Air Quality in Transportation Cabins—Part I: How Much Do We Know About It?

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ABSTRACT

Recent field studies of the air quality in transportation cabins are summarized in this paper. Overall, very limited field data are available to the public. A comparison of the methodologies showed that no common instrumentation was used in the field measurements, even for identical indoor air quality parameters. Therefore, care should be exercised when comparing the results from different studies. Most of the air contaminant concentrations in airplanes were below the threshold values during cruising and in nonsmoking environments but could reach higher levels for noncruising periods and smoking environments. The air quality in passenger vehicles varied significantly with the ventilation mode, weather, and traffic. In summary, there were limited field data available in ground transportation cabins, and no data have been reported for commercial truck cabins.

INTRODUCTION

Over the past few decades, there has been increasing interest in the air quality in transportation cabins, including airplanes and ground transportation. Similar to other indoor environments, in-cabin air quality is also dependent on temperature, relative humidity, and the concentrations of airborne contaminants. These parameters could have significant effect on the health and well-being of the occupants.

Temperature and humidity have direct impact on the thermal comfort and the performance of the occupants. The health effects of low humidity include fatigue, headaches, irritated and itchy skin, itchy or irritated eyes, stuffy and even bleeding noses, as well as impaired lung function (Spengler and Wilson 2003). Reinikainen and Jaakkola (1992) found that the dryness of skin and mucosa, allergic reactions, and the sensation of dryness were decreased by air humidification. For a sedentary person, a 30% change in relative humidity (RH) had the same effect on thermal balance and thermal sensation as a 2°F (1°C) change in temperature. In warm conditions, thermal discomfort increased with humidity (Berglund 1998). In many hot and humid climates, conventional air-conditioning units were unable to meet the latent load and, consequently, the indoor relative humidity exceeded the recommended value of 60% to 70% RH (ASHRAE 1992). Increasing outdoor ventilation without properly controlling the indoor humidity may actually decrease occupant comfort and perceived air quality (PAQ). This is because excessively low or high humidity may result in excessive evaporation from the skin and respiratory tract (Fang 1998; Simonson et al. 2002; Dowing and Bayer 1993; Toftum and Jørgensen 1998). The total heat loss affects driver performance and, therefore, road safety. The sectional heat loss determines occupant comfort, draft sensation, and the risk of cold-related muscular injury (Wyon et al. 1989).

Temperature and RH also affect PAQ. A recent study showed that the air was perceived as less acceptable with increasing temperature and humidity (Fang 1998). This impact was found to decrease with an increasing level of air pollution. When the temperature and humidity increased through a range of 18°C to 28°C and 30% to 70% RH, subjects' satisfaction decreased, and they felt more and more uncomfortable. At any given temperature, a decrease in humidity usually results in the occupants feeling cooler, drier, and more comfortable. In addition, fabrics feel smoother and more pleasant, and the air is perceived to be fresher, less stale, and more acceptable.

Temperature and relative humidity also affect the airborne level of microorganisms (e.g., molds and bacteria),

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which can cause many acute diseases, infections, and allergies. Microorganisms have different properties at various levels of temperature and humidity. They are well protected indoors by the moisture surrounding them at a relative humidity of 70% or higher. Virus survival is inversely proportional to the RH level and temperature (Akers et al. 1966). The half-lives of viruses range from about two hours at an ultra-high RH and 35°C to more than seven days at a low RH and 5°C (Mbithi et al. 1991).

Typical indoor airborne contaminants in a transportation cabin include particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen dioxide (NO_2). While fine particles are responsible for many respiratory syndromes, ultra-fine particles and nanoparticles pose more threats to indoor occupants because they can penetrate deeply into the respiratory system. The nanoparticles from engine exhaust can translocate from the lungs to the brain and blood, thereby causing an increase in blood coagulatory and inflammatory effects (The Royal Society 2003; Dreher 2004). PM can also cause irritation and dryness of the eyes and nose, as well as other allergenic responses (Hauschildt et al. 1996; Pan et al. 1999). Furthermore, PM can act as a transport vehicle for other airborne contaminants (Tan and Zhang 2003). These passenger contaminants include gaseous pollutants, viruses, bacteria, organic substances, and odors. Particulates generated by the internal combustion process have also been shown to be associated with increased hospital admissions, decreased lung function in children, and increased risk of acute respiratory infections (ARI) in young children. Exposure to combustion products has been identified as a risk factor for ARI, which is the leading cause of infant mortality in developing countries and is responsible for the deaths of three to five million children under the age of five each year.

CO_2 is a colorless and odorless gas. One major source of CO_2 in a ground transportation vehicle is the emissions from other vehicles that penetrate through the vehicle's ventilation system. Vehicles running at 60 mph will emit about 5.2% of their CO_2 emissions into the outside air (Rienstra and Rietveld 1996) and are one of the major sources of CO_2 in the air above the road, especially under heavy traffic conditions. Other major sources of CO_2 in vehicles are the occupants in the vehicles. A typical human being produces 18 liters of CO_2 per hour (Lindgren and Norback 2002). The level of CO_2 may become very high in a short time if there is insufficient outside air intake and exchange. For example, in a normal office in winter, the ratio of inside and outside concentrations of CO_2 can reach as high as 8.0 (Baek 1997).

CO_2 has obvious health effects on humans at various levels. At the concentration of 700 ppm or lower, the adverse effect is negligible, but people will start to feel uncomfortable when the CO_2 concentration reaches 800 ppm (MDH 2004). In an environment where the CO_2 concentration reaches 5,000 ppm, people will feel fatigued and lose concentration (OSHA 1995), and at 20,000 ppm they will also breathe at 150% of the normal rate. When the concentration of CO_2 is increased to 30,000 ppm, heart rate and blood pressure will increase (Schwarzberg 1993), hearing can be impaired, and most people will feel dizzy.

Carbon monoxide (CO) is a colorless, odorless, and tasteless toxic gas that is generated from incomplete fuel combustion. Engine exhausts contribute to approximately 56% of all CO emissions in the United States. Higher levels of CO in automobile cabins generally occur in areas with heavy vehicle traffic, and, in many cities, 85% to 95% of CO emissions come from motor vehicle exhaust. Emissions of CO from motor vehicles cause several hundred accidental fatal poisonings in the United States annually (Marr et al. 1998), and 57% occur in automobiles. The highest levels of CO in the outside air typically occur during the colder months of the year.

Carbon monoxide poisoning has its most acute toxic effect on organs with high oxygen requirements, which include both the heart and brain. CO is toxic because when it enters the bloodstream, it replaces the oxygen molecules found in the critical blood component, hemoglobin, depriving the heart and brain of the oxygen (Coultas and Lambet 1991). Hence, individuals with ischemic heart disease are at particularly high risk (EPA 1991). The study by Garvey and Longo (1978) also found that fetal development was affected by CO.

It should be noted that the health risks associated with CO exposure depend on both the concentration of CO and the duration of exposure. For example, exposure to 70 ppm for 189 min, 150 ppm for 50 min, or 400 ppm for 15 min can result in similar carboxy-hemoglobin levels of about 10% (Raub et al. 2000). When subjects were exposed to concentrations below 90 ppm for a long time, CO was found to have an adverse influence on their hearts, brains, and children's birth weights. Adverse cardiovascular effects may also be observed among the more susceptible individuals (Dahms et al. 1993), and angina, impaired vision, and reduced brain function may result (Townsend and Maynard 2002). When exposed to 200 ppm of CO, most people experience slight headaches, tiredness, dizziness, and nausea after two to three hours. At 400 ppm, a frontal headache occurs within one to two hours, and life can be threatened after three hours. At 800 ppm, they experience dizziness, nausea, and convulsions within 45 minutes, are unconscious within two hours, and die in two to three hours. At 1,600 ppm, headache, dizziness, and nausea occur within 20 minutes, and death occurs within an hour.

Nitrogen dioxide (NO_2) has a pungent acrid odor. NO_2 is one of the major emissions from vehicles. On-road NO_2 concentration is very high, reaching 212 ppb (Riediker et al. 2003). High NO_2 concentration in a vehicle may result in driver fatigue, lack of concentration, and loss of cognitive ability, reducing the ability of the driver to operate the vehicle safely. Consequently, there may be a link between air quality and transportation safety.

Simoni et al. (2002) showed that there was a close relationship between the indoor NO_2 levels of 33 ppm in winter and increased occurrence of acute respiratory symptoms in nonsmoking adults. At higher NO_2 levels, bronchitic and asthmatic symptoms were significantly more prevalent. They also reported that these health effects were associated with the duration of the exposure. The same exposure indices were obtained when subjects were exposed to a low dose of NO_2 (i.e., 10 ppb) for a longer duration (five hours) and to a higher NO_2 concentration (i.e., 50 ppb) for a short duration (one hour). Exposure to NO_2 of 200 ppm or greater immediately endangers life. At levels of 50–100 ppm, NO_2 will impair lung function and irritate the eyes, nose, and throat (Alberts 1994). Moreover, there is evidence that NO_2 may cause lung damage at concentrations of 300 ppb or higher (Jones 1997; Spengler 1993; Samet and Cushing 1997; Viegi et al. 1992; Frampton et al. 1991). There is also evidence that after exposure to 400 ppb of NO_2 for one hour, the forced expiratory volumes of asthmatics drop by 19% (Tunnicliffe et al. 1994). In addition, Salome et al. (1996) found a higher risk among a sample of 20 asthmatics when exposed to 600 ppb of NO_2 over a period of one hour.

Children and the elderly are the most vulnerable to NO_2. Samet et al. (1992) studied over 1300 infants aged 18 months and found that exposure to NO_2, especially in winter, may increase the frequency and severity of upper and lower respiratory diseases. Pilotto et al. (1997) monitored the influence of exposures to NO_2 among 400 children in elementary schools. Significant increases in sore throats, colds, and absences from school were observed when their exposure to NO_2 was at hourly peak levels of 80 ppb or higher. The adverse respiratory effects were considered to be at short-term peak levels. Shima and Adachi (2000) focused on 842 children (434 boys and 408 girls) from grades 4 to 6 for over three years. They found that when the annual average indoor NO_2 concentrations were more than 40 ppb, respiratory symptoms were very prevalent among girls.

In one of the few studies that examined engineering and other environmental effects, Galatsis et al. (2000) linked in-cabin air quality with fatigue and, hence, indirectly with road safety. They found that it was necessary to install gas sensors in an enclosed space. The air quality can then be improved by controlling the ventilation system. When the concentrations of the pollutants monitored are high, an alarm will be activated to inform the occupants to open the ventilation system, thereby keeping the air quality in the cabin as good as the ambient air. Sato (2002) suggested that further studies focusing on the effects of air quality on safe and comfortable driving should be conducted.

A comprehensive review of the literature on in-cabin air quality is thus essential to understand the importance of air quality parameters and their impact on human welfare, health, and the productivity of the vehicle occupants.

The objective of this paper is to establish a basic knowledge of the levels of the air pollutants in various transportation cabins. The methodologies and major findings of these studies were reviewed and compared.

FIELD STUDIES OF IAQ IN TRANSPORTATION CABINS

While numerical and computational tools have been used to study the relative humidity in airplanes (Lindgren and Norback 2002; Spengler and Wilson 2003), this paper will focus only on field measurements in transportation cabins. We found only a few studies of in-cabin air quality that were available to the public. These studies had been conducted in cars, buses, vans, trains, and aircraft. No data were found in the literature for heavy trucks. The experimental designs, methodologies, and instruments are summarized in Table 1.

IAQ Parameters Monitored

The studies of air quality in aircraft were more comprehensive than those in motor vehicles. The IAQ parameters measured in cars included temperature, relative humidity, particulate matter, CO, black carbon, nitrogen monoxide (NO), NO_2, ozone (O_3), and volatile organic compounds (VOCs) (Limasset et al. 1993; Chan and Chung 2002; Rodes et al. 1998; Sato 2002). Some studies compared the ratio of the concentrations of the indoor contaminants to outdoor air contaminants. Compared to vehicles, more air quality parameters in aircraft were available. The IAQ parameters measured in aircraft included temperature (T), RH, pressure, particulate matter ($PM_{2.5}$, PM_{10}, particle count), CO, CO_2, O_3, black carbon, chemicals (e.g., lead) on dust, PAH, NO_2, NO, and VOCs. In addition, nicotine, dust mites, allergens, sulfur dioxide (SO_2), and microbiological organisms (bacteria, fungi, endotoxins, etc.) were also measured (Dechow et al. 1997; Pierce et al. 1999; Lee et al. 2000; BRE 2003; Nagda et al. 1992; Eatough et al. 1992).

Only a few studies that provided field data of IAQ in train cabins and/or methods for controlling the air quality through ventilation in trains were found in the literature search (Aizlewood et al. 2005; Li et al. 2005; Chow 2002; Chow and Yu 2000; Dumyahn et al. 2000). In one of the few studies with field data, Li et al. (2005) reported several in-train air quality parameters including temperature, relative humidity, CO, CO_2, TVOC, TSP, PM_{10}, $PM_{2.5}$, PM_1, benzene, toluene, and xylene. Chow (2002) suggested that the ventilation rate in trains be kept at 25.2 m^3/h per person in order to prevent the CO_2 level from exceeding 1000 ppm. Aizlewood et al. (2005) did a survey of 574 subjects between 16 and 69 years old and found that the passenger satisfaction scores (1 = clearly acceptable to 10 = clearly unacceptable) for both temperature and air quality were between 3.5 and 7.74 at 24°C to 33°C with different airflow conditions. Dumyahn et al. (2000) conducted two surveys, monitoring and comparing the air quality in aircraft, trains, buses, and subways. They found that the levels of CO_2 had a close relationship with passenger loads for all of the types of vehicles studied. Also, the levels of most VOCs in ground transportation were higher than in aircraft, except acetone and ethyl alcohol.