

# **Development of Interactive Graphical Software Tools in the Context of Teaching Modeling of Internal Combustion Engines in a Multimedia Classroom**

**Dennis N. Assanis, Zoran S. Filipi and GuoQing Zhang**  
**W.E. Lay Automotive Laboratory**  
**Department of Mechanical Engineering and Applied Mechanics**  
**University of Michigan**  
**Ann Arbor, MI, 48109**

## **ABSTRACT**

The strong tendency in the automotive industry to reduce development time through virtual prototyping and optimization of design using simulation tools implies that engineers need to be proficient in using sophisticated simulations. At the same time, engineers also need to have a solid understanding of the underlying physics in order to be able to interpret the results correctly and communicate them to fellow team members. The availability of multimedia equipment in the classroom provides an opportunity to use computer simulations as a direct aid in teaching advanced modeling concepts to professional engineers. This paper presents the results of the adaptation of a suite of internal combustion engine simulations in a graphical software environment suitable for use in the multimedia teaching environment for continuing education. Within the context of a one-week intensive short course, the graphical user interface allows easy manipulation of input parameters, monitoring of selected output variables in real time and visual representation of results obtained through multiple runs for comparative studies. Our experience based on a first offering of the course indicates that simulations implemented in a graphical environment can greatly increase the effectiveness of the teaching process, especially under the constraints of a one-week intensive short course.

## **1. INTRODUCTION**

Modeling of internal combustion engines is an integral part of studying the fundamentals of processes that take place within the engine cylinder, as well as phenomena occurring in the complex engine system such as the typical turbocharged multi-cylinder engine configuration. During the course of years, a large body of engine simulations has been developed for research purposes with a high degree of sophistication and hence fidelity. Such research codes have been successfully introduced by Professor Assanis in an advanced graduate level, mechanical engineering course on Internal Combustion Engines that he has developed and taught since 1986 at the University of Illinois in Urbana-Champaign (ME 445) and the University of Michigan in Ann Arbor (ME 534). Students have repeatedly expressed favorable feedback on the value of transitioning the research tools into the classroom, thus enabling them to conduct real-life,

semester-long, open-ended projects that integrate the course principles. Based on this finding, we have been encouraged to develop a week-long, intensive short course to introduce the practicing professional engineers to the principles of modeling and simulation of internal combustion engines.

Exposing the student to the hierarchy of engine process and systems level models, and teaching them a number of complex phenomena and their interactions within the constraints of one week, creates two new challenges: (i) how to condense the lectured material and increase efficiency of the teaching/learning process in order to allow students to digest the fundamentals in a timely manner and (ii) in parallel to that, how to give the student skills necessary to run the sophisticated simulations right away. The objective of this work was to create interactive, user friendly tools for computer-aided learning based on a suite of codes previously developed for research purposes. Graphical user interface and visual representation of results are deemed necessary to allow students to perform “numerical experiments” and focus on results instead of procedures, thus increasing the pace of learning. MATLAB-SIMULINK<sup>1</sup> is selected as the software environment due to its ability to accept the modules written in other languages like FORTRAN or C, its user friendly graphical programming interface and its integration flexibility. The experience with teaching the intensive short course on modeling IC engines with the aid of instructional computer simulations indicates that didactic potential of developed tools is utilized to the fullest in the advanced multimedia classroom that provides each student with the workstation networked with the instructor’s computer.

The paper is arranged as follows: section two discusses the role of the advanced engine models in teaching while section three defines the software and hardware needed in the context of teaching the intensive, short course in the multimedia classroom. The next section presents the details of the development of the interactive graphical interface in MATLAB-SIMULINK. Section five describes the usage of the developed simulation tools in the multi-media classroom through selected parametric studies. The examples are intended not only to highlight the capabilities of individual models, but to illustrate how important phenomena can be explained and how their effect on the behavior of the complex system such as the internal combustion engine can be efficiently examined with the aid of the developed graphical simulation tools. The summary and conclusions of this work are given in the last section.

## **2. THE ROLE OF ADVANCED SIMULATIONS IN TEACHING IC ENGINES**

The automotive engineer, especially one involved in IC engine design, is facing complex issues stemming from often contradicting requirements to satisfy ever more stringent emissions and fuel economy standards, while designing a product that will be attractive and affordable for the consumer. Industry’s response to market and regulatory forces needs to be prompt, hence there is a strong tendency to reduce development time through virtual prototyping and optimization of design using simulation tools. The concurrent engineering approach implies that engineers need to be proficient in using sophisticated simulations, while at the same time having a solid understanding of the underlying physics in order to be able to select the proper tool for the

---

<sup>1</sup> MATLAB/SIMULINK are trademarks of The Mathworks, Inc.

task, interpret the results correctly and communicate them to fellow team members dealing with other aspects of the design or with system integration issues. The automotive engineer works in an environment that often requires a multi-disciplinary approach involving other specialties besides mechanical engineering, e.g. chemical engineers, electrical engineers, etc. Hence, engineers coming from different fields may need a fast and efficient way to become familiar with the internal combustion engine as an object that will define the application of their specialized expertise. This background creates a need for constant improvement of an individual's engineering skills through efficient continuous education courses in the area of automotive engineering, and in particular, internal combustion engines. In this context, it was decided to develop an intensive five day short course on modeling and computer simulation of IC engines (MCSICE), offered through the Center for Professional Development of The University of Michigan,

The concept behind the MCSICE course is to present students with lectures on process fundamentals and modeling techniques blended with hands-on exercises using research level computer simulations. The participants are introduced to the computer simulation immediately after the fundamentals of the process have been explained, hence the instructor is in the position to demonstrate the strengths and potential deficiencies of the particular modeling approach during the lecture. This way the transition from abstract concepts to model application becomes more transparent. Furthermore, instead of traditional exercises, students are given a chance to perform “numerical experiments” and investigate important trends during open sessions. Combining lectures with hands-on applications accelerates the progress towards the ultimate goal, i.e. to equip students with skills necessary for the selection of the appropriate simulation for a given task and its effective application towards finding the solution to a design problem.

### **3. SOFTWARE AND HARDWARE REQUIREMENTS**

Even though the large body of models and simulations has been developed over the years for both research purposes and optional use in the graduate level course, the prospect of teaching almost the same material in only five days created a new challenge: how to condense the lectured material and increase efficiency of teaching/learning process in order to allow students to digest the fundamentals in a timely manner and, in parallel to that, acquire skills necessary to run the sophisticated simulations after only a day. In response to that challenge, we have undertaken the task of developing a suite of new generation, computer simulation tools with interactive graphical user interfaces, with each tool covering one aspect of engine modeling. The tools include simulations that are reasonably fast when executed on modern workstations, e.g. the phenomenological diesel engine cycle simulation, the quasi-dimensional spark-ignition engine cycle simulation, the turbocharged diesel engine system simulation based on the “filling-and-emptying” technique, the gas dynamics simulation of the wave action in intake/exhaust runners and the engine dynamics simulation for engine transients. The main features of the models used to develop interactive graphical simulation tools are highlighted in an extended version of the paper that is available upon request. Additional details on the parent simulations can be found in previously published articles, e.g. Assanis and Heywood [1], Assanis, et al [2], Filipi and Assanis [3], Agarwal, et al. [4], Zhang and Assanis [5], Filipi and Assanis [6], and Zhang, et al [7].

While the hands-on use of multi-dimensional fluid dynamics and heat transfer codes was not practical due to their complexity and computational intensity, students were introduced to the appropriate modeling concepts and exposed to some previously-run examples.

The multimedia training room in the University of Michigan Media Union was selected as the site ideally suited for the short course of this type. It features Pentium PC's connected to a local network as well as the Computer Aided Engineering Network, and of course the Internet. Hence, the codes can be executed on very fast workstations, while the PC's serve only as intelligent terminals for graphical display of results. The instructor is able to transmit the images from his computer screen to all participants, either to present some pre-prepared information or to demonstrate the use of a code and display results in real time. A projector is also available for displaying the images on a large screen. When the students are running the code independently, the instructor is able to examine images on any of the student screens in case there is a question that needs to be clarified. The image from any machine could also be transmitted to others if it is in fact an educational and refreshing example. Finally, the instructor has the capability of gaining keyboard control of any of the individual PC's in case a quick intervention is needed to deal with some unexpected set-up or execution problem.

#### **4. GRAPHICAL USER INTERFACE**

All of the parent simulations were originally developed in FORTRAN programming language. Their use is typically associated with the preparation of the input parameters in the pre-defined format and the post-processing of the output data stored in ASCII text files. The new generation of graphical simulation tools had to achieve much higher degree of user friendliness, provide ease of manipulation of the input data, and enable advanced visualization capabilities. It was assessed that one of the most promising graphical software environments is the one provided by the MATLAB-SIMULINK package. The experience gained through development of a graphical research tool in the context of the ground vehicle simulation [7] indicated that the full decomposition of the parent FORTRAN code and generation of the complex simulation in SIMULINK can lead to a significant increase in computation time. However, fast execution is essential for real-time demonstrations and for analysis of complex interactions and relationships through series of parametric studies. Therefore, the approach to development of the dedicated suite of simulations for the multimedia classroom was the following: convert each of the parent simulations to a FORTRAN-MEX file, thus creating a self contained block compatible with the SIMULINK environment, but keeping the original integrator routine [8] within the module. The method marries the important features of both programming environments, i.e. flexibility and ease of manipulation of the input/output parameters and efficiency of the FORTRAN executable.

As the consequence of the decision to develop fast, self-contained simulation modules, the structure of the simulation in SIMULINK is fairly simple, e.g. the block diagram of the diesel engine cycle simulation shown in the north-east corner of Fig. 1 has only input, simulation and output blocks. The input and output windows can contain any selection of the parameters of interest - see Fig. 1. Simple clicking on the block containing the particular input parameters opens the field in which the new value can be entered - also seen in Fig. 1. The computation can

be monitored dynamically if values of the selected variables are passed to the ‘scope’ windows at each time step during execution - these windows with the green background are located in the center of the screen shown in Figure 1. Plotting routines available in MATLAB allow graphical representation of the final results in a special window. The number of graphs in a window and variables shown in each of the graphs is defined according to the user preference and is essentially limited only by the screen size. Typically, the instructor will prepare a set of scripts for plotting, i.e. a set of m-files with sequences of graphing commands tailored to the needs of a particular presentation. For the parametric study, the first of the plotting routines will create and “hold” a window with the desired graphs, while after each of the subsequent runs the execution of similar m-files will enable superimposing and comparison of results on same plots.

## 5. SAMPLE SIMULATION STUDIES

With the aid of interactive, graphical user interfaces it was possible to incorporate demonstrations in almost every instructional session of the short course, and provide instant insight into lectured phenomena. In addition, students were given a chance to independently explore the important aspects of the studied processes and investigate implications of the discovered relationships. This was started early on, after the first day of the course. Since the same “design” of the graphical interface was used for all codes, subsequent introduction of new models was seamless. This section presents selected examples of studies performed by instructors or students, each one illustrating different instructional use of the code. To help the reader assess the graphical capabilities of the interface, all of the figures are produced as copies of the screens generated within the simulation environment.

The first study is an example of the use of a simulation to demonstrate the multiple effects of a particular input parameter on simulation results. Figure 2 shows the screen with three plotting windows displayed at once, with each of the windows containing three graphs. Each of the graphs compares results obtained for three diesel engine speeds: 1000 rpm, 1500 rpm and 2000 rpm. This demonstration should follow the description of the relevant models. In order not to overwhelm the audience, the demonstration can be realized in two steps. First, the effect of engine speed on ignition delay, rate of burning, and consequently on pressure and temperature in the cylinder should be explained (“Figure No. 1” window in Fig. 2). The explanation should be complemented with comments about the development of the turbulent flow field in the cylinder and the impact of the flow parameters, as well as that of pressure and temperature on the heat transfer variables (see middle plotting window in Fig. 2). In the second step, the students can be asked to run these cases again, but plot and examine additional variables, such as characteristic temperatures used in the radiative heat transfer model, as well as the convective and radiative components of the total rate of heat transfer. The informal discussion of results among course participants and with the instructor would help students grasp complex relationships governing the heat transfer process in the cylinder, i.e. the interaction between the sub-models assembled to form the comprehensive cycle simulation.

The next study attempts to contrast two modeling options. The graphs given in Fig. 3 illustrate the predictive capabilities of the quasi-dimensional SI engine simulation versus the

conventional option that relies on a specified function for the rate of burning. The first set of lines was plotted after the simulation run with the specified burn rate, while the second and third runs were performed using the predictive model for two combustion chamber shapes, i.e., wedge and pentroof. Comparison of combustion and heat transfer results illustrates how well the predictive model captures the effect of the geometric interaction between the flame front and combustion chamber walls. After the demonstration, students should experiment themselves, i.e. vary one of the important operating parameters, perhaps the air-to fuel ratio, and run the code with both options. The results will emphasize the enhanced predictive capabilities of the turbulent entrainment model compared to an algebraic correlation for the rate of burning.

After students have absorbed a significant part of the lectured material and gained hands-on experience with the simulations, they should be prepared to attack a typical design problem. Figure 4 shows how the output generated using the manifold gas dynamic code coupled with the SI engine simulation can aid the design of the intake system. Each of the plotting windows displays results obtained for different engine speeds, i.e. 2500 rpm, 4000 rpm and 5500 rpm. The graphs show the effect of varying intake runner length on the volumetric efficiency and the gas exchange process variables. The optimum length changes significantly with speed, therefore the designer will have to accommodate that, perhaps through the use of a variable intake system. This type of study opens-up horizons for further investigations, e.g. the study of the variable valve actuation system in search for the optimum combinations of runner lengths and valve timings/cam profiles at different operating speeds.

Student feedback indicated that on-line demonstrations are very illustrative and constitute an excellent companion to the lectures. Many of the participants felt that even more hands-on simulation studies could be appropriate. Of course, this has to be balanced with the need to maintain a very fast pace of introducing new concepts, while communicating to the students an appreciation for the complexity of real engine processes and inherent limitations of physical models.

## 6. SUMMARY AND CONCLUSIONS

A suite of engine simulations with interactive, graphical user interfaces has been developed to be used as an aid in teaching the intensive five day course on modeling the internal combustion engine in the multimedia classroom. The initial experience showed that graphical simulation tools can enhance the effectiveness of the lecturing through on-line demonstrations of the model behavior and also aid learning through hands-on exercises. The following conclusions can be drawn from the work presented here:

- Advanced engine simulations can be a powerful aid in teaching because of their ability to realistically represent the modeled processes/systems and to allow exploration of the phenomena in question and of the system behavior through “numerical experimentation”.
- The implementation of research grade simulation in a graphical environment enables real time demonstrations as a direct teaching aid in the multimedia classroom.

- Learning how to use the interactive, graphical software simulation tools requires little lead time; thus students can start with open, hands-on simulation sessions early on during the course.
- The reactions of the first generation of participants in the intensive short course on IC engine modeling seem to indicate that the use of the interactive computer simulations in the course could be increased.

## ACKNOWLEDGMENT

The short course on Modeling and Computer Simulation of Internal Combustion Engines was developed under the auspices of the Center for Professional Development (CPD) of the University of Michigan in Ann Arbor, and offered for the first time in the Media Union of the North Campus during September 9-13, 1996. The course chair was Professor Dennis N. Assanis, and instructors also included Dr. Zoran S. Filipi of the University of Michigan and Dr. Douglas M. Baker of M.A.N.A.G.E., Inc. Dr. Guoqing Zhang was responsible for implementation of the parent simulations in the MATLAB-SIMULINK environment. The continuous encouragement and contributions of Mr. Edward Borbely, CPD Director, during the development of the short course are gratefully appreciated.

## REFERENCES

1. Assanis, D.N., Heywood, J.B., "Development and Use of a Computer Simulation of the Turbocompounded Diesel System for Engine Performance and Component Heat Transfer Studies", SAE paper 860329, *SAE Transactions*, Vol. 95, 1986.
2. Assanis, D.N., Ekchian, J.E., Heywood, J.B., Replogle, K.K., "Computer Simulation of the Turbocompounded Diesel Engine System", SAE Publication P-155, *Proc., 22nd Automotive Technology Development CCM*, Dearborn, MI, Oct.29.-Nov.2, 1984., pp. 297-316
3. Filipi, Z., Assanis, D. N., "Quasi-Dimensional Computer Simulation of the Turbocharged Spark-Ignition Engine and its Use for 2- and 4-Valve Engine Matching Studies", SAE Paper 910075, *SAE Transactions*, Vol. 100, 1991. Blizard, N. C., Keck, J. C., "Experimental and Theoretical Investigation of Turbulent Burning Model for Internal Combustion Engines", SAE paper 740191, *SAE Transactions*, Vol. 83, 1974.
4. Agarwal, A., Filipi, Z. S., Assanis, D. N., Baker, D. M., "Assesment of Single- and Two-Zone Turbulence Formulations for Quasi-dimensional Modeling of Spark-Ignition Engine Combustion", submitted for publication in *Combustion Science and Technology*, 1997.
5. Zhang, G., and Assanis, D. N., 1997, "Manifold Gas Dynamics Modeling and its Coupling with Single-Cylinder Engine Models using SIMULINK," *ASME-ICE Spring Technical Conference Proceedings*, ICE-Vol. 28-1, Fort Collins, CO.
6. Filipi, Z. S., and Assanis, D. N., "A Non-Linear, Transient, Single-Cylinder Diesel Engine Simulation for Predictions of Instantaneous Engine Speed and Torque," *ASME-ICE Spring Technical Conference Proceedings*, ICE-Vol. 28-1, Fort Collins, CO.
7. Zhang, G., Filipi, Z. S., and Assanis, D. N., 1997, "A Flexible, Reconfigurable, Transient Multi-Cylinder Diesel Engine Simulation for System Dynamics Studies," accepted for publication in *Mechanics of Structures and Machines*.
8. Shampine, L. F., and Gordon, M. K., *Computer Solution of Ordinary Differential Equations: The Initial Value Problem*, Freeman, 1974.

DENNIS ASSANIS is a Professor at the University of Michigan College of Engineering and a Director of the W.E. Lay Automotive Laboratory. He received his Ph.D. in Mechanical Engineering from M.I.T. in 1985. He was an Assistant Professor at the University of Illinois from 1985.-1990. and an Associate Professor at the same University from 1990.-1994. He is currently the chair for the short course on Modeling and Computer Simulation of IC Engines. Research interests include modeling and computer simulation of engines, engine heat transfer, direct injection of natural gas and engine friction.

ZORAN FILIPI holds an Asst. Research Scientist position at the University of Michigan College of Engineering. He earned his Ph.D. degree in ME at the University of Belgrade in 1992. after completing part of his Ph.D. research at the University of Illinois in 1989/90. He is currently one of the instructors for the short course on Modeling and Computer Simulation of IC Engines. Research interests: modeling and computer simulation of engines, turbocharging, transient engine testing, engine combustion diagnostics.

GUOQING ZHANG is a Research Investigator at the University of Michigan College of Engineering. In 1994 Dr. Zhang joined the U of M from the University of Illinois at Urbana-Champaign where he was a Post-Doctoral Research Associate since 1993. He received his Ph.D. degree in ME from the Chinese Academy of Sciences (CAS), China, in 1990. Research interests include modeling of manifold gas dynamics and system modeling in a graphical software environment.



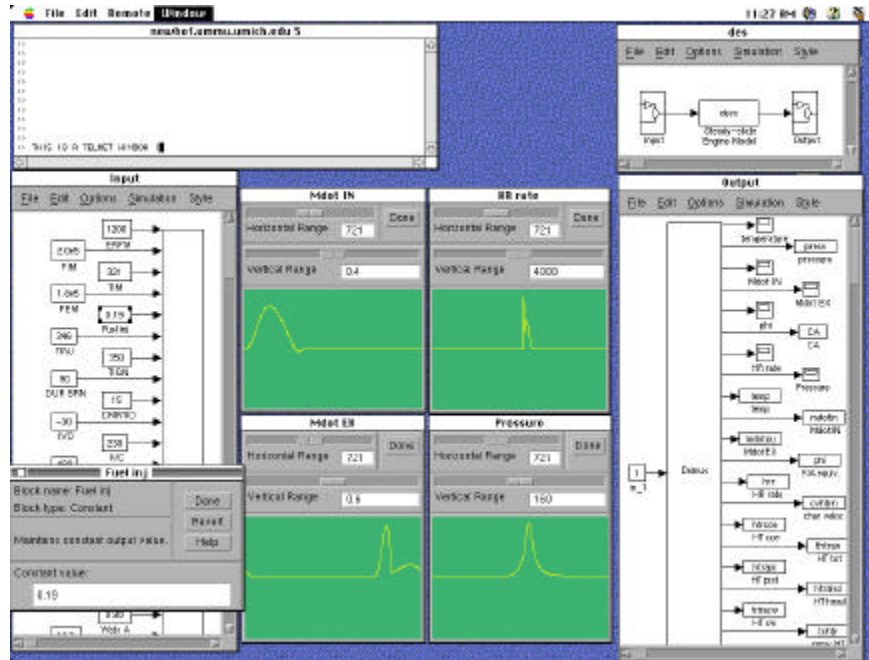


Fig. 1 Graphical user interface for the diesel engine cycle simulation: telnet window, simulation window, input and output windows and scope windows in the middle of the screen.

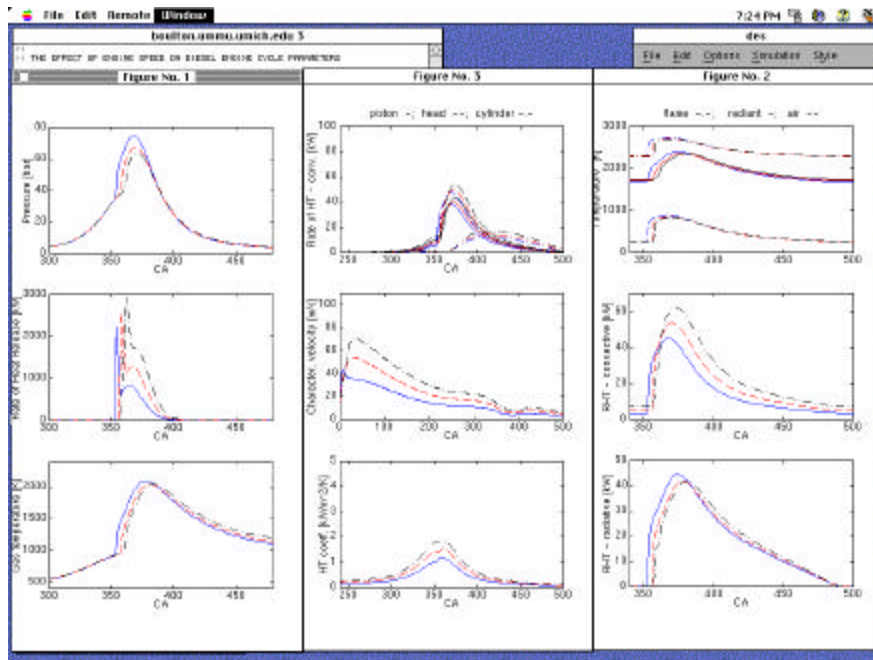


Fig. 2 Diesel engine simulation user interface with three plotting windows comparing predictions for 1000 rpm (blue solid line), 1500 rpm (red dashed line), and 2000 rpm (black dash-dot line). Windows show: #1) in-cylinder pressure, heat release and temperature; #2) characteristic temperatures, total rate of the convective and radiative component of the heat transfer; #3) rates of heat transfer to engine components, turbulence intensity and the heat transfer coefficient.

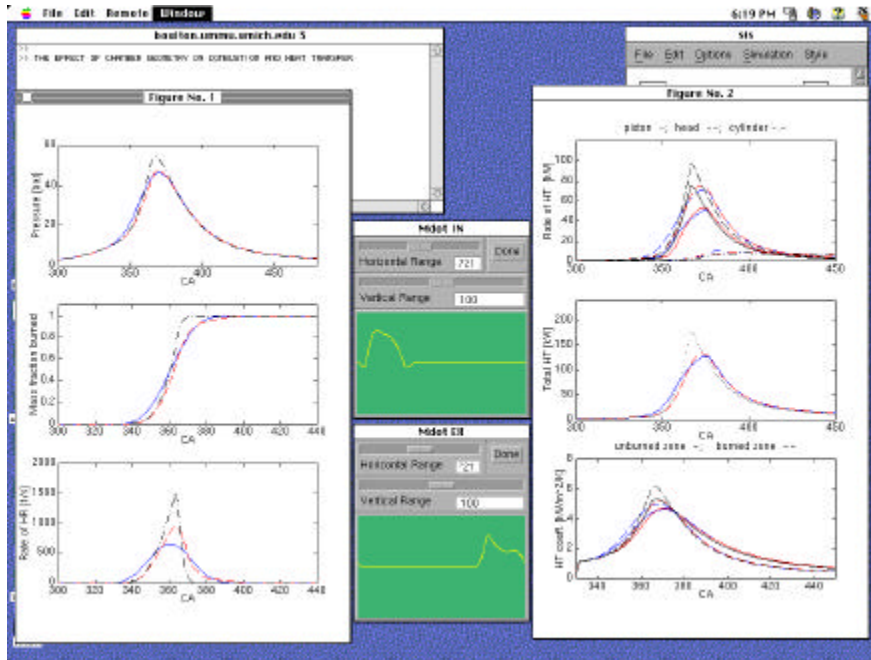


Fig. 3 Spark ignition simulation user interface with two plotting windows comparing predictions obtained with: the specified burn rate function (blue solid lines); the quasi-dimensional model for the wedge combustion chamber (red dashed lines); and quasi-dimensional model for pentroof combustion chamber with the spark-plug in the center (black dash-dot line).

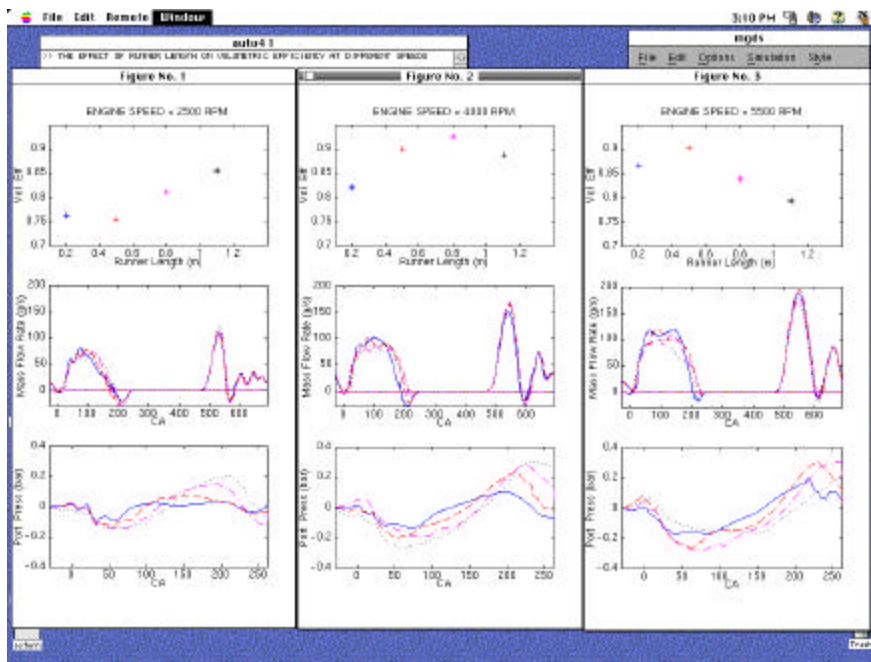


Fig. 4 User interface for the gas dynamic simulation coupled with the SI engine code. Three plotting windows illustrate the effect of the intake runner length at: 2500 rpm, 4000 rpm

and 5500 rpm. Simulated runner lengths are: 0.2 m (blue solid line); 0.5 m (red dashed line), 0.8 m (magenta dash-dot line) and 1.1 m (black dotted line).