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Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range

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Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range

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Abstract:

Vehicle air-conditioning can significantly impact fuel economy and tailpipe emissions of conventional and hybrid electric vehicles (HEV) and reduce electric vehicle (EV) range. In addition, a new U. S. emissions procedure, called the Supplemental Federal Test Procedure (SFTP), has provided the motivation for reducing the size of vehicle air-conditioning systems in the United States. The SFTP will measure tailpipe emissions with the air-conditioning system operating. Current air-conditioning systems can reduce the fuel economy of high fuel-economy vehicles by about 50% and reduce the fuel economy of today's mid-sized vehicles by more than 20% while increasing NOx by nearly 80% and CO by 70%.

1. Introduction

The mission at the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) is to lead the nation toward a sustainable energy future by developing renewable energy technologies, improving energy efficiency, advancing related science and engineering, and facilitating commercialization. The goal of the Cool Car Project is to work with the automotive industry to reduce the fuel used for vehicle climate control by 50% in the short-term and 75% in the long-term while maintaining or improving the occupants' thermal comfort and safety.

The power necessary to operate a vehicle air-conditioning compressor is significant – it can be greater than the engine power required to move a mid-sized vehicle at a constant speed of 56 km/h (35 mph). A 400-W load on a conventional engine can decrease the fuel economy by about 0.4 km/L (1 mpg). The United States could save over $6 billion annually if all the light-duty vehicles in the country achieved a modest 0.4-km/L (1-mpg) increase in fuel economy.

The size of the air-conditioning system is related to the peak thermal load in the vehicle. The peak thermal load is generally related to the maximum temperature the cabin will reach while soaking in the sun. The thermal load can be further reduced by using more efficient distribution of the treated air as well as using more efficient equipment (such as by using waste heat to provide cooling). We have considered a variety of technologies to reduce climate control loads such as advanced glazings, heated/cooled seats, parked car ventilation, recirculation strategies, and air cleaning[1,2]. In this paper, we present the benefits of solar-reflective glazing, the impact of treating large volumes of outside air, and thermal comfort. The peak load can be reduced by reducing the solar gain into the vehicle and by using ambient air to cool the hot vehicle cabin. Solar energy enters the vehicle and raises the cabin soak temperature through two paths: the windows and the opaque components of the vehicle, such as the roof. Although it may seem intuitive to insulate the vehicle roof to reduce the solar gain, roof insulation can actually increase the cabin temperature, because the roof (particularly if it is light-colored) serves as a heat rejection path as the cabin temperature rises.

An automobile is used, on average, about 249 hours annually[3] or about 41 minutes per day, 365 days a year. Estimates of air-conditioning use range from 107 to 121 hours per year[4] or 43% to 49% of vehicle usage. Actual use varies considerably depending on such factors as climate, time of day, time of year, type of vehicle (including vehicle color), outdoor/indoor parking, occupant clothing, recent occupant activity levels, length of trip, vehicle speed, and personal preference. Gasoline use in the U.S. in 1998 was about 473 billion liters (125 billion gallons) for on-road use[5] including gasoline-fueled commercial trucks. In 1998 there were about 203.6 million cars and light duty trucks on the road[6] including sport utility vehicles and minivans. This resulted in an average fuel use of 2316 liters (612 gallons) of gasoline per vehicle, or about 8.3 km/l (19.6 mpg) for an average of 19,300 km/yr (12,000 miles/year) at an average speed of 77.5 km/h (48.2 mph) (assuming 249 hours of driving time per year). Each vehicle, on average, uses about 235 liters (62 gallons) of gasoline annually for operating the air-conditioning system. Fischer has estimated that the annual fuel required to carry the additional weight of the air-conditioning system is about 12.7 liters (3.4 gallons) per vehicle. Given the above assumptions, the estimated total fuel used for air-conditioning, if 80% of the vehicles have working air-conditioning systems, is about 40 billion liters (10.6 billion gallons) of gasoline annually.

Until recently, little has motivated U.S. auto makers to find ways to reduce the impact of air-conditioning on fuel economy and emissions. But a new emissions regulation, the Supplemental Federal Test Procedure[7] (SFTP), will include air-conditioning as part of the emissions testing procedure. Table 1 shows the SFTP implementation schedule and the specifications are given in Table 2. The test procedure consists of the current emissions test (called the Federal Test Procedure or FTP), an air-conditioning test (SC03), and a high-speed, high-acceleration test (US06). The SFTP applies to vehicles with a gross vehicle weight under 2608 kg (5750 lb). The air-conditioning portion of the SFTP will contribute 37% of the total tailpipe emissions. The SC03 is conducted at 35°C (95°F), 850 W/m^2, and 100 grains of water per pound of dry air.

Although the SFTP is not used to measure fuel economy, reducing the weight of a mid-sized vehicle's air-conditioning system by 9.1 kg (20 lb) results in about a 0.04 km/L (0.1 mpg) increase in fuel economy on the current combined city/highway test.

Table 1. SFTP Implementation Schedule

	Percent of vehicles subject to SFTP
MY[a] 2001	25%
MY 2002	50%
MY 2003	85%
MY 2004	100%

[a] Model year

Table 2. Supplemental Federal Test Procedure Specifications

	FTP	SC03	US06
Time (s)	1877	594	600
Max. speed, km/h (mph)	91.2 (56.7)	88.2 (54.8)	129.2 (80.3)
Max. acceleration, km/h/s (mph/s)	5.8 (3.6)	8.2 (5.1)	12.9 (8)
Distance, km (miles)	17.8 (11.1)	5.8 (3.6)	12.9 (8)
Contribution to total emissions value	35%	37%	28%

2. Fuel Economy and Range Impacts of Air-Conditioning

Figure 1 shows the impacts of auxiliary loads on a conventional vehicle and on a high fuel economy vehicle for the SC03 drive cycle. Using ADVISOR[8,9] (ADvanced VehIcle SimulatOR), the conventional vehicle is modeled as a 1406-kg (3100-lb), 3.0-L, spark-ignition engine, with an 800-W auxiliary load resulting in a combined city-highway fuel use of 8.78 L/100 km (26.8 mpg). The high fuel economy vehicle is modeled as a 907-kg (2000-lb), 1.3-L, direct-injection, compression-ignition engine, parallel hybrid with a base auxiliary load of 400 W and a resulting combined metro-highway fuel use of 2.89 L/100 km (81.5 mpg). The fuel economy of a nominally 3.0 L/100-km (80-mpg) vehicle over the SC03 drive cycle could drop from 37 km/L (87 mpg) with 400-W base electric load to about 21.1 km/L (50 mpg) with an auxiliary load of 2000 W.

To analyze the impacts of air-conditioning loads on the range of a near-term EV and on the fuel economy of a near-term HEV, we modeled two vehicles: a lightweight-chassis, five-passenger, NiMH battery EV (Table 3) and a lead-acid battery HEV (Table 4). Two engine manufacturers are listed for the HEV because two engines were scaled to the same maximum power and efficiency, separately modeled in the simulations, and the fuel economy results averaged.

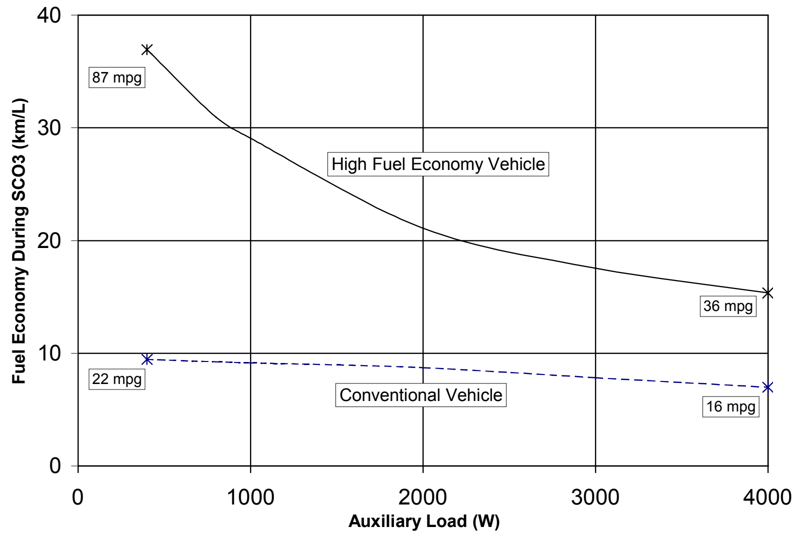

Figure 1. Fuel Economy Impacts of Auxiliary Loads

Table 3. EV Specifications

Parameter	Value	Motor		Battery Pack	
Test Mass	1599 kg	Max. Power	75/135 kW (continuous/ intermittent)	Type	NiMH
C_D*A	0.67 m^2	Max. Torque	271/488 Nm (continuous/ intermittent)	Manufacturer	Ovonic
Fixed Gear Ratio	6.7	Max. Speed	10,000 rpm	Pack Voltage	327 V
Accessory Load	500 W			Pack Energy	30.4 kWh
				Pack Mass	412 kg

Table 4. HEV Specifications

Parameter	Value	Motor		Battery Pack		Fuel Converter (Engine)	
Test Mass	1136 kg	Max. Power	41/68 kW (continuous/ intermittent)	Type	Lead-acid	Manufacturer	Isuzu / Chrysler
C_D*A	0.67 m^2	Max. Torque	171/284 Nm (continuous/ intermittent)	Manufacturer	Hawker	Max. Power	55 kW
Number of gears	5	Max. Speed	7500 rpm	Pack Voltage	144 V	Max. Efficiency	38% (spark ignition)
Accessory Load	500 W			Pack Energy	3.7 kWh		

We estimated the impact of auxiliary loads for the driving cycles scheduled for use in U.S. EPA certification procedures: FUDS (an urban driving cycle), HWFET (a highway driving cycle), SC03, and US06. The HEV had a combined metro-highway fuel economy of 5.19 L/100 km (45.4 mpg).

The maximum thermal cooling load was assumed to be 7 kW. The net coefficient of performance of the electrically driven air-conditioning system, including the efficiency of the compressor and the electric motor required to drive it, was assumed to be 2.33. This yielded a maximum electrical load (resulting from air-conditioning) of 3 kW, which was added to the baseline value of 500 W in increments of 1000 W to determine the impact of auxiliary loads. All simulated cycles for the HEV model started and ended at the same battery state-of-charge, to within 0.5% of the initial pack capacity.

Table 5 shows the results for the EV range and Table 6 presents the HEV fuel economy. The first row indicates that an increase of the accessory load from 500 W to 3500 W will cause the EV range on a repeated FUDS cycle to decrease by 38%. The first 1000-W increase, which increased the accessory load from 500 W to 1500 W, caused a greater percentage decrease in range than did the successive increases in accessory load.

Table 5. Electric Vehicle Range Simulation Results

	500 W	1500 W		2500 W		3500 W	
	Range km (mi)	Range km (mi)	Change from 500 W Case	Range km (mi)	Change from 500 W Case	Range km (mi)	Change from 500 W Case
FUDS	175.9 (109.3)	147.7 (91.8)	-16%	125.5 (78.0)	-29%	108.9 (67.7)	-38%
HWFET	183.6 (114.1)	167.5 (104.1)	-9%	154.0 (95.7)	-16%	142.1 (88.3)	-23%
US06	116.0 (72.1)	107.6 (66.9)	-7%	102.5 (63.7)	-12%	95.3 (59.2)	-18%
SC03	174.3 (108.3)	146.9 (91.3)	-16%	126.8 (78.8)	-27%	111.2 (69.1)	-36%

The peak air-conditioning load of 3000 W of electric power (in addition to the base electrical load of 500 W) reduces EV range over SC03 drive cycle by 36%. An electrical air-conditioning load of 1000 W, which might meet steady-state air-conditioning requirements for a small sedan, reduces SC03 range by 16%. Peak air-conditioning load, 3000 W of electric power, increases SC03 HEV fuel use by 57%. An electrical air-conditioning load of 1000 W, which might meet steady-state air-conditioning requirements for a small HEV sedan, increases SC03 fuel use by 16%.

3. Tailpipe Emissions

Table 7 presents the modeled increase in tailpipe emissions for a conventional vehicle and the SC03 drive cycle that results from air conditioning use, where the net coefficient of performance (COP) is defined as the product of the air-conditioning system's COP and the compressor efficiency. The baseline without air conditioning assumed an auxiliary load of 500 W. There is significant engine-to-engine variation for each pollutant as well as a dependence on the COP. The results from the modeling show that the air conditioning system can increase tailpipe emissions significantly, more than doubling the CO and NO_x depending on the engine modeled.

Table 6. Hybrid Electric Vehicle Fuel Economy Simulation Results

	500 W	1500 W		2500 W		3500 W	
	Fuel Use (L/100 km) Fuel Economy [mpg]	Fuel Use (L/100 km) Fuel Economy [mpg]	Change from 500 W Case	Fuel Use (L/100 km) Fuel Economy [mpg]	Change from 500 W Case	Fuel Use (L/100 km) Fuel Economy [mpg]	Change from 500 W Case
FUDS	5.45 [43.2]	6.51 [36.1]	19% [-16%]	7.69 [30.6]	41% [-29%]	9.03 [26.0]	66% [-40%]
HWFET	4.88 [48.3]	5.18 [45.4]	6% [-6%]	5.48 [42.9]	12% [-11%]	5.84 [40.3]	20% [-16%]
US06	6.64 [35.4]	6.94 [33.9]	5% [-4%]	7.30 [32.2]	10% [-8%]	7.70 [30.6]	16% [-12%]
SC03	5.96 [39.5]	6.91 [34.1]	16% [-10%]	7.96 [29.5]	34% [-19%]	9.38 [25.1]	57% [-28%]

Table 7. Predicted Increase in Tailpipe Emissions Resulting from AC During SC03 Drive Cycle

Engine	Net COP = 2.25			Net COP = 1.25		
	HC	CO	NO_x	HC	CO	NO_x
1.5-L Geo	31%	22%	52%	50%	50%	113%
1.9-L Saturn	4%	51%	39%	13%	125%	58%
3.0-L Dodge	24%	26%	29%	46%	68%	56%
3.0-L Toyota	18%	11%	31%	29%	20%	54%

The Clean Air Vehicle Technology Center used the SC03 test to measure the effect of the air-conditioning system on fuel economy and tailpipe emissions for a variety of vehicles[10]. Table 8 shows the average impacts of seven vehicles ('95 Voyager, '97 Taurus, '95 Civic, '95 F-150, '97 Camry, '96 Camaro, and '95 Skylark) with the air-conditioning system on, compared with the results with the air-conditioning system off.

Table 8. SC03 Test Results

	Increase
CO	+71%
NOx	+81%
NMHC	+30%
Fuel Economy (km/L or mpg)	-22%

On average, the CO emissions increased 0.42 g/km (0.675 g/mile) and NOx increased 0.053 g/km (0.085 g/mile) with the air-conditioner operating. If we assume that 19,300 km (12,000 miles) are driven annually, with the air-conditioner operating 45% of the time, (or for 8700 km (5400 miles)), that the test results, (including the SC03 drive cycle) are representative of light duty vehicles, and that 80% of the vehicle fleet have working air-conditioning systems, then vehicle air-conditioning use increases CO by 594,000 metric tons (655,000 tons) and NOx by 74,000 metric tons (82,000 tons).

4. Opportunities to Reduce Air-Conditioning Loads

Vehicle air-conditioning systems in the United States are often sized to provide adequate cool down time for a peak cooling load in Phoenix, Arizona, with a solar load of 1 kW/m^2 and 49°C (120°F) ambient temperature. Such conditions can lead to surface temperatures of more than 121°C (250°F) and cabin air temperatures higher than 82°C (180°F). The peak load can be two to four times greater than the steady-state cooling load. The cabin soak temperature must be lowered to reduce the size of the air-conditioning system.

Advanced Glazings

The Federal Motor Vehicle Safety Standards require that all glazing in passenger cars have a photopically-weighted transmissivity of 70% while light trucks, SUVs, and minivans have no transmissivity requirement for glazing behind the front seats. If transmissivity requirements for passenger cars were the same as SUVs and minivans, then more efficient glazing could be used resulting in less fuel for air-conditioning. The transmissivity of the glazing is measured perpendicular to the glazing. If the standards were to measure the transmissivity parallel to the road, in-line with the driver's normal eye sight, then angularly selective glazings could be used to keep solar energy out of the vehicles.

Using a Plymouth Breeze as the test vehicle, we measured the effect of advanced glazings. We tested three windshields supplied by PPG: Solex®, a standard windshield in the United States; Solar Green®, a windshield used in European vehicles; and Sungate®, an advanced ultraviolet and infrared reflecting windshield.

Advanced windshields, such as PPG's Sungate®, effectively reduce the transmission of ultraviolet and infrared solar radiation into the vehicle compartment. Figure 2 compares the transmittance of the Sungate® windshield with that of a conventional windshield. The Sungate® windshield uses a multi-layer silver coating deposited on the glass between the inner and outer glass of the windshield to reflect infrared radiation. The electrically conductive coating can serve as the radio antenna and can also be used to electrically de-ice the windshield.

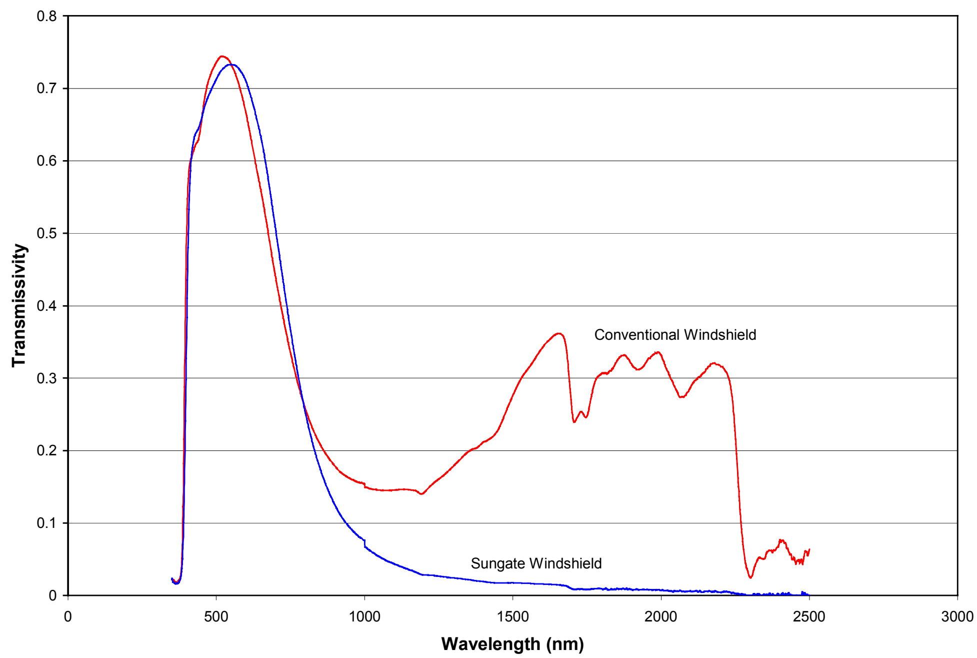

Figure 2. Transmittance of Solar-Reflecting Windshield

The Solex® windshield had 17% more thermal gain than the Sungate® windshield. The solar gains in the vehicle decreased by 27% when the standard front windshield (Solex®) was replaced with the Sungate® windshield. If the compressor is appropriately downsized, the Sungate® windshield can increase the fuel economy of the Breeze by about 1.9% or 0.2 km/L (0.5 mpg) over the SFTP, and by about 3.5% or 0.3 km/L (0.7 mpg) over the SC03 drive cycle as shown in Table 9. At noon the Sungate® windshield reduced the solar gain by 187 W more heat than the Solex® windshield under the test conditions.

Table 9. Modeled Sungate Fuel Economy Impacts

Wind-shield	Load kW (hp)	SFTP		SC03	
		Fuel Economy km/L (mpg)	% Change from Solex	Fuel Economy km/L (mpg)	% Change from Solex
Solex®	3.9 (5.2)	10.88 (26.2)	-	8.47 (20.4)	-
Sungate®	3.5 (4.7)	11.09 (26.7)	1.7%	8.76 (21.1)	3.4%

<u>Recirculated Air</u>
After reducing the peak thermal load and the solar gain, the next most important approach to minimizing air conditioning loads is to reduce the amount of outside air brought in for ventilation. It is more effective to condition recirculated cabin air than to treat very cold or very hot air from outside.

Figure 3 illustrates the modeled benefits of using recirculated air. As the percentage of recirculated air is increased, the amount of heating or cooling thermal power required is reduced. The figure shows that only 1.2 kW is needed to maintain the cabin air at 30°C (54°F) above ambient using 100% recirculated air; 4.5 kW is needed if only outside air is used. The vehicle skin heat transfer coefficient was 50 W/K and the air flow rate for climate control was 0.167 kg/s (300 cfm) for cooling and 0.111 kg/s (200 cfm) for heating. The thermal power required is a function of the ambient temperature, total air flow rate, percent recirculated air, humidity (cooling only), and the heat gain/loss of the passenger compartment. Humidity can more than double the cooling load, which can be seen by comparing the cooling load in Denver to that in Miami.

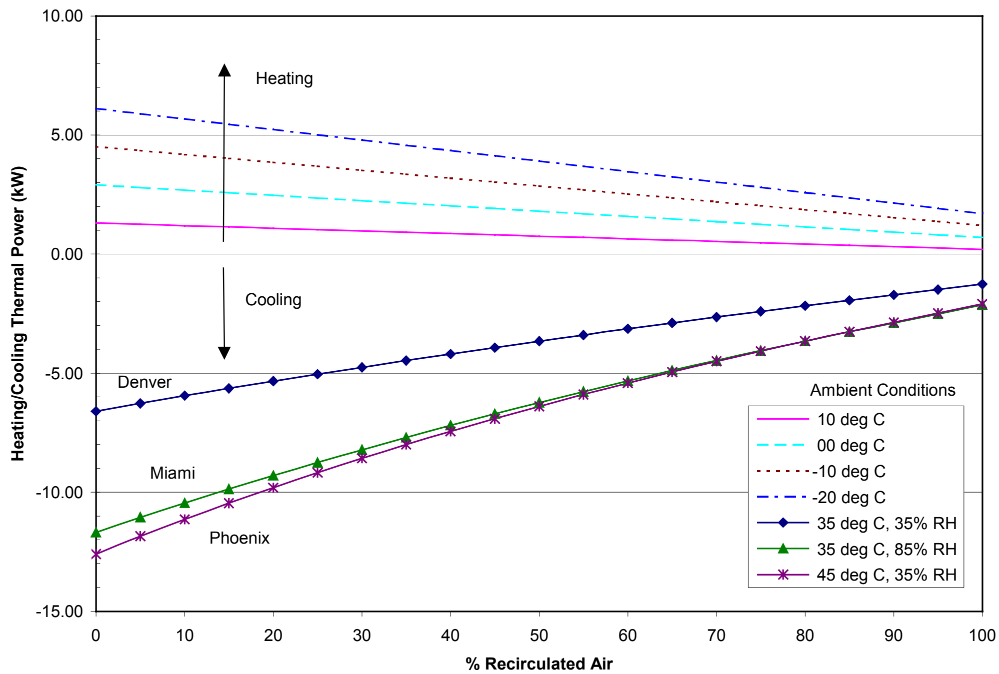

Figure 3. Heating/Cooling Thermal Power as a Function of Percent Recirculated Air and Ambient Conditions

By using advanced heating and cooling techniques and alternative means of de-icing and defogging glazings, high air flow rates become unnecessary for achieving thermal comfort. Typically 0.0084 kg/s (15 cfm) per person is needed in building applications. However, with potentially higher concentrations of VOCs in newer vehicles, higher fresh airflow rates may be desirable unless the contaminant levels are reduced. With four adults in a vehicle, approximately 0.034 kg/s (60 cfm) of outside air may be needed. This corresponds to 70% recirculated air for vehicle heating in Figure 3 and 80% recirculated air for vehicle cooling. Intelligent sensors may be used to control the amount of outdoor air as a function of the number of occupants, ambient conditions, or the contaminant concentration levels in the passenger compartment.

Thermal Comfort

After safety considerations such as defogging and deicing the windows, the next most important function of the climate control system is to provide comfort to the occupant. Thermal comfort effects driver alertness. In one study[11], drivers of a moving vehicle missed 50% of test signals at 27°C with reaction times 22% slower than at 21°C. The focus should be on the comfort of the occupant and not on achieving a uniform thermal environment within the cabin, regardless of the number of occupants. An advanced climate control system might minimize radiant loads on the occupant, remove moisture from the occupant (such as from a ventilated seat), and include direct heating and cooling of the occupants.

NREL has developed a transient thermal comfort model that estimates a person's comfort level in a vehicle during transient and steady-state conditions. The current model[12] predicts an overall thermal sensation based on a variety of environmental parameters and thermal boundary conditions. It also has the capability to measure heat exchange by conduction (such as from a heated or cooled seat.) NREL is also developing a non-homogeneous, transient model that will predict thermal sensation variations over the body under highly non-uniform conditions.
The thermal comfort model uses a time-dependent heat balance of the occupant in the cabin (including air, radiant, and contact surface temperatures; air velocity and humidity; initial body temperature; body mass; clothing type; and metabolic heat generation) to predicts physiological response of the occupant (such as core and skin temperature, blood flow, sweating, and shivering as functions of time). A statistical correlation relates these parameters to comfort parameters such as Thermal Sensation Value (TSV) and Predicted Percent Dissatisfied (PPD). TSV is a numerical scale expressing thermal sensation (0 is neutral; 1, 2, and 3 are increasingly warm sensations; -1, -2, and -3 are cold). PPD is the predicted percentage of the population that would be dissatisfied with the current thermal conditions.

Figures 4 and 5 show the results of two initial cabin temperatures, 82°C (180°F) and 66°C (151°F), with a vehicle exposed to full sun and an ambient temperature of 38°C (100°F). The lower temperature could be achieved by a

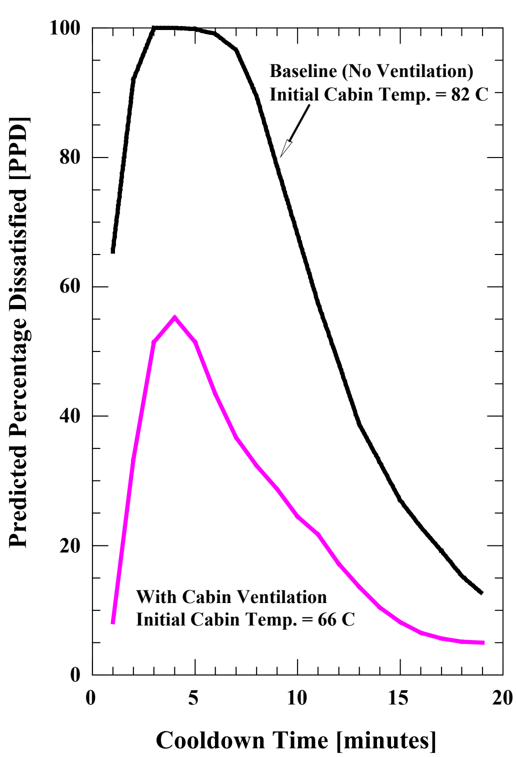

Figure 4. Example of Thermal Comfort Modeling – TSV

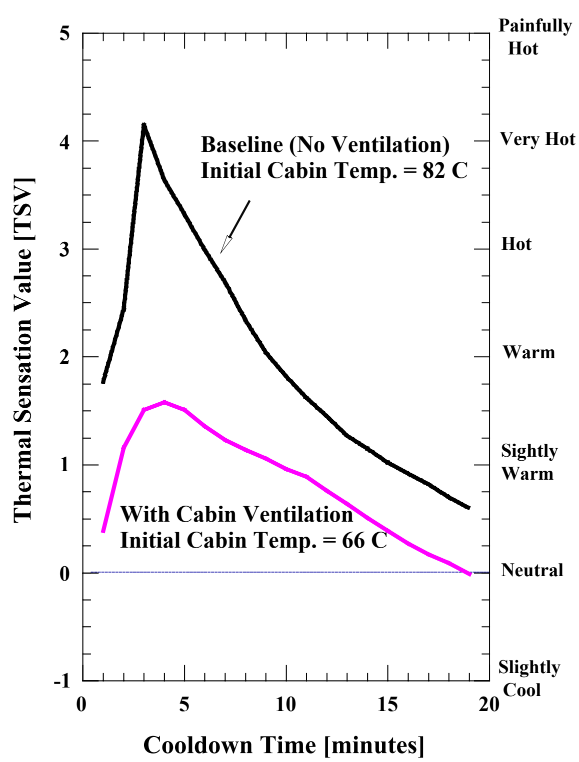

Figure 5. Example of Thermal Comfort Modeling – PPD

combination of advanced glazing and parked car ventilation. Thermal discomfort peaks after about 3 minutes as the core body temperature increases. Note that although it is possible to dissatisfy 100% of the population (at 3 minutes in the upper figure), it is not possible to satisfy 100% regardless of the allowable conditioning time.

5. Conclusion

The air conditioning system is the single largest auxiliary load on a vehicle by nearly an order of magnitude. Current air conditioning systems reduce the fuel economy of conventional vehicles, thus incremental improvements can have a significant near-term benefit because of the large number of new cars sold each year. For high fuel economy vehicles, current air conditioning systems have a completely unacceptable impact on fuel economy.

For example, conventional air-conditioning loads can reduce EV range and HEV fuel economy by nearly 40% depending on the size of the air-conditioner and the driving cycle. The peak cabin soak temperature must be reduced if a smaller air-conditioning system is to be used. Advanced glazings and cabin ventilation during soak conditions are effective ways to reduce the peak cabin temperature. To fully understand the thermal impact of vehicle modifications, effective modeling and testing must be conducted. We are continuing to investigate advanced glazing and ventilation techniques, but it is apparent that great opportunities exist to improve EV and HEV performance while reducing fuel consumption and improving air quality.

A significant benefit could be achieved if the Federal Motor Vehicle Safety Standards were modified to allow lower transmissivity for glazing behind the front seats in all light duty vehicles and if transmissivity requirements were measured parallel to the driver’s eyesight and maintained at current levels in that direction.

It is clear that significant reductions in automotive auxiliary loads are needed, making tomorrow's vehicles safer, quieter, and more fuel efficient, while making passengers comfortable more quickly. New U.S. emissions standards are also providing the impetus for evaluating new climate control designs and approaches. Vehicle climate control loads can be reduced in many ways-some of which can be readily implemented in today’s vehicles, and others that will require more development. Increasing vehicle efficiencies and decreasing polluting emissions will go a long way toward achieving the national and global goals of reduced dependency on foreign oil and improved air quality.

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