

# Using a Driving Game to Increase the Realism of Laboratory Studies of Automobile Passenger Thermal Comfort

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## ABSTRACT

The thermal comfort of automobile occupants depends on many complex heat exchanges, and it follows that many comfort research projects are done in laboratories, where conditions can be more readily controlled and the human subjects closely monitored. The laboratory setting, however, may appear unrealistic to a subject because it does not move and it does not afford the experience of driving or being a passenger. This could affect the research results if the test subject's level of exertion were inappropriate, or if the unrelieved focus on comfort questionnaires caused the subject to be unduly sensitive to his or her thermal comfort. In a recent laboratory study, a computer driving game was used as an inexpensive way to increase the realism for the subjects, and this paper examines the physiological effects of using the game. The metabolic rates of subjects playing or watching the game were found to be very close to their rates when driving or riding in a real car. The method used is new and may be of equal interest for vehicular research: the metabolic rates were estimated from heartbeat data, which can be conveniently obtained from portable and non-intrusive fitness monitors.

## INTRODUCTION

Passengers in automobiles often experience highly variable thermal stimuli due to the effects of the sun, the temperatures outside, and the operation of the car's HVAC (heating, ventilating, and air conditioning) system. The HVAC systems are designed to bring the interior to a comfortable level quickly, and then to counteract thermal asymmetries, by circulating air to various areas of the cabin. How these systems affect a passenger's perception of comfort is an ongoing subject for research.

In recent years researchers have examined subjects in thermally realistic automobile mockups, with the purpose of defining the comfort effects of such automotive surroundings.

## BACKGROUND

In Jan-July 2002, a study of comfort effects of asymmetrical and transient thermal environments was carried out in a controlled environment chamber. Heated or cooled air was circulated around different parts of the body through a specially designed set of fabric air sleeves (Figure 1). Rapid changes in air and skin temperature could be introduced in this way.



**Figure 1. Controlling arm skin temperature**

Subjects' skin and core temperatures were measured, and their subjective reactions (opinions) surveyed throughout the tests. The relationships between the body-segment temperatures and subjects' perceptions are being incorporated in a computer model for predicting human thermophysiology and comfort [1].

It is important that such predictions be applicable to automobile drivers and passengers, rather than to subjects seated in a laboratory chamber. Human reaction to the thermal environment is affected by at least two factors: level of physical activity, and level of psychological attention to the thermal environment.

Expanding on these factors:

- Activity level affects the physiological heat balance of the body by determining the metabolic rate. The higher the metabolic heat generation, the lower the environmental temperature at which a subject will be comfortable, and so in laboratory comfort studies the subjects should exercise to a realistic activity level [2]. Metabolic rate is traditionally measured in watts per unit of body surface area ( $W/m^2$ ), with a special unit, the *met*, based on the rate of a person quietly sitting at rest,  $58 W/m^2$ . (For example, a person with a surface area of  $1.72 m^2$  generates 100 W when resting at met 1). Metabolic rates cited for automobile occupants are 1 met for passengers [3], and for drivers, a range of 1 to 1.6 met [4, 5] and 1 to 2 met [6].
- The psychological attention to the thermal environment is likely to be different between a laboratory situation, where subjects are only asked to focus their attention on the thermal environment, and in actual driving, where their minds are engaged with the task of driving. Attention to the road or traffic could make them less sensitive to the thermal environment, or possibly more so. (For example, in mental tasks involving concentration and problem solving, discomfort can interrupt the train of thought and make the discomfort more noticeable [7]. It is probable that driving involves a type of focus different from concentrated problem-solving, but this, and how it affects a driver's attention to thermal environment, does not appear to be discussed in the literature).

Two approaches are commonly used to evaluate thermal comfort in automobiles: thermal manikin measurements and human subject tests. Thermal manikins are used to measure the heat losses to a given environment and to calculate the Equivalent Homogeneous Temperature (EHT), the temperature of a uniform environment producing the same heat losses [8]. A limited number of comfort criteria have been published for EHT [9]. Human subject tests on the other hand directly obtain the subjects' subjective perceptions of the thermal environment. A review of such tests in the literature found no examples in which the driving experience was actively simulated. Hagino and Hara [10] used a mock-up car in an environmental chamber in which seated human subjects answered thermal comfort questionnaires. Taniguchi et al. [11] examined the relationship between thermal comfort and face skin temperature, in which the human subjects sat in a simulated car environment with no driving activity. Kataoka [12] tested an actual car in a wind tunnel in which the subjects sat as passengers and recorded their thermal comfort. None of these studies involved driving simulation, either in terms of moving visual scenery or in the physical act of driving.

In recent years, computer driving games have become available. Some of these involve navigation and racing tasks, and have very natural scenery and driving characteristics. They might serve to improve the realism of laboratory studies of thermal comfort in vehicles.

Steering wheels and foot pedals for accelerator and brake are now inexpensively available for such games. They are typically clamped to the table in front of the computer monitor. The fancier steering wheels involve a 'force-feedback' feature where the wheel's turning resistance varies with driving conditions. Bumps in the simulated road are transmitted through to the wheel. The extent of this feedback can be adjusted in the wheel's software, and can be adjusted to provide a very realistic feel.

In the current laboratory comfort study mentioned above, some subjects occupied themselves with a computer driving game as they were exposed to the experiment's various thermal conditions. Figure 2a shows the setup of the game. As the subjects drove through set road courses, the game would periodically be interrupted by thermal sensation or comfort questions on an analog scale superposed on the screen (Figure 2b). The subject would use the mouse to move the slider to the appropriate spot on the scale, click, and the scale would disappear and the driving game would resume automatically. The subjective vote would be stored on the computer together with the simultaneously measured physiological data (skin and body core temperatures).

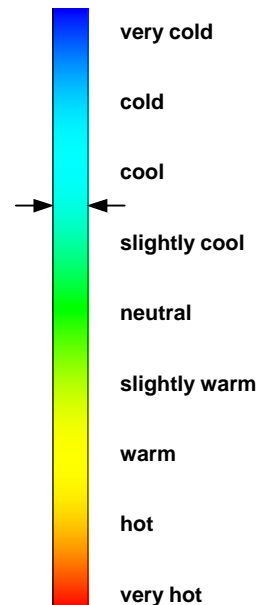
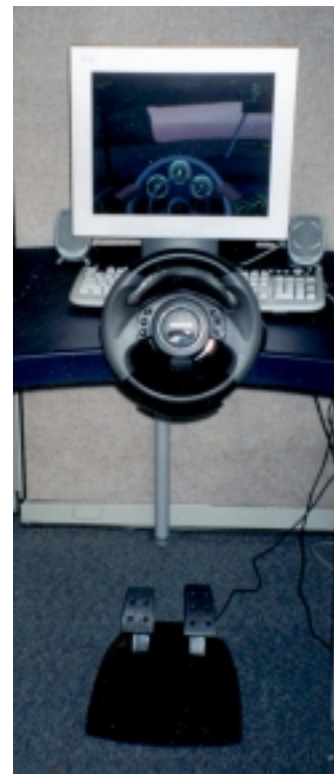


Figure 2b. Thermal sensation scale that periodically appears on the screen.

Figure 2a. Laboratory installation of driving game.

It was not possible for us to scientifically examine the psychological effects of playing the game. We can report that our subjects reported that the attention demanded, and distraction provided, by the game felt very similar to that of actual driving. We hope that this reduced the subjects' focus on their thermal state to a realistic extent.

## METHOD

This paper examines the physiological match between the simulated driving and actual driving by comparing the metabolic rates required for each. First we will describe our game setup in more detail:

### Test program

We initially researched several driving simulation games, attempting to choose one with the best graphics and the most realistic physics. We avoided games with police chases, explosions, etc., even though most of the available games are of this sort, because we wanted the game to focus primarily on driving itself. "Need for Speed" by Electronic Arts stood out as being able to represent a pleasant and not necessarily arduous driving experience. The scenery in this game is realistic, and the software supports the steering wheel and throttle feedback. The difficulty level can be adjusted. These experiments were done with the game set to a low level of difficulty, but set to include traffic in the oncoming direction.

We also purchased a 'force-feedback' computer steering wheel and pedals for use with the game, and tuned it to a realistic level of sensitivity by adjusting the settings in the wheel's control software. The subjects sat in a mesh chair in front of a 17.5" (diagonal) display on a table, with the steering wheel attached to the front edge and the pedals beneath.

Metabolic rate is usually measured by oxygen consumption, which requires a breathing mask and a set of relatively large and immovable equipment [4]. We needed another approach to do this study, because the subjects would be driving in an actual car. We used a heartbeat monitor (a common fitness product) strapped to the chest to measure subjects' physiological activity, with the monitor reporting through a wireless link to a wearable datalogger at the waist. The heart rate was used to calculate the metabolic rate through a procedure described below.

The three authors were the subjects in this study. They performed the following activities: sitting quietly to establish their baseline heart rates, driving the actual car (Figure 3a) on two types of roads (city and freeway), driving the game (figure 3b), sitting as passengers in the actual car and in the lab, and--for general comparison--doing computer work (surfing the web or typing) in the lab.



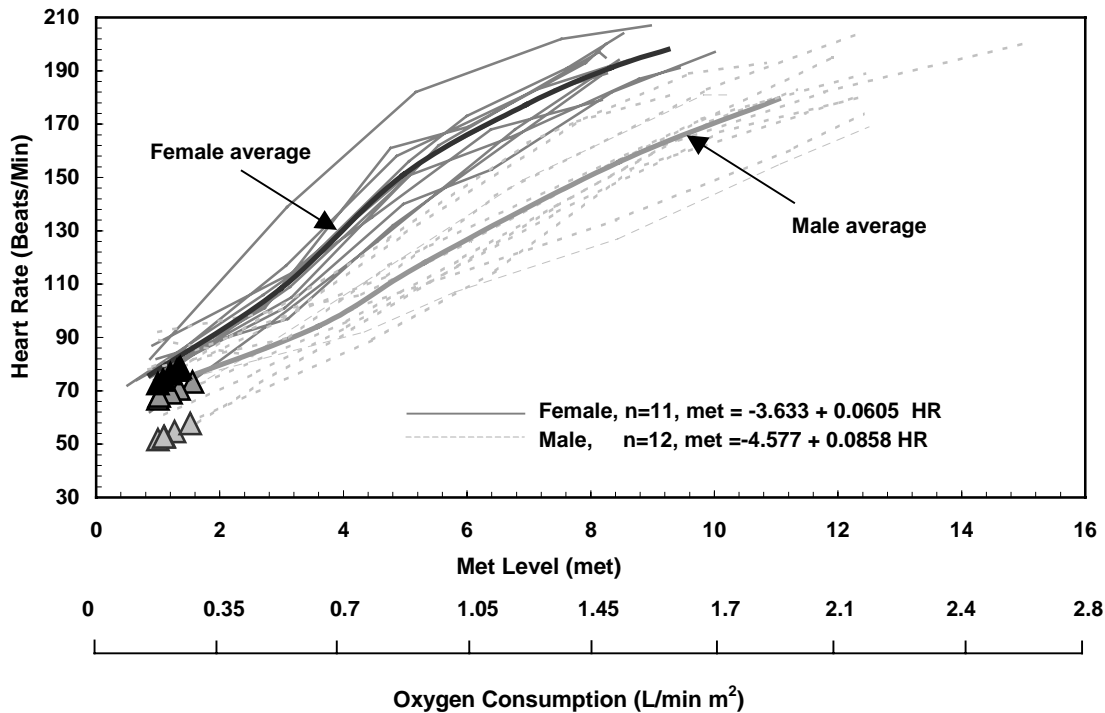
**Figures 3a and 3b. Driving in the real car and in the game.**

### Metabolic rate determination

We needed the subjects' relationships between heartbeat rate and metabolic rate to determine the metabolic cost of these various activities. We could not find such relationships in the literature. However, Dr. Richard Gonzalez of the U.S. Army Research Institute for Environmental Medicine (USARIEM) was able to provide new experimental data giving the relationship between the heart rate and measured oxygen consumption for 21 subjects. The subjects, 11 females and 12 males, had their respired oxygen consumption measured as they rode a stationary exercise cycle at levels ranging from resting to maximum exertion. We converted the oxygen consumption into metabolic rate as follows.

When proteins, carbohydrates, and lipids are burned, the gaseous exchange in W h per liter of oxygen is: 5.86 for carbohydrates, 5.51 for lipids, and 5.18 for protein. An average mixed diet produces 5.52 W h per liter of oxygen [13]. This allows us to convert the body's rate of oxygen consumption into the whole-body metabolic rate in W, which is often expressed per unit body surface area ( $W/m^2$ ). This can be converted to met units by dividing by the met unit definition ( $58 W m^{-2}/met$ ). This produces the scales on the x-axis of Fig. 4.

## Heart Rate vs. Met Level



**Figure 4. Heart rate versus metabolic rate and oxygen consumption**

Regression of the USARIEM heart rates versus metabolic rates yields:

For females,  $\text{met (met)} = -3.633 + 0.0605 \text{ HR}$   
 $(R^2=0.94)$  Eq(1)

For males,  $\text{met (met)} = -4.577 + 0.0858 \text{ HR}$   
 $(R^2 = 0.91)$  Eq(2)

Figure 4 demonstrates individuals having different base level heart rates, but with the slopes of the individual lines being very close once males and females have been separated. Therefore, an individual's heart rate versus met rate can be estimated by using the slope for the individual's gender as in Equations (1) and (2), and adjusting the Y-intercept value. This is done by measuring the heart rate of each subject while at rest, which by definition is 1 met, and manipulating algebraically:

For females, the individual intercept =  $1 - 0.0605 \text{ HR}_{\text{rest}}$   
 Eq(3)

For males, the individual intercept =  $1 - 0.0858 \text{ HR}_{\text{rest}}$   
 Eq(4)

Equations (1) through (4) provide a simple way to calculate the met level. The only parameter needed is the heart rate, which can be obtained relatively easily.

## RESULTS

### Metabolic rate for driving

Our measured heart rate results are shown in Tables 1a and 1b. The ratios of driving-to-resting heart rates tend to be relatively small, in the vicinity of 110%.

**Table 1. Heart rate measurement summary**  
**A. Heart rate (Beats/min)**

Subject	Resting	City Drive	Freeway	Driving Game	Car Passenger	Game Passenger	Computer
Cmale	66.9±4.9 (82)*	73.3 ±5.1 (92)	70.7±5.5 (40)	69.3±5.3 (51)	67.1±4.6 (100)	68.5±4.6 (11)	66.9±5.4 (200)
Emale	51.7±3.8 (271)	55.0±3.7 (86)	52.8±2.4 (83)	57.7±2.9 (29)	51.7±1.7 (66)	52.7±1.7 (14)	51.9±2.7 (152)
Hfemale	72.7±1.6 (51)	78.7±6.2 (81)	77.8±2.9 (140)	78.3±3.3 (46)	73.3±3.1 (42)	74.1±4.4 (15)	76±4.4 (180)

\* In 66.9±4.9 (82), 66.9 is the average heart rate, ±4.9 is the standard deviation, and 82 is the sample size. This format applies to the entire table.

## B. Heart rate ratio to resting

Subject	Resting	City Drive	Freeway	Driving Game	Car Passenger	Game Passenger	Computer
Cm	1	1.10	1.06	1.04	1.00	1.02	1.00
Em	1	1.06	1.02	1.12	1.00	1.02	1.00
Hf	1	1.08	1.07	1.09	1.01	1.02	1.05

**Table 2. Metabolic level (met)**

Subject	Resting	City Drive	Freeway	Game	Car Passenger	Game Passenger	Computer
Cm	1	1.56	1.34	1.21	1.02	1.08	1.00
Em	1	1.27	1.10	1.52	1.00	1.09	1.03
Hf	1	1.36	1.31	1.34	1.03	1.08	1.20

Table 2 shows the metabolic rates for the different types of driving in our test, calculated by applying Equations 1 through 4 to the measured heart rate shown in Table 1A. These results are also shown in Figure 4 as the triangles, black for female and gray for male. Because our test is for driving, with its relatively low exertion requirements, the met levels are all located at the lower end of the Figure 4 plots.

It can be seen from Table 2 that the ratio of driving-to-resting metabolic levels is higher than that of heart rates, ranging up to 156%.

For drivers, the metabolic rates for the game, the real car on the freeway, and in the city ranged from about 1.1 to 1.56, significantly higher than resting (two-tailed t-test,  $p < 0.01$ ). For all three subjects, the city driving required more metabolic effort than freeway driving ( $p < 0.001$ ). The computer game caused a range of metabolic rates slightly larger than the range for real driving in city and freeway. It seemed to be a function of computer game experience: the oldest subject (Em, age 60) had his highest metabolic rate playing the game, while for the youngest subject (Cm, age 18) the game required the lowest rate. For all subjects, the metabolic rates found for driving the actual car on the freeway and in the city match the values provided in [4] and [5]. We conclude that the game provides a good simulation of the metabolic rates in real driving.

Non-driving passengers in the actual car and the game were found to have metabolic rates between 1. to 1.1 met, close to the value 1 met provided by [3]. These sedentary activities are not significantly different from resting. For work on the computer, the metabolic rate was close to resting and lower than that of real or game driving.

### Validation of Equations (1) through (4)

a) Brooks [13, p. 284] provides the heart rate, the heart stroke volume, and the arteriovenous oxygen difference [(a-v) $O_2$  difference] of a 30-year-old man during a standard Bruce treadmill test at rest, stage1, stage2, stage3, and maximum. Table 4 compares the metabolic

rates derived from these values to the metabolic rates obtained from Equations 2 and 4.

Multiplying Brooks' three physiological parameters, we obtained the oxygen consumption of the whole body. Dividing by the body weight (assuming 75 kg), and dividing by the 3.5 ml  $kg^{-1}$  of body weight per minute of oxygen uptake (which corresponds to 1 met), we obtained the measured metabolic rate during the treadmill test, as listed in the 2<sup>nd</sup> column of Table 4. We applied the resting heart rate to Eq [4] to get the intercept for that person. Then we applied both this intercept and the measured heart rate to the regression Eq [2] to get the predicted metabolic rate shown as the 3<sup>rd</sup> column. In general the measured and the predicted metabolic rate are close, except for Stage1.

**Table 4. Comparison of met measured from  $O_2$  uptake and met predicted from heart rate, through the stages of a standard Bruce treadmill test**

Stage	Measured by $O_2$ uptake	Predicted by HR
rest	1.1	1
Stage1	4.6	5.4
Stage2	7.5	8.0
Stage3	10.0	9.8
maximum	11.7	11.0

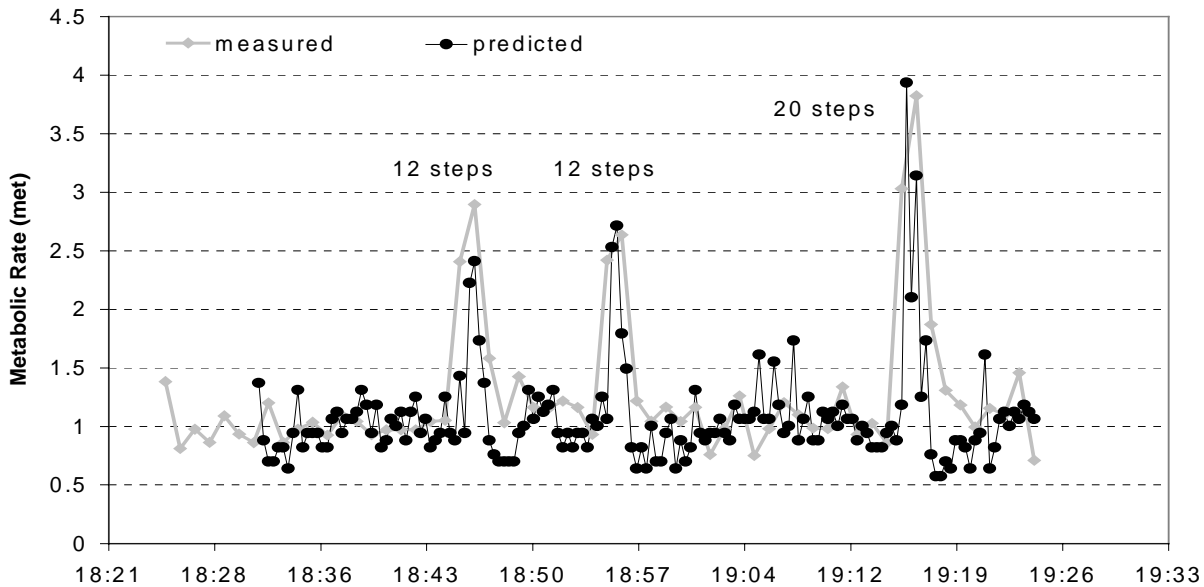
b) Brooks [13, p.253] also provides the heart rate vs. power output for a 20-year-old male. The test condition progressed from rest to 90% of maximum respired oxygen volume ( $VO_{2max}$ ). We compared the measured metabolic rate by assuming a work efficiency of 0.17, with the calculated metabolic rate from Eq [2]. The comparison is shown in Table 5.

**Table 5. Comparison of measured met (converted from workload) and predicted met (from hr) during rest and exercise**

	Converted from workload	Predicted by HR
rest	1	1
Stage1	2.8	3.7
Stage2	6.1	6.1
Stage3	11.7	10.4

c) In the third validation, we measured subject Hf's metabolic rates via the  $VO_2$  method in the Exercise Physiology Laboratory at UC Berkeley. The test

consisted of 20 minutes resting, followed by two 12-step exercises separated by a 10-minute interval, followed by a 20-step exercise after 20 minutes. We measured heart rates in a second test, from which the same metabolic rates can be predicted via Eq [1]. The comparison between the measured metabolic rate and the predicted metabolic rate is shown in Figure 5. In general, the peak metabolic rates are close. The rates predicted from HR drop faster than the measured values. This is probably because the heart's stroke volume increases during exercise, and does not decrease as rapidly after exercise as the HR itself. Excluding such highly transient periods, the HR method works very well. Both methods predict the resting metabolic rate (before the first 12 steps) to be 1 Met. During the second resting period (before the 20 steps) the HR method predicts 1.08 compared to 1.04 for the oxygen consumption method.



**Figure 5. Comparison of measured ( $O_2$  consumed) versus predicted (HR equation) metabolic rates**

## DISCUSSION

We must assume, in applying the two regressions to obtain metabolic rate from heart rate, that the subjects' resting metabolic rate is 1 met, and that they follow the slope of the two regression lines. This seems warranted, given the colinearity of the data in the USARIEM plots.

Individuals' resting rates do vary with lack of sleep, stress, and other factors. To use the heart rate method, it is desirable to establish the resting rate each time a metabolic rate test is done. Fortunately this only takes 2 to 3 minutes, because the heart rate reacts very quickly to change in activity, and one can see in the successive measurements when the resting heart-rate value is reaching steady state.

Although the study was small, it does demonstrate that playing a realistic driving game produces a similar metabolic rate as city and freeway driving, significantly different from the resting rate. Conversely, both the actual and the game-watching non-driving passengers had metabolic rates indistinguishable from resting, suggesting that traditional laboratory test techniques are appropriate for non-driving passengers.

We could not detect any metabolic effect of the lateral and vertical accelerations that occur during real driving but not in the computer driving game. This suggests that it is not necessary to include realistic accelerations in laboratory simulations of normal vehicle driving.

We also found that music can affect the heart rate by as much as 5 beats per minute. It makes sense to keep the test environment reasonably constant during metabolic rate determinations.

## CONCLUSION

We found the metabolic level of subjects performing the driving game to be similar to that of actual driving on the road. The metabolic difference between sitting quietly and playing the game is on the order of 40%, so it can be a significant effect for laboratory studies. We conclude that computer driving games with steering wheels and pedals can usefully increase the physiological realism of laboratory studies of drivers' thermal comfort in automobiles. The psychological realism of driving games may also help such studies by reducing the subjects' focus on the thermal test conditions, but that could not be evaluated here

A convenient mobile method was developed to obtain metabolic level by measuring heartbeat rate. Two regression equations are provided for females and males, respectively. In using them, one must also measure individual subjects' resting heart rates to establish their 1-met intercepts, since this varies considerably among individuals. Because it is easy to measure and record heart rate, this method can be applied to many vehicular test situations where measuring the actual oxygen consumption would be inconvenient if not prohibitively difficult.

## ACKNOWLEDGMENTS

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## DEFINITIONS

The unit of metabolic activity is the *met*, where 1 met is the activity associated with resting quietly in a seated position, defined as 58 watts/square meter of body surface area.