Ancillary Load Reduction Task Overview

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National Renewable Energy Laboratory

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Outline

• Introduction
• Why A/C Systems?
• Industry Collaborative Vehicle Projects
  – Ford Lincoln Navigator Project
    • Solar Load Reduction
    • Parked Car Ventilation
  – DaimlerChrysler
    • Integrated Modeling Validation
    • Parked Car Ventilation
    • Test Cell Comparison with Outdoor Testing
  – Johnson Controls Distributed Cooling
• Future Opportunities
  – A.D.A.M.
  – Climate Control Lab
  – Waste Heat Utilization
• Conclusions
Demand for Fuels Outstrips Supply
Domestic Production with Transportation Use (1970-2020)

Vehicle Ancillary Load Reduction Goal

To work with industry to reduce energy use for vehicle climate control by 50% in the short-term and 75% in the long-term while maintaining passenger thermal comfort and safety.
Cool Car - Approach

To develop integrated analysis tools and testing to analyze advanced climate control systems for a diverse supplier base from a systems perspective (thermal comfort, fuel economy, tailpipe emissions)
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Energy Used in Conventional Vehicle

Energy Usage for Composite FTP & Highway
Numbers in ( ) are MJ

Input 100% (48.8)

Rolling 5.0% (2.4)

Aero. 5.3% (2.6)

Driveline 3.4% (1.7)

Acc. 2.8% (1.4)

Engine 79.3% (38.6)

Braking 2.5% (1.2)

21.3 city, 39 highway: 26.7 mpgge

Reduce Size of Existing AC Systems

Without AC

w/AC 10% (5.6)
Measured Insight and Prius Fuel Economy Impacts from A/C
Measured Insight and Prius Fuel Economy Impacts from A/C

53% increase in fuel use
35% drop in mpg

43% increase in fuel use
30% drop in mpg
Modeled U.S. Mobile AC Fuel Use

7.0 billion gallons used for air conditioning annually
Equivalent to 5.5% of the national fuel use,
or ~9.5% of the imported crude oil!
European Union and Japan: Fuel Used for Cooling and Demisting

EU: 6.9 billion liters (1.8 billion gallons, 16 billion kg CO₂) used for air conditioning annually, Equivalent to 3.2% of the total fuel use

Japan: 1.7 billion liters (0.5 billion gallons, 4 billion kg CO₂) used for air conditioning annually, Equivalent to 3.5% of the total fuel use
Why So Much Fuel for A/C?

Metabolic Heat Generation

150 Watts

A/C Cooling 6000 Watts!
Systems Approach

Traditional Approach - Equipment Emphasis

VERSUS

REDUCE LOAD

EFFICIENT DELIVERY

EFFICIENT EQUIPMENT

Decreases in load have a larger impact on fuel use due to equipment and delivery losses.
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Collaborative Projects with Ford
Lincoln Navigator Project

- Examine technologies to reduce solar heat gain
  - Improve thermal comfort
  - Improve fuel economy
  - Reduce emissions
Ford L/N Industry Partners

- Shades, reflective and absorptive
  - BOS Automotive
- Window glazings, Solar Reflective
  - PPG
  - Guardian Automotive
- Roof reflective films
  - 3M: Infrared reflective, visibly reflective
- Patterned glass
  - Solutia: VancevaTM Design Pattern
- Thermal insulation
  - 3M: ThinsulateTM
  - Lawrence Berkeley Lab gas filled panels
- Vehicle testing and data analysis
  - NREL
Temperature Reduction Variable

% of maximum possible temperature reduction

\[
\theta = 1 - \left( \frac{\overline{T_{\text{cabin \ air}}} - T_{\text{ambient}}}{\overline{T_{\text{cabin \ air}}} - T_{\text{ambient}}} \right)_{\text{modified}} \left/ \left( \overline{T_{\text{cabin \ air}}} - T_{\text{ambient}} \right)_{\text{baseline}} \right.
\]

All results referenced to \((T_{\text{cabin}} - T_{\text{ambient}})_{\text{baseline}} = 20^\circ C\)

\(\theta = 1, \ T_{\text{cabin,modified}} = T_{\text{ambient}}\)

\(\theta = 0, \ T_{\text{cabin,modified}} = T_{\text{cabin,BL}}\)
Navigator Results

Theta = 1, $T_{cabin,modified} = T_{Ambient}$
## Estimated Fuel Economy Impacts
(L/N Cabin Results)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Compressor Power</th>
<th>Fuel Economy Improvement</th>
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</thead>
<tbody>
<tr>
<td>Passive vent</td>
<td>34.0%</td>
<td>6.6 %, 1.1 mpg</td>
</tr>
<tr>
<td>Active vent</td>
<td>24.0%</td>
<td>4.8 %, 0.76 mpg</td>
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<tr>
<td>Shades</td>
<td>14.3%</td>
<td>2.9 %, 0.45 mpg</td>
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<tr>
<td>Roof film</td>
<td>9.4%</td>
<td>1.9 %, 0.3 mpg</td>
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<tr>
<td>Reflective Windows</td>
<td>11.4%</td>
<td>2.3 %, 0.36 mpg</td>
</tr>
<tr>
<td>Insulation</td>
<td>6.6%</td>
<td>1.3 %, 0.22 mpg</td>
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</tbody>
</table>
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Collaborative Projects with DaimlerChrysler
DaimlerChrysler Grand Cherokee Test Project

- Examine technologies to reduce solar heat gain
- Data for validating integrated modeling tools
DaimlerChrysler Industry Partners

- DCX - European Jeep Grand Cherokee
  - U.S. glazings installed prior to delivery
- PPG - Sungate® windshield, door sidelites
- 3M - Thinsulate® acoustic/thermal insulation
- NREL – Vehicle testing and data analysis
Integrated Modeling

- Solar Radiation
- Glazing
- Cabin Thermal/Fluid
- Vehicle

- CAD

- Air Conditioning

- Thermal Comfort

- Fuel Economy
- Tailpipe Emissions
- Occupant Thermal Comfort
Integrated Modeling

Mesh the geometry of your car

Solar Radiation → Glazing
Air Conditioning → Cabin Thermal/Fluid
Vehicle

CAD

Fuel Economy
Tailpipe Emissions
Occupant Thermal Comfort

NREL National Renewable Energy Laboratory
Integrated Modeling

- Solar Radiation
- Glazing
- Cabin Thermal/Fluid
- Vehicle

Find the solar radiation in your city

Fuel Economy
- Tailpipe Emissions
- Occupant Thermal Comfort

- CAD
- Air Conditioning
- Thermal Comfort

- NREL National Renewable Energy Laboratory
Integrated Modeling

Model temperatures and airflow in the cabin

- Solar Radiation
- Glazing
- Cabin Thermal/Fluid
- Vehicle
- Thermal Comfort
- Fuel Economy
- Tailpipe Emissions
- Occupant Thermal Comfort

NREL National Renewable Energy Laboratory
Find the power consumption and cooling amount of the AC.
Integrated Modeling

Solar Radiation → Glazing → Cabin Thermal/Fluid → Vehicle → Thermal Comfort → Fuel Economy

Air Conditioning → Cabin Thermal/Fluid → Thermal Comfort

Model your car over a drive cycle and find the fuel economy.
How comfortable are you inside your car?
Modeled Air Temperature Reduction

Baseline
- Gold exterior

- All Glazing - Sungate™
- 25 scfm ventilation
- White exterior

-7.9°C
ADVISOR Model Summary

Reducing the A/C system 32% can:
- Improve fuel economy 6% or 1 mpg (SCO3)
- Reduce emissions of NO\textsubscript{x} by 12.8% or 0.05 gr/mi
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Jeep Grand Cherokee
Parked Car Ventilation Test Program

Assess effect of:

– Forced ventilation
– Natural convection ventilation

DAIMLERCHRYSLER

National Renewable Energy Laboratory
### Measured Cabin Air Temperature

#### Baseline Cabin Air Temperature = 45°C

<table>
<thead>
<tr>
<th>Ventilation Technique</th>
<th>Cabin Air Temperature (°C)</th>
<th>Power (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flow / Panel</td>
<td>44.1</td>
<td>13</td>
</tr>
<tr>
<td>Medium flow / Panel</td>
<td>42.5</td>
<td>81</td>
</tr>
<tr>
<td>Sunroof open 6cm</td>
<td>38.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Sidelites open 2cm</td>
<td>35.7</td>
<td>13</td>
</tr>
<tr>
<td>Sunroof 6cm/double floorvents</td>
<td>32.5</td>
<td>81</td>
</tr>
<tr>
<td>Sunroof 6cm/double floorvents/3 fans</td>
<td>27.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

#### Ambient Temperature = 30°C

- Low flow / Panel: 34.2°C (13 watts)
- Medium flow / Panel: 32.1°C (81 watts)
- Sunroof open 6cm: 30.7°C (4.1 watts)
- Sidelites open 2cm: 27.5°C (13 watts)
- Sunroof 6cm/double floorvents: 30.2°C (81 watts)
- Sunroof 6cm/double floorvents/3 fans: 25.1°C (4.1 watts)

**Ventilation Technique**

- Low flow / Panel
- Medium flow / Panel
- Sunroof open 6cm
- Sidelites open 2cm
- Sunroof 6cm/double floorvents
- Sunroof 6cm/double floorvents/3 fans
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DaimlerChrysler Test Cells Correlation: Outdoor vs. Indoor

NREL, Golden, CO
Outdoor Tests

Emissions Test Cell
Sodium Scandium
dosed Metal Halide

How well do indoor tests simulate outdoors?

Environmental Test Cell
IR –Tungsten Filament
Quartz Tubes

DaimlerChrysler, DCTC, Auburn Hills, MI
### Indoor Temperatures Compared to Outdoor

(Averaged between 1:30 and 2:00 p.m.)

<table>
<thead>
<tr>
<th>Component</th>
<th>Outdoor</th>
<th>Metal Halide</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windshield</td>
<td>-3.4°C</td>
<td>+0.5°C</td>
<td>+24.5°C</td>
</tr>
<tr>
<td>IP</td>
<td>-13.8°C</td>
<td>-4.8°C</td>
<td>+20.1°C</td>
</tr>
<tr>
<td>Driver Seat</td>
<td>-1.4°C</td>
<td>-2.3°C</td>
<td>+1.5°C</td>
</tr>
<tr>
<td>Trim, average</td>
<td>+1.5°C</td>
<td>+0.7°C</td>
<td>-0.1°C</td>
</tr>
<tr>
<td>Air, average</td>
<td>+0.7°C</td>
<td>-0.4°C</td>
<td>-0.4°C</td>
</tr>
<tr>
<td>Vehicle Exterior</td>
<td>+20.1°C</td>
<td>+24.5°C</td>
<td>+20.1°C</td>
</tr>
</tbody>
</table>
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JCI Distributed HVAC Project

- Assess human thermal comfort impact of JCI distributed HVAC system
  - Flow circulation & impingement
  - Steady state air temperature
  - Cooldown performance
Pathlines from Body Coolers and Seat Vents
Driver Overall
Equivalent Homogeneous Temperature (EHT)

EHT – eqv. uniform temp. and 0 air velocity with same dry heat transfer as nonuniform test conditions
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Thermal Comfort Assessment Tools
Predicting the comfort of vehicle occupants

ADvanced Automotive Manikin
Manikin presentation

Human Thermal Physiological Model
Physiological

Human Thermal Comfort Empirical Model
Psychological
ADvanced Automotive Manikin (ADAM)

- On-board power, water, communications
- Designed to respond to a transient, non-uniform thermal environment like a human:
  - Sweating
  - Breathing
- Wears clothes
- 175 cm tall, 61 kg
- 126 elements (~120 cm²), 120 zones
Surface Segment Details

- Outer surface - low porosity metal
- Distribution layer - high porosity metal
- Water barrier layer
- Fine grid distributed heater wire
- Carbon fiber structural backing and insulation
- Multiple temperature sensor array
- Backside heat flux gauge
- Local controller and fluid control valve
Segment with Exaggerated Sweat Rate
ADAM’s Carbon Fiber Skeletal System
Battery System

- 4 nickel-metal hydride modules
- Onboard charging
- 2 hr capability

Modules in each thigh

2 Modules in torso

Charge Controller
Breathing System

- 5 L/min periodic exhalation and inhalation
- 10 L/min continuous exhalation
- 100% R.H. at body temperature
Breathing System (cont.)

- Tubes to nose
- Nose breathing port
- Neck auxiliary breathing port (inlet for continuous exhale mode)
IR Image of breathing

Heated plume of air
Fluid System Filter

- Added to mitigate contamination problem with segment capillary tubes
ADAM’s Active/Inactive Segments
Ready for a Brain!
Human Thermal Physiological Model
A Numerical Person

- Predicts transient thermal response of the body
- Receives data from and provides data to ADAM
- ANSYS model (40,000 elements, transient, 3D)
- Fully parametric for size and position of the human
- Body mass (tissues, bones, organs)
Human Thermal Physiological Model
Thermoregulatory System

• Circulatory system (network of circular tubes of variable cross sections for arteries & veins)

• Respiratory system (series of tubes between the mouth and lungs)

• Published control equations used for heat generation, sweat rate, shivering rate, vaso-dilation/constriction
Section View of Upper Right Leg

- Skin
- Fat
- Muscle
- Bone
FEA Model of the Flow Network of Upper Arm

- Thermal-flow elements:
  - Conduction within fluid
  - Mass transport of fluid
  - Convective heat transfer coefficient to tissues varies with fluid flow rate

- Cross-section of elements adjustable at every time step for vaso-dilation/constriction
Blood Vessel Temperatures

- Blood flow rate to arteries of 1380 cc/h @ 37°C
- Muscle tissue 750 W/m³
- Skin tissue 1005 W/m³
- Skin heat loss 100 W/m²
Body Skin Temperatures

NODAL SOLUTION

STEP = 1
SUB = 1
TIMH = 1
TEMP = (AYC)
PSYS = 0
SMN = 25.42
SMX = 48.403

Body Section Temperatures
Interface program

Substitute Table
(model uses data from good segment in place of a malfunctioning segment)

Heat flux multiplier
(ability to adjust heat flux from ADAM)
The Human Thermal Comfort Empirical Model
How You Feel Thermally

- Determines local thermal sensation
- Determines local and global thermal comfort (thermal perception) from local sensations
- Accounts for non-uniform and transient thermal environment of vehicle cabin
Model Overview

Physiology
$T_{\text{skin,local}}, T_{\text{skin,mean}}, T_{\text{core}}$

Local Thermal Sensation: $S_l$

Overall Thermal Sensation: $S_o$

Local Thermal Comfort: $C_l$

Overall Thermal Comfort: $C_o$
Human Subject Testing

• Individual segments (plus breathing temperature) were heated and cooled
• 110 separate tests performed at U.C. Berkeley
• 64 tests performed in Delphi wind tunnel
Back Cooling

Troom = 28.2°C

Skin Temperature (°C)

Back Temperature

overall_sensation

back_sensation
Body Core Heating With Local Cooling

\[ T_{\text{room}} = 28^\circ\text{C}, \quad T_{\text{supply}} = 12^\circ\text{C} \]
Physiological/Psychological Model Coupling

Converts temperatures to sensation and comfort

- Physiology: $T_{\text{skin}}$, $T_{\text{core}}$
- Local Thermal Sensation
- Overall Thermal Sensation
- Local Thermal Comfort
- Overall Thermal Comfort
- Overall Thermal Comfort

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Set Point</th>
<th>Old Value</th>
<th>New Value</th>
<th>Sensation Site</th>
<th>Sensation Type</th>
<th>Sensation</th>
<th>Comfort</th>
<th>Local</th>
<th>Comfort</th>
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<tr>
<td>1</td>
<td>Forehead</td>
<td>34.20</td>
<td>31.20</td>
<td>31.20</td>
<td>-0.75</td>
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<td>33.70</td>
<td>33.70</td>
<td>32.70</td>
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<td>-0.08</td>
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<td>32.70</td>
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<td>1.53</td>
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<td>33.70</td>
<td>32.70</td>
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<tr>
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<td>32.20</td>
<td>31.20</td>
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<td>-0.10</td>
<td>-0.58</td>
<td>0.77</td>
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<tr>
<td>20</td>
<td>Dist/Mean</td>
<td>36.00</td>
<td>36.00</td>
<td>36.40</td>
<td>Overall</td>
<td>-0.48</td>
<td>0.67</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Linking the Tools Together

120 surface heat fluxes transmitted

Dynamic interaction with environment

Surface and core temperatures transmitted

Transmits 120 target skin temperatures and sweat rates

Is the environment comfortable?
Model and Manikin Data Loop

Model reads $q_{\text{loss}}$ every ~2 minutes

Model calculates new $T_s$ setpoints and writes to file ~2 minutes

Manikin continuously adjusts heater power to meet $T_s$ setpoints

Manikin reads $T_s$ setpoints, changes heater power, sweat rate, and breathing

FEA Output File of $T_s$

Manikin Output File of $q_{\text{loss}}$

Writes $q_{\text{loss}}$ to file every 15 seconds
Manikin Controlled by Model
Human & Manikin Comparison

* >35.9°C

* <29.4°C
Outline

• Introduction
• Why A/C Systems?
• Industry Collaborative Vehicle Projects
  – Ford Lincoln Navigator Project
    • Solar Load Reduction
    • Parked Car Ventilation
  – DaimlerChrysler
    • Integrated Modeling Validation
    • Parked Car Ventilation
    • Test Cell Comparison with Outdoor Testing
  – Johnson Controls Distributed Cooling
• Future Opportunities
  – A.D.A.M.
  – Climate Control Lab
  – Waste Heat Utilization
• Conclusions
VCCL Objective

Evaluate occupant thermal comfort response to advanced cabin climate control systems in a controlled asymmetric, thermal environment and predict impact on:

- Fuel use
- Thermal comfort
Cabin Thermal Test Cell

Solar Simulator

Room Temp. Control (hidden)

Air Conditioning System

Passenger Compartment
Solar Simulator Uniformity Test
Air Conditioning

- **Actual Neon A/C System**
- **Electrically Driven**
  - 5.6 kW motor (7.5 hp)
Thermal Comfort Test Process

Heat Soaked Vehicle

Cool-Down Test

TC & Vehicle Modeling

Improved Comfort Energy & Fuel Saving
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Objectives and Goals

• Our primary objective would be to utilize high-grade heat from engines in light-duty vehicles to produce cooling and/or electrical power generation.

• Our primary goal would be to reduce the fuel used by light-duty vehicles’ ancillary systems by 75% by 2010.
Availability of Waste Heat in a Light-Duty Vehicle

- Average waste heat available would be 23 kW.
- Exhaust temperature varied from 200°C to 600°C.
- Generally, the waste heat available is twice as much as the mechanical output of the engine.
Heat Generated Cooling Opportunities

Absorption Heat Pump Cycle

Thermoacoustic Engine

Zeolite/Desiccant Cooling

Metal Hydride Heat Pump
Heat Generated Electric Generation

Thermoelectrics, Thermionics, and Quantum Well Technologies

Organic Rankine Cycle

Thermoacoustic Resonator
Waste Heat Utilization Laboratory
Long Term: Waste Heat Utilization

- Too long-term for industry
- Potentially eliminate all fuel used for air-conditioning
- Opportunities exist but require R&D
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Solutions to Reduce AC Fuel Use
Vehicle Design

- Reduce the load (e.g. cabin soak temperature)
- Improve distribution of cooling
- Improve equipment efficiency
- Effective tools (modeling and testing)
Future Opportunities

• Implement integrated model with industry-partnered vehicle testing to evaluate benefit of advanced climate control systems

• Evaluate advanced concepts with thermal manikin and modeling

• Demonstrate heat-generated cooling concepts

• Demonstrate heat-generated electricity concepts
Vehicle Level Opportunities

- Reduced Fuel Consumption
- Reduced Tailpipe Emissions
- Increased Comfort
- Avoided Costs - avoid second evaporator, tubes, controls, ducts or larger system
- Underhood Issues
  - Space
  - Lack of air flow for cooling
  - Overheating components, particularly battery and electronics
  - Condenser fan power
- Material life, color, and cost
- Enable advance vehicle technologies
  - HEV
  - FCV

Reduce compressor size and use
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