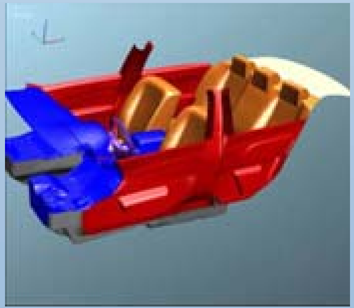
NREL National Renewable Energy Laboratory
Innovation for Our Energy Future
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

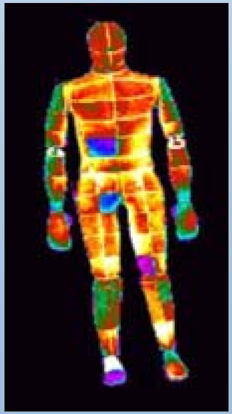
Predicting Human Thermal Comfort in Automobiles

John Rugh, Project Leader, Vehicle Ancillary Loads
Desikan Bharathan, Ph.D., Principal Engineer
Larry Chaney, Senior Engineer

June 13, 2005

Advanced Simulation Technologies User Meeting 2005
Graz, Austria





NREL/PR-540-38236

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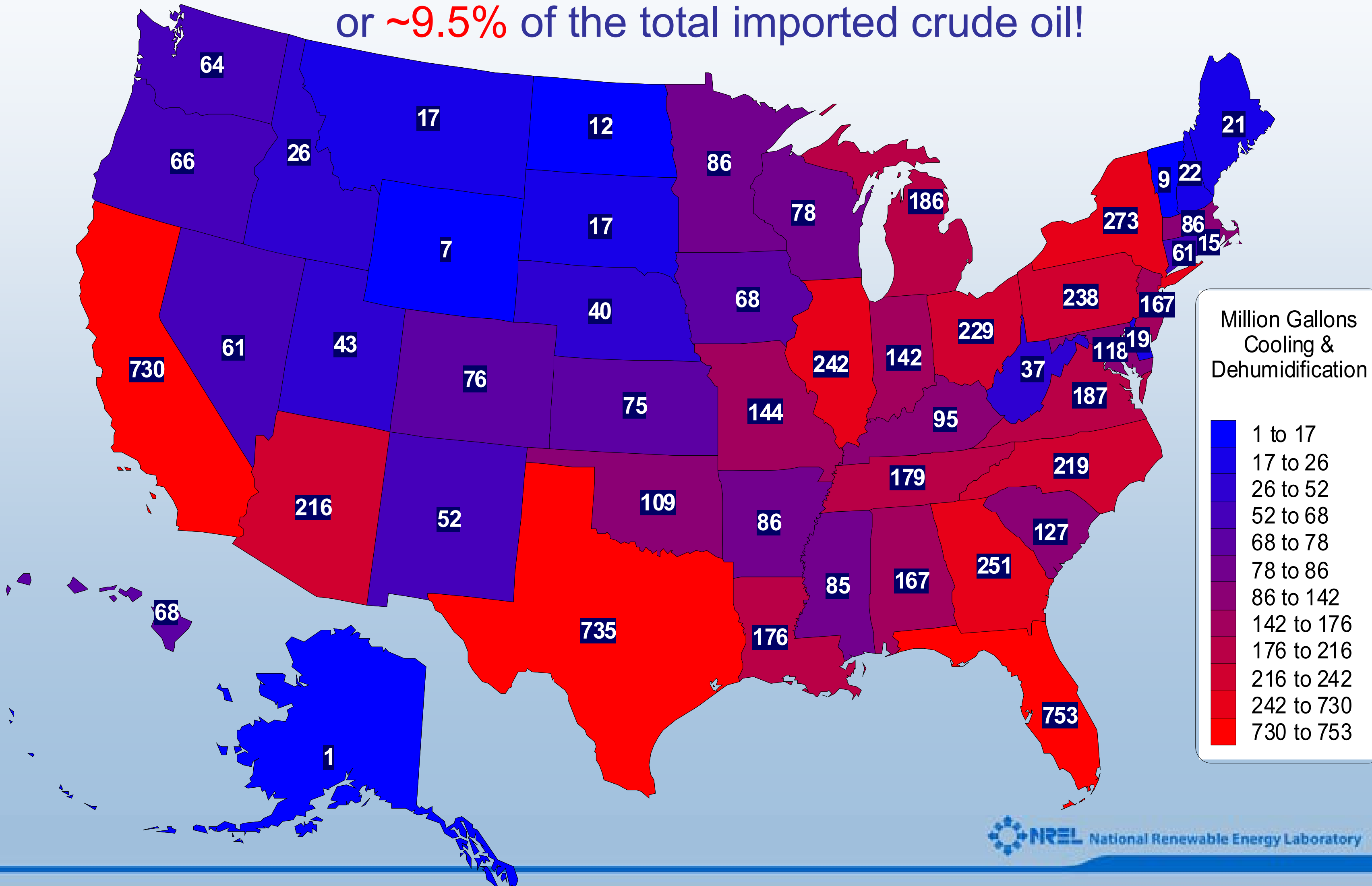
Outline

- Introduction
- Integrated Modeling Process for Cabin Thermal Management
  - Vehicle Solar Load Estimator (VSOLE®)
  - Thermal Comfort Tools
    - Manikin
    - Human Thermal Physiological Model
    - Human Thermal Comfort Empirical Model
- Linking the Models
- Conclusions

Modeled U.S. Mobile AC Fuel Use

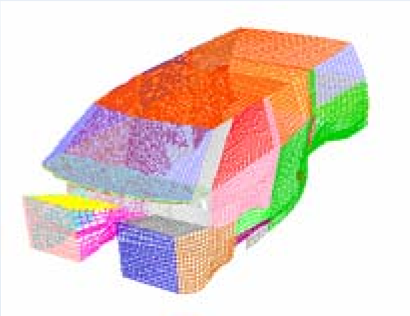
7.0 billion gallons used for air conditioning annually
Equivalent to 5.5% of the national fuel use,
or ~9.5% of the total imported crude oil!



NREL National Renewable Energy Laboratory

Objectives

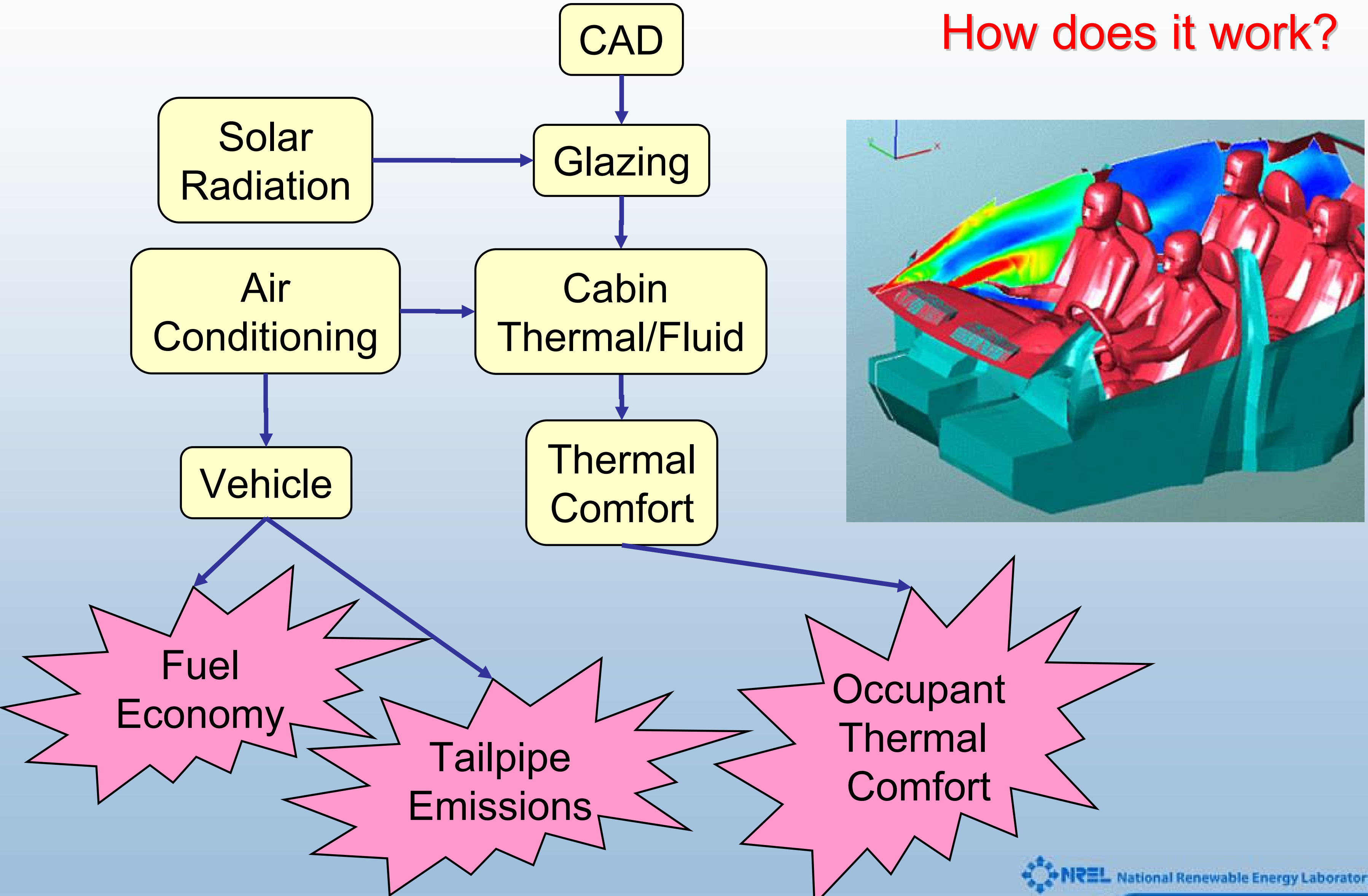
- Increase national energy security by reducing fuel use for vehicle climate control systems
- Show/demonstrate technology that can reduce the fuel used by LD vehicles' ancillary systems
- Develop tools to evaluate the effectiveness of energy-efficient systems including:
  - comfort, cost, practicality, ease-of-use, reliability . . .



Integrated Modeling

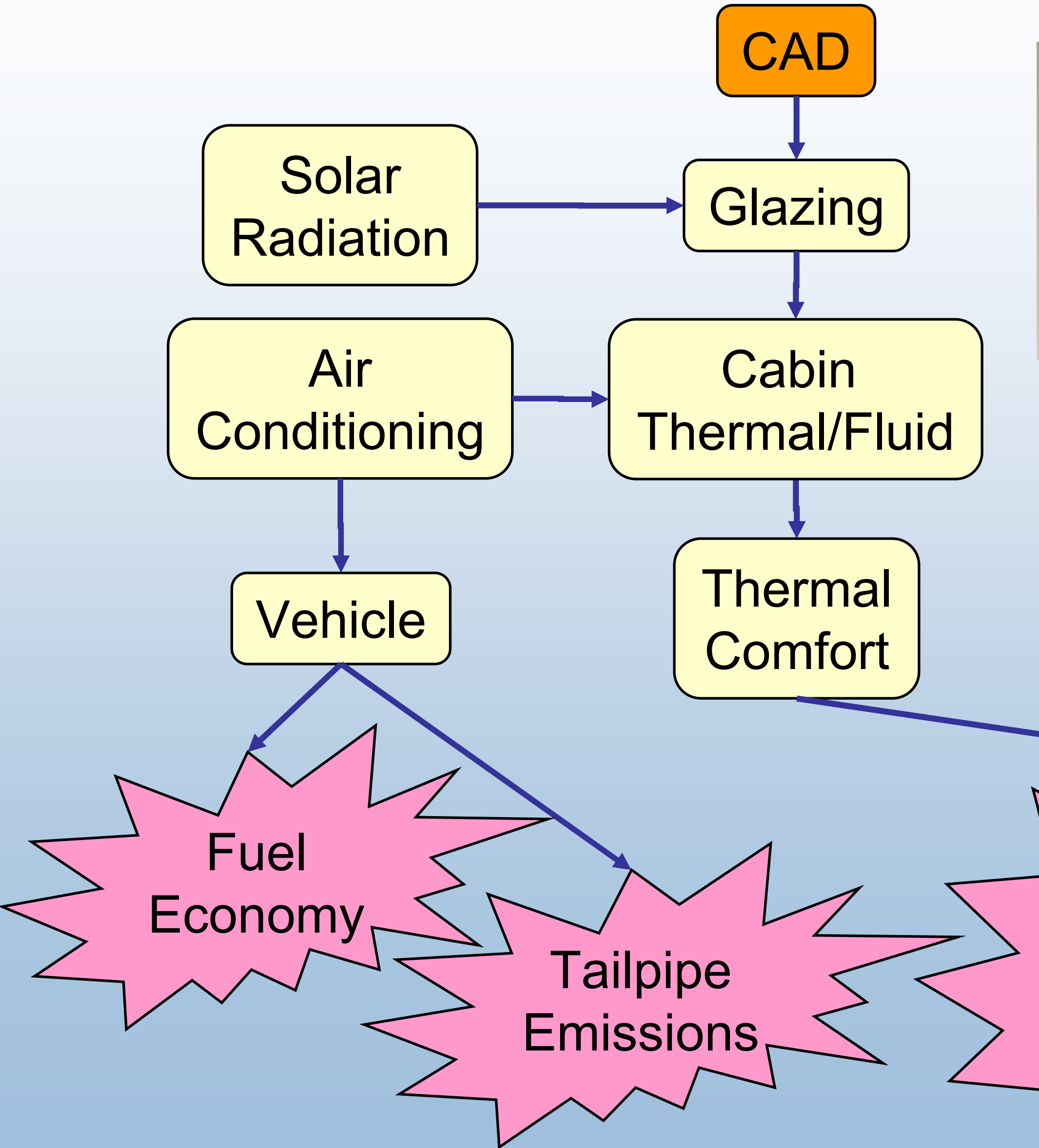
How does integrated modeling help you?

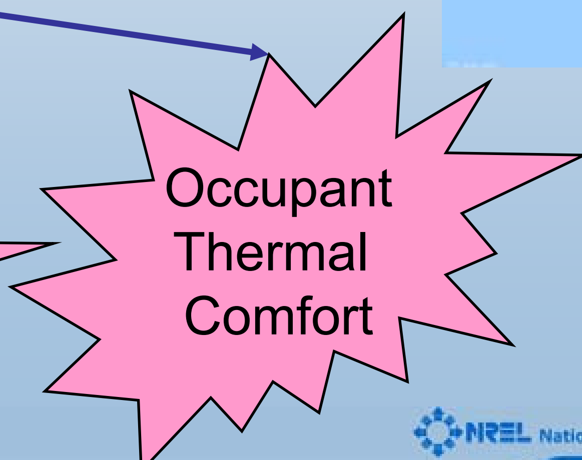
How does it work?

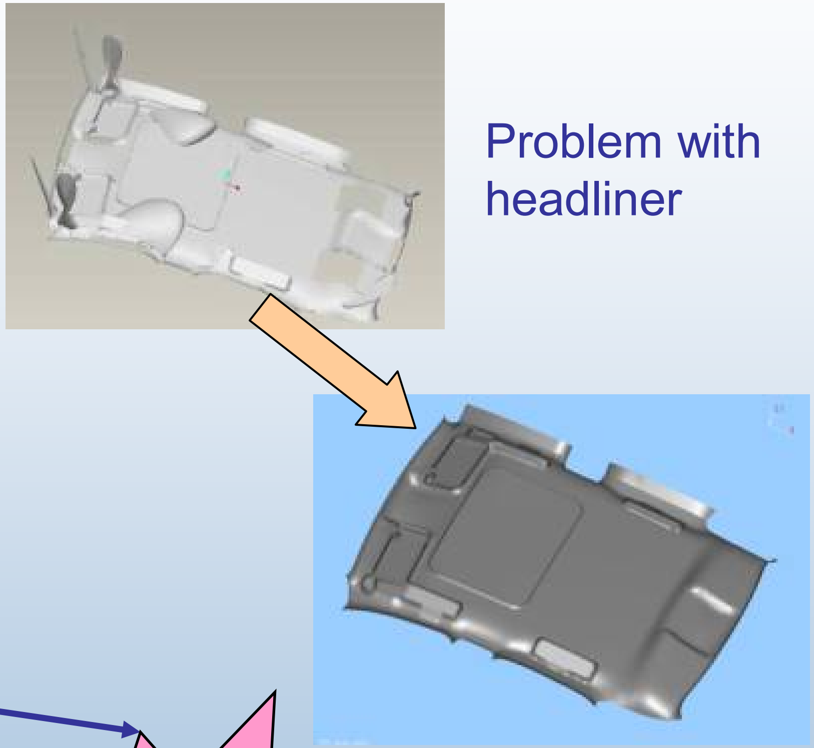


Integrated Modeling

Mesh the geometry of your vehicle



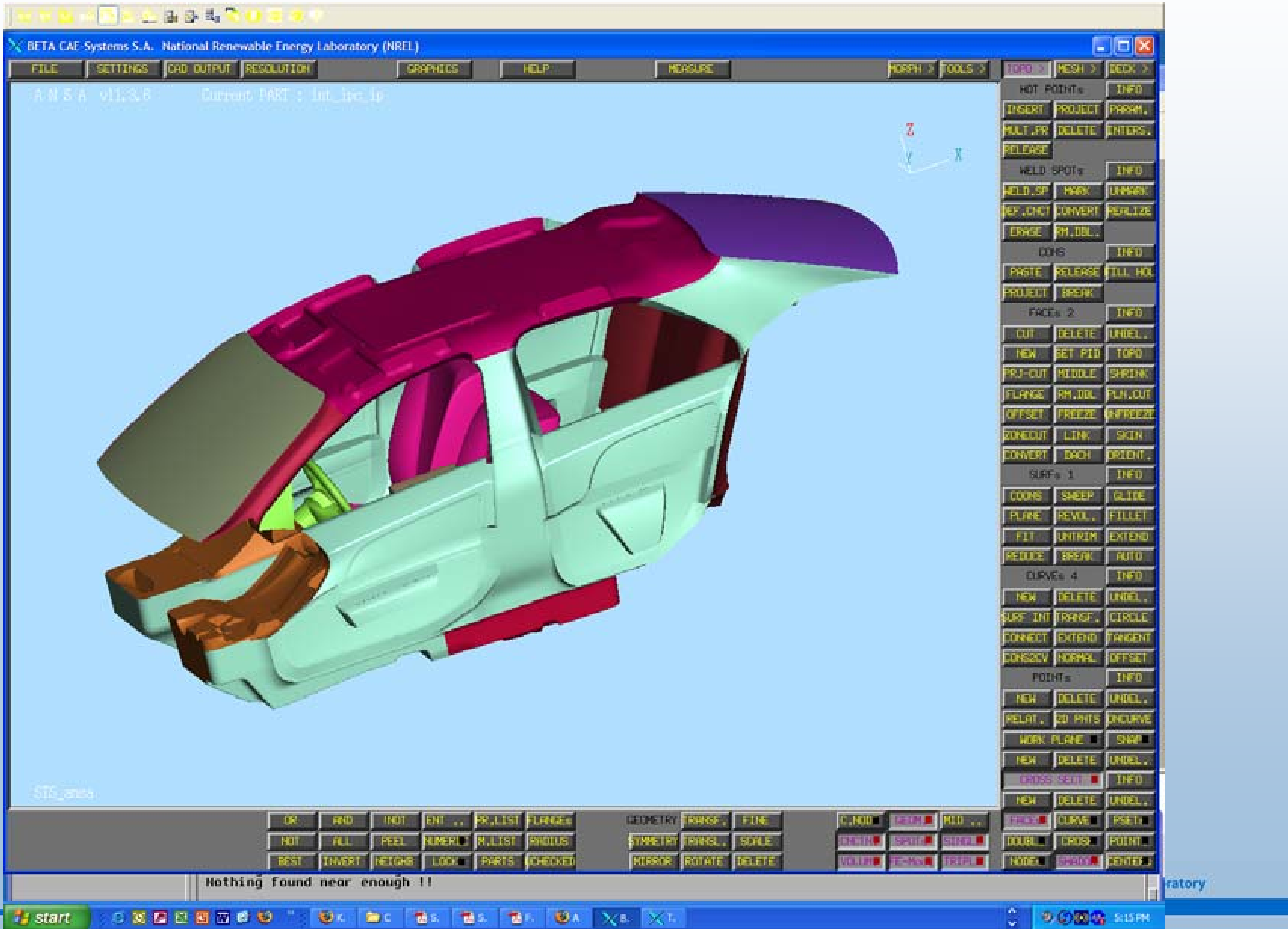




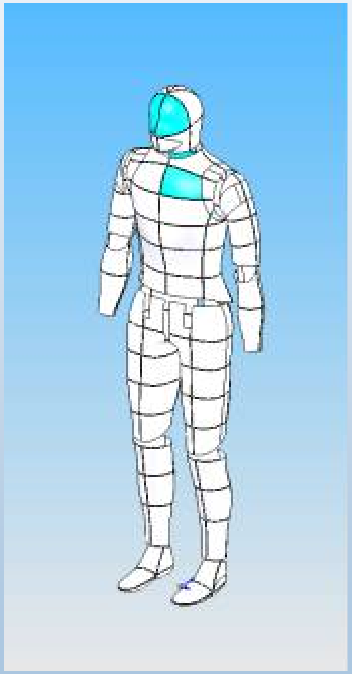
Problem with headliner

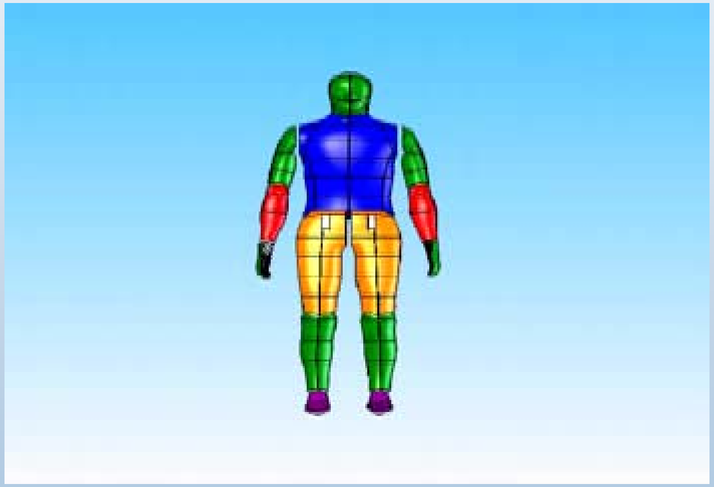
Correct headliner

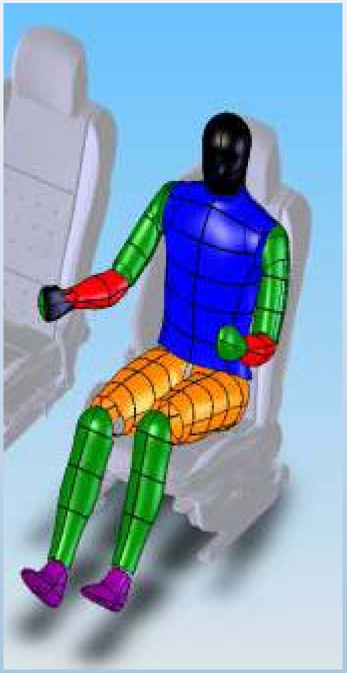
Using ANSA Software for CAD Clean-Up



Getting ADAM in the Drivers Seat

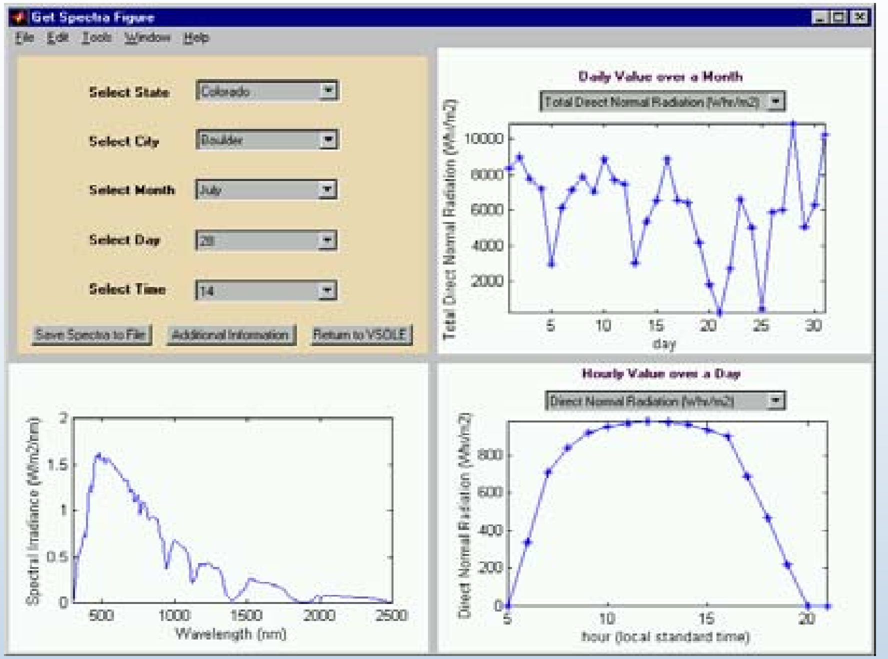


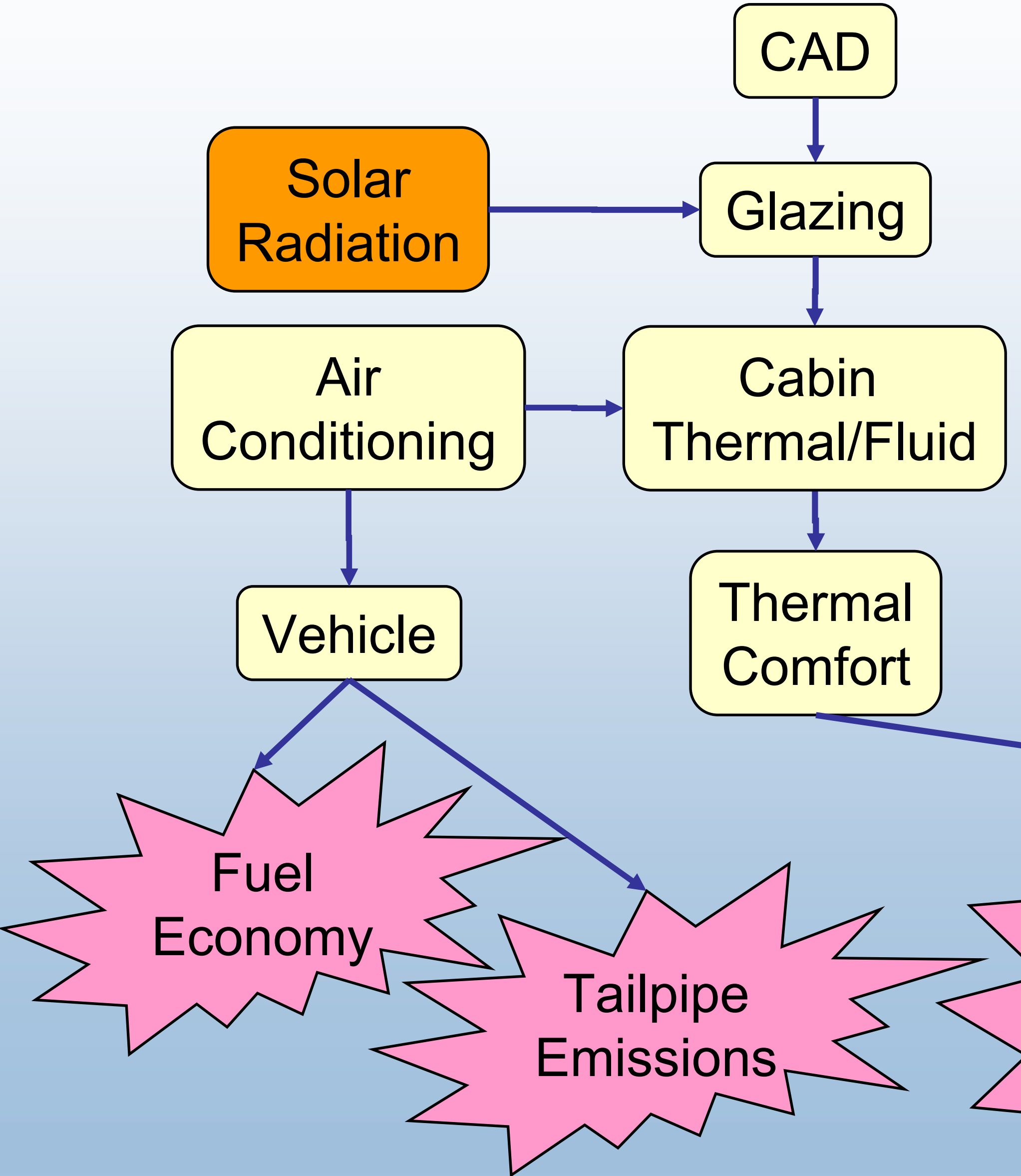


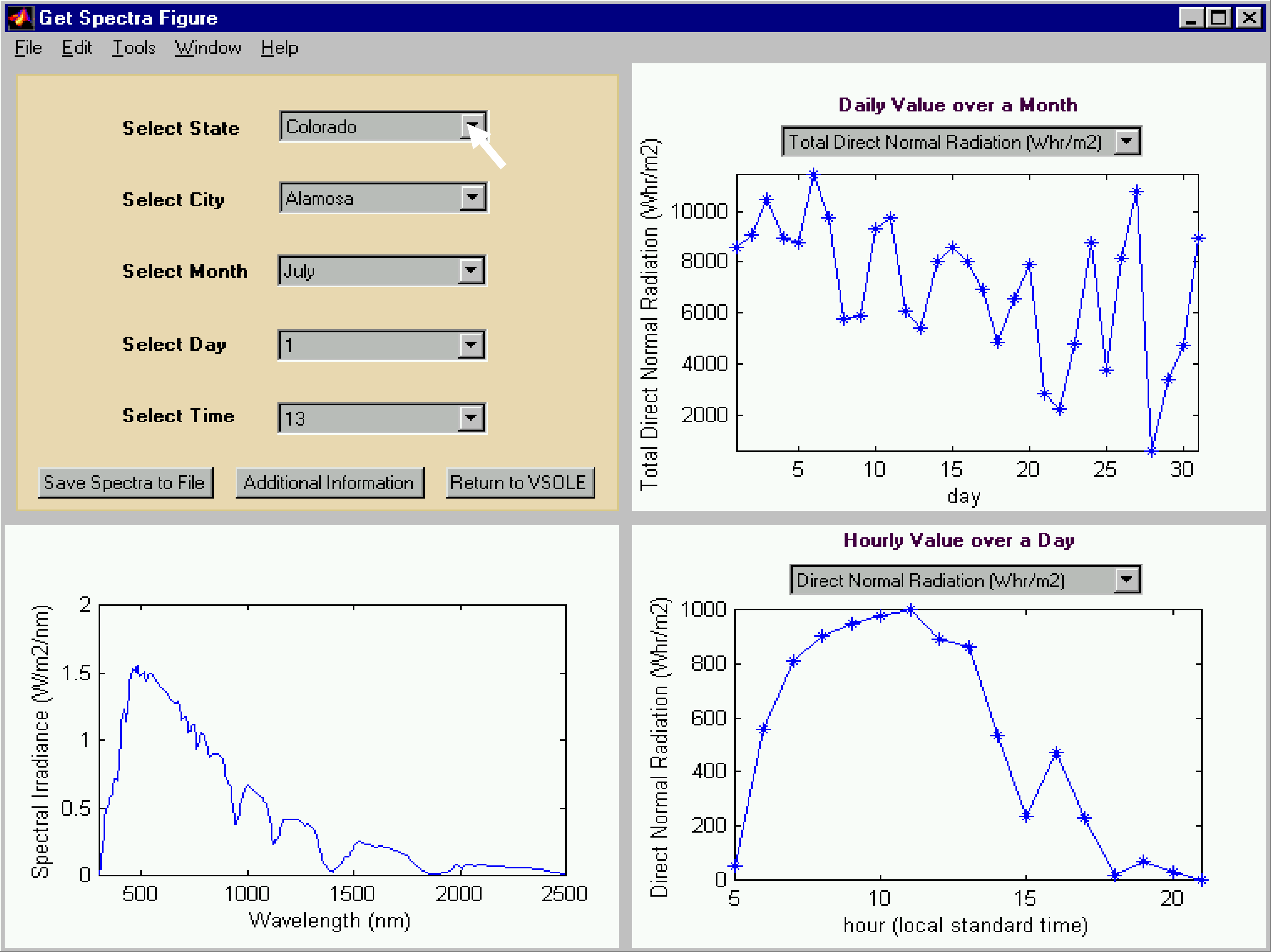


Integrated Modeling

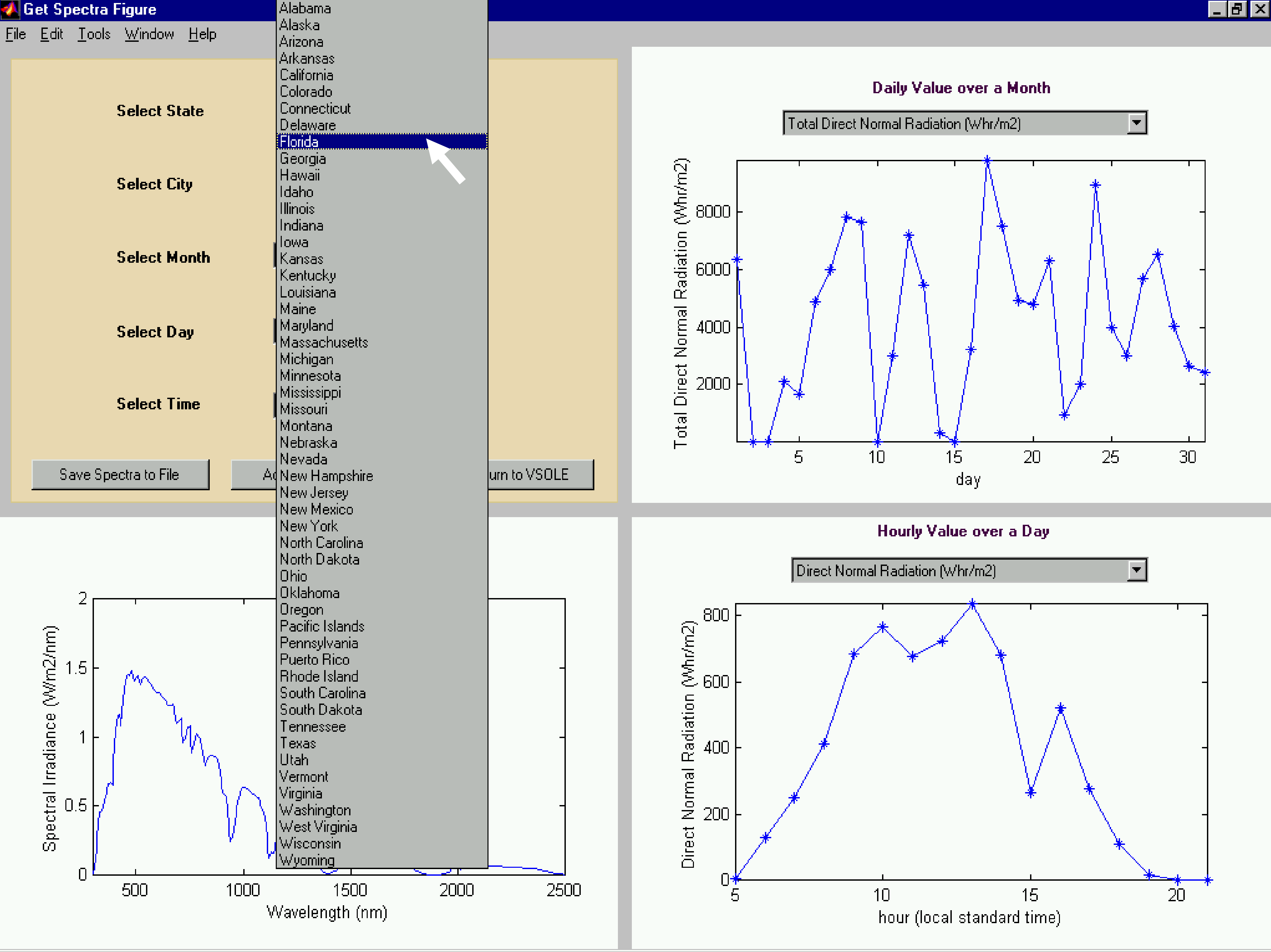
Find the solar radiation in your city



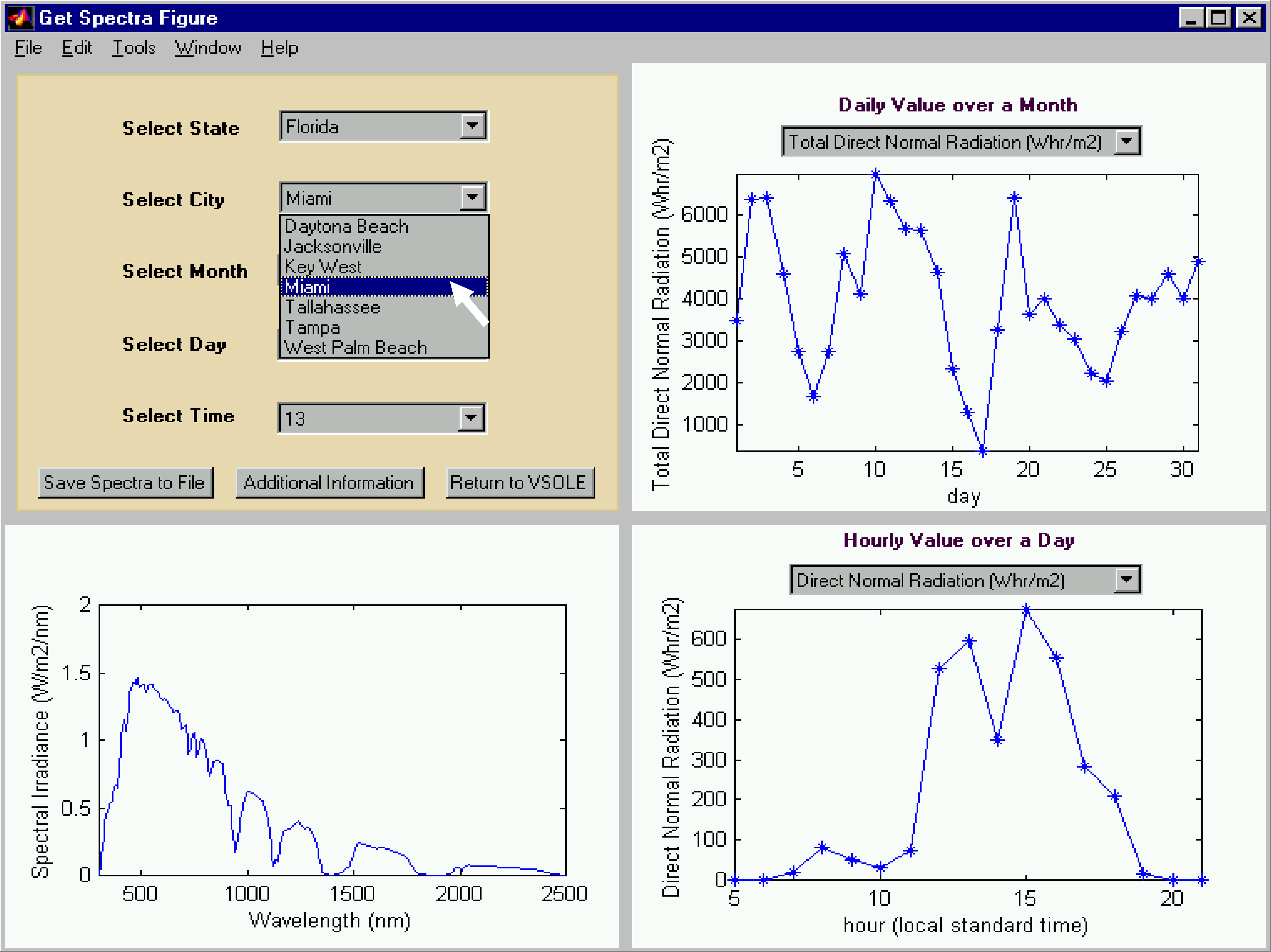




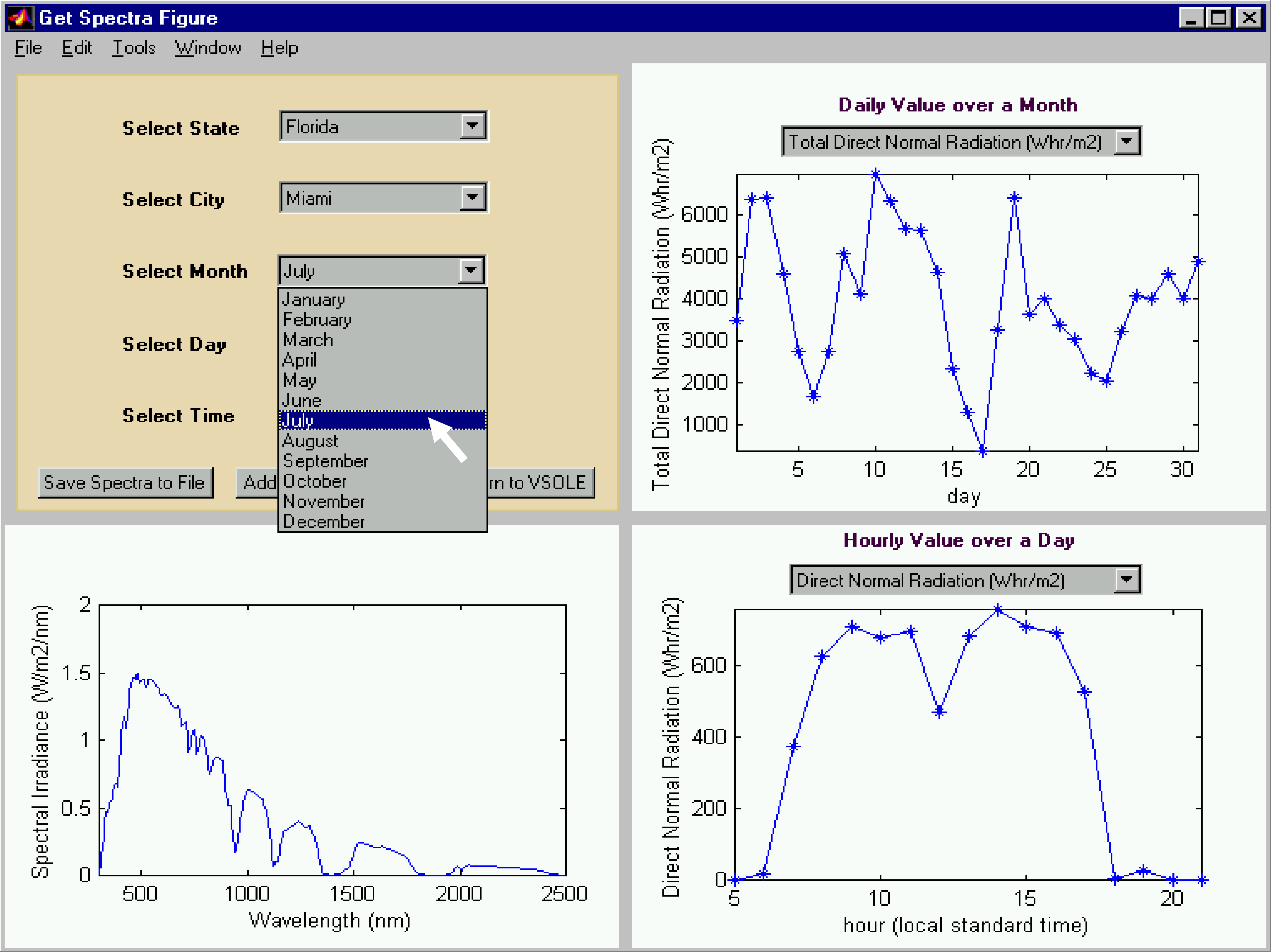
Get Spectra Figure
File
Edit
Tools
Window
Help
Select State
Colorado
Select City
Alamosa
Select Month
July
Select Day
1
Select Time
13
Save Spectra to File
Additional Information
Return to VSOLE
Daily Value over a Month
Total Direct Normal Radiation (Whr/m2)
day
Hourly Value over a Day
Direct Normal Radiation (Whr/m2)
hour (local standard time)
Spectral Irradiance (W/m2/nm)
Wavelength (nm)

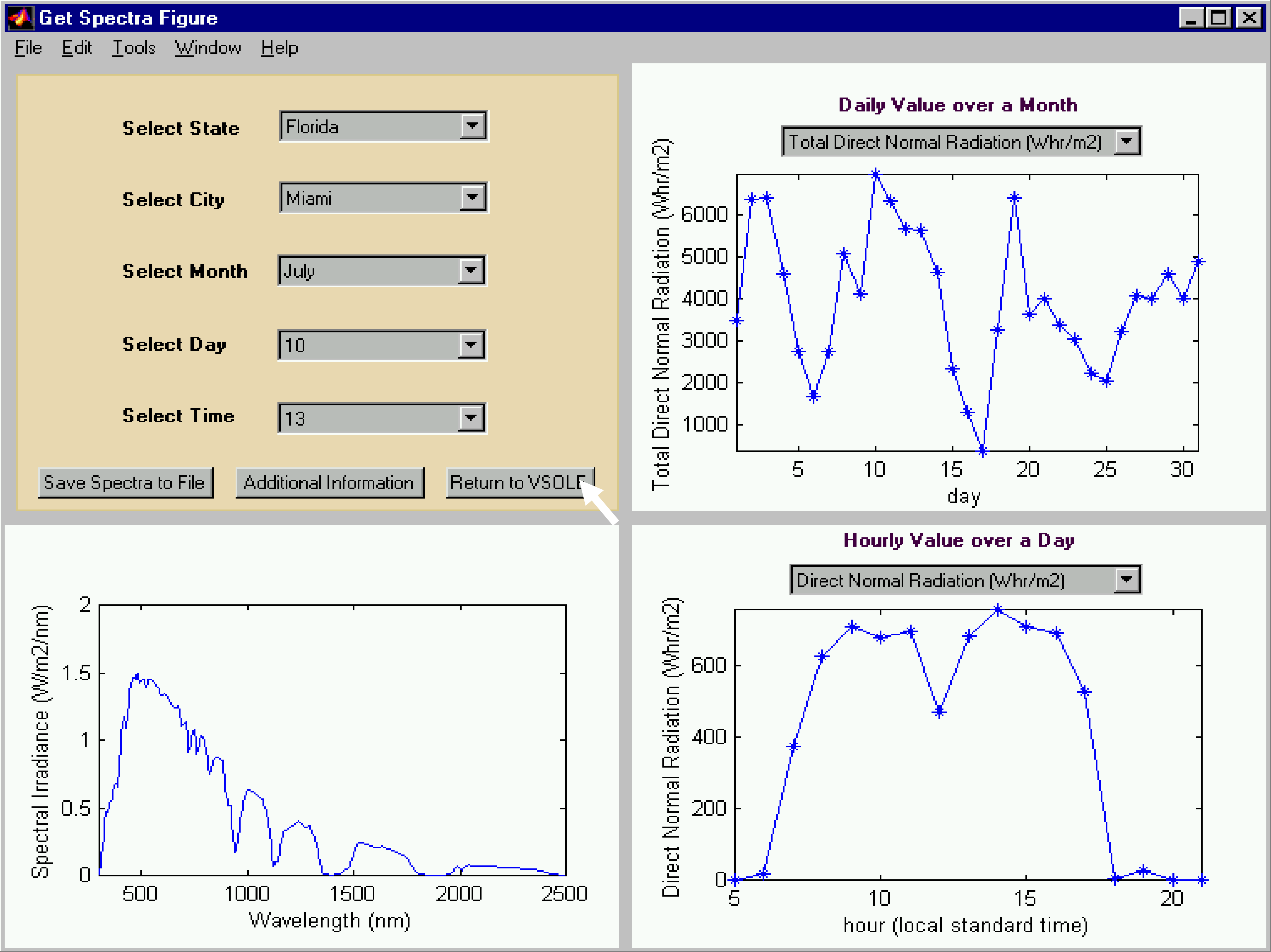


Get Spectra Figure
File Edit Tools Window Help
Select State
Select City
Select Month
Select Day
Select Time
Save Spectra to File
Alabama
Alaska
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Florida
Georgia
Hawaii
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pacific Islands
Pennsylvania
Puerto Rico
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
Daily Value over a Month
Total Direct Normal Radiation (Whr/m2)
Total Direct Normal Radiation (Whr/m2)
day
Hourly Value over a Day
Direct Normal Radiation (Whr/m2)
Direct Normal Radiation (Whr/m2)
hour (local standard time)
Spectral Irradiance (Wm2/nm)
Wavelength (nm)



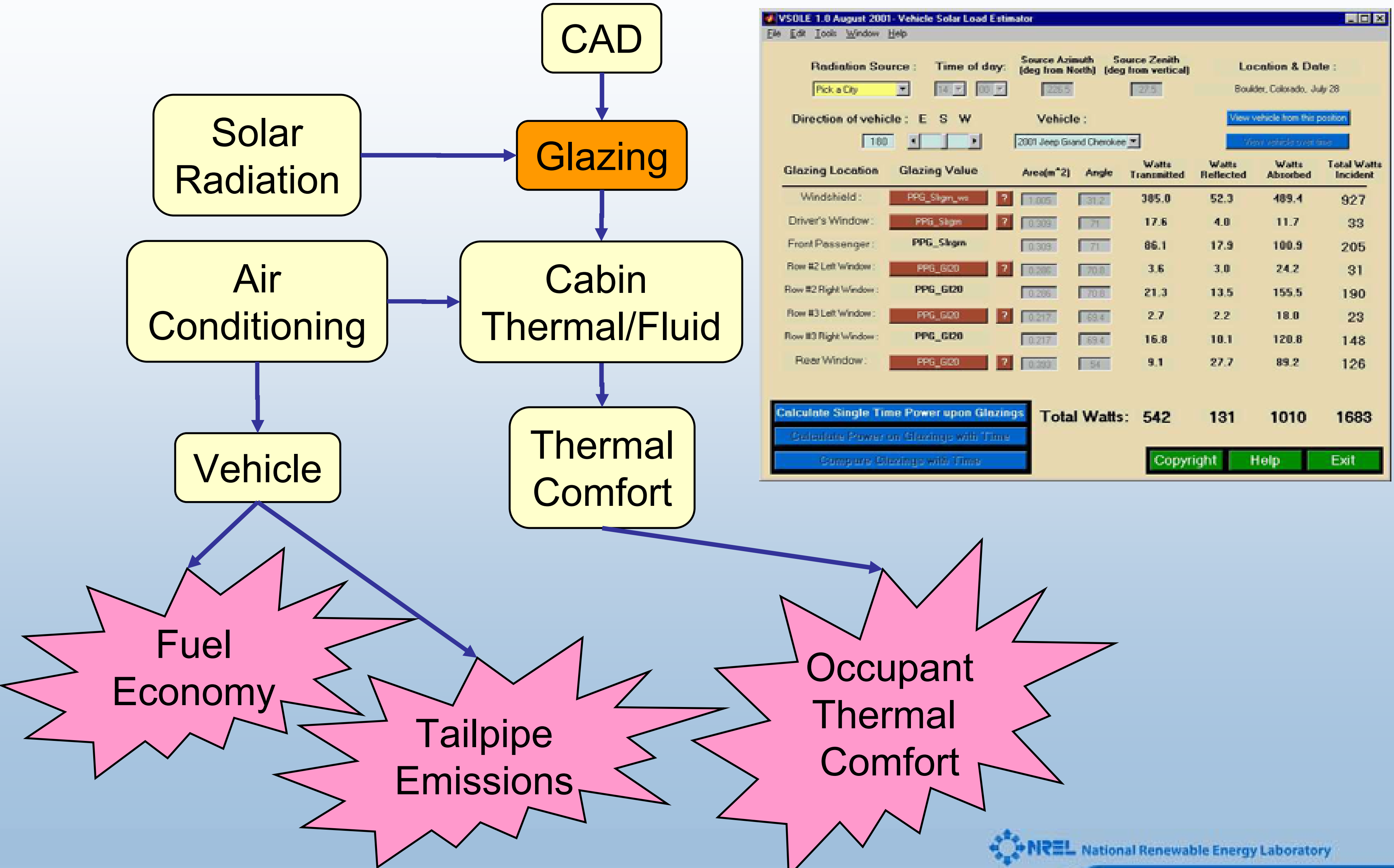
Get Spectra Figure
File Edit Tools Window Help
Select State
Florida
Select City
Miami
Daytona Beach
Jacksonville
Key West
Miami
Tallahassee
Tampa
West Palm Beach
Select Month
Select Day
Select Time
13
Save Spectra to File
Additional Information
Return to VSOLE
Daily Value over a Month
Total Direct Normal Radiation (Whr/m2)
day
Hourly Value over a Day
Direct Normal Radiation (Whr/m2)
hour (local standard time)
Spectral Irradiance (W/m2/nm)
Wavelength (nm)

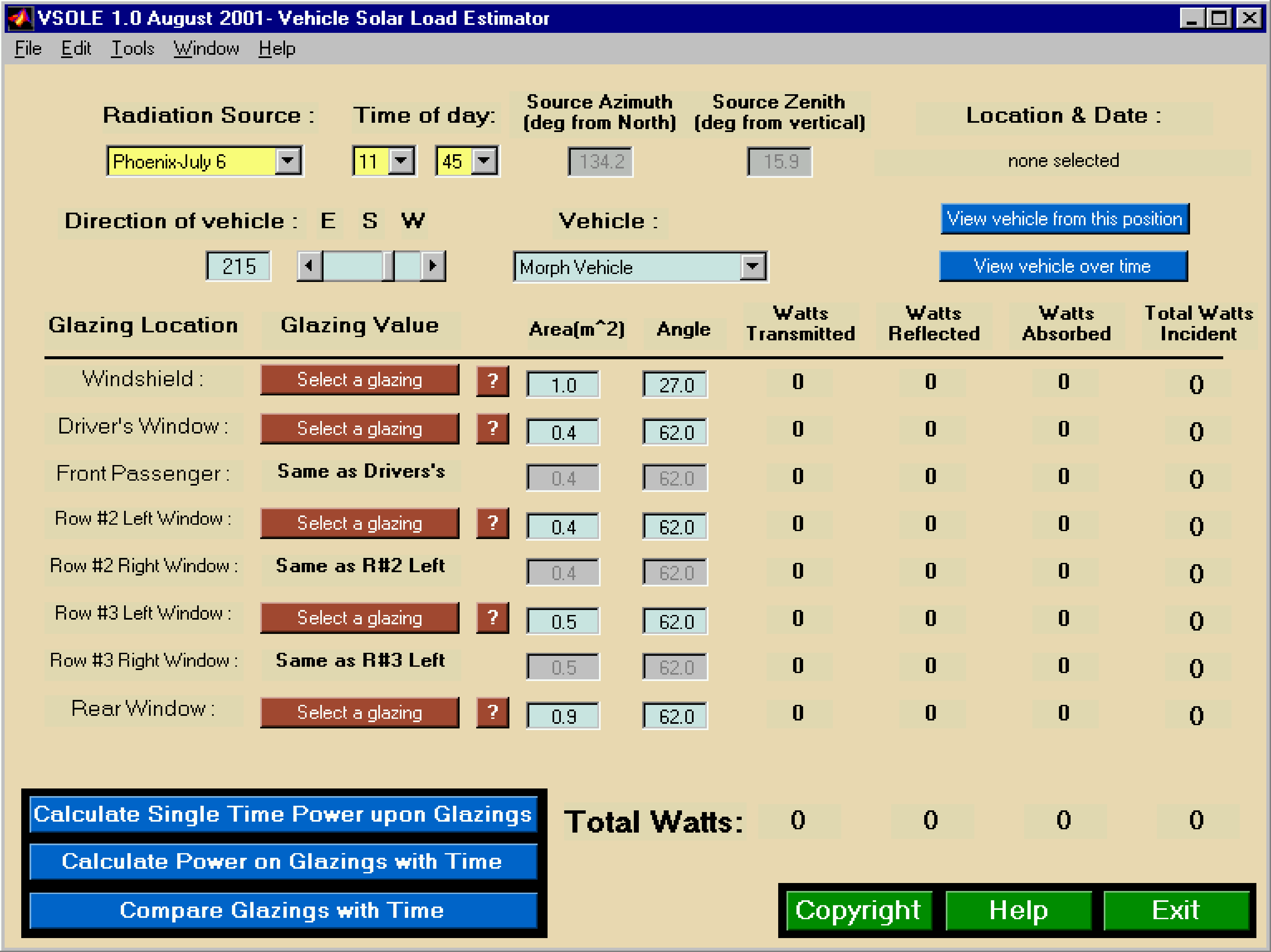

Get Spectra Figure
File Edit Tools Window Help
Select State
Florida
Select City
Miami
Select Month
July
January
February
March
April
May
June
July
August
September
October
November
December
Select Day
Select Time
Save Spectra to File
Add
rn to VSOLE
Daily Value over a Month
Total Direct Normal Radiation (Whr/m2)
day
Hourly Value over a Day
Direct Normal Radiation (Whr/m2)
hour (local standard time)
Spectral Irradiance (W/m2/nm)
Wavelength (nm)


Get Spectra Figure
File
Edit
Tools
Window
Help
Select State
Florida
Select City
Miami
Select Month
July
Select Day
10
Select Time
13
Save Spectra to File
Additional Information
Return to VSOLE
Daily Value over a Month
Total Direct Normal Radiation (Whr/m2)
6000
5000
4000
3000
2000
1000
5
10
15
20
25
30
day
Spectral Irradiance (W/m2/nm)
2
1.5
1
0.5
0
500
1000
1500
2000
2500
Wavelength (nm)
Hourly Value over a Day
Direct Normal Radiation (Whr/m2)
600
400
200
0
5
10
15
20
hour (local standard time)

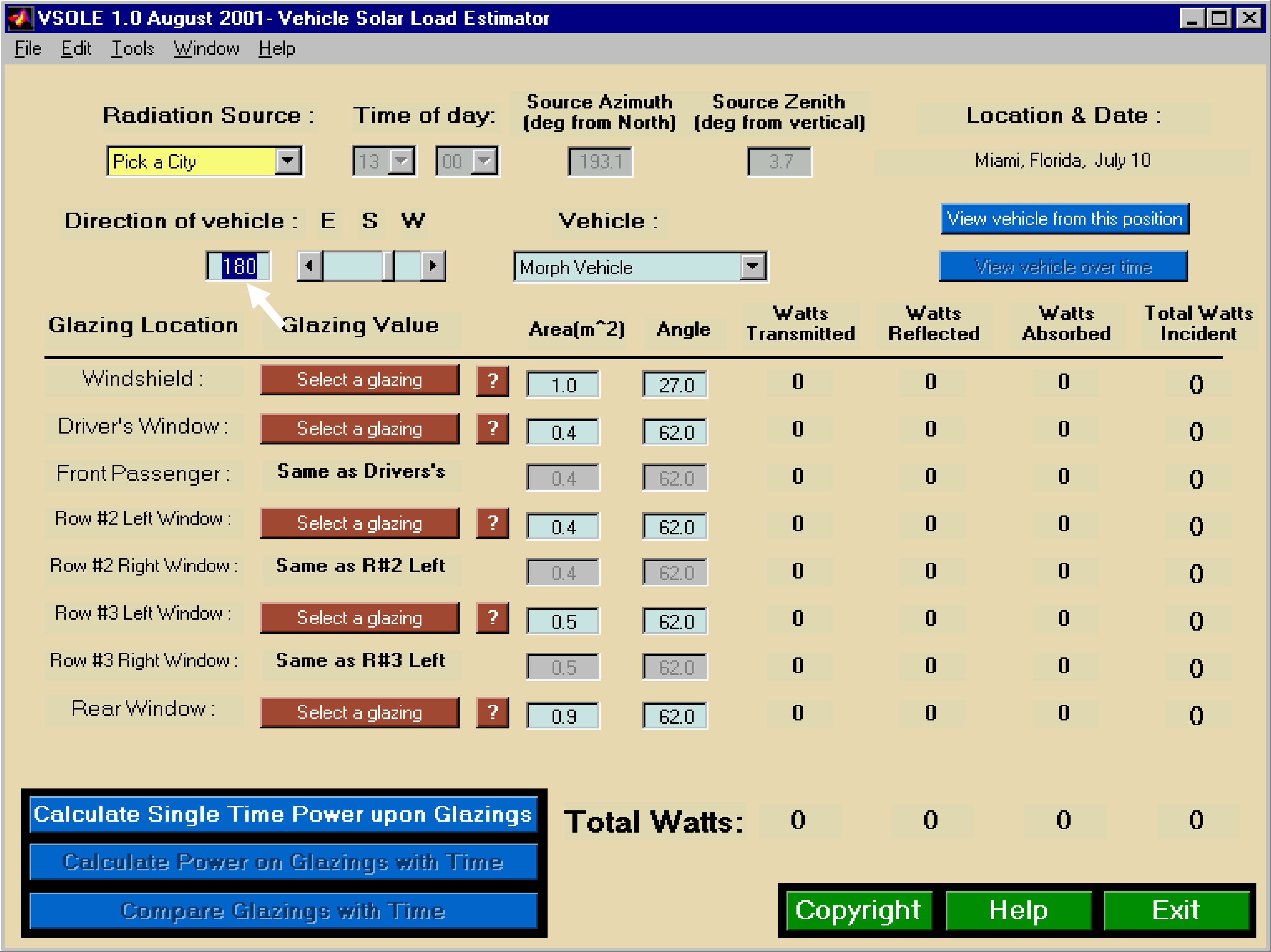
Integrated Modeling

Determine the solar load into your vehicle

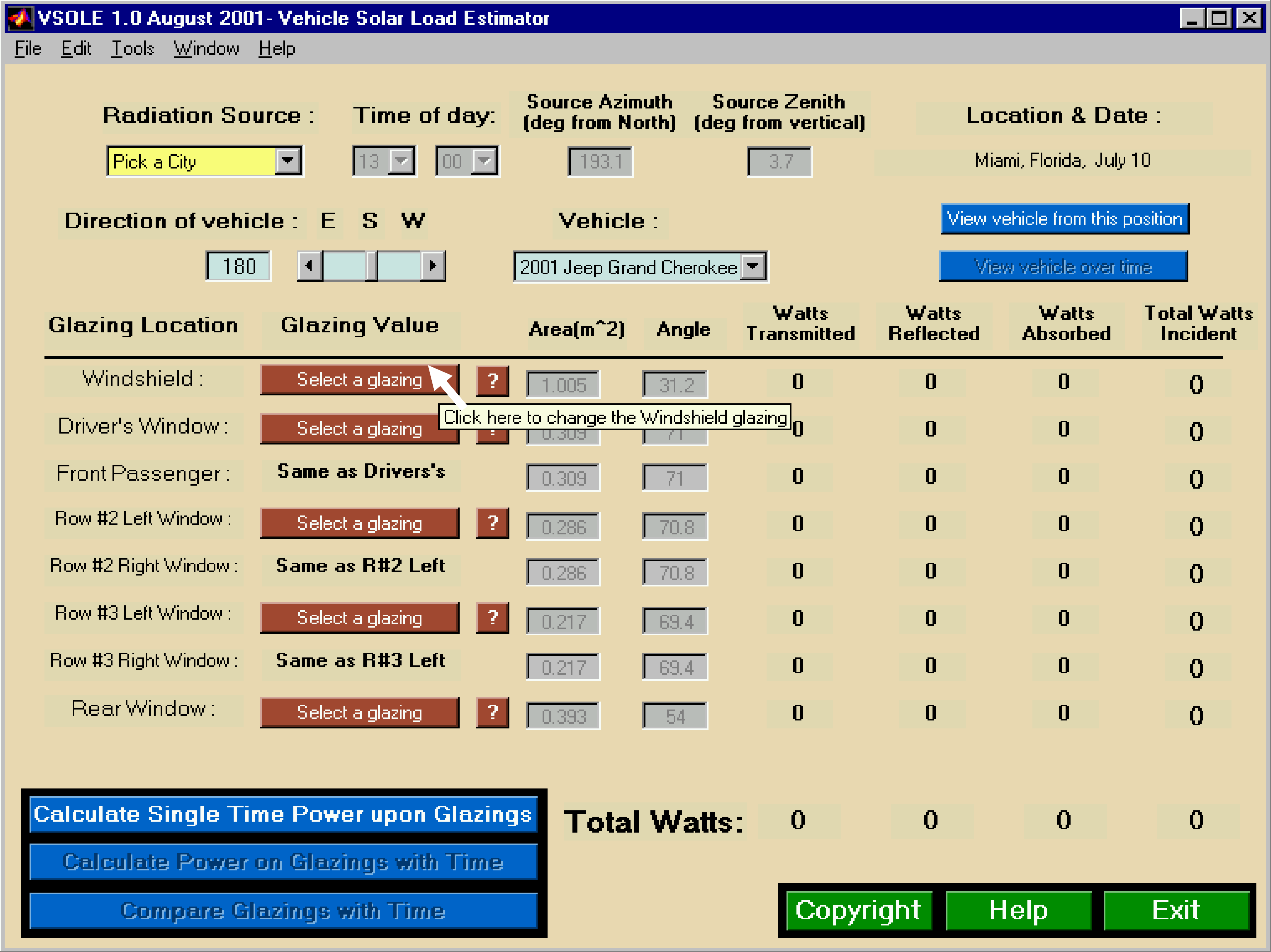



VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Time of day:
Source Azimuth (deg from North)
Source Zenith (deg from vertical)
Location & Date :
Phoenix-July 6
11
45
134.2
15.9
none selected
Direction of vehicle :
E S W
Vehicle :
View vehicle from this position
215
Morph Vehicle
View vehicle over time
Glazing Location
Glazing Value
Area(m^2)
Angle
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield : Select a glazing ? 1.0 27.0 0 0 0 0
Driver's Window : Select a glazing ? 0.4 62.0 0 0 0 0
Front Passenger : Same as Drivers's 0.4 62.0 0 0 0 0
Row #2 Left Window : Select a glazing ? 0.4 62.0 0 0 0 0
Row #2 Right Window : Same as R#2 Left 0.4 62.0 0 0 0 0
Row #3 Left Window : Select a glazing ? 0.5 62.0 0 0 0 0
Row #3 Right Window : Same as R#3 Left 0.5 62.0 0 0 0 0
Rear Window : Select a glazing ? 0.9 62.0 0 0 0 0
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Total Watts: 0 0 0 0
Copyright
Help
Exit


VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Time of day:
Source Azimuth (deg from North)
Source Zenith (deg from vertical)
Location & Date :
Pick a City
13
00
200.3
15.2
Alamosa, Colorado, July 1
Phoenix-July 6
ASTM E-891
ASTM E-892
Xe Lamp
Metal Halide
Pick a City
E S W
Vehicle :
View vehicle from this position
Morph Vehicle
View vehicle over time
Glazing Location
Glazing Value
Area(m^2)
Angle
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield :
Select a glazing
?
1.0
27.0
0 0 0 0
Driver's Window :
Select a glazing
?
0.4
62.0
0 0 0 0
Front Passenger :
Same as Drivers's
0.4
62.0
0 0 0 0
Row #2 Left Window :
Select a glazing
?
0.4
62.0
0 0 0 0
Row #2 Right Window :
Same as R#2 Left
0.4
62.0
0 0 0 0
Row #3 Left Window :
Select a glazing
?
0.5
62.0
0 0 0 0
Row #3 Right Window :
Same as R#3 Left
0.5
62.0
0 0 0 0
Rear Window :
Select a glazing
?
0.9
62.0
0 0 0 0
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Total Watts:
0 0 0 0
Copyright
Help
Exit


VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Time of day:
Source Azimuth (deg from North)
Source Zenith (deg from vertical)
Location & Date :
Pick a City
13
00
193.1
3.7
Miami, Florida, July 10
Direction of vehicle : E S W
Vehicle :
View vehicle from this position
180
Morph Vehicle
View vehicle over time
Glazing Location
Glazing Value
Area(m^2)
Angle
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield :
Select a glazing
?
1.0
27.0
0
Driver's Window :
Select a glazing
0.4
62.0
Front Passenger :
Same as Drivers's
0.4
62.0
Row #2 Left Window :
Select a glazing
0.4
62.0
Row #2 Right Window :
Same as R#2 Left
0.4
62.0
Row #3 Left Window :
Select a glazing
0.5
62.0
Row #3 Right Window :
Same as R#3 Left
0.5
62.0
Rear Window :
Select a glazing
0.9
62.0
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Total Watts:
0
0
0
0
Copyright
Help
Exit


VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Pick a City
Time of day:
13
00
Source Azimuth (deg from North)
193.1
Source Zenith (deg from vertical)
3.7
Location & Date :
Miami, Florida, July 10
Direction of vehicle : E S W
180
Vehicle :
Morph Vehicle
Morph Vehicle
2001 Honda Insight
2001 Toyota Prius
1998 Chrysler Minivan
2001 Jeep Grand Cherokee
View vehicle from this position
View vehicle over time
Glazing Location
Glazing Value
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield :
Driver's Window :
Front Passenger :
Same as Drivers's
Row #2 Left Window :
Row #2 Right Window :
Same as R#2 Left
Row #3 Left Window :
Row #3 Right Window :
Same as R#3 Left
Rear Window :
Select a glazing
?
0.4
0.5
0.9
62.0
0
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Total Watts:
Copyright
Help
Exit


VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Time of day:
Source Azimuth (deg from North)
Source Zenith (deg from vertical)
Location & Date :
Pick a City
13
00
193.1
3.7
Miami, Florida, July 10
Direction of vehicle : E S W
Vehicle :
View vehicle from this position
180
2001 Jeep Grand Cherokee
View vehicle over time
Glazing Location
Glazing Value
Area(m^2)
Angle
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield :
Select a glazing
?
1.005
31.2
0
0
0
0
Click here to change the Windshield glazing
Driver's Window :
Select a glazing
0
0
0
0
Front Passenger :
Same as Drivers's
0.309
71
0
0
0
0
Row #2 Left Window :
Select a glazing
?
0.286
70.8
0
0
0
0
Row #2 Right Window :
Same as R#2 Left
0.286
70.8
0
0
0
0
Row #3 Left Window :
Select a glazing
?
0.217
69.4
0
0
0
0
Row #3 Right Window :
Same as R#3 Left
0.217
69.4
0
0
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0
Rear Window :
Select a glazing
?
0.393
54
0
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0
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Total Watts:
0
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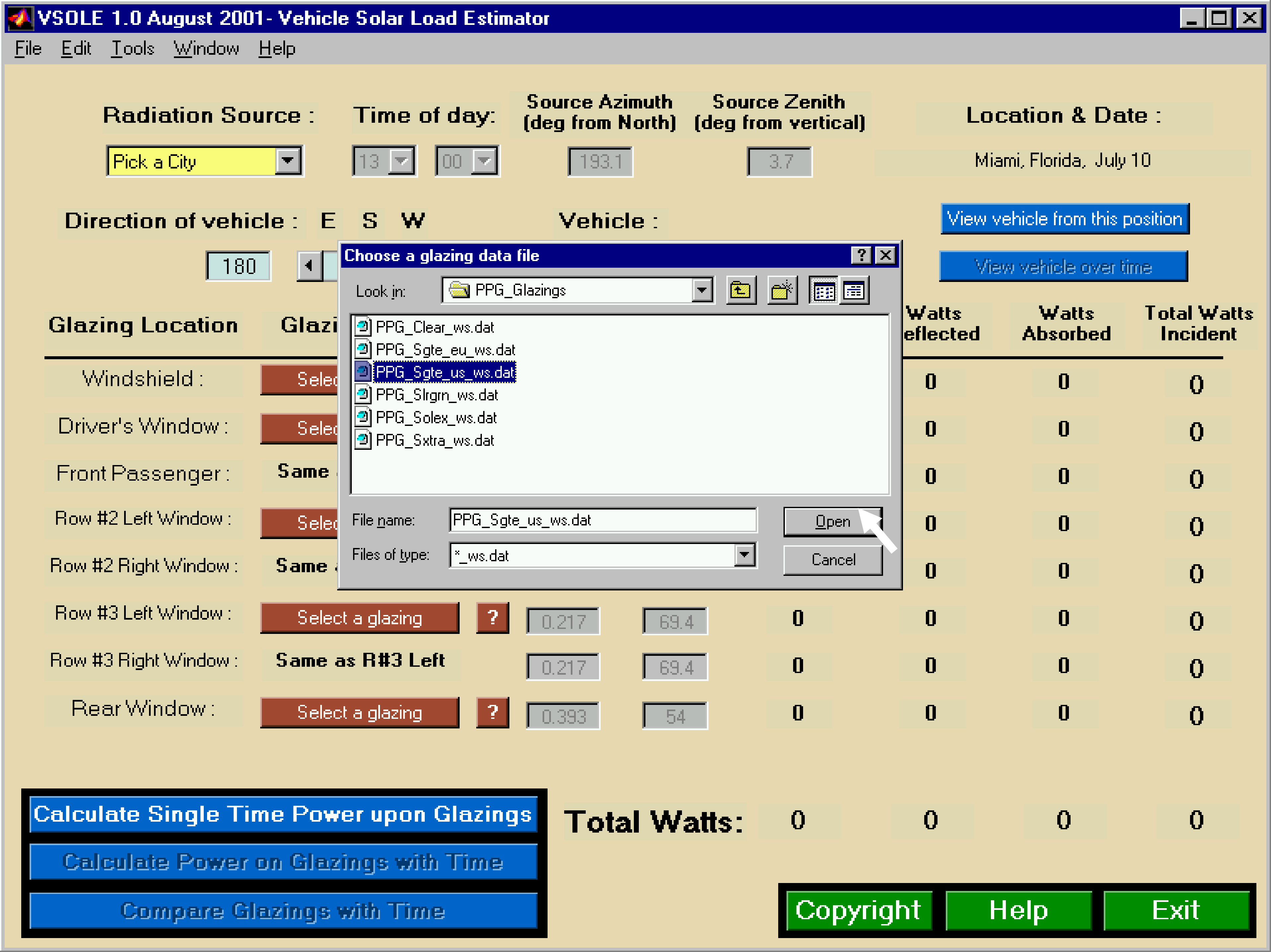
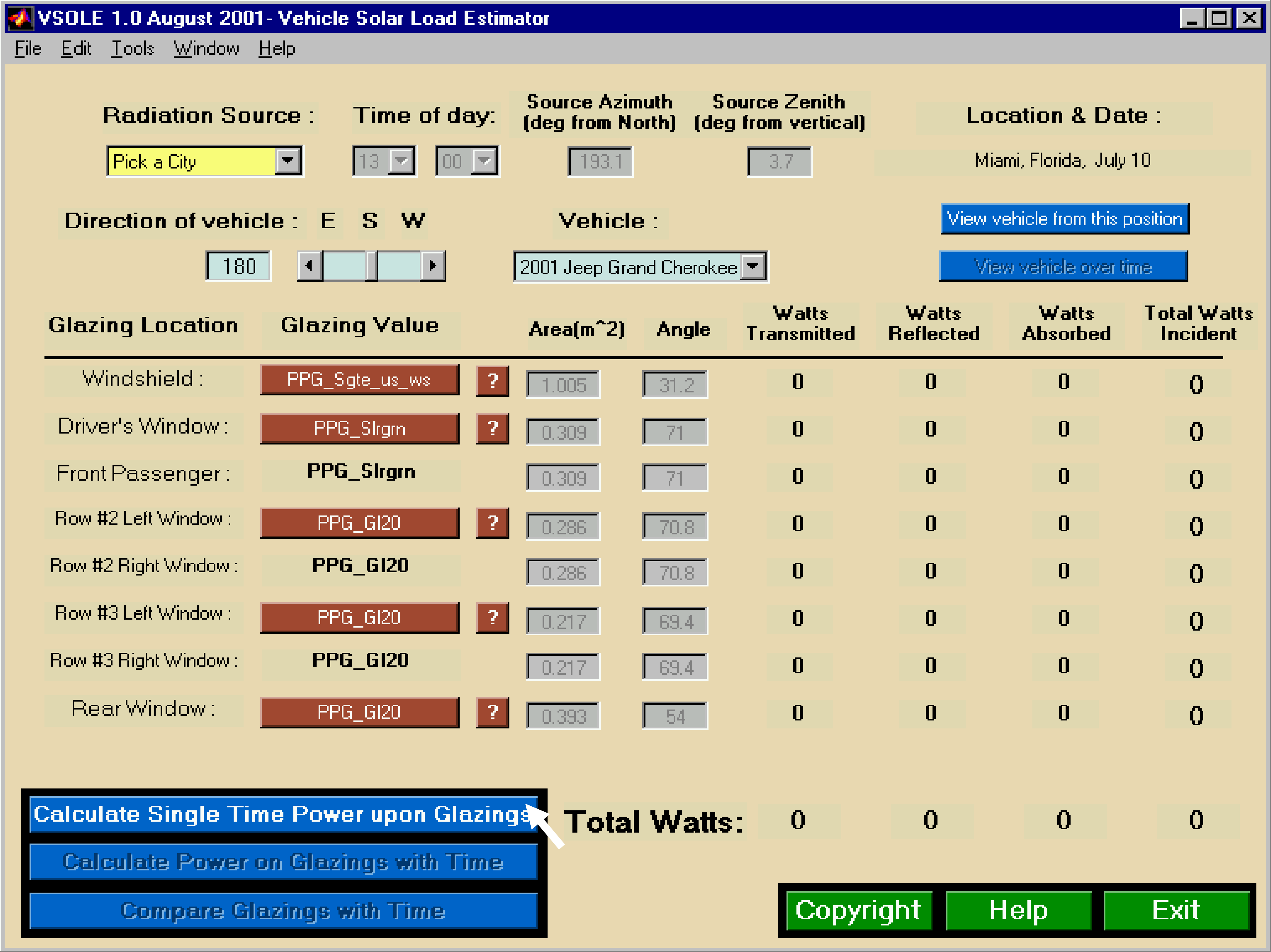
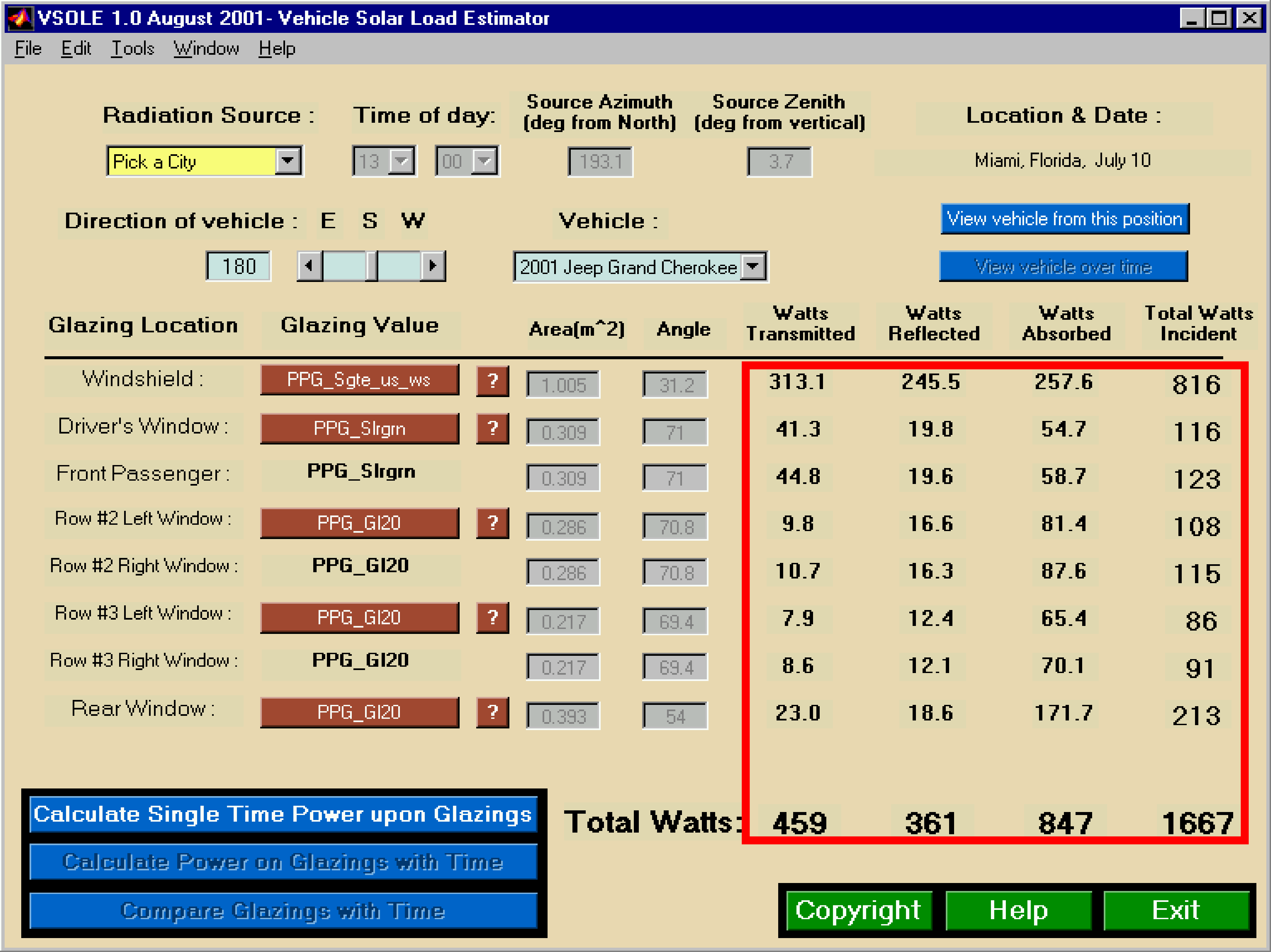
0
0
Copyright
Help
Exit


VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Pick a City
Time of day:
13
00
Source Azimuth (deg from North)
193.1
Source Zenith (deg from vertical)
3.7
Location & Date :
Miami, Florida, July 10
Direction of vehicle : E S W
180
Vehicle :
View vehicle from this position
View vehicle over time
Glazing Location
Windshield :
Driver's Window :
Front Passenger :
Row #2 Left Window :
Row #2 Right Window :
Row #3 Left Window :
Row #3 Right Window :
Rear Window :
Select a glazing
Same as R#3 Left
0.217
69.4
0.393
54
Watts Reflected
Watts Absorbed
Total Watts Incident
Choose a glazing data file
Look in: PPG_Glazings
PPG_Clear_ws.dat
PPG_Sgte_eu_ws.dat
PPG_Sgte_us_ws.dat
PPG_Slrgrn_ws.dat
PPG_Solex_ws.dat
PPG_Sxtra_ws.dat
File name: PPG_Sgte_us_ws.dat
Files of type: *_ws.dat
Open
Cancel
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Total Watts: 0 0 0 0
Copyright
Help
Exit

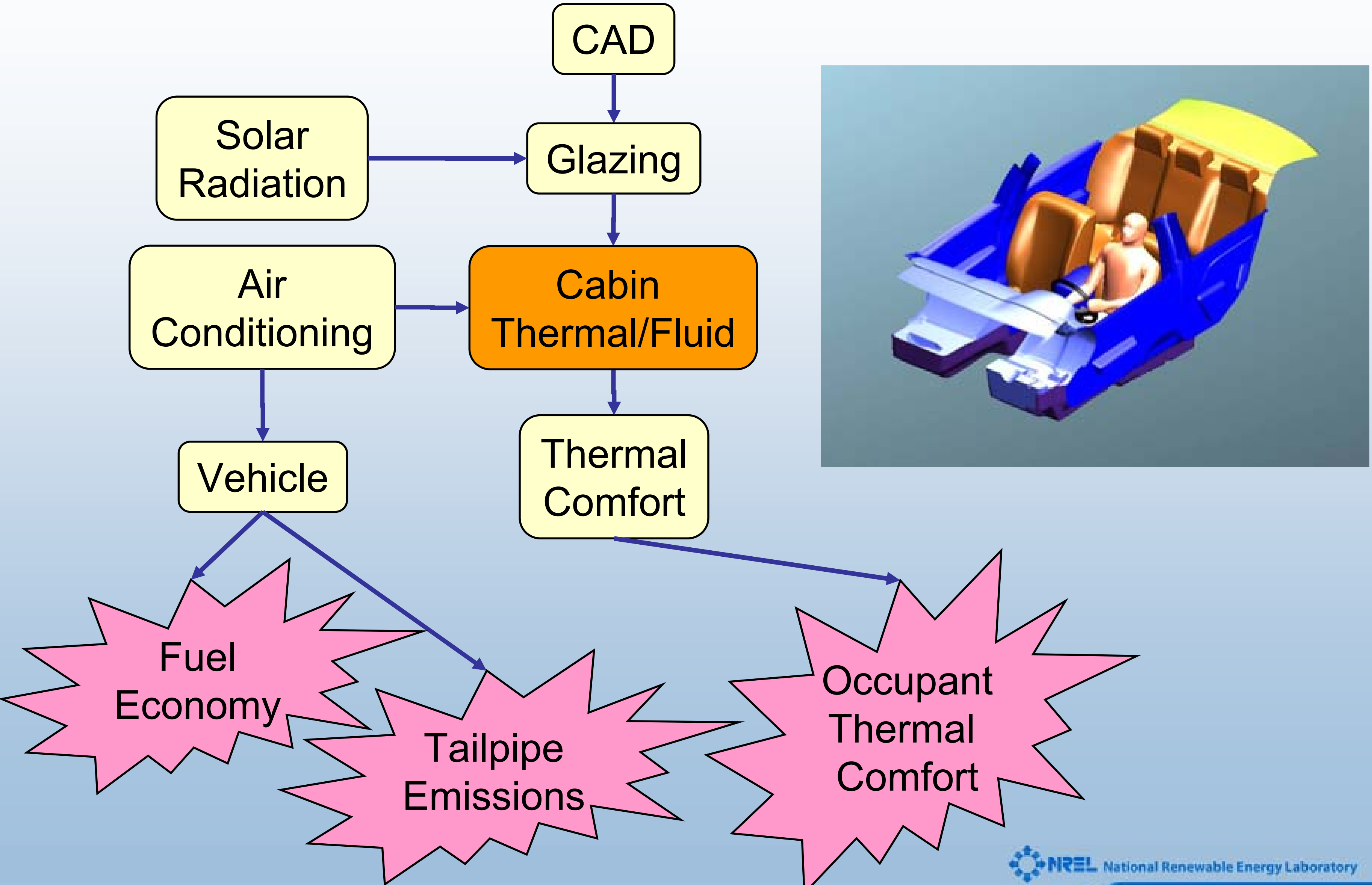

VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Time of day:
Source Azimuth (deg from North)
Source Zenith (deg from vertical)
Location & Date :
Pick a City
13
00
193.1
3.7
Miami, Florida, July 10
Direction of vehicle : E S W
Vehicle :
View vehicle from this position
180
2001 Jeep Grand Cherokee
View vehicle over time
Glazing Location
Glazing Value
Area(m^2)
Angle
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield : PPG_Sgte_us_ws ? 1.005 31.2 0 0 0 0
Driver's Window : PPG_Slrgrn ? 0.309 71 0 0 0 0
Front Passenger : PPG_Slrgrn 0.309 71 0 0 0 0
Row #2 Left Window : PPG_Gl20 ? 0.286 70.8 0 0 0 0
Row #2 Right Window : PPG_Gl20 0.286 70.8 0 0 0 0
Row #3 Left Window : PPG_Gl20 ? 0.217 69.4 0 0 0 0
Row #3 Right Window : PPG_Gl20 0.217 69.4 0 0 0 0
Rear Window : PPG_Gl20 ? 0.393 54 0 0 0 0
Calculate Single Time Power upon Glazings
Total Watts: 0 0 0 0
Calculate Power on Glazings with Time
Compare Glazings with Time
Copyright
Help
Exit



VSOLE 1.0 August 2001- Vehicle Solar Load Estimator
File Edit Tools Window Help
Radiation Source :
Pick a City
Time of day:
13
00
Source Azimuth (deg from North)
193.1
Source Zenith (deg from vertical)
3.7
Location & Date :
Miami, Florida, July 10
Direction of vehicle : E S W
180
Vehicle :
2001 Jeep Grand Cherokee
View vehicle from this position
View vehicle over time
Glazing Location
Glazing Value
Area(m^2)
Angle
Watts Transmitted
Watts Reflected
Watts Absorbed
Total Watts Incident
Windshield : PPG_Sgte_us_ws ? 1.005 31.2 313.1 245.5 257.6 816
Driver's Window : PPG_Slrgrn ? 0.309 71 41.3 19.8 54.7 116
Front Passenger : PPG_Slrgrn 0.309 71 44.8 19.6 58.7 123
Row #2 Left Window : PPG_GI20 ? 0.286 70.8 9.8 16.6 81.4 108
Row #2 Right Window : PPG_GI20 0.286 70.8 10.7 16.3 87.6 115
Row #3 Left Window : PPG_GI20 ? 0.217 69.4 7.9 12.4 65.4 86
Row #3 Right Window : PPG_GI20 0.217 69.4 8.6 12.1 70.1 91
Rear Window : PPG_GI20 ? 0.393 54 23.0 18.6 171.7 213
Total Watts: 459 361 847 1667
Calculate Single Time Power upon Glazings
Calculate Power on Glazings with Time
Compare Glazings with Time
Copyright
Help
Exit

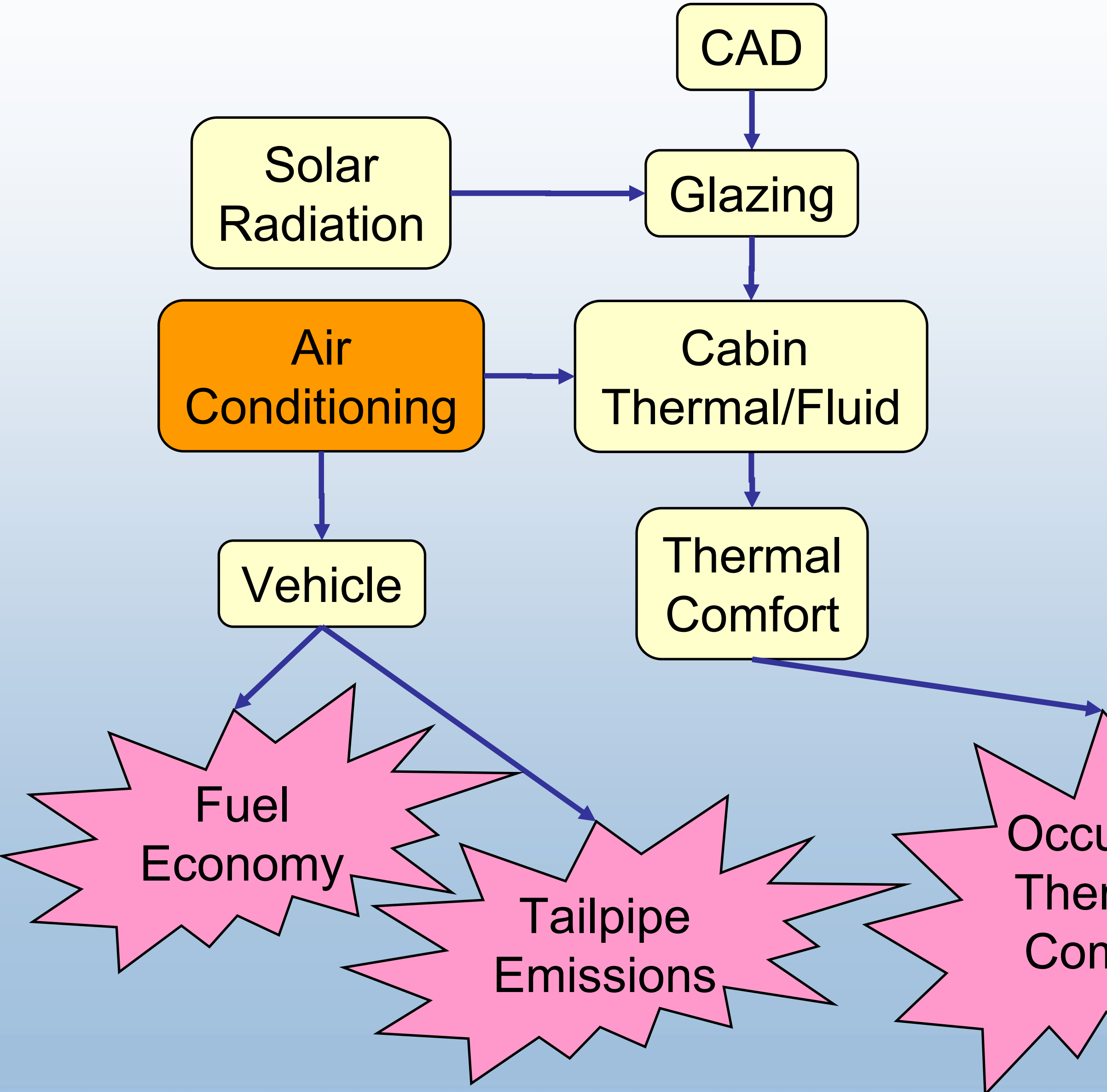
Integrated Modeling

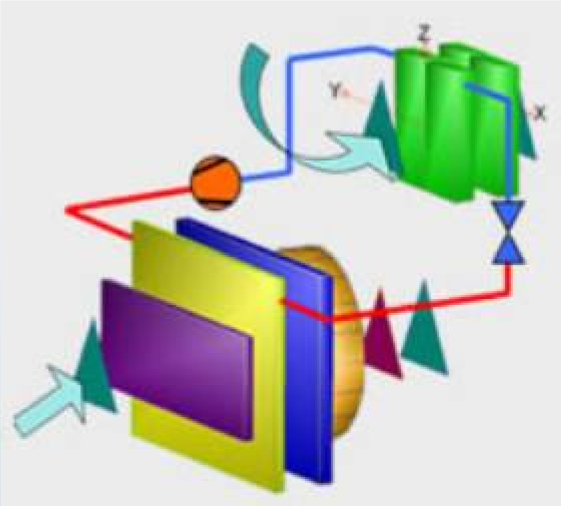
Model temperatures and airflow in the cabin



Integrated Modeling

Find the power consumption and cooling capacity of the A/C

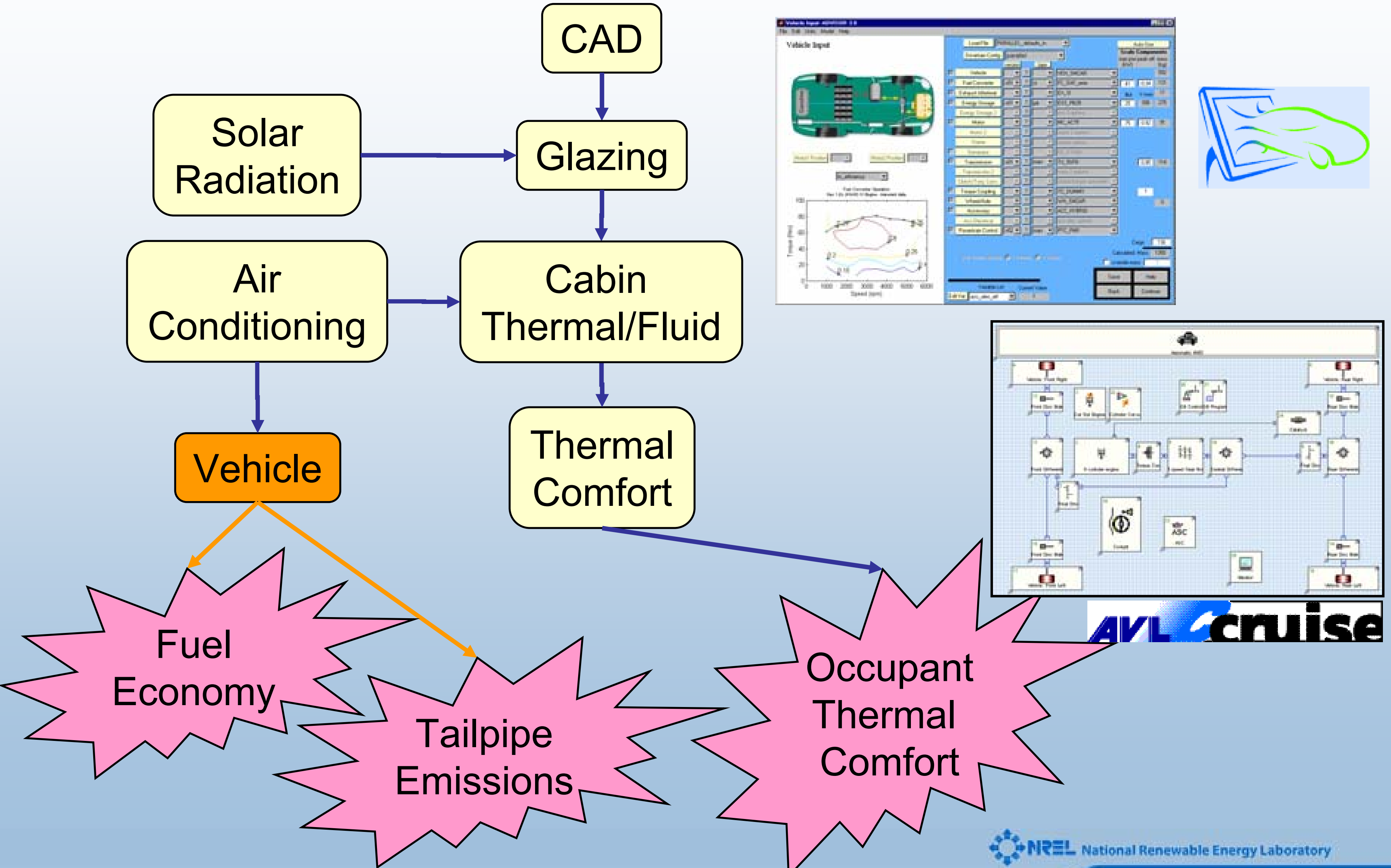




KULI

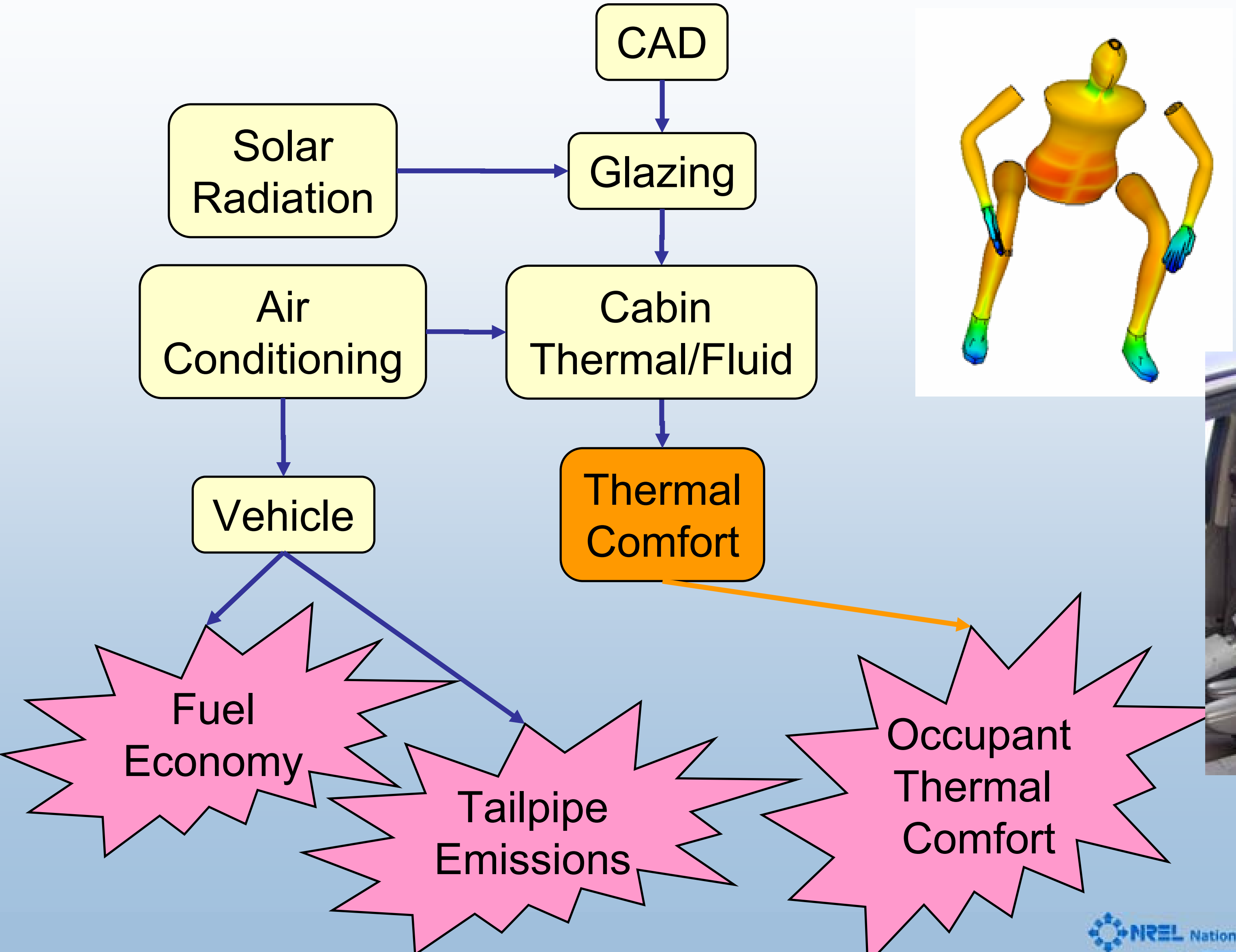
Integrated Modeling

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



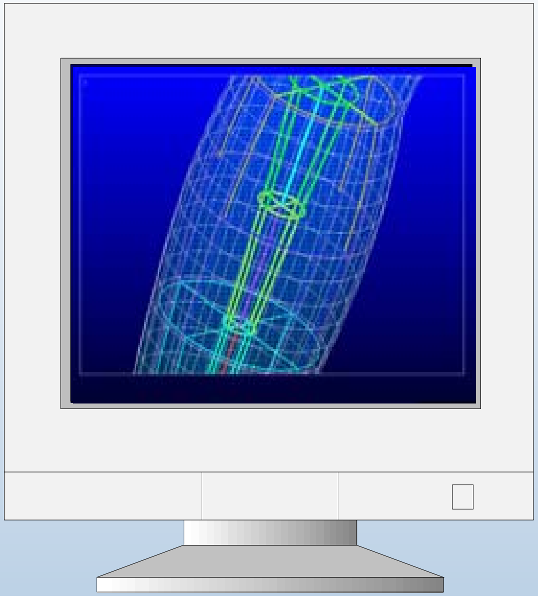
Integrated Modeling

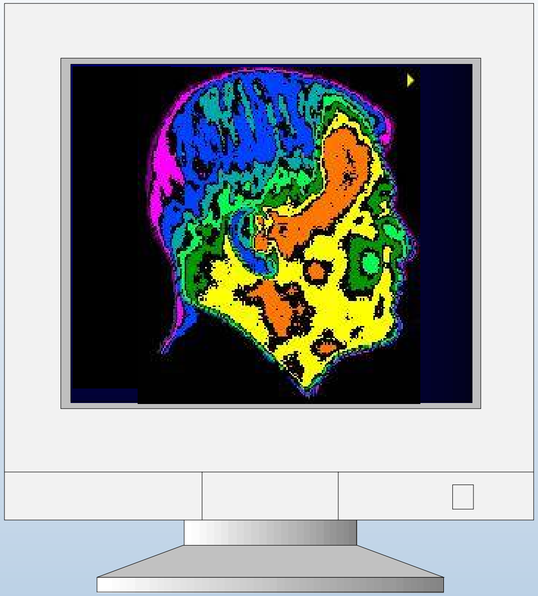
How comfortable are you inside your car?



Thermal Comfort Assessment Tools

Predicting the comfort of vehicle occupants





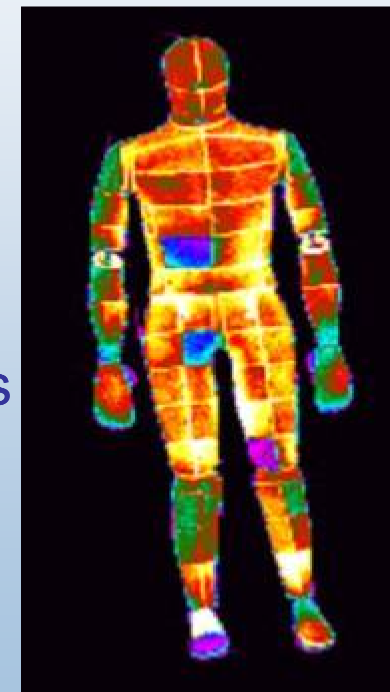
ADvanced Automotive Manikin

Human Thermal Physiological Model

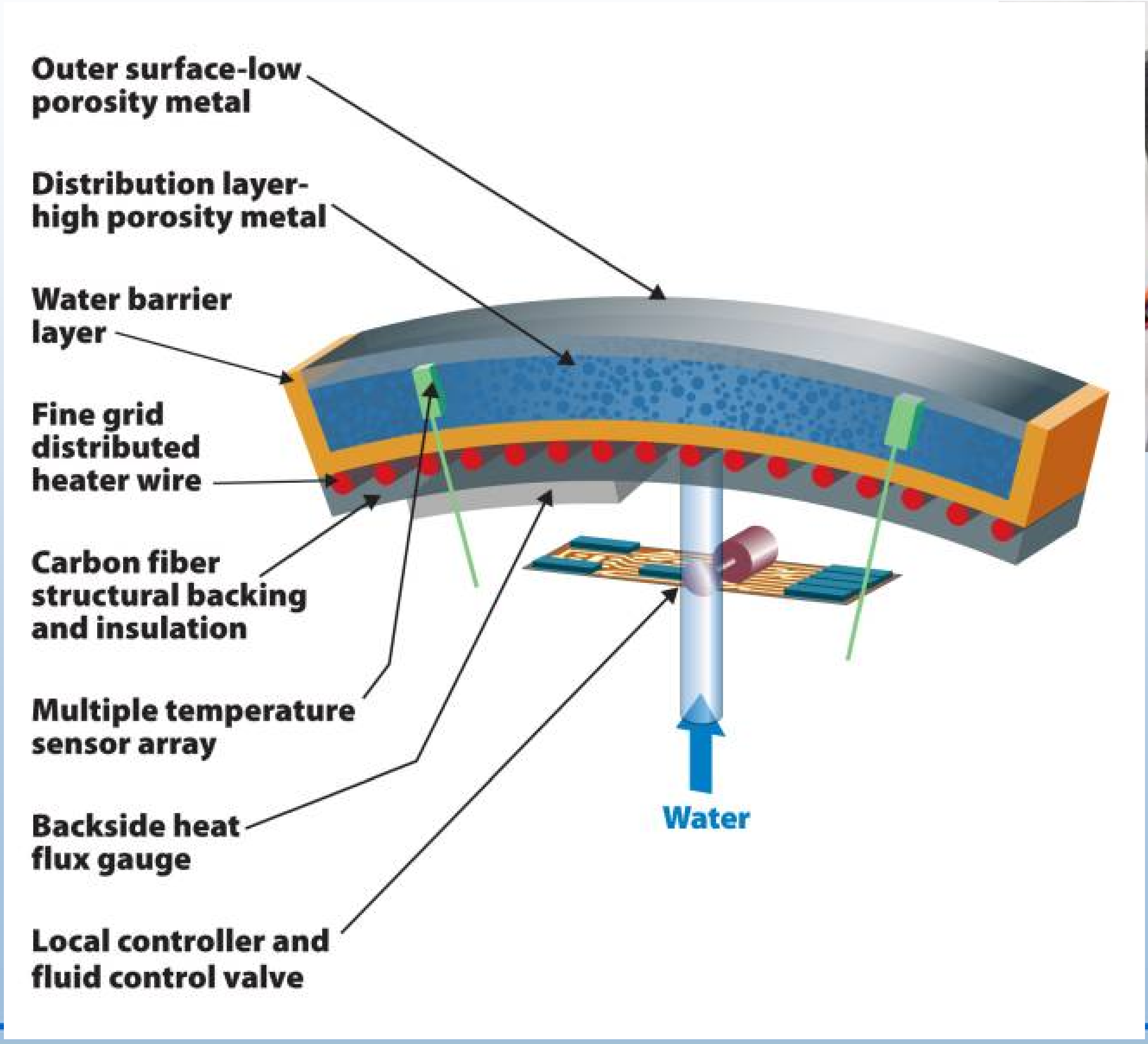
Human Thermal Comfort Empirical Model

ADvanced Automotive Manikin (ADAM)

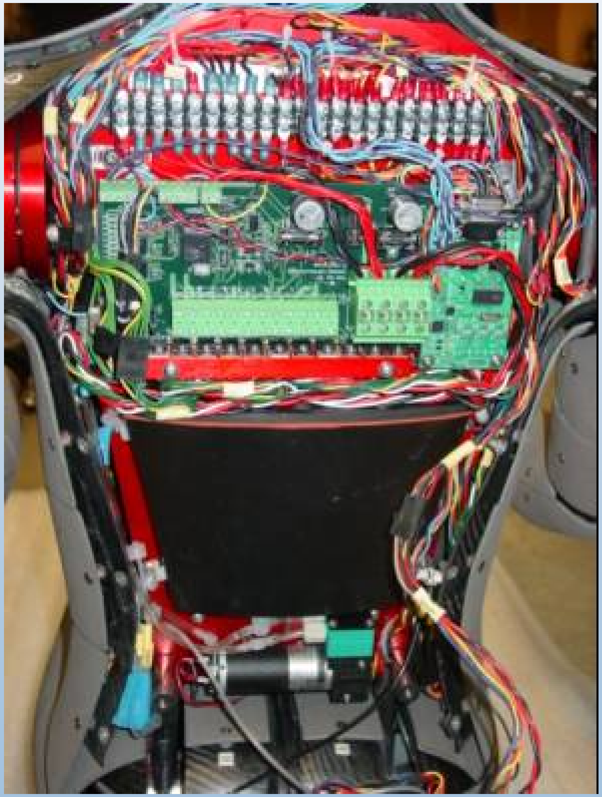
- On-board power, water, communications
- Designed to respond to a transient, non-uniform thermal environment like a human:
  - Sweating
  - Breathing
- Wears clothes
- 175 cm tall, 61 kg
- 126 segments (~120 cm^2), 120 zones



Surface Segment Details



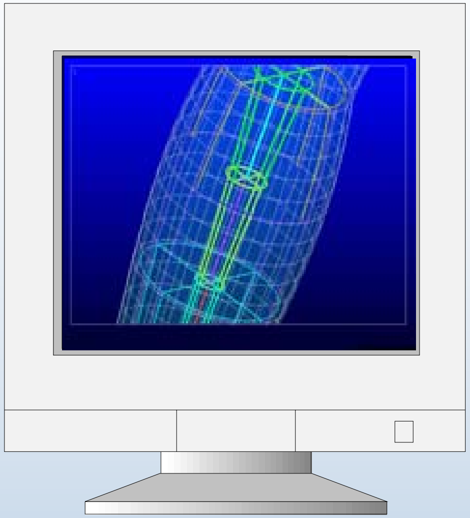
ADAM's Carbon Fiber Skeletal System



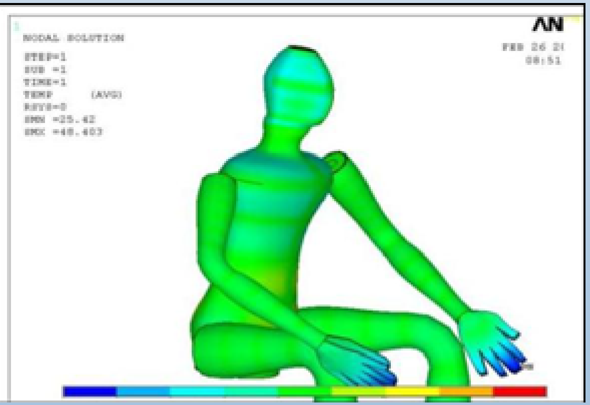
Ready for a Brain!

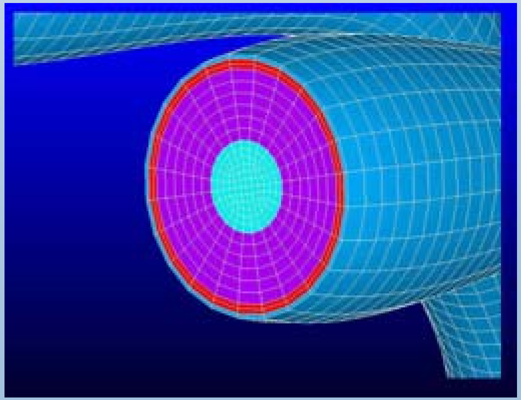
Human Thermal Physiological Model

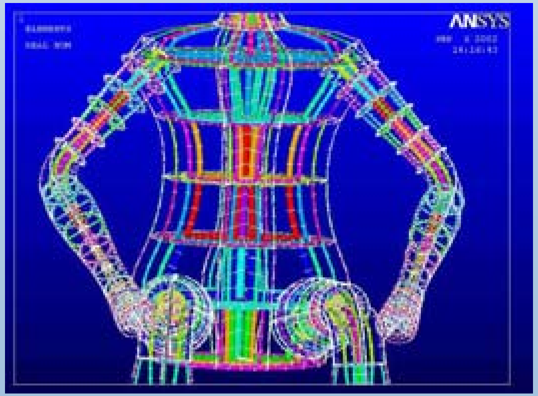
A Numerical Person



- 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)



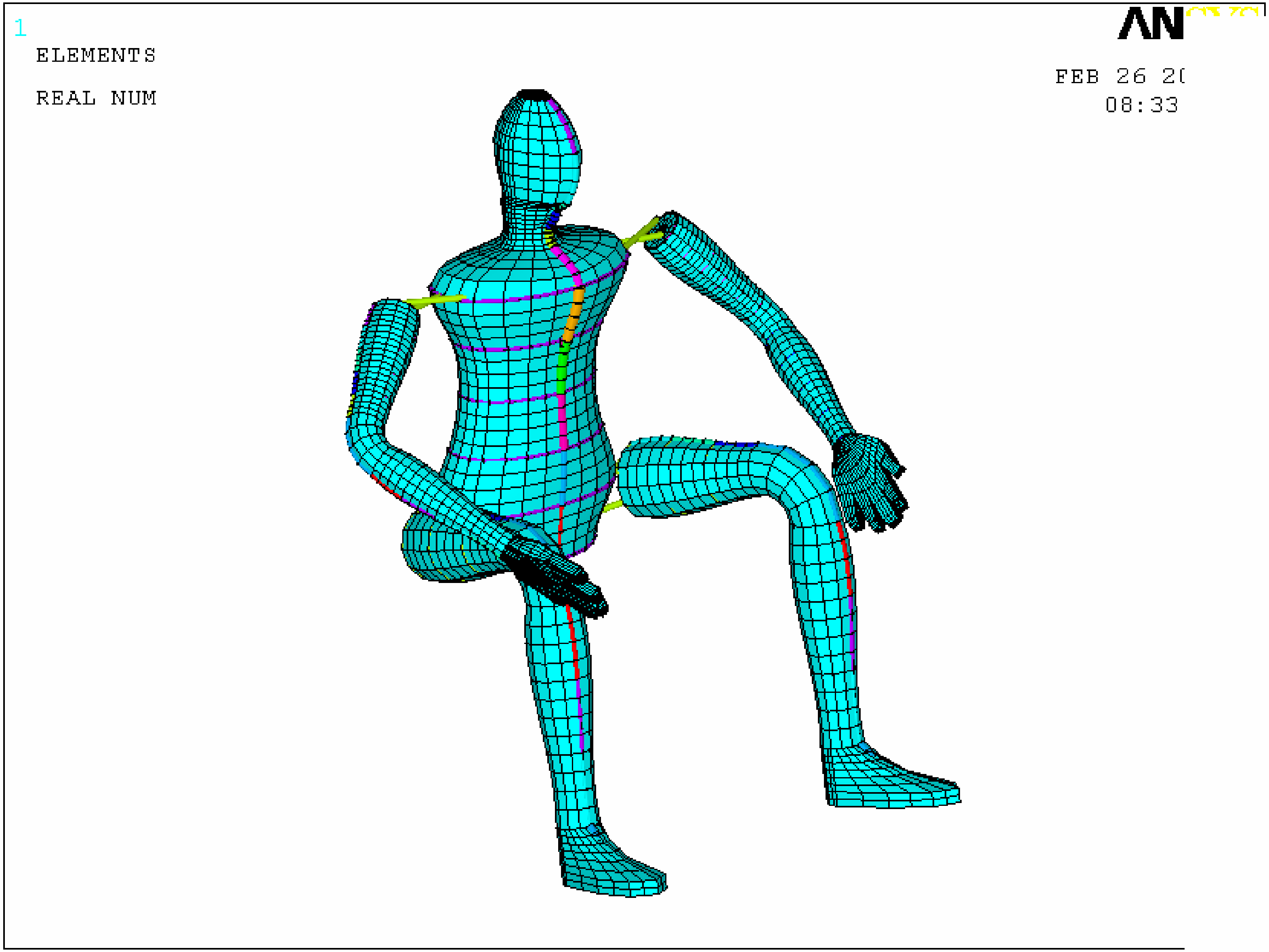




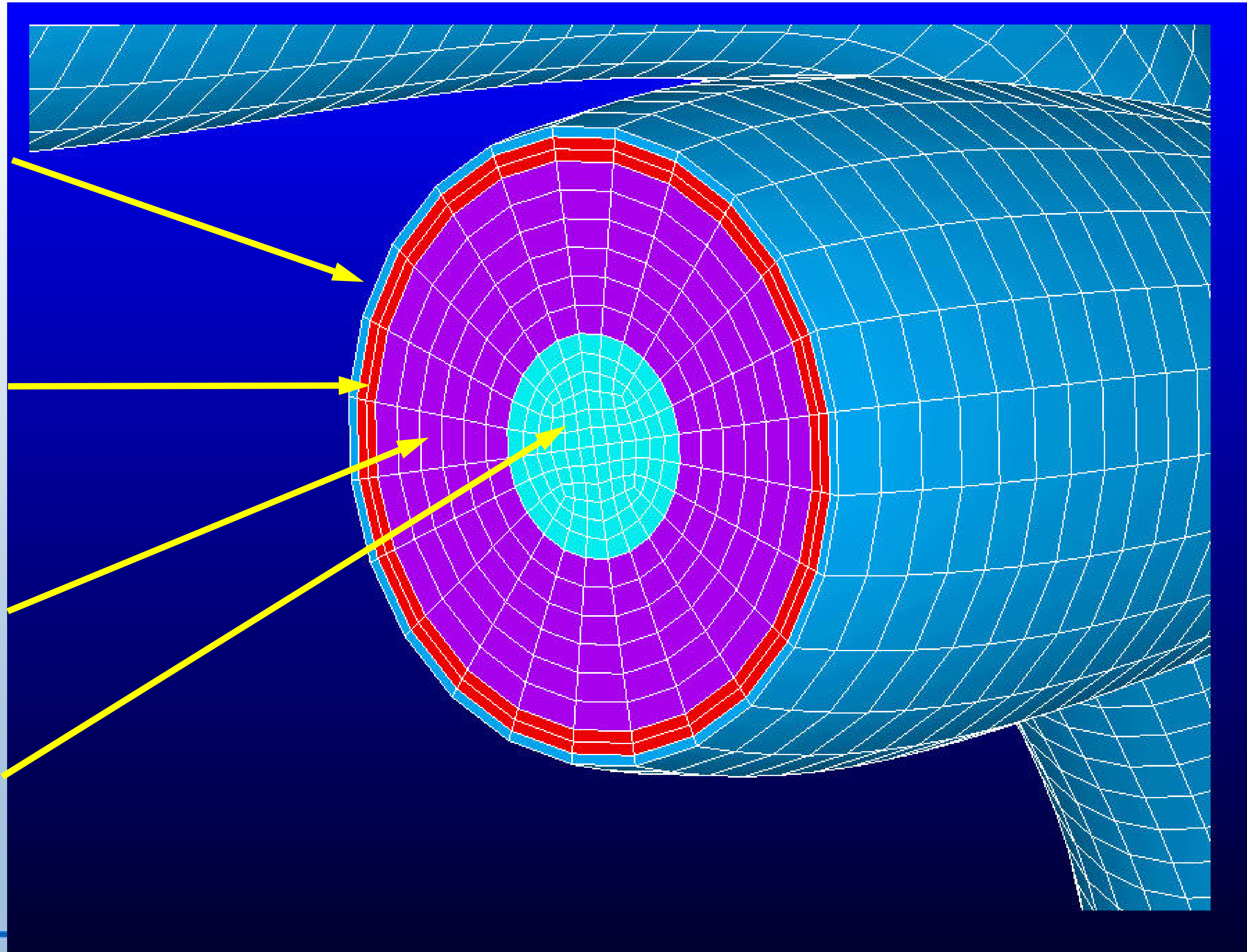
Human Thermal Physiological Model
Thermoregulatory System

- 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

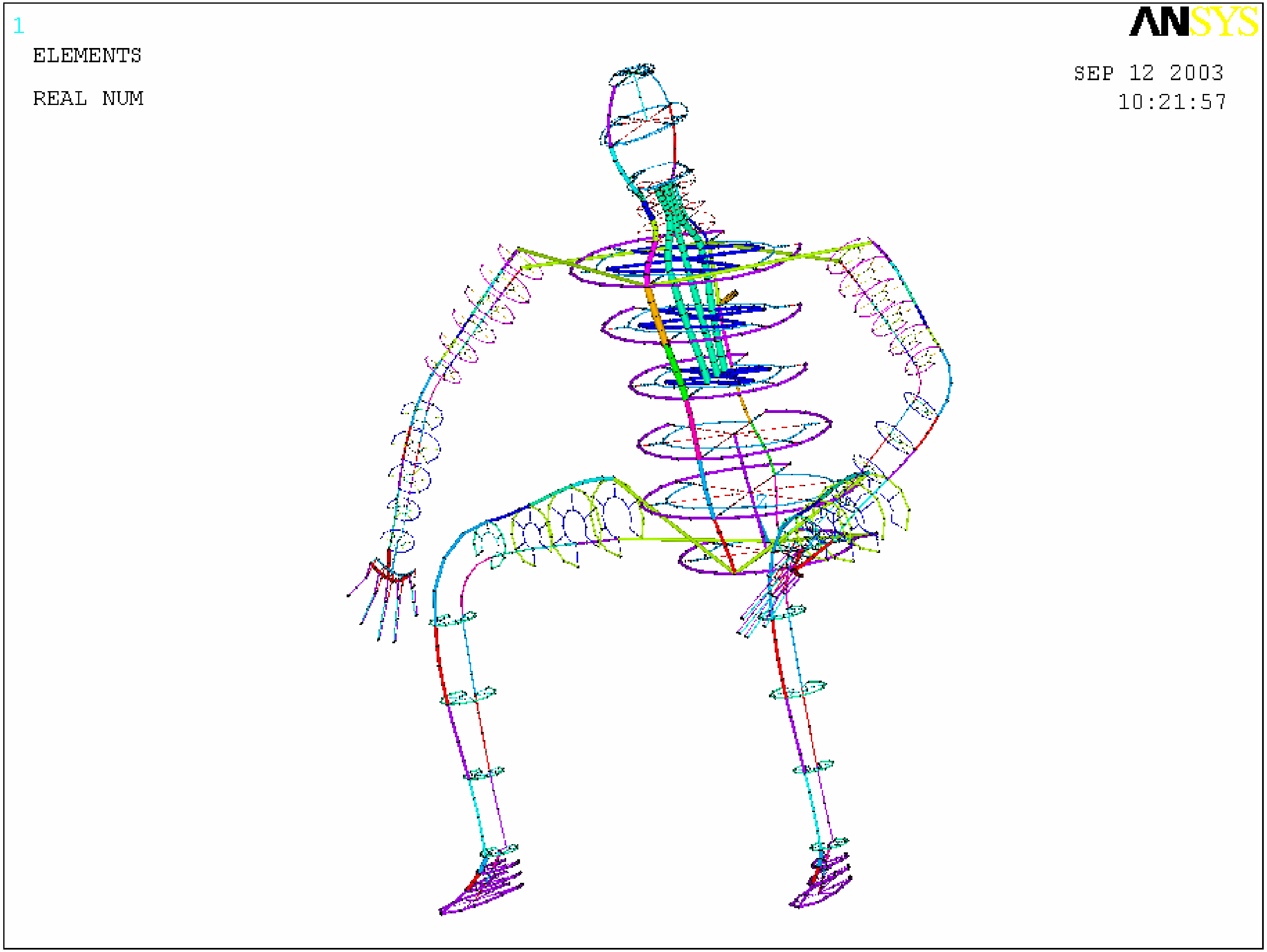
Mesh



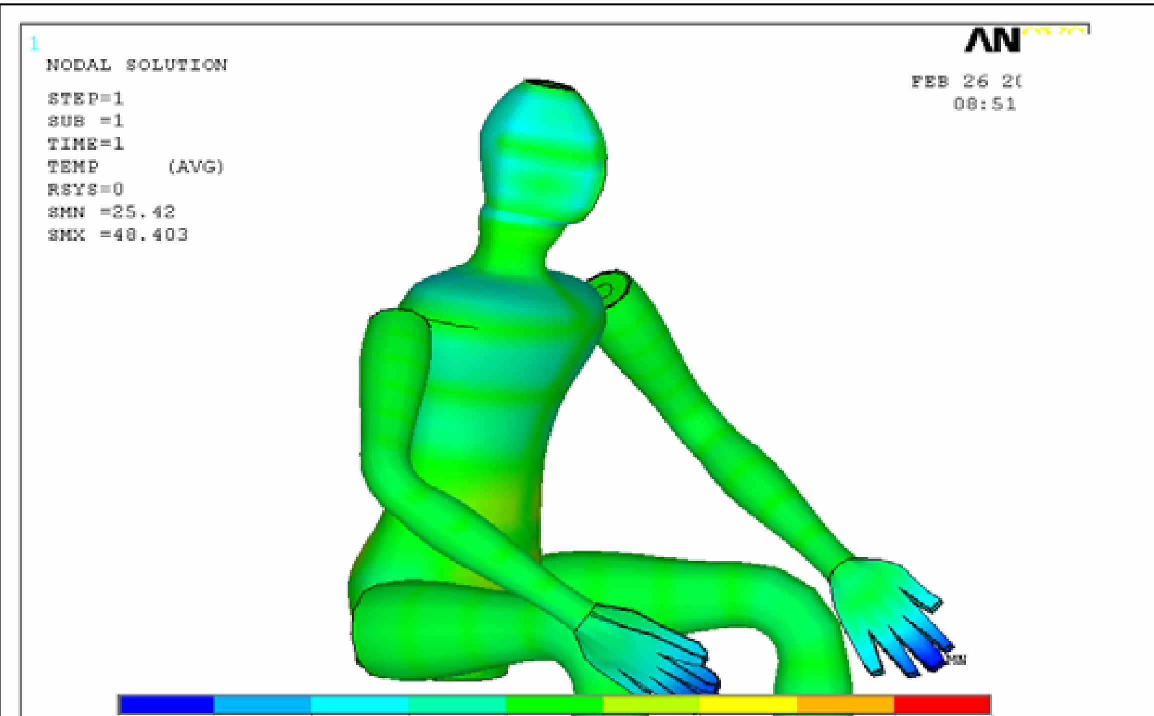
Section View of Upper Right Leg



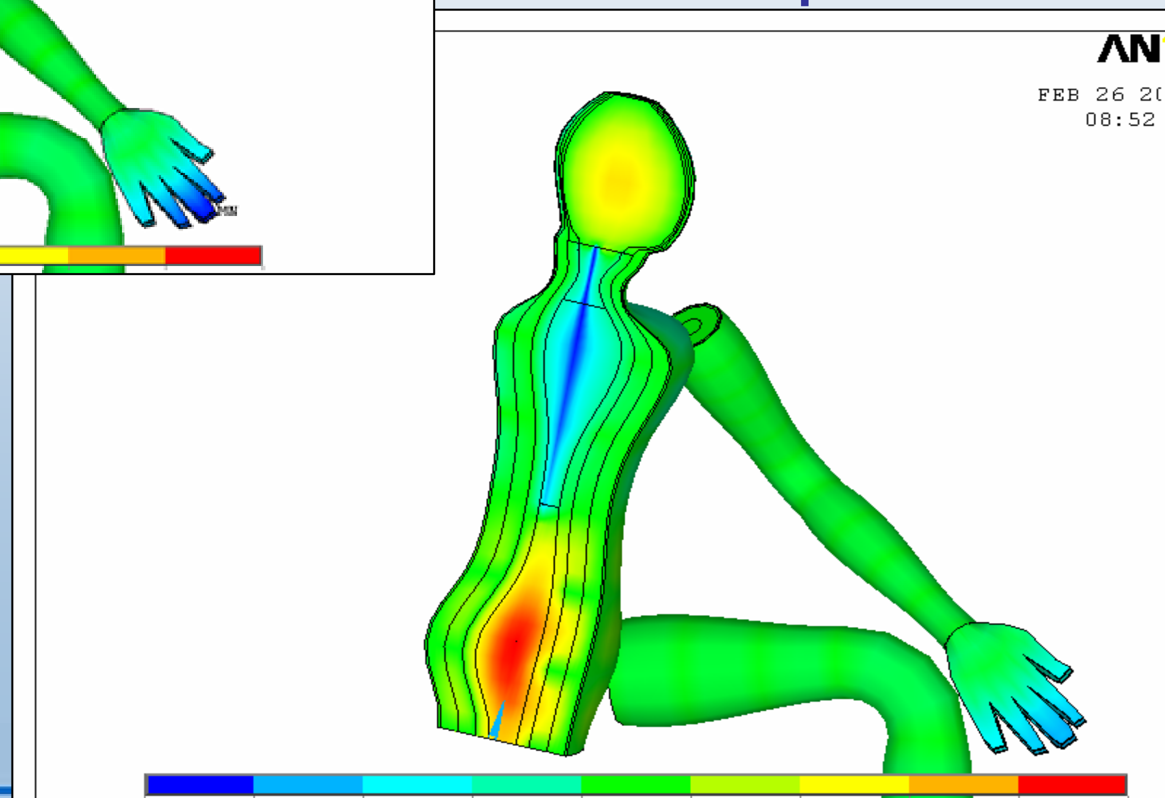
Circulation Network



Body Skin Temperatures

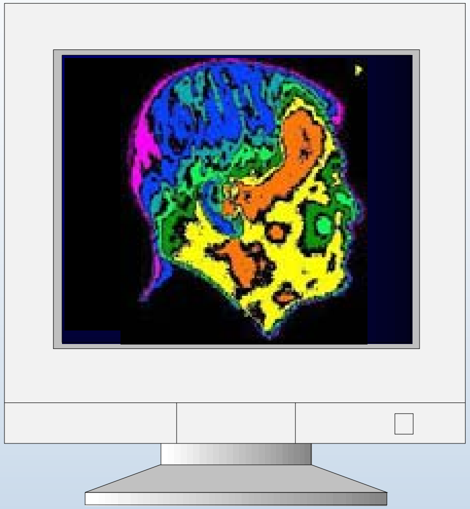


Body Section Temperatures

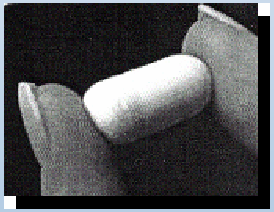


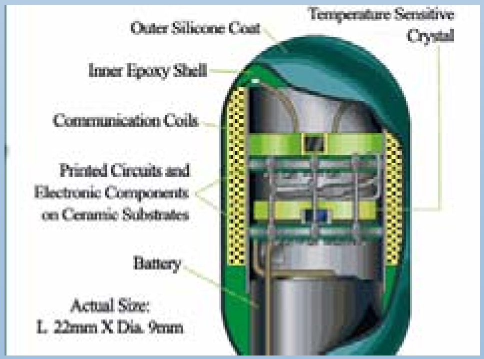
The Human Thermal Comfort Empirical Model

How You Feel Thermally



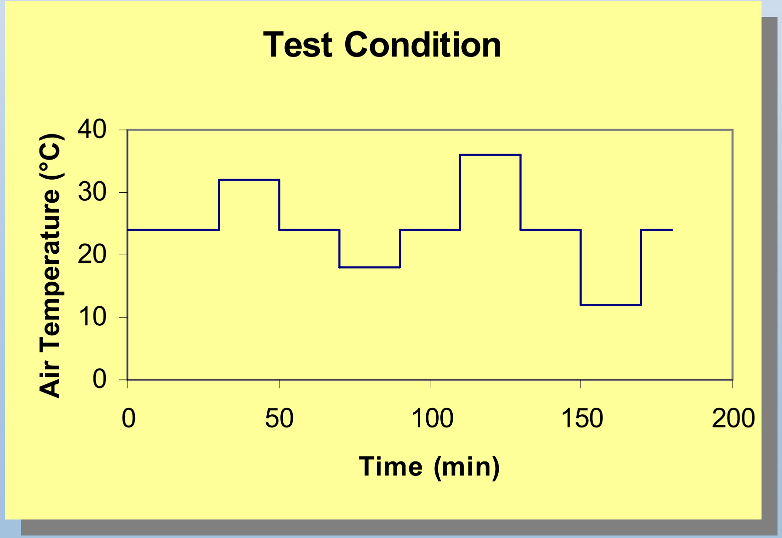
- Determines local thermal sensation
- Determines local and global thermal comfort (thermal perception) from local sensations
- Accounts for non-uniform and transient thermal environment of vehicle cabin



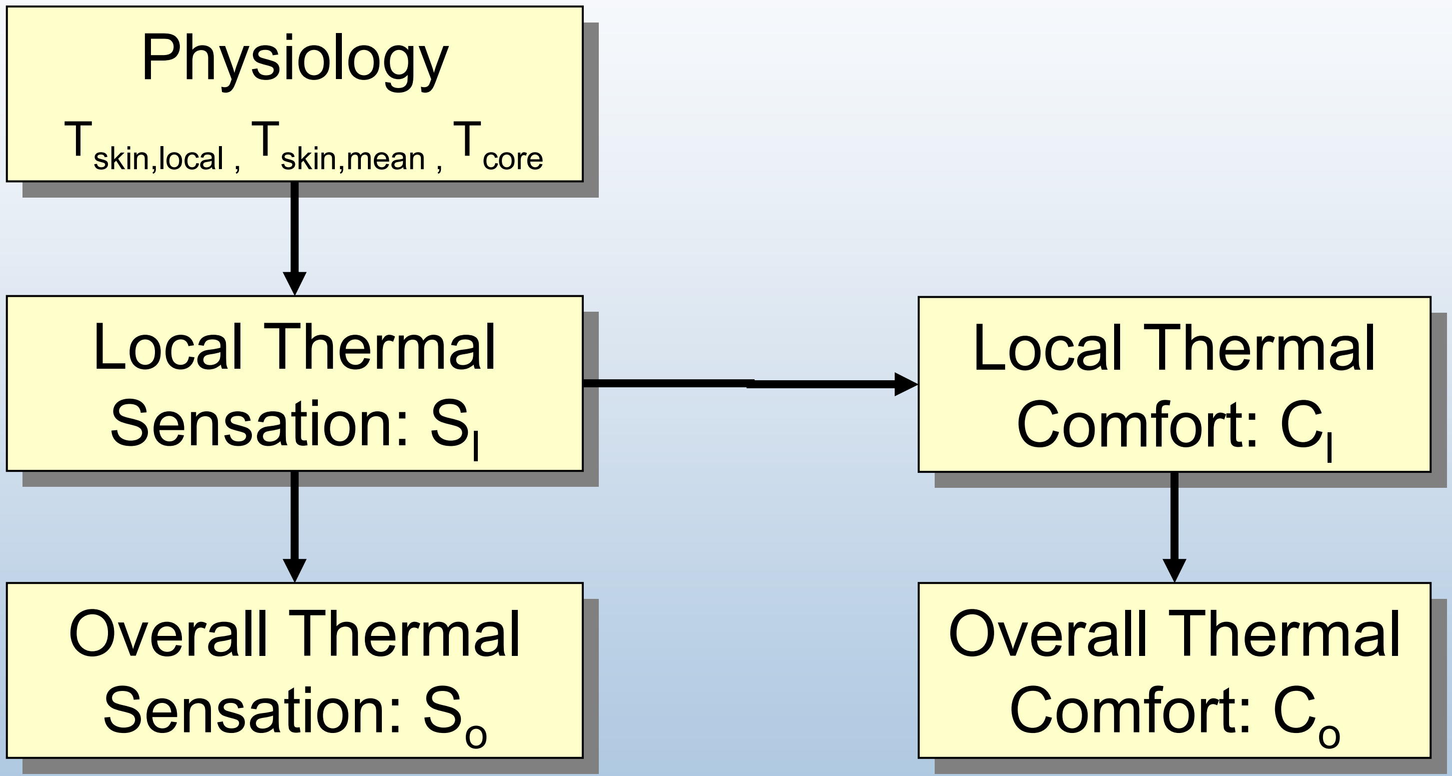


Human Subject Testing

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



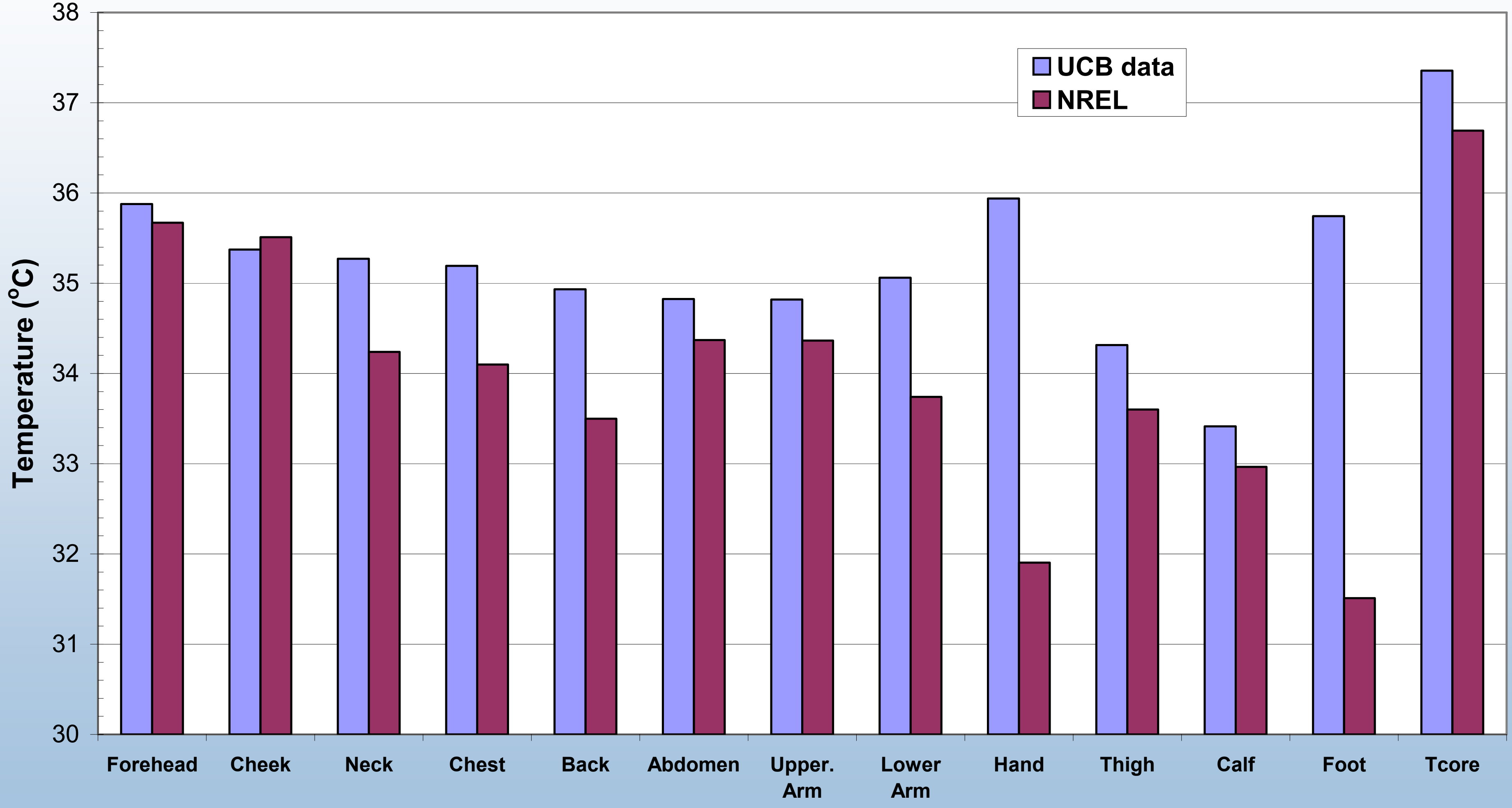
Model Overview



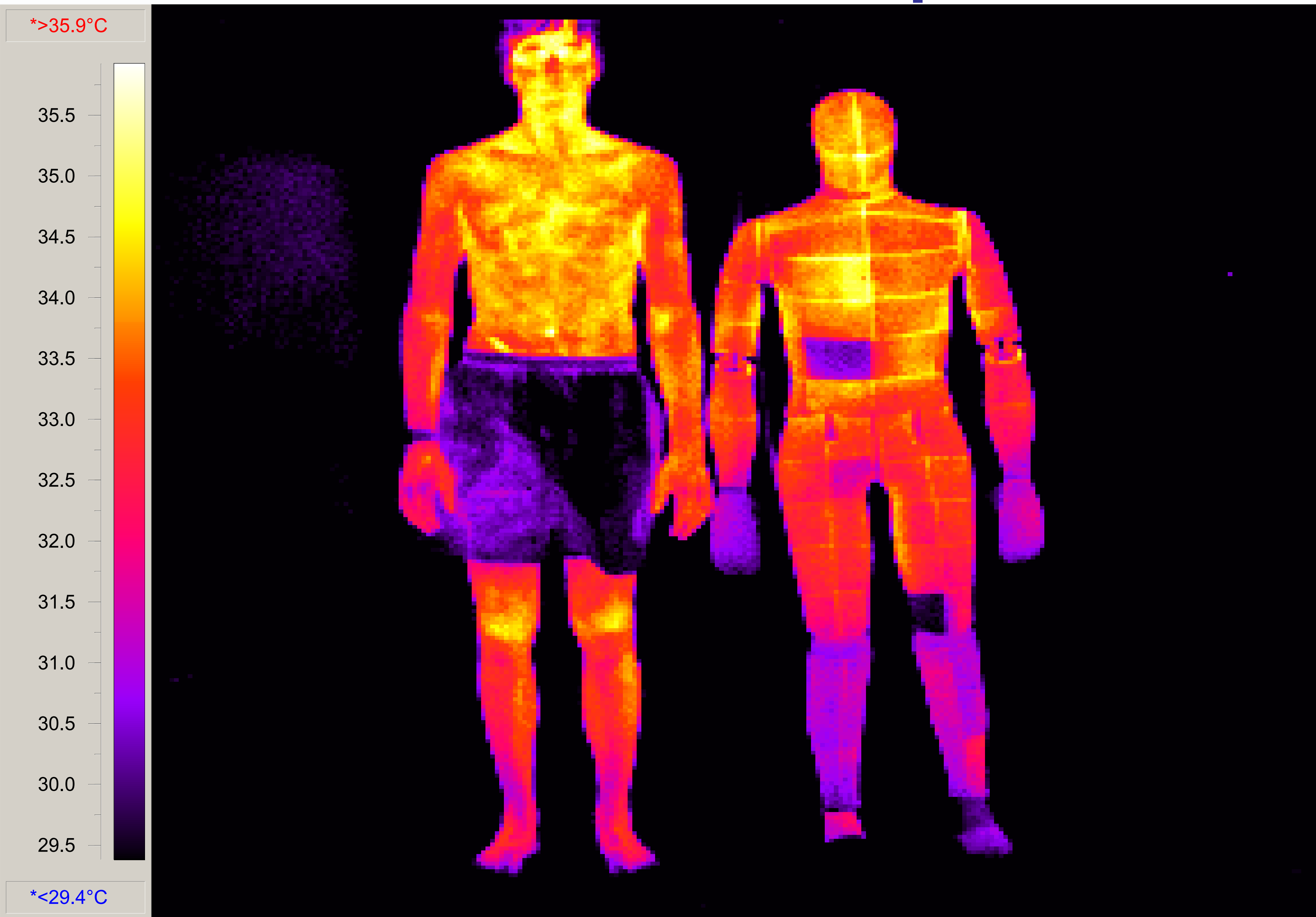
Validation Test – UCB Data

- Compare to skin temperature, sensation, and perception (comfort) data from literature
  - ADAM in leotard
  - Standing
  - Single subject
  - Tair=28.6°C
  - Ref. Zhang (2004)

Skin and Core Temperatures

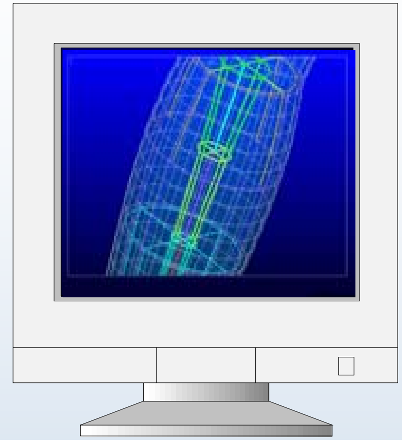


Human & Manikin Comparison



Linking the Physiological Model with a Swift Vehicle Model

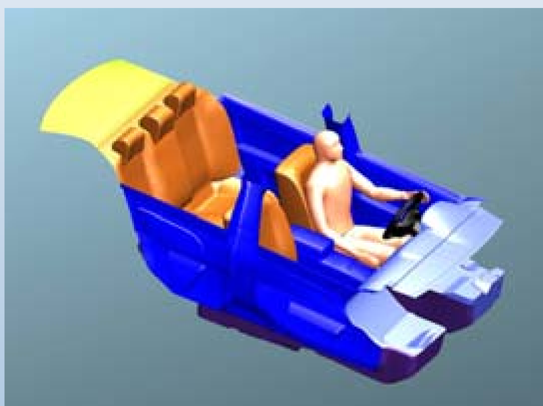
120 surface heat fluxes transmitted



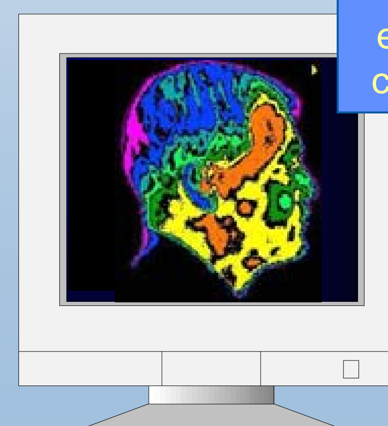
CFD Model Enhancements:

- Sweat evaporation
- Clothing microenvironment

Surface and core temperatures transmitted



Is the environment comfortable?



CFD simulates interaction with environment

Transmits 120 skin temperatures and sweat rates

Conclusions

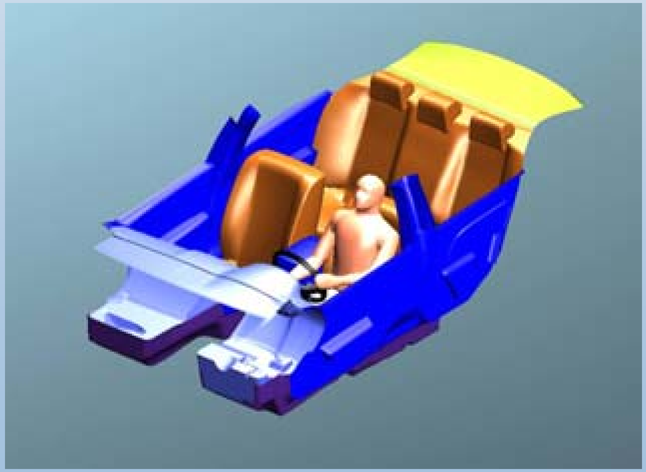
NREL has developed leading-edge cabin thermal management modeling tools in our effort to reduce vehicle fuel use

- Vehicle Solar Load Estimator
- Physiologically model with human-like skin temperature variations
- Thermal comfort model output using local thermal comfort sensitivity coefficients

Future Work

- Continue validation testing
- Use validated manikin/model to assess advanced reduced fuel use HVAC concepts
- DOE is planning the 6th International Manikin & Modeling Meeting (6I3M)
  - April 2006

www.thermalmanikins.org



- Continue collaboration with AVL to assemble an improved cabin thermal management modeling process

Acknowledgments

- U.S. Department of Energy
  - Ed Wall, Office of FreedomCAR and Vehicle Technologies (OFCVT)
  - Lee Slezak, OFCVT
- NREL
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  - Jurgen Wolfahrt (vif)
- University of California, Berkeley
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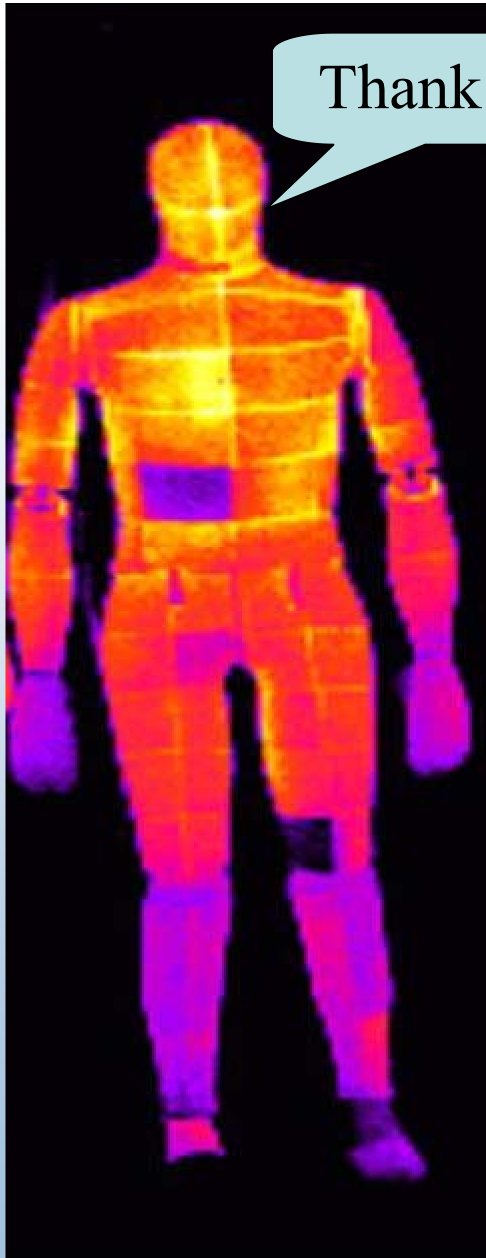
  - Hui Zhang
- Measurement Technology Northwest - Rick Burke



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