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Integrated Numerical Modeling Process for Evaluating Automobile Climate Control Systems

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ABSTRACT

The air-conditioning (A/C) system compressor load can significantly impact the fuel economy and tailpipe emissions of conventional and hybrid electric automobiles. With the increasing emphasis on fuel economy, it is clear that the A/C compressor load needs to be reduced. In order to accomplish this goal, more efficient climate control delivery systems and reduced peak soak temperatures will be necessary to reduce the impact of vehicle A/C systems on fuel economy and tailpipe emissions. Good analytical techniques are important in identifying promising concepts. The goal at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) is to assess thermal comfort, fuel economy, and emissions by using an integrated modeling approach composed of CAD, computational fluid dynamics (CFD), thermal comfort, and vehicle simulation tools. This paper presents NREL's vehicle integrated modeling process.

INTRODUCTION

The mission of NREL is to develop renewable energy and energy efficiency technologies and practices, advance related science and engineering, and transfer knowledge and innovations to address the nation's energy and environmental goals. NREL's Center for Transportation Technologies and Systems (CTTS) Auxiliary Load Reduction Team supports this mission. The team's goal is a 75% reduction by 2008 in the fuel used for climate control; while maintaining or improving occupant thermal comfort.

When operating, the A/C compressor is the largest auxiliary load on today's automobile engines and significantly impacts fuel economy and tailpipe emissions. For vehicles driven over the SCO3 drive cycle, recent tests indicate A/C use increases emissions of NO_x by about 80% and of CO by about 70%. It also reduces fuel economy by about 20%.[1]

The national impact of A/C use is staggering. A recently completed study estimates that the U.S. uses 7.5 billion gallons (28 billion liters) of gasoline every year to air condition vehicles, equivalent to 10% of U.S. imported crude oil.[2] There is great potential to reduce the A/C load on the engine and improve real-world fuel economy without impacting comfort or safety.

Since A/C systems are typically sized for a cooldown from a worst-case hot-soak condition, NREL is investigating techniques to reduce the peak soak temperature, enabling the A/C system size to be reduced. NREL is also looking at improved delivery systems and alternative methods to cool the passenger compartment which will reduce the power requirements of a vehicle climate control system.

Analysis tools are important in assessing these various techniques. Since a key requirement is to maintain or enhance passenger comfort, it is important to understand how advanced cooling techniques will impact human thermal comfort. Also critical is the accurate prediction of the effect of reduced engine loads on fuel economy and emissions. We are able to predict the impact of these advanced cooling techniques on the vehicle before testing by using a vehicle integrated modeling process. An overview of the vehicle modeling process is shown in Figure 1. Our goal is to work with industry to create the modeling tools or develop the tools in-house when appropriate.

Vehicle interior geometry is typically defined by CAD data or in the case of vehicles under development, not defined. A parametric modeling tool is used to morph a generic vehicle to the appropriate dimensions and generate a mesh in preparation for cabin thermal/fluid modeling using CFD software. A solar radiation model and vehicle solar load tool were developed to provide solar boundary conditions for the cabin thermal/fluid model. The cabin thermal/fluid model predicts the flow and temperatures within the passenger compartment. In addition to providing the air flow boundary conditions for the CFD analysis, a transient A/C model developed at NREL provides a link to the vehicle simulation software, ADVISOR, through the compressor load. The CFD model is linked to the thermal comfort model to assess occupant thermal confort. The focus of this paper is to describe an approach used to evaluate the climate control load by integrating diverse models.

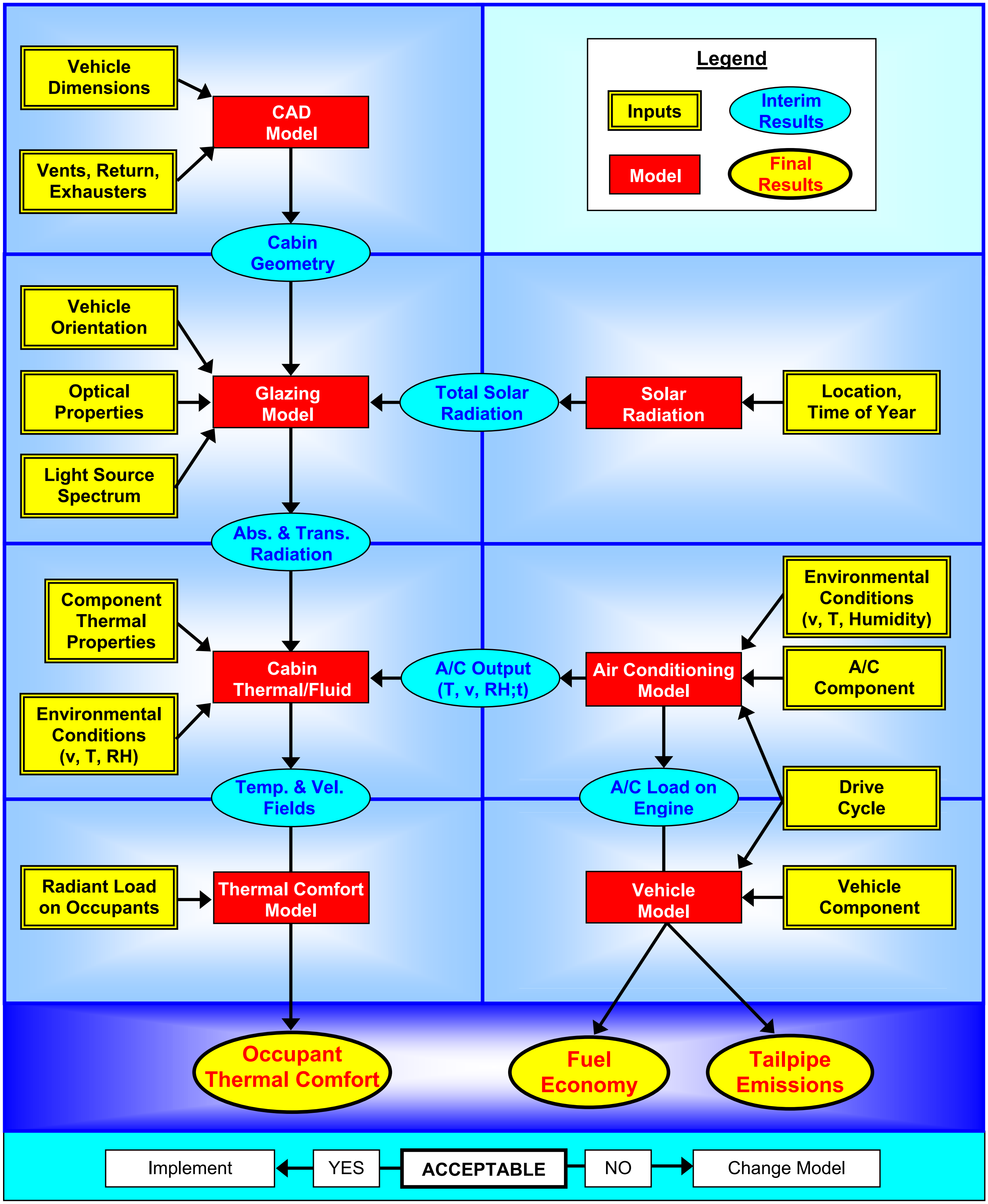

Figure 1. Overview of Integrated Modeling Process

CAD MODEL

The first step in the vehicle modeling process is to define the vehicle geometry and generate a computational mesh for CFD analysis. Vehicle information usually is defined by native CAD files or translation formats such as STEP or IGES. The challenge is to capture the important dimensions of the vehicle interior while ignoring the excessive detail that will have a negligable impact on the bulk air flow within the passenger compartment. A parametric vehicle has been developed for this purpose and is shown in Figure 2. This Pro/E vehicle model can be morphed to approximately match the geometry of the vehicle to be modeled. The advantage of using the morphable CAD model is that all the surfaces fit together and the potentially complex details of the original CAD are eliminated.

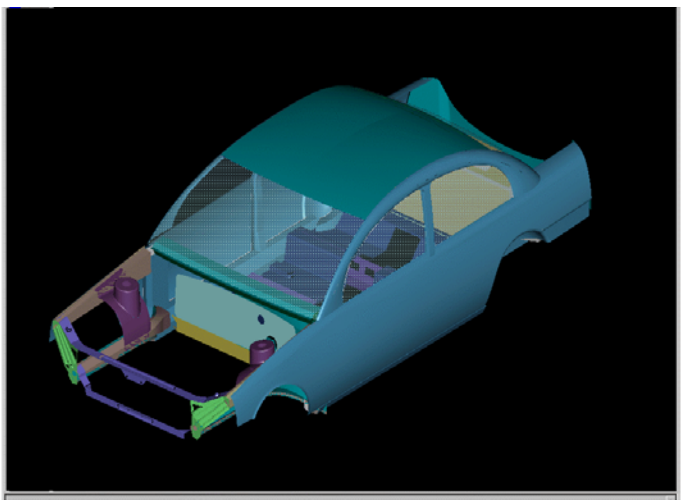

Figure 2. Parametric Vehicle

For transient simulations, a digital occupant can be placed in any of the seats. The location of the air inlets and outlets are defined at this time. The next step is to generate a mesh for CFD analysis using: the Pro/E mesher, CFD preprocessor, or 3rd party meshing software such as ICEM CFD. ICEM CFD was used to generate the sedan mesh shown in Figure 3.

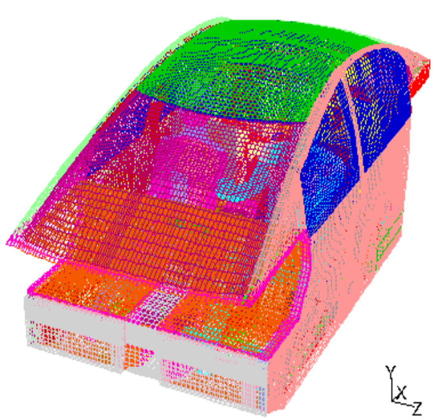

Figure 3. Sample Sedan Mesh

GLAZING MODEL

Solar load is a key input to the cabin thermal/fluid model that drives temperatures during a soak simulation. With today's advanced solar reflective glazings, understanding the spectral properties of the irradiance and the glazing is critical to performing accurate calculations. NREL has developed a vehicle solar load estimator (VSOLE) to predict the transmitted, absorbed, and reflective power of vehicle glazings.

VSOLE1.0 was written in Matlab and is easily accessed with a GUI. The program takes into account the angle of incidence and calculates the transmitted, reflected, and absorbed power based on the radiation source, vehicle geometry, vehicle orientation, and glazing type. All glazing surfaces are assumed flat, and to have constant thickness, uniform properties, and regular shape. The calculation of the optical properties as a function of wavelength and angle uses a single-pane approximation for glass.

An example of the VSOLE GUI is shown in Figure 4. The input parameters were selected to match a Jeep Grand Cherokee thermal soak test that was performed on 7/28/01 in Golden, Colorado.

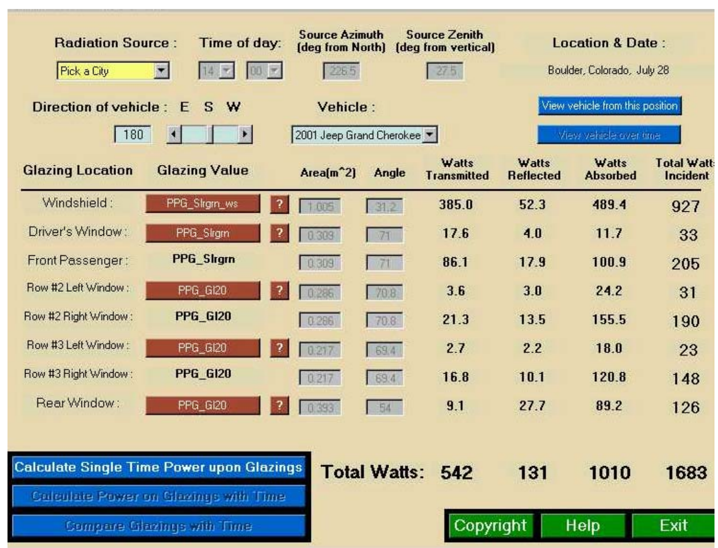

Figure 4. VSOLE Interface

The user is able to select the type of radiation source from the following options: specifications ASTM-E-891 or ASTM-E-892, xenon or metal halide lamps, an actual solar environment from a Phoenix design day, or solar radiation model. The Phoenix design day is a 99th percentile actual day in Phoenix. The solar radiation model accesses a solar radiation database of 239 U.S. cities and will be discussed in the next section.

The vehicle geometry is defined by the window area and angle from horizontal. The values are selected from a predefined list of vehicles or input interactively. The vehicle orientation can be selected from 90° to 270° from north. Industry partners have provided glazing property data files for their respective glazings. An engineer can also use the same file format to input his or her own glazing.

The transmitted, reflected, and absorbed power can be calculated at a specific time, a range of times, or a range of orientations. These data can be used to compare different glazings or can be applied as a boundary condition for a CFD analysis. NREL has made VSOLE available to the public through the word wide web. It can be downloaded as part of ADVISOR at (http://www.ctts.nrel.gov/analysis/).

SOLAR RADIATION MODEL

NREL's solar radiation model provides radiation source data for VSOLE1.0 and is accessed from within the VSOLE GUI through the "pick a city" option in the radiation source pull-down menu. The solar radiation model calculates the solar spectral irradiance incident on the vehicle as a function of location, weather, and vehicle orientation. Model 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).[3] 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.

An example of the solar radiation model GUI is shown in Figure 5. The input parameters selected were for 7/28/01 in Boulder, Colorado.

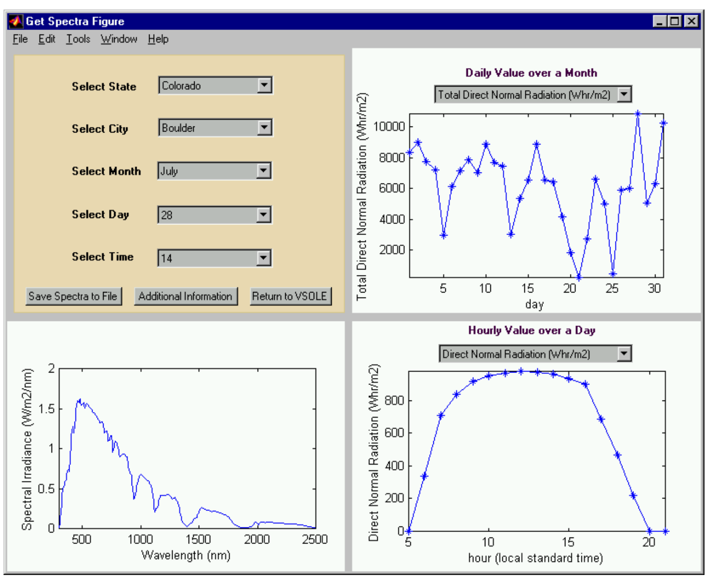

Figure 5. Solar Radiation Model GUI

The spectral irradiance is calculated over a range of 300 to 2500 nanometers (nm) at 5 nm intervals using the model SEDES developed by Nann and Riordan[4]. The irradiance and corresponding weather data are available at 1-hour intervals. Plots of the daily and hourly data assist in selecting the desired environmental conditions. Weather data can be used to define boundary conditions for a CFD analysis. After the city, month, day, and hour are selected, the spectral irradiance and sun position are returned to VSOLE to calculate the transmitted, reflected, and absorbed solar power for a vehicle in the selected city. These data can be used to define the solar loads for the cabin thermal/fluid model.

CABIN THERMAL/FLUID MODEL

The purpose of the cabin thermal/fluid model is to predict the flow field inside the passenger compartment, as well as the surface temperatures and temperature and humidity of the air. Before the simulation, the boundary conditions are defined. The transmitted and absorbed solar radiation for each glazing are generated by the VSOLE model. Information about the airflow rates, humidity, and temperatures can be passed to the CFD model from the transient A/C model. The thermophysical and radiative properties (conductivity, specific heat, density, emissivity, etc.) are required for each material. The external boundary conditions such as the heat transfer coefficient, heat flux, ambient air temperature, and solar load are defined. Additionally, the thermal condition of the occupants can be taken from the human thermal comfort model.

There are 2 CFD analyses that are useful in the integrated vehicle modeling process. A steady-state analysis of a hot soaking vehicle can be performed to investigate techniques to reduce the peak soak temperature. Transient analysis of a vehicle cooldown are required when assessing techniques to improve passenger comfort.

Continuing with the vehicle example presented in the previous sections, we modeled a Jeep Grand Cherokee soak test using environmental conditions from an actual Colorado test day. The test vehicle had a gold exterior, tan interior, leather seats, and was oriented to face south as seen in Figure 6.

Figure 6. Test Vehicle in Golden, Colorado

The vehicle had full instrumentation, including heat flux gauges on the roof and floor, exterior pyranometer, and anemometer. Cabin air temperatures were measured at eight locations with type K thermocouples protected by radiation shields. The air temperatures at 5 panel vents were also measured. Surface temperatures were measured on the glazing interior, door trim, seats, roof, door exterior, and instrument panel.

DaimlerChrysler provided the mesh of the Grand Cherokee shown in Figure 7. Fluent v5.6.4 was the solver used for the CFD analysis.

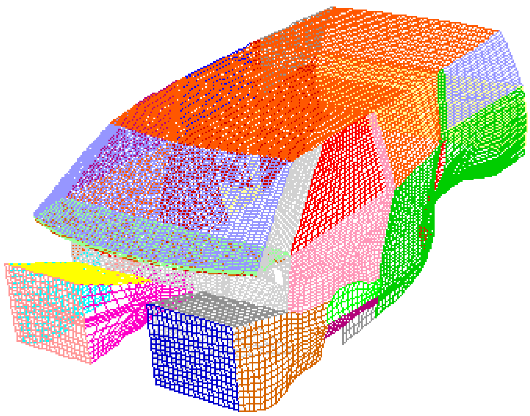

Figure 7. Jeep Grand Cherokee Mesh

External and solar environments were taken from actual conditions on 7/28/01 at 15:00 MDT in Golden, Colorado. The day was cloudless and the ambient temperature was 35.7°C. The standard k-epsilon turbulence model and discrete ordinates radiation model were used. Since the flow in the vehicle was driven by natural convection, it was necessary to use the unsteady solver to obtain a steady-state solution. Figures 8 and 9 show the predicted surface and air temperatures, respectively.

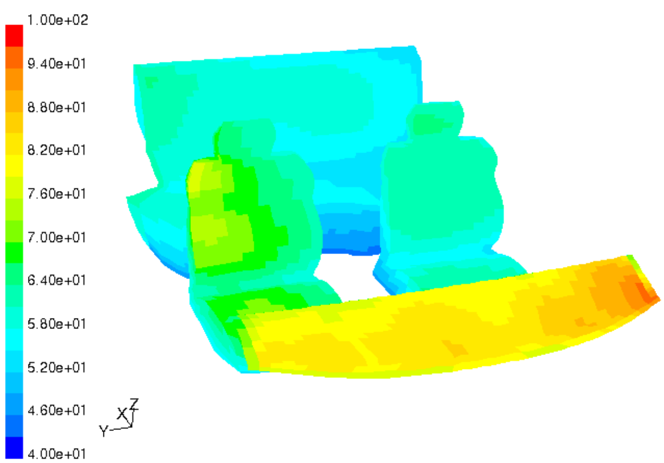

Figure 8. Interior Surface Temperatures (°C)

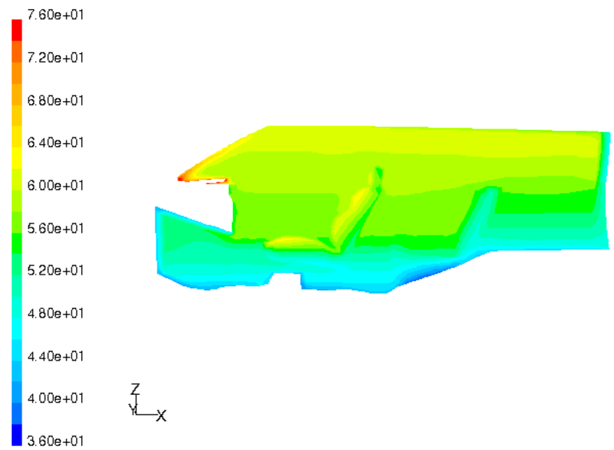

Figure 9. Static Air Temperature (°C)

Table 1. Comparison with Test Data

	Air (°C)	**Windshiel d (°C)**	**IP (°C)**	**Driver Seat (°C)**
Baseline CFD	53.3	63.6	82.1	55.6
Test Data	50.3	64.7	78.1	54.0

Table 1 shows that the predicted temperatures compared favorably with the test data.

After the model was verified against the test data, predictions were made with techniques to reduce the peak soak temperature. VSOLE was used to predict the reduction in solar gain due to the addition of solar reflective glass. With the updated solar loads, the interior air temperature was reduced by 2.4°C which is consistent with previous tests[5,6]. Next a 50-scfm ambient air purge flow was introduced to the passenger compartment through the panel and floor HVAC vents. This resulted in an additional 9.2°C drop in interior air temperature. To determine the impact of the total 11.6°C drop in interior temperature, thermal comfort and air conditioning modeling are necessary.

HUMAN THERMAL COMFORT MODEL

The purpose of the human thermal comfort model is to predict the physiological and psychological response of a human to a transient non-uniform thermal environment. The physiological model is a three-dimensional finite-element model of the human thermal physiological systems and thermoregulatory systems using ANSYS software.[7] NREL's model is based on a model from Kansas State University and is currently being upgraded and improved. The model consists of bone, muscle, fat, and skin layers, as well as macro and micro blood circulation. Using recent test data, the thermoregulatory system physiological responses of sweating, shivering, vasomotor control, and variable metabolic or cardiac rates are simulated. The model allows for the addition of variable clothing layers. The heat and moisture transfer of the body can then be calculated.

The finite-element mesh and physiological systems are scalable across the human population distribution factors of height, weight, fat content, age, and gender. The human geometry segments of the model are modified from the current crude cylinders to a real 3-D human geometry by using data from MRI scans. A sample of the finite-element mesh is shown in Figure 10. The temperatures and airflow around the occupant are predicted by the cabin thermal/fluid model and passed to the comfort model. The output from the physiological model is the transient temperatures of the skin and internal tissues with a spatial resolution of a few centimeters. The updated skin temperatures are linked back to the human in the CFD model.

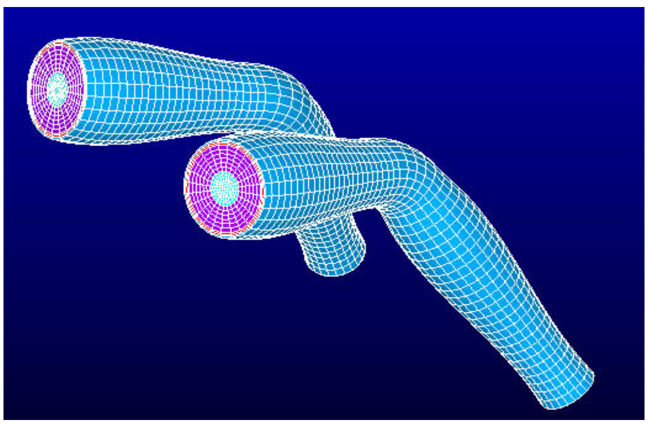

Figure 10. Finite Element Mesh of Legs

A psychological model will then convert the internal body and skin temperatures predicted by the physiological model into local and global perceptions of thermal comfort. The psychological model will simulate the mental perceptions of thermal comfort while subjected to transient and asymmetric thermal fields. A series of human subject tests will be conducted to determine the thermal comfort sensitivities for each body segment. The skin of each body segment will be subjected to various static and transient temperatures and the thermal comfort response at each body segment due to the heating/cooling will be acquired. 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. A model will be developed based on summations of the firing rates to predict local and global thermal comfort in a transient asymmetric thermal field.

TRANSIENT A/C MODEL

NREL has developed a detailed transient A/C system/simplified cabin model[8] that can be used to estimate A/C compressor power reductions possible from cabin temperature reductions. NREL developed this model using SINDA/FLUNT analysis software and integrated it with the ADVISOR[9,10] (Advanced VehIcle SimulatOR) vehicle systems analysis software. This transient one-dimensional, thermal-hydraulic model captures all the relevant physics of transient A/C system performance, including 2-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. It predicts typical transient A/C compressor power requirements, system pressures and temperatures, system mass flow rates, and 2-phase/single-phase flow conditions throughout the A/C system flow circuit, as well as transient cabin temperature conditions during a user-defined drive cycle. The model relies on detailed physical characteristics of the components in the A/C system.

For the integrated vehicle modeling process, the simplified cabin thermal model can be replaced by the cabin thermal/fluid CFD model. During a transient CFD simulation, the A/C model can provide vent air temperatures, humidities, and flow rates. In return, the cabin air temperature and humidity can be provided to the transient A/C model if recirculation air is used. The transient A/C model provides the link between the cabin thermal conditions and the fuel economy and emissions through the compressor load on the engine.

To assess the impact of the 11.6°C reduction in passenger compartment soak temperature from the CFD model, the results of a previous transient A/C analysis can be used[6]. In that case, an SUV was found to have a 4% drop in compressor power for every °C drop in cabin soak temperature while maintaining the same cooldown performance 30 to 50 minutes after the start of cooldown. Therefore, an 11.6°C reduction in cabin air temperature means the A/C compressor load can be reduced by 46%.

ADVISOR

The impact of the A/C load on the engine can be estimated by ADVISOR that NREL developed.[9,10] ADVISOR helps us to more completely understand and quantify the interaction between various vehicle systems and their impact on vehicle fuel consumption and emissions. This model can simulate a variety of vehicle configurations, including conventional internal combustion engine, series and parallel hybrid, electric, and fuel cell powertrains.

As input to the model, the user chooses from various transmissions, engines, energy storage systems, and electrical accessory loads to define the vehicle of interest. Figure 11 shows the setup screen where the vehicle parameters are selected. In general, the inputs to the model are component performance maps. 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. 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.

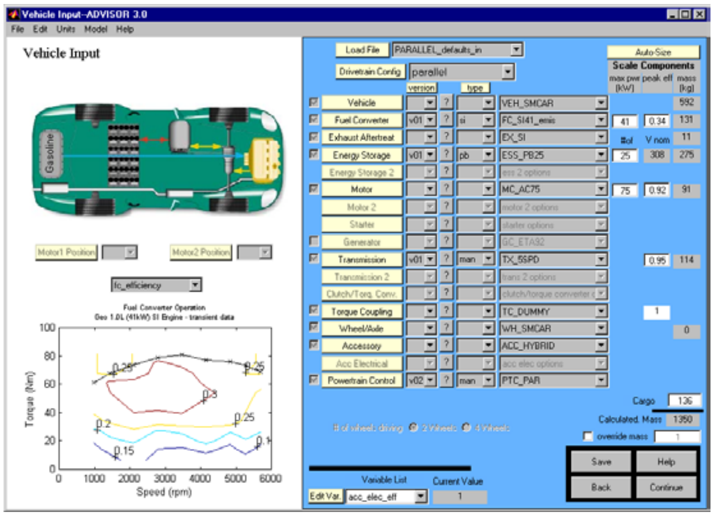

Figure 11. ADVISOR GUI Setup Screen

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 computer processing time. The tool also provides the ability to perform vehicle design optimization studies. The model predicts loads (power and energy) for all modeled vehicle components, including vehicle fuel usage, tailpipe emissions, energy usage profiles, and many other vehicle performance parameters. The link between the transient A/C model and ADVISOR has been completed. When the cabin thermal/fluid model link to the transient A/C model is complete, the relationship between human thermal comfort and vehicle fuel usage will be defined.

Using ADVISOR, the impact of A/C load on the fuel economy of a Ford Explorer driven over the SCO3 drive cycle has been determined[6]. Figure 12 shows that a 46% reduction in A/C load translates to a 9.2% increase in fuel economy (1.5 mpg) over the SCO3 drive cycle. This illustrates how the vehicle integrated modeling tools can work together to predict the impact of peak soak temperature reduction techniques on fuel economy.

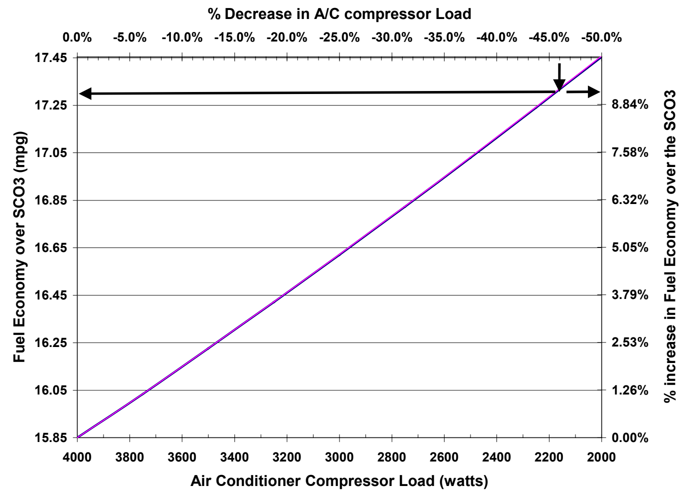

Figure 12. Impact of A/C load on Ford Explorer Fuel Economy over the SCO3 drive cycle

CONCLUSION

The task of developing an integrated modeling process can be broken down into 2 steps: 1) develop models, and 2) develop links between the models. NREL is developing or working with industry to develop the following models that enable integrated vehicle modeling: parametric CAD, glazing, solar radiation, cabin thermal/fluid, transient A/C, human thermal comfort, and ADVISOR. A significant challenge is to link these models in a seamless manner. Specific issues include differing analysis time scales and automation of data transfer. NREL has made great progress in developing a functional integrated modeling process.

NREL's goal is to use the integrated modeling process to evaluate advanced concepts that will reduce the peak soak temperature and improve passenger comfort. The ultimate benefit is improved efficiency of vehicle climate control systems and reduced fuel use. We are working with several industry partners to apply the integrated modeling process to their development vehicles and concepts. The example peak soak temperature reduction presented in this paper demonstrated that fuel economy could be improved 9.2% with an 11.6°C drop in cabin air temperature.

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