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Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning

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ABSTRACT

Vehicle air conditioning (A/C) systems significantly increase the fuel use and tailpipe emissions of automobiles. In addition, emissions of the A/C refrigerant are greenhouse gases. In 2002, the National Renewable Energy Laboratory (NREL) determined the U.S. national and state-by-state fuel use impact of air conditioning in light duty vehicles. In 2003, we expanded the analysis to cover Europe and Japan. With the assistance of the automotive climate control community, we have updated the analysis to include demisting, soak temperatures that vary with vehicle type, simplified clothing assumptions, and improved A/C compressor power definition. The updated NREL study shows that the United States uses 7.0 billion gallons (26.4 billion liters) of fuel a year for vehicle air conditioning, equivalent to 5.5% of the total national fuel use and 9.5% of the imported crude oil. If all vehicles had air conditioning, the EU would use 1.8 billion gallons (6.9 billion liters) of fuel per year or 3.2% of total vehicle fuel consumption. Japan would use 0.5 billion gallons (1.7 billion liters) or 3.4% of total vehicle fuel consumption. Converting the fuel consumption data into CO_2 emissions determines the indirect impact of air conditioning on the climate. We also determined the magnitude of the potential reduction in fuel use due to incremental improvements in A/C coefficient of performance (COP) over a baseline and the potential fuel saved per vehicle. For example, with a 25% improvement in A/C COP, a car in Arizona could save 15.7 gallons per year. These data highlight the potential to reduce operational costs, A/C fuel use, and CO_2 emissions by implementing advanced vehicle climate control technologies.

INTRODUCTION

Almost all vehicles sold today in Europe, Japan, and the United States have air conditioning, but many older vehicles in Europe do not. Air conditioning has become a near-standard feature on new vehicles because it provides driving comfort, reduced road noise, and improved safety by rapidly demisting windows and enhancing driver vigilance.

An operating air conditioning system compressor is the largest ancillary load on an automobile with the alternator load typically second and hydraulic power steering third. An air conditioner compressor can add up to a 5-6 kW peak power draw on a vehicle's engine, which is about the same load as air conditioning a small single family home. This load significantly impacts the fuel economy of traditional vehicles. The impact on advanced vehicles such as electric, hybrid electric, and fuel cell vehicles is even greater. The combustion products generated by the extra fuel required to power to the A/C system are the indirect environmental impact of mobile air conditioning (MAC) systems. Our goal is to determine the increased fuel use and additional CO_2 emissions of MACs.

Our initial analysis of U.S. A/C fuel use was presented at the 2002 Earth Technology Forum[1] and 2002 Future Car Congress[2]. The analysis, broadened to include Europe and Japan, was presented at the 2003 MAC Summit in Brussels[3]. A new analysis, based on suggestions from the automotive industry, was presented at the 2003 Alternative Refrigerant Systems Symposium[4]. This paper further updates results, documents the potential fuel saving improvements, and gives an overview of the increasingly sophisticated and accurate methodology.

This analysis is particularly timely because vehicle industry experts predict that improved MACs using the traditional refrigerant (HFC-134a) can achieve at least a 50% reduction in direct refrigerant greenhouse gas emissions and a 30% reduction in energy usage using existing technologies. MAC systems using alternative refrigerants may outperform even the impressive results of the improved HFC-134a system.

APPROACH

Our analysis used a bottom-up approach to estimate the fuel used in vehicles for air conditioning per year. A thermal comfort model determined the percentage of time that a driver used the air conditioning based on the premise that people dissatisfied with their thermal environment will turn on the air conditioning. Environmental conditions were an important input to the comfort model. The thermal comfort results were then combined with statistics on when people drive (time of day), where they live (climate including cloud cover), 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.

THERMAL CONDITION OF THE VEHICLE

The first step in predicting A/C use is determining the thermal condition of the vehicle, using the environmental conditions defined in a Typical Meteorological Year (TMY) database. 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 United States over a period of 30 years (1961-1990)[5].

To focus on the environments that have the most vehicles, only cities with populations greater than 100,000 were used (Figure 1). 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).

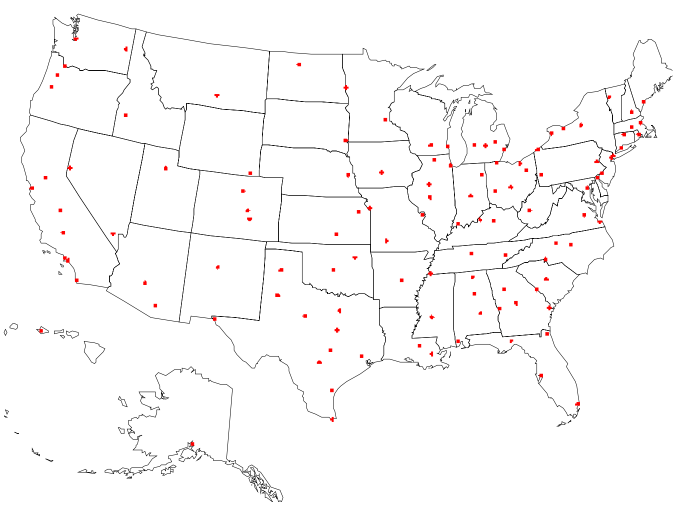

Figure 1. 116 Cities Used from TMY Data Base

Ambient Temperature – Our model reads the TMY data and uses it in the form presented in Figure 2. The figure shows air temperature as a function of month and time of day. This is used in the thermal comfort model as the initial air temperature in the vehicle when the occupants determine A/C usage. In reality, the initial air temperature will be higher than ambient if the windows are closed. This model conservatively assumes that the hot soak air is quickly extracted from the vehicle through the introduction of outside air at startup.

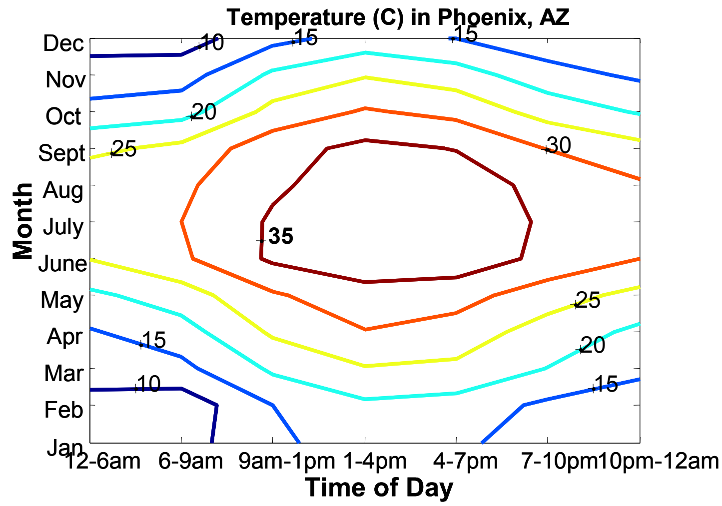

Figure 2. Phoenix, AZ: Ambient Air Temperature

Humidity Ratio – The humidity is another input to the thermal comfort model that was gleaned from the TMY data. In addition to the impacts on thermal comfort, humidity is also important to A/C performance due to the energy used to condense water on the evaporator.

Mean Radiant Temperature – 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 radiant heat as they do in the actual non-uniform thermal environment. When a person enters the vehicle, the temperature and emissivity of all the surrounding surfaces determine the MRT. The surface temperatures are a function of air temperature and solar load. We updated the MRT model to account for the difference in soak temperatures between sedans and SUVs as:

$$MRT(car,time) = 27°C * Radiation(t) / 1000\ W/m^2 + Tamb(t) \quad (1)$$

$$MRT(truck,time) = 24°C * Radiation(t) / 1000\ W/m^2 + Tamb(t) \quad (2)$$

Figure 3 shows a comparison between the model and measured vehicle surface temperatures for a sedan. The resulting MRT adequately represents the average surface temperature. Using the environmental data from the TMY database and the above equations, the MRT as a function of month and time of data was determined for each city. Figure 4 is an example MRT contour plot for Phoenix.

THERMAL COMFORT MODEL

A person's use of A/C depends on their level of thermal comfort. We used a Fanger-based thermal comfort model to determine the predicted mean vote (PMV) and predicted percent dissatisfied (PPD)[6,7,8]. This approach is covered in great detail in Reference 1, therefore it will not be covered here. Besides the inputs from the environment (ambient temperature, humidity, and MRT), an air velocity of 0.1 m/s and metabolic rate of 1.5 met are assumed. An update from the previous model is that a single clothing ensemble is now assumed, consisting of trousers and a long sleeve shirt (clo=0.6).

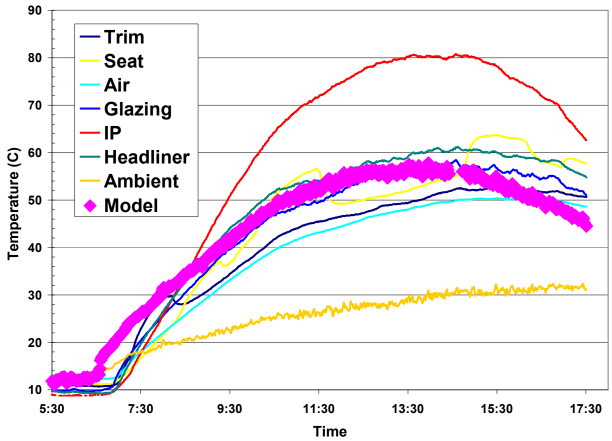

Figure 3. Comparison of Sedan MRT to Test Data

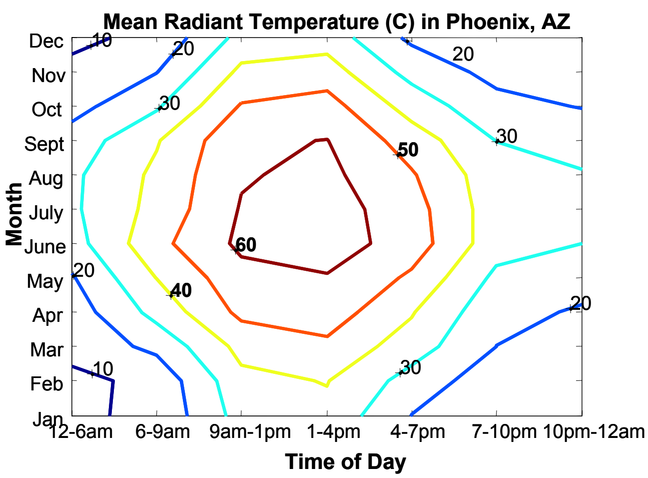

Figure 4. Sedan Mean Radiant Temperature for Phoenix

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” (votes of +2 or +3 on the thermal sensation scale), they are assumed to be uncomfortable. The PPD, as indicated by its name, is the percentage 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 parameter, by 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). 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.

Using the thermal comfort model, PPD was determined as a function of time of day and month of the year for each city. Figure 5 shows PPD contours for Phoenix. There is a large contour island around midday in July and zero percent dissatisfied at night from October through April. Therefore, midday in July, 100% of the population is expected to use the A/C, and no one is expected to use the A/C at night from October through April.

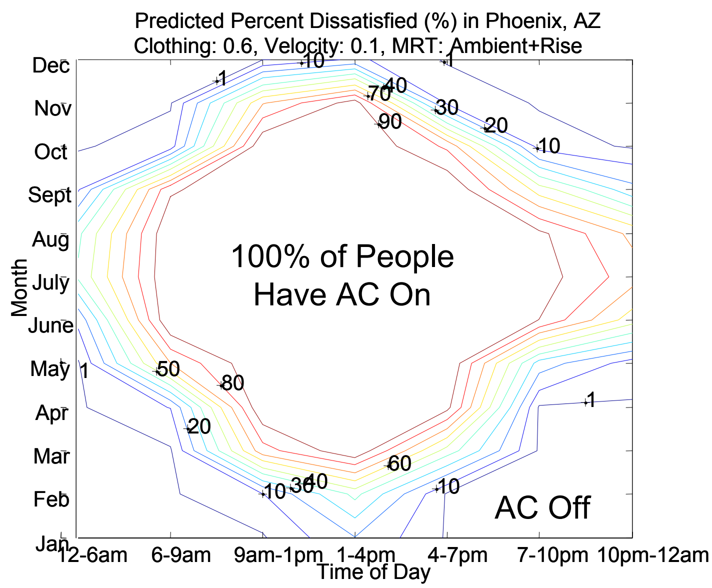

Figure 5. A/C Usage for Cooling

DEMISTING MODEL

One improvement recently incorporated into the analysis is the additional energy use of the A/C system for demisting. The A/C is assumed to be operating for demisting if the temperature is between 1.7°C and 12.8°C (35°F-55°F) and the relative humidity is > 80%. Figure 6 shows the predicted A/C operation for demisting in Brussels, Belgium. The center island represents no demister usage in the summer due to warm conditions.

DRIVER DATA

The time of day when vehicle trips occur and the month of the year are also important inputs[9]. The driver behavior data were used to collapse the PPD maps into a single A/C usage percentage (PPD) for each city. The relative population percentages gave a weighting for each city’s PPD within a state to determine the overall PPD for a state. Figure 7 shows the percent of time the A/C is on for comfort and demisting for a single vehicle by state. Note, Hawaii has the highest A/C percent on time with 69%, while Arizona, Florida, and California are 58%, 57%, and 29% respectively. Oregon and Maine have unusually high usage compared to their neighbors. This is thought to be a function of where the population is located and the corresponding environmental data.

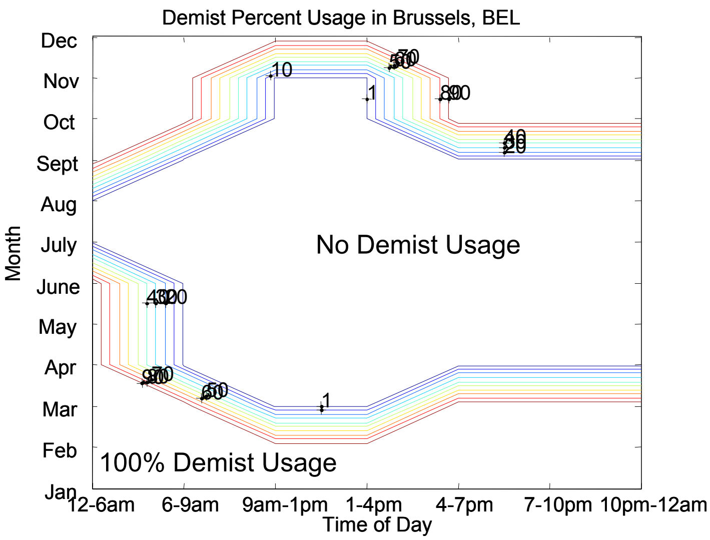

Figure 6. A/C Usage for Demisting

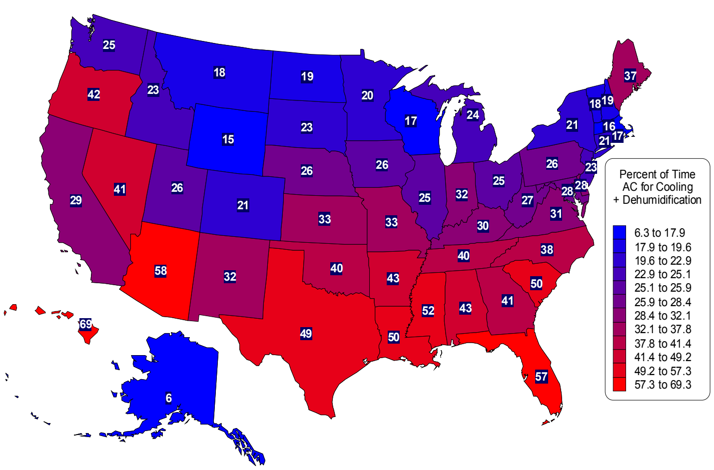

Figure 7. Percent of Time A/C is On: Cooling + Demist

A useful output from the model is the ambient temperature, MRT, and humidity during A/C usage as shown in Figures 8, 9, and 10 respectively. For the United States, the average ambient air temperature during A/C usage is 25ºC and the average relative humidity is 66%. The average MRT is 35ºC.

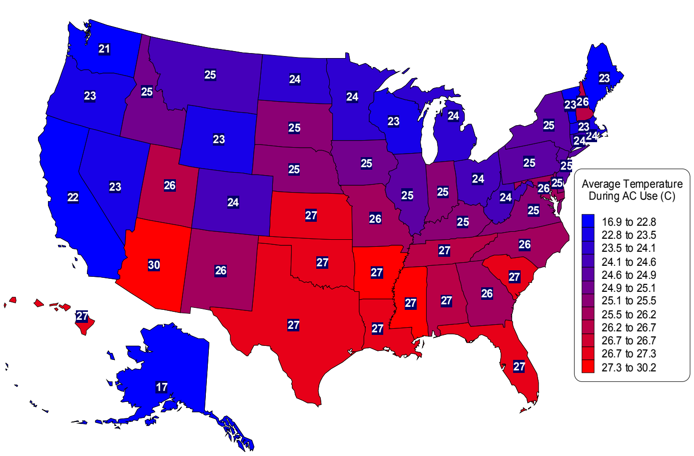

Figure 8. Ambient Air Temperature during A/C Use

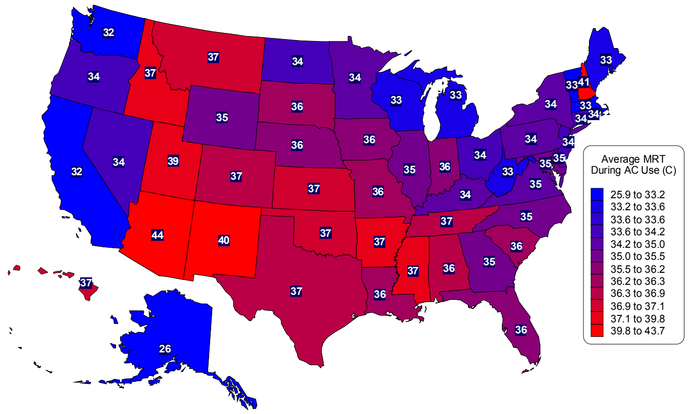

Figure 9. Mean Radiant Temperature During A/C Use

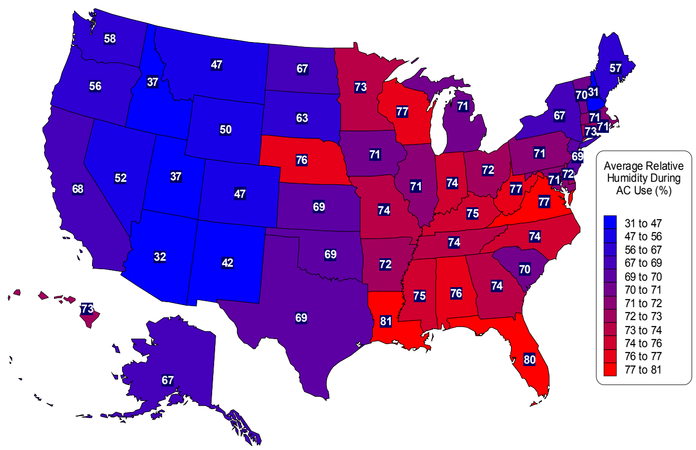

Figure 10 . Ambient Relative Humidity During A/C Use

VEHICLE MILES TRAVELED AND GALLONS/VEHICLE

Average vehicle miles traveled (VMT) for cars and trucks were obtained from Wards 2001 Automotive Yearbook[10]. On average, cars were driven 11,850 miles (19,070 km) and trucks were driven 11,958 miles (19,244 km) in 1999.

A key assumption in this study is that the percent-on time (e.g. California has a 29% A/C-on time) is equivalent to the percentage of miles driven with the A/C on during the year (e.g. 0.29 * 11,850 miles = 3,436 miles). In general, 40% of vehicle trips are under 10 minutes, 85% are under 30 minutes, and 92% are under 40 minutes[9]. These driving statistics support the assumption that in hot weather, drivers tend to leave air conditioning on for their entire trip, as most trips are short in duration.

The vehicle miles traveled with A/C was calculated by multiplying the vehicle miles traveled by the PPD. The next step was to determine fuel use (gallons/vehicle) with and without A/C. A typical car and truck were modeled using ADVISOR™ software[11] (version 3.2) and simulated over the FTP (Federal Test Procedure) drive cycle. Table 1 shows the updated engine, weight, and compressor assumptions used in this analysis.

Table 1. Vehicle Parameters

Vehicle	Engine (kW)	Weight (kg)	Compressor (cc)
US Car	115 SI	1300	180, fixed
US Truck	144 SI	1924	210, fixed
EU Car	91 comp. Ign. diesel	1220	125, var. disp.

The previous analysis used a constant compressor load. In this updated analysis, we used fixed displacement and variable displacement compressor data published by Delphi[12]. Compressor power curves were selected for 27ºC and 60% relative humidity, which are very close to the average environmental conditions during A/C operation. For demist mode, the compressor performance was selected consistent with 16ºC and 80% relative humidity conditions. The power curves were scaled by the ratio of compressor displacement to obtain the power for the compressors identified in Table 1.

Figure 11 shows the compressor load as a function of compressor rpm. It is assumed that the engine/compressor pulley ratio is 0.64. The load was increased by 120 W to account for the power needed to run the AC blower but did not include the condenser fan power. The assumptions and methodology resulted in a low variable displacement power curve, which will under-predict EU and Japan A/C fuel use. Table 2 shows the fuel economy with and without A/C for the three vehicles from the ADVISOR analysis.

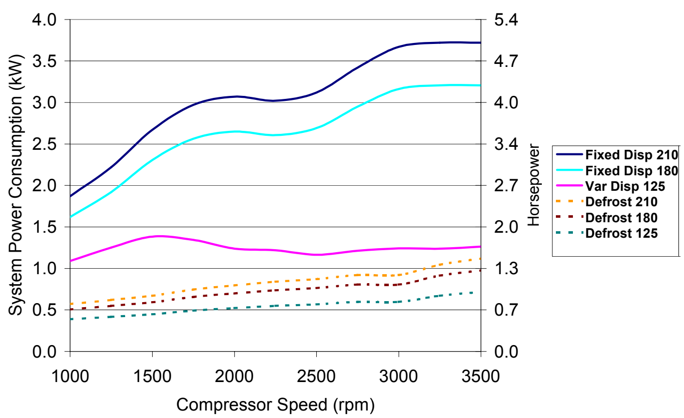

Figure 11. Compressor Power vs. Compressor Speed

Table 2. Fuel Economy Results

	US Car	US Truck	EU Vehicle
Fuel Economy no AC	22.0	18.8	30.4
Fuel Economy with AC	18.0	16.2	27.3
Fuel Economy defrost	21.1	18.1	29.0

The gallons of fuel used for air conditioning were then determined by taking the difference between the fuel consumed to drive the vehicle the number of miles traveled with the A/C on and a hypothetical amount of fuel that would have been consumed if those same miles were traveled without the A/C.

$$\text{Gallons for A/C} = \text{Gallons AC}_{on} - \text{Gallons AC}_{off} \quad (3)$$

or

$$\text{Gallons for A/C} = \text{VMT}_{AC}/\text{FE AC}_{on} - \text{VMT}_{AC}/\text{FE AC}_{off} \quad (4)$$

Note that these calculations are preformed for cars and SUVs in each geographic area. Vehicle registration data is used to estimate the total gallons of fuel used for A/C within each geographic area.

It is understood that without A/C, some vehicle occupants would choose to lower the windows, which also degrades fuel economy due to increased aerodynamic drag. Since most vehicles are sold with A/C, we analyzed the most common way people maintain comfort in their car.

RESULTS

A/C fuel use by state is shown in Figure 12. Note that states with large populations and in warmer climates have higher A/C fuel use. For the United States, the total fuel use for A/C is 7.0 billion gallons per year. This is equivalent to 5.5% of the total fuel consumption or 9.5% of imported crude oil. The fuel use percentages are based on a total annual light duty vehicle fuel use of 125.9 billion gallons[10] and imported oil of 73 billion gallons[13]. Putting the increased fuel consumption in terms of impact on the environment, A/C usage results in 62 billion kg of CO_2 released into the atmosphere per year.

Using the same analytical process for Europe and Japan, the usage per country is shown in Figure 13, assuming that 100% of the fleet has A/C. Summing the usage for each country, the EU would use 1.8 and Japan would use 0.45 billion gallons of fuel annually for A/C. This is equivalent to 3.2% and 3.4% of the respective total fuel consumption. EU A/C use would generate 16 billion kg of CO_2 and A/C use in Japan would generate 4 billion kg CO_2.

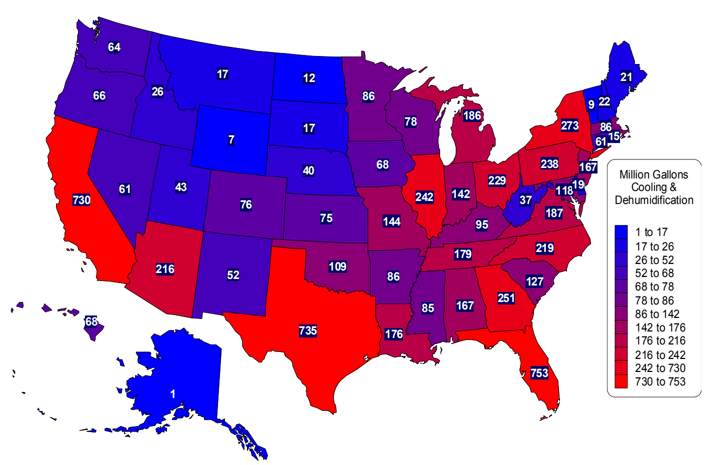

Figure 12. U.S. Fuel Used for A/C

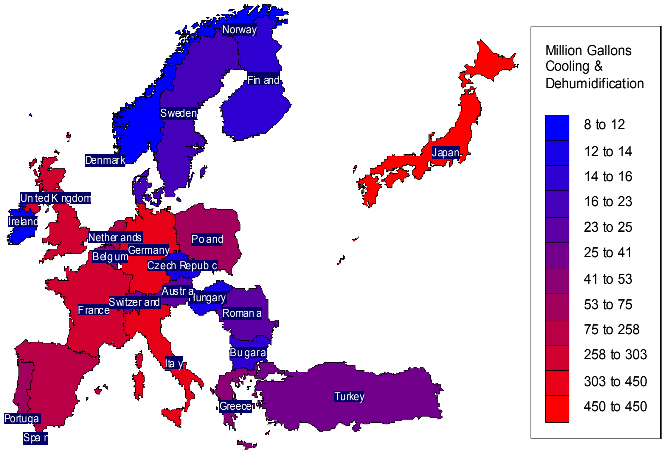

Figure 13. EU and Japan Fuel Used for A/C

By incrementally scaling the A/C power consumption, we were able to generate an estimate of U.S. fuel savings and greenhouse gas emission reductions vs. improvement in COP (Figure 14). If the COP of the existing fleet of vehicles could be improved by 30%, the U.S. annual A/C fuel consumption would be 5 billion gallons, saving 2 billion gallons of fuel a year. Of course, it will take many years for new vehicles with improved air conditioning to replace existing vehicles.

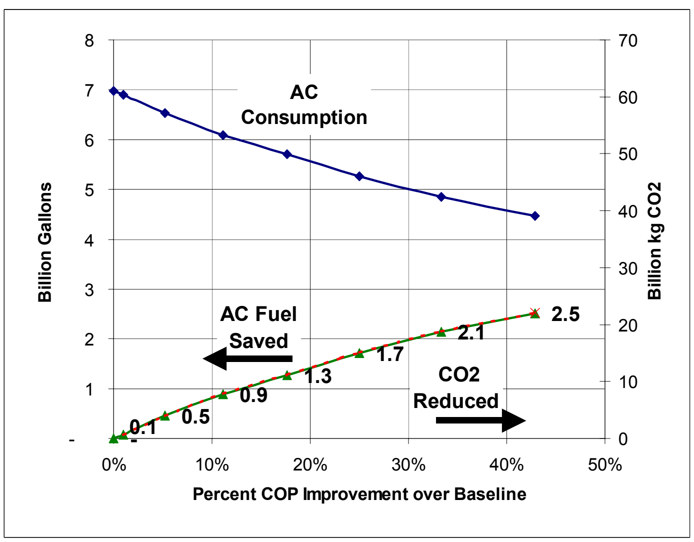

Figure 14. U.S. Fuel Saved & CO2 Reduced by Increasing COP

We also looked at the impact of reducing A/C power on an individual vehicle case for the United States. Figure 15 shows that if the A/C power were reduced to 70% of baseline, an average of 11 gallons would be saved per vehicle. This fuel savings curve enables a simple calculation of the money that can be saved by using more fuel-efficient climate control systems.

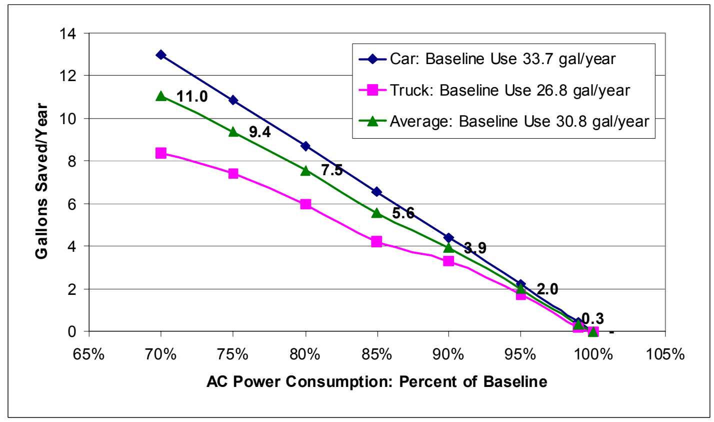

Figure 15. Per Vehicle Fuel Saved by Reducing A/C Consumption

The improved A/C systems will provide a package of savings to new vehicle owners including fuel savings, repair savings from lower refrigerant leakage, and time savings by less frequent refueling and maintenance. Figure 16 shows the estimated cost savings as a function of length of vehicle ownership. If the average vehicle life was 12 years, the savings from an improved A/C system would be $338 in 2004 dollars. If the original cost of the improved A/C system was less than $338, the owner would recover the initial investment and save money over the life of the vehicle. If the improved A/C system resulted in a smaller fuel tank while the driving range was maintained, vehicle fuel use would be reduced because less fuel mass would be carried around in the tank.

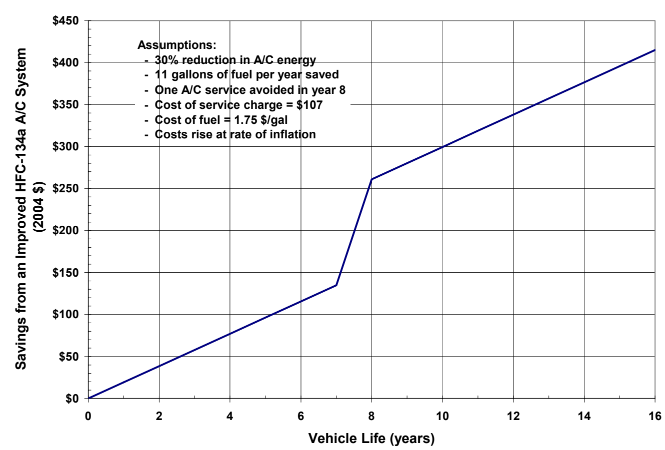

Figure 16. Savings from an Improved A/C System

It is understood that in order to impact national A/C fuel use, a fuel reduction technology would have to be introduced in new vehicles and the fleet composition would gradually change as older vehicles were retired. Figure 17 shows the fuel saved for a 15% and 30% reduction in A/C power. In 2025, the United States could save 3.7 billion gallons per year if the A/C power consumption were reduced 30%. For this example, the A/C fuel reduction technology was incorporated in 2010. Using DOE's Vision model, the fleet was assumed to grow through time with 234 million vehicles in 2010 and

293 million in 2050. We assumed the fleet turned over in 16 years and the VMT increased from 13,500 miles in 2010 to 19,950 miles in 2050.

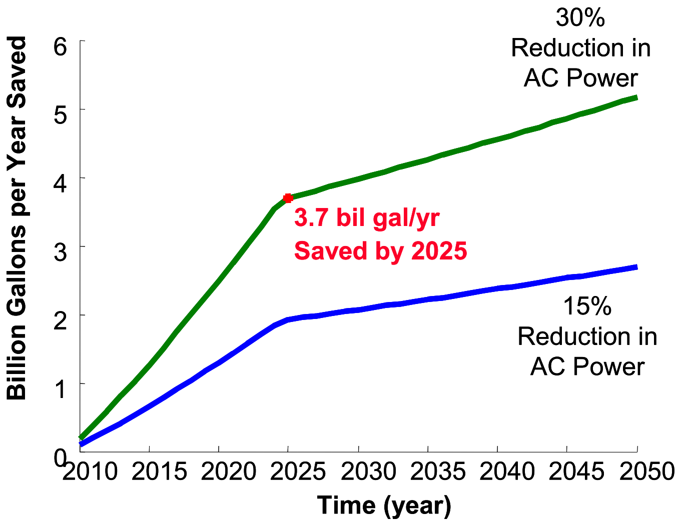

Figure 17. U.S. Fuel Savings Taking into Account New Technology Penetration

For the EU, the annual fuel savings as a function of percent of baseline A/C power consumption is shown in Figure 18. If the A/C power consumption was 70% of baseline, 1.26 billion gallons of fuel would be used for MACs resulting in a savings of 0.56 billion gallons.

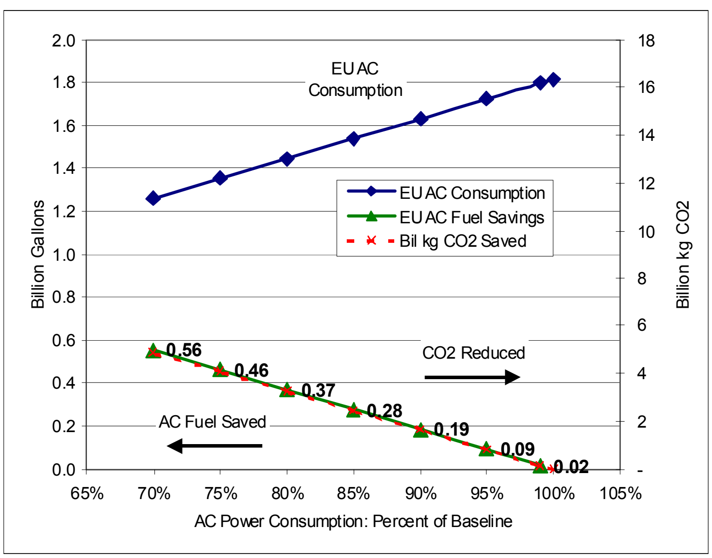

Figure 18. EU Fuel Saved by Reducing AC Power Consumption

CONCLUSION

NREL performed a rigorous bottom-up analysis to predict current average A/C fuel use and potential fuel savings. The analysis includes such factors as environmental conditions, vehicle type, thermal comfort, vehicle usage patterns, and vehicle registrations. Updates from the previous analyses include a single clothing assumption, new compressor power data, MRT model, and A/C use for demisting. The modeling results show that the United States uses at least 7.0 billion gallons of fuel a year for A/C, which is equivalent to 5.5% of the total consumption or 9.5% of imported oil. Assuming 100% of vehicles have A/C, the EU would use 1.8 billion gallons annually. This is equivalent to 3.2% of the total consumption. From a greenhouse gas perspective, vehicle MACs generate 62 billion kg of CO_2 a year in the United States and 16 billion kg of CO_2 in the EU. A/C fuel use impacts the world's energy and environmental security.

By reducing the passenger compartment thermal load, improving the effectiveness of the delivery of the conditioned fluid to provide comfort, and improving the efficiency of A/C components and systems, countries can reduce A/C fuel use and emissions while reducing the amount of imported oil.

ACKNOWLEDGMENTS

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