01A1024

INTEGRATED MODELING TO PREDICT OCCUPANT THERMAL COMFORT

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Abstract

The two primary functions of a vehicle climate control system are safety through de-icing and de-fogging windows, and occupant thermal comfort. However, vehicle air-conditioning systems can significantly impact fuel economy and tailpipe emissions of conventional and hybrid electric vehicles (HEVs) and reduce electric vehicle (EV) range. In order to meet the new U. S. Supplemental Federal Test Procedure (SFTP), as well as growing concern about vehicle fuel economy, automotive engineers are being challenged to evaluate a multitude of new opportunities for reducing the impact of vehicle air-conditioning systems on fuel economy and tailpipe emissions. Because there isn't enough time to fabricate and test each system, a good modeling approach is essential. However, many models are required to evaluate solar spectral data, glazing spectral properties, cabin temperature and velocity fields, occupant thermal comfort, and vehicle fuel economy and tailpipe emissions. The focus of this paper is to describe an approach used at the U.S. Department of Energy's National Renewable Energy Laboratory to evaluate the largest climate control load, air conditioning, by integrating diverse models.

1.0 Introduction

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

This paper focuses on the largest vehicle auxiliary load – air conditioning. The power necessary to operate a vehicle air-conditioning compressor can be greater than the engine power required to move a mid-sized vehicle at a constant speed of 56 km/h (35 mph). The air-conditioning load can decrease the fuel economy of a conventional vehicle by 10-20%, a mild HEV by up to 35%, and 3L/100-km vehicle by 50%. The United States could save over $6 billion annually if all the light-duty vehicles in the country achieved a modest 0.4-km/L (1-mpg) increase in fuel economy.

It is challenging to reduce the climate control loads in a vehicle without adversely affecting occupant thermal comfort. Occupant thermal comfort modeling is essential to ascertain the acceptability of advanced, energy-efficient thermal comfort systems. Modeling has certain limitations and assumptions, however it can provide a relative comparison between system configurations. A benefit of modeling is to evaluate and select systems prior to fabrication and testing, therefore, there is a great need to rapidly evaluate advanced thermal comfort system designs[1] through modeling. The models involved are inter-disciplinary, including expertise in thermal/fluids, statistics, meteorology, optics and materials, human physiology and psychology, and vehicle systems, leading to creative thinking and innovation.

2.0 Background

In 1998, gasoline use in the United States was about 473 billion liters (125 billion gallons) for on-road use,[2] including gasoline-fueled commercial trucks. Also in 1998, there were about 203.6 million cars and light-duty trucks on the U.S. roads[3] using an average of 2316 liters (612 gallons) of gasoline per vehicle annually. Given certain assumptions[4] about automobile use[5] and air-conditioning use[6], about 235 liters (62 gallons) of gasoline are required annually for operating the air-conditioning system. An additional 12.7 liters (3.4 gallons) per vehicle are used to carry the additional weight of the air-conditioning system[6] leading to about 40 billion liters (10.6 billion gallons) of gasoline annually in the United States for operating vehicle air conditioning.

Until recently, little has motivated U.S. auto makers to find ways to reduce the impact of air conditioning on fuel economy and emissions. But a new emissions regulation, the Supplemental Federal Test Procedure[7] (SFTP), includes operating the air conditioning during part of the emissions testing procedure. The SFTP for vehicles with gross vehicle weight under 2720 kg (6000 lb.) applies to 25% of model year (MY) 2001 vehicles, 50% of MY2002 vehicles, 80% of MY2003 vehicles, and 100% of MY2004 vehicles. Although the SFTP is not used to measure fuel economy, reducing the weight of a mid-sized vehicle's air-conditioning system by 9.1 kg (20 lb.) results in about a 0.04 km/L (0.1 mpg) increase in fuel economy on the current combined city/highway test.

The Clean Air Vehicle Technology Center has measured the effect of the air-conditioning system on fuel economy and tailpipe emissions for a variety of vehicles.[8] Table 1 compares seven vehicles ('95 Voyager, '97 Taurus, '95 Civic, '95 F-150, '97 Camry, '96 Camaro, and '95 Skylark) with the air-conditioning system on and with the air-conditioning system off over the SC03 drive cycle.

Table 1. Measured Impacts of Air-Conditioning System Operation

	Increase with Air Conditioning On
CO (g/km)	+71%
NO_x (g/km)	+81%
NMHC (g/km)	+30%
Fuel Economy (km/L or mpg)	-22%

On average, the air-conditioning system increased CO emissions by 0.42 g/km (0.675 g/mile) and NO_x emissions by 0.053 g/km (0.085 g/mile). If we assume that vehicles are driven 19,300 km (12,000 miles) annually, the air-conditioning system operates 45% of the time,[6] the test results are representative of light duty vehicles, and 80% of the vehicle fleet have working air-conditioning systems, then vehicle air-conditioning use in the United States increases CO emissions by 594,000 metric tons (655,000 tons) and NO_x emissions by 74,000 metric tons (82,000 tons).

3.0 Integrated Modeling Approach

Evaluating occupant thermal comfort is complex. For example, a key element for determining occupant comfort is the amount of thermal radiation on the occupant's face, which can be from direct solar radiation as well as re-radiation from an absorbing glazing. Air-conditioning systems compensate for this thermal load by forcing air across the face to reduce the skin temperature. Predicting occupant thermal comfort requires an understanding of the solar radiation transmitted through the glazing, thermal re-radiation from the glazing to the face due to absorbed solar radiation, the air temperature and velocity passing the face from the air-conditioning system (which vary with engine speed and vehicle speed), and the surface temperatures of the cabin that also re-radiate thermal energy to the face. Additionally, the transient air-conditioning load on the engine affects fuel use and tailpipe emissions.

There is no single comprehensive model that incorporates every variable needed to predict occupant thermal comfort because different equations and different solution techniques are required to model different factors leading to the prediction of thermal comfort. In our integrated modeling, the cabin thermal/fluid model uses finite volume techniques, the transient air-conditioning model uses a lumped capacitance solution, the solar radiation modeling uses statistical analysis, the vehicle simulation depends on component maps, the glazing model is based on fundamental physics including index of refraction, and the thermal comfort model uses finite element techniques. It is critical to understand the assumptions and limitations of each model as errors can compound as results are passed between models. Figure 1 shows the various diverse models needed to predict specific behavior for an aspect of the problem.

4.0 Model Descriptions

4.1 CAD Model

Description

The first step in the analysis process is to define the vehicle geometry. Typically this information is in the form of detailed CAD data. So, a parametric CAD program, such as Pro/E, is used to create a simplified representation of the passenger compartment. Digital occupants can be added to the geometry before the passenger compartment is meshed.

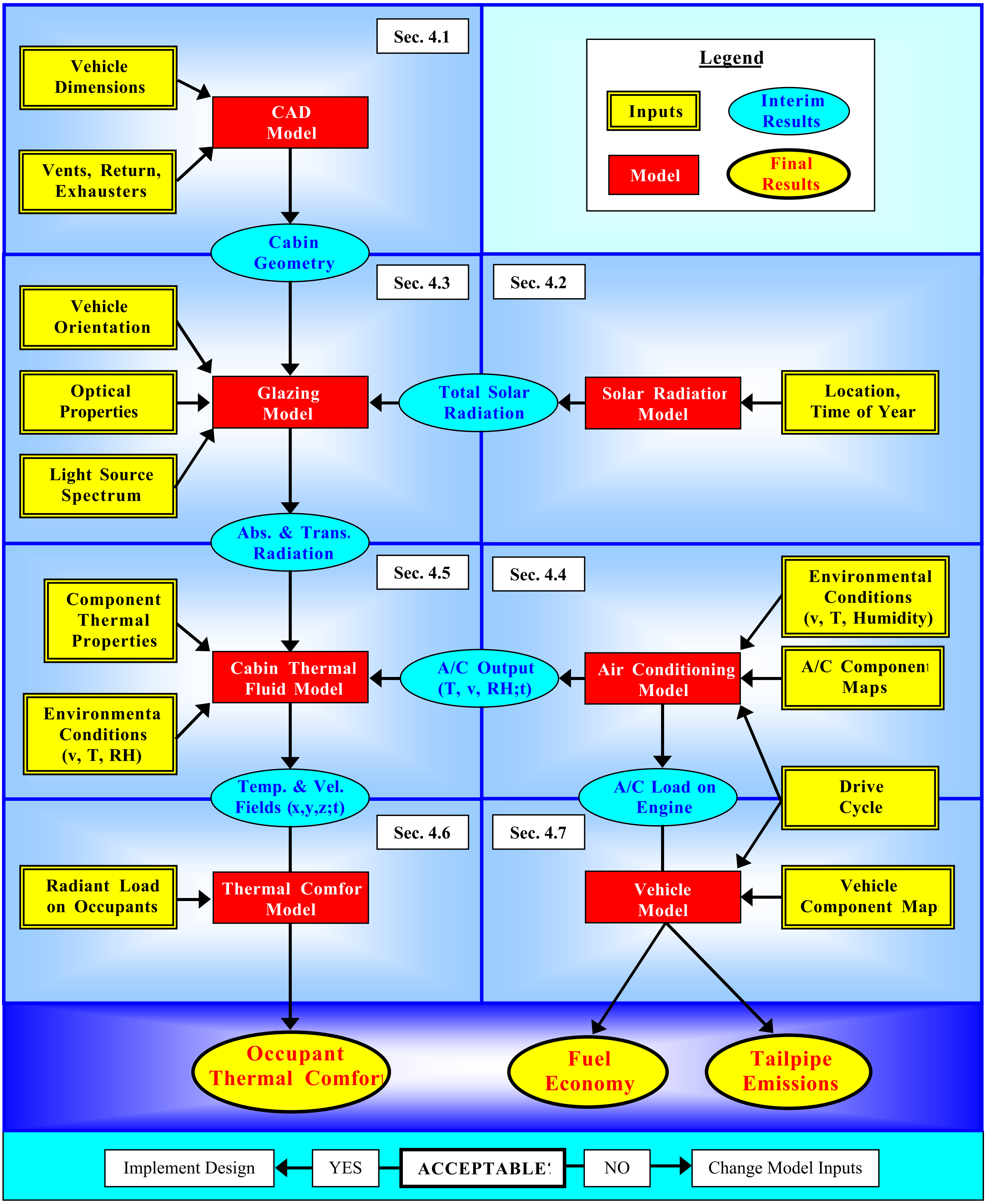


Figure 1. FLOWCHART – Integrated Modeling of Thermal Comfort Systems

Inputs

The CAD data can be in the form of native files or translation files such as STEP or IGES. These CAD surfaces are used to morph a generic parametric vehicle or to create a simplified one-time Pro/E model to approximate the cabin geometry. The vents, recirculation inlet, and extracters are defined, as are the CAD occupant models, such as shown in Figure 2.

Results

The passenger compartment interior and occupants are meshed by using a 3rd party mesh generator, a computational fluid dynamics (CFD) preprocessor, or the Pro/E mesh generator. The mesh, an example of which is shown in Figure 3, has an exact correspondence to the CAD geometry; including open areas and walls and is comprised computational fluid volumes, boundaries, and blocked elements.

Limitations and Assumptions

The results are affected by the choices made, such as how much detail of the cabin interior to model. Users must decide if computational time should be expended modeling the conduction heat transfer inside the headliner, door cavities, seats, instrument panel, etc. or to define the passenger compartment at the inner surfaces. Users must also decide if they should model the air flow external to the cabin or simulate the external heat transfer with boundary conditions. Key limitations of this model include grid resolution, the time step for transient solutions, the turbulence model, and the convergence criteria. A fine mesh may be needed around turbulent jets while a coarser mesh may be acceptable in areas of low air velocity.

Validation

The quality of the geometry is checked by a visual comparison of the Pro/E model and mesh with the original vehicle CAD data.

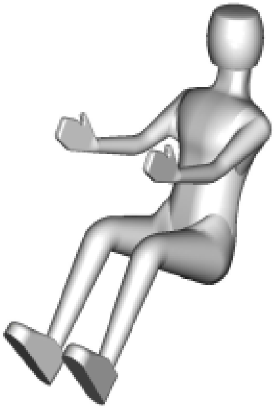


Figure 2. Digital Occupant

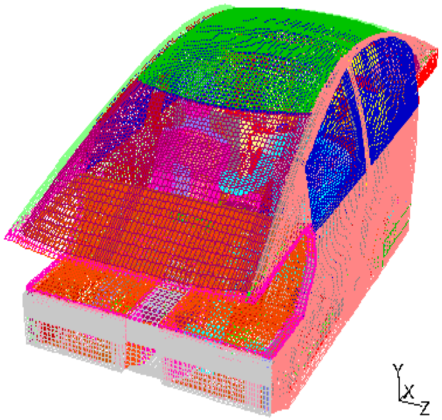


Figure 3. Sample Mesh

4.2 Solar Radiation Model

Description

The solar radiation model calculates the solar spectral irradiance incident on the vehicle as a function of location, weather, and vehicle orientation. The spectral irradiance is calculated over a range of 300-2500 nm at 5 nm intervals using the model SEDES developed by Nann and Riordan[9].

Inputs

Model inputs include the sun's position as described by its zenith angle and azimuth angle, atmospheric ozone, dew point temperature, pressure, ground reflectivity, direct normal solar radiation, diffuse horizontal solar radiation, and the vehicle surface and glazing orientations as described by angles of azimuth heading and tilt from horizontal.

Model input data are available for 239 locations in the United States and its territories in the form of weather and sun position data extracted or derived from typical meteorological years (TMY).[10] A TMY is a data set of hourly values of solar radiation and meteorological elements for a one-year period judged to be typical for the particular location. To meet users' needs, data from any hour of the day from 239 locations may be used as input to the spectral irradiance model.

Results

Figure 4 compares modeled spectra for a surface directly facing the sun for Phoenix, Arizona on July 13, 1989 with the ASTM E 892 standard spectra. In the figure, air mass values represent equivalent path lengths through the atmosphere, with a value of one corresponding to sea level and the sun directly overhead. Modeled values show both greater and lesser values than the ASTM E-892, with a noticeable shift in the relative spectral distribution as the air mass increases.

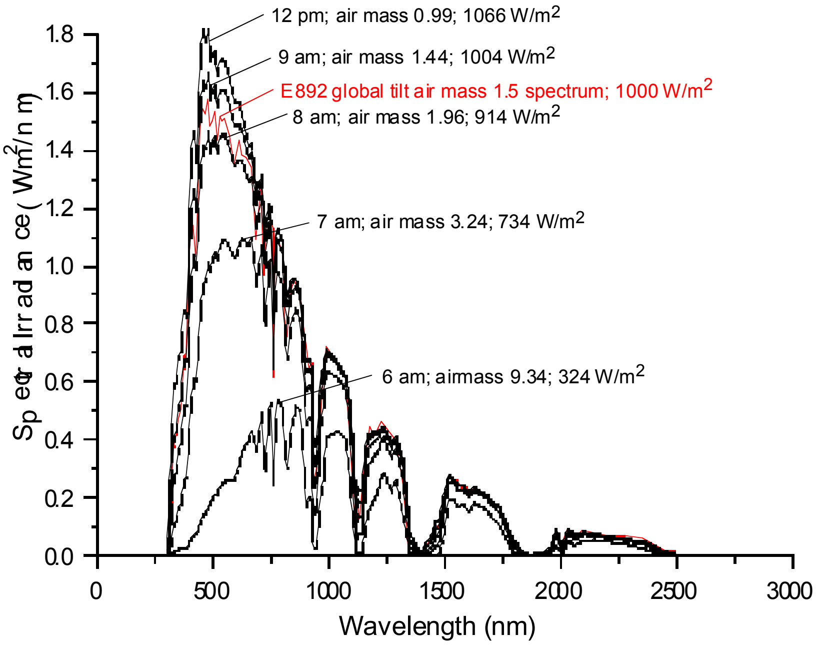


Figure 4.
Modeled spectra
for clear skies for
Phoenix, Arizona
for July 13, 1989

4.3 Glazing Optical/Thermal Model

Description

The glazing model is a GUI-driven, NREL-developed model, programmed in the MATLAB environment. The model calculates radiation transmitted, absorbed, and reflected by glazings as a function of the optical properties of the glazing, glazing location, vehicle geometry, vehicle orientation, time, and radiation source. The model currently accounts for the angular dependence of the optical properties for glass. The program can also display glazing properties and comparisons of different glazings under the same solar load and vehicle orientation as function of time.

Inputs

Glazing Location/Properties: users can select different glazing types for each vehicle window. The glazings are typically commercially available and manufacturers supply the optical properties (reflectance, transmittance, and absorptance) as a function of wavelength. Additionally, users can easily evaluate the impact of proprietary and theoretical glazings by using data in a simple columnar format.

Radiation Source/Load: users can select to use radiation data supplied by the Solar Radiation Model or one of several other radiation sources including ASTM E-891[11] (Direct Normal Solar Radiation), ASTM E-892[11] (Direct Normal Solar Radiation plus Diffuse Solar Radiation), filtered xenon arc lamp, or a metal halide lamp. The filtered xenon arc lamp and metal halide lamp irradiances are adjusted so that their integrated intensities equal that of ASTM E-892.

Vehicle Geometry: several default vehicles are available for evaluation or a user can create their own vehicle. A ‘vehicle geometry’ consists of the average angle of the glazing from horizontal and the area of that glazing as a function of location. Average roof width and length information is also required to account for shading effects.

Vehicle Orientation: the model vehicle may face from east through south through west (90° to 270° from north). This is because the greatest solar load transmitted into the cabin will occur within this range of vehicle direction.

Time: users can evaluate glazing loads either for single points in time or as a function of time.

Results

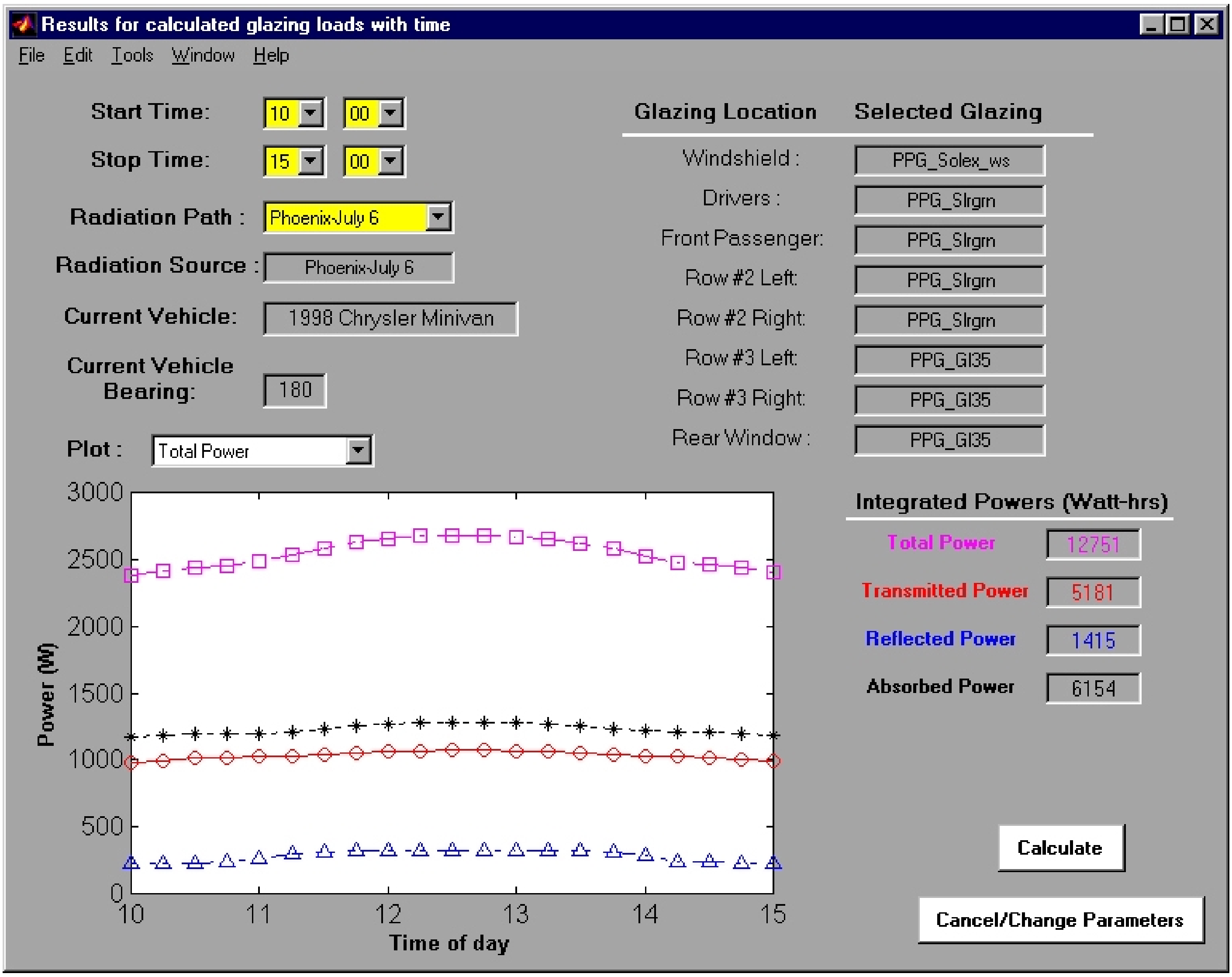
A sample output screen from the evaluation of a 1998 Chrysler Minivan as a function of time using radiation supplied from the 99th percentile day in Phoenix, AZ is shown in Figure 5. The user can view either the vehicle glazing total radiation load (transmitted and absorbed radiation) or the loads by each glazing location.

Limitations and Assumptions

All glazing surfaces are assumed to be flat, have a constant thickness, uniform properties, without window hardware or shaded borders, and are constructed of combinations of rectangles and triangles. The error introduced by this approximation is believed to be small. At low solar angles, when direct normal radiation can pass through the cabin from one window and out of an opposite or adjacent window, the model takes any negative solar flux through the glazing surface and sets it to zero. The calculation of the optical properties of each individual glazing as a function of wavelength and angle uses a single-pane approximation for glass. The approximations should introduce only small errors for glass. For thin film reflective glazings, the errors introduced by the approximations are unknown at this time.

Validation

This model has not been validated yet, but comparisons of model results and outdoor test data show good correlation.



Start Time: 10 00

Stop Time: 15 00

Radiation Path : Phoenix-July 6

Radiation Source : Phoenix-July 6

Current Vehicle: 1998 Chrysler Minivan

Current Vehicle Bearing: 180

Plot : Total Power

Glazing Location	Selected Glazing
Windshield :	PPG_Solex_ws
Drivers :	PPG_Slrgrn
Front Passenger:	PPG_Slrgrn
Row #2 Left:	PPG_Slrgrn
Row #2 Right:	PPG_Slrgrn
Row #3 Left:	PPG_GI35
Row #3 Right:	PPG_GI35
Rear Window :	PPG_GI35

Integrated Powers (Watt-hrs)	
Total Power	12751
Transmitted Power	5181
Reflected Power	1415
Absorbed Power	6154

Figure 5. Sample of Glazing Model Results

4.4 Transient Air-Conditioning Model

Description

In order to understand transient air-conditioning system performance and its impact on vehicle fuel consumption and emissions, NREL is developing a transient air-conditioning model within the SINDA/FLUINT analysis software environment and integrating it with the ADVISOR vehicle systems analysis software. The transient, one-dimensional, thermal-hydraulic model was developed using a nominal representative air-conditioning system that was identified in discussions with NREL's automotive industry partners. This model captures all the relevant physics of transient air-conditioning system performance, including two-phase flow effects in the evaporator and condenser, system mass effects, air side heat transfer on the condenser/evaporator, vehicle speed effects, temperature-dependent properties, and integration with a simplified cabin thermal model. This model can predict typical transient air-conditioning compressor power requirements, system pressures and temperatures, system mass flow rates, and two-phase/single-phase flow conditions throughout the air-conditioning system flow circuit.

The simplified cabin thermal model predicts cabin and panel outlet temperatures during transient cool-down periods and during steady state operational periods. The combined model predicts air-conditioning system and cabin thermal conditions during various drive cycles so that transient performance and optimization results can be tailored to each unique set of driving conditions.

With its current integration to a simplified cabin model and ultimate integration to the cabin thermal/fluid model discussed in Section 4.5, the transient air-conditioning system model thereby provides the system link that connects the cabin thermal comfort requirements with vehicle fuel consumption and tailpipe emissions.

Inputs

Model inputs include compressor performance characteristics; condenser and evaporator tube diameters and lengths, overall dimensions, and air-side design parameters; transport and suction line diameters and lengths; ambient temperature; solar thermal loads; compressor pulley ratio; and orifice tube diameter.

Figure 6 shows a schematic diagram of the transient SINDA/FLUINT model of the nominal representative air-conditioning system. The model consists of a nominal compressor, condenser design (HX 3000), orifice tube expansion device, and evaporator design (HX 6000). The model includes thermal regeneration between the orifice tube and suction line. The compressor is characterized by representative compressor displacement, isentropic efficiency, and volumetric efficiency. The condenser is a serpentine-type heat exchanger that has 6 passes, 10 parallel channels, and weighs 5 kg (11 lb.). The evaporator is also a serpentine-type heat exchanger that has 12 passes, a tube diameter of 1.6 mm (0.0625 in.), and weighs 3 kg (6.6 lb.). The heat exchangers are typical of designs shown in Kargilis.[12]

SINDA/FLUINT can rigorously analyze the various two-phase flow regimes, such as bubbly flow, slug flow, annular flow, as well as the heat transfer and pressure drop conditions in both the evaporator and condenser. It contains built-in heat transfer coefficient and friction factor correlations that are used to automatically evaluate heat transfer, pressure drop, and flow quality conditions within the air-conditioning system components during its system computations. SINDA/FLUINT also has built-in correlations for determining transitions between the different two-phase flow regimes in the condenser and evaporator, and can easily

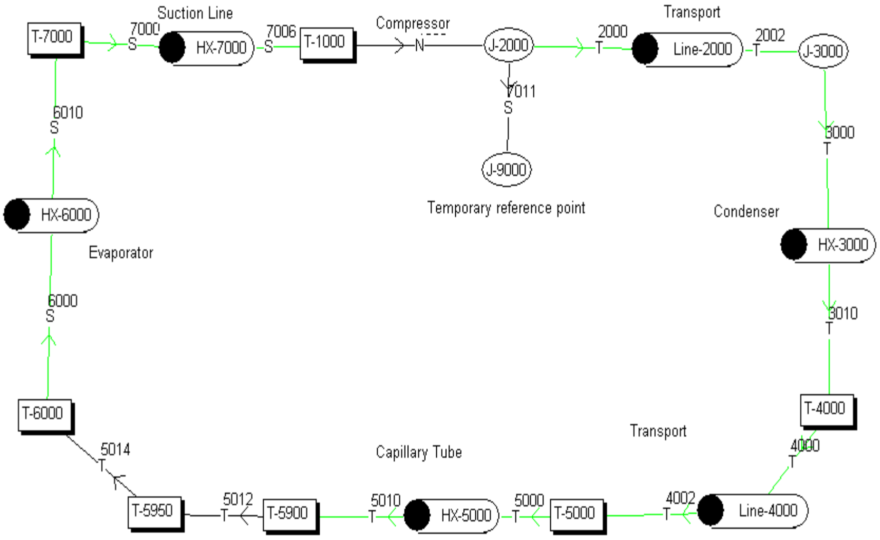


Figure 6. Schematic of SINDA/FLUINT Transient Air Conditioning System Model

analyze slip flow conditions that may occur during two-phase flow in these components. Hendricks[13,14] presents flow quality and flow regime results and discusses the influence of system components on flow quality and flow regimes in the condenser and evaporator.

The transport lines between the compressor and condenser and between the condenser and the expansion device, shown in Figure 6, are critical components in the air-conditioning system design. Their diameter and length can impact system performance. Compressor characteristics and orifice diameter are other key system parameters that impact system performance. Hendricks discusses how these component designs are important to optimizing system coefficient-of-performance (COP) and interdependent on other important system components, particularly the condenser.

Results

Figure 7 shows a typical transient compressor power prediction from the transient air-conditioning/cabin thermal model during the 10-minute SC03 drive cycle after extreme hot soak conditions to an air temperature of 75°C (167°F). The compressor power has been normalized by the average compressor power over the SC03 drive cycle, but the variation in compressor power is quite substantial. Figure 8 displays the corresponding typical transient system pressure prediction from the transient air-conditioning model during the same 10-minute SC03 drive cycle after the same extreme hot soak conditions to 75°C (167°F).

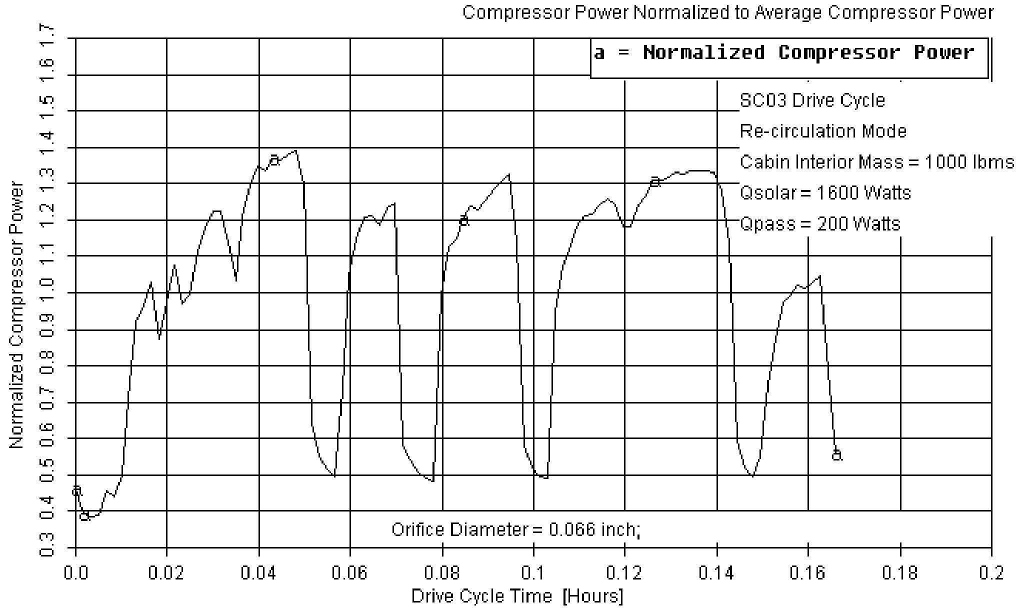


Figure 7.
Typical Compressor Power Prediction During SC03 Drive Cycle After Hot Soak Conditions to 75°C (167°F)

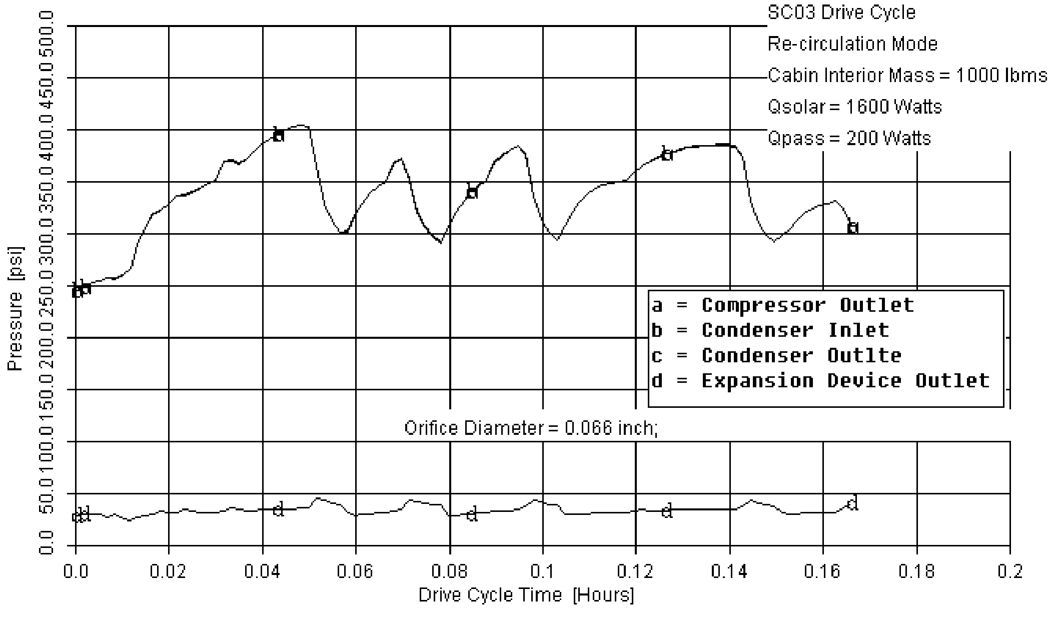


Figure 8.
Typical System Pressure Predictions During SC03 Drive Cycle After Hot Soak Conditions to 75°C (167°F)

Limitations and Assumptions

The transient air-conditioning model in its current state of development makes several assumptions including:

- Internal, one-dimensional flow throughout system components
- Low-speed, viscous flow throughout the flow loop
- No lubricants included
- R-134a fluid properties
- Orifice tube system (TXV system versions are planned in the future)
- REFPROP Version 6 fluid property data base

Validation

The model is still being developed and improved. We are working with industry to identify model validation opportunities and system and vehicle level test configurations.

4.5 Cabin Thermal/Fluid Model

Description

The cabin thermal/fluid model is a finite-volume model that uses the CAD geometry, solar radiation loads from the solar radiation and glazing models, and air temperatures and flow rates from the air-conditioning model, to predict the temperature and air velocity at every location in the mesh. The peak soak temperature can be predicted in a steady-state mode with a constant sun position with the CFD model solving natural convection flows in the cabin. Transient cabin temperatures can be predicted with a moving sun. The model simulates forced convection when predicting cabin conditions with the air-conditioning system operating, such as during a transient cool-down simulation.

Inputs

The transmitted and absorbed solar radiation data for each glazing come from the glazing model. Information about the panel vent airflow rates, humidity, and temperatures are passed to the CFD from the transient air-conditioning model. The thermophysical and radiative properties (conductivity, specific heat, density, emissivity, etc.) are required for each material. The external boundary conditions such as heat transfer coefficient, heat flux, ambient air temperature, solar load are defined. The boundary condition for the air exiting the passenger compartment is also defined. Additionally, uniform heat generation of the occupants is included in the model.

Results

The flow field inside the passenger compartment is predicted as are the surface temperatures and temperature and humidity of the air. An example of the predicted surface temperatures in a sedan is shown in figure 9. If the air-conditioning system is in 100% recirculation mode, the air temperature and humidity are passed back into the transient air-conditioning model. The air temperature, velocity and radiant load are sent to the thermal comfort model in order to assess the comfort of the passengers.

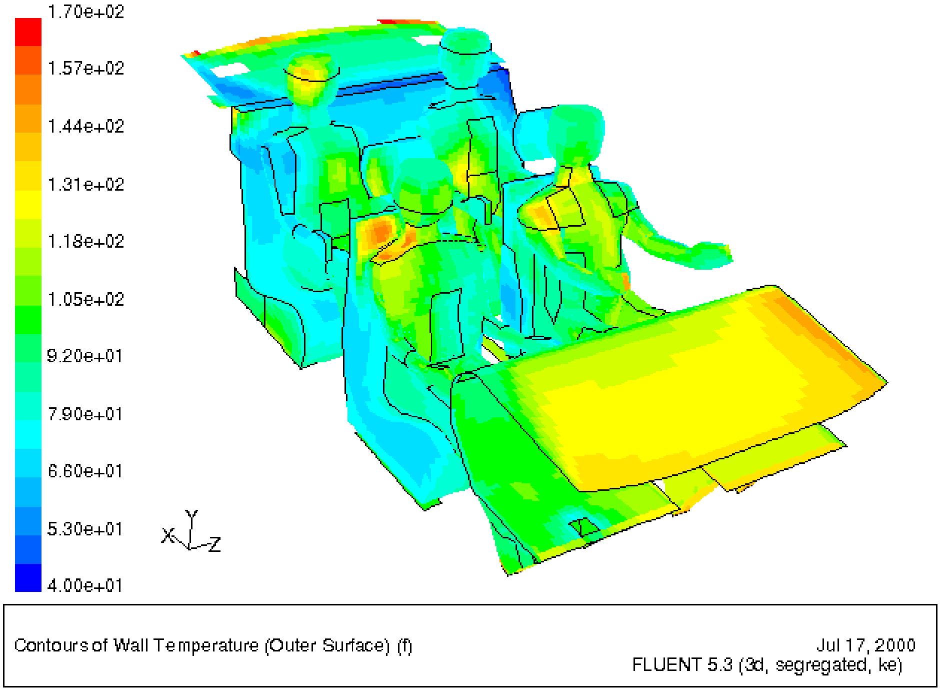


Figure 9.
Sample Cabin
Temperature Field

Limitations and Assumptions

The human thermal comfort model is used to calculate occupant skin temperatures needed to predict thermal comfort. The predicted surface temperatures of the occupants from the cabin thermal/fluid model do not include actual occupant physiology. The occupants are included in the CFD model only to estimate their obstruction in the flow field and heat generation into the passenger compartment. Leakage into the passenger compartment is not generally included unless it can be quantified. Decisions about grid resolution, turbulence model, time step increment, cabin component thermal properties, time-dependent boundary conditions, and cabin geometry detail will all affect the final result. Likewise, assumptions made in the solar radiation model, the glazing model, and the air-conditioning model will impact the temperature and velocity fields.

Validation

NREL has been involved in numerous vehicle test programs where soak and cool-down data were measured. The model is being validated with the test data.

4.6 Occupant Thermal Comfort Model

Two models are used to predict occupant thermal comfort. The first model predicts the physiological response of the occupant to environmental and metabolic conditions. The second model predicts the occupant's perception of the thermal environment based upon their physiological response to the thermal environment.

4.6.1 Finite Element Human Thermal Physiological Model

Description

The objective of this model is to predict the human thermal physiological response to a transient asymmetric environment. The model is a three dimensional finite element simulation of human thermal systems. It simulates the passive response of the bone, muscle, fat, and skin layers, and the active response of the circulation system, respiratory system, and thermoregulatory system. The circulation system consists of a right-angled network of pipes in each body segment with temperature dependent pipe diameters to simulate vasoconstriction and dilation. The thermoregulatory system contains the latest measurements of metabolic, shivering, and sweating responses specific to each body segment. Clothing heat transfer is also modeled. Clothing layers can be added and the transport of heat and moisture is calculated. An extensive library of clothing heat transport properties is included. An original version of the model written in Fortran is being updated using ANSYS allowing some significant improvements.[15] The human mesh will be scalable allowing the simulation of any human height, weight, fat content, and sex. The model will also predict the response of populations across the characteristics. The human geometry is also being upgraded from simple circular cylinders to a real three-dimensional human body. A schematic of the original finite element model of the human model is found in Figure 10.

Inputs

The inputs to the model are the transient air temperatures next to the skin surface, or solid contact temperatures, surface air velocities, and radiation at each body surface boundary element. The type of physical activity, which translates to metabolic rate, is also required.

Results

The outputs of the model are the transient temperatures at each element internally and externally throughout the body. Heat loss to the environment is also computed. Physiological information such as blood flows, sweating, and shivering is also calculated.

Limitations and Assumptions

The primary limitations of the model involve measurements of the thermoregulatory responses in human subjects. Few measurements have been made of transient and local body area responses. Data from current experiments are used to update the models. There is also a large uncertainty in the blood perfusion rates in each body segment. New data from measurements using laser-based sensors will improve the models. Real clothing undulations and creases are not accounted for in the model. Clothing fiber wicking is also not modeled.

Validation

The original Fortran version of the model has been validated. The model was within 1°C for the average skin temperature, and within 10% for overall body heat loss. The new version of the model will be validated when it becomes available.

4.6.2 Human Thermal Comfort Psychological Model

Description

The objective of this model is to convert the internal body and skin temperatures predicted by the physiological model into psychological feelings of thermal comfort. The psychological model will simulate the mental perceptions of both local and global thermal comfort while subjected to transient and asymmetric thermal fields. Human subject tests are being conducted to determine the thermal comfort sensitivity of each body segment. An apparatus has been developed to locally heat/cool each body segment and control the transient output. The sensitivities of each body segment will then be combined to predict global comfort. The human subject tests will guide the development of the combination algorithms. The psychological model will have a physiological basis using the hot and cold thermal receptors of the human body. The firing rates of these receptors as a function of transient temperature have been measured and modeled.[16,17,18] Thermal comfort will then be based on summations of firing rates. Modeling the actual input and nervous systems of the body will provide a more accurate prediction of thermal comfort, and allow for improvement of the model in the future as new data becomes available.

Inputs

The inputs to the model are the transient temperatures internally and on the skin of the body. The specific body type and physiological characteristics are input into the physiological model.

Results

The results of the model are the transient perceptions of local and global thermal comfort.

Limitations and Assumptions

The model is limited to a spatial resolution of the 16 body segments. The first version of the model will be based on the responses of only 20 human subjects, due to the large number of tests for each body segment. The measurements of receptor firing rates have currently only been conducted on chimpanzees.[18] Only a few measurements of the transient response of receptors have been made, and more data is needed for an accurate simulation. The first version of model will only acquire the thermal comfort response from skin surface heating/cooling. Internal conditioning of the body or core temperature control will be performed in the future to incorporate that effect.

Validation

A set of human subject tests will also be conducted in a climate-controlled wind tunnel that will allow validation of the model in a realistic automobile environment with transient cabin climate conditions and a variety of controlled external environment conditions.

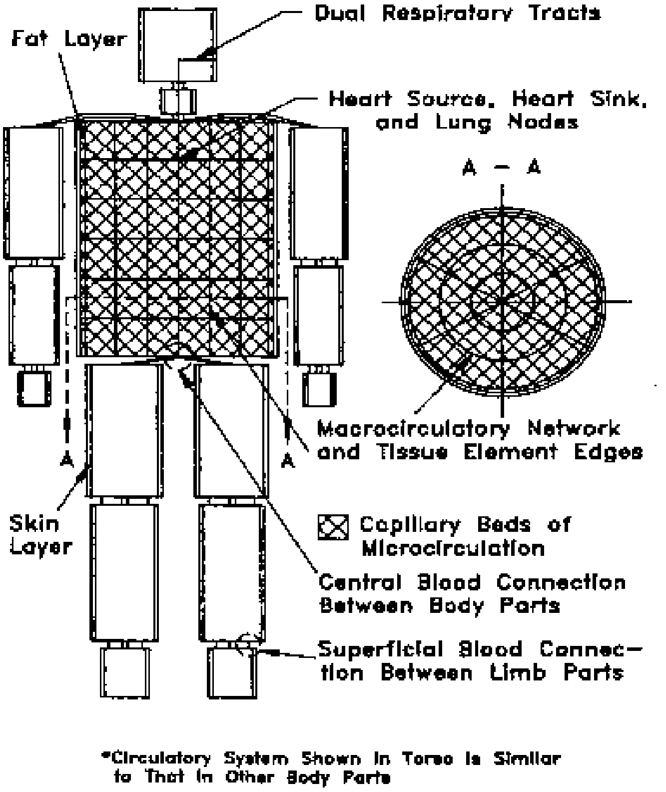


Figure 10.
Human Thermal Model
Finite Element Mesh[15]

4.7 ADVISOR Vehicle Simulation Model

Description

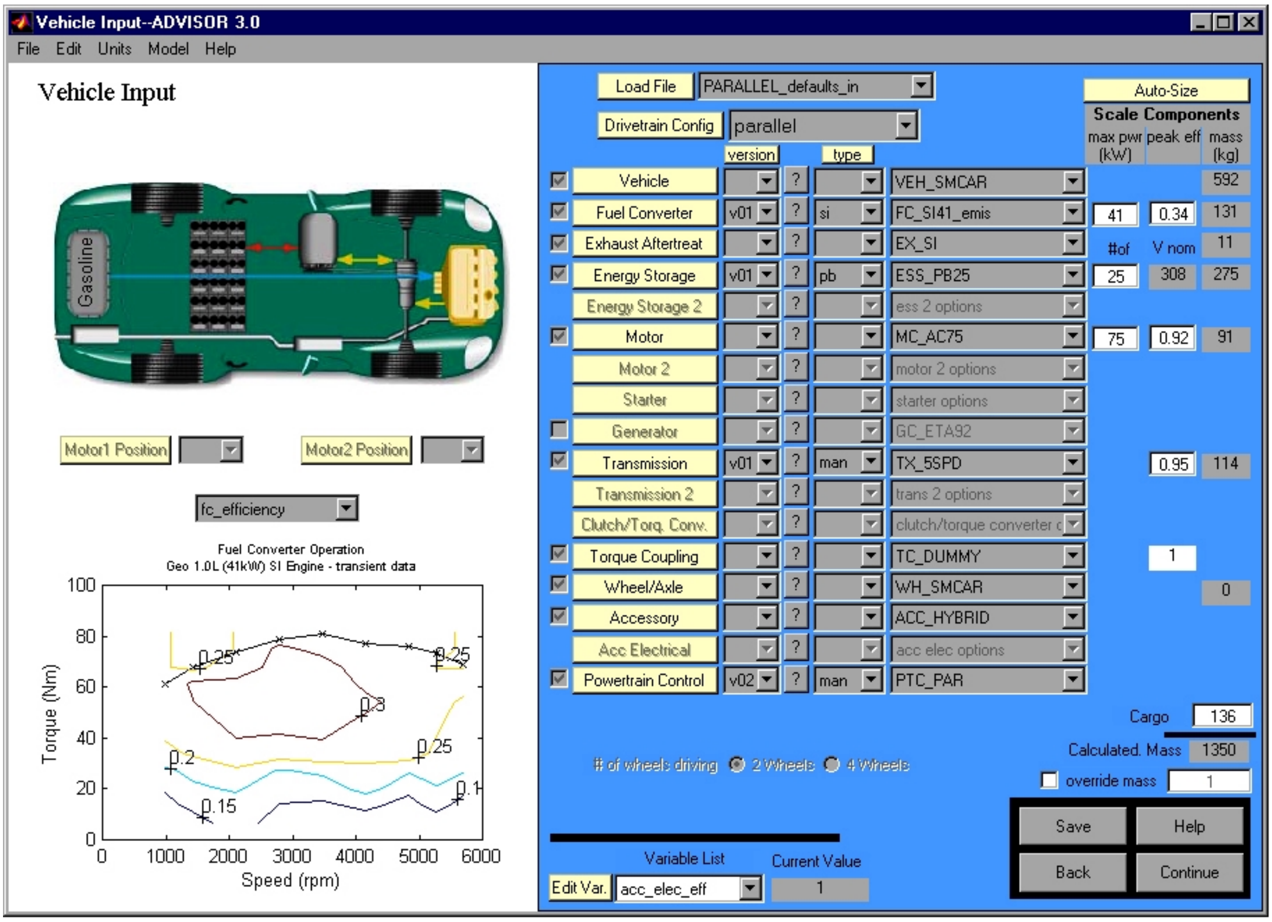
In order to more completely understand and quantify the interaction between various vehicle systems and their impact on vehicle fuel consumption and emissions, NREL has developed a vehicle systems analysis code called ADVISOR (ADvanced VehIcle SimulatOR).[19,20] This model can simulate a variety of vehicle configurations including conventional internal combustion engine powertrains, series and parallel hybrid electric powertrains, electric and fuel cell powertrains. As input to the model, the user can choose from various transmissions, engines, energy storage systems, and electrical accessory loads as appropriate to define the vehicle of interest. The tool allows the user to simulate the vehicle under a variety of conditions defined by basic drive cycles (FTP, Japanese 1015, NEDC, etc.) and test procedures (gradeability, acceleration, etc.). The basic drive cycle defines the desired vehicle speed as a function of time. Based on the vehicle requirements to satisfy the cycle demands, the model determines the operating point of each component working backwards from the roadway to the wheels to the power source. As a result, the calculations are simple and the simulations take very little CPU time. The tool also provides the ability to perform vehicle design optimization studies.

Inputs

In general, the inputs to the model are component performance maps (e.g. fuel usage as a function of speed and torque out for an engine) and characteristics (mass, torque limits, etc.). Figure 11 shows the vehicle input screen from ADVISOR v3.0. The user may build a vehicle from the default vehicle configurations, by selecting the individual components, and/or overriding specific vehicle or component parameters. The inputs are highly parameterized providing the user with significant flexibility in design analysis. Other inputs include the drive cycle (vehicle speed as a function of time) or test procedure for which vehicle simulation results are desired.

Results

The model predicts loads (power and energy) for all modeled vehicle components including vehicle fuel usage (Figure 12), tailpipe emissions (Figure 13), energy usage profiles, and many other vehicle performance parameters, such as engine thermal energy, braking energy, and exhaust temperatures, as a function of time for any user-specified driving profile.



Load File: PARALLEL_defaults_in

Drivetrain Config: parallel

		version	type		max pwr (kW)	peak eff	mass (kg)
☑	Vehicle			VEH_SMCAR			592
☑	Fuel Converter	v01	si	FC_SI41_emis	41	0.34	131
☑	Exhaust Aftertreat			EX_SI	#of	V nom	11
☑	Energy Storage	v01	pb	ESS_PB25	25	308	275
	Energy Storage 2			ess 2 options			
☑	Motor			MC_AC75	75	0.92	91
	Motor 2			motor 2 options			
	Starter			starter options			
☐	Generator			GC_ETA92			
☑	Transmission	v01	man	TX_5SPD		0.95	114
	Transmission 2			trans 2 options			
	Clutch/Torq. Conv.			clutch/torque converter c			
☑	Torque Coupling			TC_DUMMY		1	
☑	Wheel/Axle			WH_SMCAR			0
☑	Accessory			ACC_HYBRID			
	Acc Electrical			acc elec options			
☑	Powertrain Control	v02	man	PTC_PAR			

Cargo 136

Calculated. Mass 1350

☐ override mass 1

# of wheels driving ● 2 Wheels ○ 4 Wheels

Variable List: acc_elec_eff

Current Value: 1

Figure 11. ADVISOR User Input Interface

Limitations and Assumptions

ADVISOR is a quasi steady-state model and not a true transient model. The results are limited to component map accuracy and resolution. There are potential errors introduced when operating at component performance limits due to the backward-facing modeling approach. The model is limited to available component maps or components that can be extrapolated from existing maps. The engine thermal models approximate complex engine heat transfer with a one-dimensional, multi-node, lumped-capacitance formulation.

Validation

ADVISOR has been validated with prototype hybrid electric vehicles and is currently being validated with experimental data from the Honda Insight and Toyota Prius.

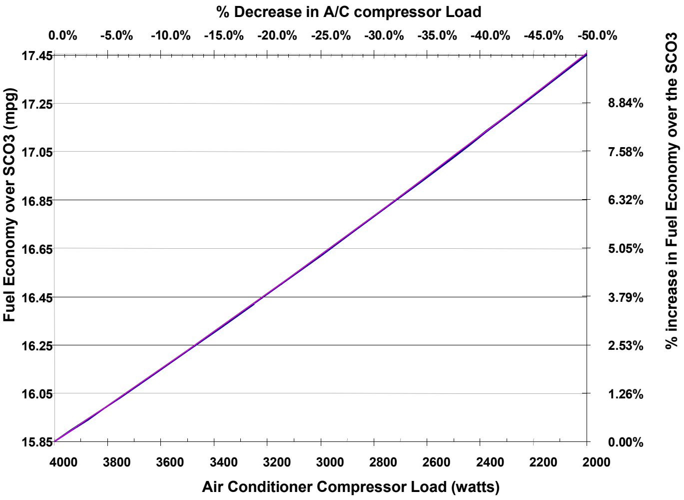


Figure 12. Change in Fuel Economy

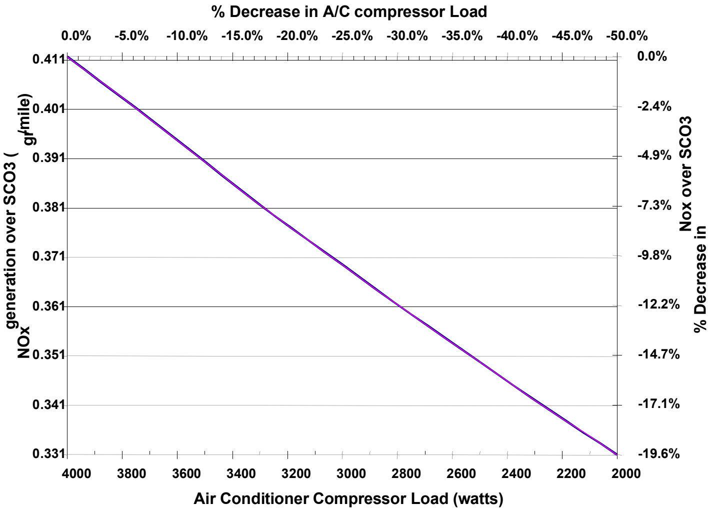


Figure 13. Change in NO_x

5.0 Conclusions

It is difficult to predict the impact of advanced climate control technologies on occupant comfort, fuel economy, and tailpipe emissions because of the many driving factors and complex interactions. Occupant comfort is driven by the solar inputs, the glazing properties, the air-conditioning system operation as a function of engine speed and vehicle speed, the resulting temperature and velocity flow fields, and an occupant's physiological and psychological responses to the environmental conditions. An integrated modeling tool is needed.

Not only is integrated modeling a useful tool in evaluating new concepts and strategies and for selecting which configurations to fabricate and test, it also offers the potential for creative thinking and innovation because of the interdisciplinary nature of such modeling. Modeling is faster than repeated fabrication and testing and offers good repeatability that is not available with outdoor testing. It is well suited for relative comparisons, however, modeling is still labor-intensive and passing data between models is still challenging. Users must recognize model assumptions and limitations and the lack of model validation, particularly with new concepts.

Successful implementation of energy-efficient thermal comfort systems will have a large national and global benefits including reduced fuel use and improved air quality. It will also provide users with more comfortable environments and may increase driver vigilance and safety.[21] It will benefit vehicle manufacturers by assisting them in meeting new Federal emissions standards and may reduce cost and weight by eliminating a second cooling system in minivans and sport utility vehicles.

It is clear that significant reductions in automotive auxiliary loads are needed and that integrated modeling is one tool that helps to achieve that goal.

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Acknowledgments

This work was supported by DOE's Hybrid Vehicle Propulsion Program, which is managed by the Office of Advanced Transportation Technologies. The authors appreciate the support of DOE Program Managers Robert Kost and Roland Gravel; NREL HEV Technology Manager Terry Penney; and NREL Center for Transportation Technologies and Systems Director Barbara Goodman. The authors would like to acknowledge the significant contributions provided by our industry partners including DaimlerChrysler, Ford Motor Company, Delphi Automotive, Guardian Automotive Products, Johnson Controls Inc., PPG, and 3M; and by our NREL colleagues, Tom Thoensen, who assisted with the fabrication, operation, and data collection of many of the experiments, and Valerie Johnson, who provided an in-depth review of the paper.