Ancillary Load Reduction Task Overview

John Rugh, Task Leader
Desikan Bharathan
Jason Lustbader
Matthew Keyser

Center for Transportation Technologies & Systems
National Renewable Energy Laboratory

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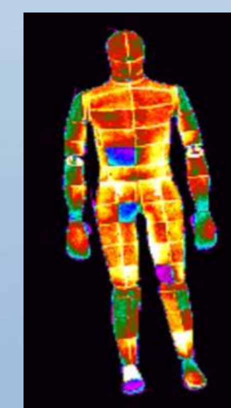

Outline

- Introduction
- Why A/C Systems?
- Industry Collaborative Vehicle Projects
  - Ford Lincoln Navigator Project
    - Solar Load Reduction
    - Parked Car Ventilation
  - DaimlerChrysler
    - Integrated Modeling Validation
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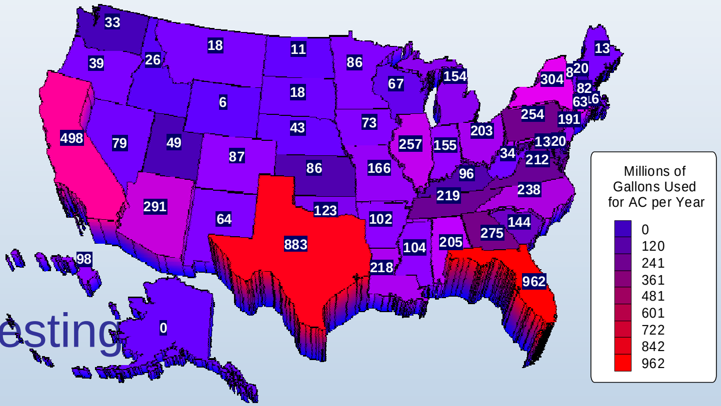
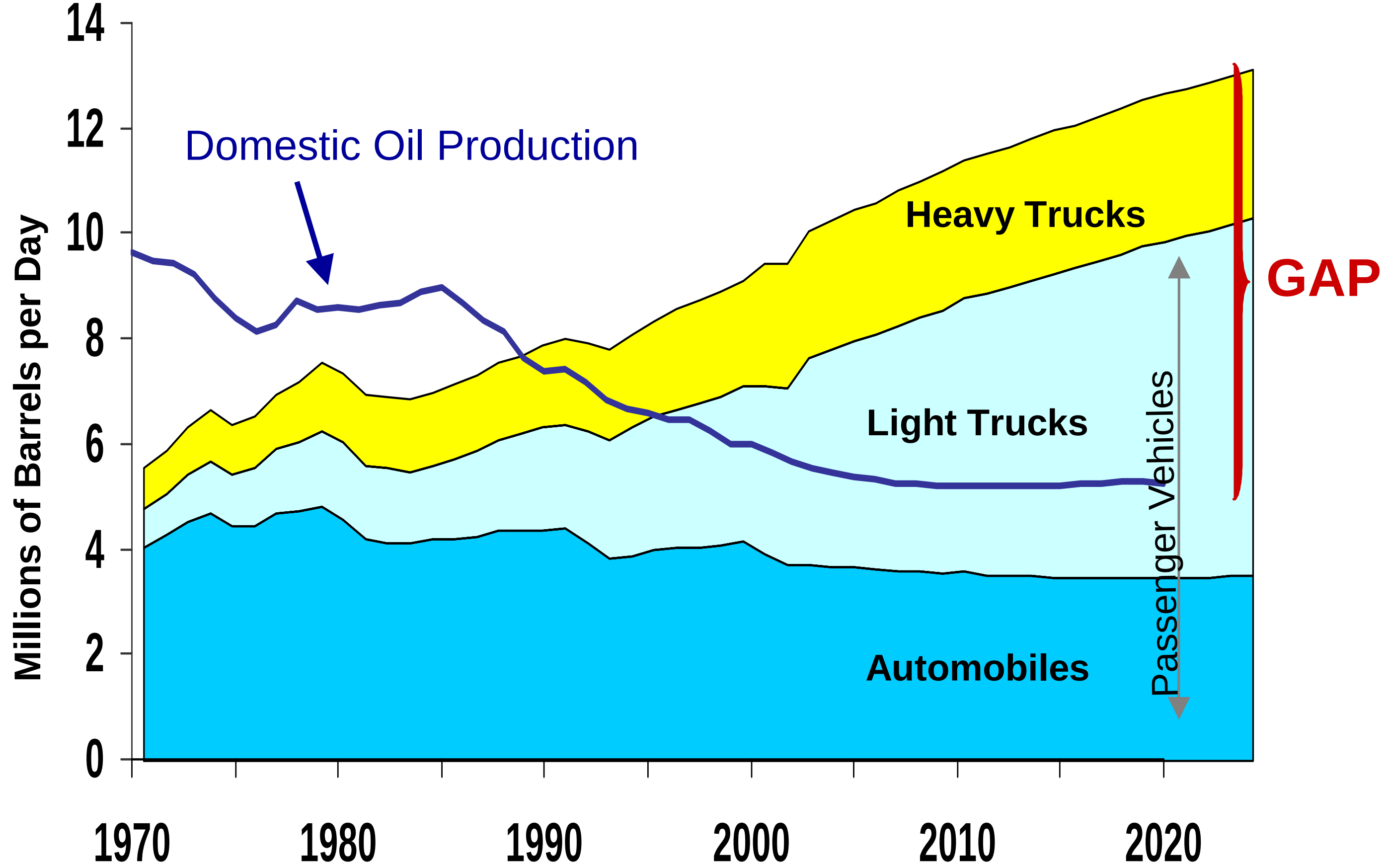
  - Johnson Controls Distributed Cooling
- Future Opportunities
  - A.D.A.M.
  - Climate Control Lab
  - Waste Heat Utilization
- Conclusions



Demand for Fuels Outstrips Supply

Domestic Production with Transportation Use (1970-2020)



Source: Transportation Energy Data Book: Edition 19, DOE/ORNL-6958, September 1999, and EIA Annual Energy Outlook 2000, DOE/EIA-0383(2000), December 1999

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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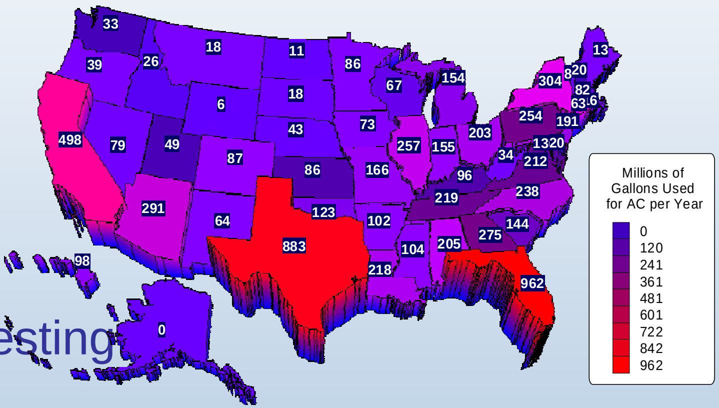
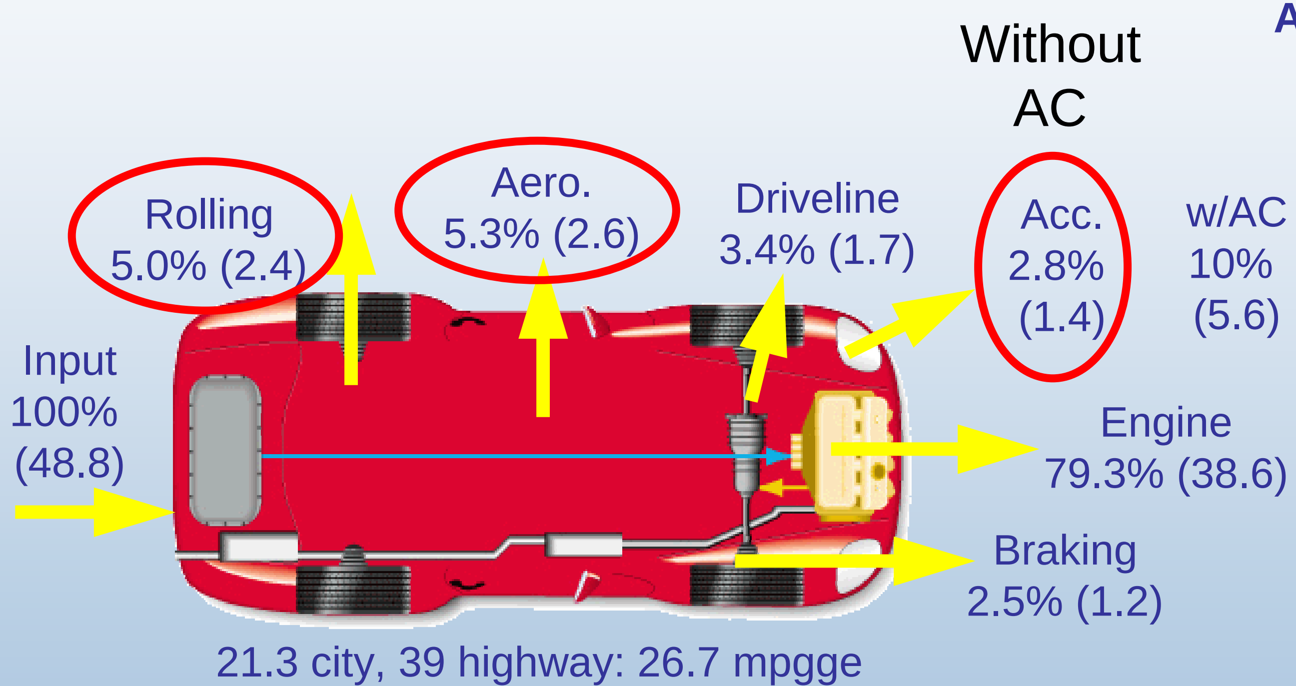


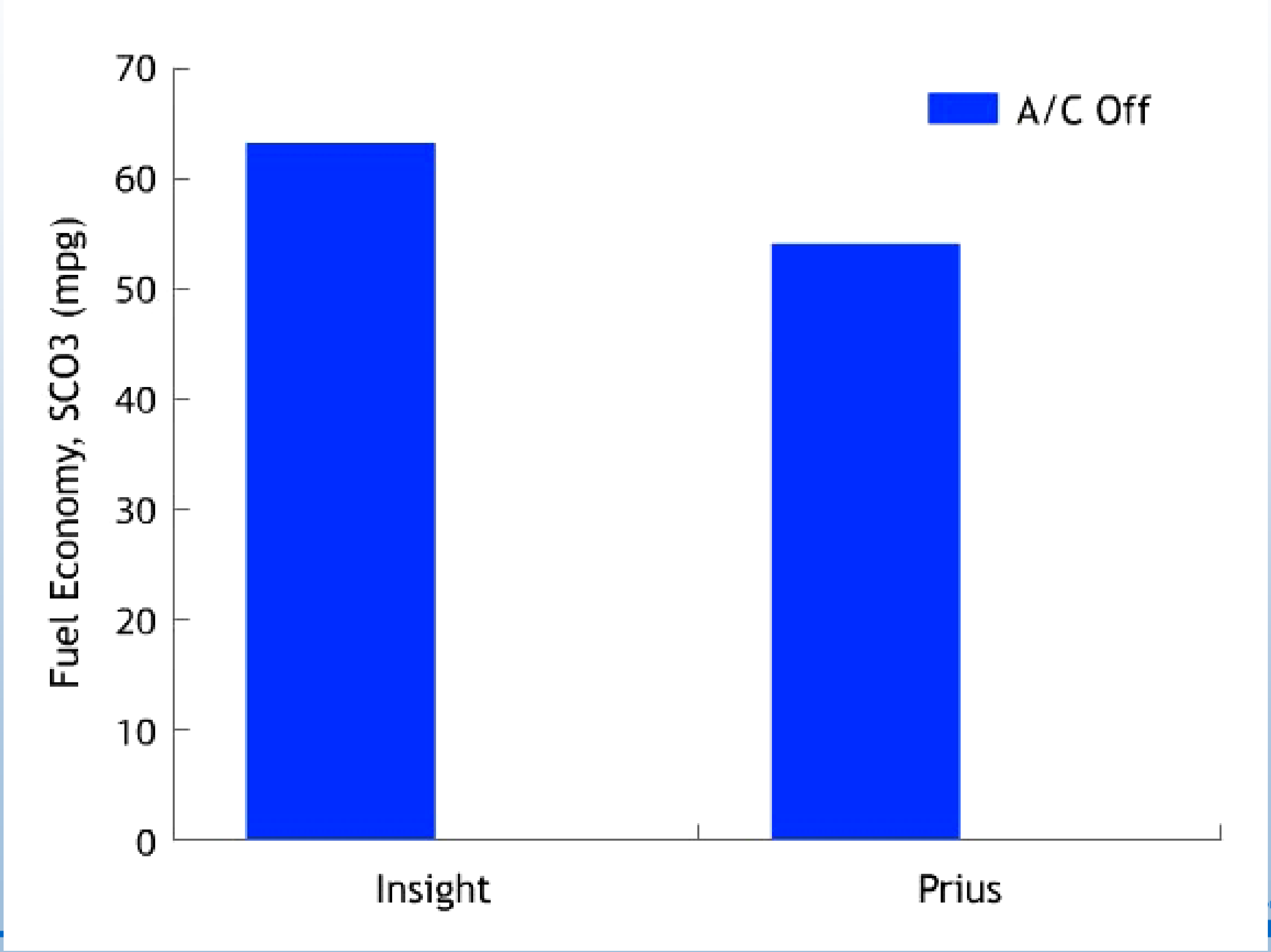
Energy Used in Conventional Vehicle

Reduce Size of Existing AC Systems



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

Measured Insight and Prius Fuel Economy Impacts from A/C



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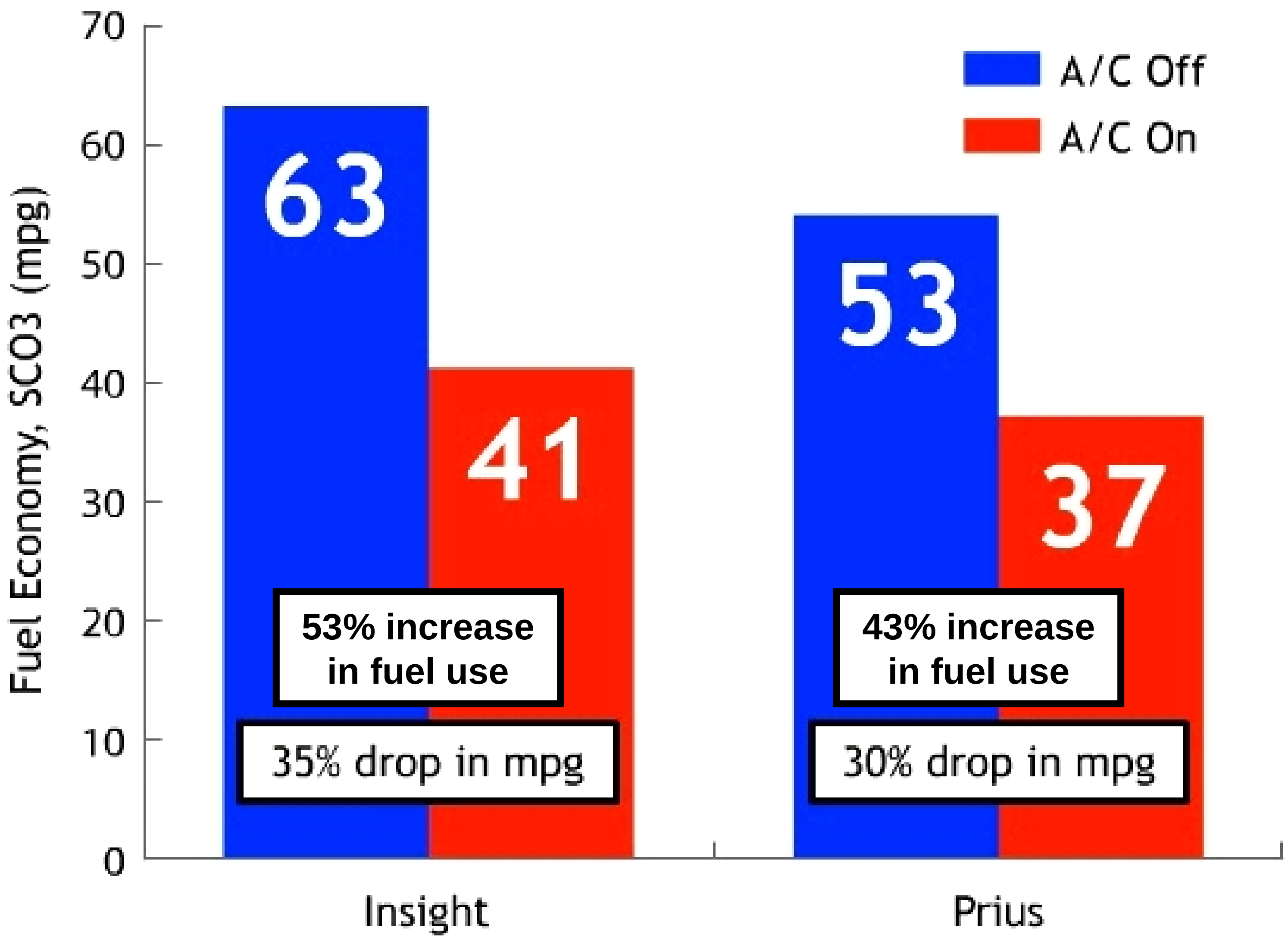
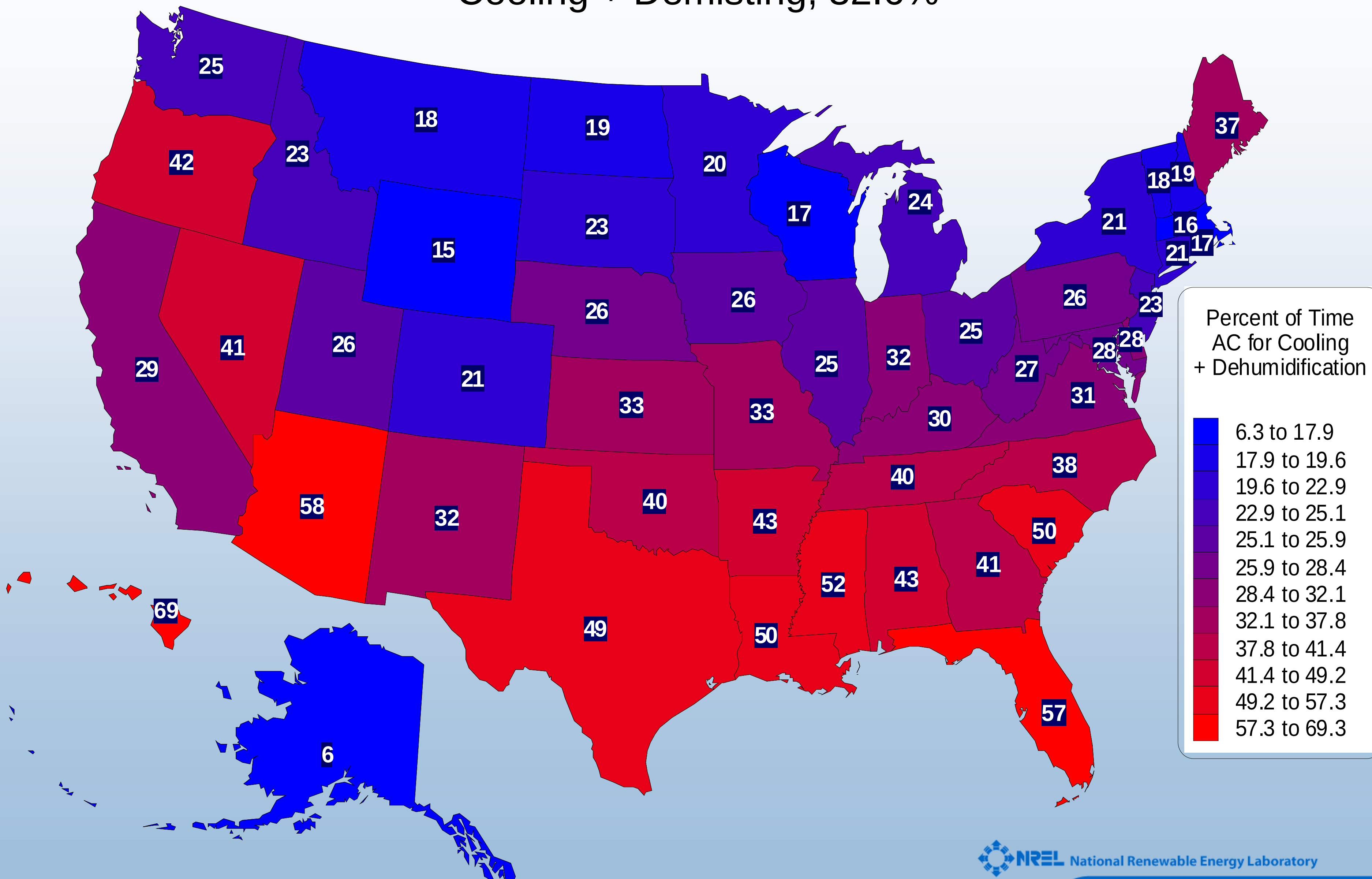


Percent of Time AC Used

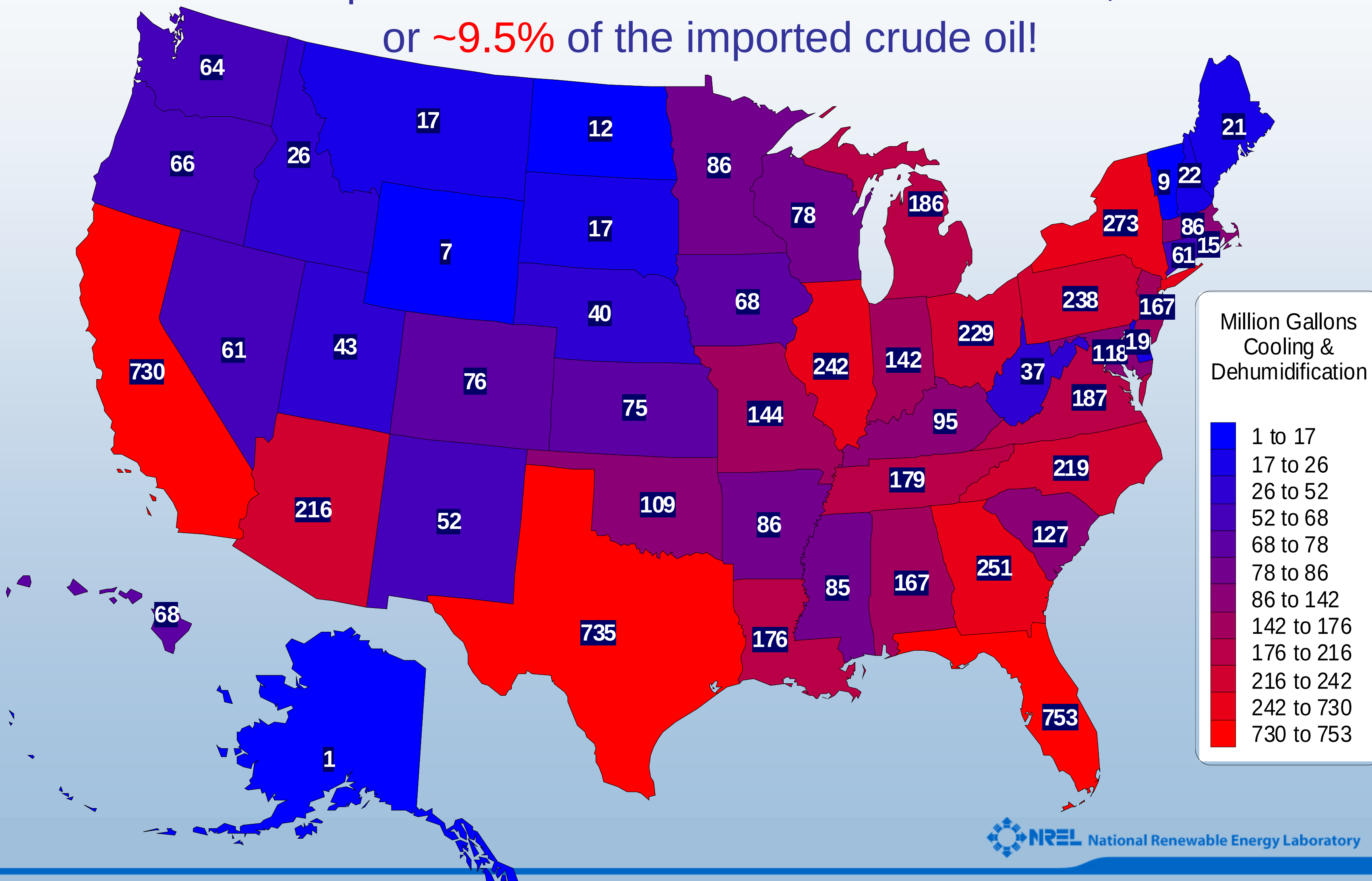
Cooling + Demisting, 32.6%



NREL National Renewable Energy Laboratory

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!

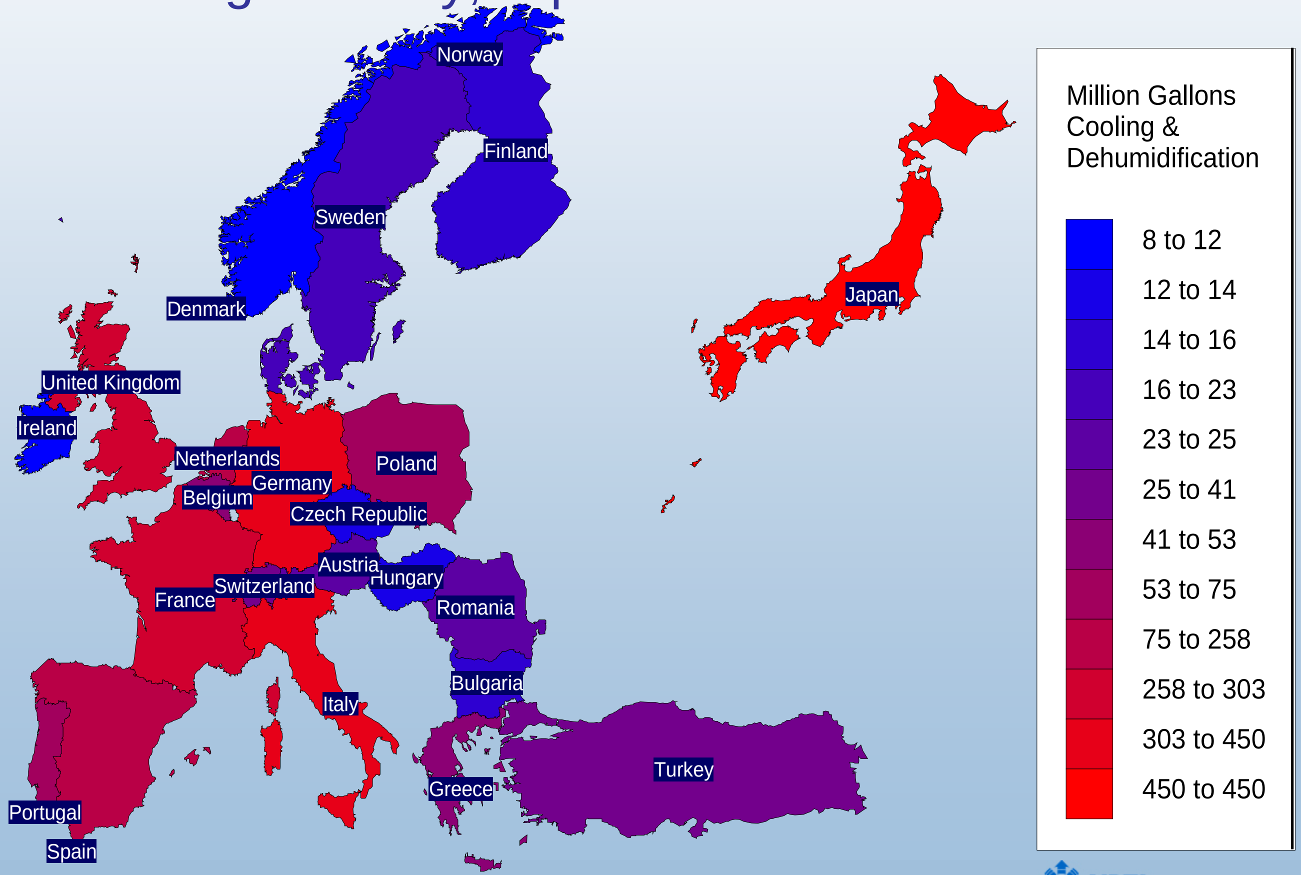


NREL National Renewable Energy Laboratory

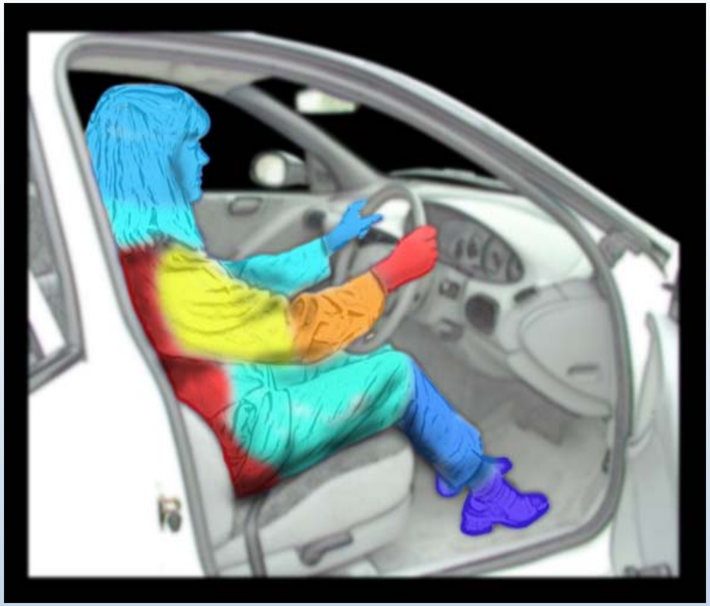
European Union and Japan: Fuel Used for Cooling and Demisting

EU: 6.9 billion liters (1.8 billion gallons, 16 billion kg CO_2) 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 CO_2) 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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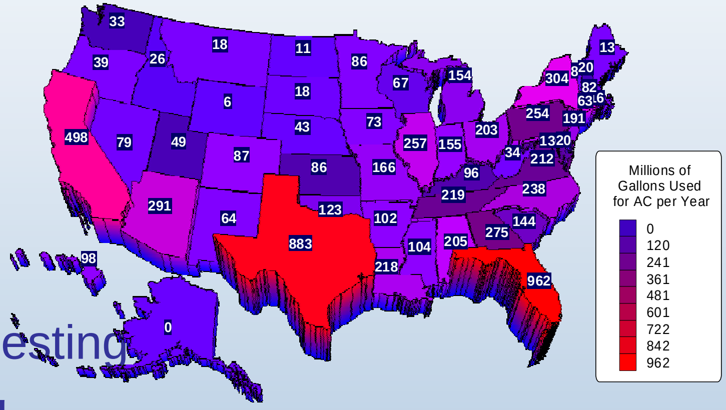


Collaborative Projects with Ford

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

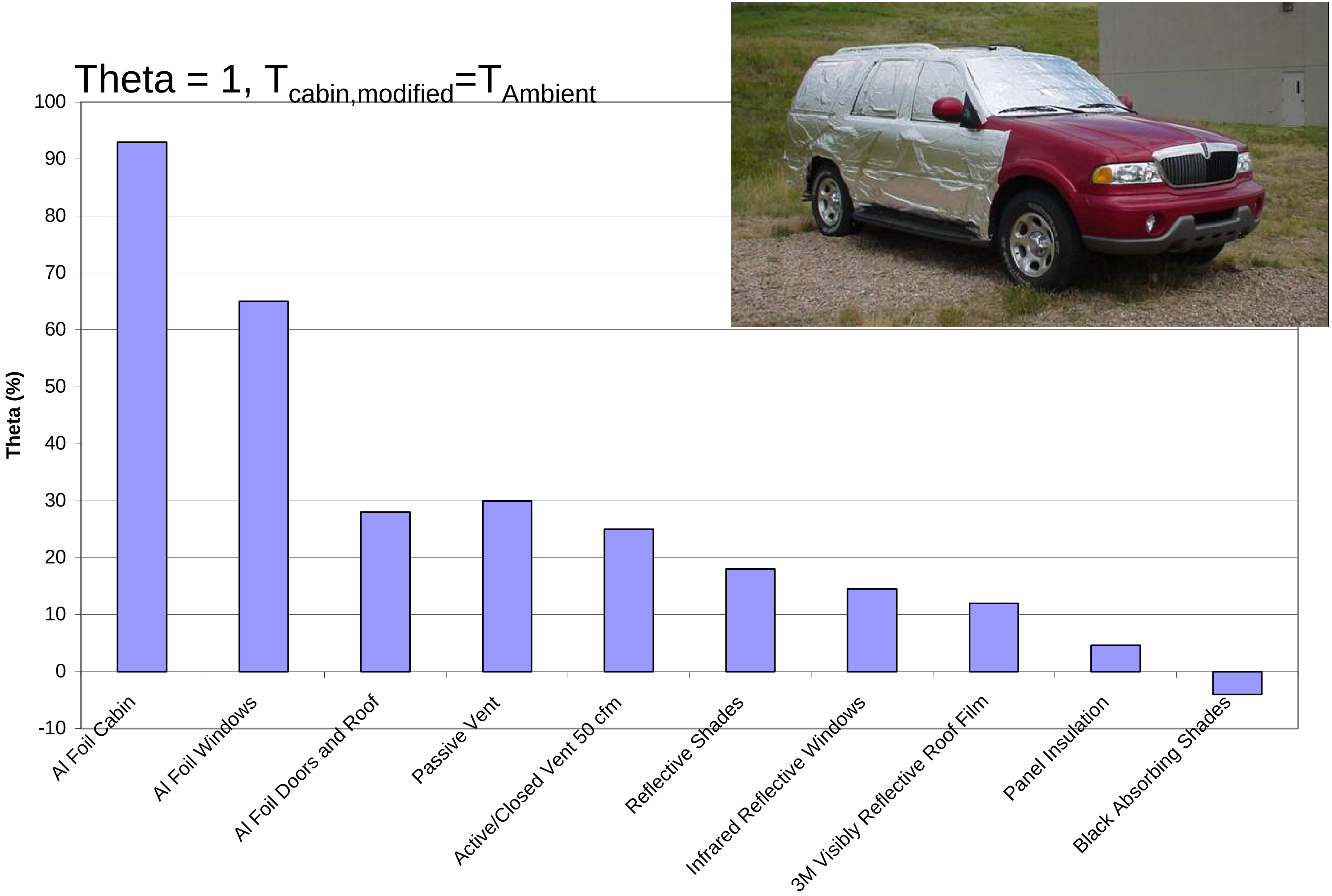
$$\theta = 1 - \frac{\left(\bar{T}_{\text{cabin air}} - T_{\text{ambient}}\right)_{\text{modified}}}{\left(\bar{T}_{\text{cabin air}} - T_{\text{ambient}}\right)_{\text{baseline}}}$$

All results referenced to $(T_{cabin} - T_{ambient})_{baseline} = 20°C$

Theta = 1, $T_{cabin,modified} = T_{ambient}$

Theta = 0, $T_{cabin,modified} = T_{cabin,BL}$

Navigator Results



Estimated Fuel Economy Impacts
(L/N Cabin Results)

Technology	Compressor Power	Fuel Economy Improvement
Passive vent	34.0%	6.6 %, 1.1 mpg
Active vent	24.0%	4.8 %, 0.76 mpg
Shades	14.3%	2.9 %, 0.45 mpg
Roof film	9.4%	1.9 %, 0.3 mpg
Reflective Windows	11.4%	2.3 %, 0.36 mpg
Insulation	6.6%	1.3 %, 0.22 mpg

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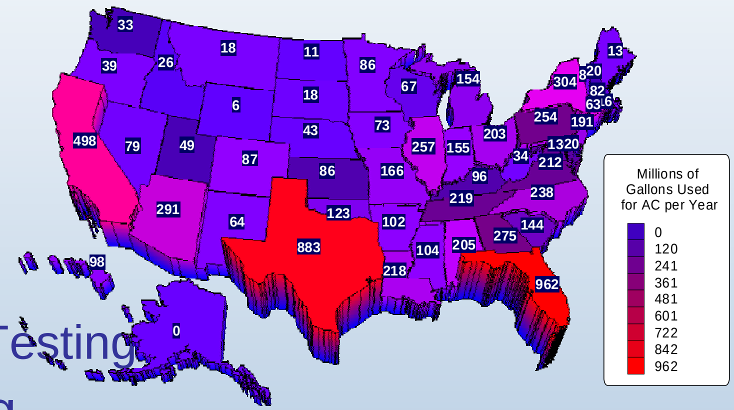


Collaborative Projects with DaimlerChrysler

DaimlerChrysler

DaimlerChrysler Grand Cherokee Test Project



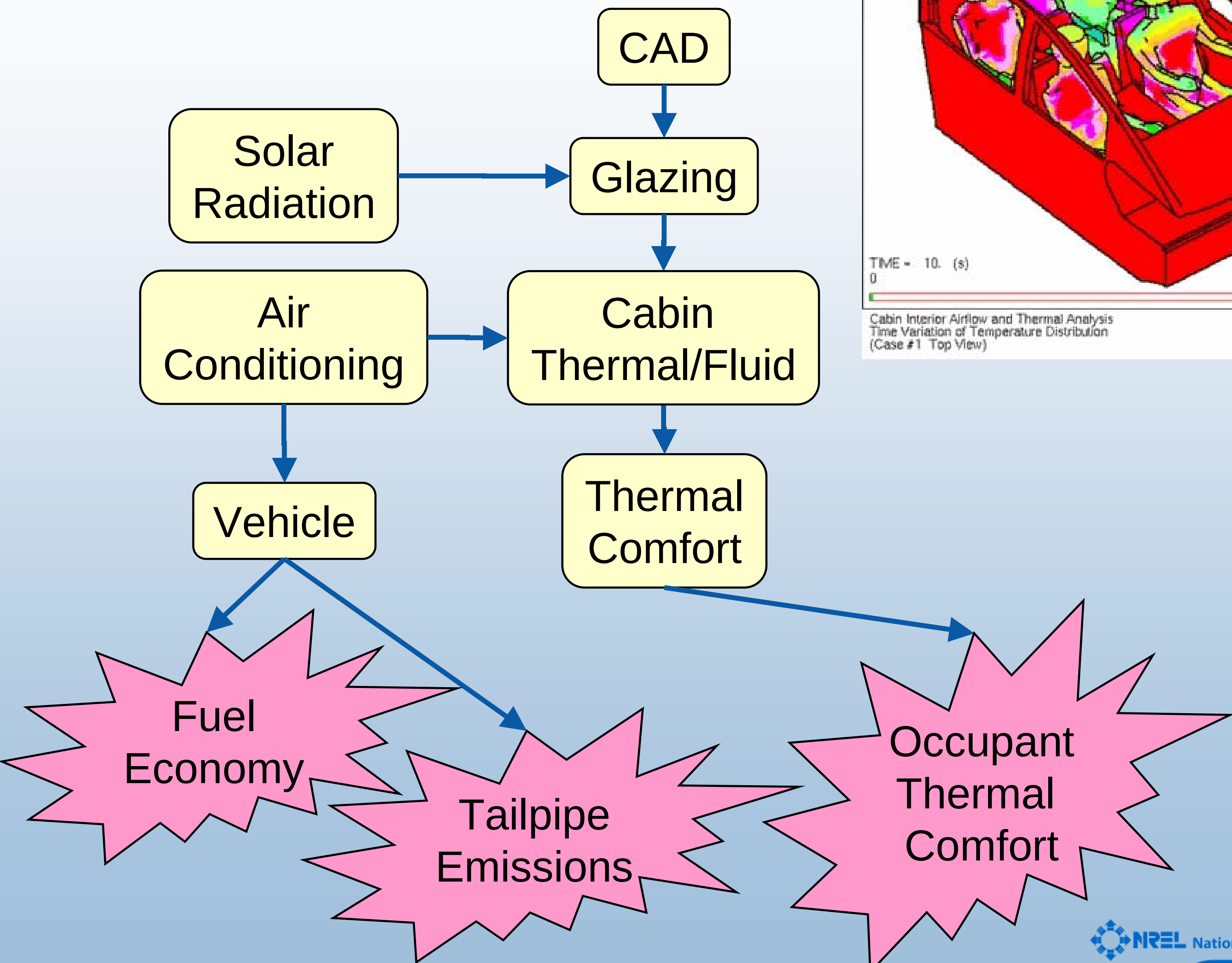

- Examine technologies to reduce solar heat gain
- Data for validating integrated modeling tools

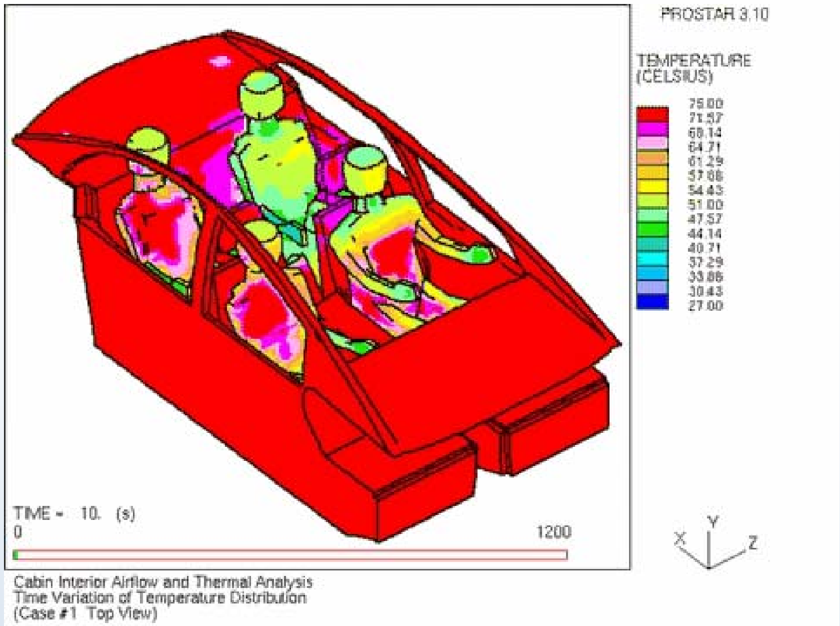
DaimlerChrysler Industry Partners

- 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

DAIMLERCHRYSLER

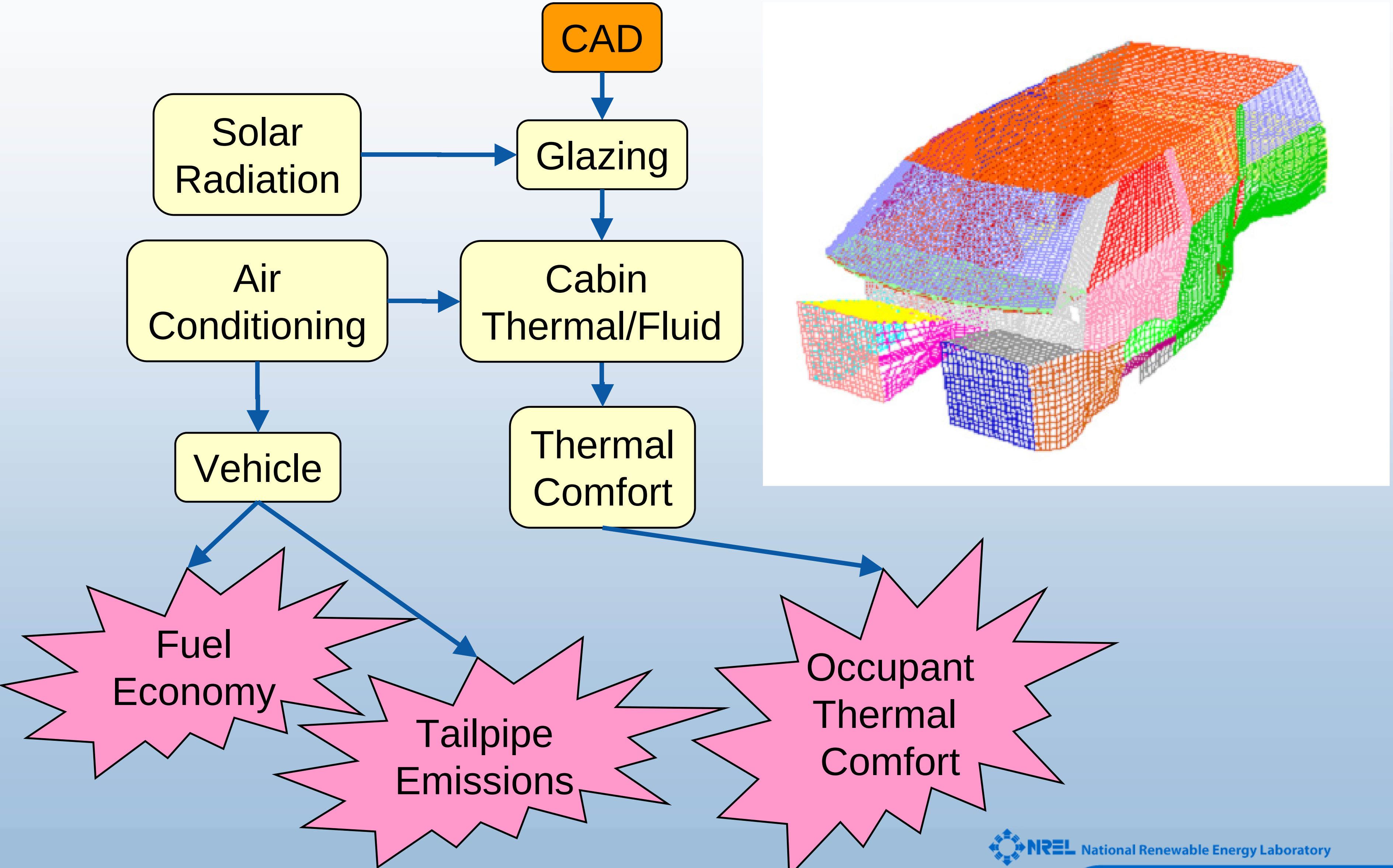
Integrated Modeling





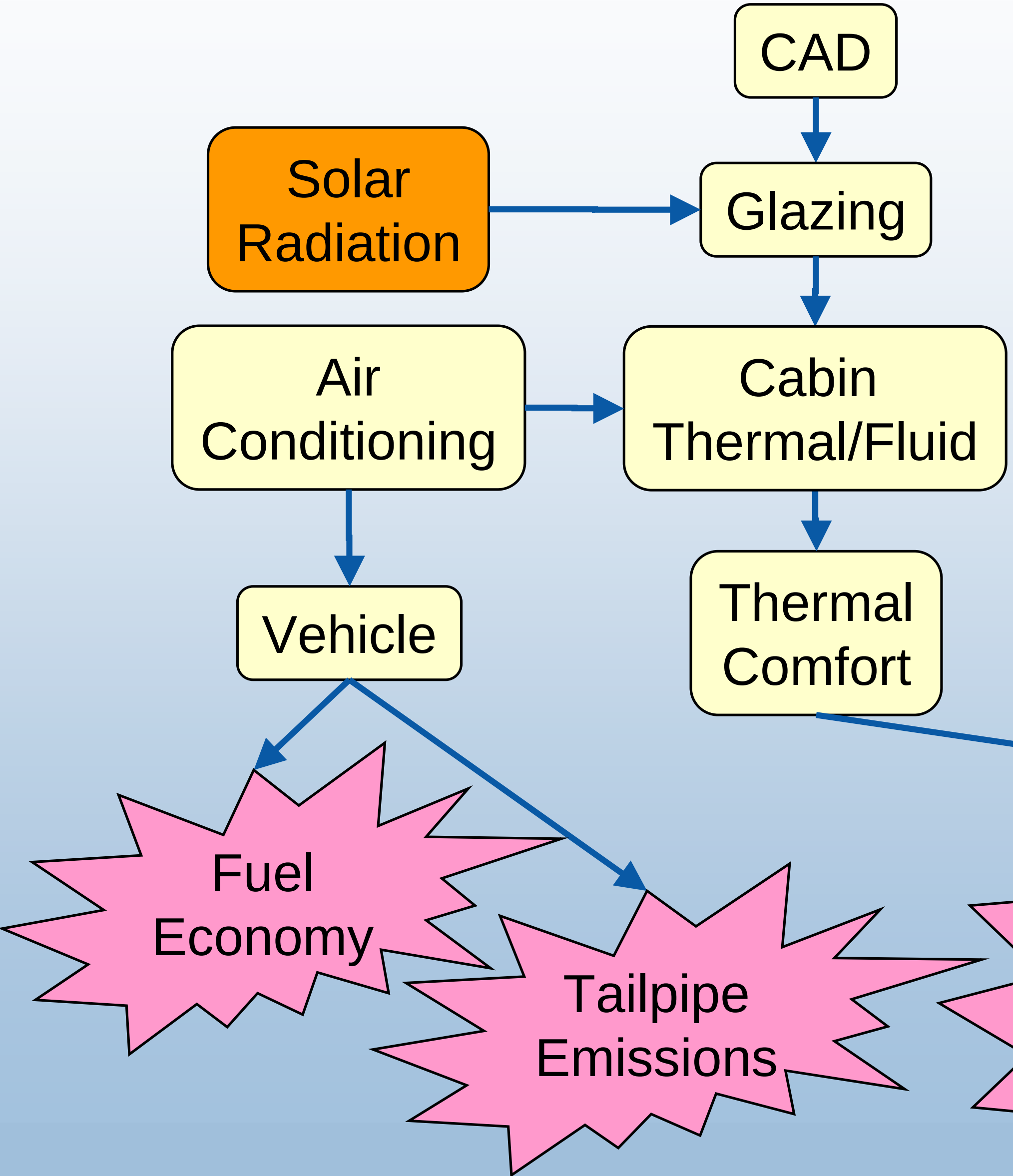
Integrated Modeling

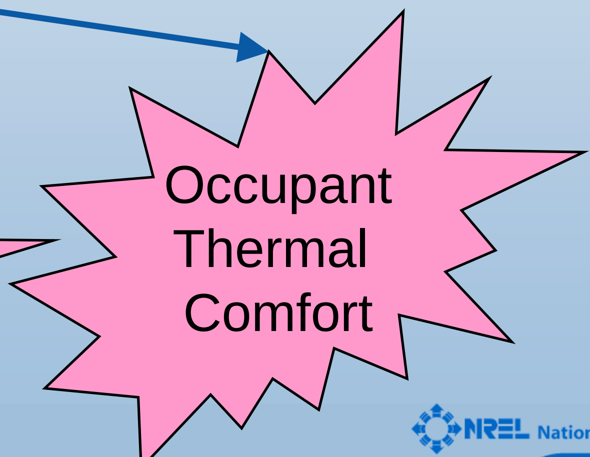
Mesh the geometry of your car

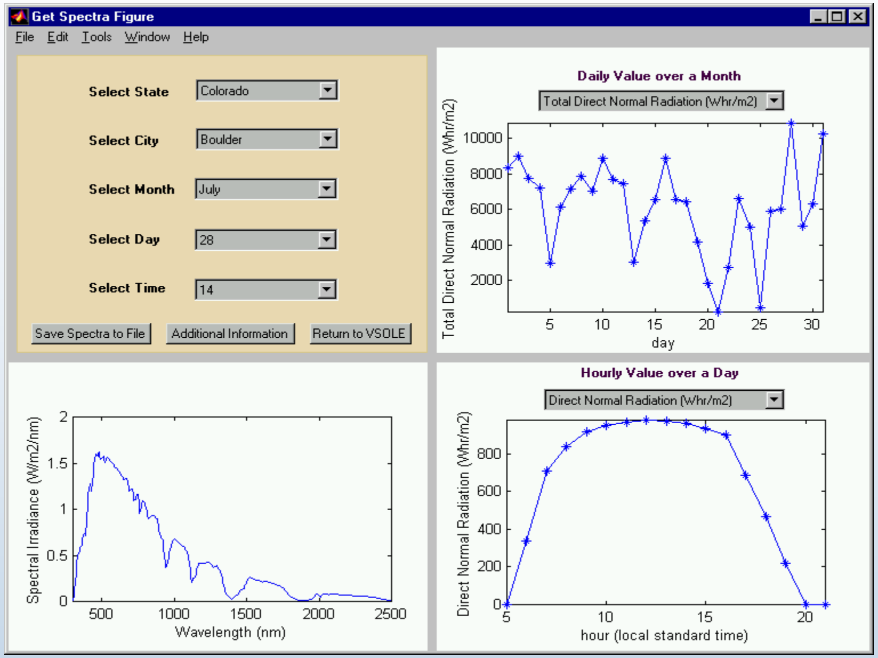


Integrated Modeling

Find the solar radiation in your city

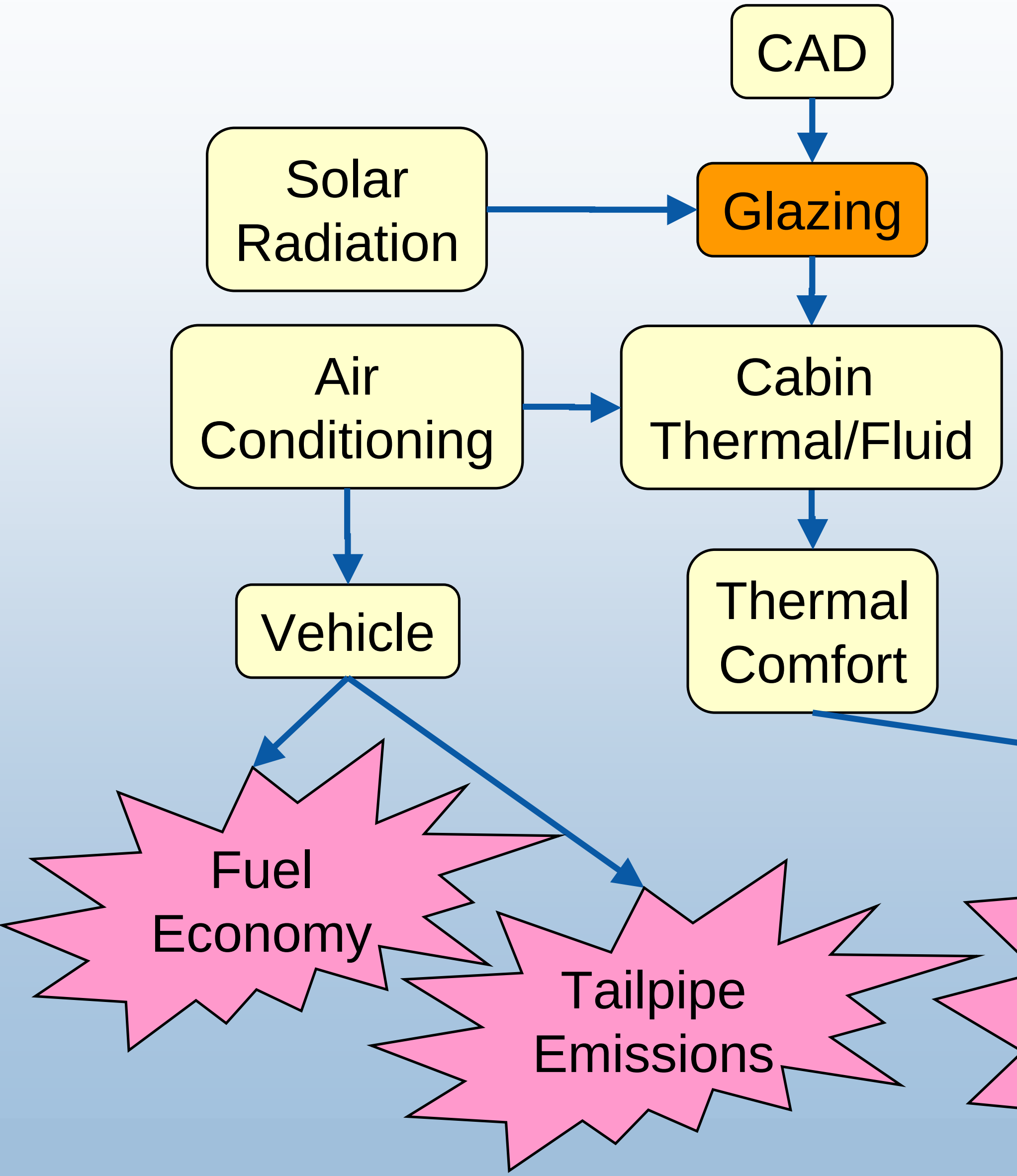


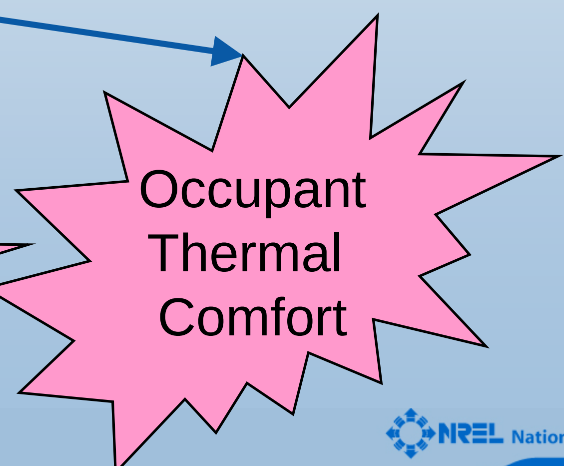




Integrated Modeling

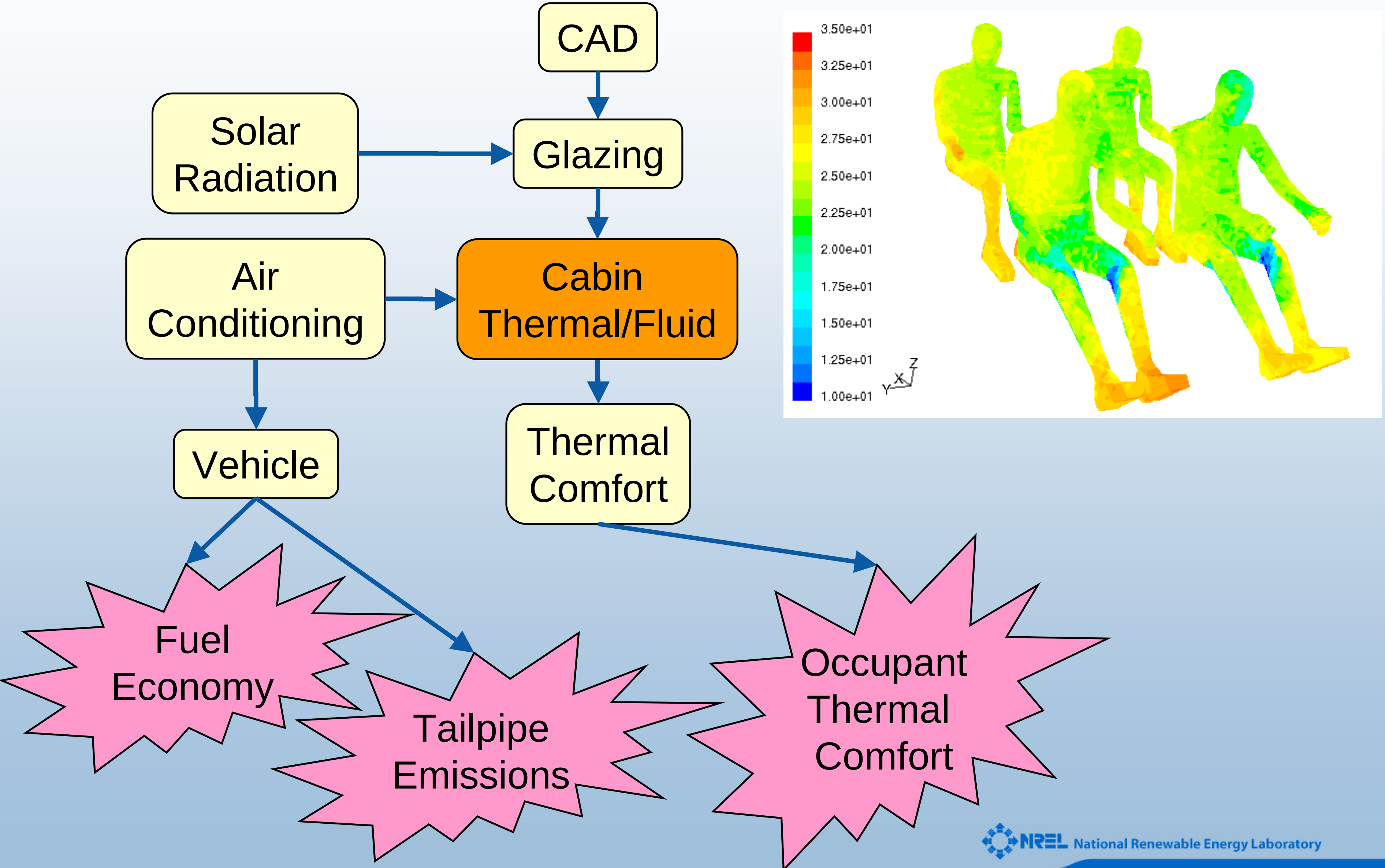
Find the heat coming into your car





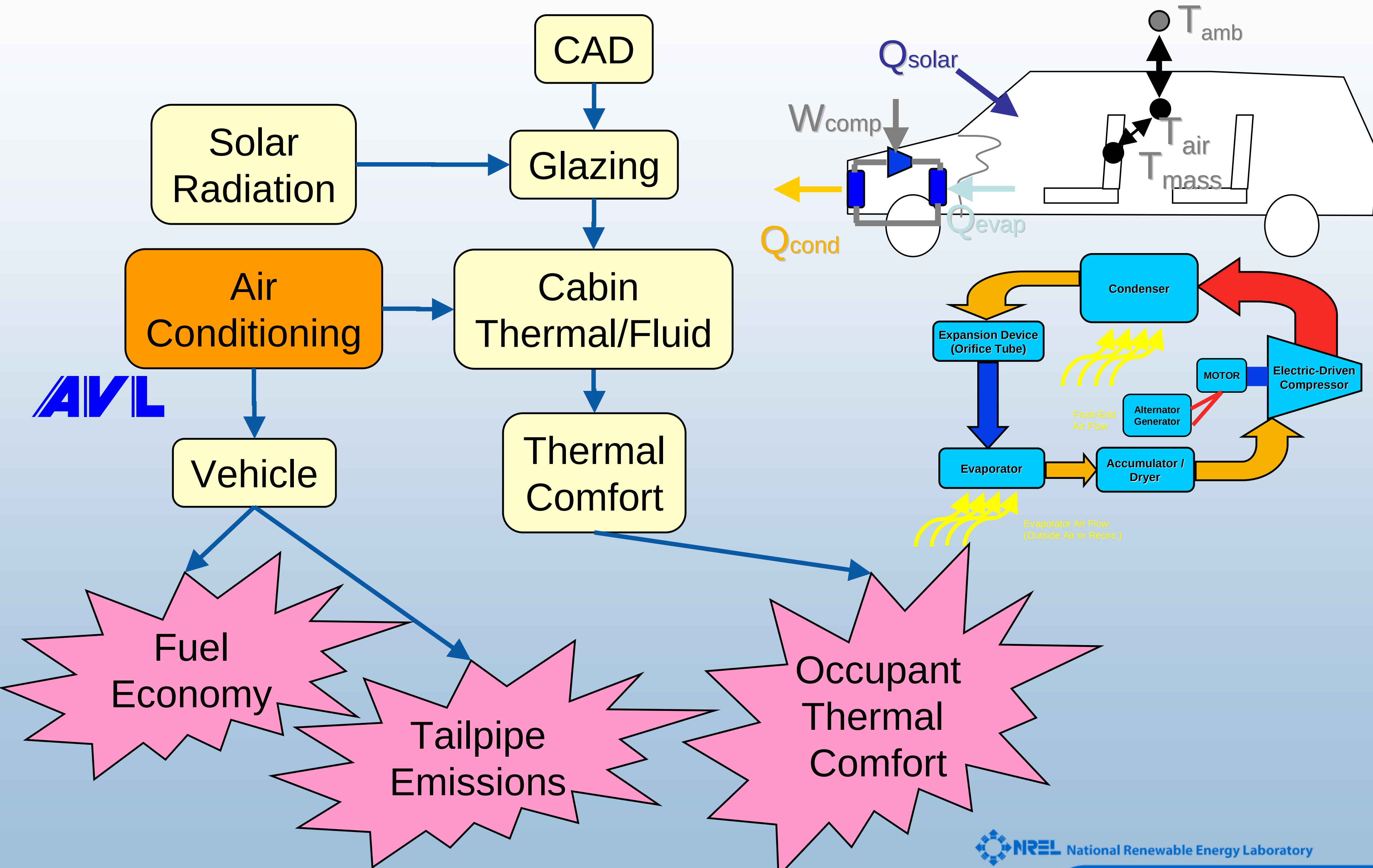
Integrated Modeling

Model temperatures and airflow in the cabin



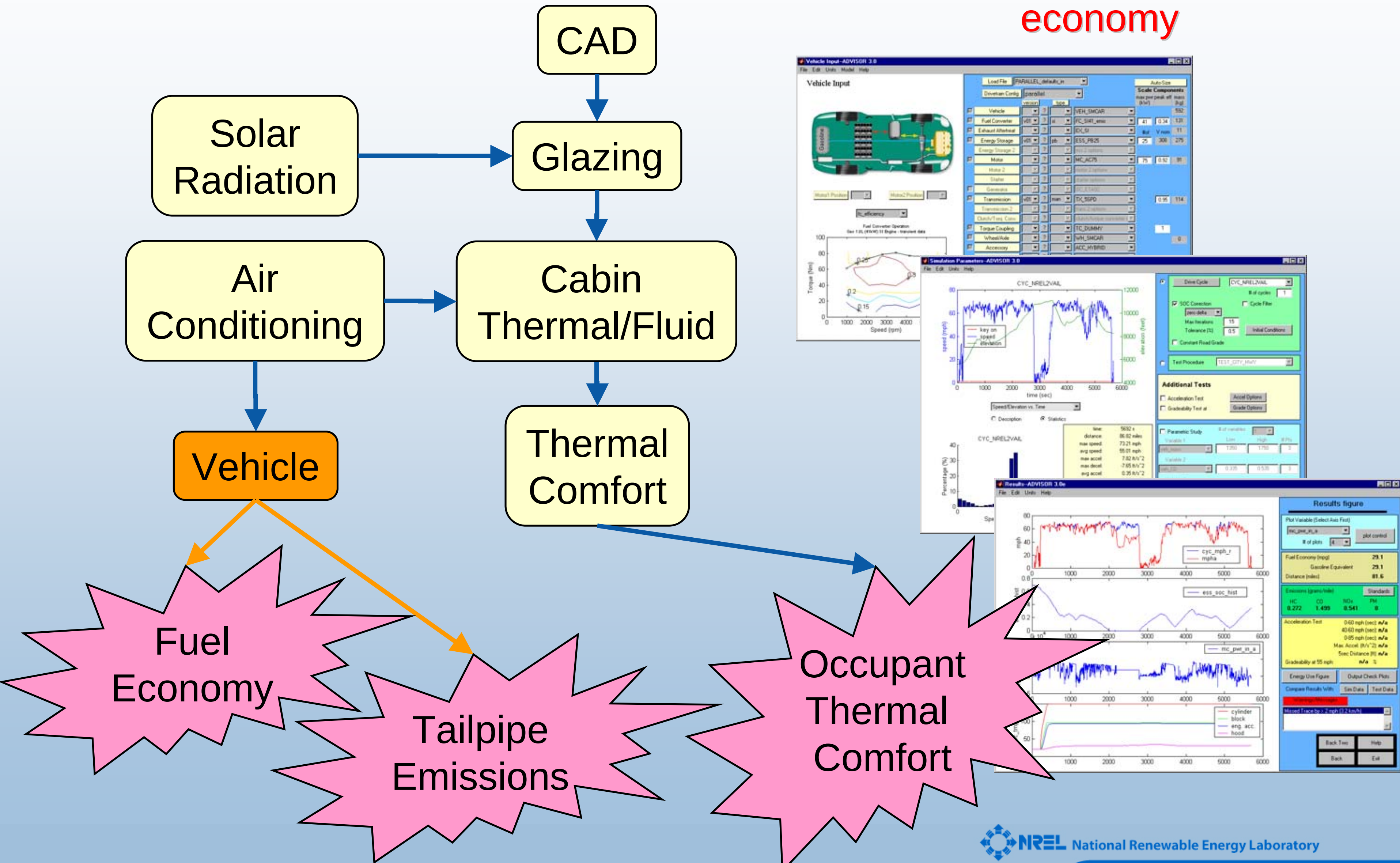
Integrated Modeling

Find the power consumption and cooling amount of the AC



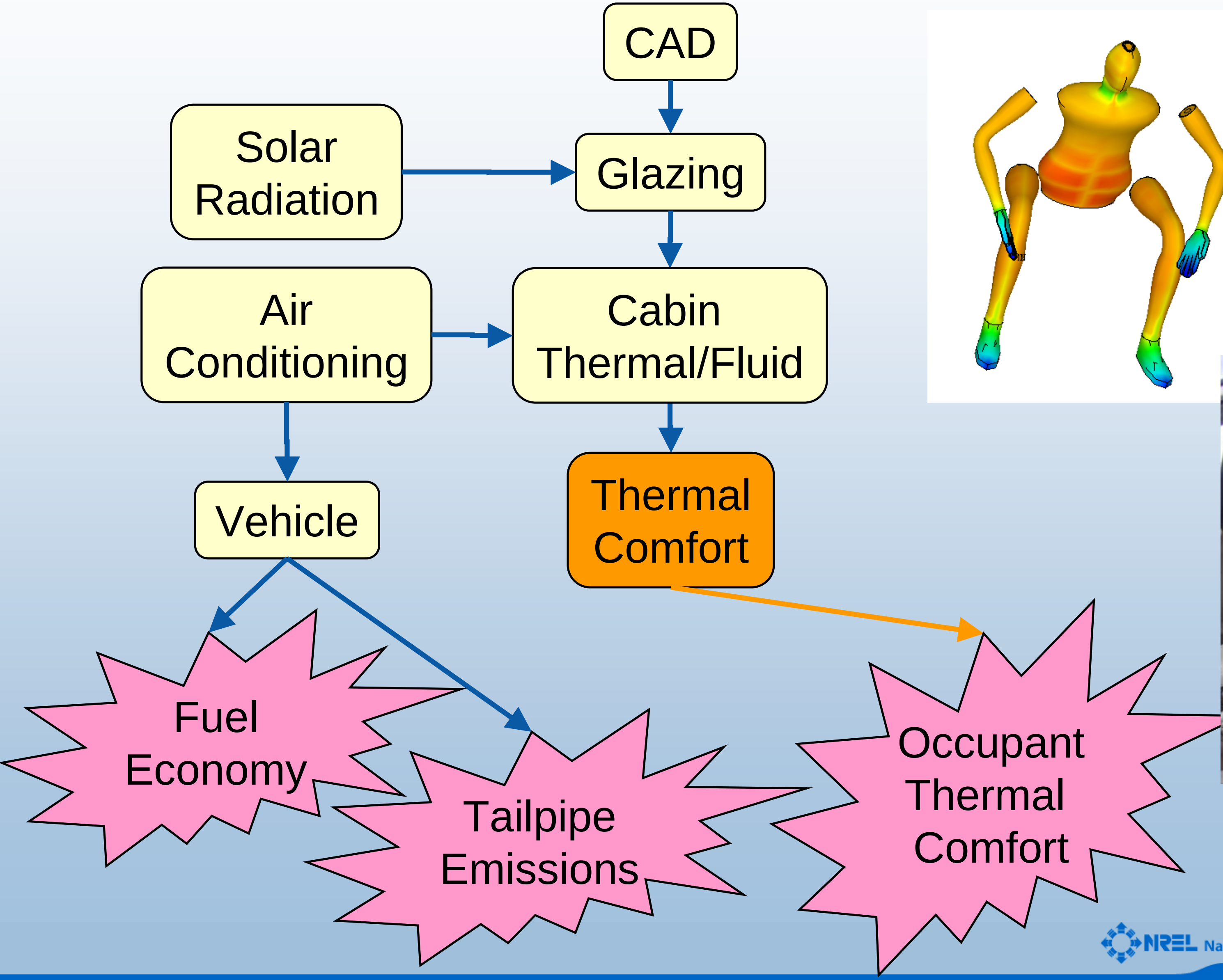
Integrated Modeling

Model your car over a drive cycle and find the fuel economy

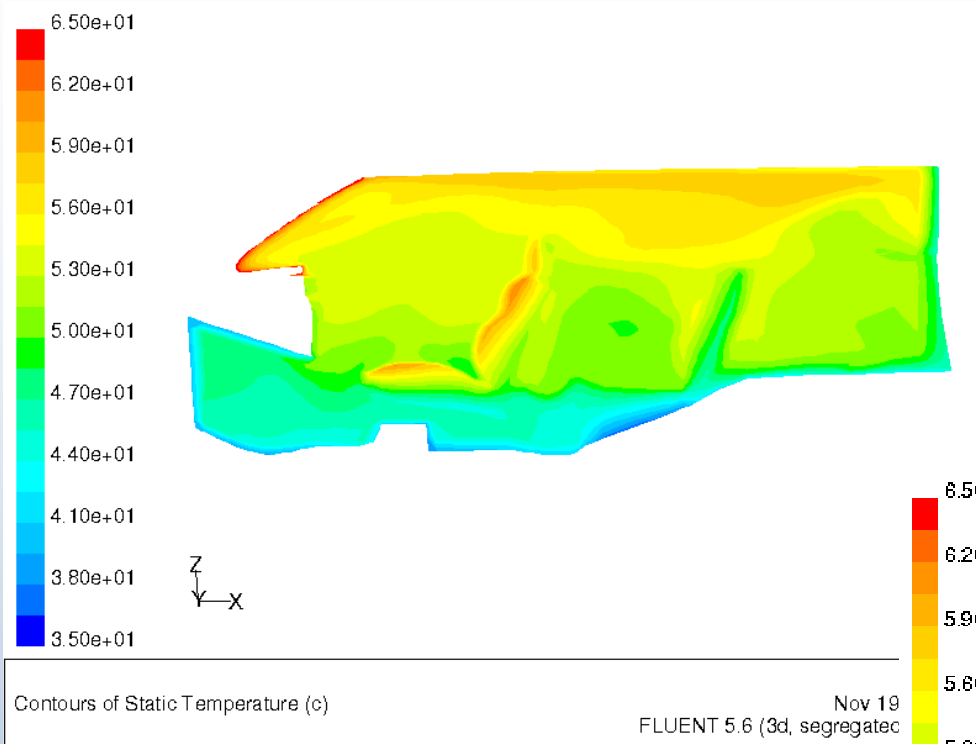


Integrated Modeling

How comfortable are you inside your car?



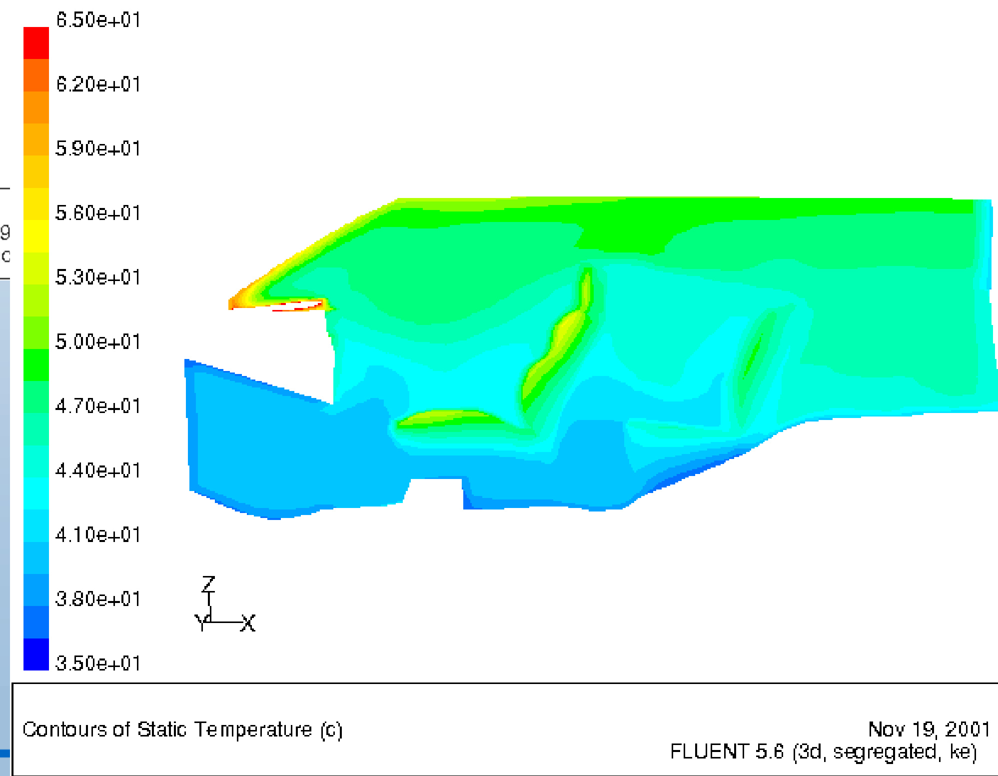
Modeled Air Temperature Reduction



Baseline

- Gold exterior

-7.9°C



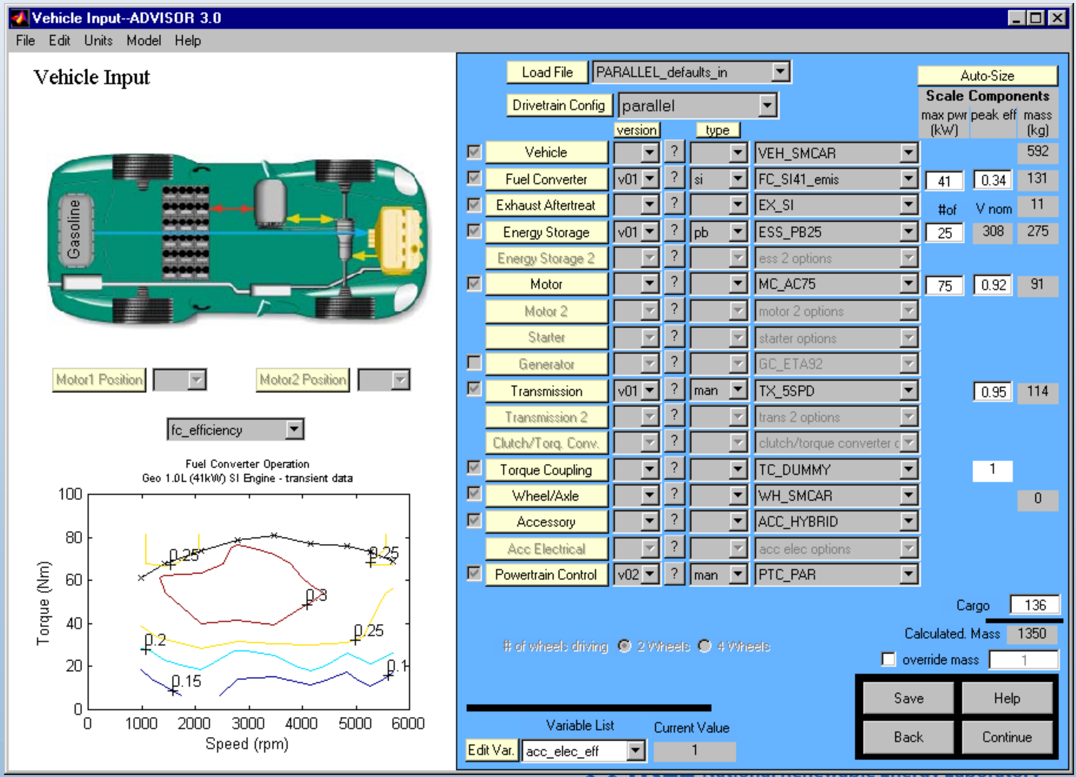
- All Glazing - Sungate™
- 25 scfm ventilation
- White exterior

ADVISOR Model Summary

Reducing the A/C system 32% can:

– Improve fuel economy 6% or 1 mpg (SCO3)

– Reduce emissions of NO_x by 12.8% or 0.05 gr/mi



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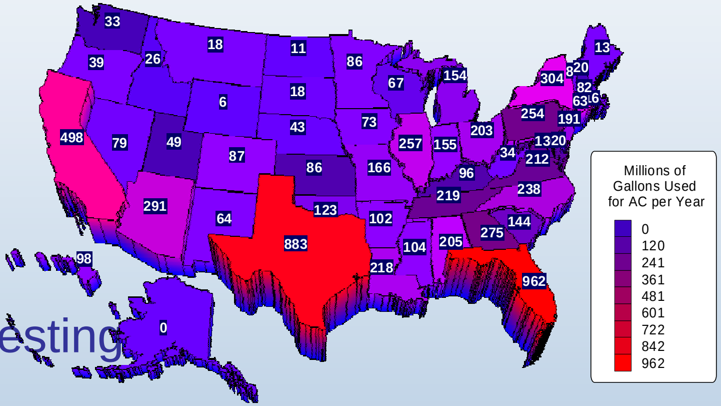


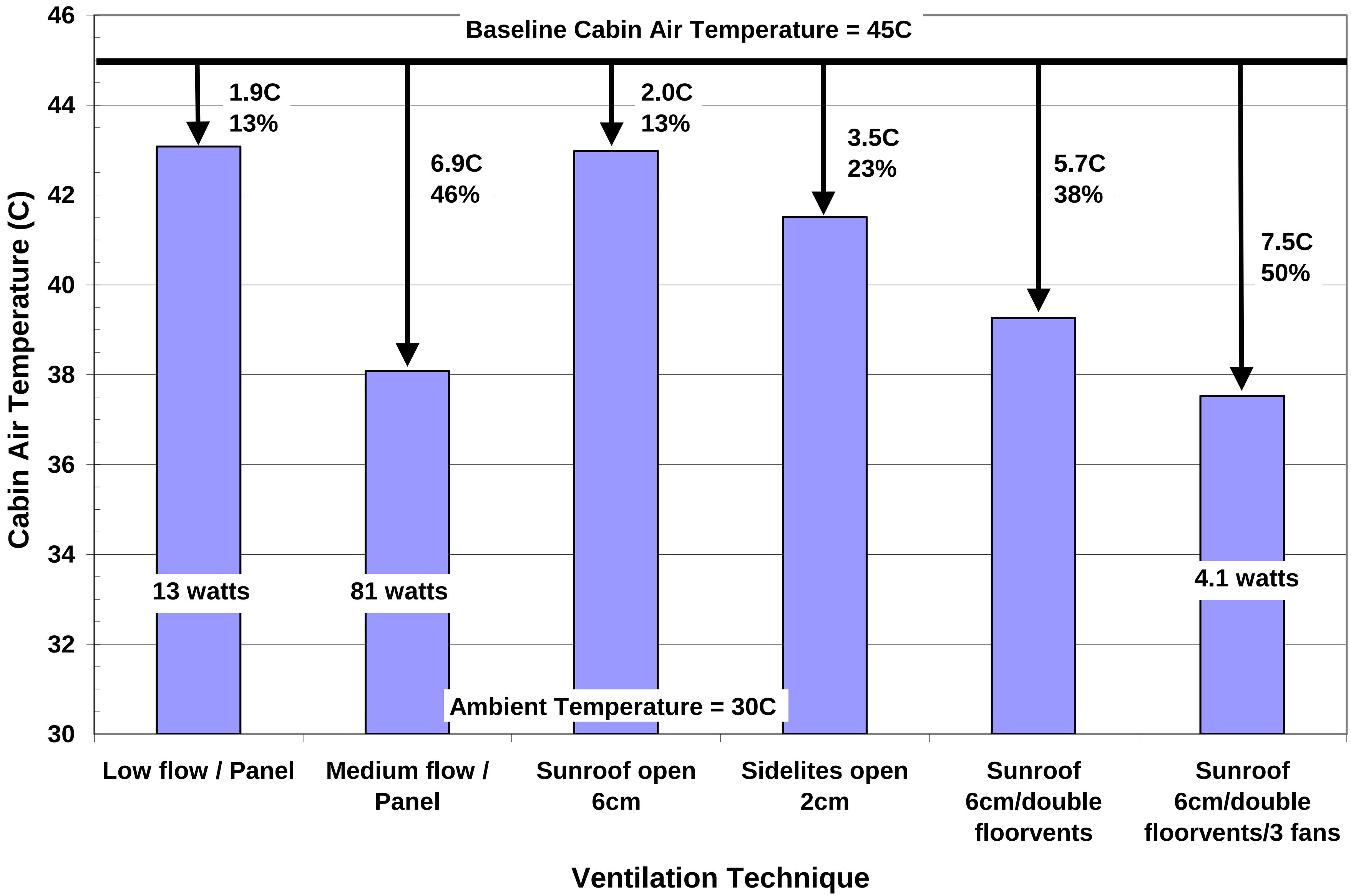
Jeep Grand Cherokee Parked Car Ventilation Test Program

DaimlerChrysler

Assess effect of:

- Forced ventilation
- Natural convection ventilation

Measured Cabin Air Temperature



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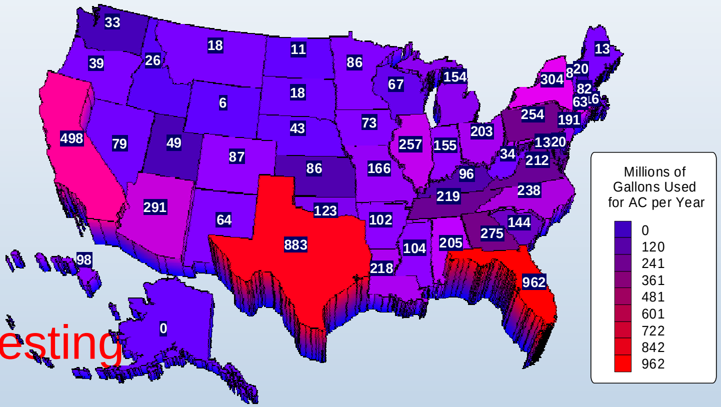


DaimlerChrysler Test Cells Correlation: Outdoor vs. Indoor

How well do indoor tests simulate outdoors?

NREL, Golden, CO

Outdoor Tests

Emissions Test Cell

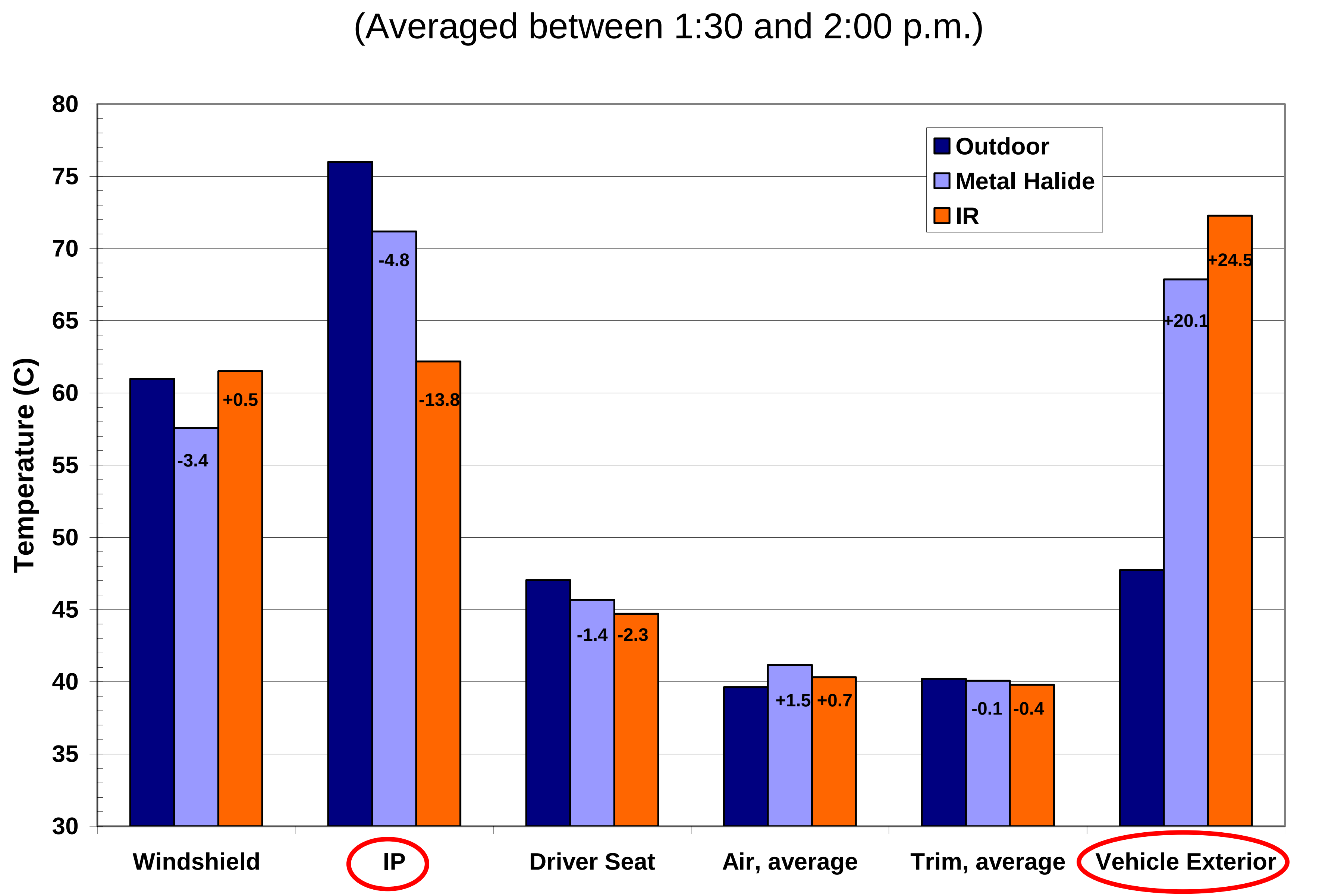
Sodium Scandium dosed Metal Halide

Environmental Test Cell

IR –Tungsten Filament Quartz Tubes

DaimlerChrysler, DCTC, Auburn Hills, MI

Indoor Temperatures Compared to Outdoor



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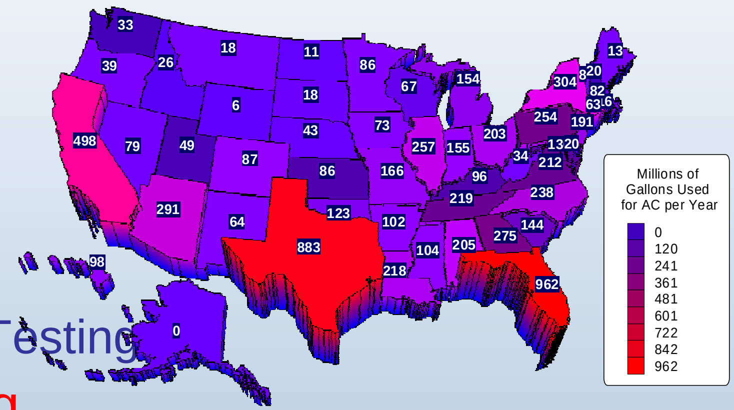
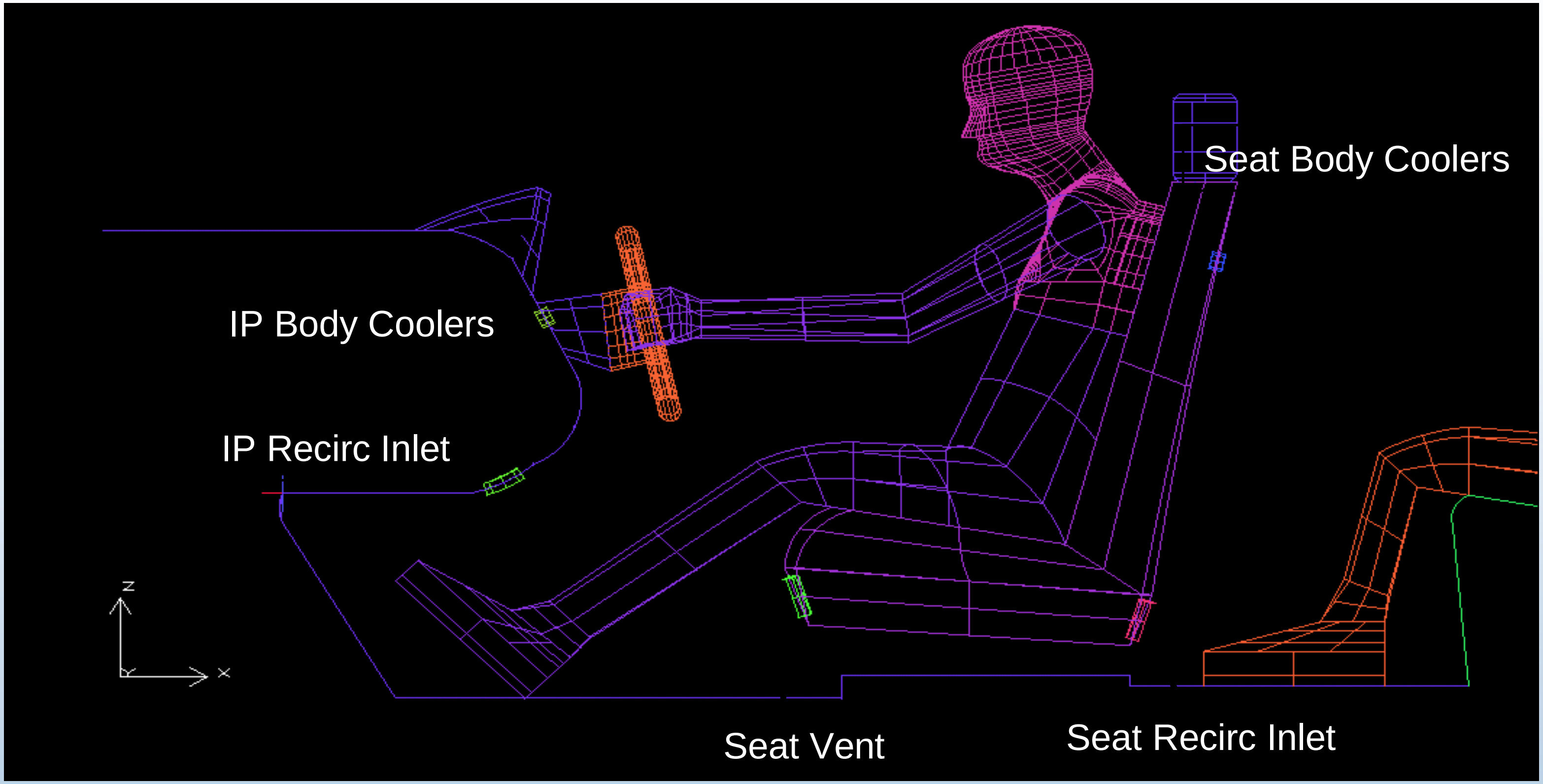


JCI Distributed HVAC Project

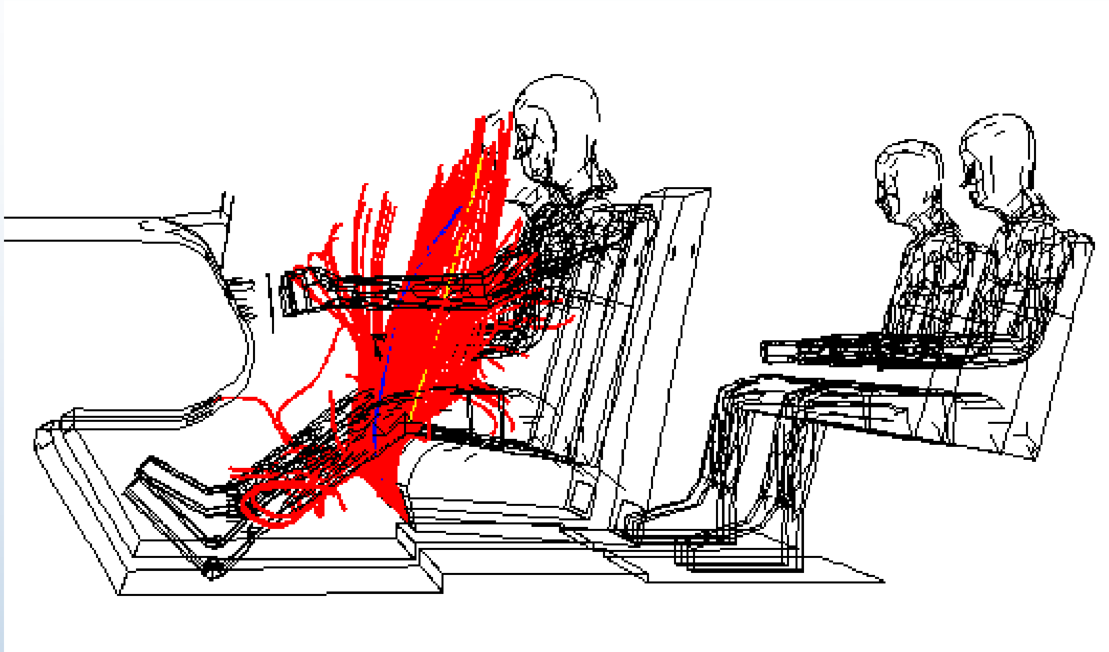


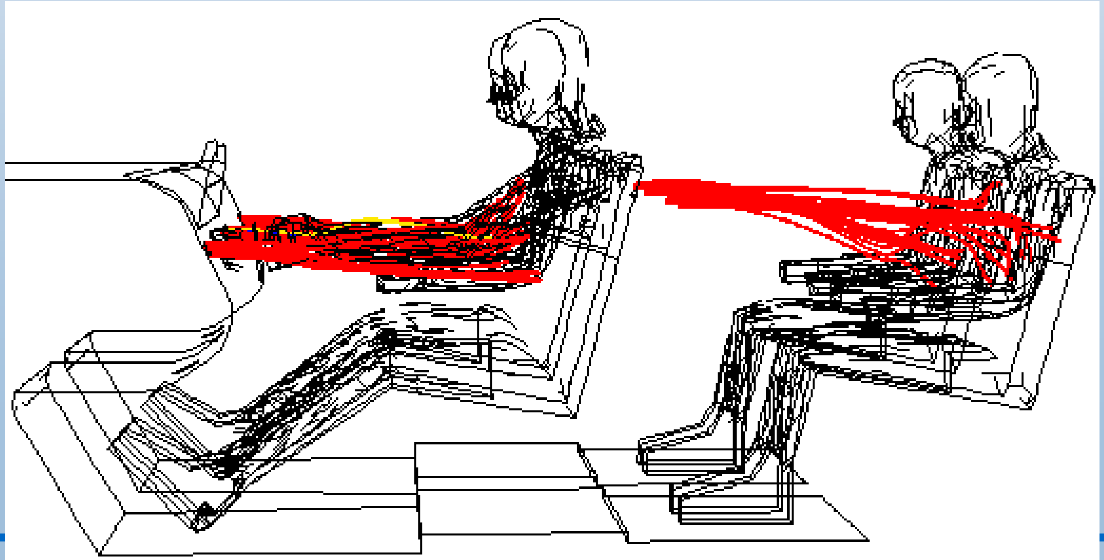
- Assess human thermal comfort impact of JCI distributed HVAC system
  - Flow circulation & impingement
  - Steady state air temperature
  - Cooldown performance

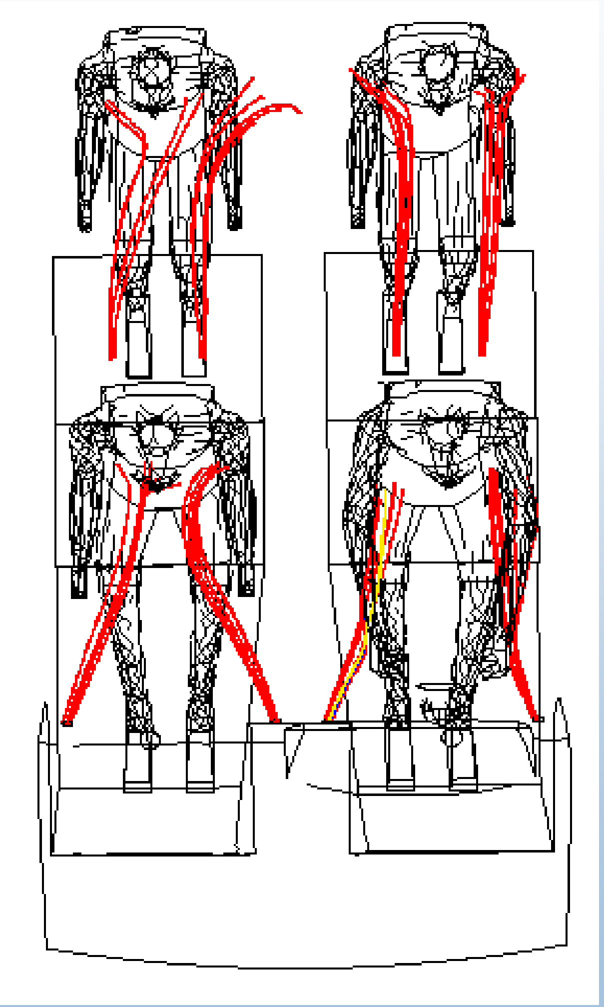
JOHNSON CONTROLS

NREL National Renewable Energy Laboratory

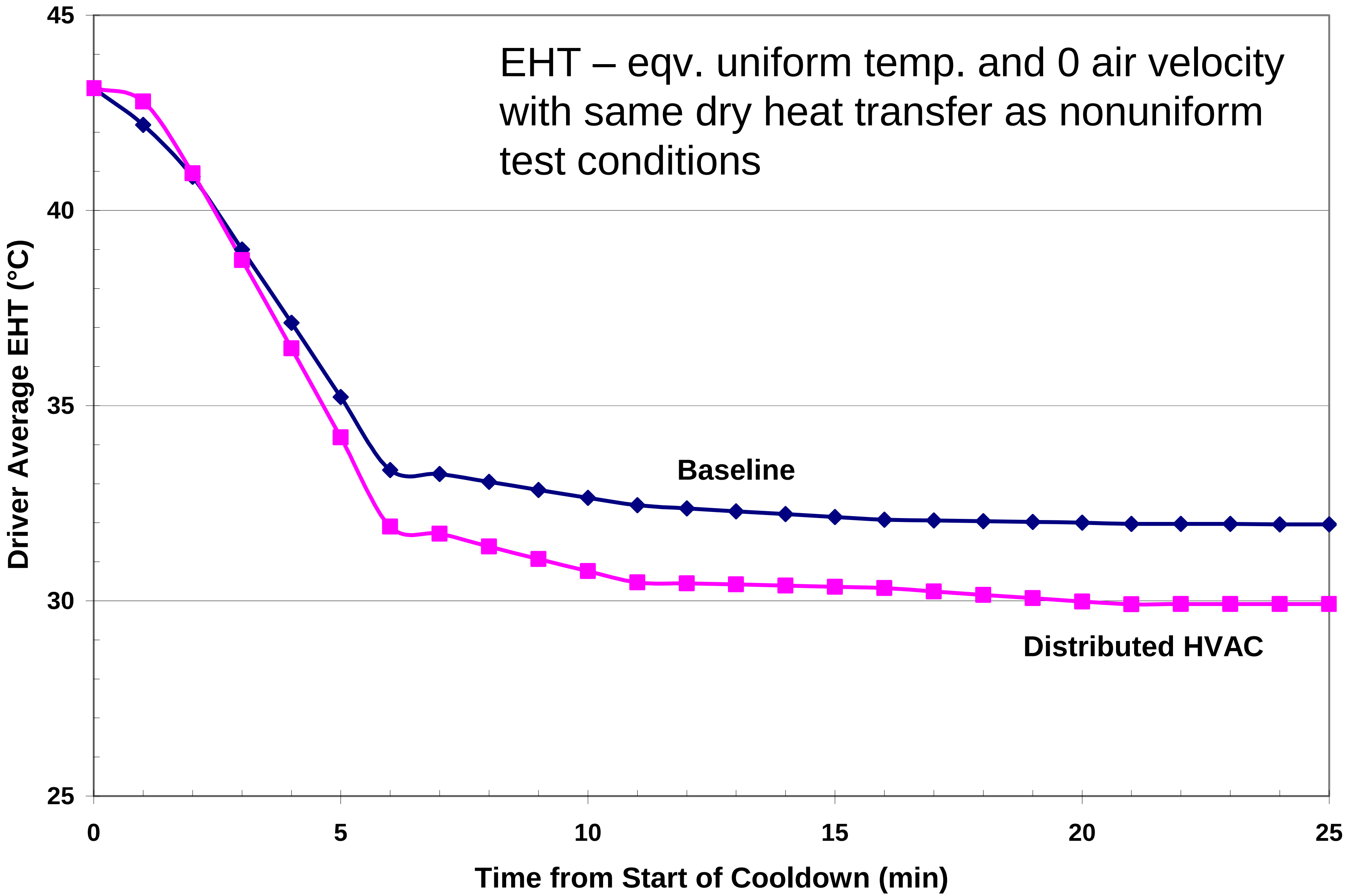
Pathlines from Body Coolers and Seat Vents







Driver Overall
Equivalent Homogeneous Temperature (EHT)



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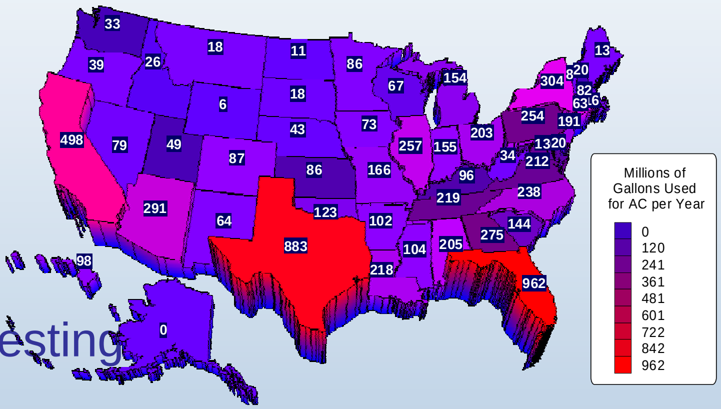
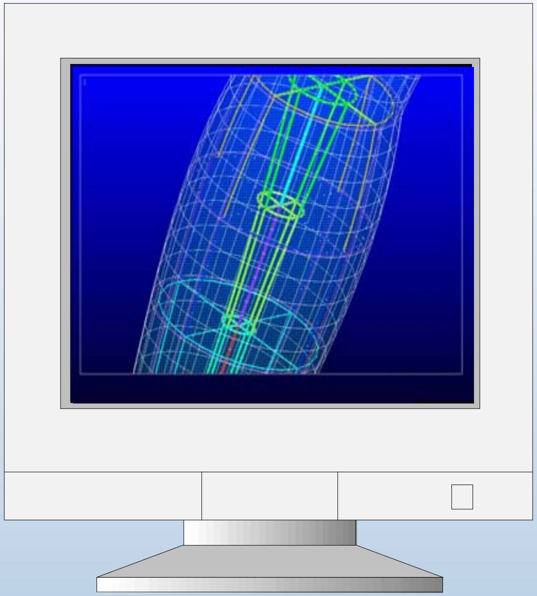


Thermal Comfort Assessment Tools

Predicting the comfort of vehicle occupants

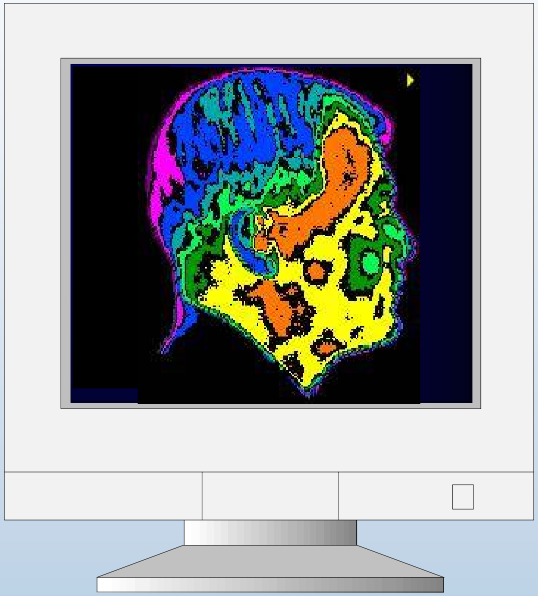
ADvanced Automotive Manikin

Manikin presentation



Human Thermal Physiological Model

Physiological

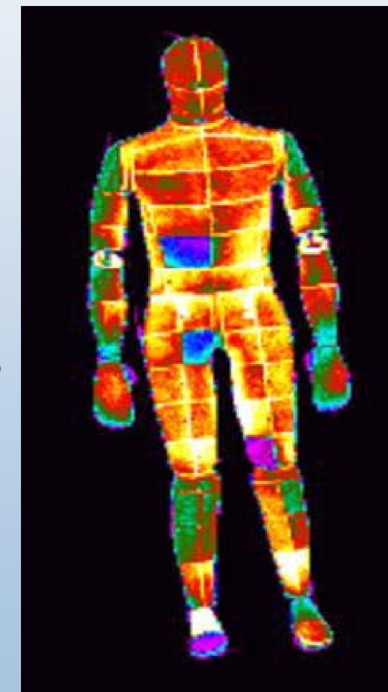


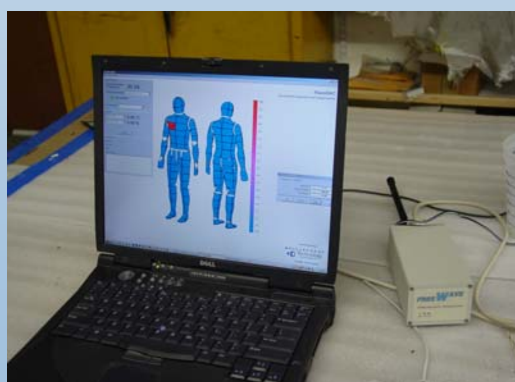
Human Thermal Comfort Empirical Model

Psychological

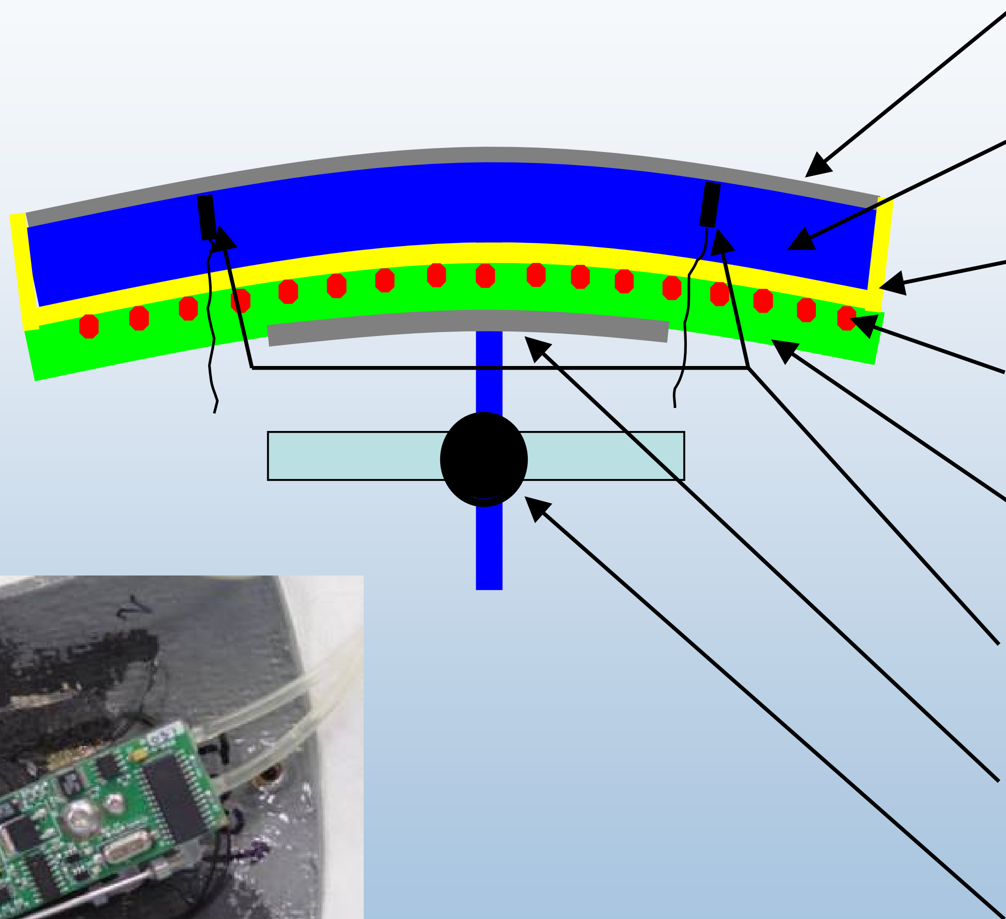
ADvanced Automotive Manikin (ADAM)

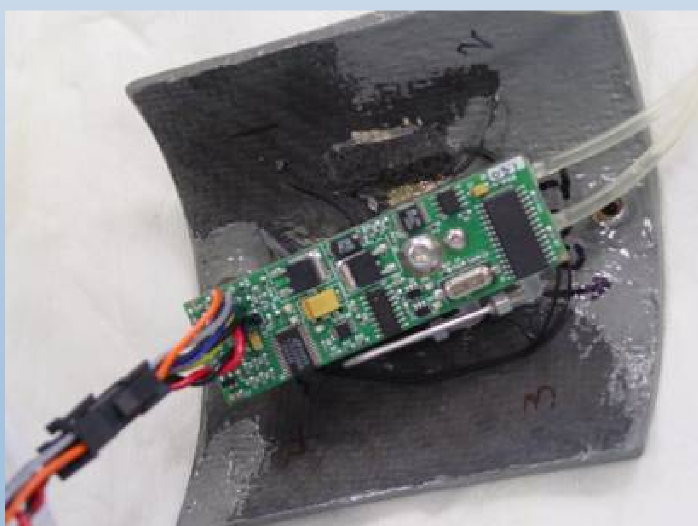
- On-board power, water, communications
- Designed to respond to a transient, non-uniform thermal environment like a human:
  - Sweating
  - Breathing
- Wears clothes
- 175 cm tall, 61 kg
- 126 elements (~120 cm^2), 120 zones





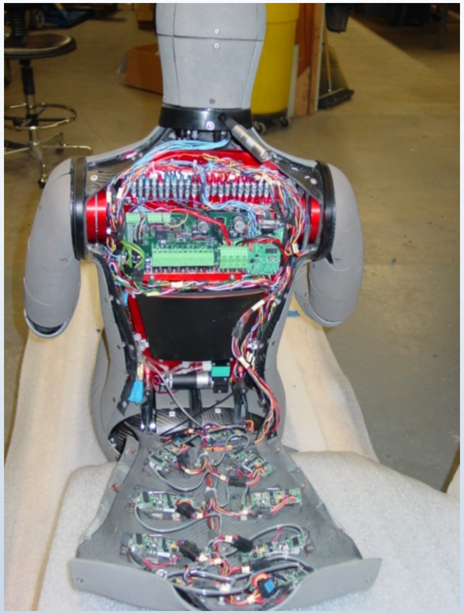
Surface Segment Details

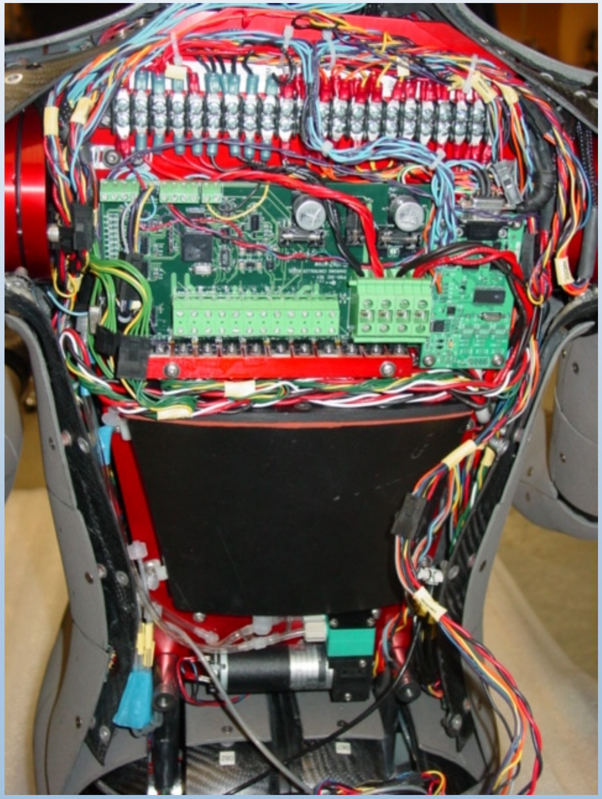




Segment with Exaggerated Sweat Rate

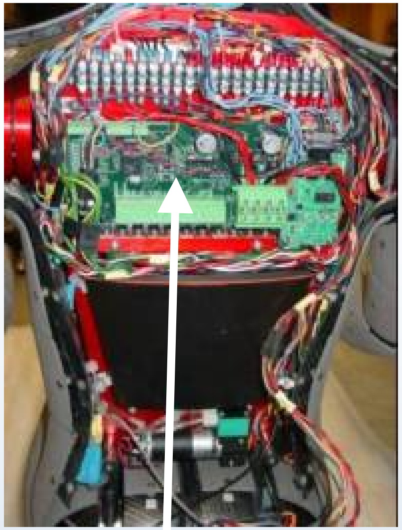
ADAM's Carbon Fiber Skeletal System



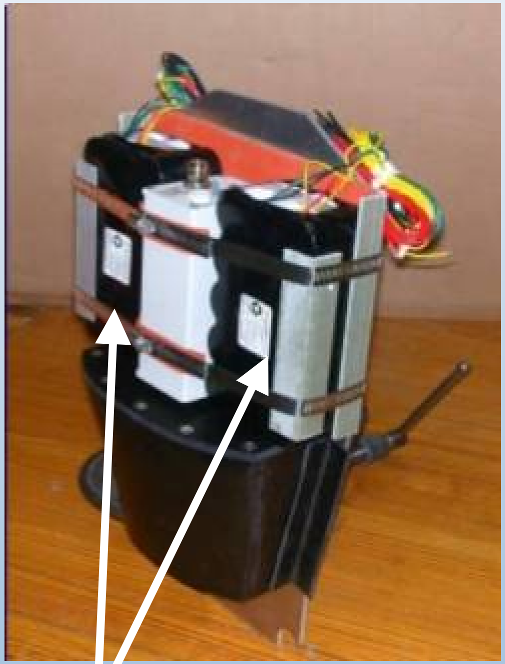


Battery System

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



Charge Controller

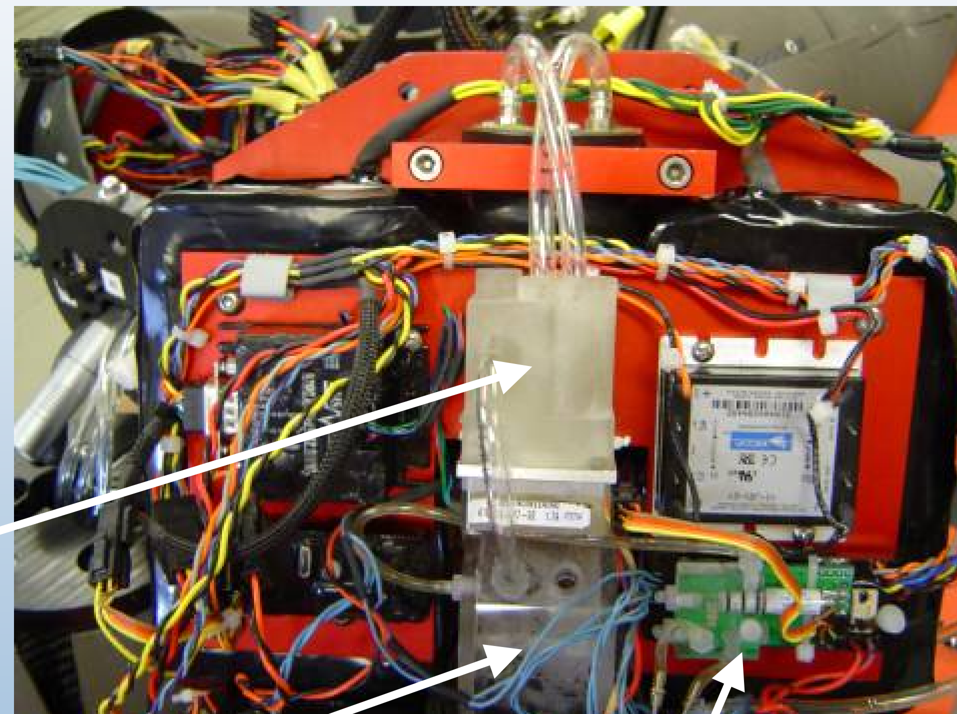


2 Modules in torso

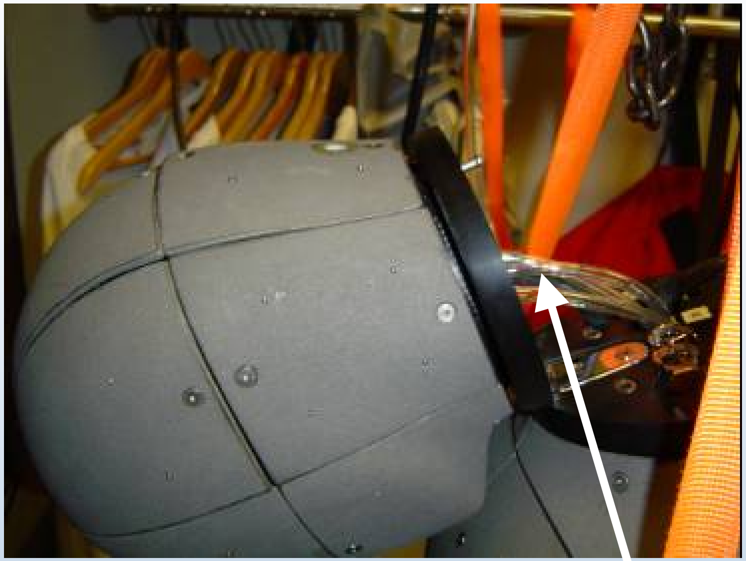
Modules in each thigh

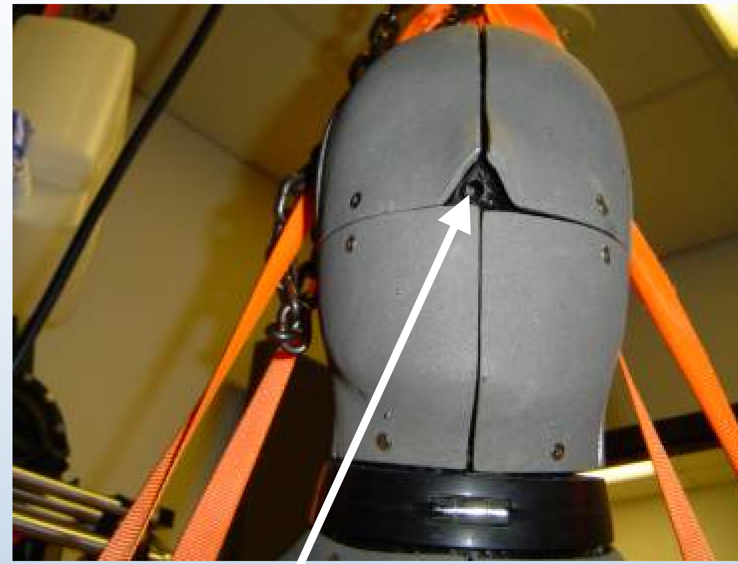
Breathing System

- 5 L/min periodic exhalation and inhalation
- 10 L/min continuous exhalation
- 100% R.H. at body temperature



Breathing System (cont.)



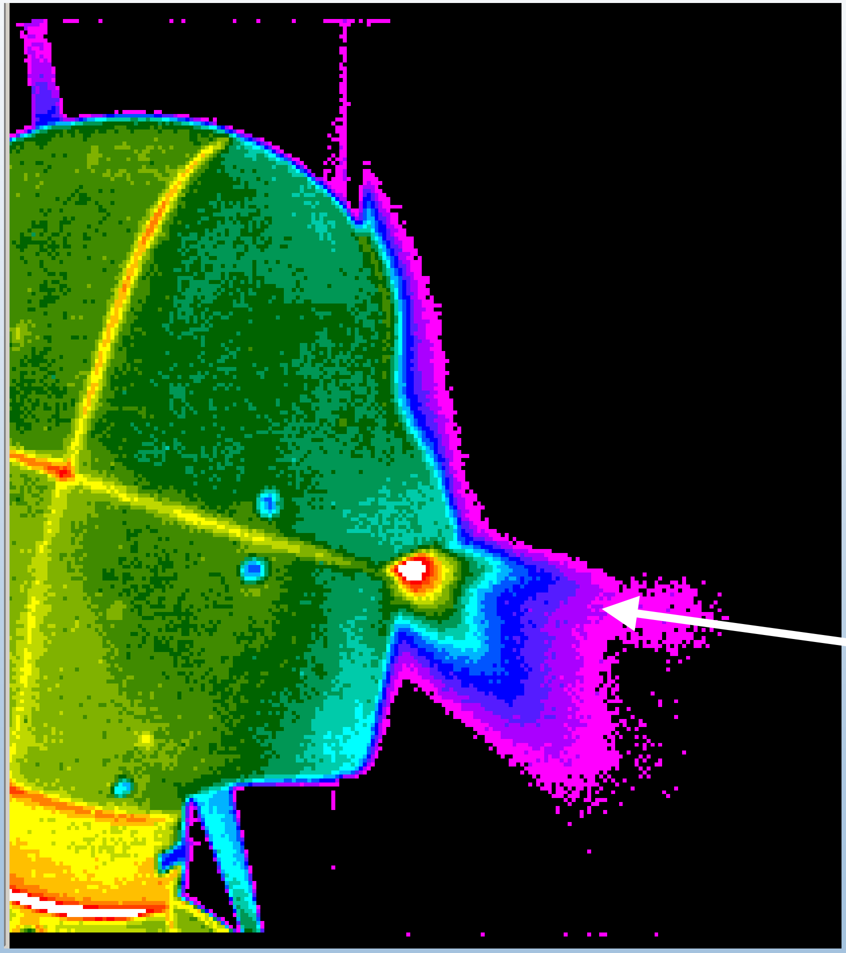


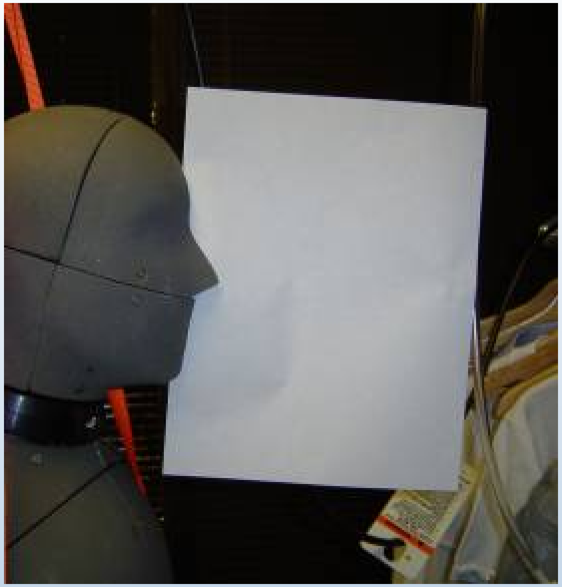
Tubes to nose

Nose breathing port

Neck auxiliary breathing port
(inlet for continuous exhale mode)

IR Image of breathing

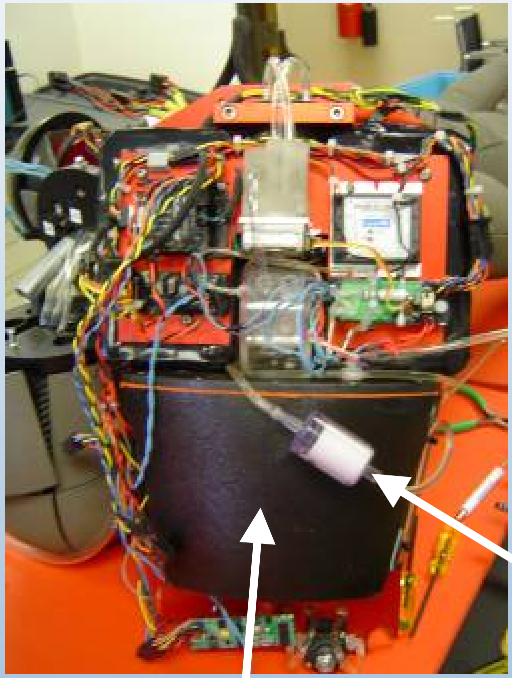


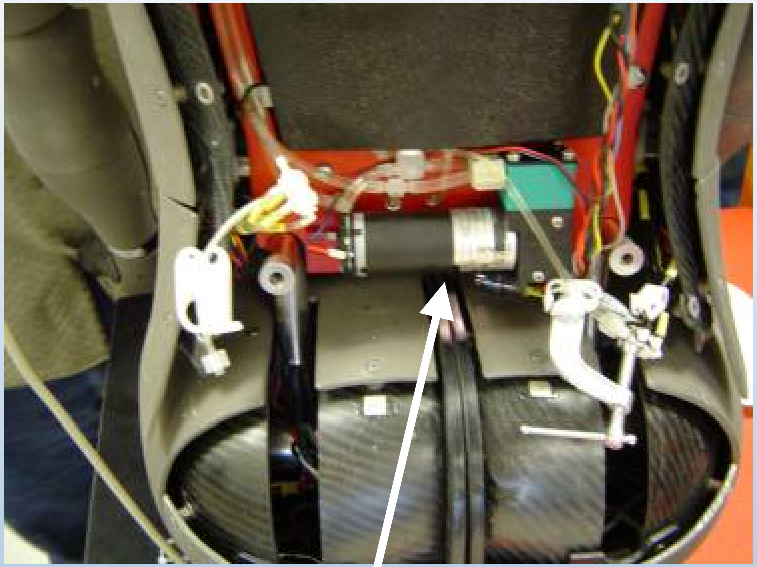


Heated plume of air

Fluid System Filter

- Added to mitigate contamination problem with segment capillary tubes



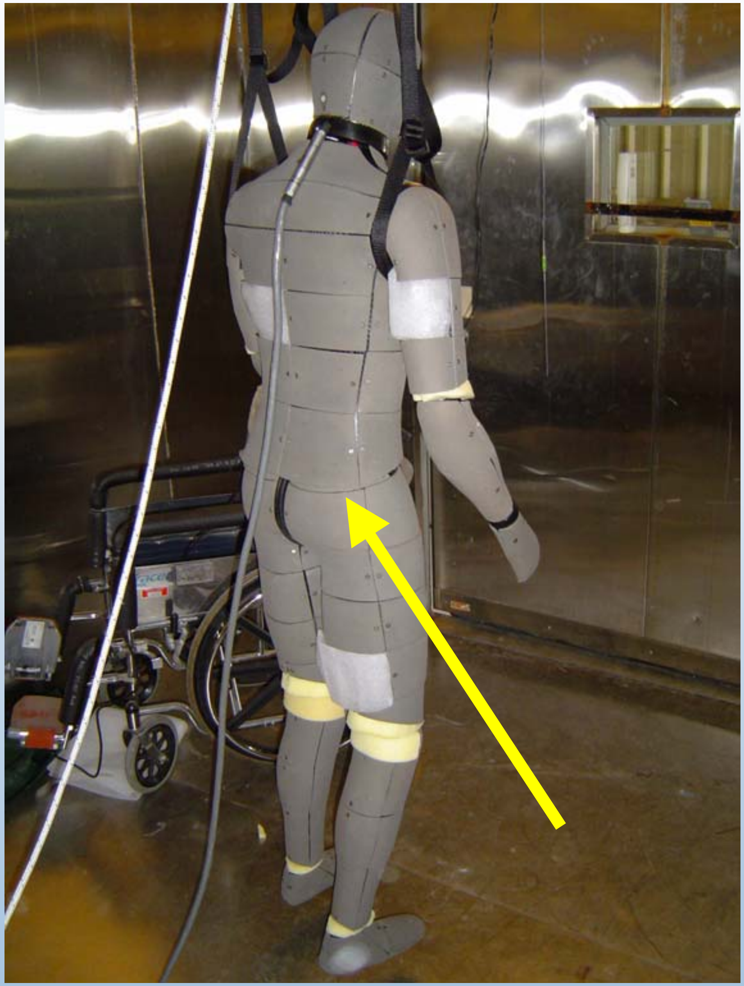


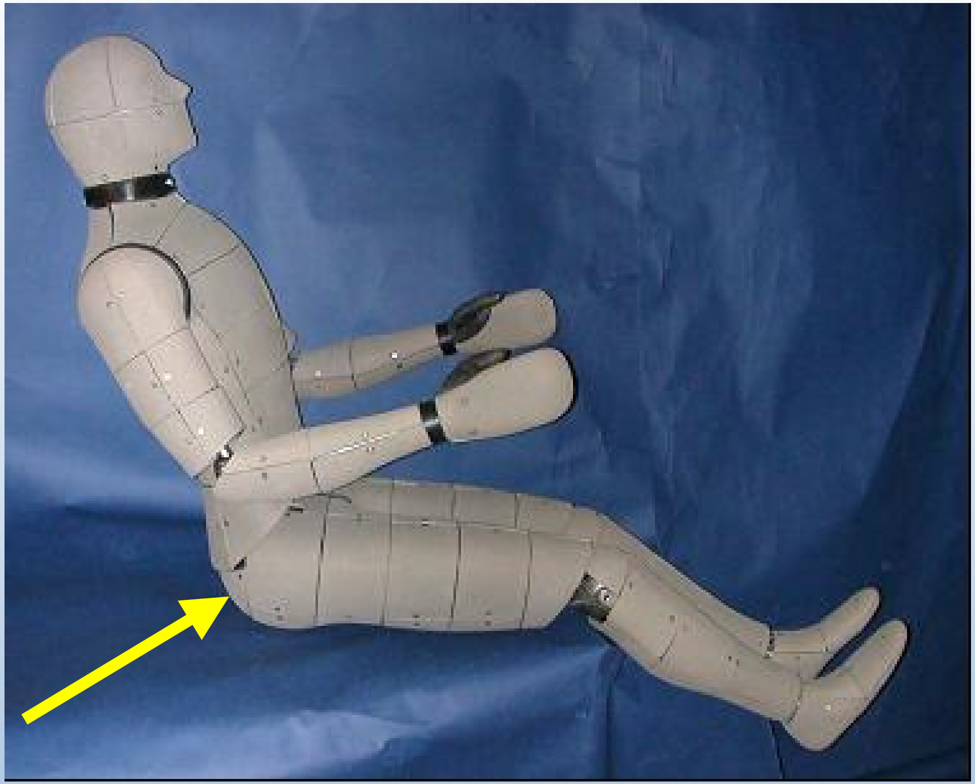
Filter

Fluid reservoir

Fluid pump

ADAM's Active/Inactive Segments

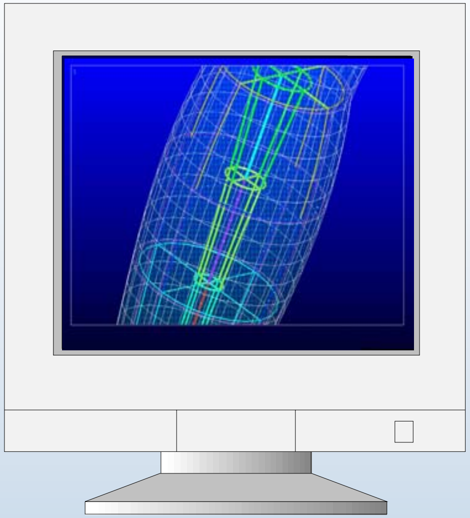




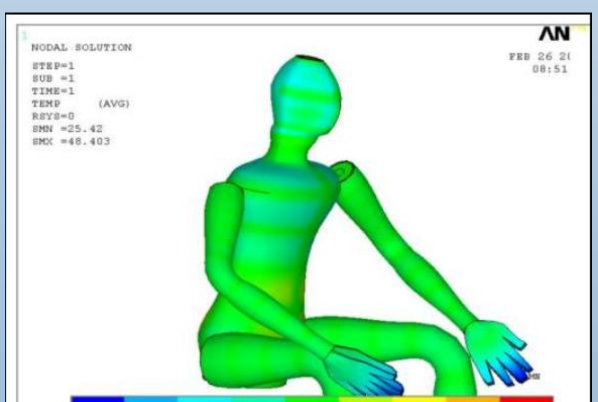
Ready for a Brain!

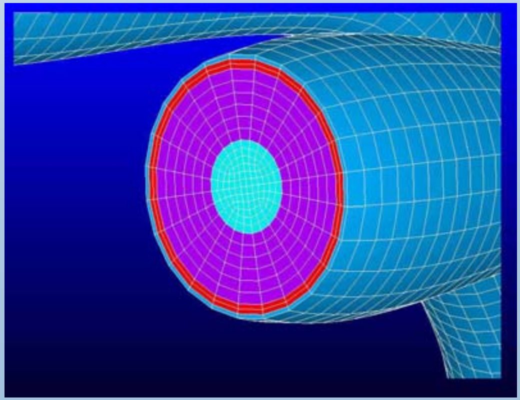
Human Thermal Physiological Model

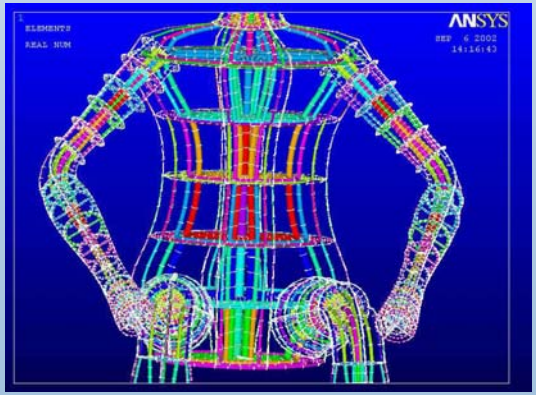
A Numerical Person



- 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)



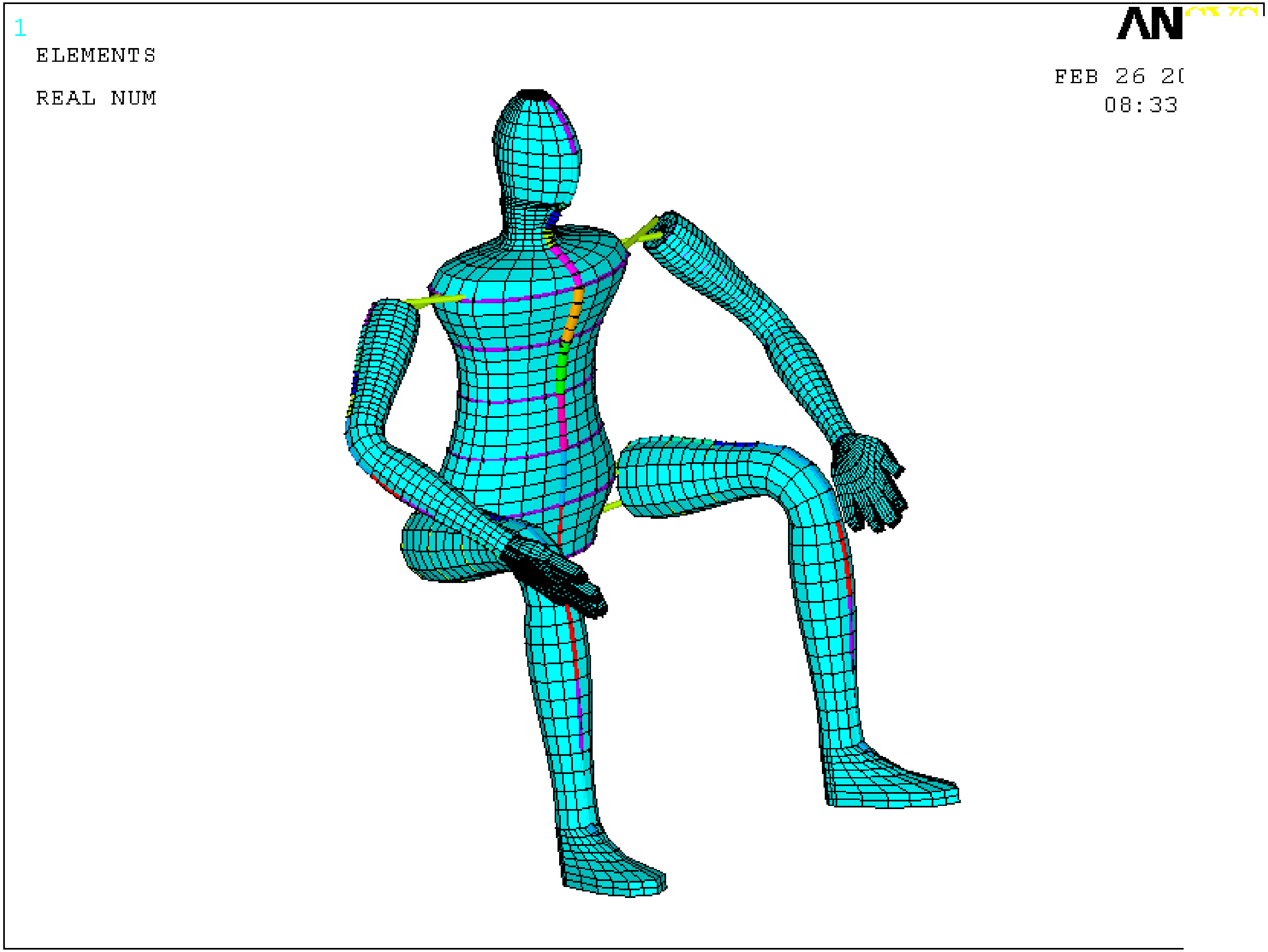




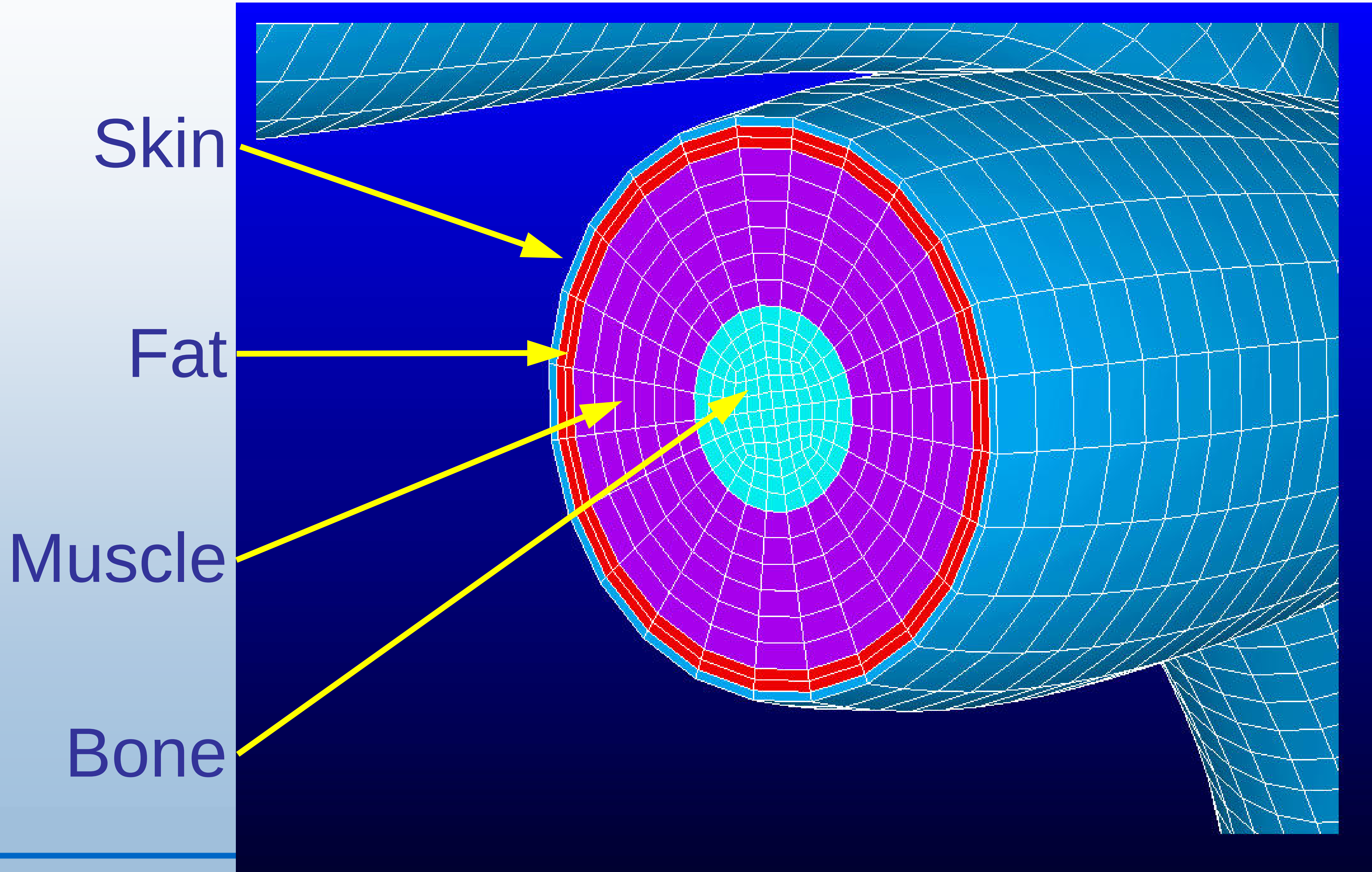
Human Thermal Physiological Model
Thermoregulatory System

- 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

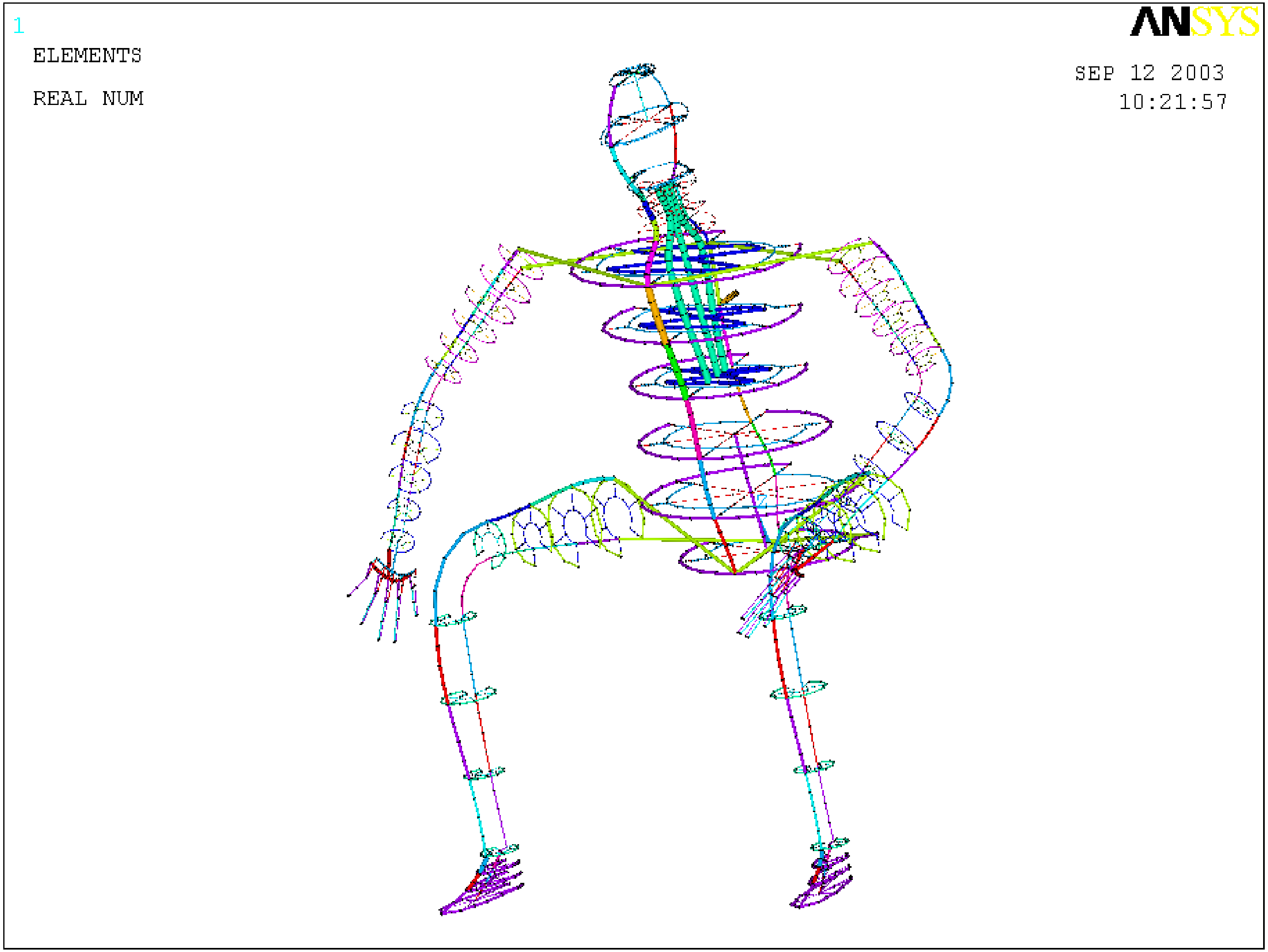
Mesh



Section View of Upper Right Leg

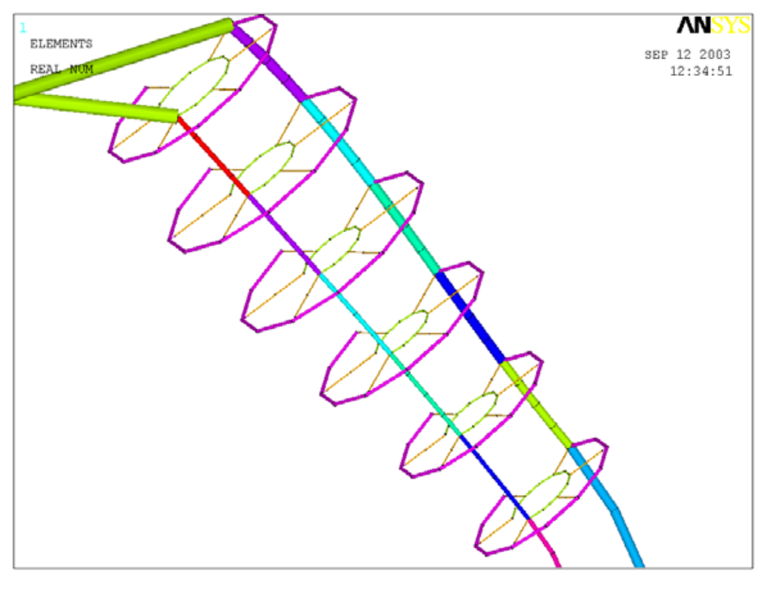


Circulation Network



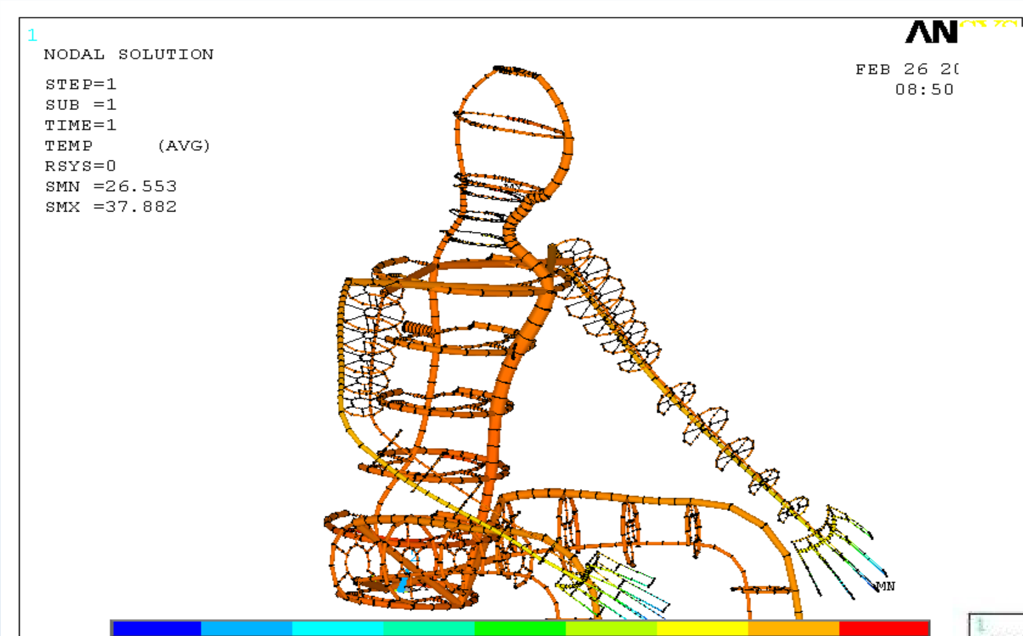
FEA Model of the Flow Network of Upper Arm

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



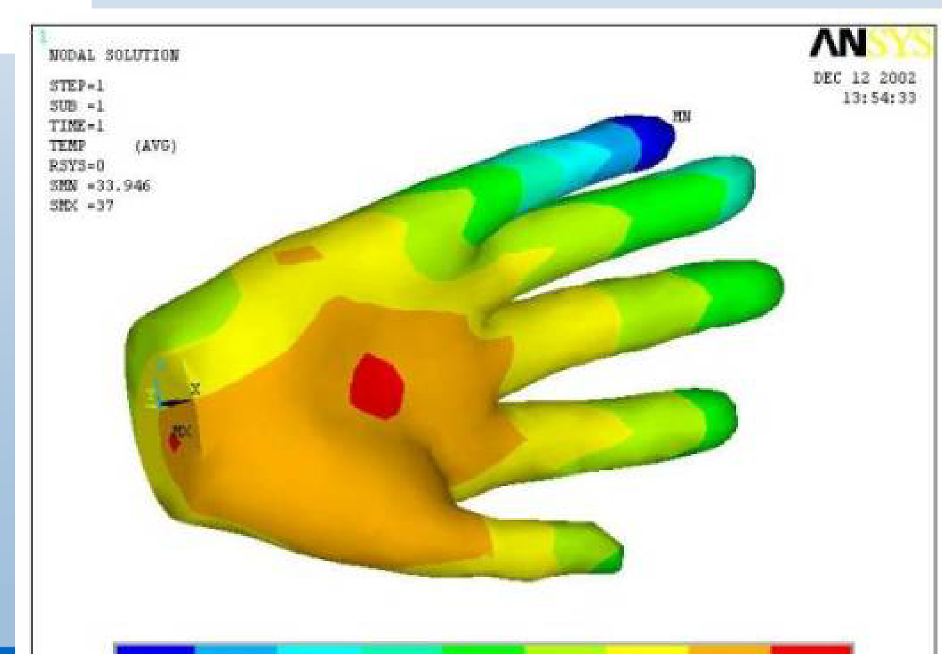
- Cross-section of elements adjustable at every time step for vaso-dilation/constriction

Blood Vessel Temperatures

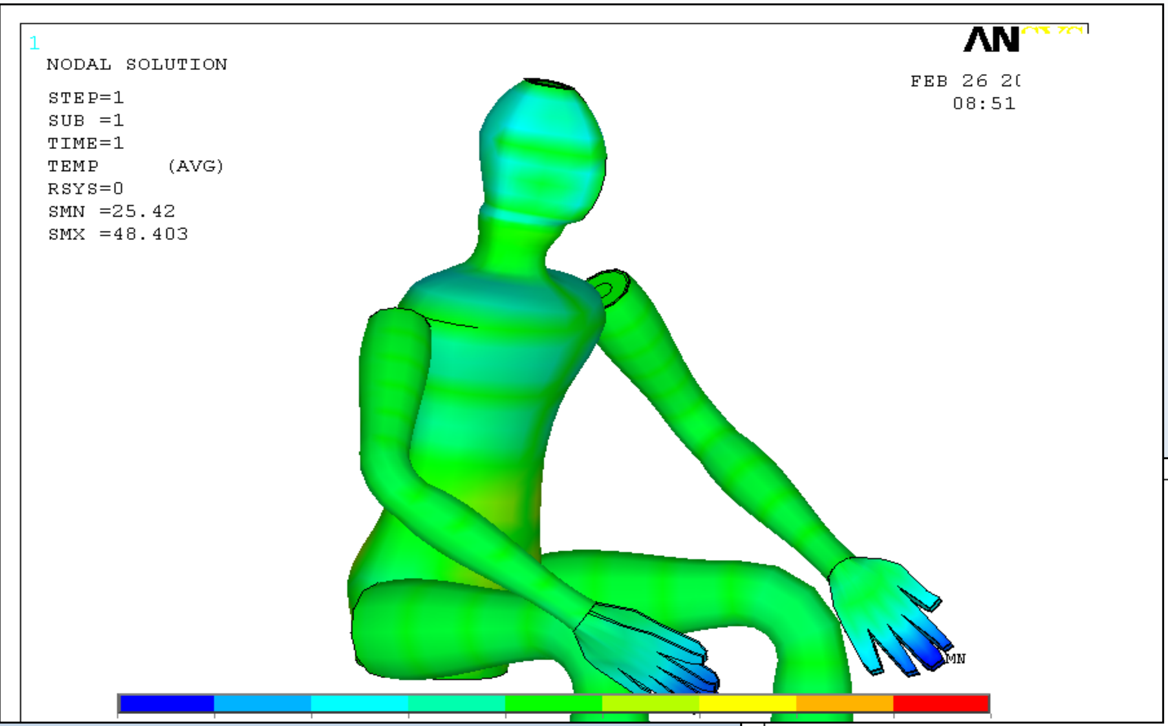


Hand Skin Temperatures

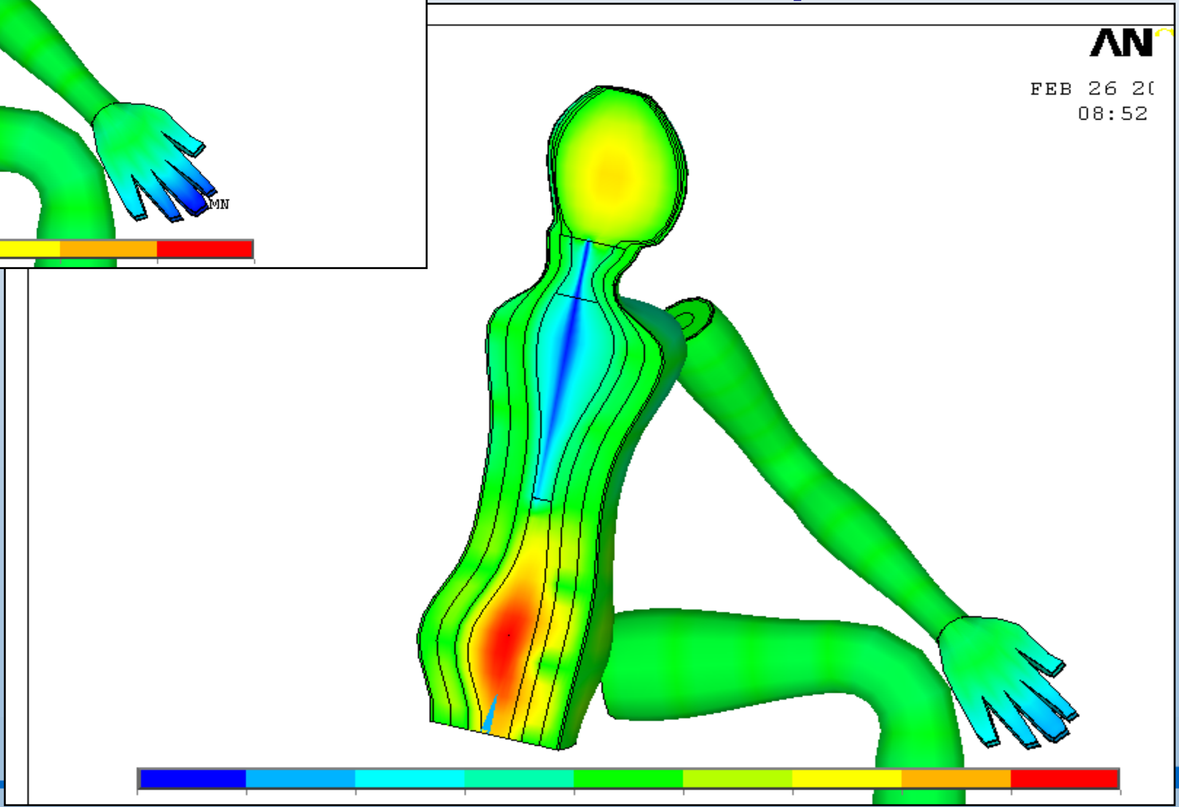
- Blood flow rate to arteries of 1380 cc/h @ 37ºC
- Muscle tissue 750 W/m3
- Skin tissue 1005 W/m^3
- Skin heat loss 100 W/m^2



Body Skin Temperatures



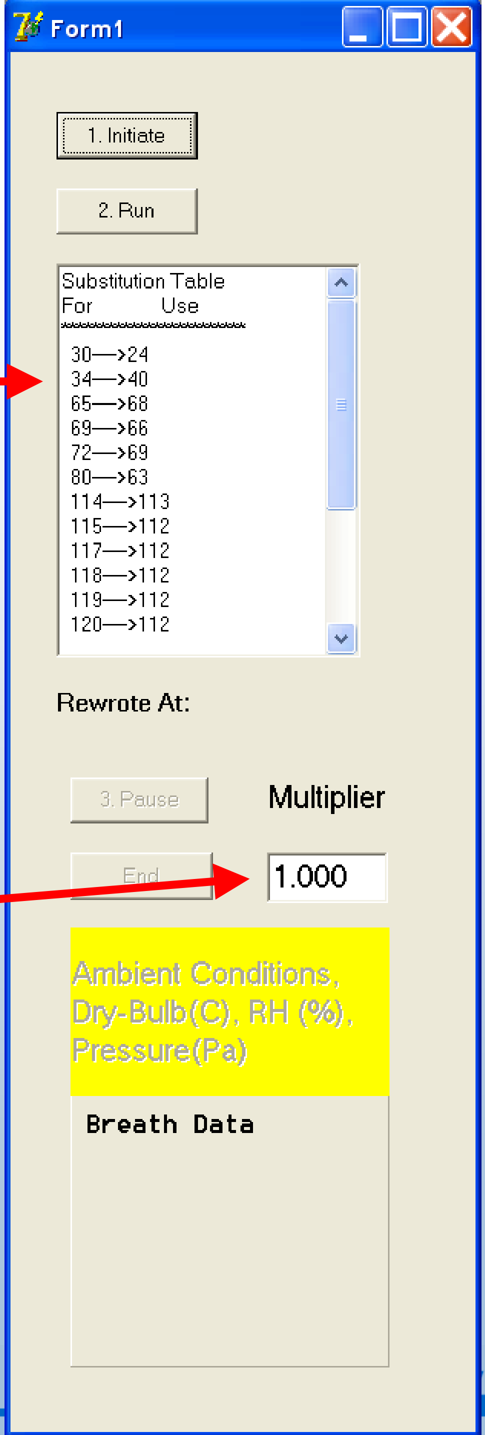
Body Section Temperatures



Interface program

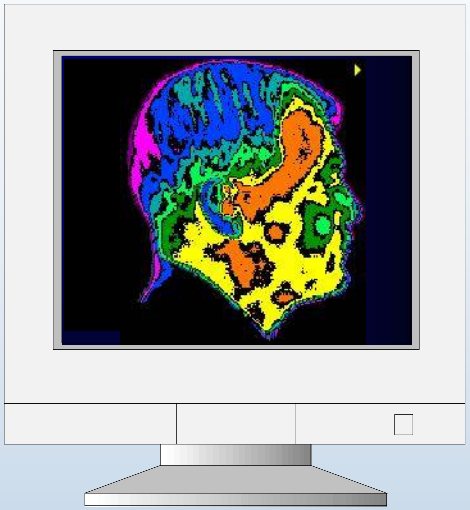
Substitute Table
(model uses data from good segment in place of a malfunctioning segment)

Heat flux multiplier
(ability to adjust heat flux from ADAM)

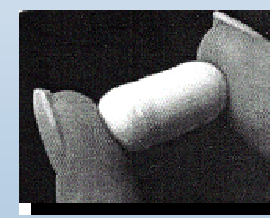


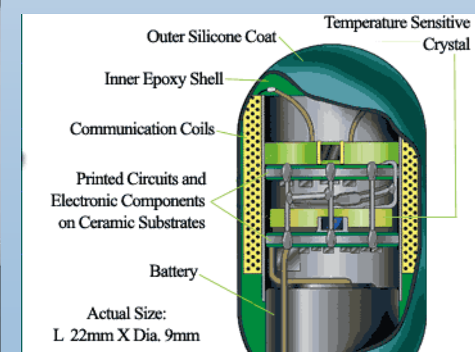
The Human Thermal Comfort Empirical Model

How You Feel Thermally

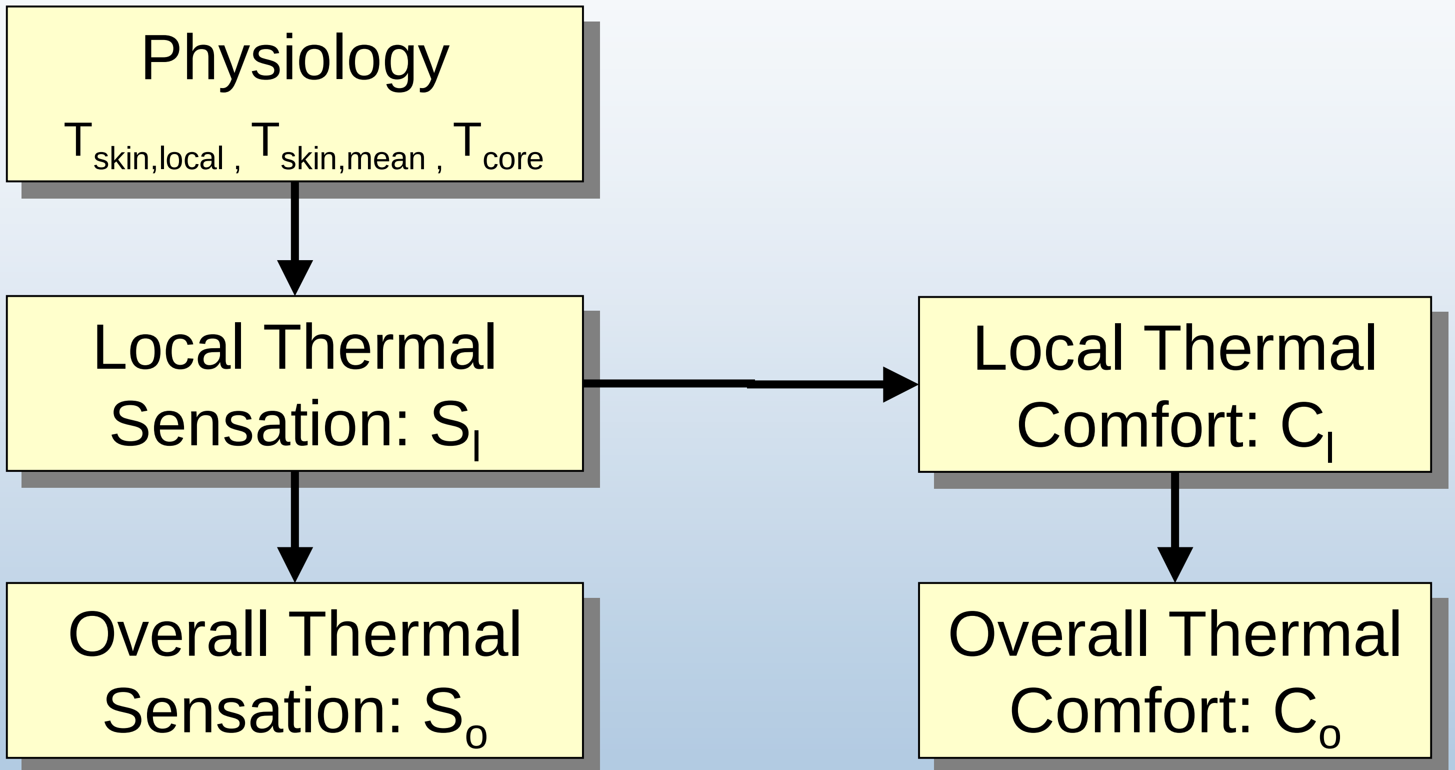


- Determines local thermal sensation
- Determines local and global thermal comfort (thermal perception) from local sensations
- Accounts for non-uniform and transient thermal environment of vehicle cabin



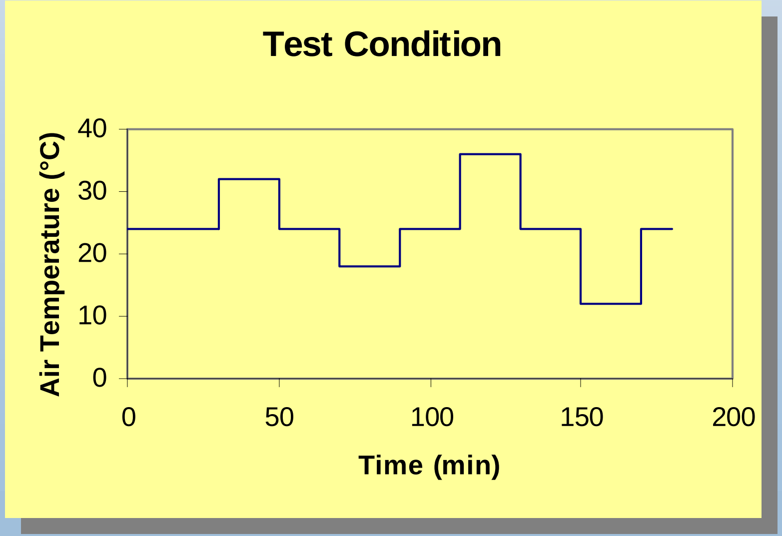


Model Overview

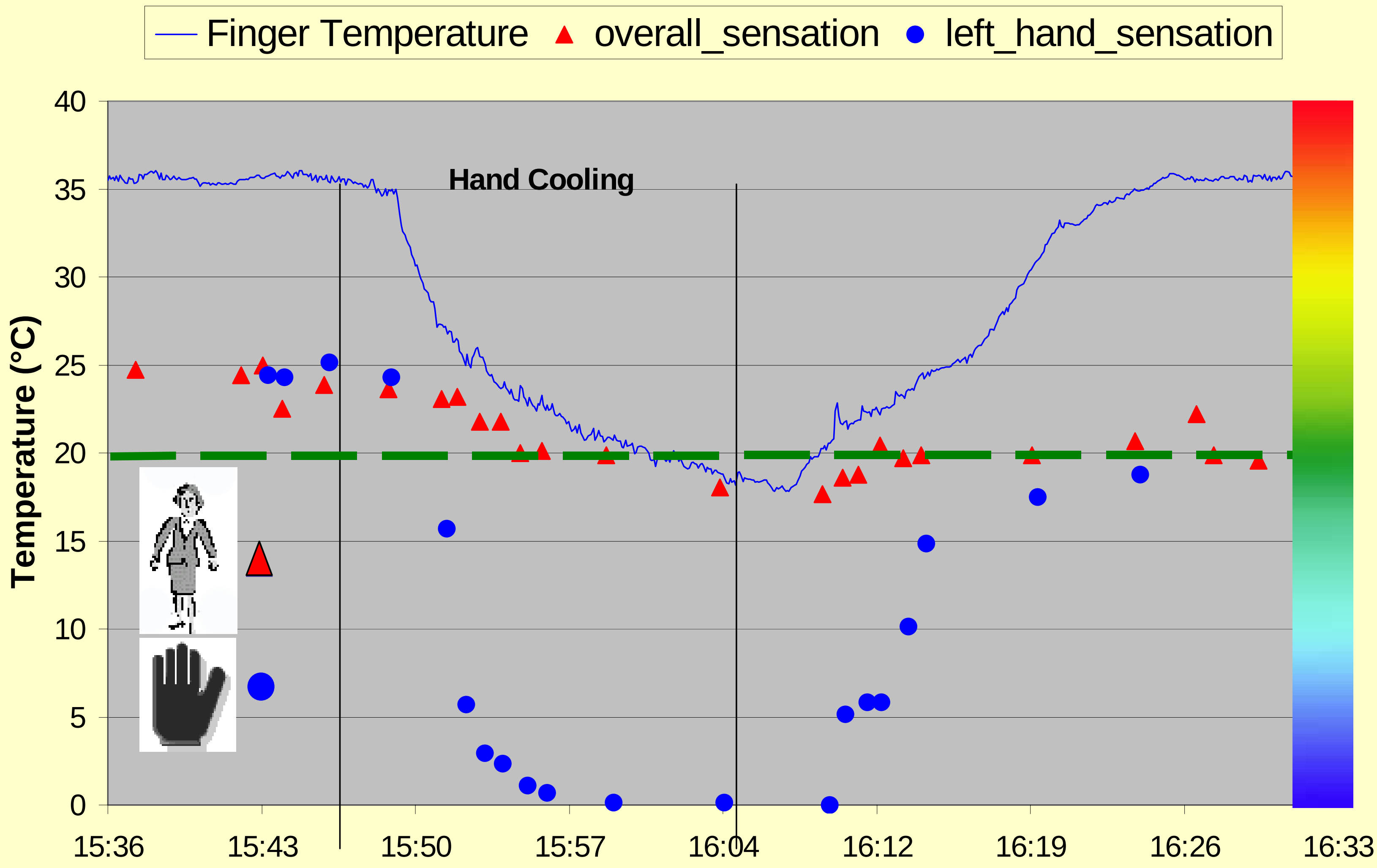


Human Subject Testing

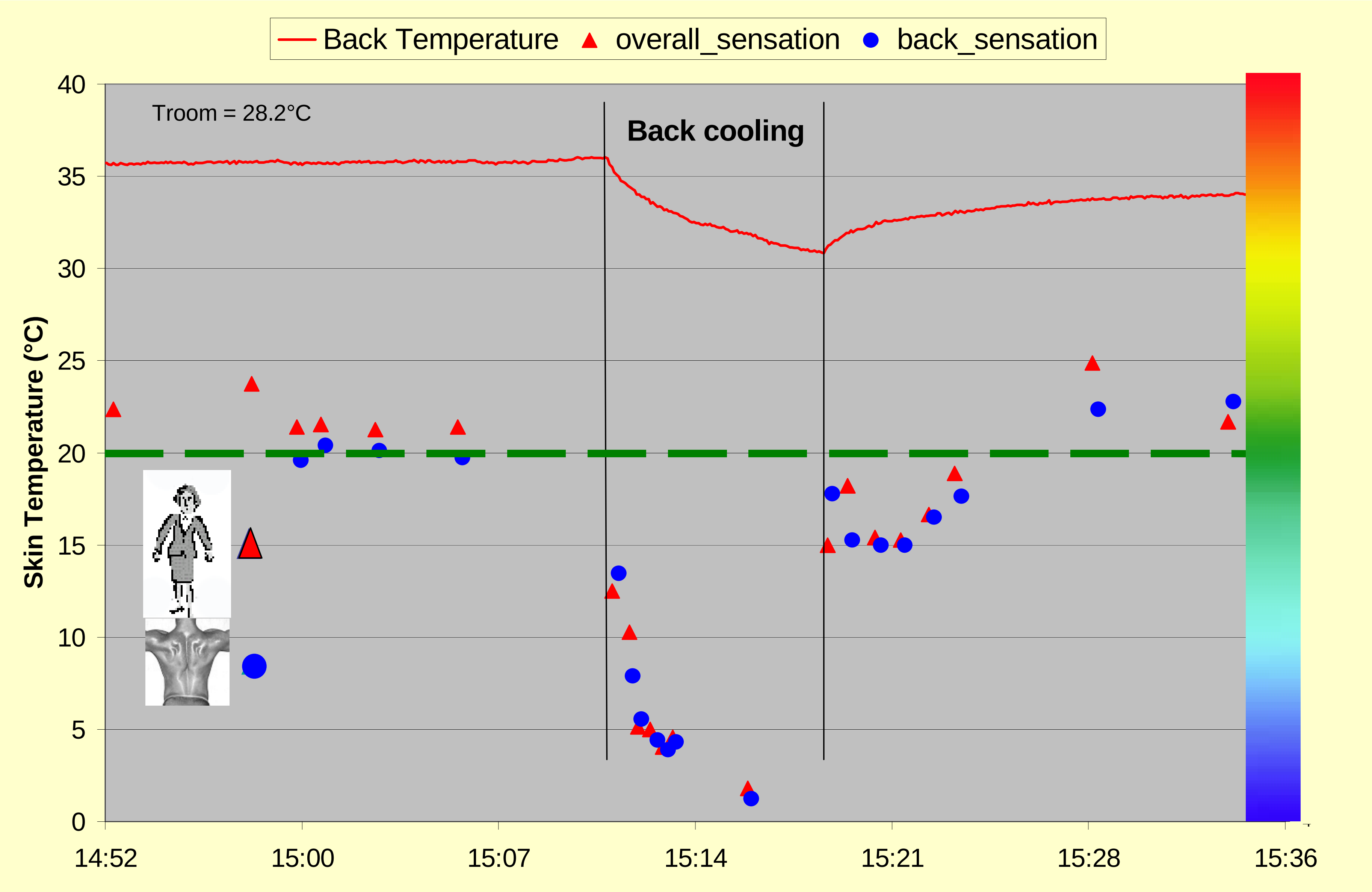
- Individual segments (plus breathing temperature) were heated and cooled
- 110 separate tests performed at U.C. Berkeley
- 64 tests performed in Delphi wind tunnel



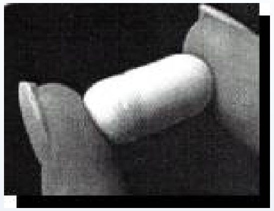
Left Hand Cooling

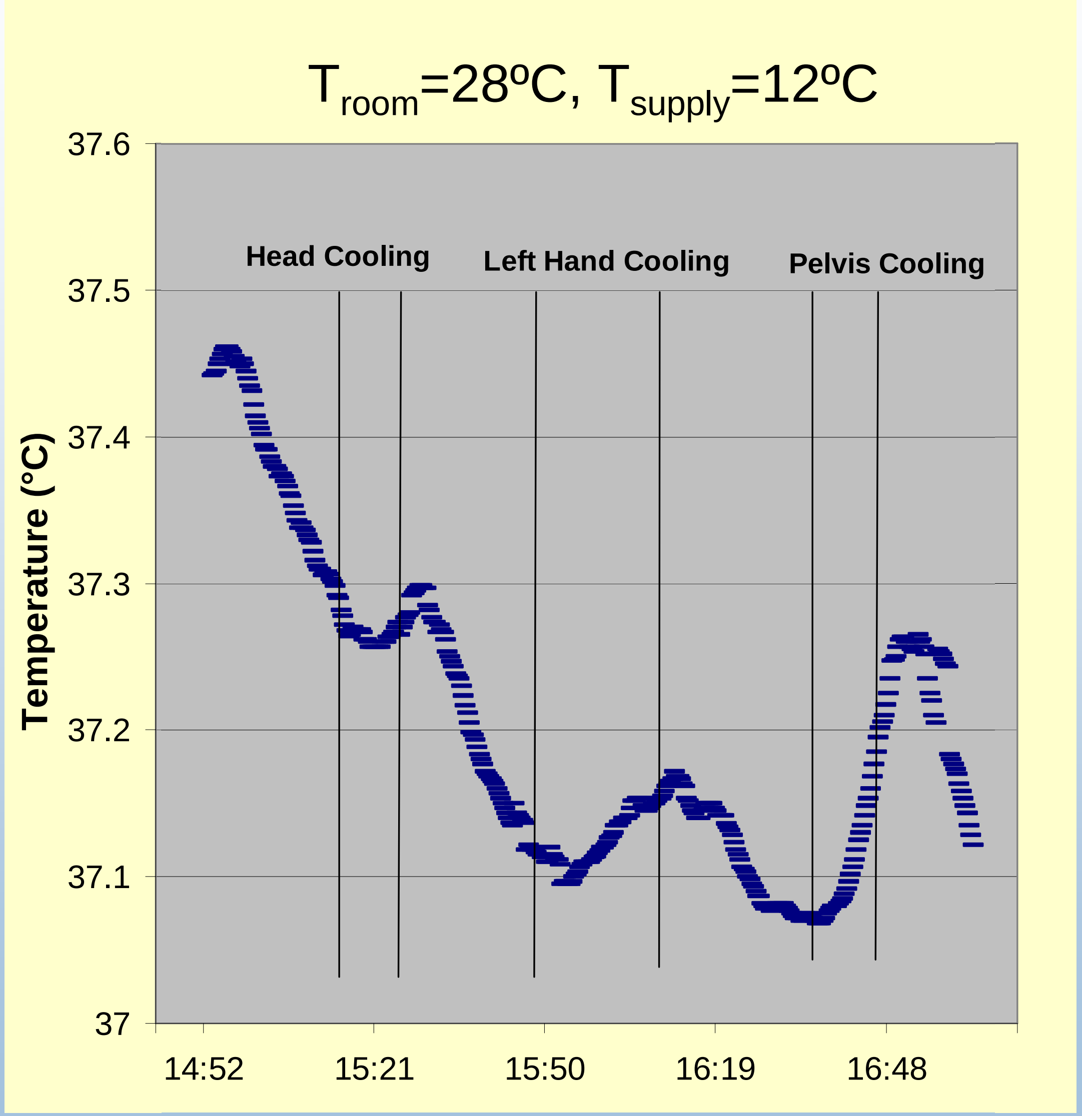


Back Cooling



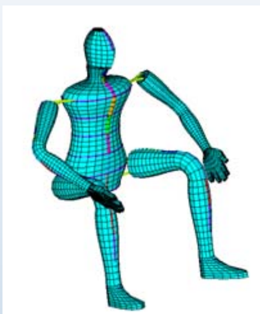
Body Core Heating With Local Cooling

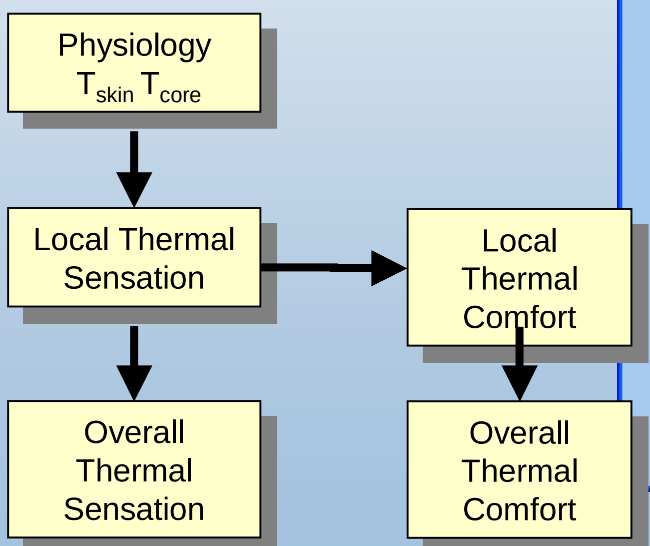




Physiological/Psychological Model Coupling

Converts temperatures to sensation and comfort





NREL Psychological Evaluation - Thermal only

No	Description	Set Point	Old Value	New Value	Sensation Sta	Sensation Dyr	Sensation	Comfort Local	Comfort
1	Forehead	34.20	34.20	33.20	-0.75	-0.27	-0.75	1.60	
2	Cheek	34.20	34.20	33.20	-0.30	0.10	-0.30	2.25	
3	Breath	34.20	34.20	33.20	-0.20	-0.03	-0.20	3.62	
4	Neck	34.70	34.70	33.70	-0.79	-0.09	-0.79	0.62	
5	Chest	34.50	34.50	33.50	-0.69	0.09	-0.69	1.21	
6	Back	34.40	34.40	33.40	-0.60	0.16	-0.60	1.34	
7	Pelvis	33.50	33.50	32.50	-0.40	0.22	-0.40	0.86	
8	LU Arm	33.50	33.50	32.50	-0.58	-0.08	-0.58	0.72	
9	LL Arm	32.70	32.70	31.70	-0.60	-0.07	-0.60	0.72	
10	L Hand	33.50	33.50	32.50	-0.40	-0.01	-0.40	1.15	
11	RU Arm	33.50	33.50	32.50	-0.58	-0.08	-0.58	0.72	
12	RL Arm	32.70	32.70	31.70	-0.60	-0.07	-0.60	0.72	
13	R Hand	33.50	33.50	32.50	-0.40	-0.01	-0.40	1.15	
14	L Thigh	33.70	33.70	32.70	-0.40	-0.08	-0.40	1.53	
15	L Calf	32.20	32.20	31.20	-0.58	-0.10	-0.58	0.77	
16	L Foot	32.20	32.20	31.20	-0.50	-0.05	-0.50	1.06	
17	R Thigh	33.70	33.70	32.70	-0.40	-0.08	-0.40	1.53	
18	R Calf	32.20	32.20	31.20	-0.58	-0.10	-0.58	0.77	
19	R Foot	32.20	32.20	31.20	-0.50	-0.05	-0.50	1.06	
20	Core/Mean	36.50	36.50	36.40		Overall	-0.48	0.67	

ANSYS Run Control

Continue Run

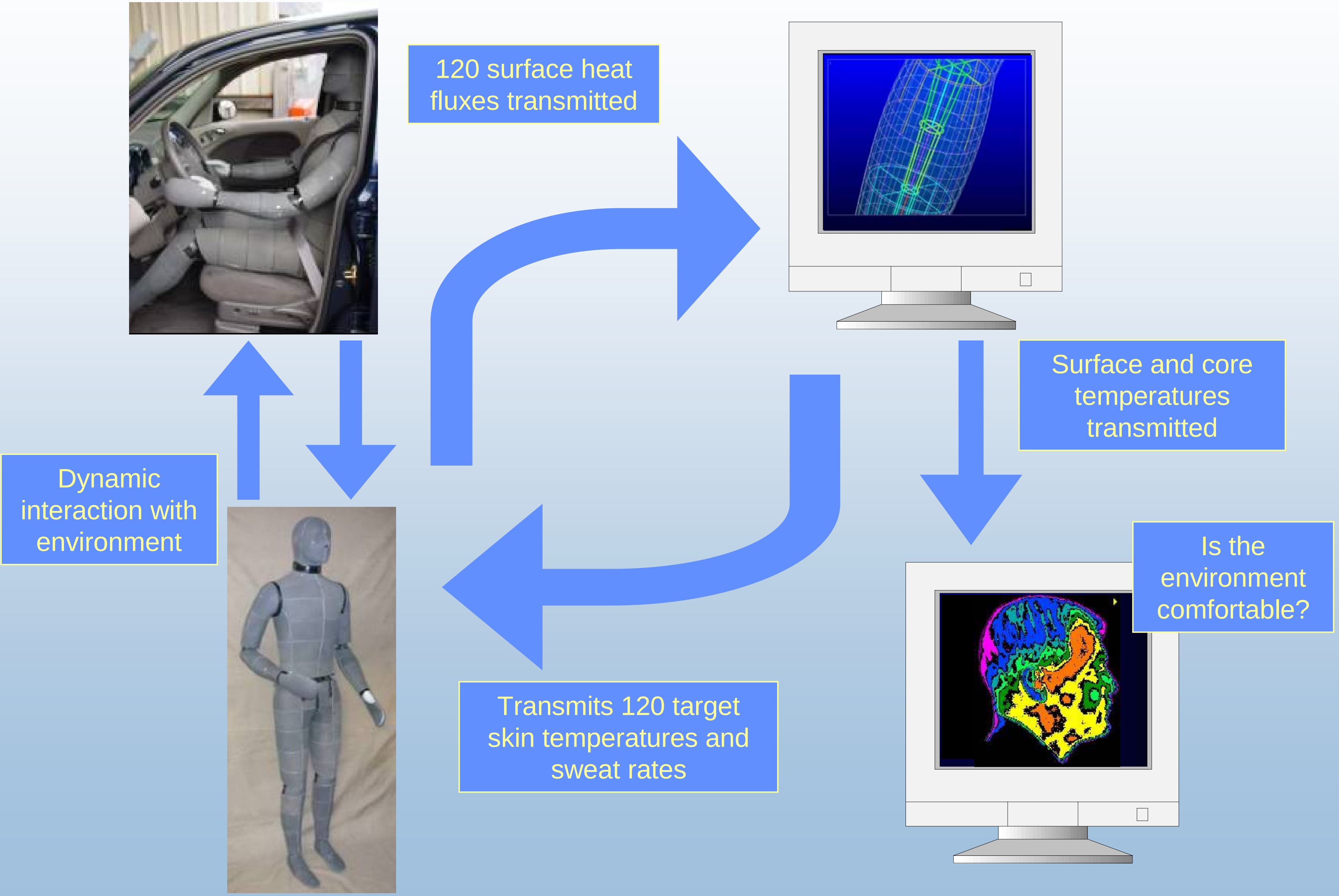
Pause ANSYS

End ANSYS

Update

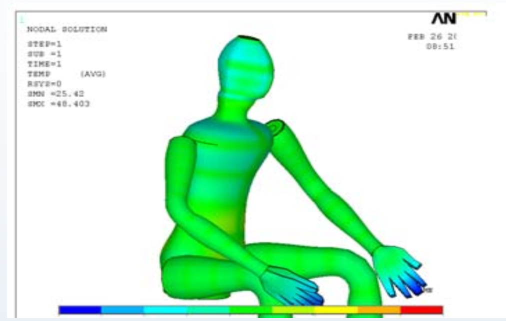
Stop Program

Linking the Tools Together



Model and Manikin Data Loop

Model reads q_{loss} every ~2 minutes



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

Manikin Output File of q_{loss}

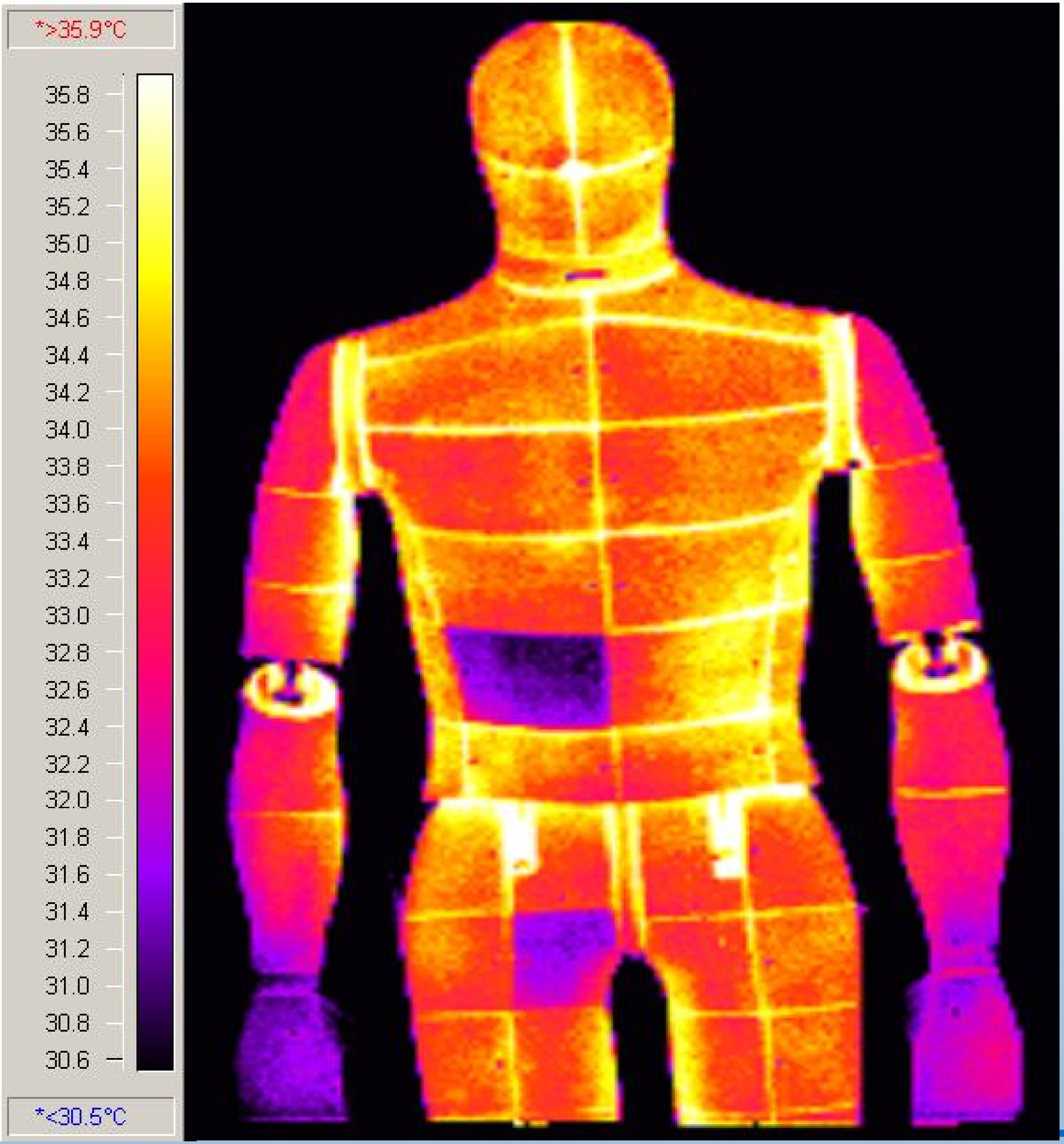
FEA Output File of T_s

Writes qloss to file every 15 seconds

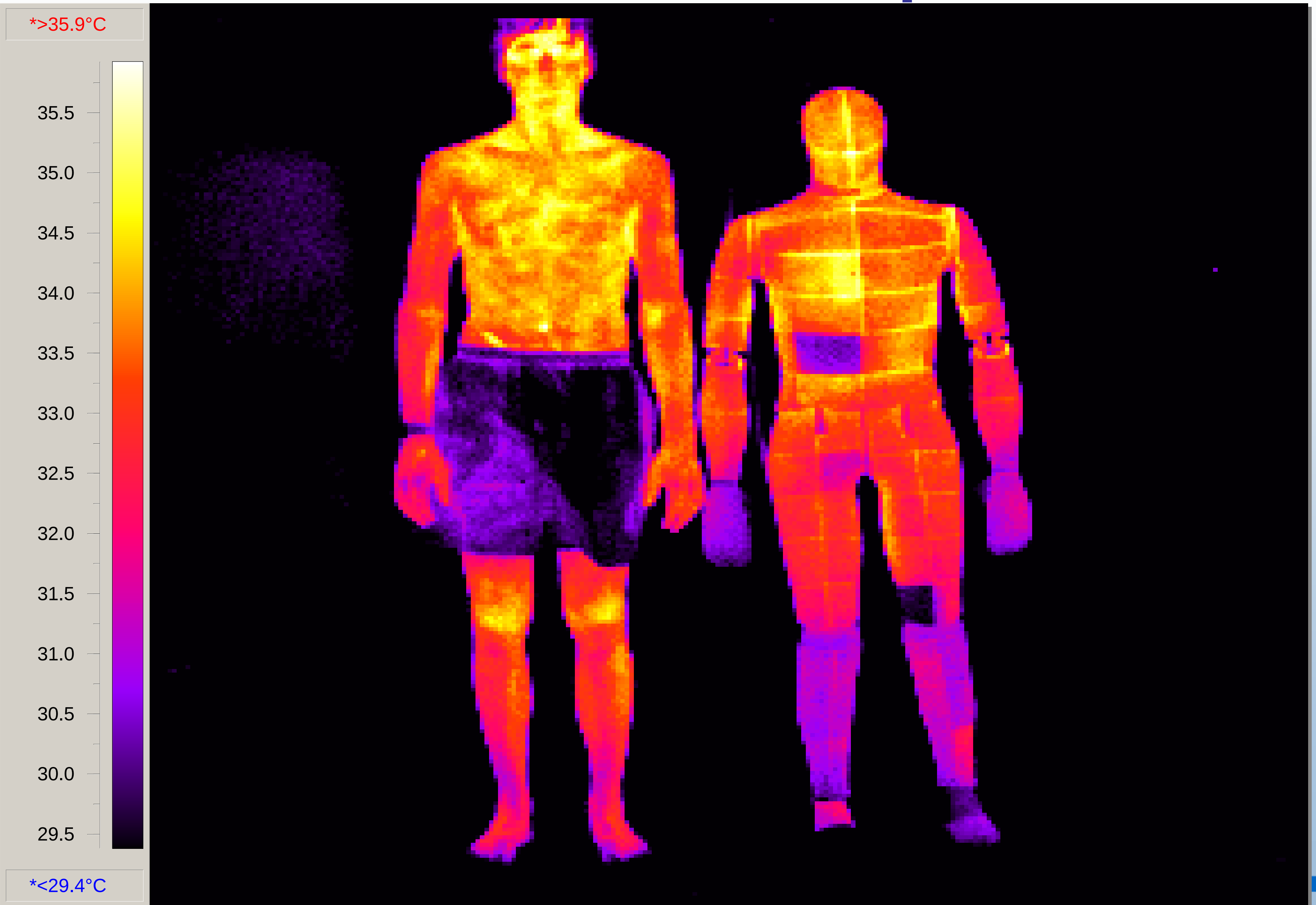
Manikin reads Ts setpoints, changes heater power, sweat rate, and breathing

Manikin continuously adjusts heater power to meet T_s setpoints

Manikin Controlled by Model

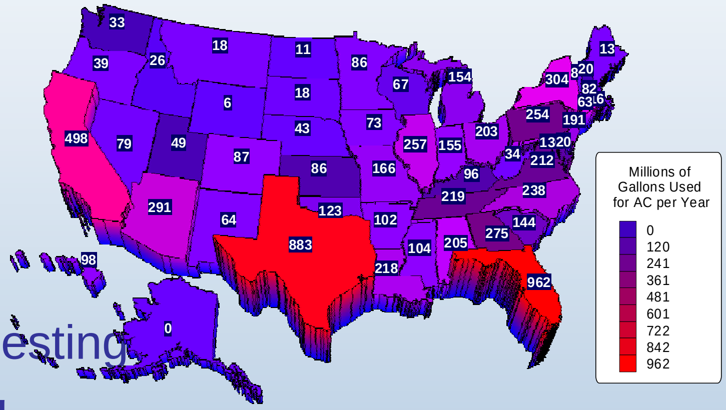


Human & Manikin Comparison



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

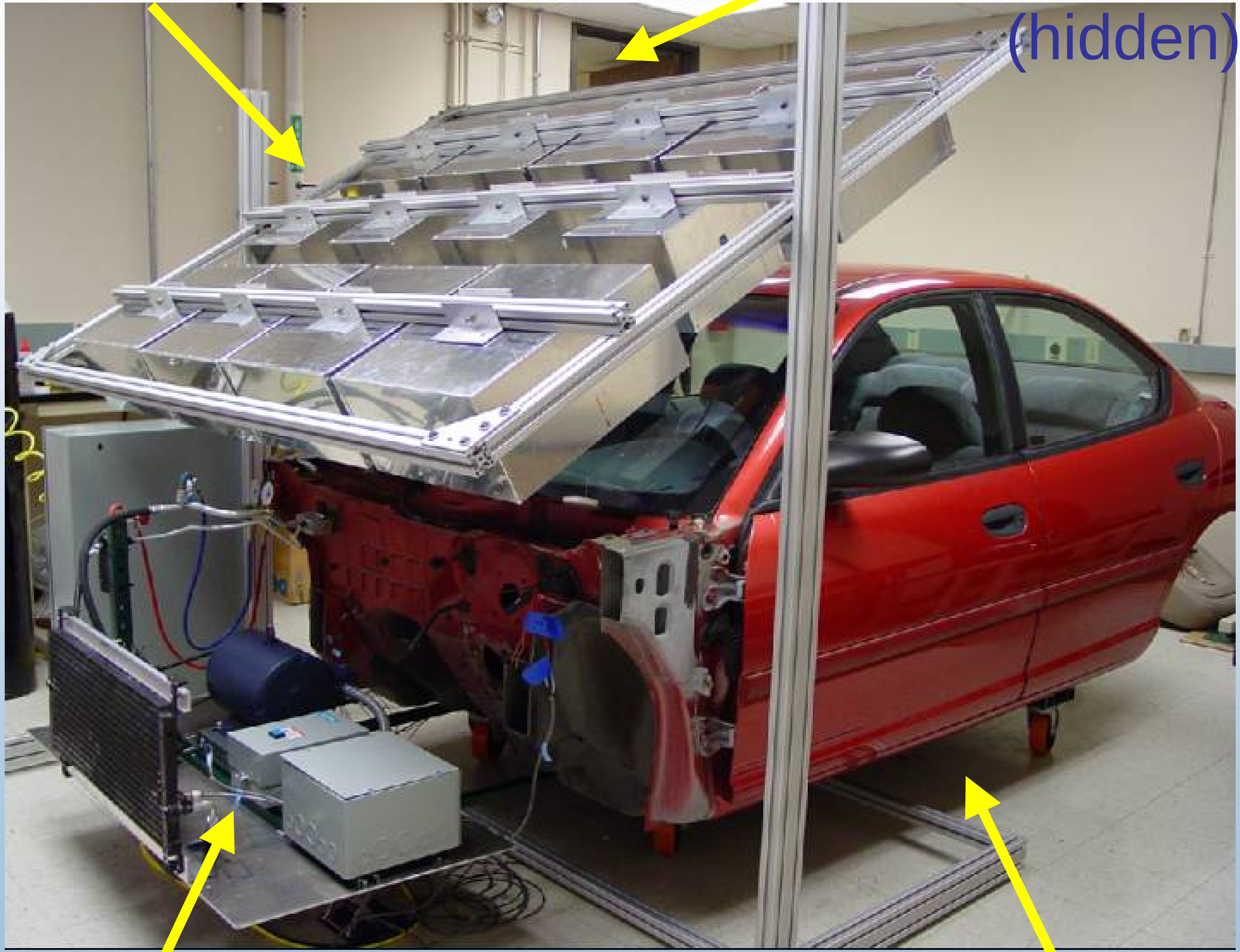


VCCL Objective

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

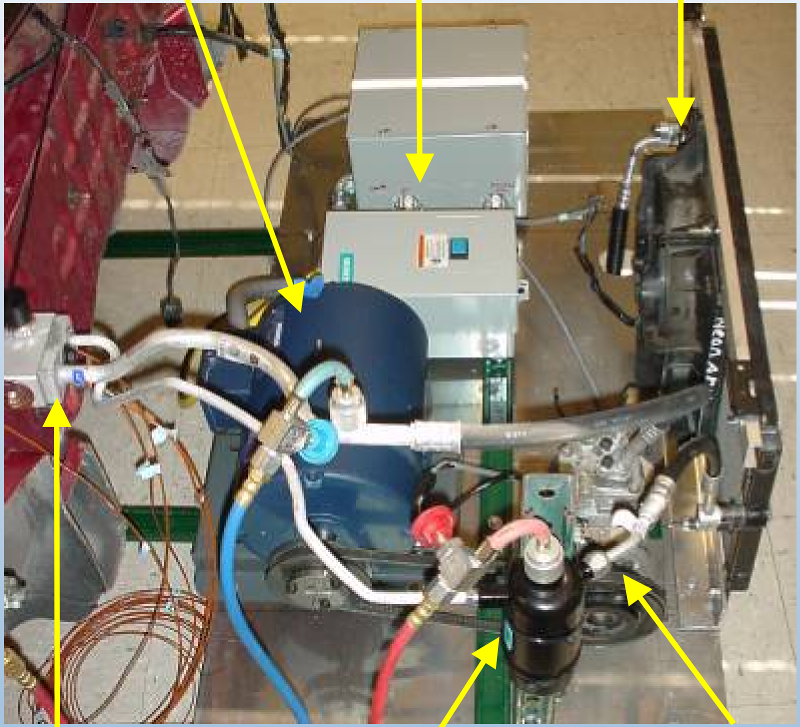
Cabin Thermal Test Cell



Solar Simulator Uniformity Test

Air Conditioning

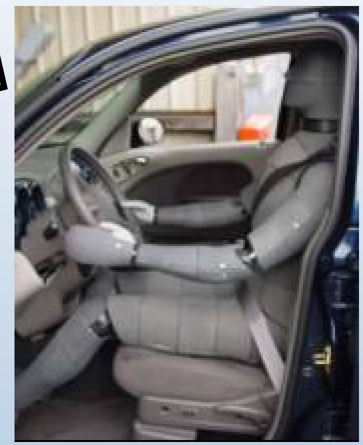
- Actual Neon A/C System
- Electrically Driven
  - 5.6 kW motor (7.5 hp)



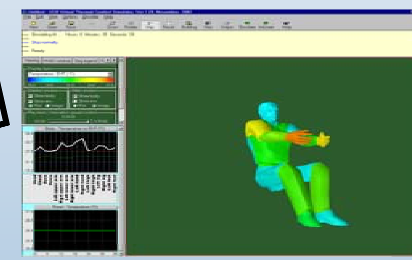
Thermal Comfort Test Process

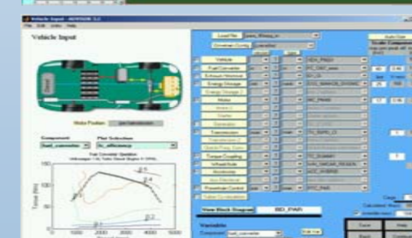
Heat Soaked Vehicle

Cool-Down Test



TC & Vehicle Modeling





Improved Comfort
Energy &
Fuel Saving

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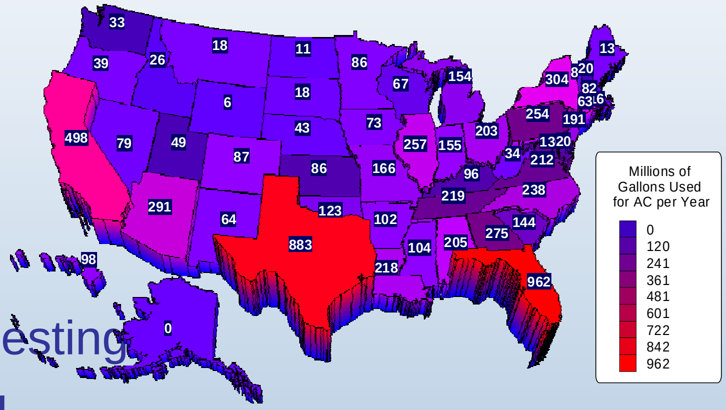
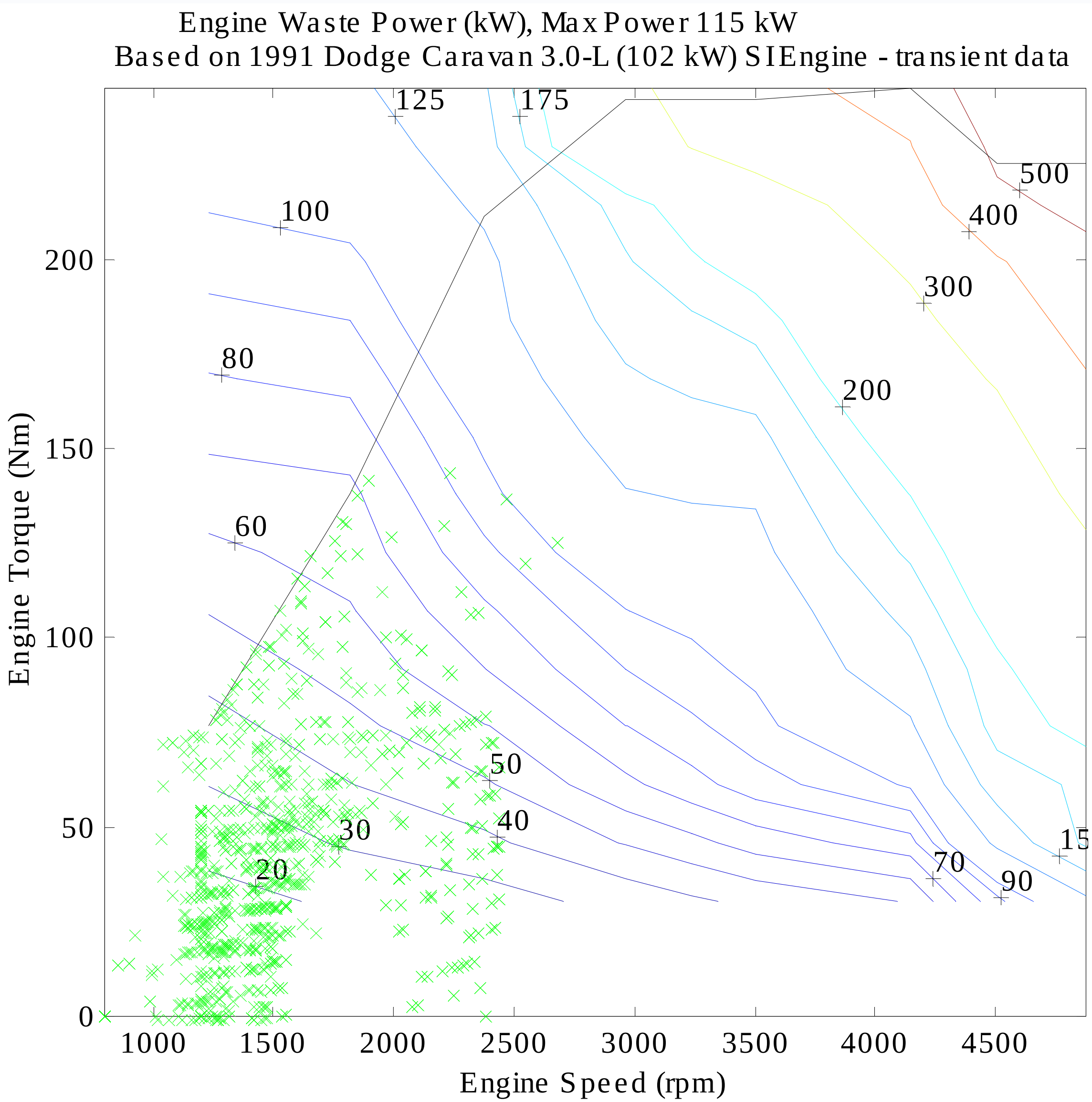


Objectives and Goals

- 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.

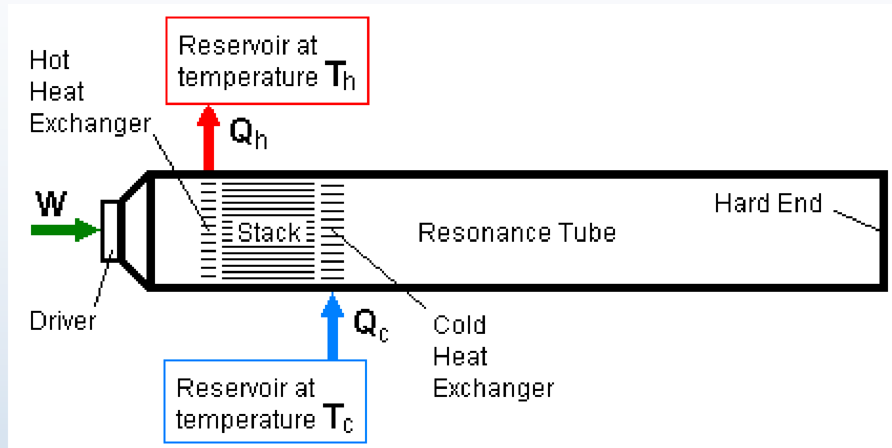
Availability of Waste Heat in a Light-Duty Vehicle



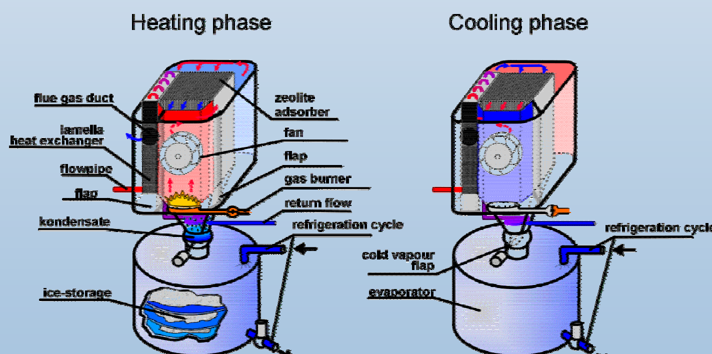
- Average waste heat available would be 23 kW.
- Exhaust temperature varied from 200ºC to 600ºC.
- Generally, the waste heat available is twice as much as the mechanical output of the engine

Heat Generated Cooling Opportunities

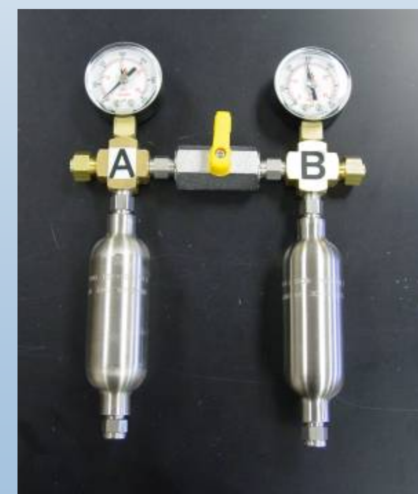
Absorption Heat Pump Cycle



Thermoacoustic Engine



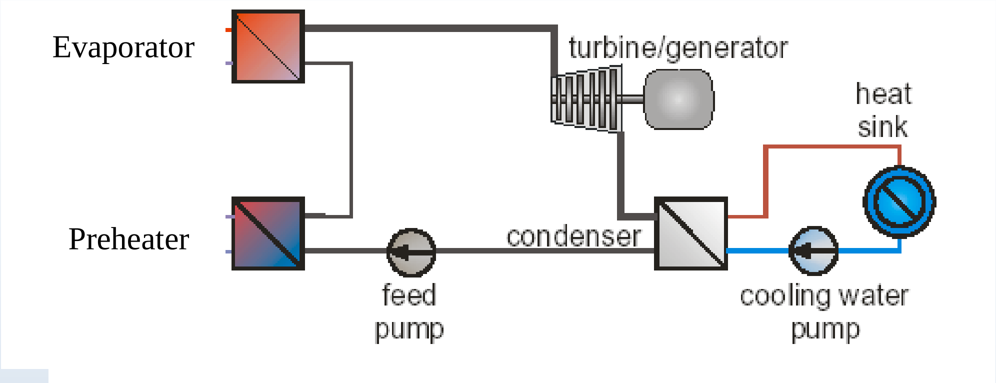
Zeolite/Desiccant Cooling



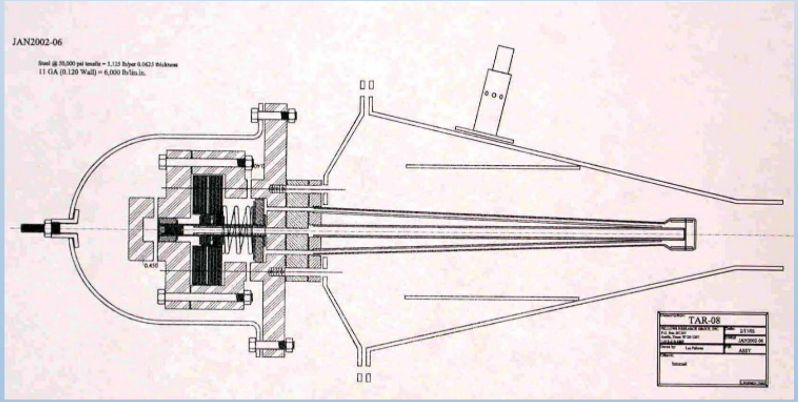
Metal Hydride Heat Pump

Heat Generated Electric Generation

Thermoelectrics, Thermionics, and Quantum Well Technologies



Organic Rankine Cycle

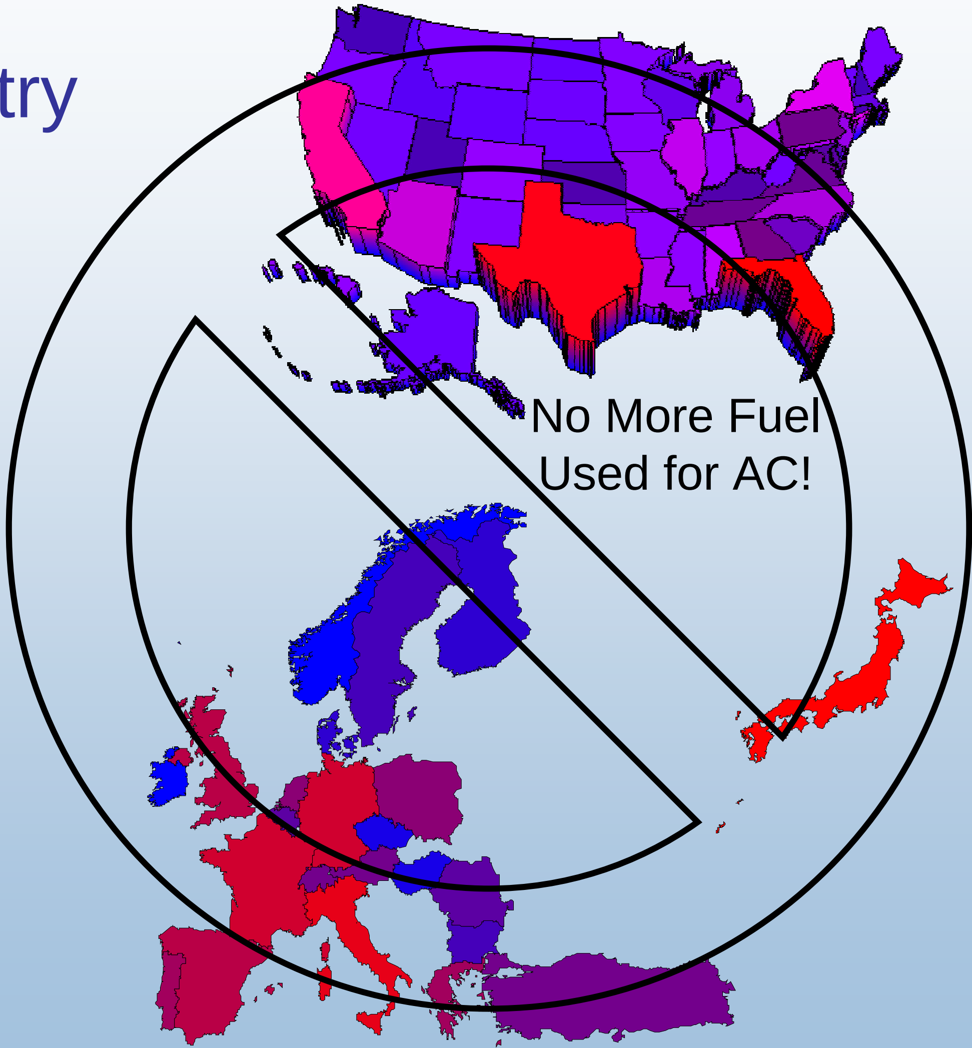


Thermoacoutic Resonator

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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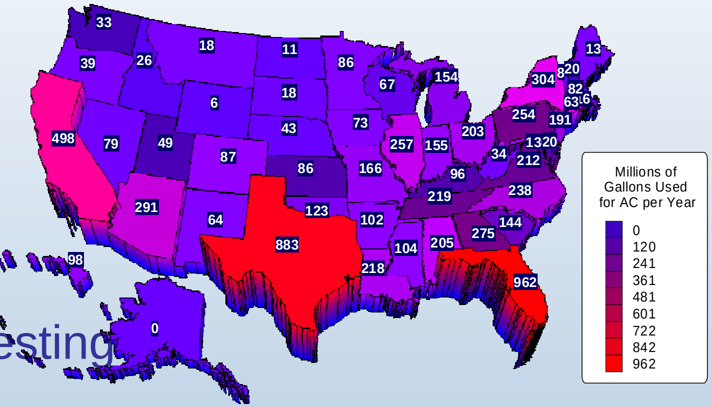
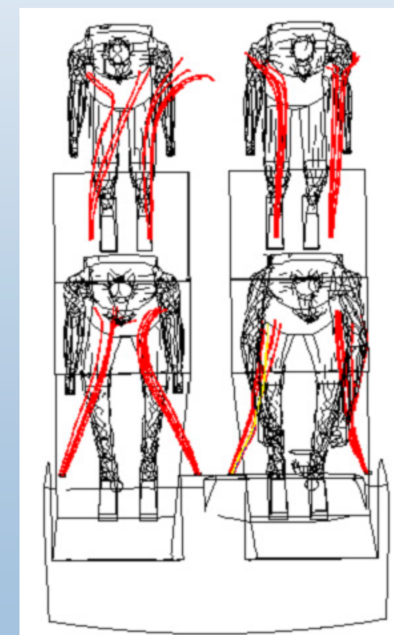


Solutions to Reduce AC Fuel Use
Vehicle Design

- 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

Reduce compressor size and use

- 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

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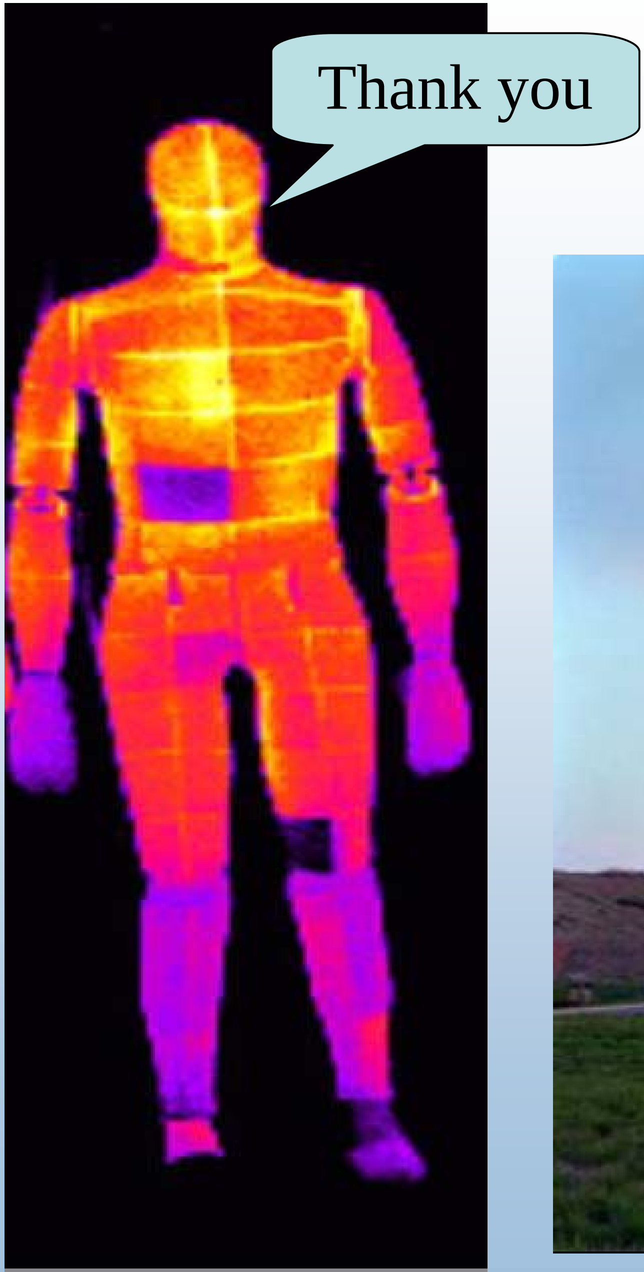

The U.S. Department of Energy's

National Renewable Energy Laboratory

John Rugh
303-275-4413
john_rugh@nrel.gov
http://www.ott.doe.gov/coolcar