Computerized Simulation of Automotive Air-Conditioning System: A Parametric Study

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Abstract

This paper presents results of a parametric study performed on an automotive air-conditioning (AAC) system of a passenger car. The goals are to assess the effects of varying the volumetric flow rate of supply air, number of occupants, vehicle speed, and the fractional ventilation air intake (XOA), on the dry-bulb temperature and specific humidity of the air inside the passenger's cabin, and on the evaporator coil cooling load of the AAC system. Results of the parametric study show that increasing the supply air flow rate reduces the dry-bulb temperature of the cabin air, increases both the specific humidity of the air and the evaporator coil load. Increasing the number of occupants in the passenger cabin causes the cabin air temperature, specific humidity and the evaporator coil load to increase. Increasing the vehicle speed causes the specific humidity of the cabin air and the evaporator coil cooling load to increase but the dry-bulb temperature of the air is not significantly affected. Increasing the fractional fresh air intake (XOA) also increases the cabin air specific humidity and the evaporator coil cooling load.

Keywords: *Automotive air conditioning (AAC), passenger car cabin, parametric study*

1. Introduction

Automotive air-conditioning (AAC) is a necessity for thermal comfort in the cabin of a passenger vehicle especially for people who are living in countries with hot and humid climate. However, the extra weight added to the vehicle and the operation of the AAC system cause the fuel consumption of the vehicle to increase. The additional fuel consumption in turn results in higher emission of greenhouse gases that pollute the environments. Therefore augmentation of the AAC system efficiency and evaluation of its thermal performance has become important. The AAC system is often operated under varying conditions thus substantial efforts are required to evaluate its performance. These conditions include the temperature of the air entering the evaporator and condenser, the evaporator air volumetric flow rate and ventilation mode, the compressor speed, the condenser face air velocity, passenger cabin's material, the number of occupants, and the weather conditions which affect the internal and external sensible thermal loads.

The largest auxiliary load on a passenger car's engine is input power required by the air-conditioning system's compressor. During a peak load the compressor would consume up to 5 to 6 kW of power from the vehicle's engine power output. This is equivalent to a vehicle being driven at a speed of 56 km/h. The additional fuel consumption when the air-conditioning system is in-used is quite substantial. One study indicated that the air-conditioner usage reduces fuel economy by about 20%. It also increases the emissions of nitrogen oxides by about 80% and carbon dioxide (CO) by about 70%, although the actual numbers depend on the actual driving conditions.

A semi-empirical computer simulation program (CARSIM) for simulating thermal and energy performance of an automotive air-conditioning (AAC) system of a passenger car has been developed [1]. The empirical correlations for evaporator sensible and latent heat transfer were embedded in the loads calculation program to enable the determination of evaporator inlet and outlet air conditions and the passenger cabin air conditions. The computer program has been validated by comparing its predicted outputs with the data obtained from an actual road test on a Proton Wira Aeroback passenger car. The results predicted by the CARSIM computer program were found to have very good agreement with the actual road test data, with errors ranging between 2 to 4%.

This paper presents results of a parametric study performed on the automotive air-conditioning (AAC) system of the Proton Wira Aeroback passenger car using the CARSIM computer simulation program. The goal is to investigate the effects of: (1) supply air volumetric flow rate, (2) number of occupants, (3) vehicle speed, and (4) the fractional outside air intake (XOA), on the cabin's air dry-bulb temperature, specific humidity and the total evaporator coil (cooling) load of the AAC system. A base case simulation was performed on the system to find out the trend of variation of the cabin air dry-bulb temperature, specific humidity and the total evaporator coil (cooling) load as the time is varied from 10 am to 2 pm.

2. Base Case Conditions

A computer simulation for the base case conditions was performed on the automotive air-conditioning (AAC) system by using the CARSIM computer simulation program developed earlier and reported in [1]. The input data used for the computer simulation are given in Table 1.

Table 1 Parameters for the base case condition.

Parameters	Value
Vehicle speed	~ 90 km/h
Occupant	~ one (1)
Colour of the car body	~ light yellow (α = 0.5)
Glass thickness	~ 3 mm (shading coefficient = 1)
A/C blower speed	~ maximum
Travelling duration	~ 4 hours (10 am to 2 pm)
Fraction of outside air (XOA)	~ 0.16 (or 16% of outside air)

The computer simulation was performed as if the vehicle is driven at a constant speed of 90 km/h with only one occupant. The travelling duration is four hours i.e. from 10 am (or 600 minutes past midnight) to 2 pm (or 840 minutes past midnight). The car air-conditioning system is turned-on during this period in which the blower fan speed is set to a maximum. The fractional outside air (XOA) is set at a fixed value of 16%. The air in the passenger's cabin gains sensible heat from the surrounding air and latent heat from the passenger. As a result, the cabin air dry-bulb temperature, specific humidity and the evaporator coil cooling load will vary with time during the simulated journey. The simulation for the base case conditions was carried out to find out the trend in which these parameters vary with the time. Figure 1 shows a schematic diagram of the simplified air-conditioning system of the passenger car considered in this study.

Figure 2 shows the variation of dry-bulb temperature of the cabin air with time in minutes, measured after midnight. The time t = 600 minutes corresponds to 10 am while t = 840 minutes corresponds to 2 pm. It can be seen that during the first five minutes after the air-conditioning system is being turned-on the cabin air temperature drops slightly by about 0.05°C. This is due to a sudden cooling of the air when cooled air is suddenly blown into the cabin. Thereafter, the cabin air temperature rises steadily with time, from 18.4°C until it reaches about 18.8°C at about 1 pm. The cabin air temperature is affected by the temperature of the ambient air, t_0. The ambient air temperature rises steadily with time as the intensity of solar radiation increases. This causes the cabin air temperature to rise in a fashion seen in the figure. However, as the solar radiation intensity decreases after 1 pm, the cabin air temperature also decreases steadily, from 18.8°C to about 18.6°C at 2 pm. Although the dry-bulb temperature of the cabin air appears to vary with time, the range of its variation is quite small, i.e. less than 0.5°C, and hence can be considered insignificant.

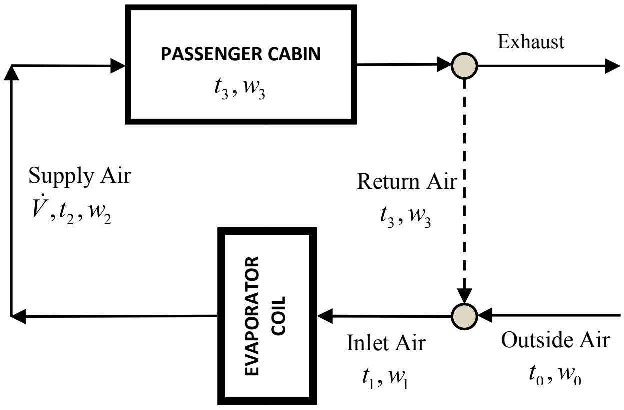

Figure 1 Schematic diagram of an air-conditioning system of a passenger car [1].

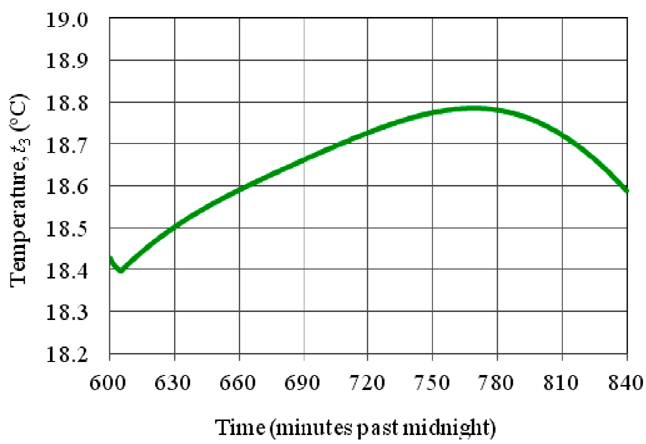

Figure 2 Variation of dry-bulb temperature of the cabin air for the base case condition.

The variation of specific humidity of the cabin air with time is shown in Figure 3. The air specific humidity is related to the saturation pressure of water vapor that exists in the air. The saturation pressure increases dramatically with the dry-bulb temperature of the air. Hence, when the temperature of the cabin air rises, the specific humidity of the air also increases in a nearly similar fashion. It can be noted that the specific humidity of the air increases steadily from about 6.26 g/kg at 10 am (600 minutes after midnight) to a highest value of about 6.45 g/kg at 1 pm (780 minutes after midnight). Thereafter, the specific humidity of the cabin air decreases with time, as the dry-bulb temperature falls. At 2 pm (840 minutes after midnight) the specific humidity of the cabin air drops to about 6.40 g/kg.

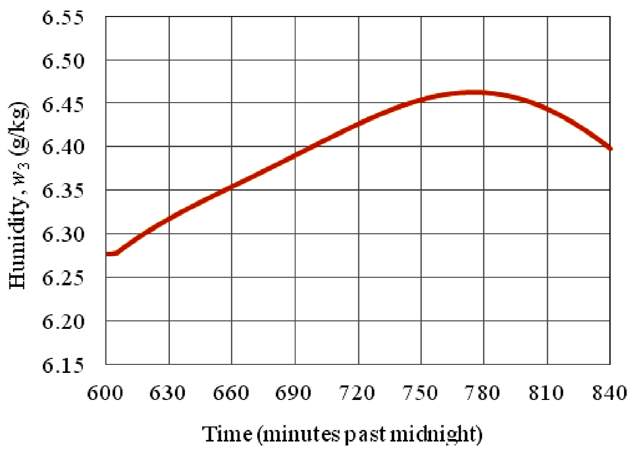

Figure 3 Variation of specific humidity of the cabin air for base case condition.

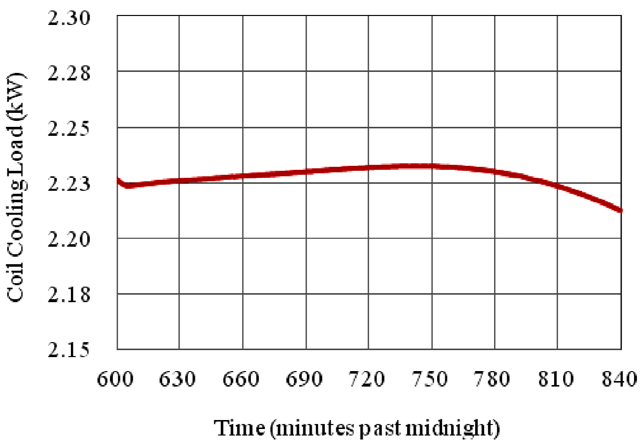

Figure 4 Variation of evaporator coil cooling load with time for base case condition.

Figure 4 shows variations of the evaporator coil cooling load with time. The cooling load is the sum of sensible heat load, $Q_{C,S}$ and latent heat load, $Q_{C,L}$. The sensible heat is influenced by the temperature t_1 of the air coming into the cooling coil. The latent heat is influenced by the specific humidity w_1 of the incoming air. The incoming air temperature t_1 is in turn affected by the temperature of the incoming outside air, t_0 and the temperature of the return air, t_3. Both the t_0 and t_3 increases with time causing the temperature t_1 to continuously increases from 10 am to 1 pm. This in turn causes a steady increase in the sensible heat load of the coil during the same period. As both the t_0 and t_3 decreases after 1 pm, the sensible heat load also decreases. The specific humidity of the air coming into the cooling coil, w_2 is influenced by the humidity of the incoming outside air, w_0 and the humidity of the return air, w_3. Both the w_0 and w_3 increase steadily from 10 am to 1 pm causing the latent heat load to rise steadily during the same period. When both the w_0 and w_3 decrease after 1 pm, the latent heat load of the evaporator coil also decreases. Although the specific humidity varies with time, the range of its variation is quite small.

3. Parametric Study

A parametric study was performed by computer simulation to investigate the effects of varying the supply-air volume flow rate, number of occupants, vehicle speed and the fractional outside air (XOA) on the cabin air dry-bulb temperature, specific humidity and the evaporator coil cooling load. The supply-air volume flow rate was varied from 70 L/s to 100 L/s with a 10 L/s interval. The number of occupants of the vehicle was varied from one to four persons. The vehicle speed was varied from 60 km/h to 105 km/h with an interval of 15 km/h. Finally, the fractional outside air (XOA) which is the ratio between the ventilation-air volume flow rate and the cooled-air volume flow rate, was varied from 0.2 to 0.3, with a 0.05 interval. When the cooled-air volume flow rate was varied during the simulation, other parameters that are listed in Table 1 were held constant at the prescribed values. Similar procedure was followed when the other parameters were varied.

4. Results and Discussion

4.1 Effects of Supply-Air Volume Flow Rate

Figure 5 shows the effect of cooled-air volume flow rate on the dry-bulb temperature of the cabin air. The simulation results show that for a given air flow rate, the dry-bulb temperature varies with time in a very similar manner as that for the base case. At a given cooled-air volume flow rate, the cabin air temperature increases steadily from 10 am (600 minutes past midnight) and reaches the highest value at about 1 pm (780 minutes after midnight). After reaching a maximum value, the cabin air temperature decreases with time. However, increasing the cooled-air volume flow rate decreases the dry-bulb temperature of the cabin air. On average, the cabin air temperature decreases by about 0.5°C (or 2.5%) for every 10 L/s increment of the cooled-air volume flow rate. The highest temperature of the cabin air temperature is 20.2°C, at 1 pm when the cooled-air volume flow rate is 70 L/s. The temperature falls to about 18.7°C when the cooled-air volume flow rate is increased to 100 L/s, which can be considered as a significant temperature change.

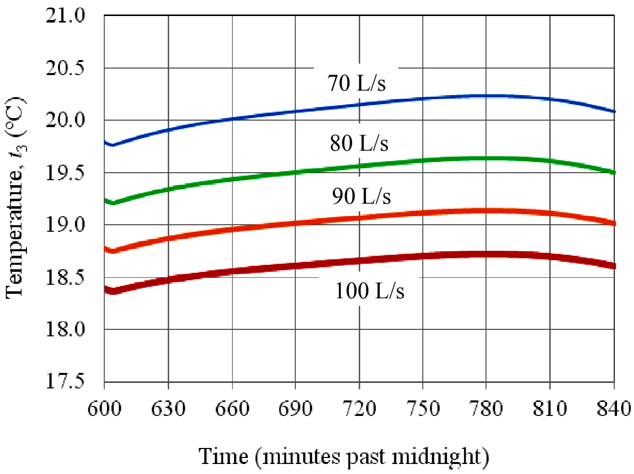

Figure 5 Variation of evaporator coil cooling load with time for base case condition.

Figure 6 shows the effect of cooled-air volume flow rate on the specific humidity of the air inside the passenger cabin. Again, the simulation results show that the humidity of the cabin air varies with time in more or less similar manner, regardless of the cooled-air volume flow rate. However, the specific humidity of the cabin air increases when the cooled-air volume flow rate is increased. Increasing the cooled-air volume flow rate means the velocity of the air flowing through the evaporator coil is increased. This reduces the ability of the evaporator coil to remove moisture from the air that is passing through it. Consequently, the specific humidity of the cabin air will rise. On average, results of the simulation results show that the specific humidity of the cabin air rises by about 5.4% (or 0.34 g/kg) for each 10 L/s increase in the cooled-air volume flow rate.

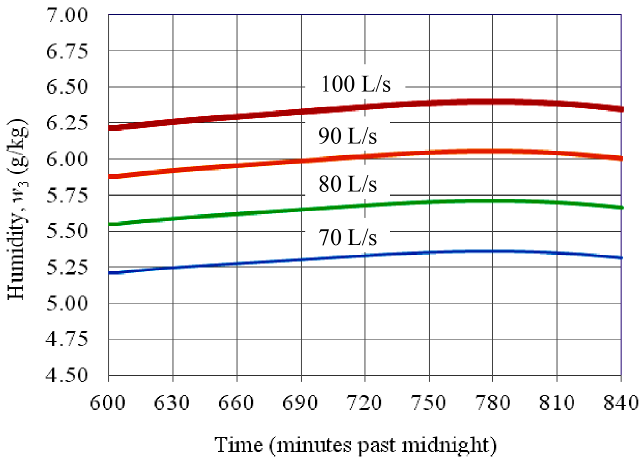

Figure 6 Effect of cooled-air volume flow rate on specific humidity of the cabin air.

The effect of cooled-air volume flow rate on the evaporator coil total cooling load is shown in Figure 7. It can be seen that, for a given air volume flow rate, the variation of the coil cooling load with time is very much similar to that for the base case. However, increasing the volumetric flow rate of the cooled-air increases the coil cooling load, at any given time. On average, the simulation results show that the cooling load increases by about 6 to 8% for each 10 L/s increase in the cooled-air volume flow rate.

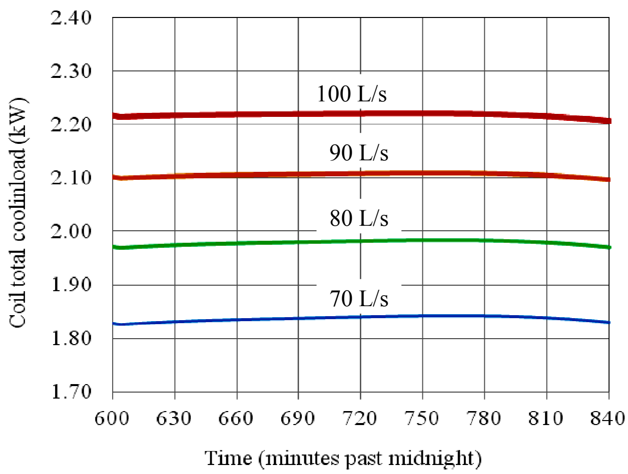

Figure 7 Effect of cooled-air volume flow rate on the evaporator coil cooling load.

4.2 Effects of Number of Occupant

The computer simulation results on the effect of the number of occupants in the passenger cabin on the dry-bulb temperature of the cabin air is shown in Figure 8.

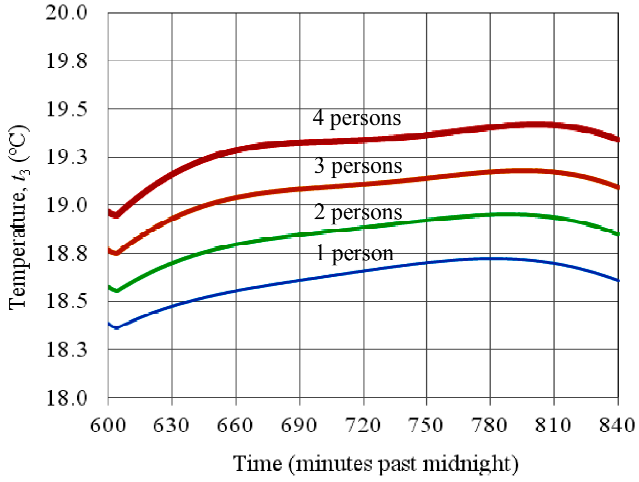

Figure 8 Effect of number of occupants on the dry-bulb temperature of the cabin air.

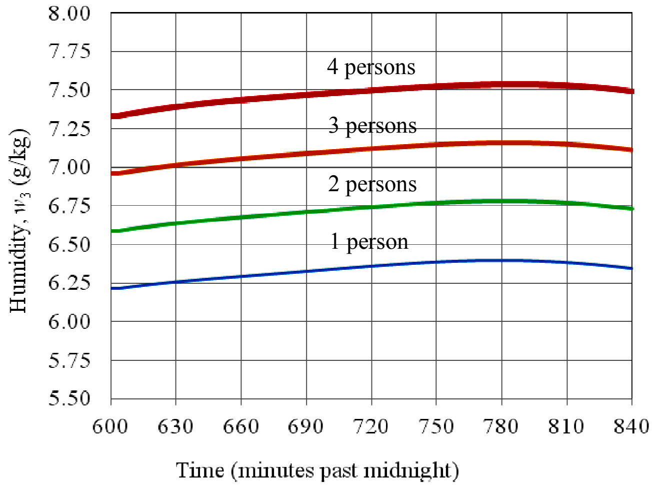

Figure 9 Effect of number of occupants on cabin air specific humidity.

Note that the curve for one person represents that for the "base case" condition (see Figure 2). The simulation results indicate that the variation of cabin air temperature with time is not much affected by the number of occupant in the cabin. However, at a any given time, when the number of occupants is increased the cabin air dry-bulb temperature increases. This is because human body continuously transfers energy in the form of sensible heat which will cause the cabin air temperature to rise. As more passengers occupy the cabin space, more sensible heat is transferred to the cabin air causing greater temperature rise of the air. On average, the simulation results show that the cabin air temperature increases by about 1.2 % or 0.23°C for each additional person occupying the passenger cabin. This can be considered as a significant increment.

The effect of the number of occupants on the specific humidity of the cabin air is shown in Figure 9. Note that the curve for one person represents the simulation result for a base case condition (see Figure 3). As seen in the figure, the variation of specific humidity of the cabin air with time is generally not affected by the number of occupants present in the passenger cabin. However, the simulation results show that at any given time, increasing the number of occupants will significantly increases the specific humidity of the cabin air. This is because human releases energy into the cabin air in the form of latent heat, through perspiration process and breathing. Hence when more people occupy the cabin space, the more latent heat and moisture are added to the cabin air resulting in significant increase in the specific humidity of the air. On average, the humidity of the cabin air rises by about 5.4% or 0.38 g/kg for each additional occupant in the passenger cabin.

Figure 10 shows the effect of the number of occupants on the evaporator coil cooling load. The curve for one person represents the simulation result for the base case condition (see Figure 4). It is seen that the variation of the coil cooling load with time appears to be unaffected by the number of occupants in the cabin. However, increasing the number of occupant will increase the amount of sensible and latent heat in the cabin air. This represents the additional thermal load that needs to be absorbed from the cabin air by the air-conditioning system. The mass flow rate of the refrigerant through the evaporator must be increase to achieve this. This is accomplished through the increase in the compressor speed. The figure shows that, on average, for each additional occupant in the cabin, the evaporator coil cooling load rises by 2.5% or about 0.06 kW.

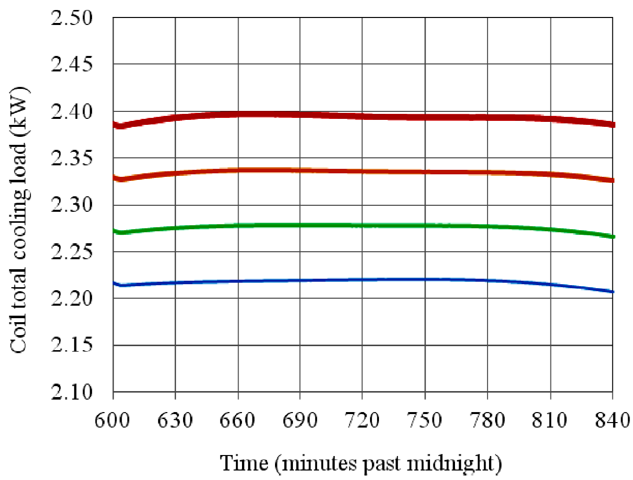

Figure 10 Effect of number of occupants on the evaporator coil cooling load.

4.3 Effects of Vehicle Speed

Computer simulation was also carried out to determine the effects of varying the vehicle speed on the dry-bulb temperature and specific humidity of the cabin air, and the evaporator coil cooling load. The vehicle speed was varied from 60 km/h to 105 km/h with 15 km/h interval.

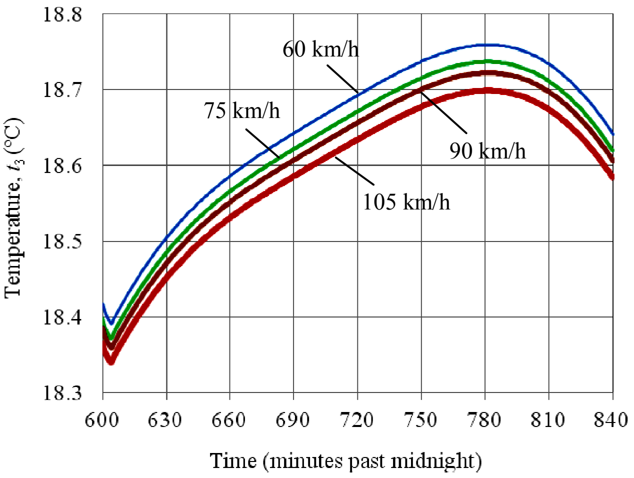

Figure 11 Effect of vehicle speed on the dry-bulb temperature of the cabin air.

Increasing the vehicle speed will cause the compressor of the air-conditioning system to operate at higher speed. This in turn leads to a higher mass flow rate of the refrigerant. As a result, more heat is absorbed by the refrigerant from the air passing through the evaporator coil [5]. The dry-bulb temperature of the cabin air will be reduced since the supply air enters the cabin at lower temperature. This is situation is shown in Figure 11. However, as seen from the figure, the reduction in the cabin air dry-bulb temperature is very small. On average, the simulation results show that the cabin air temperature drops only by about 0.1% or 0.02^{o}C for every 15 km/h increment of the vehicle speed. This result is however consistent with that reported in the literature [6].

The effect of varying vehicle speed on the specific humidity of the cabin air is shown in Figure 12. In general, the simulation results show that the vehicle speed does not have significant effects on the trend of variation of specific humidity of the cabin air with time. However, at any given time, the specific humidity of the cabin air decreases quite significantly as the vehicle speed is increased. This results suggests that as the vehicle moves at higher speed, more moisture is absorbed from the air that is passing through the evaporator coil. As a result, the air that is supplied into the cabin air is dryer. This causes the reduction in the specific humidity of the cabin air. On average, the specific humidity drops by about 5.4% or 0.33 g/kg for every 15 km/h increment of the vehicle speed.

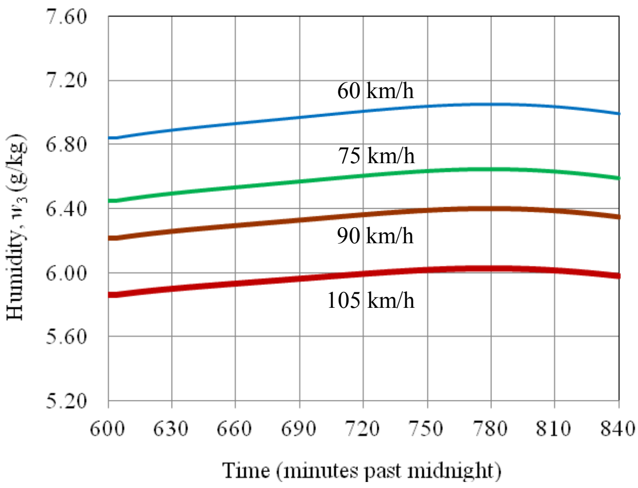

Figure 12 Effect of vehicle speed on the specific humidity of the cabin air.

The results of computer simulation shows that the vehicle speed has insignificant effects on the variation of evaporator coil cooling load with time. This is shown in Figure 13. However, at any given time, the coil cooling load increases as the speed of the vehicle is increased. On average, for every increment of 15 km/h, the coil load increases by 3.9% or 0.09 kW. However the increase in the cooling load is somewhat smaller when the vehicle speed is increased from 75 km/h to 90 km/h.

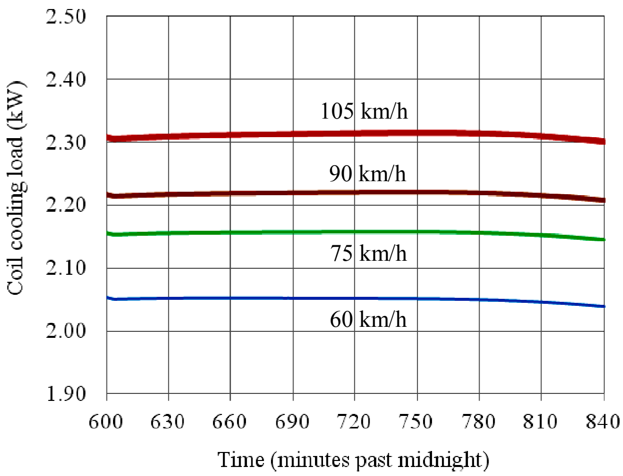

Figure 13 Effect of vehicle speed on the evaporator coil cooling load.

4.4 Effects of Fractional Ventilation Air Intake

Fractional ventilation air intake (XOA) is the ratio between the ventilation-air flow rate and the air-conditioning system's supply-air flow rate. It's value ranges from 0 for air recirculation mode (no ventilation-air) and 1 for a ventilation-air full usage (no air recirculation).

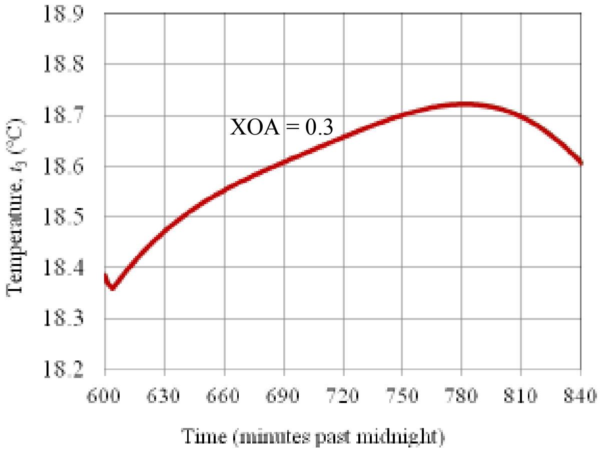

Figure 14 Effect of XOA on the dry-bulb temperature of the cabin air.

In this study the XOA was varied from 0.2 to 0.3 with a 0.05 increment the effects of doing this on the dry-bulb temperature and specific humidity of the cabin air, and the cooling load of the evaporator coil were investigated. The effects of varying the XOA on the dry-bulb temperature of the cabin air is shown in Figure 14. It is seen from the figure that the variation of the cabin air temperature with time is not significantly affected by the value of the XOA. Also, increasing the XOA from 0.2 to 0.3 does not seem to have appreciable impact on the cabin air dry-bulb temperature. This could be because the variation of the XOA considered in this study is too small.
The effect of varying the XOA on the specific humidity of the cabin air is shown in Figure 15. The simulation results show that the variation of specific humidity with time is generally not much affected by the value of the XOA. However, at any given time, increasing the value of XOA causes the specific humidity of the cabin air to increase. When the XOA is increased the specific humidity of the air at the inlet of the evaporator coil is also increased because the outside air has higher moisture content compared with the returned air from the cabin. When the moisture content of the air at the inlet of the evaporator coil is higher, the ability of the coil to remove the moisture is somewhat reduced. As a result, the air leaving the evaporator coil, which is supplied into the cabin, will have slightly higher moisture content. On average, the specific humidity of the cabin air is increased by about 5.2% or 0.37 g/kg for every 0.05 increment of the XOA.

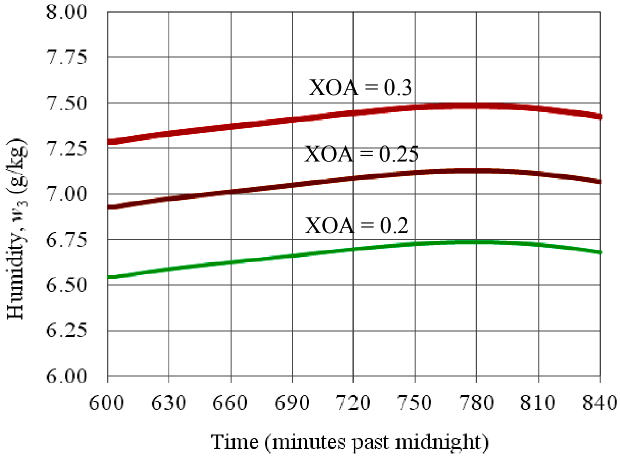

Figure 15 Effect of varying the XOA on the specific humidity of the cabin air.

The simulation result on the effects of varying the XOA on the evaporator coil cooling load is shown in Figure 16. It is seen from the figure that the value of XOA does not have any significant effect on the variation of the cooling load with time. However, at any given time, increasing the XOA causes the evaporator cooling load to increase quite significantly. The increase in the coil load is a direct consequence of the increase in temperature and specific humidity of the air inlet to the evaporator coil, as more outside air is introduced to the system. The outside air has higher temperature and humidity than the cabin. On average, for every 0.05 increment of the XOA, the coil cooling total load rises by about 6.8% (or 180 Watt), which can be considered as significant increment.

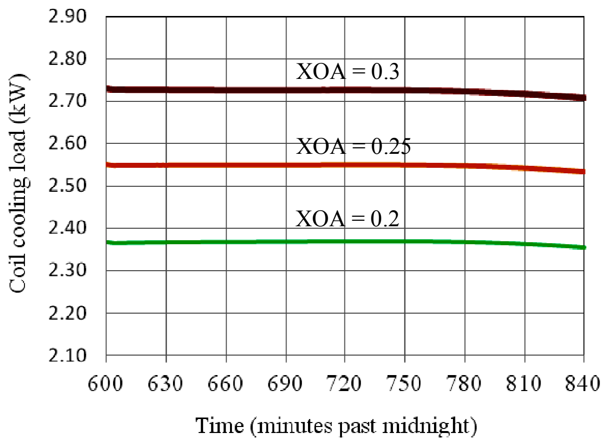

Figure 16 Effect of varying the XOA on the evaporator coil cooling load.

5. Conclusion

A semi-empirical computer simulation program (CARSIM) has been developed for simulating thermal and energy performance of an automotive air-conditioning (AAC) system. The computer program was used to perform a parametric study to investigate the effects of varying the volume flow rate of supply air, the number of occupants in the passenger cabin, the vehicle speed and the fractional outside air intake (XOA) on the dry-bulb temperature and specific humidity of the cabin air, and on the evaporator coil cooling load of a 1.6 L Proton Wira passenger car. Results of the parametric study show that for each 10 L/s increment of the supply air flow rate the cabin air temperature is reduced by about 2.5%, the specific humidity increases by 5.4%, and the evaporator coil cooling load increases by about 6%. For each additional occupant in the passenger compartment, the cabin air temperature, specific humidity, and evaporator coil cooling load are increased by 1.2%, 5.4%, and 2.5%, respectively. For every 15 km/h increase of the vehicle speed, the specific humidity of the cabin air is increased by 5.4% and the evaporator coil cooling load by 3.9%. The temperature of the cabin air appears to be not affected by the vehicle speed. The fractional fresh air intake (XOA) has no significant influence on the cabin air temperature. However, for every 0.05 increase of XOA, the interior air specific humidity increases by 5.2% and the evaporator coil cooling load also increased, by about 6.8%.

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