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Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach

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ABSTRACT

How much fuel does vehicle air conditioning actually use? This study attempts to answer that question to determine the national and state-by-state fuel use impact seen by using air conditioning in light duty gasoline vehicles. The study used data from US cities, representative of averages over the past 30 years, whose temperature, incident radiation, and humidity varied through time of day and day of year. National surveys estimated when people drive their vehicles during the day and throughout the year. A simple thermal comfort model based on Fanger's heat balance equations determined the percentage of time that a driver would use the air conditioning based on the premise that if a person were dissatisfied with the thermal environment, they would turn on the air conditioning. Vehicle simulations for typical US cars and trucks determined the fuel economy reduction seen with AC use. Combining these statistics and models with vehicle and truck registrations and vehicle miles traveled resulted in a state-by-state estimate of fuel used for air conditioning in vehicles. The study showed that the US uses 7.1 billion gallons (27 billion liters) of gasoline every year for air conditioning vehicles, equivalent to 6% of domestic petroleum consumption, or 10% of US imported crude oil.

INTRODUCTION

Vehicle air conditioning loads are the most significant auxiliary loads present in vehicles today. The AC energy use even outweighs the energy loss to rolling resistance, aerodynamic drag, or driveline losses for a typical 27-mpg (8.7-l/100km) vehicle, as shown in Figure 1. An air conditioner compressor can add up to 5-6 kW peak power draw on a vehicle's engine. This power draw is equivalent to a vehicle driving steady state down the road at 35 mph (56 kph).

The fuel economy of a vehicle drops substantially when the AC compressor load is added to the engine. The effect is larger with higher fuel economy vehicles. Figure 2 shows both simulations and test data [1, 2] of the SC03 fuel economy for a variety of vehicles (a conventional 1X—see Definitions, the Toyota Prius, the Honda Insight, a 3X Hybrid, and a Fuel Cell Hybrid) with a varying auxiliary load. For a conventional 1X vehicle, using the AC increases fuel consumption by 35% (or drops fuel economy by 26%). For the Honda Insight, using the AC increases fuel consumption 46%. For a 3X Hybrid, using the AC increases fuel consumption 128%.

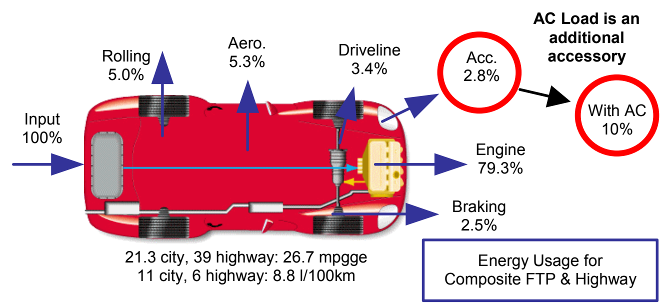

Figure 1: Percent Vehicle Energy Uses/Losses in a Conventional 27-mpg (8.7-l/100km) Vehicle

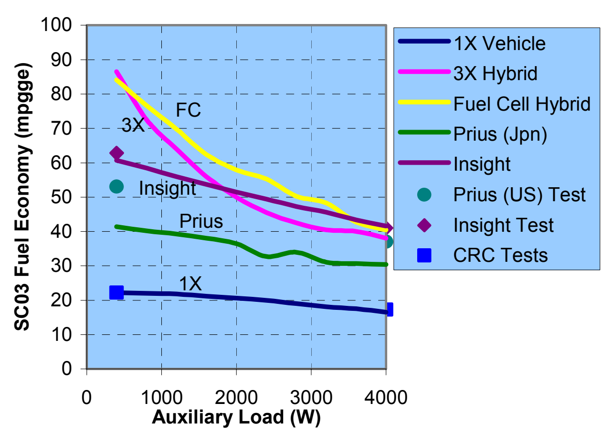

Figure 2: Fuel Economy vs. Auxiliary Load: Simulations and Test Data (Tests are with AC on, actual kW load unknown)

If all drivers used the AC all of the time, the fuel used for AC in the US would be very large. Of course, if everyone lived in northern Alaska and never turned on the air conditioning, this fuel use penalty would never be seen. This study, therefore, attempts to quantify when drivers use the air conditioning, including local weather effects and locations of population centers to estimate how much fuel the US uses for air conditioning. This approach is based on the thermal comfort of a driver and is an improvement over previous studies that relied on a single constant AC use percentage for every location in the US.

The purpose of this study was to determine the magnitude of energy used for creating thermally comfortable cabins in vehicles. Once this magnitude is known, optimization of vehicle cabins or air conditioning systems have an established metric of impact. Ways to reduce the amount of energy used for cabin environment control are multiple and include optimized conventional AC systems, advanced window glazings for reduced peak cabin soak temperatures, localized cooling, or use of alternative cabin cooling such as heat generated cooling via exhaust gases [3].

THERMAL COMFORT APPROACH FOR ESTIMATING VEHICLE AC FUEL USE

This study used a bottoms-up approach to estimate the fuel used in vehicles for air conditioning for a given year. A simple thermal comfort model determined the percentage of time that a driver used the air conditioning. The thermal-comfort link was based on the premise that if a person were dissatisfied with the thermal environment, they would turn on the air conditioning. The thermal comfort results were then combined with statistics on when people drive, where they live, and how far they drive in a year. Finally, vehicle simulations determined the fuel use penalty of using the air conditioning in cars and trucks. This algorithm determined the fuel used for air conditioning in light-duty vehicles.

TYPICAL METERORLOGICAL YEARS – A Typical Meteorological Year (TMY) is a catalog of expected environmental conditions in a given city. This data is a part of the National Solar Radiation Data Base (NSRDB) based on measurements from National Weather Service stations in 239 cities across the US over a period of 30 years (1961-1990) [4]. The cities with available data are shown in Figure 3.

The environmental conditions used in this study are dry bulb temperature (°C), humidity ratio (kg/kg of water vapor / dry air), and direct and diffuse integrated radiation (Wh/m^2).

The NSRDB data contains environmental parameters for every hour and every day of the year. The data for a given month is actual data from a month of the 30-year set. Each typical month was selected based on temperature, humidity, wind velocity, and radiation comparisons to the 30-year averages. The typical months are then concatenated, with 6-hour smoothing at the interfaces, to form a year. TMY data are within 2% of the 30-year averages.

Figure 3: TMY Cities

Figure 4 shows the subset of the TMY Cities with populations greater than 100,000 people, or at least one city per state, used in this study. This down-selecting allowed focus in the areas where most of the vehicles were in operation.

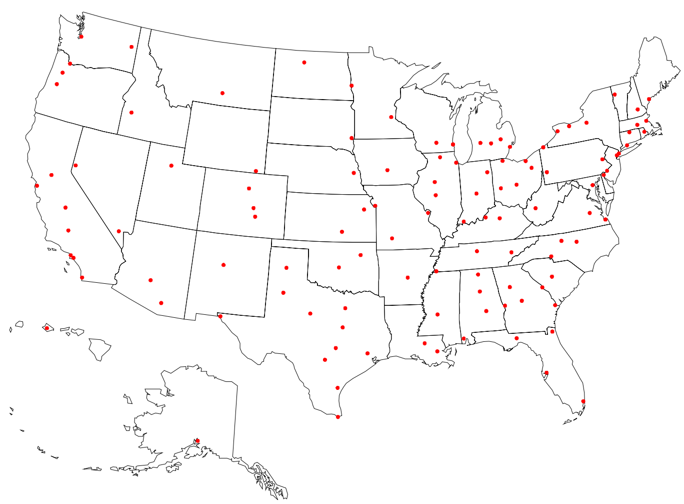

Figure 4: 116 Cities Used in AC Fuel Use Study: TMY Cities with >100,000 People

Ambient Temperature – Sample temperature values as they vary with time of day and month of the year in Denver and Phoenix are shown in Figure 5 and Figure 6. The figures show temperature differences between months and throughout the day. For example, Denver just reaches 25°C (77°F) during mid-day (1-4 pm) in June, while Phoenix is above 35°C (95°F).

Humidity Ratio – Sample values for humidity ratio as they vary with time of day and month of the year in Denver and New Orleans are shown in Figure 7 and Figure 8. The humidity ratio in the graphs is expressed in g/kg instead of kg/kg for clarity purposes. New Orleans is seen to have over twice the specific humidity as Denver (e.g. 18 g/kg vs. 9 g/kg).

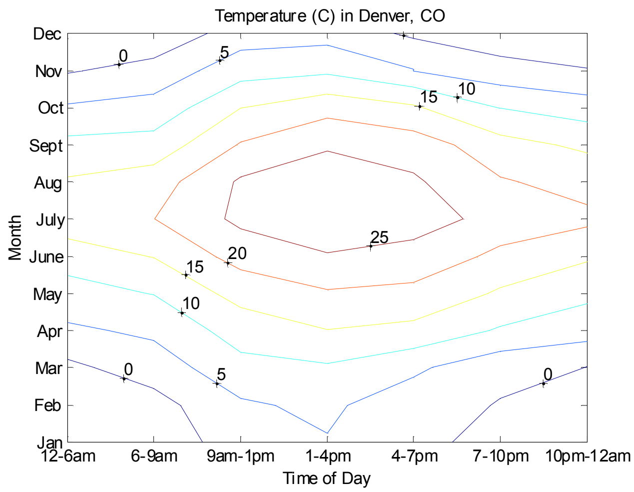

Figure 5: Denver, CO Temperature vs. Time of Day and Month

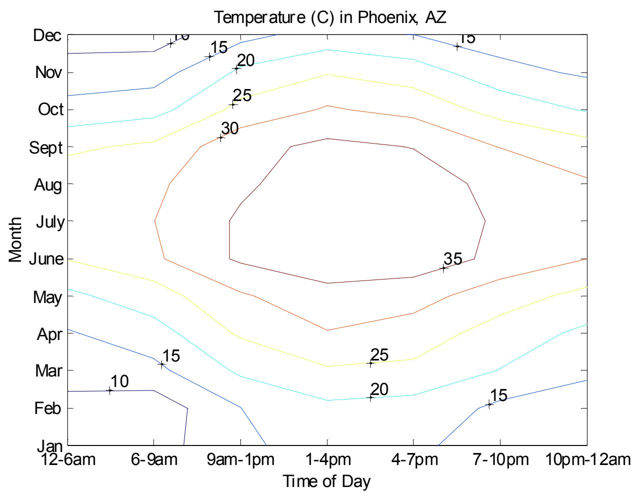

Figure 6: Phoenix, AZ Temperature vs. Time of Day and Month

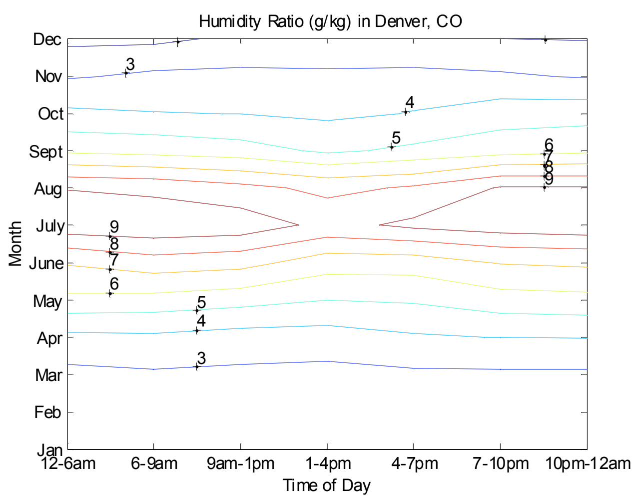

Figure 7: Denver, CO Humidity Ratio vs. Time of Day and Month

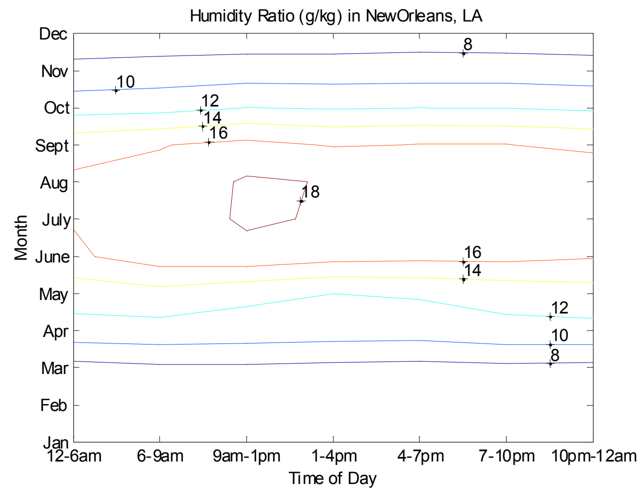

Figure 8: New Orleans, LA Humidity Ratio vs. Time of Day and Month

<u>Mean Radiant Temperature</u> – One of the derived inputs used in the thermal comfort model is mean radiant temperature (MRT). MRT is defined as the uniform black body surrounding temperature to which a person would exchange the same amount of heat as they do in the actual non-uniform thermal environment.

The value for MRT in a vehicle can be a variety of temperatures. In order to see how the magnitude of fuel used for air conditioning varied with changing MRT, two extreme cases were considered. On the low temperature side, the MRT could be ambient temperature, e.g. if the car were parked in a garage. On the high temperature side, the MRT could be significantly above ambient at a soak temperature, e.g. if the car were sitting in the sun for hours.

Various vehicle tests performed by NREL [5] showed that during soak tests in Phoenix, AZ, window and vehicle trim temperatures reached 17°C above ambient temperature at 3 pm. The integrated solar radiation up to 3 pm that day was 6.8 kWh/m^2. In other words, 6.8 kWh/m^2 of energy entering a vehicle caused the thermal mass of the cabin to increase by 17°C (see Figure 9). The effect of color on interior mean radiant temperature is negligible (within 2°C), even though exterior roof temperatures may vary 20°C.

Using the integrated radiation incident on a given city (see Figure 10), the expected temperature rise above ambient in a soaked vehicle up to that point in the day was calculated as follows, with a saturated radiation input at 3 pm:

$$MRT(t) = T_{ambient} + \frac{17°C * \int_0^t SolarRadiation\,[Wh/m^2]}{6800\,[Wh/m^2]}$$

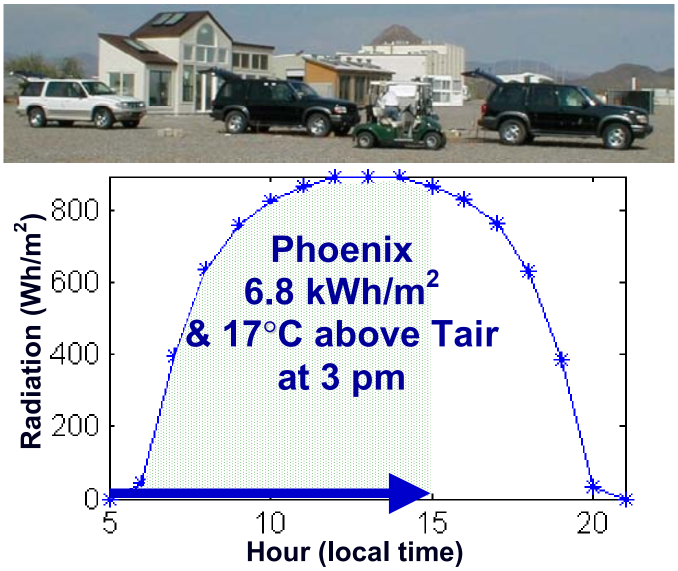

Figure 9: Reference Solar Radiation and Vehicle Temperature Rise in Phoenix, AZ

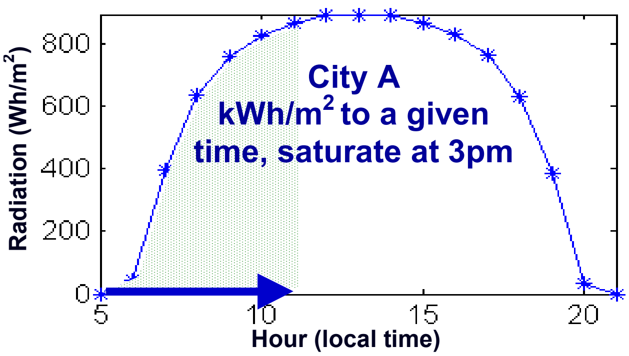

Figure 10: Incident Solar Radiation for City A Integrated through Time

This estimate for MRT, representing expected window and trim temperatures, is fairly conservative for the following reasons:

- The vehicles used for the 17°C estimate were large vehicles. Smaller vehicle would have lower cabin mass and air volume (e.g. 2 m^3 vs. 3.5 m^3) such that the temperature rise for a given amount of incident radiation could be larger than 17°C.
- Additional vehicle soak tests in Colorado showed a similar ratio of temperature rise above ambient over incident radiation, though slightly greater in magnitude (within 10%). For example, the $\Delta T/\text{Radiation}_{\text{Phoenix}}$ = 17/6.8 = 2.5°Cm^2/kWh, and $\Delta T/\text{Radiation}_{\text{Golden}}$ = 20/7.2 = 2.78°Cm^2/kWh, or 11% above the Phoenix data. The lower value was used, to avoid over-predicting MRT.
- Instrument panel temperatures may rise significantly above this average MRT (e.g. up to 100°C absolute), and depending on the geometry of the vehicle, could have an elevating influence on the MRT. Figure 11 shows the range of cabin temperatures, the average cabin temperature, ambient, and the MRT model for a soak condition. Instrument panel temperatures are greater than the cabin average by ~15°C. Figure 12 shows that the model MRT is slightly lower than the average experimental cabin and air temperatures, thus representing a conservative MRT estimate.

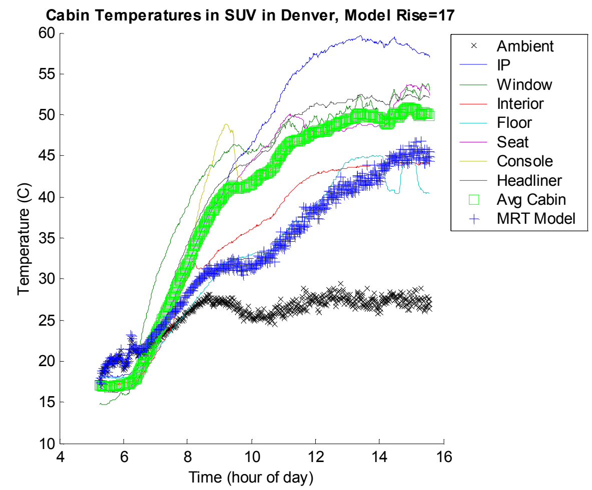

Figure 11: SUV Cabin Soak Temperatures and Model MRT in Golden, CO, June 28, 2001

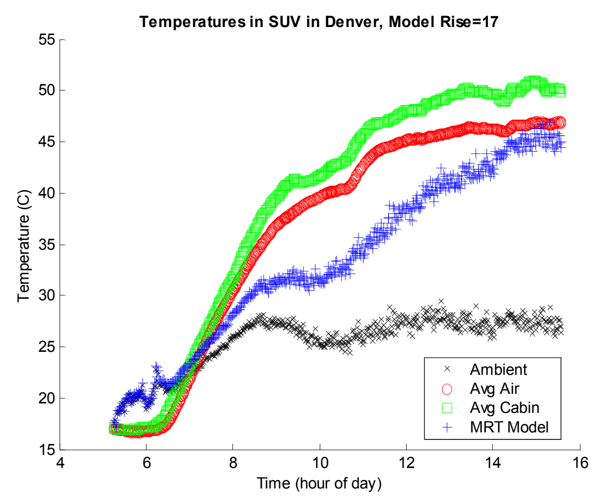

Figure 12: Average SUV Soak Temperatures and Model MRT in Golden, CO, June 28, 2001

Figure 13 and Figure 14 show sample values for MRT in a soaked vehicle, as they vary with time of day and month of the year in Denver and Phoenix. Phoenix MRT soak temperatures exceed 50°C (122°F) for a large portion of the summer. Denver soak temperatures reach 40°C (104°F) for a small portion of the summer and on average are 15°C lower than Phoenix soak temperatures.

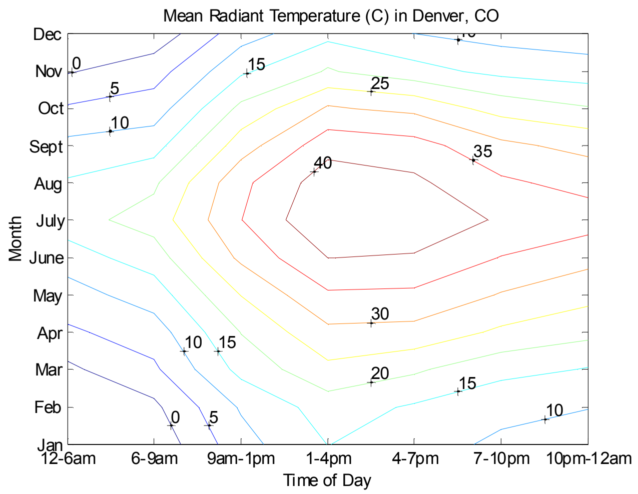

Figure 13: Denver, CO MRT vs. Time of Day and Month

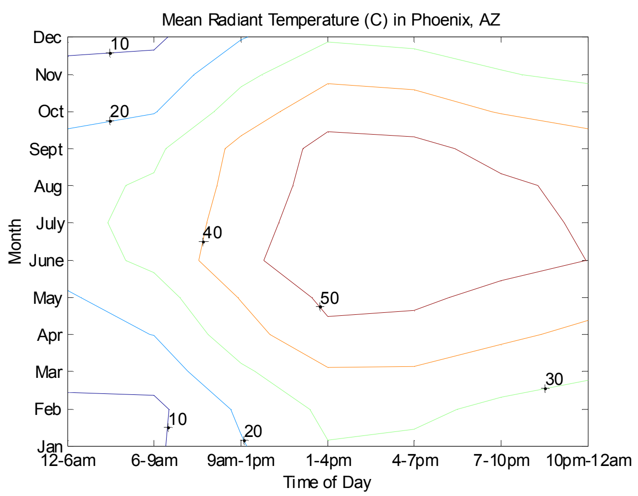

Figure 14: Phoenix, AZ MRT vs. Time of Day and Month

THERMAL COMFORT MODEL – The thermal comfort of a person in a vehicle's highly non-uniform, transient environment is difficult to predict. However, a person's thermal comfort can be estimated by using studies based on a person in a uniform, steady thermal environment [6, 7, 9].

A person's thermal sensation is mainly related to the thermal balance on the body as a whole. This balance is influenced by physical activity and clothing, as well as the environmental parameters of air temperature, mean radiant temperature, air velocity, and humidity.

When these factors have been estimated or measured, the thermal sensation for the body as a whole can be predicted by calculating the predicted mean vote (PMV) index (see Figure 15). The predicted percent dissatisfied (PPD) index provides information on the thermal discomfort or thermal dissatisfaction by predicting the percentage of people likely to feel too hot or too cold in a given environment.

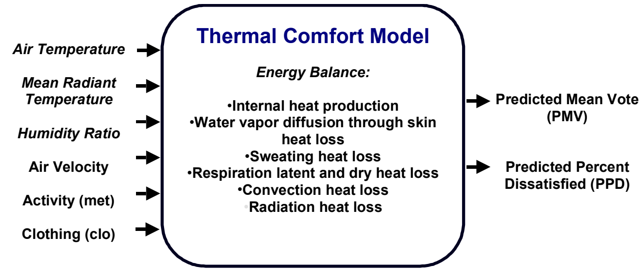

Figure 15: Thermal Comfort Flow Chart

<u>Fanger's Equations</u> – Fanger's equations describe a person's heat balance, the PMV and the PPD. The PMV is the mean vote of a large group of people on the seven-point thermal sensation scale shown in Table 1.

Table 1: Thermal Sensation Scale

PMV	Thermal Sensation
+ 3	Hot
+ 2	Warm
+ 1	Slightly Warm
0	Neutral
- 1	Slightly Cool
- 2	Cool
- 3	Cold

The PPD predicts the percentage of a large group of people likely to feel too warm or cool (e.g. votes of +2, +3, or –2, -3).

If a person's heat generation is equal to their heat loss to the environment, they are considered thermally neutral and will have a vote of zero. Any deviation in the thermal balance away from this causes positive (warm) or negative (cold) votes.

As the body generates heat, heat is transferred to the environment via the respiratory tract or the skin, or accumulated within the body. This heat balance (in W/m^2) is expressed as follows [7]:

$$\frac{dQ_{body}}{dt} = S = M - E_{diff} - E_{rsw} - E_{\mathrm{Res}} - C_{\mathrm{Res}} - R - C$$

where the heat accumulation in the body (S) is determined by the metabolic heat generation (M), natural water diffusion through the skin (E_{diff}), sweat evaporation (E_{rsw}), latent (E_{Res}) and dry respiration (C_{Res}), radiation (R) and convection (C) to the environment. External work performed and conduction were assumed negligible.

During driving, a person generates a metabolic power (M, W/m^2) of 1.5 mets [7]. This value is 50% above the resting heat production of 1 met (58.2 W/m^2).

Skin moisture losses cause evaporative heat loss from a combination of the evaporation of sweat secreted due to thermoregulatory control mechanisms (E_{rsw}) and the natural diffusion of water through the skin (E_{diff}) [7]:

$$E_{rsw} = \dot{m}_{rsw} h_{fg}$$
$$E_{diff} = (1 - w_{rsw}) 0.06 E_{\max}$$

where

$\dot{m}_{rsw}$ = rate at which regulatory sweat is generated, kg/(s·m^2)
$\propto$ metabolic rate M
h_{fg} = heat of vaporization of water = 2430 kJ/kg at 30°C
w_{rsw} = skin wettedness, = $E_{rsw} / E_{\max}$
$E_{\max}$ = maximum heat loss via evaporation if the skin were fully wetted
$\propto (p_{sk,s}-p_a)$
$p_{sk,s}$ = water vapor pressure at skin, Pa
p_a = ambient partial vapor pressure, Pa

Based on test data on subjects, Rohles and Nevins [6-8] linked the sweat rate with metabolic rate. Fanger expressed the diffusion of water through the skin as a diffusivity coefficient and a linear approximation for saturated vapor pressure evaluated at the skin temperature [6, 7]. These reductions led to the following:

$$E_{rsw} = 0.42(M - 58.15)$$
$$E_{diff} = 3.05x10^{-3}\left(5733 - 6.99M - p_a\right)$$

Heat is lost through the respiratory tract in the form of sensible, convective heat loss (C_{Res}) and latent, evaporative losses of heat and water vapor to the inhaled air (E_{Res}) [7]:

$$C_{Res} = \dot{m}_{res} c_{p,a} (t_{ex} - t_a) / A_D$$
$$E_{Res} = \dot{m}_{res} h_{fg} (W_{ex} - W_a) / A_D$$

where

$\dot{m}_{res}$ = pulmonary ventilation rate, kg/s,
$= M$ * 2.58x10^{-3} m^{2}kg/kJ
$c_{p,a}$ = specific heat of air, 1 kJ/(kgK)
t_{ex} = temperature of exhaled air, 34°C
t_a = ambient air temperature, °C
A_D = Dubois surface area of the nude body, 1.8 m^2
W_{ex} = humidity ratio of exhaled air, kg (water vapor)/kg (dry air)
W_a = humidity ratio of inhaled (ambient) air, kg/kg
$= 0.622 \dfrac{p_a}{p_t - p_a}$
p_a = ambient partial vapor pressure, Pa
p_t = total or barometric pressure, Pa

A significant amount of heat can be associated with respiration because the air is inspired at ambient conditions and expired nearly saturated at a temperature only slightly cooler than the core body temperature.

Using the assumptions and values defined above, and evaluating some of the values at STP, the respiratory losses collapse into the following:

$$C_{Res} = 0.0014M(34 - t_a)$$
$$E_{Res} = 0.0173M(5867 - p_a)$$

Heat is lost by radiation to the surroundings, which must first pass through the clothing of the person. Therefore, the radiation term is described as follows:

$$R = \varepsilon\sigma \frac{A_r}{A_D} f_{cl}\left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right]$$
$$= 3.96x10^{-8} f_{cl}\left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right]$$

where

ε = emissiviy of skin, 0.97 to 0.98
σ = Stefan - Boltzman constant, 5.67x10^{-8} W/m^{2}K^4
$\dfrac{A_r}{A_D}$ = fraction of skin surface involved in heat exchange by radiation, 0.7 seated subject, 0.77 standing
f_{cl} = clothing area factor, = A_{cl}/A_D
$= \begin{cases} 1.0 + 0.2I_{cl} & \text{for } I_{cl} \le 0.5clo \\ 1.05 + 0.1I_{cl} & I_{cl} > 0.5clo \end{cases}$
I_{cl} = clothing insulation, clo where 1clo = 0.155 °Cm^2/W
t_{cl} = mean temperature of outer surface of the clothed body, °C
$\bar{t}_r$ = mean radiant temperature, °C

Heat is lost by convection to the surroundings, which must also first pass through the clothing of the person. Therefore, the convective term is described as follows:

$$C = f_{cl} h_c (t_{cl} - t_a)$$

where

h_c = convective heat transfer coefficient, W/m^{2}K
$= \max\begin{cases} 2.38(t_{cl} - t_a)^{0.25} \\ 12.1\sqrt{AirVelocity} \end{cases}$

A final relation determines the mean temperature of the outer surface of the clothed body (t_{cl}). Data from test subjects determined a skin temperature for thermal neutrality as follows [7]:

$$t_{sk,req} = 35.7 - 0.0275M$$

The clothed body temperature is then found as follows:

$$t_{cl} = t_{sk,req} - 0.155 I_{cl} (R + C)$$

PMV and PPD – Fanger created a person's thermal sensation vote and predicted percent dissatisfied from a person's heat balance deviation from a thermally neutral sensation (e.g. the heat generation S). The Predicted Mean Vote is described by the following [7]:

$$PMV = \left(0.303*\exp(-0.036*M) + 0.028\right)* \left(M - E_{diff} - E_{rsw} - E_{Res} - C_{Res} - R - C\right)$$

or, written with expanded terms:

$$PMV = \left(0.303*\exp(-0.036*M) + 0.028\right)* \begin{pmatrix} M - 3.05x10^{-3}(5733 - 6.99M - p_a) \\ -0.42(M - 58.15) - 0.0173M(5867 - p_a) \\ -0.0014M(34 - t_a) \\ -3.96x10^{-8} f_{cl}\left((t_{cl}+273)^4 - (\bar{t}_r + 273)^4\right) \\ -f_{cl}h_c(t_{cl} - t_a) \end{pmatrix}$$

The Percent Predicted Dissatisfied is described by the following equation, and shown graphically in Figure 16:

$$PPD = 100 - 95*\exp(-0.03353PMV^4 - 0.2179PMV^2)$$

In this study, PPD was set to zero for mean votes less than one (e.g. cold conditions) because the concern was only with warm conditions where the air conditioning would be used.

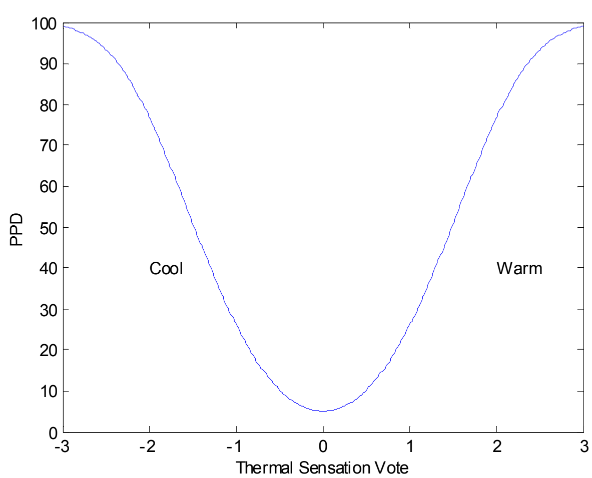

Figure 16: PPD vs. PMV

It is worth revisiting the definitions of PMV and PPD to see how they apply to vehicle air conditioning use. If a person is 'warm' or 'hot,' e.g. votes of +2 or +3 on the thermal sensation scale (Table 1), they are assumed to be uncomfortable. The PPD, by its name, is the percent of people that will be dissatisfied with the thermal environment at a given mean vote. The premise of this study is that if a person is uncomfortable with their thermal environment, when they get into the car they will turn on the air-conditioning.

The PMV indicator, by its definition, predicts the mean thermal sensation vote of a large population for a given heat balance on a typical body. In reality there is a distribution of votes about that typical 'mean vote', such that a percentage of the people are dissatisfied. For example, even if the mean vote is 'slightly warm' (a vote of +1), 26% of a large population are likely to have votes of 'warm' or 'hot' (+2 or +3), as shown by Figure 16. Therefore, for a mean vote of +1, 26% of the population would be dissatisfied and turn on the air conditioning were they to get into a vehicle. Throughout this study, therefore, PPD is synonymous with the percent of time the air-conditioning is turned on.

Sample values for PPD as they vary with time of day and month of the year in Denver, Phoenix, and New Orleans are shown in Figure 17 through Figure 19. The conditions used to determine these PPD plots are a person wearing summer attire entering a soaked vehicle (soak MRT).

Denver (Figure 17) shows a small contour island of 90% PPD around midday in July, and zero percent dissatisfied from October through April. Therefore, midday in July, 90% of the population is expected to use the AC, and no one is expected to use the AC from October through April.

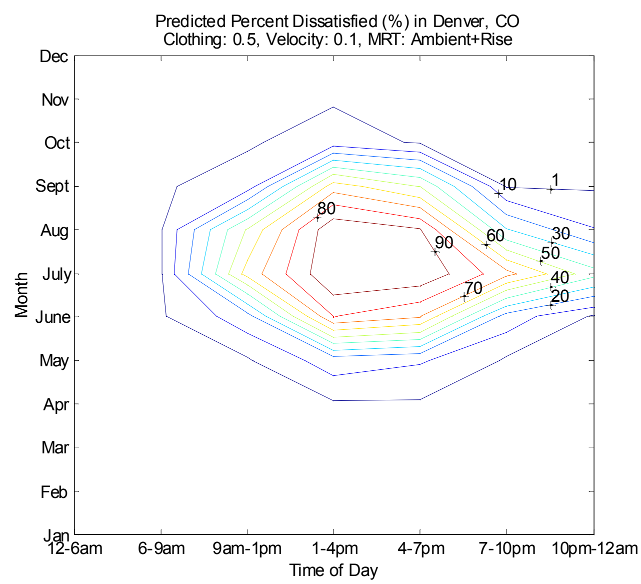

Figure 17: PPD in Denver, CO

Phoenix (Figure 18) shows much greater use of the AC than Denver, as over 90% of the people use AC from mid-morning through the end of the day for most of the summer months. Even in November, by mid-day 60% of the population is expected to be using the AC.

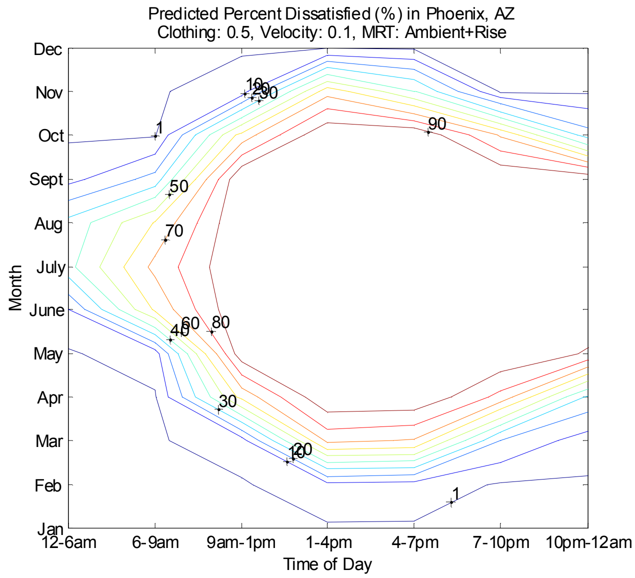

Figure 18: PPD in Phoenix, AZ

AC usage in New Orleans (Figure 19) falls between that of Denver and Phoenix. The 90% AC usage contour covers morning through evening from May through September. No AC is used in December or January.

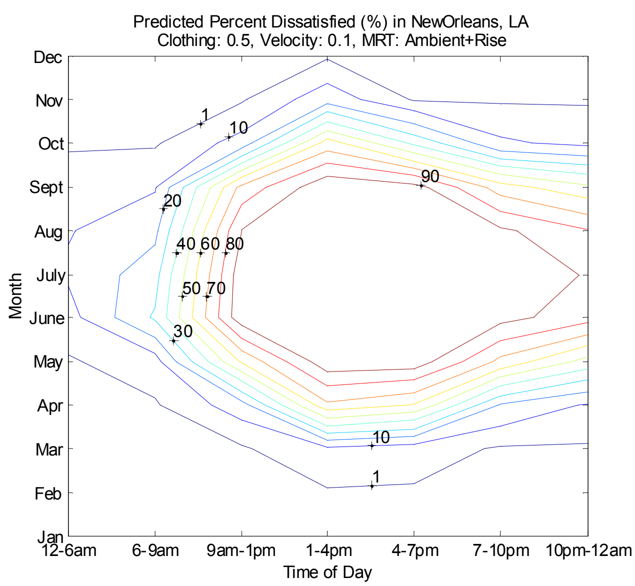

Figure 19: PPD in New Orleans, LA

Range of Thermal Comfort Inputs – As shown above in Figure 15 and Fanger's equations, the thermal comfort model uses six input parameters to predict a person's thermal comfort. If a person were dissatisfied with the thermal environment, they would turn on the air conditioning. Data were used for the thermal comfort parameters when available (e.g. air temperature, humidity ratio), and assumptions were made for the other variables (e.g. metabolic rate, clothing), as described below.

Metabolic rate (used in M, E_{diff}, E_{rsw}, E_{res}, C_{res}, R, C, and PMV) was assumed to be typical of driving a car at 1.5 mets [7], or 87.3 W/m^2.

Air temperature (used in C_{res} and C) was available from the Typical Meteorological Year data.

The thermal comfort model was evaluated at two values for Mean Radiant Temperature (used in R). These conditions were: 1) Ambient conditions and 2) Soaked vehicle conditions. The MRT was varied in order to determine the sensitivity of the final fuel use values to MRT assumptions. The two scenarios chosen give a lower and upper bound on the annual vehicle fuel use for AC.

The humidity ratio (used in E_{diff} and E_{res}) in each city as it varied through time of day and year was available from TMY data.

The air velocity (used in C) was assumed to be low, or 0.1 m/s. This meant that a lower bound for the convective heat transfer coefficient was 3.8 W/m^{2}K.

The final variable in the thermal comfort model was the amount of clothing a person wore, represented as a thermal impedance. ASHRAE Standard 55 [10] specifies a summer clothing value of 0.5 clo, where 1 clo = 0.155 °Cm^2/W. This amount of clothing corresponds to typical summer clothing such as light slacks and a shirt. However, many working adults wear professional attire, even in the summer. If a person were wearing a suit, the clo value would increase to 1.17 clo, indicating a higher thermal resistance to transfer heat away from the body. These two clothing values were used for another lower and upper bound on the annual fuel use for AC.

Using the above assumptions for the thermal comfort model inputs, a grid of results was obtained for varying clothing levels and MRT assumptions, as described by Table 2. Case B in Table 2 was taken as the representative case for overall fuel use for vehicle air conditioning.

Table 2: Grid of Thermal Comfort Results

		Mean Radiant Temperature	
		Ambient	Soak
Clothing	Summer	A	B
	Suit	C	D

To illustrate the effect of varying clothing levels and MRT temperatures, Figure 20 through Figure 23 show the PPD (or percent of the population that will turn on the AC) with varying input parameters for New Orleans.

Case A (summer clothes with ambient MRT) in Figure 20 shows the least amount of AC use of the four cases, as PPD reaches only 80% in the middle of the day in July.

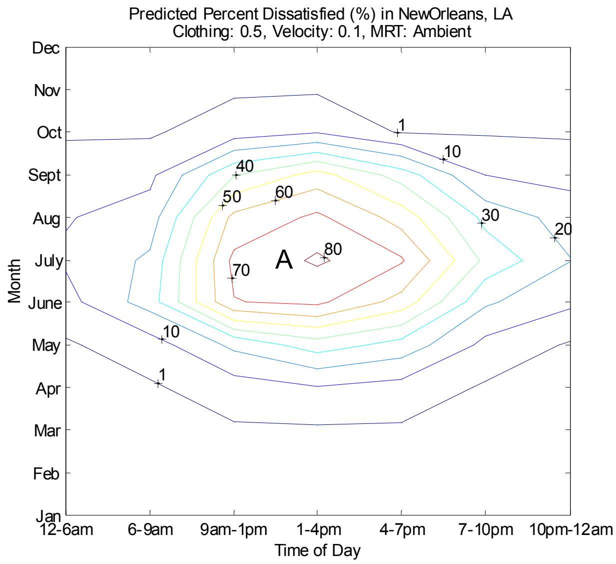

Figure 20: PPD for Case A: Summer Clothes, Ambient MRT in New Orleans, LA

Case B (summer clothes with soak MRT) in Figure 21 shows more use of the AC, as PPD reaches over 90% for a large portion of the day throughout the summer months. Again, Case B is taken as the representative case for predicting fuel use, and many of the results graphs in this paper use the assumptions of Case B.

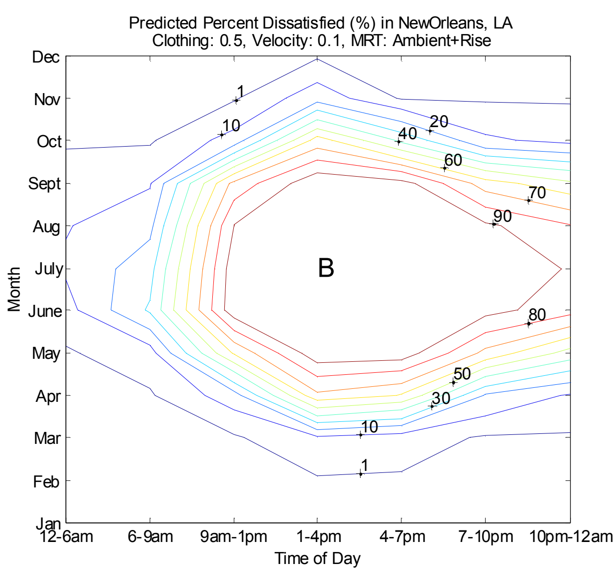

Figure 21: PPD for Case B: Summer Clothes, Soak MRT in New Orleans, LA

Case C (suit with ambient MRT) in Figure 22 shows a greater use of the AC than Case A, as PPD reaches 80% for a large portion of the day throughout the summer months. The AC use for Case C is lower than that of Case B.

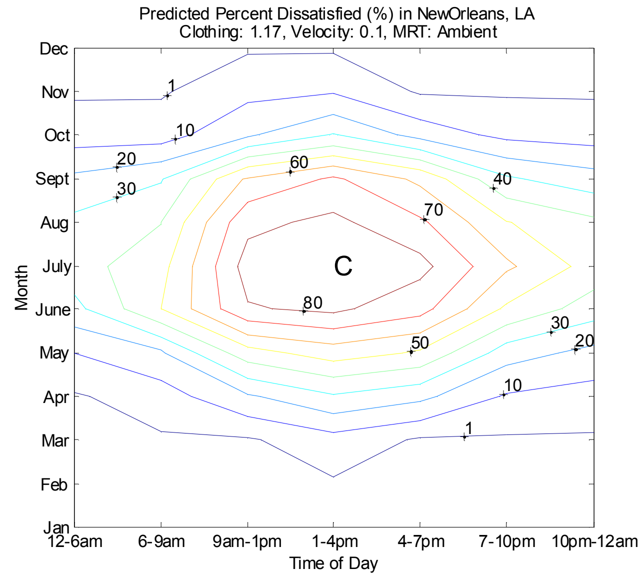

Figure 22: PPD for Case C: Suit, Ambient MRT in New Orleans, LA

The final Case D (suit with soak MRT) in Figure 23 shows the largest use of the AC, as PPD reaches over 90% for a larger portion of the day than Case B. AC use also extends further into the winter months than shown in Case B.

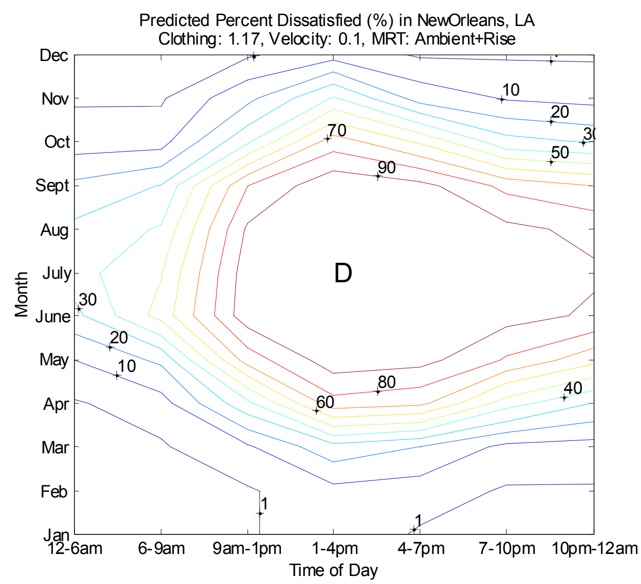

Figure 23: PPD for Case D: Suit, Soak MRT in New Orleans, LA

DRIVER DATA – The following calculations determine the fuel used for vehicle air conditioning per state, and were repeated for all 50 states.

<u>Driver behavior</u> - Information on driver behavior was obtained through the 1995 Nationwide Personal Transportation Survey (NPTS, [11]), a survey sponsored by the Federal Highway Administration and the Department of Transportation. The NPTS is a source of national data on daily trips including purpose of the trip, means of transportation, how long the trip took, day of

week and month, number of people on trip, etc. Approximately 21,000 households across the US were surveyed for the NPTS.

The NPTS data used in this study were vehicle usage with time of day (Figure 24) and time of year (Figure 25). Figure 24 shows that between 9 am and 7 pm (the time when the sun is out, temperatures are high, and AC use is high), 70% of the daily travel occurs.

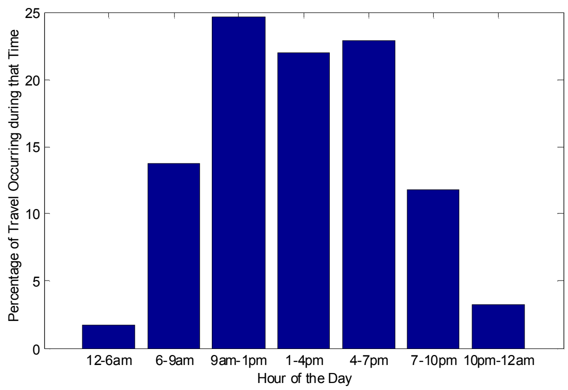

Figure 24: Percentage of Travel Occurring throughout the Day

If vehicle miles traveled were equally distributed throughout the months of the year, 8.33% of yearly travel would occur during a given month. Figure 25 shows that during the summer months, travel is slightly higher than this average; travel drops off during the winter months.

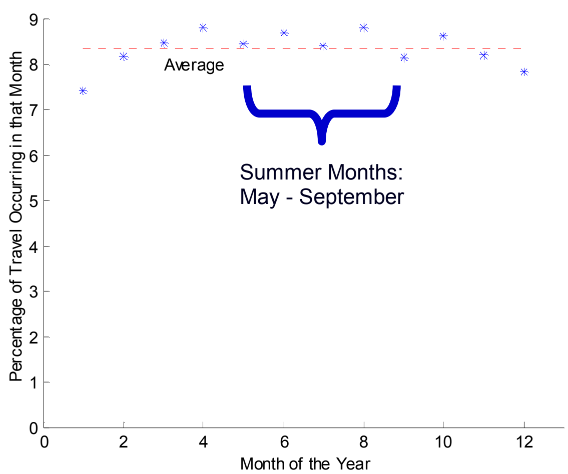

Figure 25: Percentage of Travel Occurring throughout the Year

The driver behavior data from Figure 24 and Figure 25 were used to collapse the PPD maps (e.g. Figure 23) into a single AC usage percentage (PPD) for each city.

Population data – TMY cities with populations greater than 100,000 people were used in this study. Their relative population percentages, as determined by Census 2000 data, gave a weighting for each city's PPD within a state to determine the overall PPD for a state. For example, the PPDs for Phoenix and Tuscon were population-weighted by 72% and 28% to get the overall PPD in Arizona of 54.2% AC usage.

Predicted Percent Dissatisfied – The Predicted Percent Dissatisfied with the thermal environment, assumed equal to the percent of time that the air conditioning is on, for each state is shown in Figure 26. This is the PPD plot for Case B: summer attire with vehicle soak MRT conditions.

Hawaii shows the highest AC usage throughout the year at 70%, Arizona comes in at 54%, Florida at 47%, Texas at 39%, and California at 13%. The AC usage in California is somewhat low because most of the cities lie on the coast and have very mild temperatures throughout the year.

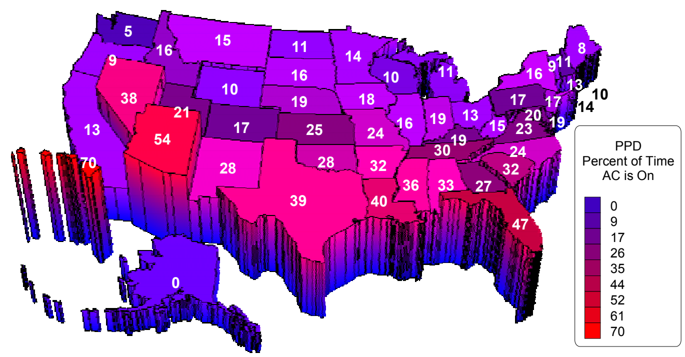

Figure 26: PPD, or Percent of Time the AC is On throughout the Year

VMT and Gallons Used per Vehicle – Average values for vehicle miles traveled (VMT) for cars and trucks were obtained from Wards 2001 Automotive Yearbook [12]. On average, a car was driven 11,850 miles (19,070 km) and a truck was driven 11,958 miles (19,244 km) in 1999.

A key assumption in this study is that the percentage of time that the air-conditioning is used is equivalent to the percentage of distance traveled. In general, 40% of vehicle trips are under 10 minutes, 85% are under 30 minutes, and 92% are under 40 minutes [11]. These numbers support the assumption that if drivers are turning on the AC, they would tend to leave it on for their entire trip, as most trips are short in duration.

The miles traveled with air conditioning (VMT_{withAC}) for both cars and trucks were found by using the PPD for a given state:

$$\begin{aligned}
&VMT_{withAC}(state, type) = VMT(type) * PPD(state) \\
&e.g. \\
&\quad VMT_{withAC}(AZ, car) = 11{,}850 * 0.542 = 6{,}423 \\
&\quad VMT_{withAC}(AZ, truck) = 11{,}958 * 0.542 = 6{,}480
\end{aligned}$$

The fuel economies of a vehicle both with and without the AC load on the engine were determined through vehicle simulations and checked with sample test data. Overall, cars in the US average 21.4 mpg (11 l/100km) and trucks average 17.1 mpg (13.8 l/100km) [12]. Typical cars and trucks with similar fuel economies were modeled in ADVISOR (version 3.2, [13]) and simulated over the FTP (Federal Test Procedure) drive cycle. The FTP cycle was chosen because the predicted fuel economies were similar to expected fuel economies in the real world, based on real-world data taken by CARB. The AC load was assumed to be a 3 kW mechanical auxiliary load on the engine. This estimate is somewhat conservative, as vehicle tests on the Insight, Prius, and other conventional vehicles [1, 2] corresponded to an approximate 4 kW AC load (see Figure 2). Note that these are small cars with small engines, and a peak AC load of 5-6 kW is more typical for a sedan. AC use of 3 kW penalized fuel economy by 24% (22 mpg to 16.7 mpg) for cars and 16% (17.7 mpg to 14.9 mpg) for trucks.

The gallons of fuel used for air conditioning were then determined by using the fuel consumed to drive the vehicle the number of miles traveled with the AC on and a hypothetical amount of fuel that would have been consumed if those same miles were traveled without the AC:

$$
\begin{aligned}
&Gallons_{TotalWithAC}(state, type) = \\
&\qquad VMT_{withAC}(state, type) / MPG_{withAC} \\
&Gallons_{TotalWithoutAC}(state, type) = \\
&\qquad VMT_{withAC}(state, type) / MPG_{withoutAC} \\
&Gallons_{ForAC}(state, type) = \\
&\qquad Gallons_{TotalWithAC}(state, type) - \\
&\qquad Gallons_{TotalWithoutAC}(state, type) \\
&e.g. \\
&\quad Gallons_{TotalWithAC}(AZ, car) = 6{,}423/16.7 = 385 \\
&\quad Gallons_{TotalWithoutAC}(AZ, car) = 6{,}423/22 = 292 \\
&\quad Gallons_{ForAC}(AZ, car) = 385 - 292 = 93 gal \\
&\quad Gallons_{TotalWithAC}(AZ, truck) = 6{,}480/14.9 = 435 \\
&\quad Gallons_{TotalWithoutAC}(AZ, truck) = 6{,}480/17.7 = 366 \\
&\quad Gallons_{ForAC}(AZ, truck) = 435 - 366 = 69 gal
\end{aligned}
$$

Registrations – In 2000, there were a total of 213 million light-duty vehicles registered in the US [12]. The vehicle distribution throughout the states is shown in Figure 27.

Vehicle registrations were used to find the total amount of fuel used for air conditioning in a given state:

$$
\begin{aligned}
&Gallons_{TotalForAC}(state) = \\
&\qquad Gallons_{ForAC}(state, car) * \# Cars(state) \\
&\qquad + Gallons_{ForAC}(state, truck) * \# Trucks(state) \\
&e.g. \\
&\quad Gallons_{TotalForAC}(AZ) = 93 * 1{,}858{,}255 + 69 * 1{,}528{,}261 \\
&\qquad\qquad = 277 \text{ million gallons}
\end{aligned}
$$

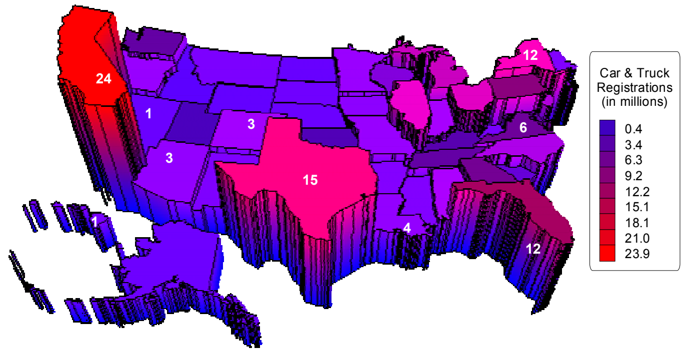

Figure 27: Vehicle Registrations (Cars + Trucks)

NATIONAL AIR CONDITIONING FUEL USE MAP

The amount of fuel used for light-duty vehicle air conditioning by state for the representative Case B (summer attire, soak MRT) is shown in Figure 28.

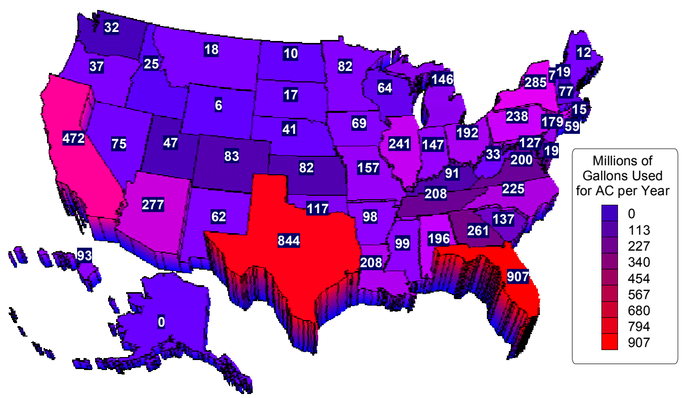

Figure 28: Millions of Gallons Used for Light-Duty Vehicle Air Conditioning

The top AC fuel consumption states, shown in Figure 29, are Florida, Texas, California, New York, Arizona and Georgia. Florida and Texas are significantly above other states, as their AC fuel use is near 900 million gallons. Combining the fuel use for AC in all of the states totaled to 7.14 billion gallons (27 billion liters) of gasoline used for AC.

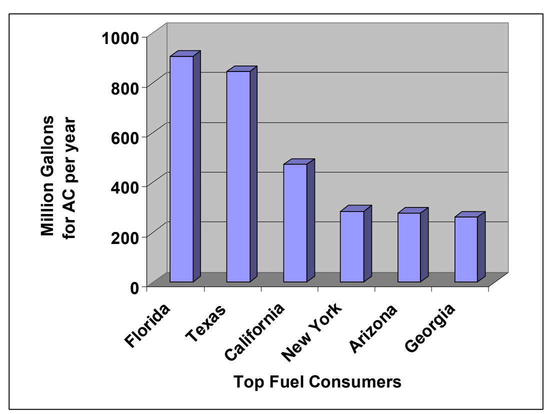

Figure 29: Top AC Fuel Consumption States

NATIONAL AC FUEL USE MATRIX – Table 3 shows the combined AC fuel use for all the states, with a grid of values describing a range of thermal comfort inputs.

Case B is highlighted as the representative case of 7.14 billion gallons (27 billion liters) used for vehicle AC. The range of results based on varying thermal comfort input assumptions is from 2.6 to 9.2 billion gallons (10 to 35 billion liters) of gasoline for light-duty AC use.

Table 3: Billions of Gallons Used for AC in Light-duty vehicles

		Mean Radiant Temperature	
		Ambient	Soak
Clothing	Summer	2.57	7.14
	Suit	4.7	9.23

Table 4 compares the AC fuel use numbers to the US consumption for light-duty vehicles of 125.9 billion gallons (476.6 billion liters) of gasoline [12].

Table 4: AC Use as a Percentage of US Consumption

		Mean Radiant Temperature	
		Ambient	Soak
Clothing	Summer	2.0%	5.7%
	Suit	3.7%	7.3%

According to DOE's Energy Information Administration [14], the US imports 11.1 MMBD (million barrels of oil per day), of which 43% is crude oil. This corresponds to 73 billion gallons (276 billion liters) of gasoline per year. Table 5 compares the AC fuel use numbers with the crude oil imports.

Table 5: AC Use as a Percentage of Crude Oil Imports

		Mean Radiant Temperature	
		Ambient	Soak
Clothing	Summer	3.5%	9.8%
	Suit	6.4%	12.6%

As a final comment on this study, note that the predictions for AC fuel use are conservative estimates. The results are conservative for several reasons:

- The AC load on the engine was assumed to be a 3 kW load (a cautious average load) vs. 4 kW estimated on sample vehicles. The resulting fuel economy penalty used was 24% vs. a 26% penalty expected at 4 kW.
- The air temperature in Fanger's equations was assumed to be ambient for all cases, where in a vehicle, the initial breath temperature when entering a soaked vehicle could be above ambient (e.g. closer to the soak MRT than ambient).
- Predicted Percent Dissatisfied may underestimate the use of AC. PPD does not model the uncomfortable effect of sitting on a hot seat with a sweating back, or a non-uniform environment such as the sun shining on one side of the driver. Also, humidity effects on discomfort may be greater than predicted with Fanger's heat balance equations, which were originally intended for indoor thermal comfort assessment.
- The study ignores AC use in vehicles due to defrost, automatic temperature control, or driver behaviors such as simply avoiding the noise of rolled-down windows.

CONCLUSION

This study used a bottoms-up approach to determine the amount of fuel used for light-duty vehicle air conditioning based on occupant thermal comfort. Representative data over 30 years in cities throughout the US gave temperature, radiation, and humidity variations throughout the day and year. The study integrated this environmental data, driver behavior, a basic thermal comfort model, vehicle simulations, and US population and vehicle statistics to determine the final AC fuel use numbers.

The amount of fuel used for air conditioning is significant. In absolute terms, 7.1 billion gallons of gasoline (27 billion liters) are used in the US for air conditioning light-duty vehicles. Put in relative terms, the AC fuel use is equivalent to 6% of domestic petroleum consumption, or 10% of crude oil imports.

The range of fuel used for vehicle air conditioning based on different thermal comfort inputs was 2.6 to 9.2 billion gallons (10 to 35 billion liters) of gasoline. Optimization of vehicle cabins or air conditioning systems now have an established metric of impact. Thus, reducing the amount of energy used for air conditioning a vehicle by 50% could reduce the nation's fuel consumption by 3.6 billion gallons (13.5 billion liters), or equivalently reduce crude oil imports by 5%. As mentioned previously, ways to reduce the amount of energy used for cabin environment control are multiple and include optimized conventional AC systems, advanced window glazings for reduced peak cabin soak temperatures, localized cooling, or use of alternative cabin cooling such as heat generated cooling via exhaust gases.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS\

1X: One times the fuel economy of a 1993 vehicle with 27.5 mpg, or 8.8 l/100km

AC: Air Conditioning

ASHRAE: American Society for Heating, Refrigeration, and Air-Conditioning Engineers

CARB: California Air Resources Board

DOE: Department of Energy

IP: Instrument Panel in a vehicle

ISO: International Standards Organization

MMBD: Million Barrels of Oil per Day

MPGGE: Miles per gallon, gasoline equivalent

MRT: Mean Radiant Temperature

NREL: National Renewable Energy Laboratory

PMV: Predicted Mean Vote

PPD: Predicted Percent Dissatisfied

TMY: Typical Meteorological Year

US: United States

SC03: Drive cycle used in the Supplemental Federal Test Procedure for AC use

STP: Standard Temperature and Pressure

VMT: Vehicle Miles Traveled