Energy Conversion for Thermal Comfort and Air Quality Within Car Cabin

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Abstract. Thermal comfort and air quality within a car cabin are required during driving throughout various climates where energy is efficiently consumed to maintain acceptable conditions by air conditioning (AC) unit. This paper proposes an analysis of energy conversion within a car cabin for thermal comfort and air quality. Mathematical models, based on energy and mass balances, are developed to determine process variables of a car cabin. Experimental data from real conditions is compared with simulated results for model validation. There is very good agreement between those results. The proposed models are used to simulate interesting case studies in real circumstances for investigation on trade-off among thermal comfort, air quality, and energy usage.

1. Introduction
Nowadays, people spend a lot of time in cars to travel. It is challenging to automotive engineering design in automatically making passengers comfortable within cars all the time. Weather and ambient conditions mainly determine thermal conditions of an air within a car cabin. In sunny day, air temperature within a car cabin can reach 70°C during parking [1]. Besides temperature, an amount of CO₂ can also affect comfortable conditions of passengers. High concentration of CO₂ makes passengers sleepy and dizzy. With three passengers in a sedan, concentration of CO₂ can reach 3,500 ppm, which is much higher than acceptable level [2].

With those conditions, thermal comfort and air quality are needed to be investigated when a car is driven in long period, especially in a hot climate. Typically, an Air Conditioning (AC) unit is designed to make up the air within a car cabin. Its capability is implemented to maintain temperature, humidity, and CO₂ concentration under comfortable conditions. In that case, the AC unit consumes an amount of energy efficiently.

Recently, researchers have paid attention to analysis on energy conversion for thermal comfort and air quality within a car cabin. For example, mathematical models of car cabins have been developed to describe thermal conditions [1], [3-5]. Most of those works used temperature and humidity to represent thermal conditions within a car cabin. In few cases, air quality of car cabin is indicated by CO₂ concentration [2]. It should be noticed that the previous works analyzed thermal conditions and air quality, separately.

In this work, mathematical models of energy conversion for thermal comfort and air quality are proposed. The usage of Predicted Mean Vote (PMV) index and CO₂ concentration in quantifying thermal comfort and air quality, respectively, is novelty of this work.
2. Experiments
A sedan car is used as an experimental rig for model verification in this study as shown in figure 1. An experiment is performed during night time with ambient temperature of 31 °C and humidity of 70%, respectively. There are 2 passengers inside the car where an AC unit is turned on. The air temperature, humidity, and CO₂ concentration within the care cabin are measured every 30 seconds in 10 minutes. They are recorded by a data acquisition system.

The temperature within the car cabin is measured by a thermistor with measuring range from 0°C to 100°C with an accuracy of ±0.3°C. The relative humidity is measured by a hygrometer with measuring range from 10 to 90 % RH with an accuracy of <3% RH. The CO₂ concentration is measured by a carbon dioxide sensor with measuring range from 0 to 5,000 ppm with an accuracy of ±40 ppm. An anemometer with measuring range 0 to 20 m/s with an accuracy of ±3% is used to measure a wind speed for airflow of a AC unit.

3. Methodology
3.1. Mathematical model
Mathematical models are developed to determine the air temperature, humidity, and CO₂ concentration within a car cabin by applying principles of mass and energy balances. Figure 2 shows a schematic diagram of energy and mass transfers across the car cabin from environment.

From figure 2a, the energy equations of a car cabin can be expressed in equation (1)-(2).

\[ m_d(C_v_d + w_c C_v_w) \frac{dT_c}{dt} = M + G + E_A + \dot{Q}_e - m_{AC}(C_v_d + w_c C_v_w)(T_c - T_{AC}) \]  

\[ \dot{Q}_e = hA(T_e - T_c) + \varepsilon A\alpha(T_e^4 - T_c^4) \]  

where \( m \) is the mass (kg), \( C_v \) is the specific heat (J/kg°C), \( w \) is the absolute humidity (kg/kg), \( M \) is the metabolic rate (W), \( G \) is the solar radiation of sunlight, which is transmitted to car envelope (W), \( E \) is the heat generation (W), \( \dot{Q} \) is the heat transfer (W), \( h \) is the heat transfer coefficient W/m²°C, \( A \) is the
area of car envelope (m$^2$), $\varepsilon$ is the emissivity, $\sigma$ is the Stefan-Boltzman constant, $\dot{m}$ is the mass flow rate (kg/s), and $T$ is the temperature ($^\circ$C). The subscripts, such as $d$, $w$, $c$, $A$, $e$, and $AC$, represent the dry air, water vapor, car cabin, auxiliaries, envelope of car cabin, and AC unit, respectively. The left term of (1) is the internal energy of an air within the car cabin, which consisting of dry air and water vapor. The right hand terms are the metabolic rate of human, radiation heat from windshield, heat generation from auxiliaries, convective and radiative heat transfers between air within car cabin and envelope, and heat extraction of an AC unit, respectively.

From figure 2b, the mass equations are written in terms of the absolute humidity and CO$_2$ concentration in equation (3)-(5).

$$m_d \frac{dw}{dt} = \dot{m}_i w_a - \dot{m}_o w_c + N \dot{m}_p - (1-X) \dot{m}_{AC} w_e + \dot{m}_{AC} w_{AC}$$

$$m_d \frac{dC}{dt} = \dot{m}_i C_a - \dot{m}_o C_{cab} + X \dot{m}_{AC} C_a + NC_p$$

$$X = \frac{\dot{m}_{fa}}{\dot{m}_{ra}}$$

where $N$ is the number of passengers, $X$ is the ratio of fresh air to return air in AC unit, and $C$ is the CO$_2$ concentration (ppm). The subscripts, such as $i, a, o, p, fa,$ and $ra$, represent infiltration, ambient, exfiltration, passenger, fresh air, and return air, respectively. It should be noticed from equation (3)-(5) that the air temperature, absolute humidity and CO$_2$ concentration within a car cabin is affected by infiltration, exfiltration, human exhale, and, in particular, functions of a AC unit.

### 3.2. PMV index

The PMV index, which is proposed by Fanger, is used to quantify thermal comfort of the passengers [6]. According to ISO standards 7730, PMV index is the function of air temperature ($T_c$), air velocity ($v$), relative humidity ($RH$), mean radiant temperature ($MRT$), clothing ($Clo$), and metabolic activity ($M$), as summarized in equation (6).

$$PMV = f(T_c, v, RH, MRT, Clo, M)$$

The value of $Clo$ and $M$ are determined by human clothing and activity. In this work, the value of $Clo$ and $M$ are chosen to be 0.5 for general clothing and 70 W for driving activity, respectively.

The values of PMV index with respect to thermal sensation is shown in figure 3. The acceptable range for PMV index for comfortable environment is from -0.5 to +0.5 [7].

![Figure 3. Scales of PMV index for thermal sensation](image)

### 3.3. CO$_2$ concentration

The CO$_2$ concentration has unit in ppm (part per million). The standard indicates that the CO$_2$ concentration must be below 700 ppm over ambient condition to accomplish the air quality [2].

### 3.4. Energy conversion

In achieving acceptable conditions of thermal comfort and air quality, the AC unit consumes an amount of energy to make up the supply air, which is mixed of the return air within the car cabin together with fresh air from environment. The amount of energy for making up air is called cooling load $CL$, which can be calculated by equation (7)-(8).

$$CL = \dot{m}_{AC} C_v (T_m - T_{AC})$$

\[ T_m = (1 - X)T_c + (X)T_{fa} \]  

(8)

where \(T_m\) is the temperature of mixing air between return air and fresh air (°C) and \(T_{fa}\) is the temperature of fresh air (°C).

4. Results and discussion

4.1. Performance of proposed model

The mathematical models of equation (1)-(5) are numerically solved. The simulated results are compared with experimental data. For model validation, several experiments are performed as a driver and a passenger sit in the car when the AC unit operates. An experiment is observed that the air temperature and relative humidity decrease from an initial condition as shown in figure 4a and figure 4b, respectively. After 300 s, the air temperature and humidity reach their steady state conditions. In figure 4c, two persons inside the car cabin cause increase of CO\(_2\) concentration. However, the CO\(_2\) concentration slowly rises due to taking fresh air to the car cabin. There is very good agreement between the simulation and experiment.

![Figure 4a](image1)

(a)

![Figure 4b](image2)

(b)

![Figure 4c](image3)

(c)

Figure 4. Comparison between simulated results and experimental results of (a) temperature, (b) relative humidity, and (c) CO\(_2\).

4.2. Analysis on thermal comfort and air quality

The validated model is used to simulate some case studies. Accordingly, the PMV index, CO\(_2\) concentration, and cooling load of the car cabin are determined. The simulation takes place in the
morning with ambient temperature of 32°C and relative humidity of 70%. There are six conditions in the simulation. These conditions are continuing. Each condition is separated by dash lines in figure 5 and figure 6.

4.2.1. Condition A. The car is parked outside without any cover or roof. The PMV index increases because the air temperature get high since solar radiation is transmitted to the envelope of the car cabin. The CO₂ concentration remains during this period. Obviously, there is no cooling load.

4.2.2. Condition B. This condition is similar with the condition A. One driver and one passenger get on the car. Consequently, the air temperature increases. It is shown in figure 6 that the PMV index drastically increases. The CO₂ concentration has the same trend due to CO₂ production from human exhale and lack of fresh air from an AC unit.

4.2.3. Condition C. In this period, the car is driven with speed of 20 m/s. The AC unit is turned on with mass flow rate of 0.0548 kg/s, supply air temperature of 12°C and mixing ratio of 0.4. It is expected that the air temperature decreases. In turn, the PMV index decreases to reach the acceptable level. Also, the fresh air, which is taken into the car cabin, dilutes the CO₂ concentration. The cooling load increases in making up the hot return air and fresh air.

4.2.4. Condition D. Another passenger gets on the car in this time. This minor change in number of passengers causes the heat and CO₂ generations from metabolism of humans. The PMV index and CO₂ concentration slightly increase.

4.2.5. Condition E. To obtain comfortable conditions, the mass flow rate of the AC unit is changed to 0.0948 kg/s. The PMV index rapidly decreases until it reaches -0.1, which is in the acceptable level. More amount of fresh air alleviates the CO₂ concentration to 700 ppm. However, the cooling load of the AC unit is an energy usage of 1,600 W.

4.2.6. Condition F. To reduce the CO₂ concentration, the mixing ratio is changed to be 0.8. The CO₂ concentration decrease significantly to 500 ppm. The air quality is acceptable. The higher cooling load with 1,800 W is traded off than Condition E.

5. Conclusion
Mathematical models of car cabin are developed in this paper. Analysis on energy conversion for thermal comfort and air quality within a car cabin is performed effectively. The model validation is confirmed by a very good agreement between simulated results and experimental data. Some interesting case studies are simulated in real circumstances. The simulations show the dynamic changes of thermal comfort and air quality. The proposed models can be used for design in automatic trade-off among thermal comfort, air quality, and energy usage in making up the air within the acceptable conditions.

![Figure 5. Plots of PMV index and CO2 concentration within car cabin against time.](image-url)
Figure 6. Plots of cooling load of car cabin against time.

6. References
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