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Hot Cars, Cool Bodies, No Air Conditioners?

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Abstract

A typical modern automobile compressor-driven air conditioner, about powerful enough to cool a house, may not be needed even in very hot, humid climates if we combine insights from comfort theory with innovations in comfort delivery, photonics, and superefficient thermal and air-handling devices. Recent advances can successively minimize unwanted heat gain into the passenger cabin, cool people's bodies rather than the vehicle, deliver highly effective radiant cooling, passively reject extracted heat to the sky, and, if needed, move air very efficiently and quietly to expand the human comfort range. Together these proven innovations may give automotive occupants excellent hot-weather comfort without refrigerative air conditioning. This substitution could improve climate protection and electric-vehicle range, cut the automobile's weight and cost, avoid climate and ozone harm from refrigerants, reduce noise and air pollution, make autos more energy-efficient, and save the United States gasoline costing many billions of dollars per year. Prompt experimental tests of such integrative designs are warranted.

History

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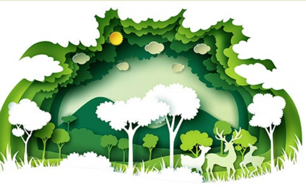



Introduction

Safe, healthful, and satisfying car driving requires an alert driver, comfortable occupants, ample ventilation, and glazings clear of ice and fogging. This article emphasizes summer comfort because it is generally more challenging than winter comfort; the world's people live mainly and increasingly in hot, humid climates; and the same or similar methods can serve both needs.

Most modern automobiles (autos) in upper-income societies have a 14 kg to ≥40 kg, ≥$1k refrigerative (vapor compression) air-conditioning system. On the United States (U.S.) average, it runs nearly half the driving time and uses ~114 L/y of fuel. Such U.S. systems in 2001 used ~26 GL of fuel or 5.5% of the U.S. autos' gasoline, costing ~$7b/y and equivalent to 9.5% of 2001 crude-oil imports [1, 2]. In 2000, a typical air-conditioning compressor could use more engine power than propelling the auto at 56 km/h [1].

Automotive air conditioning is sized for its peak load—pulling down the interior "soak temperature" (up to ~80–90°C) of a closed car parked in the sun on a hot day. Older systems sized the air conditioner like an Atlanta house (~10–15 thermal kW, or kW_t), drawing peak shaft power up to ~5–6 kW. Newer autos gain less heat, have more-efficient ≤6–9 kW_t systems, and may reduce peak shaft load to ~3 kW, but air-conditioning remains by far the largest non-propulsive load of autos, cutting the electric vehicle range by tens of percent or increasing costly and heavy battery needs for the same range. This inhibits sales and inflates recharging time and investment.

Reducing Cabin Heat Gain

Cooling loads are complex but dominated by unwanted solar heat entering through the glass and heating opaque surfaces, and by the heat and humidity of incoming air. Light-colored or sun-reflecting exterior paint can make the interior 5–6C° cooler [3], or up to ~11–12C° with sun-rejecting interior finishes and fabrics. Solar-control glass is especially important, formerly cutting ~2000 U.S. auto air-conditioning fuel use by 6–12% and cabin air temperature by ~5C° [1], or reducing a whole-cabin solar heat gain by 27% with just a solar-control windshield [1], but have since become far more sophisticated. Spectrally or angularly selective glazings can admit ample visible light but block nearly all infrared. Thermochromic or electrochromic glass—the latter now in a few autos and poised for wider affordability—can widely control optical density, if not also spectral selectivity.

Recirculating air can also save many thermal kilowatts (kW_t), especially in humid climates and with interior materials that minimize off-gassing. Air-to-air heat exchangers can recover the coolth from cabin exhaust into makeup air. A passive latent heat exchanger could also recover dryness. (Precool outside air as it enters—I'll explain how in a moment—and then evaporate its condensate into drier exhaust air; capture the resultant evaporative cooling in a heat exchanger; then heat-pipe that coolth back to the makeup-air intake to cool the outside air.)

Improving Refrigerative Air Conditioning

Automotive air conditioning typically delivers ~2–4 units of cooling per unit of input electricity or shaft power (a coefficient of performance, or COP, of ~2–4). However, fist-sized low-lift high-speed turbocompressors delivering ~9–20 kW_t can achieve [4] >60% of Carnot efficiency limits, e.g., COP of 6–15 for a lift (ΔT) of 13–31C° when heating water to 44°C. A lower-speed commercial model (bs2.ch) yields a COP of 7–8 for 5–18 kW of cooling at ΔT = 20C°.

Auto designers could emulate and miniaturize Lee Eng Lock's (李永禄) tripled-efficiency practice in cooling big Singapore buildings: design-hour whole-system (supply fans through cooling towers) COP 6.8, 3× normal, or even COP 9.4, 4.7× normal, with lower capital cost and better comfort. Heat-driven Pennington or van Zyl desiccant cycles could be far more efficient still. But the most elegant, and probably cheapest, would be nearly or entirely *passive* cooling. Is that possible?

Cooling Human Bodies

People have nervous systems and comfort sensations; autos do not. To deliver "task cooling" like task lighting, Peter Rumsey installed silent 3 × 0.9 W computer muffin fans in the mesh back of an office chair and automotive car-seat heaters (2 × 7 W) behind the back and seat meshes, all battery powered and controlled by a slider switch or smartphone app. Such "Hyperchairs" deliver ASHRAE comfort to individual needs in 16–29°C room dry bulb temperatures [5], outperforming ambient or cooled air blown through automotive seatbacks [6]. Light, crashworthy, advanced-composite-frame auto seats developed by tier-one suppliers Johnson Controls International (JCI) and BASF, starting with JCI's Genus concept seat for the Detroit Auto Show in 2005, could support such meshes.

Radiant Cooling

Automotive thermal comfort traditionally relied mainly on air conditioning, with limited attention to radiant heat transfer. With few and small exceptions, the potential for silent radiant cooling was considered unimportant. Yet a startling 2020 paper [7] demonstrated thermal comfort *with purely radiative delivery* outdoors in Singapore in a ~10-m^2 shaded pavilion. The hot, humid, still air was not cooled, dried, or moved. Instead, metal wall and roof panels were slightly cooled by circulating water. The psychrometric chart had to be extended to show this unexplored range: 17°C water provided comfort at 29.6°C ambient even with one-sided radiant cooling, and ~23–25°C could provide comfort up to ≥32°C ambient with 80% relative humidity. An air-gapped 50 μm polyethylene sheet, transmitting 82% of the infrared radiated by human bodies meters away, eliminated energy-intensive dehumidification and condensation by separating humid air from cool surfaces. Small versions of such radiant panels (durable, attractive, crash safe) could be built into an automotive headliner, subtending a big solid angle above the nearby head and neck that dominate heat transfer from otherwise clothed human bodies.

The minor cooling needed could be delivered extremely efficiently, with COP of ~10–11, by a low-lift miniature turbocompressor as mentioned above. But more elegant would be thermostatically valved or otherwise passively controlled heat piping to a *passive*, silent, zero-electricity infrared radiator [8] on the vehicle roof. Earth radiates to the cold universe as much energy flux as it receives from the Sun, and this ~100 PW outbound resource can be locally enhanced by suitable materials [9]. A spectrally selective surface tuned to reflect incident solar energy but emit infrared through the 8–13 μm atmospheric window can cool ~5C° below ambient temperature and reject 40 W/m^2 even in direct sunlight [10] or ~100 W/m^2 in commercial plates (www.skycoolsystems.com) or more: some newer materials [11, 12, 13, 14] reject ~100–120 W/m^2 for up to 13C° or 16C° of subambient cooling in direct sunlight. An approximately 3 m^2 to 5 m^2 automotive roof could thus reject heat from ~3 to 5 occupants. (The theoretical limit of 24-h-average subambient cooling is ~60C° [15].) Some radiative coolers can be applied as paint [16, 17] or fabric [18] and can be cheaply made paintable [19], flexible, and roll to roll [20]; 3M is developing an improved film for ARPA-E.

High ambient humidity reduces but does not prevent [21] radiative heat rejection ([14], Fig. 4b). For example, a structured polymer film averaging ~85 W/m^2 cooling by 6–8.9C° at midday under ~900 W/m^2 insolation also achieved ~5.5C° under even higher insolation (~930 W/m^2) at ~64% relative humidity in Xiamen [22]. Other experiments verified subambient cooling by 6–8C° in South/Central China [23], or >10C° even in Seoul and Chiang Mai [24]. A global map of radiative cooling potential ([9], Fig. 4B) shows high values in virtually all humid and populous areas. "Even under 100% relative humidity in humid areas, experiments have demonstrated >5C° subambient cooling (from 29°C ambient [25]) using a wavelength-selective radiative cooling surface" [9].

If necessary, more narrowly tuned emitters [26] could also exploit gaps in or around the water-vapor absorption spectrum (Ref. [9], Fig. 1D). Directionality can further markedly improve radiative effectiveness [27], and thermal emittance can be passively varied >4× by ambient temperature [28]. Diverse radiative heat rejection materials and technologies continue to evolve very rapidly and present options suitable for automotive use.

Passive cooling can work outdoors 24/7 (though not in garages or tunnels or under heavy foliage). Silicon too is transparent at 8–13 μm, so photovoltaics with strip rather than sheet metallic coatings could perhaps stack atop passive infrared radiators, adding passive cooling to solar-propelled superefficient vehicles (aptera.us, lightyear.one).

Efficient Air Movement

For seated office workers, an efficient ceiling fan (with velocity low enough not to ruffle papers on the desk) expands comfort range by 3C°, assuming laminar flow; or 5C°, recognizing actual turbulent flow; or ~7C° if vertical air velocity is perturbed at ~0.3–0.5 Hz (~0.42 Hz in a commercial version) to emulate the coevolution of skin neurons with the frequency spectrum of natural wind gusts [29, 30, 31]. If largely passive automotive summer comfort using radiative cooling needed more air movement than seat fans offer, the torso (to avoid corneal drying) could be frontally ventilated with a superefficient fan, e.g., PAX Scientific's biomimetic Flair fan (http://bit.ly/flairfans) quietly moves 307 L/s (650 cfm) of air using just 6.2 W—~2–5× less than competing table fans. Such comfort-range extension helps ensure the adequacy of radiant cooling.

Conclusions

This synergistic and incomplete menu of nonrefrigerative methods could probably cut automotive air-conditioning energy by at least an order of magnitude. This implies a potential to save on the order of 5% of U.S. automotive fuel or ~$6–7b/y while significantly reducing CO_2, problematic refrigerants, air pollutants, capital cost, weight, complexity, maintenance, and range anxiety. Peeling a strip off the edge of the engine map could make engines cleaner and more efficient. Fuel used for rest-period idling of long-haul diesel trucks, mainly for cabin air conditioning, could also be slashed. Perhaps the greatest value could be in shrinking batteries or extending the range of electric vehicles.

Industry and National Laboratory simulation tools (e.g., [32]) do not yet test such efficient options, but could. That plus laboratory and field validation—starting with simple tests that could be easier than modeling—seem worthwhile to test the hypothesis that a well-integrated nonrefrigerative package could suffice for summer comfort. If the roof radiator did not get quite cold enough on the hottest days for fully passive, purely radiant cooling (supplemented by fans)—most likely due to very high ambient humidity—then a little boost could come from thermoelectric cooling or an active nonrefrigerative cooler or if needed a very small and extremely low-lift/high-efficiency turbocompressor. Regardless, energy use for automotive summer comfort should shrink dramatically. Let us find out.

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Disclaimer

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