chambers. The greatest merit of the laboratory approach is the convenience of conducting large-scale experiments on specific scenarios. Many benchmarks for thermal comfort, e.g. ISO 7730 (ISO 2005) and ISO 14505-2 (ISO 2006a), are based on results obtained from this approach. Two examples of this type of study are the research conducted by Nilsson and Holmér (2003) and Hodder and Parsons (2007). Nilsson and Holmér, using 20 subjects, conducted a comfort survey under 30 different conditions in chambers, and their results led to the definition of acceptable temperature ranges for passengers, for whole body and localized portions of bodies (Nilsson and Holmér 2003). Hodder and Parsons, using eight male subjects in a laboratory chamber, examined the effects of different types of glazing on thermal perceptions under different levels of radiation (0–600 W/m^2). The relationship between radiation levels and thermal perceptions for the driver was established in their study (Hodder and Parsons 2007).

The second approach is to conduct field thermal comfort surveys. Proponents of the field approach consider that the influence of the occupants' psychological behaviour cannot be reflected in experiments conducted in a chamber, resulting in uncertainty in applying chamber test results to real-life. Many studies on thermal comfort (e.g. de Dear and Brager 1998; Hwang et al. 2006, 2009b; Lin 2009) are performed onsite in order to examine thermal adaptation from the perspectives of physiology, psychology, and behaviour, and are able to determine how people feel about thermal environments in ways that cannot be fully explained by physiological heat equilibrium models (Brager and de Dear 1998), as past experience (Wohlwill 1974), expectations (McIntyre 1980; Hwang and Lin 2007) and perceptions of controls (Paciuk 1990; Brager et al. 2004), all have significant effects on the perception of thermal environments. A well-known instance is the ASHRAE Standard 55 (ASHRAE 2004) and ISO 7730 (ISO 2005), which included the thermal adaptation comfort model (de Dear 1998; de Dear and Brager 1998, 2002) linking the optimal operative temperature for thermal comfort with monthly average outdoor air temperatures, into their newest versions. The perspective of thermal adaptation is also involved in the study of thermal comfort in vehicles because the thermal adaptation model is more in line with the thermal needs of passengers. Da Silva et al. (2006) performed a survey on a total of 28 pre-arranged subjects on a bus and examined, through artificial neural analysis, how these subjects' thermal sensations were affected by the physical environment. Shek and Chan (2008), conducting a survey on buses in Hong Kong, found that both the level of air quality and the level of thermal satisfaction affected passengers' assessment of the thermal environment in the buses. They found passengers on non-air-conditioned buses were relatively more concerned with air quality than those on air-conditioned buses. This difference could be explained by the presence of natural ventilation on non-air-conditioned buses, which keeps the in-bus air quality in flux, influenced by the dynamic surrounding environment.

Evaluating thermal comfort in a laboratory chamber involves a chamber that is often a closed space with a steady physical environment, conditions that are not directly comparable with those in a vehicle. Additionally, subjects inside the chamber cannot adjust their clothing and behaviour, which differs from passengers in an actual vehicle. Therefore, this study adopts the field survey approach, in which measurements and questionnaires are conducted in the operating vehicle to accurately reflect how passengers adapt to various thermal conditions, including psychological and behaviour factors.

In Taiwan, there is no guideline for temperature settings in vehicles, and no studies have tried to understand passenger requirements for thermal comfort. Thus, vehicle management staff determine the setting of air temperature in the vehicle based on their own experience. This potentially results in a waste of energy and complaints of discomfort from passengers. In order to understand how passengers in Taiwan actually feel in vehicles, and their thermal comfort requirements, a field survey in vehicles was conducted with the aim of comprehensively clarifying questions regarding thermal comfort: Why do passengers feel thermal discomfort? What are the adaptation behaviours passengers take to eliminate or alleviate their thermal discomfort? What kind of thermal environments are expected by passengers? What are the optimal temperatures and acceptable ranges for thermal comfort in vehicles? Once these questions are clarified, it is possible to effectively and reasonably manage temperature setting in vehicles to satisfy both the needs of passengers in terms of thermal comfort and the necessity for energy savings.

Methods

Vehicle types

The field experiment was conducted in both buses and trains, including short-haul buses (e.g. city buses), long-haul buses (e.g. coaches), short-haul trains (e.g. local trains) and long-haul trains (e.g. limited express trains). Short-haul mass transportation vehicles in Taiwan are normally used for travel lasting less than 30 min, while long-haul vehicles are normally for travel of longer than 60 min. Among the vehicles surveyed, short-haul buses normally travel in urbanised areas at a speed of around 40 km/h, while long-haul buses travel on highways in both urban and suburban areas at a speed of 100 km/h. Both short- and long-haul trains travel in urban and suburban areas at speeds of 110–120 km/h. All vehicles in the survey travel in central and southern Taiwan, including Taichung, Changhua, Yunlin, Chiayi, Tainan, Kaohsiung and Pingtung counties. All vehicles are air-conditioned.

Defining short- and long-haul vehicles requires consideration of vehicular types and the duration of passenger time. For instance, passengers spending a short time in long-haul vehicles may behave differently from those spending a long time in long-haul vehicles. Therefore, passengers in short-haul vehicles are referred to herein as those spending less than 30 min in short-haul buses or trains, while passengers in long-haul vehicles refer to those spending more than 60 min in long-haul buses or trains. Accordingly, this study does not include passengers spending 30–60 min in either type of vehicle.

Questionnaire survey

The questionnaire on thermal comfort is based on ISO 10551 (ISO 1995) and ISO 14505-3 (ISO 2006b), with adjustments in order to adapt to the situation in vehicles in Taiwan. The questionnaire starts with a section on demographic data, duration of journey, activity levels, and clothes worn, followed by a section of assessment on the thermal environment in the vehicle. In this section, passengers were asked to express their thermal sensations, thermal preferences, and thermal acceptance regarding the temperature, humidity, air movement, and solar radiation in vehicles. At the end of the questionnaire, respondents were asked to indicate the behaviours they usually use to eliminate or alleviate thermal discomfort in vehicles.

Physical measurements

In terms of physical environmental factors, this study measured air temperature, relative humidity, air speed, and globe temperature in vehicles using instruments complying with ISO 7726 specifications (ISO 1998). Air temperature and relative humidity were determined using a temperature and humidity data logger (Center 314), while globe temperature was evaluated using a K-type thermocouple in a standard globe with a diameter of 150 mm. Air speed was assessed using an omni-directional anemometer (Delta-OHM 2103.2K and AP471S4). All instruments were positioned at a height of 1.1 m from the floor of the vehicle and placed as close to the subjects as possible. Due to the slow response of the globe temperature, in order to reach equilibrium, the instruments were positioned at least 20 min before the questionnaire survey was initiated to ensure that the measurement data correspond to the thermal environment that the subjects were exposed to.

Field investigation procedure

Field experiments were conducted from February 2007 to September 2008. While conducted proportionately throughout this time period, the field experiments were performed during non-congested traffic periods. Each experiment involved surveyors, who were present throughout the entire journey to measure the physical environments in the vehicles and solicit passenger volunteers to complete the questionnaire surveys.

A total of 2,129 questionnaires were collected, include 597 and 314 passengers in short- and long-haul buses, respectively, and 597 and 750 passengers in short- and long-haul trains, respectively, i.e. 1,347 and 782 cases for short- and long-haul vehicles, 911 and 1,218 cases for buses and trains. Demographically, 47% of the respondents were male, while 53% were female, and 31%, 56% and 13% of the subjects were younger than 20 years old, between 21–40 years old, and older than 41 years old, respectively.

Results and discussion

Preliminary thermal comfort analysis of passengers compared various vehicular types (bus and train) and different trip distances (short- and long-haul vehicles) in terms of thermal comfort requirements. These preliminary results revealed that bus and train passengers did not differ significantly in terms of thermal comfort requirements. Therefore, our analysis focussed only on comparing short- and long-haul vehicles in this category.

Results of physical measurements in vehicles

The measured air temperature, relative humidity, air speed, and mean radiant temperature in the vehicles we surveyed are summarised in Table 1. As can be seen from these measurements, there are only small variances in the average values of the environmental parameters between short- and long-haul vehicles.

Comparing the measurements in this study to measurements taken in air-conditioned offices in Taiwan (Hwang et al. 2008) reveals similar levels of air temperature and relative humidity in vehicles; however, air speed and mean radiant temperature (which reflects solar radiation) have obvious differences. Regarding air speed, due to the

Table 1 Basic statistics of physical measurements, thermal indices, and subjective sensations in field experiments. *PMV* Predicted mean vote, *PPD* predicted percentage dissatisfied, *TSV* thermal sensation vote, *HSV* humidity thermal sensation vote, *WSV* wind sensation vote, *SSV* sun sensation vote

	Short-haul vehicles			Standard deviation	Long-haul vehicles			Standard deviation
	Mean	Minimum	Maximum		Mean	Minimum	Maximum	
Air temperature (°C)	24.8	17.6	29.9	2.3	24.8	20.4	27.9	1.7
Relative humidity (%)	59.0	40.3	82.1	7.9	57.5	42.5	74.1	6.5
Mean radiant temperature (°C)	26.5	21.4	31.9	2.3	26.0	21.8	29.5	1.8
Air speed (m/s)	0.29	0.11	0.79	0.14	0.24	0.06	0.71	0.14
Operative temperature (°C)	25.7	20.1	30.9	2.2	25.5	21.1	28.6	1.7
PMV (–)	0.10	–2.92	2.13	0.82	0.20	–2.58	1.39	0.61
PPD (%)	18.3	5	100	17.6	13.3	5	94.9	11.6
TSV	–0.03	–3	3	0.89	–0.07	–3	3	0.70
HSV	–0.05	–3	3	0.65	–0.09	–2	1	0.44
WSV	–0.27	–3	3	0.90	–0.26	–3	3	0.77
SSV	0.12	–3	3	1.04	0.30	–2	3	0.71
Percentage of unacceptance (%)	5	0	100	21	2	0	100	13

individual design of air outlets in vehicles, passengers experienced different air speeds according to their respective position and distance from the air outlets. The measurements show that the maximum air speed (0.74 m/s) does not exceed the upper limit of 0.8 m/s, as suggested by the ASHRAE Standard 55. Meanwhile, the average air speed (0.29 m/s for short-haul vehicles; 0.24 m/s for long-haul vehicles) is close to 0.2–0.4 m/s, as measured in offices. Due to the design of large windows on both sides and seating arranged adjacent to the windows, the mean radiant temperatures in vehicles are high. Accordingly, the measured average mean radiant temperature is 1.2°C (long-haul) to 1.7°C (short-haul) higher than the average air temperature in the vehicle.

In addition to primary parameters relating to thermal comfort, some common comfort indices used to describe comfortable conditions of thermal environments were calculated based on the measured data, and are listed in Table 1. In the following analysis, the operative temperature (T_o), is used as an integrated parameter, representing the thermal environment in the vehicles surveyed for this study.

The lower part of Table 1 summarises the sensations of the subjects in the four environmental parameters, including the thermal sensation vote (TSV) scale (i.e., −3, cold; −2, cool; −1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; and 3, hot), the humidity thermal sensation vote (HSV) scale (i.e., −3, too dry; −2, dry; −1, slightly dry; 0, neutral; 1, slightly humid; 2, humid; and 3, too humid), the wind sensation vote (WSV), and sun sensation vote (SSV) scales (i.e., −3, too weak; −2, weak; −1, slightly weak; 0, neutral; 1, slightly strong; 2, strong; and 3, too strong). In terms of average values, passengers indicated that they felt the thermal environment in vehicles was slightly cool in temperature (TSV=−0.03 for short-haul and −0.07 for long-haul), slightly dry in humidity, slightly weak in air speed, and slightly strong in solar radiation. When the average values of predicted mean vote (PMV) and TSV are compared, the averaged PMV for short- and long-haul vehicles are 0.10 and 0.20, respectively, corresponding to the slightly-warmer-than-neutral sensation; and the averaged TSV for short- and long-haul vehicles are −0.03 and −0.07, respectively, corresponding to a slightly-cooler-than-neutral sensation. Meanwhile, the average dissatisfaction levels in predicted percentage dissatisfied (PPD) for short- and long-haul vehicles are 18.3% and 13.3%, respectively, i.e. higher than the percentage of acceptability from the questionnaire survey (5% for short-haul vehicles and 2% for long-haul vehicles).

Clothes worn by passengers

The thermal adaptation comfort model suggests that people take spontaneous behavioural action to make themselves feel thermally comfortable. The most important and most convenient behaviour is adjustment of clothing.

A linear regressive analysis was applied to determine the relationship between T_o in vehicles and the overall clothing insulation (I_{cl}) worn by passengers. Regressive results show that the correlation between overall I_{cl} and T_o in vehicles is weak for both for long-haul vehicles (R^2=0.42) and short-haul vehicles (R^2=0.47). However, the linear regression analysis on the overall I_{cl} and outdoor air temperature, as shown in Fig. 1, finds a strong correlation with the correlation coefficients, being 0.84 for short-haul vehicles, and 0.88 long-haul vehicles, respectively. It is reasonable to assume that passengers decide on what to wear depending on the outdoor air temperature more than on the T_o in vehicles.

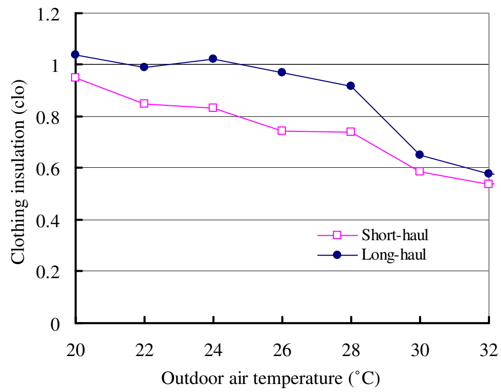

Fig. 1 The relationship between clothes worn by passengers for short- and long-haul vehicles, and external air temperatures

Figure 1 shows that passengers in long-haul vehicles wear more clothing than those in short-haul vehicles, particularly when the outdoor temperature is in the range of 24–28°C. The average overall insulation of clothing of passengers in long-haul vehicles is greater than that of passengers in short-haul vehicles by 0.2 clo. It was suggested that this phenomenon results from the passengers of long journeys carrying coats or jackets in order to avoid discomfort when they nap in the vehicle. In short-haul vehicles, the journeys are too short for the passengers to have a nap in the vehicle, thus it is unusual to find them carrying coats or jackets. In the temperature range of 20–32°C, the clothing insulation of passengers is in the range of 0.54–1.01 clo. Compared to the clothing insulation of 0.4–0.9 clo for occupants in the office in the same temperature range (Hwang et al. 2008), people in Taiwan tend to wear more in vehicles than in offices.

Passengers' habitual thermal adaptive behaviours in vehicles

If the habitual behaviours and actions of passengers in vehicles for thermal adaptation were clarified, relevant facilities can be designed and offered in vehicles for promoting passengers' thermal comfort and quality of service. In the questionnaire, the question regarding thermal adaptive behaviour is as follows:

> If you feel thermal discomfort in a vehicle, please tick three actions you usually take to make yourself feel comfortable. Please select the facilities or services according to your habits, and do not consider whether they are provided in this vehicle.

This question was designed to understand the thermal adaptation behaviours that respondent usually use in public transportation, rather than current behaviours that he/she was using at the time of the survey. Thus, the question allows the respondent to select the facilities or services not provided in the vehicle he/she was currently travelling in. Figure 2 illustrates the thermal adaptive behaviours chosen by over 5% of respondents in short- and long-haul vehicles, respectively.

For passengers in short-haul vehicles, the "air outlet adjustment" was the most common adjustment, with the highest relative frequency of 64%; followed by "clothing adjustment" with a relative frequency of 62%; "drawing the drapes" had a relative frequency of 56%; and "drinking", "changing seats", and "temperature set-point adjustment" had relative frequencies at a level of about 30%. For long-haul passengers, "drawing the drapes" had the highest frequency (73%); followed by "clothing adjustment" (70%); and "drinking" (45%); with "air outlets adjustment", "temperature setting adjustment", and "changing seats", with relative frequencies less than 40%.

The results reveal that passengers in short- and long-haul vehicles have different habits for adapting themselves to the thermal environment of the vehicle. Passengers in short-haul vehicles prefer to use adjustment of air outlets as a habitual behaviour, meaning that they hope to quickly eliminate the discomfort resulting from a sudden change in temperature when they go from the vehicle to outdoors. Passengers in long-haul vehicles preferred to draw the drapes, meaning that they are more concerned with solar radiation through the windows on long-haul journeys. When there are no facilities in the vehicle allowing passengers to adjust the temperature, about 30% of passengers in both short- and long-haul vehicles still stated they would prefer to adjust the temperature set-point.

A study on thermal comfort requirements in residential spaces (Cheng et al. 2008) showed that the first three most common habitual behaviours of occupants when feeling

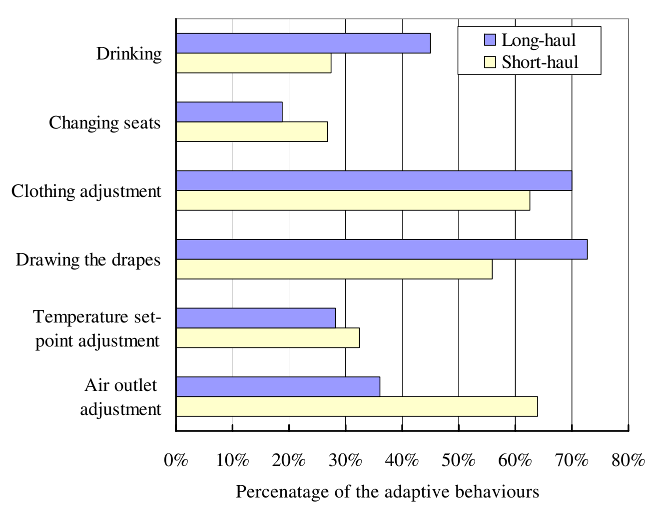

Fig. 2 Habitual thermal adaptive behaviour of passengers in short- and long-haul vehicles

thermal discomfort is to use air-conditioners (41%), using electric fans (26%), and opening windows (12%). Less than 2% of the occupants in residential spaces used the adjustment of clothing as the preferred adaptive behaviour. In comparison, this study shows that over 60% of the passengers used adjustment of clothing as the most frequent adaptive behaviour, which indicates that the habitual thermal adaptive behaviours people use in vehicles are different to those they use in indoor spaces.

Passengers' thermal sensations and expectations

A quick and effective method of understanding the characteristics of passengers' requirement for thermal comfort in vehicles is to ask them directly to provide their assessment of the thermal environment. Items in the questionnaire relating to the passengers' assessment of the thermal environment are listed in Fig. 3.

Figure 4 shows the results of passengers' thermal comfort votes (question 1 in Fig. 3) against the sensation votes on temperature, humidity, air speed, and solar radiation (question 2) for both short-haul (Fig. 4a) and long-haul (Fig. 4b) vehicles. Figure 4 reveals that the average sensation votes on temperature, humidity, air speed, and solar radiation at which people feel "comfortable" all occurred in the region of −0.2 to +0.2, which is very close to "neutral" on the sensation scale. This result shows that "thermal neutrality" and "thermal comfort" are synonyms for passengers in both short- and long-haul vehicles.

Examination of the sensation votes for passengers expressing "uncomfortable" (in question 1) is helpful in gaining an understanding of why the passengers are not pleased with the thermal environment in vehicles. The average sensation responses of the passengers that expressed "uncomfortable" in the solar radiation is "slightly strong" (+0.6 for short-haul and +0.4 for long haul), and the air speed is "slightly weak" (−0.8 for short-haul and −0.6 for long haul). It should be noted that passengers feel "slightly warm" (+0.6) in short-haul vehicles but "slightly

1. How would you rate the thermal environment in the vehicle?

__Comfortable __Uncomfortable

2. How do you feel at the moment?

For TEMPERATURE: __cold(–3) __cool(–2) __slightly cool(–1) __neutral(0) __slightly warm(+1) __warm(+2) __hot(+3)

For HUMIDITY: __too dry(–3) __dry(–2) __slightly dry(–1) __neutral(0) __slightly humid(+1) __humid(+2) __too humid(+3)

For WIND: __too weak(–3) __weak(–2) __slightly weak(–1) __neutral(0) __slightly strong(+1) __strong(+2) __too strong(+3)

For SUN: __too weak(–3) __weak(–2) __slightly weak(–1) __neutral(0) __slightly strong(+1) __strong(+2) __too strong(+3)

3. What would you prefer at the moment?

For TEMPERATURE:	__cooler	__no change	__warmer
For HUMIDITY:	__dryer	__no change	__more humid
For WIND:	__weaker	__no change	__stronger
For SUN:	__weaker	__no change	__stronger

Fig. 3 Questions in the questionnaire relating to passengers' assessment of the thermal environment

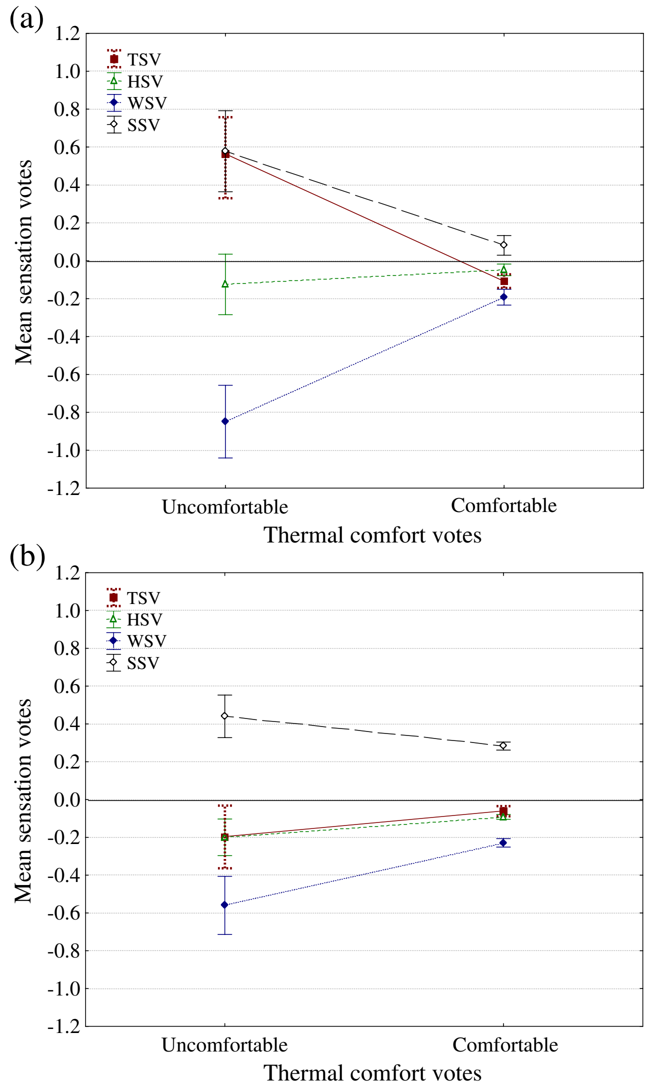

Fig. 4 The status of feeling comfortable/uncomfortable for (**a**) short-haul and (**b**) long-haul passengers against average sensation scales in individual factors. *Boxes* Average values, *whiskers* 95% confidence interval

cool" (−0.2) in short-haul vehicles when they feel uncomfortable. Regarding humidity, passengers report similar feelings when they feel comfortable or uncomfortable in both types of vehicles. This result suggests that the primary environmental factors in vehicles that cause passengers to feel uncomfortable are air temperature, solar radiation, and air speed. Furthermore, passengers have a different perception of temperature between short- and long-haul vehicles when they report feeling uncomfortable.

Exploration of the relationship between thermal comfort votes (question 1) and expectation votes of passengers in thermal environment (question 3) helps to further understand their thermal comfort requirements in vehicles. Figure 5 plots the preference votes of passengers in short- and long-haul vehicles for temperature, humidity, air movement, and solar radiation. The comparisons in Fig. 5a–d show that, regardless of their vote on "comfortable" or "uncomfortable", passengers in short-haul vehicles reported a higher percentage of expecting to change air temperature, humidity, air movement, and solar radiation for thermal comfort than those in long-haul vehicles.

Among passengers voting for "comfortable" in short-haul vehicles, 35% wished for a change in solar radiation (with 28% wanting weaker; 7% stronger), 30% wished for a change in temperature, 26% for air movement, and 16% for humidity in vehicles. Passengers voting "uncomfortable" in short-haul vehicles wished most for a change in temperature (79%), followed by changes in air movement change (68%), solar radiation (53%), and humidity (44%). Passengers voting "comfortable" in long-haul vehicles wished for a change in solar radiation (27%), followed by temperature (26%), air movement (25%), and humidity (12%). For those passengers who voted "discomfort", they wished for a change in temperature (68%), followed by air movement (64%), solar radiation (56%), and humidity (44%).

Among passengers who voted "uncomfortable", 46% of short-haul vehicles passengers and 44% of long-haul vehicles passengers wanted the temperature to be lower; 52% of passengers in short-haul vehicles and 44% in long-haul vehicles wanted higher air movement. In addition, 46% of short-haul vehicle passengers, and 56% of long-haul vehicle passengers would prefer to suffer less solar radiation in vehicles. The results indicate that passengers who feel uncomfortable would prefer lower temperatures, stronger air movement, and weaker sunlight thermal environments in vehicles. Although Fig. 4 indicates that passengers reported similar humidity sensation votes, regardless of whether they felt comfortable or uncomfortable, Fig. 5 demonstrates that passengers who felt uncomfortable reported a higher expectation for a change in humidity than those who felt comfortable.

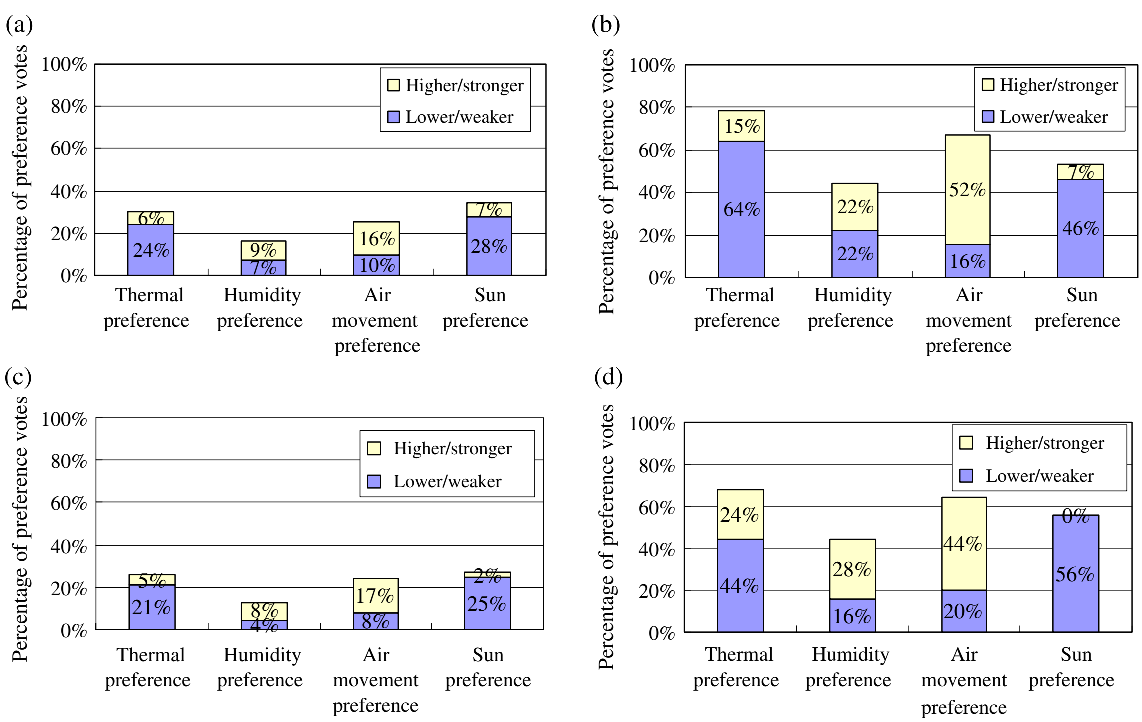

Fig. 5 Passenger preferences for the four environmental factors of feeling **a** comfortable, **b** uncomfortable in short-haul vehicles, and feeling **c** comfortable and **d** uncomfortable in long-haul vehicles

Optimal temperature and thermal comfort zones in vehicles

In addition to establishing an understanding of passengers' perceptions and preferences of thermal environments, and the behaviours most frequently used for thermal adaptation, this research also aims to determine "optimal temperatures" and "thermal comfort zones" in vehicles.

The optimal temperature perceived by passengers as a neutral temperature is the temperature at which passengers do not feel either cool or warm (Fanger 1972). The general approach is to calculate the mean TSV (MTSV) in each temperature interval (in T_o), and then establish a linear relationship between MTSV and T_o (de Dear and Fountain 1994). The temperature interval in this paper is 1°C. The MTSVs of each T_o interval, as reported by passengers in short- and long-haul vehicles, are shown in Fig. 6. The optimal fitted linear equations are:

$$\text{Short-haul}: \quad \text{MTSV} = 0.15\text{To} - 3.82 \quad R^2 = 0.83 \qquad (1)$$

$$\text{Long-haul}: \quad \text{MTSV} = 0.09\text{To} - 2.58 \quad R^2 = 0.85 \qquad (2)$$

$$\text{All}: \quad \text{MTSV} = 0.14\text{To} - 3.66 \quad R^2 = 0.86 \qquad (3)$$

By substituting MTSV=0 into Eqs. 1 and 2, the neutral temperatures for passengers in short- and long-haul vehicles were found to be 26.2°C and 27.4°C, respectively. There is a deviation of 1.2°C in neutral temperature for short- and long-haul passengers. When the two groups of passengers were pooled together, the neutral temperature occurred at 26.4°C, which is obtained by substituting MTSV=0 in Eq. 3.

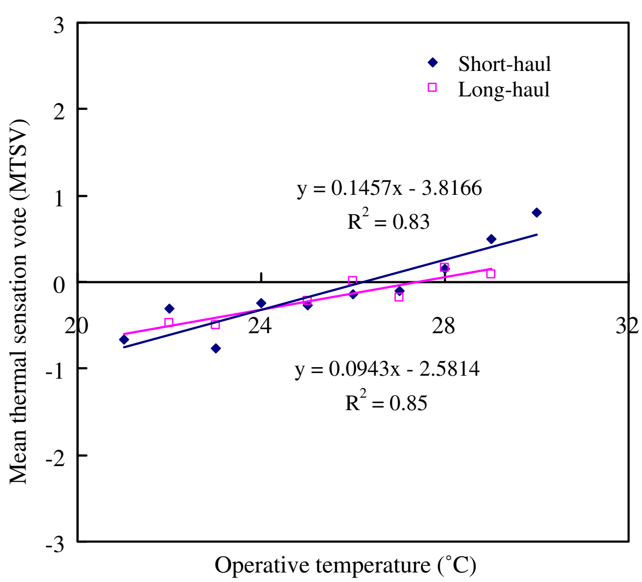

Fig. 6 Neutral temperatures of short- and long-haul vehicles

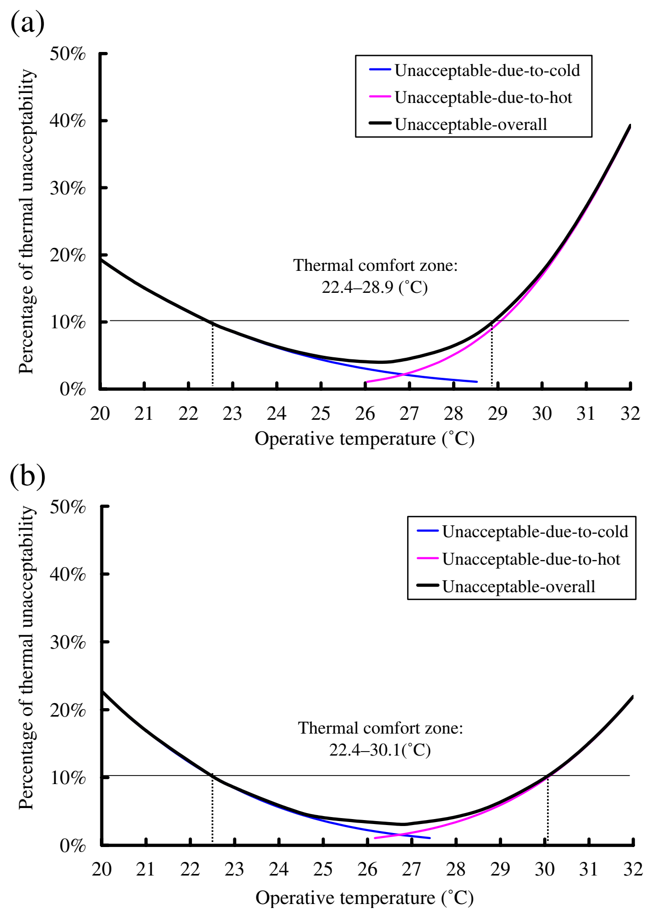

Fig. 7 Thermal comfort zones for **a** short- and **b** long-haul vehicles

The method used by de Dear and Fountain (1994) is used again in this study to determine the thermal comfort zone in vehicles. In the de Dear and Fountain method, the thermal acceptance is equivalent to the three central categories of the TSV scale, i.e. slightly cool (−1), neutral (0), and slightly warm (+1). Thus, the percentage of passengers voting cool (−2) and cold (−3), or warm (+2) and hot (+3) were calculated, respectively, to represent the percentage of un-acceptance due to cold or hot in each temperature interval. A probit model of logistic regression (Ballantyne et al. 1977) was applied to obtain the best fit curves for "unacceptable-due-to-heat" and "unacceptable-due-to-cold", as show in Fig. 7. The line, symbolized with unacceptable-overall, is obtained by the sum of the curves of unacceptable-due-to-cold and unacceptable-due-to-heat, and is used to determine acceptable comfortable temperatures ranges for vehicles. In the ASHRAE Standard 55 (ASHRAE 2004), the comfort zone is defined as the temperature range in which 80% of the occupants feel comfortable. Given that space in vehicles lack dimensions, and thermal environments in vehicles are prone to be affected by outdoor climates, the distribution of air temperature in vehicles is not as uniform as in indoor spaces. Therefore, this research used 90% acceptance as the criterion to define the comfort zone. The other 10% of unacceptance is reserved for the discomfort that may caused by the non-uniformity of thermal environments in vehicles. Hence, the temperatures corresponding to two intersects of unacceptable-overall curves, and the line of 10% unacceptability, are taken as the upper and lower limits of thermal comfort zones, respectively. As shown in Fig. 7, the thermal comfort zone is 22.4–28.9°C for short-haul vehicles, and 22.4–30.1°C for long-haul vehicles. The passengers of the two types of vehicles share the same lower limit; however, long-haul passengers have a higher upper limit threshold, by 1.2°C.

Comparison with indoor thermal comfort

Several studies have been conducted in Taiwan on the thermal comfort of various indoor spaces. Here, we compare the findings of this research and those earlier studies. A neutral temperature is 25.4°C in residences (Cheng et al. 2008), and 25.8°C in offices (Hwang et al. 2009a). The neutral temperature in vehicles, as determined by this study, is 26.4°C, which is higher than that determined in living and working spaces. The comfort zone ranges are 22.4–28.9°C and 22.4–30.1°C for short- and long-haul vehicles, respectively, compared to 22.7–27.2°C in residences and 22.5–29.2°C in offices. The results show that, in order to cater for the thermal comfort requirements of passengers, it is inappropriate to use a temperature set-point used in living or working spaces as the set-point for vehicles.

Conclusions

The present study conducted field investigations in vehicles in order to understand the thermal adaptation responses of passengers in the areas of physiology, psychology, and behaviour. By cross-tabulating passengers' comfort votes, sensations votes, and preference votes, it was found that higher temperatures, strong solar radiation, and low air speeds are the primary reasons for passenger thermal discomfort. The neutral temperatures for short- and long-haul vehicles are 26.2°C and 27.4°C, respectively, and the corresponding comfort zones are 22.4–28.9°C and 22.4–30.1°C, respectively.

In the investigation of behaviours frequently adopted by passengers for thermal adaptation, it was found that short-haul passengers tend to choose behaviours, such as adjustment of air outlets, that can immediately relieve the thermal discomfort resulting from sudden temperature changes when moving from vehicles to outdoors. Long-haul passengers prefer to draw the drapes to eliminate the discomfort resulting from exposure to solar radiation on long-haul journeys. The overall insulation value of clothes worn by passengers is found to have a robust relationship with the outdoor temperature when boarding vehicles. Passengers in Taiwan usually wear more clothing than those in living or working environments. It was also found that passengers in long-haul vehicles are dressed more heavily than those in short-haul vehicles.

The neutral temperature and thermal comfort zones proposed by this study could be helpful to management staff of vehicles to control temperatures, and the observations regarding behaviours for thermal adaptation used by passengers can also serve as a reference for the design of in-vehicle facilities that meet both the thermal comfort requirements of passengers and the need to save energy for the transport sector. For example, short-haul vehicles should enhance the adjustability of air outlets, and long-haul vehicles should deploy drapes.

It should be noted that passenger's thermal comfort requirements may vary over different seasons. Although this study attempted to analyse the neutral temperature in different seasons, the models are not fitted well owing to the limited number of subjects in each season. This issue should be a potential area of future research.

Acknowledgment The authors would like to thank the National Science Council of Taiwan, for financially supporting this research under Contract No. NSC 96-2629-E-150-001.

References

ASHRAE (2004) ASHRAE Standard 55-2004, Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA

Ballantyne ER, Hill RK, Spencer JW (1977) Probit analysis of thermal sensation assessments. Int J Biometeorol 21(1):29–43

Bhatti MS (1999a) Evolution of automotive air conditioning—riding in comfort: part II. ASHRAE J 41(9):44–52

Bhatti MS (1999b) Evolution of automotive heating—riding in comfort: part I. ASHRAE J 41(8):51–57

Brager GS, de Dear RJ (1998) Thermal adaptation in the built environment: a literature review. Energ Build 27(1):83–96

Brager GS, Paliaga G, De Dear R, Olesen B, Wen J, Nicol F, Humphreys M (2004) Operable windows, personal control, and occupant comfort. ASHRAE Trans 110(2):17–35

Cheng MJ, Hwang RL, Lin TP (2008) Field experiments on thermal comfort requirements for campus dormitories in Taiwan. Indoor Built Environ 17(3):191–202

da Silva MC, Alcobia C, Martinho NAG, Ramos JME (2006) Indoor environment in vehicles. Int J Veh Des 42(1–2):35–48

de Dear RJ (1998) A global database of thermal comfort field experiments. ASHRAE Trans 104(1B):1141–1152

de Dear RJ, Brager GS (1998) Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 104(1A):145–167 de Dear RJ, Brager GS (2002) Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energ Build 34 (6):549–561

de Dear RJ, Fountain ME (1994) Field experiments on occupant comfort and office thermal environments in a hot-humid climate. ASHRAE Trans 100(2):457–474

Fanger PO (1972) Thermal comfort. McGraw Hill, New York

Farrington B, Brodt DL, Burch SD, Keyser MA (1997) Opportunities to reduce vehicle climate control loads. In: Proceedings of the the 15th Electric Vehicle Symposium, Brussels, Belgium, 1997 European Electric Road Vehicle Association

Hodder SG, Parsons K (2007) The effects of solar radiation on thermal comfort. Int J Biometeorol 51(3):233–250

Hwang RL, Lin TP (2007) Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions. Archit Sci Rev 50(4):60–67

Hwang RL, Lin TP, Kuo NJ (2006) Field experiments on thermal comfort in campus classrooms in Taiwan. Energ Build 38(1):53–62

Hwang RL, Yang KH, Chen CP, Wang ST (2008) Subjective responses and comfort reception in transitional spaces for guests versus staff. Build Environ 43(12):2013–2021

Hwang RL, Cheng MJ, Lin TP, Ho MC (2009a) Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot-humid regions. Build Environ 44(6):1128–1134

Hwang RL, Lin TP, Chen CP, Kuo NJ (2009b) Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. Int J Biometeorol 53(2):189–200

ISO (1995) International Standard 10551, Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. International Standard Organization, Geneva

ISO (1998) International Standard 7726, Thermal environment-instruments and method for measuring physical quantities. International Standard Organization, Geneva

ISO (2005) International Standard 7730, Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Standard Organization, Geneva

ISO (2006a) International Standard 14505–2, Ergonomics of the thermal environment—evaluation of thermal environments in vehicles. Part 2: determination of equivalent temperature. International Standard Organization, Geneva

ISO (2006b) International Standard 14505–3, Ergonomics of the thermal environment—evaluation of thermal environments in vehicles. Part 3: evaluation of thermal comfort using human subjects. International Standard Organization, Geneva

Lin TP (2009) Thermal perception, adaptation and attendance in a public square in hot and humid regions. Build Environ 44 (10):2017–2026

Martinho NAG, Silva MCG, Ramos JAE (2004) Evaluation of thermal comfort in a vehicle cabin. Proc Inst Mech Eng D J Automobile Eng 218(D2):159–166

McIntyre DA (1980) Indoor climate. Applied Science, London

Mezrhab A, Bouzidi M (2006) Computation of thermal comfort inside a passenger car compartment. Appl Therm Eng 26(14–15):1697–1704

Nilsson H, Holmér I (2003) Comfort climate evaluation with thermal manikin methods and computer simulation models. Indoor Air 13 (1):28–37

Paciuk M (1990) The role of personal control of the environment in thermal comfort and satisfaction at the workplace. In: Selby R, Anthony K, Choi J, Orland B (eds) Coming of age. 21. Environment Design Research Association, Oklahoma, pp303–312

Shek KW, Chan WT (2008) Combined comfort model of thermal comfort and air quality on buses in Hong Kong. Sci Total Environ 389(2–3):277–282

Taniguchi Y (2001) Simulation models for predicting car occupants' thermal comfort. R&D Review of Toyota CRDL 36(2):1–2

Walgama C, Fackrell S, Karimi M, Fartaj A, Rankin GW (2006) Passenger thermal comfort in vehicles—a review. Proc Inst Mech Eng D J Automobile Eng 220(D5):543–562

Wohlwill JF (1974) Human adaptation to levels of environmental stimulation. Hum Ecol 2(2):127–147