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Fuel Savings and Emission Reductions from Next-Generation Mobile Air Conditioning Technology in India

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Fuel Savings and Emission Reductions from Next-Generation Mobile Air Conditioning Technology in India

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ABSTRACT

Up to 19.4% of vehicle fuel consumption in India is devoted to air conditioning (A/C). Indian A/C fuel consumption is almost four times the fuel penalty in the United States and close to six times that in the European Union because India's temperature and humidity are higher and because road congestion forces vehicles to operate inefficiently.

Car A/C efficiency in India is an issue worthy of national attention considering the rate of increase of A/C penetration into the new car market, India's hot climatic conditions and high fuel costs.

1 INTRODUCTION

India is experiencing record economic growth and middle class affluence, and its car market is in a period of rapid expansion. In 2004, India produced more than 1 million vehicles domestically (1); 65% of those were equipped with air conditioning (A/C). As India grows in affluence, A/C is increasingly a standard feature on new vehicles. By 2010, 100% of cars are expected to be sold with factory-installed A/C systems (2). In light of the expanding car A/C market and worldwide energy security issues, The Energy Resources Institute (TERI) and the National Renewable Energy Laboratory

(NREL) collaborated to quantify the fuel consumption of passenger car A/C systems in India.

Previous analysis by NREL determined that vehicle A/C systems account for 5.5% of total vehicle fuel consumption in the United States (3). NREL estimated if all vehicles in the European Union and Japan had A/C systems, 3.2% and 3.4% of total vehicle fuel consumption, respectively, would be devoted to vehicle A/C (3). In India, the number of annual cooling hours is greater than in the United States, the European Union, or Japan, and Indian cars typically have smaller engines than do those in the United States, the European Union, or Japan. These factors together contribute to a higher proportion of fuel devoted to A/C in Indian cars. This higher fuel consumption leads to additional emissions from fuel combustion.

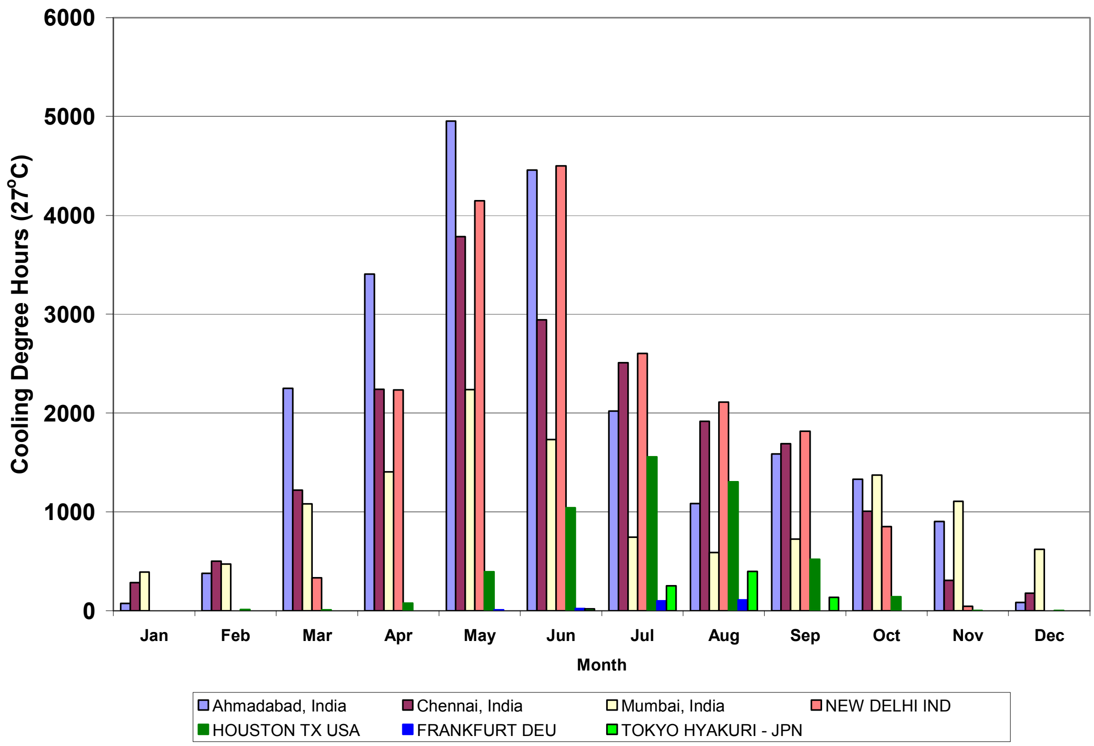

Figure 1: Cooling degree hours from around the world

Recent advances in mobile air conditioning (MAC) technology have demonstrated fuel savings and decreased tailpipe emissions from improving car A/C system efficiency. This is of particular interest in India where megacities like Mumbai and New Delhi have battled air quality issues for decades. This paper quantifies the MAC fuel consumption of the typical Indian vehicle and explores the potential fuel savings and emissions reductions by improving MAC systems with the next generation of car A/C systems.

2 BACKGROUND

As a party to the Montreal Protocol, India fully completed its new car A/C system transition to a nonozone depleting refrigerant in 2003. At the same time, to meet Kyoto

Protocol obligations, countries and regions such as Japan and the European Union began to move in earnest to the next generation of nonozone depleting, low-global warming impact A/C systems, including improved HFC-134a, carbon dioxide (CO_2), and HFC-152a. Each system has advantages and disadvantages, depending on climatic conditions, servicing requirements, and service infrastructure needs.

Aware of how the Indian car A/C market is transforming and of India's plan for export of cars, the United Nations Environment Programme, the United Nations Development Programme, TERI, the Indian Institute of Technology–Delhi (IIT−Delhi), the Ministry of Environment and Forests, Government of India and the U.S. Environmental Protection Agency (EPA) collaborated in 2005 to host a high-level policy event in New Delhi to inform the Indian government and industry officials about recent technology and policy changes in the arena of car A/C systems. At this event, titled Workshop on Technology Cooperation for Next-Generation Mobile Air Conditioning, NREL and the EPA presented a preliminary Indian MAC fuel analysis. This work used U.S. vehicle engine and A/C compressor specifications scaled down to match a Maruti 800 with a 117-cc HFC-134a compressor. That initial analysis resulted in a 20% to 30% fuel penalty associated with vehicle A/C use in Indian climatic conditions. This work builds on that earlier analysis and improves the technical specification assumptions by using data inputs directly from Indian car manufacturers, Indian A/C system suppliers, Indian industry trade organizations, and Indian government authorities[1].

3 METHODOLOGY

3.1 Data collection

This study began with TERI collecting the best available data to quantify India's fuel consumption. TERI formed the India MAC Fuel Analysis Steering Committee to guide the development, generation, and analysis of data that were most appropriate for this study. The Steering Committee included representatives from Subros, Tata Motors, IIT−Delhi, the Automotive Research Association of India, the Society of Indian Automobile Manufacturers (SIAM), the Indian Institute of Petroleum, and the Central Institute of Road Transport.

3.2 NREL models

This analysis follows the same procedure used in "Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning," which used the Advanced Vehicle Simulator 2004 (ADVISOR 2004) to determine the impact of A/C on vehicle fuel use and Fanger's thermal comfort model (4) to determine passenger comfort and A/C ON times. The thermal comfort results and ADVISOR 2004 results were

[1] Some data points used in the analysis were protected by confidential business information rules and not shared with this study. In those cases, NREL used baseline assumptions from previous cases, scaled appropriately to Indian conditions.

combined with vehicle population data and driving statistics to finally determine the fuel used for vehicle A/C.

The ADVISOR 2004 model incorporated data on typical Indian driving conditions, the typical Indian passenger car with A/C, and technical specifications of the typical Indian passenger car and its A/C compressor.

The underlying premise of this analysis is that if a person is uncomfortable, he or she will take action to become more comfortable (i.e., turn on the A/C). A person's sense of thermal comfort is primarily related to the thermal balance of the body as a whole. Physical activity, clothing, air temperature, mean radiant temperature, air velocity, and humidity all influence the body's thermal balance. When these factors are measured or estimated, the thermal sensation for the body as a whole can be predicted by calculating the predicted mean vote (PMV). The predicted percent dissatisfied (PPD) can then be calculated from the PMV. The PPD is a measure of the percentage of people likely to feel too hot or too cold in a given environment. Then, following the premise of the analysis, this percentage equals the percentage of people who would use the vehicle's A/C system if they are uncomfortably warm. Fanger's work assumes that all humans respond similarly to a given thermal environment (5). Future work on this topic may customize the analysis to specific Indian cooling comfort preferences.

3.3 Climatic conditions of India

Climatic conditions play a major role in thermal comfort calculations. India has a wide range of climatic zones, including a) hot and dry, b) warm and humid, c) moderate, d) cold and cloudy, e) cold and sunny, and f) composite. Figure 2 indicates where these climate zones are. Nine cities were selected for this study as representative of India's diverse climatic conditions; these account for approximately 80% of India's total vehicle population. Details on these cities can be found in the Appendix.

TERI compiled the weather database, based on hourly data from 1981 to 1992, for the Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE). Developing an accurate and validated weather database is a big challenge. Data are typically gathered from automated weather stations, which are usually located at airports. Airports are often located away from urban centres, so their temperature measurements are usually somewhat lower than those taken at urban centres (the heat island effect). Data often have "holes" or missing elements that must be either filled or smoothed. The final compiled database must reflect long-term representative measurements and not temporal trends. The final database is generated via a sophisticated statistical analysis. Further discussion of the methodology used to develop the data or the validity of the data is beyond the scope of this paper. A full discussion of weather data is best obtained from the American Society of Heating, Refrigerating and Air Conditioning Engineers, at http://www.ashrae.org/.

Figure 2: Climate zones of India

The primary climate data elements used in the thermal comfort model are ambient temperature, humidity ratio (kg/kg of water vapour to dry air) and direct and diffuse integrated radiation (Wh/m^2). These data were sourced from the 2005 ISHRAE data set.

Climatic conditions for the selected Indian cities were synthesized and formatted for input into the thermal comfort model. As an example, Figure 3 plots New Delhi's hourly temperature, time of day, and month. The thermal comfort model uses these data as the initial air temperature in the car when car occupants determine A/C use. This method does not consider the added solar load that contributes to higher interior car temperature, which causes the overall A/C operation estimate to be conservative.

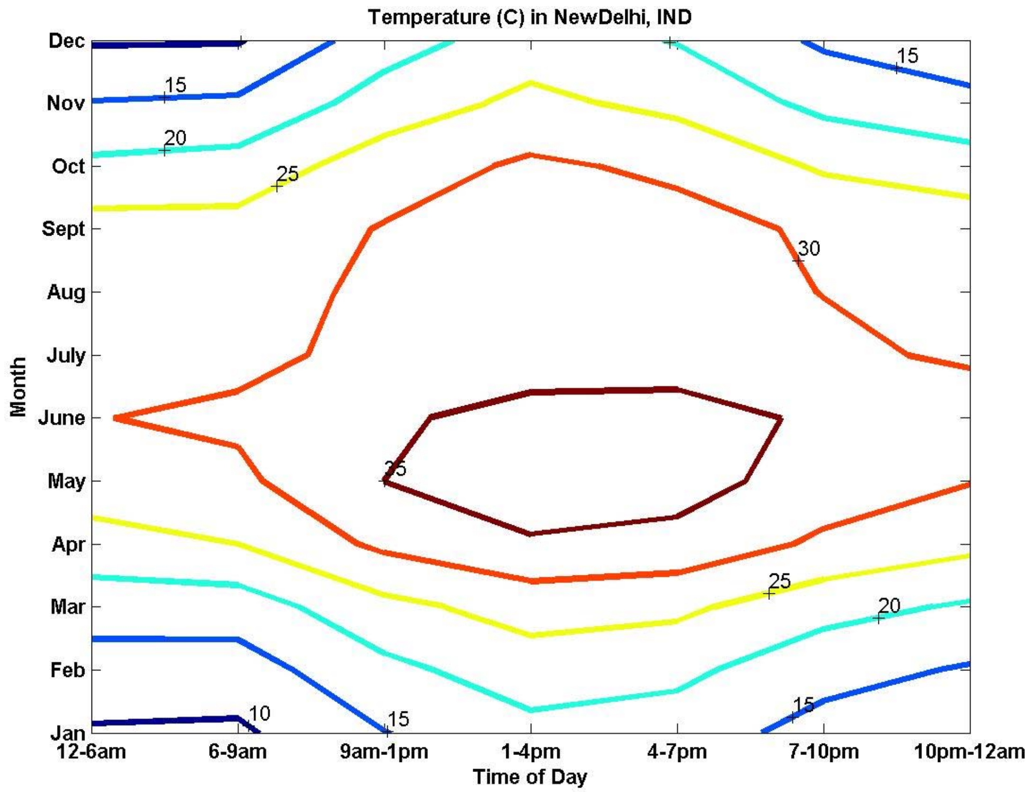

Figure 3: Ambient air temperature (°C) for New Delhi

The humidity ratio data are another input to the thermal comfort model. Humidity affects thermal comfort and is important to A/C performance because of the energy used to condense water on the evaporator.

The cabin of a passenger vehicle is a complex thermal environment that consists of hot surfaces (those exposed to the sun, such as the instrument panel) and relatively cooler surfaces that are shaded from the sun, such as the floor. The mean radiant temperature (MRT) is an average temperature of the vehicle cabin with which a passenger exchanges thermal radiation. Extensive testing at NREL has determined a correlation for MRT based on vehicle size, ambient temperature, solar radiation load, and time of day (time that the vehicle has stayed in the sun). Smaller vehicles, with their smaller mass, tend to have a higher MRTs and relatively higher ratios of glass exterior area to total car body area.

Specific data to determine the Hyundai Santro MRT were unavailable, so this study used the MRT correlation for a midsized U.S. car. The typical Indian vehicle with A/C is smaller than a midsized U.S. car, which leads to a conservative MRT value. Further details of MRT calculation can be found in Rugh et al (3).

In the thermal comfort model, Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) are used to predict the thermal comfort level. PMV is an empirical equation for predicting the average vote of a large number of people on a 7-point scale (−3 to +3) on thermal sensation scale of thermal comfort. PPD is used to predict the thermal sensation and the degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments and to specify acceptable thermal environmental conditions for comfort (6). Throughout this study, PPD is synonymous with the percentage of time the air conditioning is turned on. Figure 4 shows a PPD plot diagram of New Delhi. As shown in Figure 4, between 9am and 10 pm during the month of June, 100% of the population would be predicted to be dissatisfied with the thermal environment of the automobile's cabin, and thus turn on the A/C.

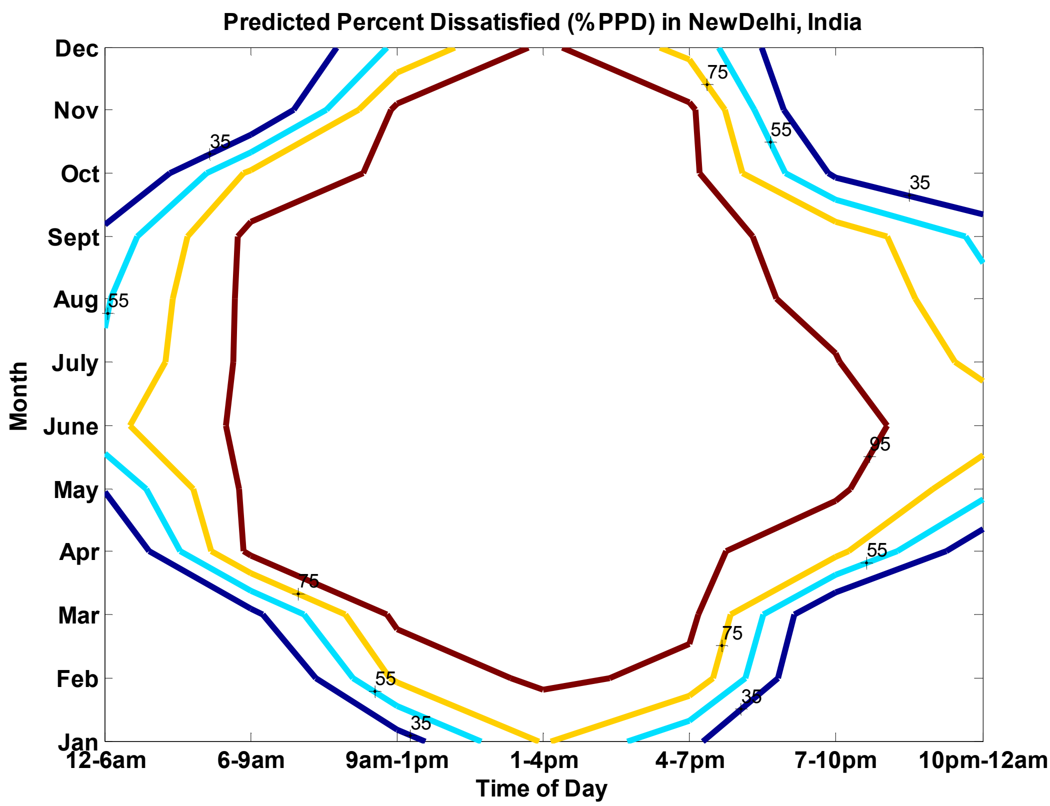

Figure 4: Percentage of time vehicle A/C is on in New Delhi

3.4 Typical Indian car with air conditioning

Based on the recommendations of SIAM and the India MAC Fuel Use Steering Committee, the Hyundai Santro (Figure 5) was selected as the typical Indian vehicle with a HFC-134a baseline A/C system. This selection is based on domestic car sales; most cars sold in India are compact models and the Hyundai Santro is a top-selling vehicle in this category. The Hyundai Santro would be considered a sub A class vehicle in the United States or the European Union. Based on input from the steering committee, this study used an A/C compressor size of 110 cc and a 46.43-kW engine.

Figure 5: Hyundai Santro

Figure 6 shows the compressor load as a function of compressor revolutions per minute. This curve was developed from the Society of Automotive Engineers Alternate Refrigerant Cooperative Research Project data. The data were interpolated to an ambient condition of 28°C and 45% relative humidity, and then the power was scaled to represent a 110-cc compressor. In ADVISOR, the compressor power was calculated using the curve in Figure 6, and the power was subtracted from engine power as a parasitic loss. The compressor/engine pulley ratio was assumed to be 1.179. Neither the A/C blower fan power nor the condenser fan power was included in the analysis. Because most vehicle trips are short and involve frequent idling, the vehicle is assumed to not achieve a cooled down status. Thus, the A/C system would operate at maximum capacity throughout its assumed operation time.

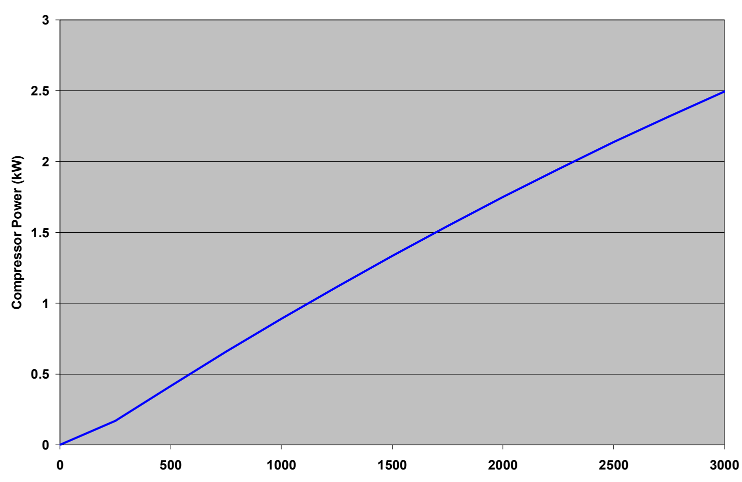

Figure 6: Compressor power versus compressor speed

3.5 Indian driving cycle

The Indian driving cycle (Figure 7) describes the speed of a vehicle over the course of a typical trip. The cycle can be graphed as the probable plot of a vehicle's speed from the start of the engine through its journey over a prescribed time given road conditions. A composite driving cycle, or a combination of highway and city drive cycles, was used to estimate fuel consumption with typical Indian driving conditions of frequent "start, stop traffic."

TERI sourced these data from the Automobile Research Corporation of India based on two drive cycles: an urban and an extra-urban cycle. TERI could not provide a combined drive cycle. Following the European Union example, a combined cycle was constructed that consisted of four urban cycles followed by an extra-urban cycle. There is no information to indicate that these cycles are used for fuel economy or emissions testing.

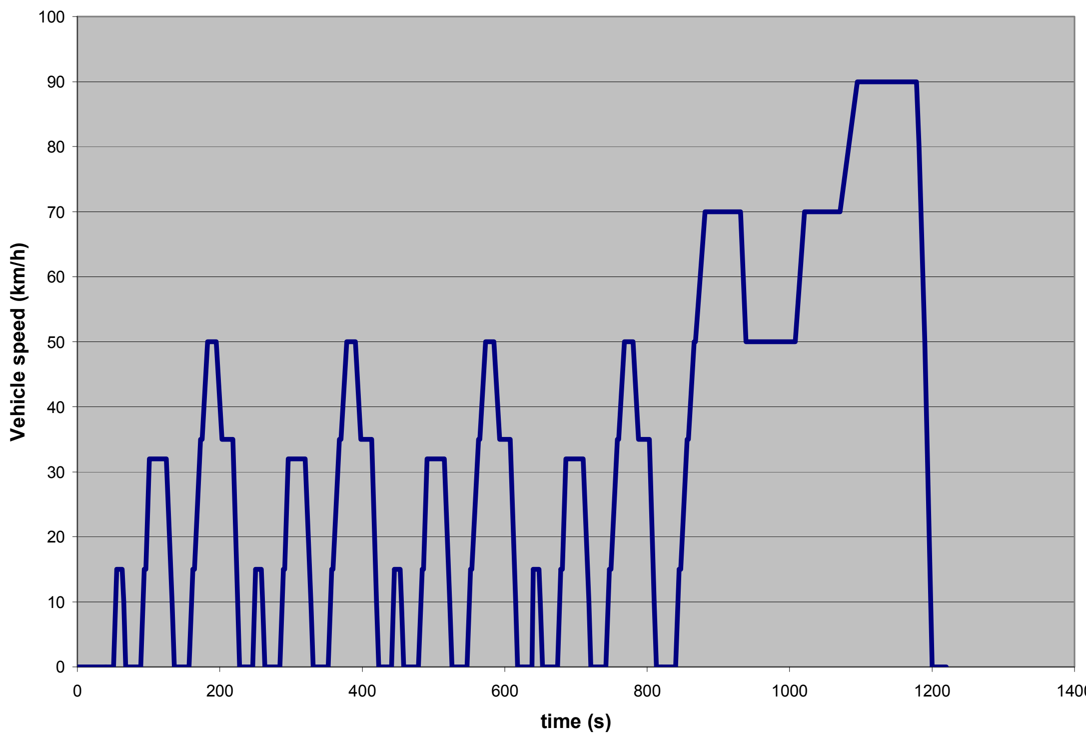

Figure 7: Composite drive cycle

3.6 Vehicle kilometres travelled and vehicle fuel economy

The India MAC Fuel Use Steering Committee reported the Indian average vehicle kilometres (km) travelled (VKT) in 2005 was 14,685 (9,125 miles) (7). In contrast, the U.S. annual average VKT is 19,171 km (11,912 miles). In this study, a key assumption is that the percent on time is equivalent to the percentage of kilometres driven with the A/C on during the year. This follows the assumption that in hot weather, drivers tend to leave A/C on for an entire trip, as most trips are short. Based on the thermal comfort model, the A/C is predicted to be on 85% of the time, so if 14,685 km (9,125 miles) are travelled in one year, 12,531 km (7,756 miles) are driven with the A/C on (14,685 km * 85.33% = 12,531 km). Some vehicle occupants lower the windows, which also degrades fuel economy as it increases aerodynamic drag. This is particularly true if the vehicle is not equipped with A/C. However, in this analysis the fuel used for A/C is computed by difference, and considers only the vehicles in the fleet that are equipped with A/C.

After determining the VKT with A/C on, the next step was to determine fuel use (litres per vehicle) with and without A/C. Fuel used per vehicle is calculated by dividing the kilometres travelled by the fuel economy (kilometres per litre [kpl]). A typical passenger car was modelled with ADVISOR 2004 software and simulated over the Indian combined driving cycle.

4 RESULTS

The typical Indian car with A/C (Hyundai Santro) uses approximately 19.4% of total vehicle fuel consumption for the A/C system. The Indian A/C fuel penalty is almost four times the fuel penalty in the United States and close to six times that in the European Union.

In this study, the A/C is assumed to be on when certain climatic conditions are met. When fuel use is observed under hotter climatic conditions, a higher fuel penalty can be associated with car A/C use.

India's higher A/C fuel consumption can be attributed to the country's smaller car engines and hotter weather. India has a substantially higher number of degree cooling hours annually. Using a baseline of 27ºC, there is a population weighted average of 14,756 annual cooling degree hours in the 9 cities in India considered in this paper. The top 10 population centres of the United States have a population weighted average 2,473 annual cooling degree hours. Comparing cooling degree hours for India and the Unites States indicates that A/C requirements in India are 6 times that of the United States.

Results from the vehicle simulation showed that the Hyundai Santro on the Indian combined drive cycle achieved a fuel economy of 19.9 km/l (46.9 mpg). As a comparison, overall cars in the United States average 9.1 kpl (21.4 mpg) and trucks average 7.3 kpl (17.1 mpg) (8). Previous analysis has assumed that European cars average 12.9 kpl (30.4 mpg). In the United States the average on time for A/C is 32.6%; in the European Union it is 21.1% (3). When the A/C load was added to the Hyundai Santro simulation, the fuel economy dropped to 15.5 km/l (36.6 mpg).

Of the next-generation refrigerant options available, TERI's car A/C market study (9) indicates that Indian car manufacturers and Indian A/C system suppliers are most prepared to move to improved HFC-134a.

Energy efficiency improvements may reduce the fuel needed by car A/C systems to obtain occupant thermal comfort. The reductions in required A/C power are hypothetical, and may result from a combination of efficiency improvements to the vehicle A/C system, from reducing the thermal load on the vehicle or from cooling the occupants more efficiently. Figure 7 shows the potential reduction in fuel used for A/C and the reduction in CO_2 emissions that could be achieved with a more energy efficient system. If these technologies were applied in India, the A/C efficiency improvements would translate to nationwide savings of up to 202 million litres (54 million gallons) of fuel saved per year and 472 metric tons (520 tons) of CO_2 emissions avoided annually (see Figure 8). Looking at per-vehicle fuel savings, almost 43 litres (11 gallons) of fuel can be saved annually.

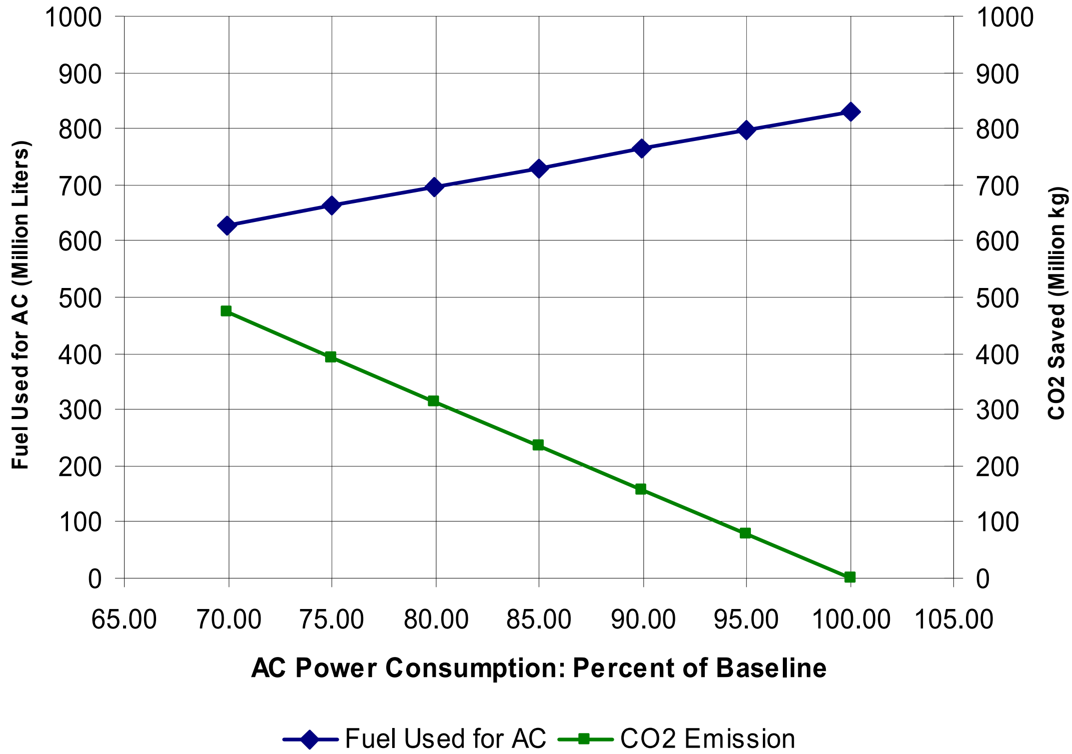

Figure 8: Fuel used and CO_2 emissions savings from improved systems

Improved HFC-134a systems provide the additional benefit of better refrigerant containment. By reducing refrigerant emissions by 50%, consumers will realize savings in repair and recharge costs.

5 CONCLUSION

Car A/C systems originally posed an ozone layer depletion concern. Now that industrialized and many developing countries have moved away from ozone-depleting substances per Montreal Protocol obligations, car A/C impact on climate has captured the attention of policy makers and corporate leaders. Car A/C systems have a climate impact from potent global warming potential gas emissions and from fuel used to power the car A/Cs. This paper focuses on car A/C fuel consumption in the context of the rapidly expanding Indian car market and how new technological improvements can result in significant fuel savings and consequently, emission reductions.

A 19.4% fuel penalty is associated with A/C use in the typical Indian passenger car. Car A/C fuel use and associated tailpipe emissions are strong functions of vehicle design, vehicle use, and climate conditions.

Several techniques: reducing thermal load, improving vehicle design, improving occupants' thermal comfort design, improving equipment, educating consumers on impacts of driver behaviour on MAC fuel use, and others - can lead to reduced A/C fuel consumption.

Car A/C efficiency in India is an issue worthy of national attention considering the rate of increase of A/C penetration into the new car market, India's hot climatic conditions and high fuel costs. Reducing A/C fuel use has the potential to greatly benefit India, including reduced reliance on imported oil and reduction of greenhouse gas emissions.

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