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Combined comfort model of thermal comfort and air quality on buses in Hong Kong

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ABSTRACT

Air-conditioning settings are important factors in controlling the comfort of passengers on buses. The local bus operators control in-bus air quality and thermal environment by conforming to the prescribed levels stated in published standards. As a result, the settings are merely adjusted to fulfill the standards, rather than to satisfy the passengers' thermal comfort and air quality. Such "standard-oriented" practices are not appropriate; the passengers' preferences and satisfaction should be emphasized instead. Thus a "comfort-oriented" philosophy should be implemented to achieve a comfortable in-bus commuting environment. In this study, the achievement of a comfortable in-bus environment was examined with emphasis on thermal comfort and air quality. Both the measurement of physical parameters and subjective questionnaire surveys were conducted to collect practical in-bus thermal and air parameters data, as well as subjective satisfaction and sensation votes from the passengers. By analyzing the correlation between the objective and subjective data, a combined comfort models were developed. The models helped in evaluating the percentage of dissatisfaction under various combinations of passengers' sensation votes towards thermal comfort and air quality. An effective approach integrated the combined comfort model, hardware and software systems and the bus air-conditioning system could effectively control the transient in-bus environment. By processing and analyzing the data from the continuous monitoring system with the combined comfort model, air-conditioning setting adjustment commands could be determined and delivered to the hardware. This system adjusted air-conditioning settings depending on real-time commands along the bus journey. Therefore, a comfortable in-bus air quality and thermal environment could be achieved and efficiently maintained along the bus journey despite dynamic outdoor influences. Moreover, this model can help optimize air-conditioning control by striking a beneficial balance between energy conservation and passengers' satisfaction level.

1. Introduction

Hong Kong is a compact city with an area of 1099 km^2 which houses a population of 7 million. Efficient public transportation is therefore compulsory. The main areas of the city are served by 133 km of train tracks spanning 4 routes, 91 km of underground subway tracks covering 5 routes. The rest of the city is made accessible by 5 franchised bus companies that cover over 600 routes. In 1988, air-conditioned buses were introduced, and there are now approximately 5750 air-conditioned buses; over 95% of the service fleets.

The Hong Kong Environmental Protection Department (HKEPD) released the Practice Note for Managing the Air Quality in Public Transport Facilities (PN-PTF) in 2003 (HKEPD,

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2003). The PN-PTF states the in-bus air quality standards as well as practical recommendations about the air temperature and relative humidity ranges for air-conditioned buses in Hong Kong. The intent of the PN-PTF is not to act as strict regulations but rather as recommendations for bus operators. These guidelines use carbon dioxide concentration levels as an indicator of air quality within bus passenger compartments. It recommends controlling the thermal environment by keeping the air temperature ranging from 20 to 28 °C and the relative humidity ranging from 40 to 70%. Furthermore, it is recommended that air quality managers from the operators should adjust these ranges by taking the passengers' preferences into consideration. The main objective of the PN-PTF focuses on the control of in-bus air quality to achieve a safe and healthy in-bus environment, while the issue of thermal comfort is merely briefly stated in the appendix.

Considering the in-bus thermal environment, the recommended ranges by PN-PTF lie within the comfort zone stated in ASHRAE Standard 55-2004. However, that is not equivalent to providing a thermally comfortable environment for passengers. A variety of factors must be considered in order to achieve thermal comfort. There are six major thermal factors stated in Fanger (1970): air temperature, radiant temperature, relative humidity, air velocity, clothing insulation and activity level, but of these six, only two (air temperature and relative humidity) are stated in the PN-PTF which shows the laxity in the control of the thermal environment.

Passengers expect comfort on air-conditioned buses. However, numerous complaints about thermal discomfort or stuffiness suggest less-than-satisfactory environments on these buses. Large in/out-bus air temperature differences cause transient discomfort (De Dear et al., 1993). Insufficient fresh air ventilation weakens the dilution of in-bus air contaminants, bioeffluents and bacteria, causing passenger exposure to poor air quality; whilst high ventilation rate increases the risk of infiltrating vehicular exhaust from the busy roadway environment.

Local air quality surveys concerning the in-bus air parameters concentration levels have been reported. Chan et al. (1999a,b), Chan and Wu (1993), Chan and Liu (2001) and Wu (1990) reported practical in-bus air quality and evidenced the conformance with prescribed levels in standards. However, complaints of poor in-bus environments have been ceaseless. Green groups conducted surveys concerning these issues during summers in Hong Kong. They received over 120 complaints on excessive cooling in bus cabins in June 2005 with passengers describing the thermal environment on buses as an 'Arctic condition' (The Standard, 2005). Complaints of hot and stuffy air on air-conditioned buses were also made in the same summer of 2005 (Oriental Daily, 2005). From these studies, it was inferred that the bus service operators have not mastered in setting the air-conditioning system to satisfactorily achieve a comfortable in-bus environment.

Complaints concerning in-bus air quality and thermal comfort were received, even though local surveys reported the conditions as conforming to the local prescribed levels. These revealed the inconsistence between the prescribed levels and the passengers' actual comfort. To provide quality service, it is inadequate to simply provide a safe and healthy in-bus environment. Improving passengers' commuting comfort, subjective feelings towards in-bus air quality and thermal comfort must be achieved, with an emphasis on satisfaction and comfort.

In this study, combined comfort models for indicating the in-bus commuting comfort (including thermal comfort and air quality) were developed through the correlation of objective parameters and the passengers' subjective sensation votes. Additionally, the models classified individual data into practical and significant indices for operation and monitoring processes to create a more comfortable commuting environment.

2. Methodology

In this study, both questionnaire survey and physical parameters measurement were conducted on buses to collect subjective sensation responses and physical parameter levels concerning in-bus thermal comfort and air quality. The physical parameters measurement and questionnaire survey commenced in September 2004 and were completed by August 2005. Thus data from both summer and winter was obtained.

A total of 115 measurements were conducted (including 73 air-conditioned journeys and 42 non-air-conditioned journeys) on 21 selected bus routes which traveled through Hong Kong Island, Kowloon peninsula and the New Territories. The major criterion for selecting the bus routes was that the traffic conditions and route natures must closely resemble the general bus operation conditions in Hong Kong. The questionnaire survey and parameters measurement were conducted during the journeys. There were a total of 883 passengers who participated in the survey, including 563 who completed the whole questionnaire. (54.7% completed, 31.1% incomplete and, 14.2% refused to participate.)

Both the air-conditioned and non-air-conditioned buses were considered in this study. The air-conditioned buses have fixed-type windows installed preventing the infiltration of ambient air into the cabins. Ventilation is achieved by mechanical ventilation and door openings. A filtering system is also available to reduce in-bus particulates. Windows that can be opened are installed on non-air-conditioned buses. The application of natural ventilation helps dilute in-bus air contaminants and release heat energy through induced aerodynamic drag. Hence, the in-bus air quality is not under control but fluctuates according to surrounding environments along the bus journey.

In each measurement trial, three thermal parameters (air temperature, relative humidity and air velocity) and three air parameters (carbon monoxide, carbon dioxide and respirable suspended particulates) were recorded. Meanwhile, questionnaire surveys were conducted with individual passengers concerning subjective preferences and dissatisfaction levels towards the in-bus thermal comfort and air quality.

The in-bus CO concentration level was recorded to measure air leakage in passenger compartments. CO_2 concentration level served as the indicator of ventilation sufficiency and odor; while RSP concentration level gauged the effectiveness of particulate-filtering.

Air temperature, relative humidity and air velocity were measured, while the radiant temperature was neglected and the parameter of clothing insulation replaced. This