A New Method to Predict the Thermal Sensation of an Occupant Using a Neural Network and Its Application to the Automobile HVAC System*

Matsuei UEDA**, Yousuke TANIGUCHI**
and Hiroshi AOKI**

The purpose of this study is to develop a method for predicting the thermal sensation of an automobile occupant, and evaluate the prediction method's effectiveness in controlling an automobile heating, ventilating and air conditioning (HVAC) system. The main purpose of a HVAC system is not to keep the temperature constant, but to make people comfortable. This HVAC system was designed to control the interior environment according to the thermal sensation of an occupant, and thus has a direct effect on the occupant's comfort. The thermal sensation level was predicted by a neural network from the interior temperature of the vehicle and facial skin temperature of the occupant. The prediction of the thermal sensation using the neural network was satisfactorily accurate. The HVAC system using the neural network could control the thermal sensation of the occupant and could maintain the occupant's level of comfort even if the air temperature was constant.

Key Words: Air Conditioning, Neural Network, Human Engineering, Automobile

1. Introduction

Enjoyable driving requires not only a good engine but also a comfortable passenger compartment. An optimally controlled heating, ventilating and air conditioning (HVAC) system is the best way to maintain a comfortable compartment in automobiles. In recent years, the introduction of microcomputers has made it possible to precisely control the thermal environment with the aid of sensors which detect the temperature or solar radiation^{(1),(2)}. However, the basic concept for controlling automobile HVAC systems has not changed greatly; that is, the scheme is based on sensing the interior air temperature, and maintaining a constant temperature. Since the primary purpose of an HVAC system is not to maintain air temperature but to make the occupants comfortable, the HVAC system should be controlled according to the environment the thermal sensation of the occupant. In the

case of air conditioning for a room, some HVAC systems use PMV (the predicted mean vote) for the thermal sensation of the occupant⁽³⁾⁻⁽⁵⁾. The PMV defined by Fanger is the scale which indicates the thermal sensation of a person staying in a room, so it is applicable only under the condition that the environment is constant^{(5),(6)}. In the case of an automobile, the surroundings of an automobile continuously change as it moves and its interior environment also changes continuously; thus the application of PMV is not possible. Moreover, the PMV is predicted from only the environmental parameters (air temperature, wind velocity, etc.), and it does not measure the condition of the person directly. Thus the task of creating a comfortable environment for the occupant is not always achieved with the HVAC system.

With regard to the thermal sensation, it has been pointed out in the field of thermal physiology that the sensation depends not only on the thermal environment, but also on the thermal state of a person in the environment. Skin temperature is determined by the heat balance between the thermal environment and thermal state of a person, and plays an important role in evoking such feelings as "cool" and "hot"⁽⁷⁾. On

* Received 8th December, 1995.

** Mechanical I Division, Toyota Central Research and Development Laboratories Inc., 41-1 Aza Yokomichi, Oaza Nagakute, Nagakute-cho, Aichi-gun, Aichi-ken 480-11, Japan

these bases, skin temperature is a promising index of the thermal sensation of a person, and it was used in this study to determine the thermal sensation of the occupant. However, the relationship between the skin temperature and the thermal sensation is connected with the complexities of the human nerve system and the human heat transfer system. In particular, the relationship might be nonlinear in the unstable environment that often arises in the case of the automobile. Therefore, a function that can treat nonlinearity is also needed to predict the thermal sensation of the occupant. To solve these problems, we used a neural network to determine the relationship between the skin temperature and the thermal sensation. A neural network has been applied to many other nonlinear problems and has achieved good results⁽⁸⁾. Appropriate control of the HVAC by using this method was considered.

The purpose of this study is to develop a new method to predict the thermal sensation and to evaluate the HVAC system controlled by the predicted thermal sensation. In this paper, the method of determining the relationship between the skin temperature and the thermal sensation using a neural network, the evaluation of the accuracy and comparisons between this method and other methods are described. The results and evaluation of the HVAC system controlled by the predicted thermal sensation using the NN are also described.

2. Architecture of a Neural Network

The study of neural networks originated from the study of the nervous system of living organisms. In recent years, neural networks have been applied to various engineering fields, especially to those concerning nonlinear problems and pattern recognition⁽⁸⁾.

The architecture of our neural network is shown in Fig. 1. This is known as a layered network^{(9),(10)}.

Fig. 1 Architecture of neural network

There are 8 units in the input layer, 4 units in the hidden layer and 1 unit in the output layer. Each unit in the input layer inputs a signal to each unit of the hidden layer. Each unit of the hidden layer performs the calculations given by Eqs. (1) to (3).

$$net_i = \sum w_{ij} o_j \quad (1)$$

$$o_j = f(net_i - \theta) \quad (2)$$

$$f(x) = 1 / (1 + \exp(-x)) \quad (3)$$

w_{ij} : combined weight of the i -th unit and the j -th unit

O_j : output of j -th unit

net_i : inside state of i -th unit

θ : threshold value

Equation (3) is called a sigmoid function. Each unit in the hidden layer inputs a signal to a unit in the output layer. The unit in the output layer performs the same calculations (Eqs. (1) to (3)) as in the unit in the hidden layer. Finally, the output is obtained from a unit in the output layer.

3. Prediction of the Transition of Thermal Sensation

We considered that the transition of thermal sensation could be predicted from the patterns of transition of the skin temperature and the environment. The skin temperature was determined by the heat balance between the human body and the environment, and we assumed that the information needed to predict the thermal sensation of an occupant was the skin temperature and the air temperature. We used the facial skin temperature, because the face of an occupant is usually uncovered and it is easy to measure facial skin temperature. Furthermore, the influence of the body temperature was considered from the air temperature. Figure 2 shows a schematic of our method⁽¹⁰⁾. The facial skin and air temperature data for 30 seconds were selected as input data and the thermal sensation 30 seconds into the future was predicted. However, the relationship between the

Fig. 2 The prediction of the transition of thermal sensation

temperatures and the thermal sensation is very complicated. Therefore, a neural network is used for estimating the thermal sensation of an occupant, because the neural network is a good tool for imitating a nonlinear system.

The details of our neural network are shown in Fig. 3. The time series of the occupant's facial skin temperature and the interior air temperature were fed into the neural network after normalization. Both facial and air temperature inputs were normalized as shown in Fig. 4. The facial skin temperature is well

Fig. 3 The detailed architecture of the neural network

Fig. 4 Normalization of input data

Fig. 5 The relationship between the output of neural network and thermal sensation

correlated with thermal sensation⁽¹¹⁾, and is easily measured because the face is not covered by clothing. The air temperature was measured at the center of the compartment. The prediction of the thermal sensation of an occupant a short time into the future (30 seconds) was obtained from the neural network. The relationship between the output value and the thermal sensation levels is shown in Fig. 5.

4. Evaluation of the Predicted Thermal Sensation of an Occupant

The experiments were performed in order for the neural network to learn and for evaluating the thermal sensation predicted using it.

4.1 Method of experiments

Experiments were performed with subjects in an environmental chamber. The subjects included 62 males between the ages of 22 and 36, and everyone wore the same type of clothing. Thermocouples (0.1 mm diam., K type) were taped to their faces, as shown in Fig. 6, as they sat in an automobile in an environmental chamber. Facial skin temperatures were measured at 7 points and the mean value was used for predicting the thermal sensation of the occupant. In addition, the temperature of the passenger compartment was measured using a thermocouple placed at the center of the passenger compartment. The temperatures were recorded with a data logger (TR2731 ADVANTEST) at ten-second intervals.

The subject selected one of thermal sensation levels at one minute intervals for the first 10 minutes, and at two minutes intervals after that. The experimental conditions are shown in Table 1. The interior environment of the automobile was controlled by a conventional automobile air conditioner.

4.2 Learning of neural network

To output the correct answer, the neural network must first learn from teacher data. The teacher data were selected from this experimental data (Table 1), but not all data were used. The total number of

Fig. 6 Measurement points of facial skin temperature

Table 1 Basic experiments conditions. These experimental data were used to learn a neural network and to test its' performance

Subject	Male 22 - 36 years old
Air Temp.	
Outside	-10 - 30 °C
Inside	-10 - 50 °C
Solar Radiation	0 - 900 W/m ²
Number of Tests	238 cases
Outlet Mode	Face, Foot, Face+Foot
clo	0.6 - 0.8

teacher data points was about 200. The transition measurements of the facial skin and air temperatures were fed into the units in the input layer, and the thermal sensation 30 seconds later was used as teacher data. The method of learning was the error back-propagation method⁽¹²⁾. Learning was repeated 10 000 times until this neural network was able to produce the correct output.

4.3 Results of basic experiments

The learned neural network was tested by comparing the predicted thermal sensation level with the thermal level actually felt by the subject. The remaining data (those not used for learning) were used to test the neural network. Figure 7 shows an example of prediction results. The conditions under which these results were obtained were as follows: the outside air temperature was 28°C with a solar radiation value of 686 W/m². The interior air temperature before starting the air conditioner was 50°C. From Fig. 7, the predicted and actual thermal sensation levels were in agreement and the neural network was capable of predicting the thermal sensation of an occupant. The mean error of all data was 0.5 unit of the thermal scale used (see Fig. 8).

To determine the usefulness of the neural network, the results predicted using this method were compared with results obtained using other methods. The following three alternative methods were selected for comparison.

- (1) The neural network using 4 facial skin temperatures only
- (2) The neural network using 4 interior air temperatures only
- (3) The one-dimensional regressive expression using 4 facial skin temperatures and 4 interior air temperatures,

Predicted thermal sensation =

$$a_1 Ts_1 + a_2 Ts_2 + \dots + b_1 Ti_1 + b_2 Ti_2 + \dots + c \quad (4)$$

where Ts is the facial skin temperature, Ti is the interior air temperature and a , b and c are coefficients

Fig. 7 Predicted and actual thermal sensation level (Outside: 28°C, Solar radiation: 686 W/m²)

Fig. 8 The category scale for thermal sensation level

and a constant.

In the case of alternatives No.1 and No.2, the neural network that had 4 input units, 4 hidden units and 1 output unit were used. The teacher data and the learning method were the same as in our experiments.

There was a large difference in the results obtained by the three methods when the air conditioning was initially turned on and at the semi-equilibrium condition. Figure 9 shows typical results of the difference. The environmental conditions included outside air temperature of 0°C with no solar radiation, interior air temperature of 0°C before starting the air conditioner and the airflow of the air conditioner was directed towards the feet of occupants. At the beginning of air conditioning (range A in Fig. 9), the neural networks using facial and interior temperatures (Base) and only the interior temperatures (No.2) could predict the thermal sensation correctly, but the neural network using only the facial skin temperatures (No.1) and the one-dimensional regressive equation (No.3) could not. The neural network using only the facial skin temperature (No.1) could not predict the thermal sensation, because the thermal

Fig. 9 Predicted and actual thermal sensation level (Outside: 0°C , Solar radiation: 0 W/m^2)

sensation of the human body is complicated. Figure 10 shows the facial and body skin temperatures at range A. The facial skin temperature increased comparatively quickly due to the natural convection from body heat when sitting in an automobile. However, the skin temperature at the abdomen and legs decreased slowly during the first six minutes until the interior air temperature increased, because the initial interior air temperature was very low. The subject felt cold because of the coldness of the abdomen and legs, so that the method using only facial skin temperature could not be used to predict the thermal sensation correctly. In the case of the method using the interior air temperature (No.2), body coldness could be determined indirectly through the interior air temperature and the thermal sensation was predicted correctly. The method using only skin temperatures could predict the thermal sensation if it also used the body skin temperature, but it is very difficult to make such measurements.

The reason why the one-dimensional regressive equation (No.3) could not predict the thermal sensation is the nonlinearity between the thermal sensation and the temperatures. Figure 11 shows the relationship between the thermal sensation and the facial skin and interior air temperatures. The relationship was nonlinear. Therefore the predicted values of the thermal sensation does not accurate, especially in the range of very cold and very hot facial skin or interior

Fig. 10 The facial and body skin temperature of the occupant

air temperature, when the one-dimensional regressive equation was used.

On the other hand, the neural network using the interior air temperature (No.2) could predict the thermal sensation in range A, but not in range B. Under the semi-equilibrium condition, such as in range B, the thermal sensation is not always constant, even if the interior air temperature is constant. For example, a person who wears heavy clothes feels warmer than a person who wears normal clothes even when the air temperature is constant. As another example, it can easily be understood that the thermal sensation predicted by the method using only the

Fig. 11 The relationship between the thermal sensation and the facial skin and interior temperatures

interior temperature is incorrect if the occupant has just completed a strenuous activity, because he feels warmer than a person who has done nothing. The neural network using only interior air temperature cannot identify the differences in people's conditions, and therefore cannot predict the thermal sensation. In the case of range B, it is considered that the neural network using only the interior temperature had been adjusted mainly for the summer conditions, which resulted in the prediction of an incorrect thermal sensation under winter conditions when the occupant wore more clothes.

Although facial skin temperature and air temperature were used to predict the thermal sensation of an occupant in our method, factors such as wind velocity and solar radiation, were not considered directly. However, our method could predict the thermal sensation of an occupant correctly, because the influence of those factors are reflected in the facial skin temperature. As mentioned above, the skin temperature is determined by the heat balance between the human body and environment, and the thermal sensation is obtained from the skin temperature. The environmental conditions such as air temperature, wind velocity and solar radiation are considered to influence the skin temperature. For example, when the wind velocity changes, not only the thermal sensation of the occupant but also the skin temperature changes because of the heat balance between the body and the environment. Thus, the thermal sensation can basically be obtained from only the skin temperature. However, we also had to use the air temperature since we used only the facial skin temperature but not the body skin temperature. The influence of wind velocity, solar radiation, etc. is considered via the skin temperature in this method.

The neural network using the facial skin temperature and the interior air temperature is capable of predicting the thermal sensation of an occupant.

5. Control of an Automobile Air Conditioner and Heating System According to the Thermal Sensation of an Occupant

The automobile HVAC was controlled using the predicted thermal sensation and the characteristics of this system were evaluated.

5.1 Method of control

The control of an automobile air conditioner and heating system is as follows.

Step 1. The target of thermal sensation is set based on outside and inside environmental information measured using a sensor, and target facial skin temperature is calculated using Eq. (5) with the target thermal sensation⁽¹¹⁾.

Step 2. The temperatures of the face and compartment are measured and fed into the neural network.

Step 3. The neural network predicts the thermal sensation of a passenger a short time into the future (30 seconds).

Step 4. The air-mixed damper was controlled according to the predicted thermal sensation and the target thermal sensation. The controlled pattern of the air-mixed damper is shown in Fig. 12. For example, if the difference (ΔT_{sv}) between the target thermal sensation and the predicted one is +2, the air-mixed damper is moved for 20% cooling. One hundred percent is defined as the motion between the coldest and hottest air-mixed damper positions.

Step 5. The airflow strength is determined by the facial skin temperature and the target facial skin temperature. The pattern of the airflow strength is shown in Fig. 13.

HVAC system repeats from step 2 to step 5, and controls the thermal sensation of an occupant.

$$T_{skn} = TSV/0.82 + 33.9 \quad (5)$$

T_{skn} : target facial skin temperature

TSV : target thermal sensation

In step 1, we used a linear equation (Eq. (5)) to obtain the target facial skin temperature. The reason

Fig. 12 The controlled pattern of an air mixed damper (100% is the motion between coolest and hottest positions)

Fig. 13 The controlled pattern of airflow strength

why we used a linear equation is as follows. The target thermal sensation is the level at which an occupant feels comfort when the environment in the passenger's compartment is air-conditioned sufficiently and is under an equilibrium condition. The thermal sensation can be obtained from the facial skin temperature when the environment is constant (see range B of No. 1 in Fig. 9). Furthermore, the target thermal sensation is at a neutral level (within ± 2 of the scale used). The relationship around the neutral level under the equilibrium condition between the facial skin temperature and the thermal sensation level can be regarded as linear. According to Ref. (11), the relationship between the facial skin temperature and the thermal sensation level is given by Eq. (5) when the rate of change in facial skin temperature is equal to 0.

The airflow strength, that is, the air velocity, was determined from the difference (ΔT_{sk}) between the measured facial skin temperature and the target facial skin temperature. The target facial skin temperature is the temperature obtained using Eq. (5). According to Ref. (13), the comfortable air velocity depends on the difference between the facial skin

Table 2 Experimental conditions. HVAC system controls the interior environment according to the thermal sensation of an occupant

Subject	Male 22 - 36 years old	
Season	Summer	Winter
Air Temp.	28 °C	-10 - 10 °C
Outside	28 - 50 °C	-10 - 10 °C
Inside	28 - 50 °C	-10 - 10 °C
Solar Radiation	0 - 686 W/m ²	0 - 686 W/m ²
Number of Tests	6 cases	15 cases
Outlet Mode	Face	Foot
do	0.6	0.8

Fig. 14 Target and actual thermal sensation and comfort level (Outside : 28°C, Solar Radiation : 0 W/m²)

temperature and the target skin temperature. Therefore, we used the relationship between air velocity and the skin temperature difference to determine the airflow strength.

5.2 Experiments with subjects

The experiments with subjects were performed to confirm the response of the system. The subjects were four males between the ages of 28 and 36. Their thermal sensation levels according to the 11-category scale are shown in Fig. 8. The 2 000 cc class passenger car was used. The experimental conditions are shown in Table 2.

5.3 Results and discussion

Figure 14 shows the results obtained under summer conditions; the outside and initial inside air temperatures were both 28°C with no solar radiation. The target thermal sensation level was 0 (neutral) for the first 30 min. and -1 (slightly cool) after that. As can be seen in this figure, this HVAC system can control the thermal sensation of an occupant. The lower graph in Fig. 14 shows the comfort level of the occupant. In this HVAC system, the target thermal sensa-

Fig. 15 The air temperature around subject's face (Outside: 28°C, Solar Radiation: 0 W/m²)

Fig. 16 The effect of the subject's condition before getting into the vehicle (Outside: 28°C, Solar Radiation: 0 W/m²)

tion level is very important for the comfort of an occupant. As seen in Fig. 14, the comfort level improved after the target thermal sensation was changed; the neutral level of the thermal sensation was not always comfortable in the case of an automobile. It is necessary to find the optimal thermal sensation level using experimental data of subjects, because the comfortable thermal sensation level depends on the environmental conditions. A fine-tuning function is needed for coping with the preference of the occupant.

In Figs. 15 and 16, the effects of the subject's condition before getting into the vehicle were studied. Two experiments were performed. In experiment 1, a subject stayed for 20 min. in a room in which the air temperature was 35°C before getting into the automobile, and the HVAC system was started. In experiment 2, a subject stayed for 20 min. in a room with an air temperature of 20°C before getting into the automobile, and the HVAC system was started. The air temperature outside the automobile was 28°C with no solar radiation. According to Fig. 15, the air temperature around each subject's face was controlled

Fig. 17 Target and actual thermal sensation level (Outside: 0°C, Solar Radiation: 0 W/m²)

differently. That is, the subject who felt hot from standing in the 35°C room, was air-conditioned cooler and the subject who felt neither hot nor cold from standing in the 20°C room, was air-conditioned slightly warmer. In the case of a conventional HVAC system controlled by the air temperature, the different levels of air conditioning based on the subject's perception could not be produced, and the air conditioning level was always the same because of the environmental condition was constant (see Fig. 15). Our HVAC system changed the air conditioning level based on the subject's perception so that the two subjects felt the same degree of thermal comfort (see Fig. 16). Thus, our HVAC system, which is controlled by the thermal sensation of the occupant, could provide air conditioning appropriate to individual perceptions.

Figure 17 shows the results obtained under winter conditions. The outside air temperature was 0°C with no solar radiation, and the target thermal sensation was +1 (slightly warm). This figure shows that our HVAC system could produce the appropriate thermal sensation of subjects in about 12 minutes. In the case of winter, the airflow was directed to the feet of occupants and did not blow directly onto the body. Therefore it took a long time for the thermal sensation of the subject to reach the target level. However, the thermal sensation of the subject remained constant after 12 minutes.

6. Conclusion

The following conclusions were obtained from the experiments.

1. By using the transitions of the facial skin temperature of an occupant and the air temperature inside the vehicle, the neural network is capable of predicting the transition of the occupant's thermal

sensation. The mean error between the thermal sensation level of an occupant and the thermal sensation level predicted by this method was within 0.5 unit of the scales used.

2. The relationship between the thermal sensation and the temperature was nonlinear. Therefore the one-dimensional regressive equation could not be used to predict the thermal sensation. The method using only the facial skin temperature could not be used to predict the thermal sensation. The interior air temperature, that indirectly expresses the thermal sensation of the body, is needed to predict the thermal sensation correctly.

3. By using the thermal sensation predicted with the neural network, a HVAC system capable of controlling the thermal sensation of occupants was developed.

4. The HVAC system is capable of controlling the interior environment based on the thermal condition of an occupant, and can regulate the temperature to be cooler for an occupant who feels hot, and warmer for an occupant who feels cool.

5. In this HVAC system, knowing the target thermal sensation is very important for obtaining the comfort of the occupant. If an unsuitable target thermal sensation were set, comfort could not be obtained. The comfortable target thermal sensation depends on the environmental conditions. It is necessary to determine the comfortable target thermal sensation levels for each set of environmental conditions through experiments with subjects. Furthermore, a fine-tuning function is needed on the HVAC system for coping with the preferences of the subject.

References

- (1) Ishimaru, T. and Kataoka, M., Present Status and Future of Automotive Air Conditioning Systems, *Jour. Soc. Auto. Eng. Jpn.* (in Japanese), Vol. 36, No. 1 (1982), p. 19.
- (2) Yamaoka, F., *Jidousha air-con no Kandokoro*, (in Japanese), ISBN 4-88543-015-1 (1993), Testudo Nihon Sha.
- (3) Yoshida, K., Naka, M., Akamine, I. and Fujiwara, K., Neural Network Controlled Air Conditioner—Comfort Level Control with Neural Network—, National Technical Report, (in Japanese), Vol. 37, No. 6 (1991), p. 639.
- (4) Mistry, S.I. and Nair, S.S., Nonlinear HVAC Computations Using Neural Networks, *ASHRAE Trans. : Symposia* (1993), p. 775.
- (5) ISO 7730, Moderate thermal environments—Determination of the PMV and PDD Indices and specification of the conditions for thermal comfort.
- (6) Fanger, P.O., *Thermal Comfort: Analysis and Applications in Environmental Engineering*, (1972), New York, McGraw-Hill Book Co.
- (7) Hensel, H., *Thermoreception and Temperature Regulation*, (1981) : Academic Press, London.
- (8) See for example, Sejnowski, T.J. and Rosenberg, C.G., Parallel Networks that Learn to Pronounce English Text, *Complex System 1* (1987), p. 145.
- (9) Ueda, M., Ohno, Y., Taniguchi, Y. and Aoki, H., A New Method Using Neural Networks to Evaluate the Thermal Sensation of an Automobile Occupant, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 58, No. 545, B(1992), p. 254.
- (10) Ueda, M., Ohno, Y., Taniguchi, Y. and Aoki, H., A New Method Using Neural Networks to Evaluate the Transitional Thermal Sensation of an Automobile Occupant, *SAE 92 Transaction*, Vol. 6, No. 101 (1992), p. 187.
- (11) Taniguchi, Y., Aoki, H., Fujikake, F., Tanaka, H. and Kitada, M., Study on Car Air Conditioning System Controlled by Car Occupants' Skin Temperature—Part 1: Research on a Method of Quantitative Evaluation of Car Occupants' Thermal Sensations by Skin Temperatures, *SAE paper*, No. 920169 (1992).
- (12) Rumelhart, D.E., Hinton, G.E. and Williams, R.J., Learning Representations by Back-propagating Errors, *Nature*, Vol. 322 (1986), p. 533.
- (13) Tanaka, H., Kitada, M., Taniguchi, Y., Ohno, Y., Shinagawa, T. and Aoki, H., Study on Car Air Conditioning System Controlled by Car Occupants' Skin Temperatures—Part 2: Development of a New Air Conditioning System., *SAE paper*, No. 920170 (1992).