Office for the Study of Automotive Transportation
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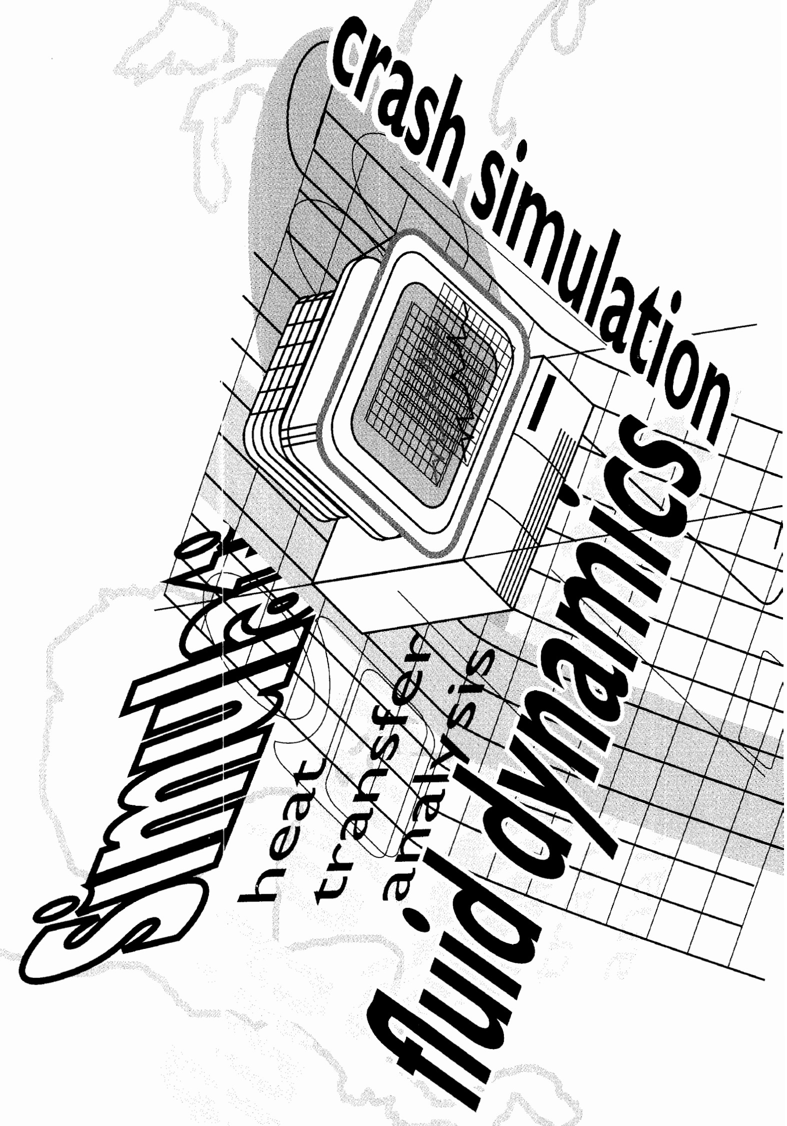
AUTOMOTIVE MODELING AND SIMULATION

FORECAST OF THE GLOBAL AUTOMOTIVE INDUSTRY

DELPHI

Forecast
and
Analysis of

TRENDS THROUGH 2006



Commissioned by
Automotive Research Center

Delphi Forecast of Modeling and Simulation Applications for the Global Automotive Industry

March 1998

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FOREWORD

Introduction

The Delphi Forecast of Modeling and Simulation Applications is a detailed analysis of forecasts by three separate panels of automotive industry executives, directors, managers and engineers as well as academic specialists and consulting technical-engineering specialists who are expert in automotive modeling and simulation of engines, vehicle dynamics, and vehicle structures. These individuals were selected because they occupy positions of responsibility within the automotive industry and have strategic insight into important industry trends. In many cases they are in a position to influence these trends.

This study was funded by the Automotive Research Center (ARC) which is based at the University of Michigan. ARC is a consortium of the University of Michigan and four other universities: Howard University, University of Iowa, University of Wisconsin, and Wayne State University. ARC is funded by the Tank-Automotive Research Development and Engineering Center (TARDEC), a division of the United States Army. The goal of the consortium is to provide advanced research in the areas of mobile transport, and to create synergies between the government and commercial sectors.

The Office for the Study of Automotive Transportation (OSAT) and the Office for Engineering and Research Relations (OERR), which is part of the University of Michigan College of Engineering, collected, analyzed, and interpreted the data. Since the forecasts are those of the panelists, the Delphi Forecast of Modeling and Simulation Applications is essentially the industry's own consensus forecast. These forecasts are not "crystal ball" predictions. Rather, they are well-informed estimates, perspectives, and opinions. Such forecasts present an important basis for business decisions and provide valuable strategic-planning information for those involved in all areas of the global automotive industry: manufacturers; service, component and materials suppliers; government; labor; public utilities; and financial institutions. We believe these to be the most authoritative and dependable global automotive forecasts available.

A key point to keep in mind is that the Delphi forecast presents a vision of the future. It obviously is not a precise statement of the future but, rather, what the industry thinks the future will likely be, given current trends.

As an industry-wide survey, the project also allows individual companies to benchmark their vision and strategy against consensus industry opinions.

The Delphi method: general background

The study is based on the Delphi forecasting process. This process requires that experts consider the issues under investigation and make predictions about future developments. Developed by the Rand Corporation for the U.S. Air Force in the late 1960s, Delphi is a systematic, interactive method of forecasting based on independent inputs regarding future events.

The Delphi method is dependent upon the judgment of knowledgeable experts. This is a particular strength because, in addition to quantitative factors, predictions that require policy decisions are influenced by personal preferences and expectations. Delphi forecasts reflect these personal factors. The respondents whose opinions are represented in this report are often in a position to influence events and, thus, make their forecasts come true. Even if subsequent events result in a change of direction of a particular forecast, this does not negate the utility of the Delphi. This report's primary objective is to present the direction of modeling and simulation developments within the industry, and to analyze their potential strategic importance.

Process

The Delphi method utilizes repeated rounds of questioning, including feedback of earlier-round responses, to take advantage of group input, while avoiding the biasing effects possible in face-to-face panel deliberations. Some of those biasing effects are discussed in this excerpt from a 1969 Rand memorandum:

> The traditional way of pooling individual opinions is by face-to-face decisions. Numerous studies by psychologists in the past two decades have demonstrated some serious difficulties with face-to-face interaction. Among the most serious are: (1) Influence, for example, by the person who talks the most. There is very little correlation between pressure of speech and knowledge. (2) Noise. By noise is not meant auditory level (although in some face-to-face situations this may be serious enough) but semantic noise. Much of the "communication" in a discussion group has to do with individual and group interest, not with problem solving. This kind of communication, although it may appear problem-oriented, is often irrelevant or biasing. (3) Group pressure for conformity. In experiments at Rand and elsewhere, it has turned out that, after face-to-face discussions, more often than not the group response is less accurate than a simple median of individual estimates without discussion (see N. C. Dalkey, The Delphi Opinion. Memo RM 5888 PR, p. 14, Rand Corp., 1969).

In the Delphi method, panelists respond anonymously, preventing the identification of a specific opinion with any individual or company. This anonymity also provides the comfort of confidentiality, allowing panelists to freely express their opinions. Among other advantages, this process enables respondents to revise a previous opinion after reviewing new information submitted by other panelists. All participants are encouraged to comment on their own forecasts and on the combined panel results. The information is then furnished to the panel participants in successive iterations. This procedure reduces the effects of personal agendas or biases and assists the panelists in remaining focused on the questions, issues, and comments at hand.

Panel characteristics and composition

The very essence of a Delphi survey is the careful selection of expert respondents. The selection of such experts for this Delphi survey is made possible by the long-standing association between The University of Michigan and representatives of the automotive industry. Lists of prospective experts were assembled for Engine, Vehicle Dynamics, and Vehicle Structures panels. Members were selected on the basis of the position they occupy within the automotive industry and their knowledge of the topic being surveyed. They are extremely knowledgeable and broadly experienced in the subject matter.

The names of the panel members and their replies are known only to our office and are maintained in the strictest confidence. Replies are coded to ensure anonymity. The identity of panel members is not revealed. All identifying information contained on any documents is stripped from the documents, which are then placed in locked storage.

The characteristics of the 100-member panels are as follows: 3 percent of the Engine Panel was composed of CEOs, presidents, or vice presidents; 18 percent were directors; 24 percent were executives, managers, or supervisors; 32 percent were engineers (senior, assistant chief, and staff), and 23 percent of the panel was made up of academic specialists and consulting technical-engineering specialists. The Dynamics Panel was composed of 3 percent CEOs, presidents, or vice presidents; 6 percent were directors; 22 percent were executives, managers, or supervisors; 38 percent were engineers (senior, assistant chief, and staff), and 31 percent of the panel was made up of academic specialists and consulting technical-engineering specialists. Among the Structures panelists 4 percent were directors; 25 percent were executives, managers, or supervisors; 58 percent were engineers (senior, assistant chief, and staff), and 13 percent of the panel was made up of academic specialists and consulting technical-engineering specialists.

Presentation of Delphi forecasts and analyses

Data tables. When a question calls for a response in the one-to-five range, the collective response is reported as a mean or average response. The mean reported is from the round of questioning that represented the consensus opinion of the experts for that question. When a question calls for a response of a number that is a percentage or a number that can range anywhere on the spectrum of possible numbers, responses are reported as the median value and the interquartile range (IQR). The median is a measure of central tendency that mathematically summarizes an array of judgmental opinions while discounting extremely high or low estimates; it is simply the middle response. The IQR is the range bounded at the low end by the 25th-percentile value and at the high end by the 75th-percentile value. For example, in a question calling for a percentage forecast, the median answer might be 40 percent and the IQR 35 to 45 percent. This means that one-quarter of the respondents answered 35 percent or less, another one-quarter chose 45 percent or more, and the middle half of all responses ranged between 36 percent and 44 percent, with 40 percent as the middle response. That narrow interquartile range would indicate a fairly close consensus among the respondents.

In contrast, the percentage forecast for a different question might show a similar median forecast of 40 percent, but with an interquartile range of 20 to 70 percent, indicating less consensus and a considerable degree of uncertainty about the issue in question.

Uncovering differences of opinion is one of the major strengths of the Delphi method. Unlike other survey methods, where differences of opinion among experts are often obscured by statistical averages, the Delphi highlights such differences through the presentation of the interquartile range.

Some questions in the report simply ask respondents to list their responses in the form of statements that describe what they think on a particular topic (for example, "What are the major areas where further research is necessary for CFD models?"). These open-ended responses are listed in alphabetical order with numbers in parentheses following a response noting whether more than one person reported the same idea. In other open-ended questions where a shorter list of responses is presented, responses are counted and a percentage of respondents who mentioned a particular item is reported.

Selected edited comments. Selected edited comments from the Delphi panelists are shown following each data table in order to provide some insight into the deliberative process by which panelists arrived at their forecast. If more than one respondent reported the same comment, a number in parentheses at the end of the comment indicates how many others reported the same comment.

In a Delphi survey, respondents are encouraged to contribute comments to explain their forecast and to perhaps persuade other respondents to change their positions. Many of these edited comments are included. These replies may provide important information that is not evident in the numerical data. An individual panelist may have unique knowledge that planners should carefully consider. However, readers should be careful not to overemphasize a particular comment. It is possible for a well-stated contrary opinion to mislead the reader into ignoring an important majority opinion that is accurately reflected in numerical data.

Summary. Narrative summaries are presented to highlight and explain a particular set of data.

Comparison of panels. The three groups of Delphi panelists (Engines, Vehicle Dynamics, and Vehicle Structures) are asked questions that specifically focus on their respective areas of expertise. However, a few questions are considered common to two or more panels. For example, the question about the percentage of cost savings that will be gained because of improved models in each of the areas is of interest to respondents from all three panels.

At times, the panels will give differing responses to these questions. This may reflect the makeup of a particular panel and the panelists' subjective perception of the issue in question. Where differences do exist between the panels, serious consideration should be given to whether the difference reflects the composition and proprietary interest of that particular panel or whether there exists a substantial degree of uncertainty regarding the issue in question. We try to highlight both the differences and similarities. The following abbreviations are used to describe each panel: Engine (ENG), Vehicle Dynamics (DYN), and Vehicle Structures (STR).

Strategic considerations. Based on the replies to a particular question, other relevant Delphi forecasts, other research and studies, and the University of Michigan's extensive interaction with the automotive industry, this report makes inferences and interpretations as to the core issues in questions and their potential impact on the industry. By no means are they exhaustive statements of critical issues. Rather, they are points that the reader might consider useful.

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EXECUTIVE SUMMARY

Studying the current and future state of modeling and simulation in the context of the global automotive industry is a daunting task. It offers researchers the chance to measure opinions on a topic that is not well understood because of the complexity of the processes involved with the vehicle. All manufacturers report that they use modeling and simulation in their design and development processes, though most suppliers do not. But the crucial differentiator among the manufacturers is how well modeling and simulation is integrated into their processes. Some managers do not place much value on modeling and some think modeling can do everything. Many of our respondents think that today there is a fundamental understanding of modeling, but not the complexity of modeling. These issues make modeling and simulation a challenging topic for investigation.

The goal of the Automotive Research Center (ARC) is to provide advanced research in the area of mobile transport and to create synergies between the government and commercial sectors. The ARC is particularly interested in developing an integrated model that reduces the time needed to make system-related decisions, to create liaisons between researchers and designers, and to refine simulations to reduce the number of physical tests needed to develop vehicles. This report provides the views of experts, allowing companies to benchmark their vision of the future against an industry consensus.

General Modeling and Simulation Results. The following results are based on the combined responses of two or more of our panels. Overall, our respondents, experts in the fields of engines, vehicle dynamics, and vehicle structures, think currently that modeling and simulation is somewhat meeting the needs of manufacturers, and will approach completely meeting the needs of manufacturers by 2006. They believe modeling and simulation has provided nearly a 30% improvement in process design efficiency over pre-simulation days, and they see another 30% by 2001, and a 40% improvement over 1996 by 2006. They also see a 20% cost savings by 2001, and another 10% cost savings occurring between 2001 and 2006.

These efficiency improvements will shorten future development cycles for new vehicles to 32 months by 2001, and 24 months by 2006. For re-designed vehicles, the development cycle will reach 18 months by 2001 and 16 months by 2006. These advances will come because of more powerful computers, software advances, a better understanding of physical processes, and designers and modelers working together. But costs will not be cut drastically, because more time will be spent examining design alternatives. Moreover, the training requirements of modelers will increase as their importance within the design and development process rises.

Some experts believe that as modeling becomes more user-friendly because of object-oriented programming, the expertise needed to model will substantially decrease. Our respondents did report a slight decrease in required expertise by 2006. But the complexity of modeling known physical processes as well as complex multiphysics processes yet to be modeled demands an intimate understanding of the mechanics and physics of an engine, suspension, or structure.

The modeling experts see defining the appropriate level of model complexity as an important issue. Unfortunately, they are not in agreement about what that level of complexity should be. One group sees the need for very complex models with a multitude of data points to generate a useful result, while another group prefers a simplified model that is less time consuming to produce and uses experimental data to supplement predictive functions. The third group thinks modelers should be able to decide when to use either. There are undoubtedly situations where each of these three levels of complexity is appropriate. However, the limitations of current computing power, which makes model building a very time consuming process, makes choosing the proper level of complexity a strategic decision.

One way modelers believe they may improve models is by using advanced systems such as expert systems, neural networks, or artificial intelligence. In both the short term (1996 to 2001) and long term (2002 to 2006), the experts believe that it is somewhat likely that these systems will see expanded use. Expert systems are more likely to see expanded use, but artificial intelligence and neural networks offer the promise of learning from experience, anticipating problems, and even creating novel approaches to modeling challenges.

A number of order reduction methods are available for reducing the complexity of models. Mesh techniques, modal analysis, and component synthesis analysis are expected to reduce model complexity by 2006. The need for these methods springs from the time it takes to develop and run models, and the very complex nature of some models, such as those that model nonlinear events.

Our respondents think it is only somewhat likely that accurate models will be created using experimental or statistical data in the long term. Experimental data relies on building prototypes to test models, a very expensive process, or using less accurate data from previous versions of a component, which reduces the model's accuracy. This type of data may be useful in simplifying models, thus making them less computer intensive, but if too much test data is used, the value of the model is lost. One issue that would be of value to all modelers would be good, available databases of current experimental data.

Accurate and reliable models will reduce the number of prototypes for a vehicle or component, which is a major goal for all manufacturers. Our panelists believe modeling and simulations will yield close to a 50% reduction in physical prototypes in the short term and slightly more in the long term. They see less of a reduction for validation and more of a reduction for development and testing. Manufacturers will always rely somewhat on prototypes because of the need to crash-test vehicles, to test the effects of new manufacturing techniques, and to test new innovations and methodologies used in a new model. But despite this continued reliance on prototypes, the number of prototypes will be fewer and will be produced later in the development cycle.

Engine Models. Engine panelists were asked their views about the accuracy of phenomenological and computational fluid dynamics (CFD) models. They think that for phenomenological models, flow rates and thermodynamic properties have reached acceptable accuracy. They believe cylinder valve geometry, heat transfer, combustion rates, turbulence, friction, and noise, vibration, and harshness (NVH) are approaching acceptable accuracy, while transient behavior still has unacceptable accuracy. In the short term, they see a moderate probability of burn rate, turbulence, mixing, and friction being accurately simulated and effectively integrated into the design process. In the long term, they see a good probability of this for burn rate and friction, and a moderate probability for turbulence and mixing.

The experts' predictions for CFD models are similar to those of phenomenological models. This is a curious result because CFD models are newer and more complex. In terms of cost, phenomenological models are more economical than CFD models in the short term, but in the long term both models have good probability of producing economical models.

One of the challenges of engine modeling involves moving from a steady state model that represents a snapshot of the engine to a transient model that represents the dynamics of a moving engine. The advantages of transient models include better accuracy and more realistic simulations. But the disadvantages include 1) increased computational resource requirements, 2) an added level of complexity that makes model building more difficult and time consuming, and 3) the difficulty of defining boundary conditions. In the short term, phenomenological models offer a higher probability of producing accurate models for both steady state and transient models, but in the long term, CFD models equal phenomenological models for steady state models and do better for transient models.

In the area of emissions models, experts ranked NOx, carbon monoxide, hydrocarbons, and particulates in this order for developing accurate models of them in the long and short terms. Spark-ignited engines are consistently given a higher probability of having accurate emissions models than are diesel engines. The experts noted that cycle-to-cycle variations were the most difficult to incorporate into an emissions model, followed by knock, mixing, spark advance, EGR (exhaust gas recirculation), and compression ratio.

Two of the biggest challenges for engine modeling include incomplete knowledge of the physics involved in gas dynamics, and large-scale fluid modeling. One technique that offers promise for modeling the internal processes within the cylinder is flexible grid CFD models that expand and contract within the cylinder to give a more accurate view of internal cylinder conditions. As with all other models in the short and long term, a major trade-off will be between the time needed to model (speed) and the complexity of the model.

Vehicle Dynamics Models. On specific issues concerning dynamics models, our panelists currently report acceptable accuracy only in the modeling of handling, and close-to-acceptable accuracy only in the modeling of ride quality. Durability, off-road behavior, friction, and ground/tire interactions all have unacceptable modeling accuracy. The panelists believe models focusing on higher frequency vibrations, dynamics of the human body, and the load path to driver and passengers are unacceptable currently. However, they will reach near acceptable accuracy by 2001 and acceptable accuracy by 2006.

Incorporating flexible components is also an important issue for dynamics modelers, and the experts feel confident they will be able to incorporate them in the short term. They see the major roadblock being time, as measured by a lack of computing power, rather than the theoretical models necessary to model component behavior. This lack of computing power was also noted as a constraint in modeling nonlinear behavior and for developing real-time simulations (However, a reduction of model complexity would improve the possibility of real-time simulations).

One of the stretch goals of dynamics modeling is the inclusion of driver-in-the-loop simulations. These simulations will include ride, handling, driver interaction and response in emergency situations, design of interior space, and sound. Besides these driver-related issues, three very interesting potential uses for driver-in-the loop models emerged: the ability to model the impact of safety regulations before they are legislated, a better assessment of the usage/duty cycle of a vehicle, and the ability to fine tune the design to a particular driving population.

Finally, the dynamics experts offer a array of needed improvements in dynamics modeling, from the general (improved nonlinear behavior models, hierarchical models, statistical energy models, and distributed parameter systems) to the specific (models for vehicle/tire-to-road interaction, friction, bushings and flexible joints and bodies, human interface, and shock and vibration). Vehicle/tire-to-road models were mentioned most frequently as specific models in need of improvement, followed by bushings and flexible joints and bodies, friction, and models involving a human interface.

Vehicle Structures Models. Modeling structures has become more important as new vehicle designs have become stiffer structurally. The panelists project that these models will reach near acceptable accuracy within the next five years and exceed acceptable accuracy within the next ten years. They believe the current tools for modeling structures are sufficient, but the lack of computing power, the need to create new models for nonfrontal collisions, and understanding the properties of composite materials offer the greatest challenges.

The Structures experts think durability and fatigue models have less than acceptable accuracy currently, but will reach acceptable accuracy within the next five years. They also believe simulating noise, vibration, and harshness (NVH) has only a moderate probability of being accurately modeled within the next five years, but a good probability within the next ten years. The key issue for simulating durability, fatigue, and NVH is the ability to model nonlinear effects such as friction, contact boundary conditions, excitation models, connection models, and damping.

Crash simulations, which are unique to structures modeling, are at near acceptable accuracy today, reaching acceptable accuracy by 2001, and attaining a high level of accuracy by 2006. The panelists estimate that crash models currently have reduced costs, lessened development time, reduced prototypes, and improved the quality of design. They think these improvements will continue in the future, reducing costs by about 25% by 2006, development time by 22%, prototypes by 35%, and improving design quality by 30%.

Finally, the Structures panelists noted the conflict of building models and incorporating the results into the development process. Asked if modeling was used in a timely manner in the development process, panelists equally responded yes, no, and sometimes. They noted the conflict between modelers who think the computers they use are too slow to generate the results to fit into the tight timelines of the development process, and the designers who make fast changes and need modelers to rerun time-consuming, complex models. This disconnect between the two groups will lessen as computers become faster and managers learn to better integrate modeling into the design process.

Vehicle Integration Models. We asked questions in this section of all three expert panels. When we asked the likelihood of having complete engine, powertrain, vehicle dynamics, vehicle structures, and full vehicle models, the experts tended to be less optimistic about the possibility of complete models in their area of expertise. Overall, respondents believe it is somewhat likely we will have complete engine, powertrain, vehicle dynamics, and vehicle structures models by 2001, and it is nearly likely we will have complete engine, powertrain, and vehicle dynamics models by 2006. They think it is likely we will have a complete structures model by 2006. All three sets of experts believe it is at least somewhat likely that a complete vehicle model will be available by 2001, but by 2006, the Dynamics experts feel a complete vehicle model is somewhat likely, and the Engine and Structures experts think it is likely.

The experts all thought a complete vehicle integration model would be valuable, but they added some important caveats. It will be valuable if it is useful, if it gives insight into how systems interact, and if it gives insight into extreme events. They also mentioned some of the challenges of such a model: 1) its complexity could lead to wrong conclusions, 2) it requires a large group of engineers dedicated to maintaining and interpreting the models, and 3) most problems can be solved by just looking at subsystem models.

Some respondents see the integration of submodels as a potential opportunity to better understand their effects within the context of a larger integrated model. The integration of engineers from different disciplines may also yield important synergies between the disciplines.

The experts feel that the fidelity of vehicle integration models is low today, but they think it will reach moderate fidelity by 2001 and near high fidelity by 2006. This same pattern applies to how the experts feel about multiphysics problems (for example, the combination of fluid dynamics and heat transfer). They see the ability to solve these problems as insufficient today, nearly sufficient by 2001, and sufficient by 2006.

Finally, the decision by the manufacturers to move more of the development of components or systems to their suppliers adds a constraint on modeling and simulation. The manufacturers will continue to design the vehicle, but outsourcing large systems to suppliers for product development may create a disconnect between manufacturers who are working on vehicle integration models and suppliers who are working on subsystem models. Another challenge for suppliers will be developing the staff and expertise to take over some of the subsystem modeling that goes into designing their component or system. There be may also be costly duplication of effort between the manufacturers and suppliers and also between suppliers as each models their component or system. These issues represent some of the major challenges facing full vehicle integration and modeling in general over the next ten years. How well companies overcome these challenges may determine which companies develop vehicles that set them apart within the highly competitive new vehicle market of the next decade.

I. ENGINE MODELS

ENG-1. To what extent do present engine simulation models meet the needs of vehicle manufacturers, and will future engine models in 2001 and 2006 meet the needs of vehicle manufacturers?

Scale: 1 = needs met completely 3 = needs met somewhat 5 = needs not met at all

Engine Simulation Models	Mean Rating		
	1996	2001	2006
Closeness to meeting needs	3.1	2.6	2.2

Selected edited comments

Round 1

- One-dimensional (1-D) gas dynamics are very good at present and will get better.
- One-dimensional tools for thermodynamic process simulation are quite satisfying. Prediction of emissions is still not possible. Three-dimensional (3-D) tools, including intake flow, spray formation, and combustion, need substantial progress in improved models, numerical schemes, preprocessing, post processing, and reduction of CPU (central processing unit) time.
- With time, modeling will improve, but expectations will increase almost as fast. Also, engine complexity (and legislation) will require more complicated models in the future.
- It is not possible to meet needs in this area "completely." Current models are good, but lack integration. Fully integrated models are lacking in detail and fundamental physics.
- As of today, basic performance of the engine could be almost available like fuel consumption, horsepower, combustion analysis; but according to the further progress of simulation modeling, in 2006, every engine can be designed and optimized in the computer.
- Soot and hydrocarbon models for diesel and spark ignition engines need upgrading.

Summary

Not surprisingly, the panel believes that the current state of engine simulation meets the needs of industry "somewhat," implying that there is much room for further development and refinement. Although progress in this area is expected to continue fairly steadily, even by the year 2000, there will still remain work to be done.

Although not shown above, another interesting aspect of the panel's responses is the high degree of consensus among them. For the year 1996, nearly two-thirds of respondents (65.9%) rated the status of engine simulation as a "3," while another quarter (24.4%) gave a response of "4." The consensus continued through their predictions for 2006, where 67.5% rated engine simulation development at "2," with 15% and 10% giving it a "1" or a "3," respectively.

Comparison of forecasts: Dynamics - 1 / Structures - 1

A comparison with other panels' forecasts of the adequacy of simulation of other vehicle design aspects show a closer link to engines and vehicle dynamics compared with vehicle structures. Progress in modeling vehicle structures is expected to be greater over the next ten years than for engines or vehicle dynamics, most likely due to the number of moving parts in the latter two categories and the complexity of interactions among them.

Scale
1 = needs met completely 3 = needs met somewhat 5 = needs not met at all

Closeness to Meeting Needs	**Mean Rating**		
	1996	**2001**	**2006**
Engines	3.1	2.6	2.2
Vehicle Dynamics	3.0	2.7	2.4
Vehicle Structures	3.0	2.4	1.9

Strategic considerations

Accurate, detailed simulation of engine design, as well as other facets of automotive design, represents a significant source of competitive advantage. Therefore, the continued development of the simulation software capable of capturing and describing the structure, motions, functions, emissions, and other important aspects of engine design and performance represents a high priority for the automotive industry.

To date, the ability of such models to meet the needs of engine designers is modest, and progress is expected to be steady, if undramatic, over the next decade. By the year 2006, engine simulation software is expected to meet the needs of engine designers much of the time, but gaps in capability are expected to remain. The complexity of such software is exacerbated by the constant stream of innovations in engine design, changing performance requirements (including emissions and the appearance of new categories of vehicles) and the desire by automakers to be able to supply consumers with an increasing variety of so-called niche vehicles. Thus, in the face of this perpetually moving target, creators of engine simulation software can expect their challenges to expand as time goes on.

ENG-2. What percentage improvement do simulation models add to engine process design efficiency currently (relative to presimulation days), and what improvement over the current state should we expect by 2001 and 2006?

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	30%	40%	25%/30%	25%/30%	30%/40%

Selected edited comments

Round 1

- Analytical techniques have probably halved design/development cycles, hence, 100 percent improvement.
- Modeling will improve, but real gains in efficiency associated with modeling will come from better (proper) use of modeling as a tool. Education of the analysis community and their customers will allow them to use it effectively.
- The development goals/targets increase from 1996 to 2006 due to (1) reduction of fuel consumption and emissions, (2) customers needs and wishes, (3) cost/competitive situation.
- If we eliminate most of the experimental work of new engine design, I estimate half of the development period could be shortened.

Round 2

- If we use simulation models properly, we could reduce the number of design iterations at least 25 percent, and the engine process design efficiency could be improved at least 25 percent.

Round 3

- Advanced analysis does not cut design time so much as it improves quality and understanding of the product.
- Many of the real gains in efficiency have been realized. In the future, productivity may rise because models may have more features and will be more comprehensive.

Summary

When asked to compare the efficiency of the engine design process using today's simulation techniques with that of a recent time prior to the introduction of simulation, a strong majority (74.0 percent) of panel members estimate a 25 to 30 percent gain, with the median value at 30 percent When anticipated results by the year 2006 are compared to present-day efficiencies, a median value of 40 percent is foreseen.

Comparison of forecasts: Dynamics - 2 / Structures - 2

Though the Dynamics and Structures panelists answered this question in terms of overall vehicle process design efficiency instead of engine process design efficiency, their responses show a strong positive trend in design efficiency gains (See DYN-2 or STR-2).

Strategic considerations

The use of simulation in the design of engines has led to significant gains in efficiency in the design process during the 1990s, but as the results of question ENG-1 indicate, there is potentially much more to be achieved. The panel sees continued significant improvement in efficiency as a direct result of simulation over the short term (1996 to 2001). Five main factors appear to contribute to this result: more powerful computing hardware; developmental advances in the software itself; the ability of designers and engineers to work simultaneously during the design process; a better understanding of the physical processes involved; and more effective use of software features as designers move up the experience curve.

Somewhat surprising, however, is the panel's comparative pessimism regarding continued efficiency improvements over the longer term (2002 to 2006). While the forecast for the previous five years called for an overall improvement of some 30 percent, only an additional 10 percent growth in efficiency is seen during this period (or a total of 40 percent for the entire 1996-to-2006 period). The explanation may lie in some of the comments. Over the short term, almost all the benefits of human efficiency improvements may have been realized, with only incremental developments in hardware and software accounting for the longer-term advances. Another issue is that the internal transient processes of engines are very complex.

ENG-3. What percentage improvement in cost savings do modeling and simulation models add to engine process design efficiency currently (relative to presimulation days), and what improvement over the current state should we expect by 2001 and 2006?

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Cost savings	20%	20%	30%	15%/25%	15%/20%	25%/30%

Selected edited comments

Round 1

- Present-day simulation saves the company on the order of millions of dollars.
- Modeling will improve, but real gains in efficiency associated with modeling will come from better (proper) use of modeling as a tool. Education of the analysis community and their customers will allow them to use it effectively.
- Downstream costs in redesign and rework are replaced by upstream costs in analysis. The net effect is not as great as one might hope.

Round 2

- The importance of design efficiency depends on not only model sophistication, but also on effective utilization.

Round 3

- Cost savings will come primarily as improvements in computer hardware — raw number-crunching power.
- Today, it is very common for a full modeling study to be done, and a few design possibilities are recommended. The engineer(s) then proceed to test all possibilities because he/she doesn't trust the analysis results.

Summary

Responses for current estimates of cost savings associated with computer simulation relative to pre-simulation methods ranged greatly, from zero to 40 percent; however, they formed a distinct bell curve with the peak at 20 percent. Unlike the usual situation, however, distance into the future led to greater consensus: For 2001, fully 76 percent of respondents believe that, relative to 1996, savings will come to between 20 and 25 percent, and a similar 76 percent see the figure rising to 25 to 30 percent by 2006.

Comparison of forecasts: Dynamics - 4 / Structures - 4

Even though Dynamics and Structures panelists were asked about the cost savings associated with vehicle design efficiencies and the Engine panelists answered about cost savings associated with engine design efficiencies, all three groups see significant savings to be gained in their respective areas.

Strategic considerations

The two general areas for improvement of greatest interest to automotive manufacturers are total development cycle time (see ENG-8) and cost. Reflecting the results of question ENG-2, the panel expects significant additional cost savings during engine design to accrue from simulation. To date, relative to designs created without the benefit of simulation, such savings have amounted to an estimated 20 percent; an additional 20 percent is expected to occur over the next five years. The sources of these savings stem not only from direct factors (e.g., hardware/software improvements, improved interactions among designers, etc.) but also from downstream benefits arising from better designs (e.g., more efficient manufacturing processes, less rework, reduced offal, etc.). However, these benefits may be mitigated somewhat by increased costs, both up front (investment in hardware/software, database establishment/updating) and ongoing (more time spent examining design alternatives, increased training requirements, salaries of higher-skilled employees, etc.).

However, as with expected efficiency enhancements, the panel foresees a marked slowdown in the rate of savings derived from the use of simulation for engine design, yielding only an additional 10 percent over the subsequent five years ending in 2006. As in ENG-2, the answer behind this appears to be the completion of movement up the experience curve by designers, eliminating this as a source of continued cost reductions.

One issue that is not addressed in this question concerns increased levels of performance, complexity, and accuracy and how they will affect modeling and design costs over the next ten years. Will increasing levels of performance, complexity, or accuracy decrease potential cost savings due to modeling because of the need to increase the time to program the models, add personnel, or purchase new equipment and/or software to reach these higher levels? Or will the manufacturers continue, as they do now, to test new models, but only use models that offer a clear reduction in time and cost? From a competitive standpoint within the modeling industry, there may also be significant differences in the capability of some models or programs, which may be better than other programs and thus offer greater benefit.

ENG-4. **To what extent does your company currently use simulation models to predict the following, and to what extent do you see your company using them in 2001 and in 2006?**

Scale 1 = used very often 3 = used somewhat often 5 = not used often at all

Use of Models, by Application Area	Mean Rating		
	1996	2001	2006
Combustion	3.4	2.5	1.9
Component Thermo Loads	3.2	2.4	2.1
Cooling Requirements	3.3	2.6	2.0
Emissions	3.7	2.8	2.1
Fluid Dynamics	2.9	2.1	1.6
Friction	3.8	3.1	2.5
Lubrication	3.8	2.9	2.4
Mechanical Loads/Stresses	2.9	2.5	2.3
Noise/Vibration/Harshness (NVH)	3.4	2.7	2.1
Performance Estimation	2.1	1.8	1.7

Selected edited comments

Round 2

- A high level of expertise will be needed because modeling will become more complicated. However, modeling users should be experts on engine design.
- The NVH (noise, vibration, and handling) area is very difficult and can hardly be simulated.

Summary

Most panel members still see only limited use of simulation today among the various application areas. For 1996, panel responses tend to average between 3.2 and 3.8. Exceptions were submodels for fluid dynamics and mechanical loads (each with a mean of 2.9, implying somewhat frequent usage), and, most significantly, performance estimation (with a mean of 2.1, implying fairly frequent use). Respondents foresee a much greater reliance on these submodels in the future, probably tied to better performance as development work continues. By 2006, rankings are expected to lie between 1.7 (performance estimation) and 2.5 (friction), indicating fairly widespread use of all the submodels listed above.

Strategic considerations

Despite the potential benefits described in the previous questions, most simulation models for engine design thus far have been only modestly exploited; the lone exception is simulation for performance estimation. Although few comments were provided in this question, it appears clear that the primary reason for this underutilization is the lack of what is considered adequate development and predictive capability of these models.

Nonetheless, with the promises of a more efficient design process and enhanced cost savings, use of all the listed categories of models is foreseen to rise, though slowly in some cases. The extent of acceptance by the year 2006 appears linked to the degree of complexity of the subject of each model. Those models used to describe fluid dynamics and performance will be widely employed, whereas models to simulate friction and lubrication characteristics (to date, notoriously poorly understood, complicated, and data-intensive) will probably find major application in "rough cut" estimates at the outset of the design process. (For further discussion, see ENG-6 and ENG-10.)

ENG-5. What is the level of software modeling expertise needed by users to design engines in 2006?

Scale: 1 = high level of expertise 3 = medium level of expertise 5 = basic knowledge

Software Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	1.9	2.3	2.3

Selected edited comments

Round 1

- Only models that require the medium level of expertise will come into wide use.
- Users who apply engine simulation to engine design should be experts, in order to avoid misunderstanding of calculated results.
- Really good software is object-oriented and easier to use.
- Engine designers are specialists. We will always be experts. Modeling will make the process faster, more reliable, not easier.
- Widespread use depends critically on user-friendly codes.
- High levels of expertise will be needed only for people who are concerned with model improvements. Designers of engine need only a medium level of expertise. That will not change with time.

Round 2

- As software improves (both in functionality and ease of use) only medium level of expertise should be required. Experts will still be required in a supervisory role.
- For the time being, users who apply engine simulation to engine design should have a combination of high-level knowledge in simulation, to avoid misinterpreting calculated results, and appropriate expertise in design. However, with future software, the requirement of both simulation knowledge and design expertise will be relaxed quite a bit.

Summary

As has already been witnessed in other applications of software, panel members expect that, although a fairly high degree of expertise is currently required to run simulation software, this level will be relaxed somewhat by 2001, remaining relatively constant through 2006. However, even this "relaxed level" will call for an above-average degree of familiarity with the inner workings of the simulation package, and will still be inaccessible to a novice.

Comparison of forecasts: Dynamics - 5 / Structures - 5

Although the results across the different model categories of this study are not directly comparable, due to the unique expertise requirements of each, it is nonetheless worth noting that, in each case, expertise requirements are relatively high and are not expected to be reduced greatly over the course of the next ten years.

Scale: 1 = high level of expertise 3 = medium level of expertise 5 = basic knowledge

Software Modeling Expertise Needed	Mean Rating		
	1996	2001	2006
Engines	1.9	2.3	2.3
Vehicle Dynamics	1.5	2.0	2.4
Structure	2.0	2.2	2.7

Strategic considerations

Although it is reasonable to anticipate more user-friendly, object-oriented simulation software in the future, mirroring trends elsewhere in software development, the panel expects that users will still require a significant degree of expertise to be able to operate the software effectively in the design of engines. Given the ever-increasing complexity of engines themselves, along with the myriad of variables needed to describe geometries, motions of engine components, and internal processes, designers will still need to intimately understand the mechanics and physics of engines, as well as the intricacies of multidisciplinary simulation software used to describe everything from combustion to mechanical stress to friction. Thus, while friendlier interfaces and greater use of standardized components will help reduce the demands on designers somewhat, the effect on needed expertise will be limited.

ENG-5a. Some modelers also see a trend toward extensive use of neural networks, expert systems, and artificial intelligence (AI) systems as playing an increasing role in vehicle simulation. What is the likelihood of expanding the use of these systems in the short term (1996-2001) and the long term (2002-2006)?

Scale: 1 = very likely 3 = somewhat likely 5 = not very likely

Use of Neural Networks, Expert Systems, and Artificial Intelligence	Mean Rating	
	Short Term 1996-2001	Long Term 2002-2006
Neural Networks	3.4	2.5
Expert Systems	2.1	1.8
Artificial Intelligence	3.4	2.7

Selected edited comments

Round 2

- Does not contain enough predictive power.

Round 3

- Before these (neural nets, expert systems, AI) are put to use, a lower level of general purpose optimizers will play a bigger role.
- There will be a trend in the use of simple models (quick and dirty) at the early design process to compare general design alternatives.

Summary

There seems to be little doubt that some degree of expert systems and/or artificial intelligence will enter the engine design process by 2006. However, these technologies apparently continue to have a long way to go, even by 2006. In looking at the coming five years, 84.6 percent of respondents rate the usefulness of expert systems at either "3" or "4," indicating that needs are not expected to be met; an identical percentage said the same about artificial intelligence. For neural networks, a technology just getting off the ground, fully 80 percent provide ratings of "4" or "5" – almost no usefulness whatsoever.

In the longer term (2002 to 2006), the situation is expected to improve a bit. Some 92.3 percent of the panel foresee expert systems deserving a "2" or a "3," indicating a fair amount of employment, though significant development work will remain. With regard to artificial intelligence, nearly two-thirds (65.4%) give it a "3," indicating that needs will be met "somewhat." Neural networks, not surprisingly, are foreseen to be still lagging, with over three-quarters of respondents giving it a "3" or "4" ranking.

Comparison of forecasts: Dynamics - 8 / Structures - 6

The panelists are fairly divided in their visions of when expanded use of these advanced techniques will occur. In the short term, of all three techniques, only the Engine experts believe that expert systems are likely to play an expanding role in vehicle simulation. In the long term, all three panels feel that expert systems are more likely to play an expanding role, and the Structures and Engine panelists both think neural networks and artificial intelligence are at least somewhat likely to play an expanding role in vehicle simulation.

Likelihood of Increased Use of Alternative Systems		
System	Mean Rating	
	Short Term 1996-2001	Long Term 2002-2006
Dynamics Panelists		
Neural Networks	4.0	3.5
Expert Systems	3.4	2.8
Artificial Intelligence Systems	3.9	3.3
Structure Panelists		
Neural Networks	3.7	2.6
Expert Systems	3.2	2.5
Artificial Intelligence Systems	3.3	2.8

Strategic considerations

Expert, or rule-based, systems are already being employed rather extensively in the automotive industry as an increasingly important tool in vehicle design. Such systems help designers in routine functions, such as selecting from inventories of standard part geometries, but have limited analytical or predictive capabilities.

AI and neural networks remain a long-term goal of computer science. AI software and neural net hardware hold the promise of programs and machines that can "learn" from experience, "anticipate" problems, and even "think" of novel approaches to surmount unexpected problems. Development of these technologies could lead to a reduction in the level of expertise needed by engine designers, because much of the necessary knowledge would reside within the machine. However, despite significant advances, true AI and neural nets are unlikely to develop far enough within the next ten years to find wide use in the automotive industry.

ENG-6. There is a debate in the modeling community about the need for complexity in modeling engines. One side argues that a model must incorporate as many variables as can be measured when defining a model, while another side says that a model should be more simplified in nature, concentrating efforts in understanding the variables that have the most effect on the model. What do you feel is the necessary level of complexity in engine modeling?

Response	Percent of Respondents
Simplified	32%
Complex	22%
Both / Hybrid	41%
"It depends..."	5%

Simplified Models:

- Model should only contain necessary physics (i.e., "simplified in nature").
- There are two major difficulties in engine modeling: (1) The complex shape of engine, and (2) physical phenomena in engine. For (1): Compromise in shape cannot be made so that the software with a pre-post system will become popular. For (2): It will take the longest period of time to solve combustion. In general, the model should be as simplified as possible.
- The simplified approach is probably more appropriate when it is combined with appropriate empiricism. The engine phenomena are too complex to be modeled from first principle. Some of the details are never to be verified. The complexity usually does not substantially improve the prediction, but adds uncertainty as to values of model parameters.
- A model should be more simplified if the model is utilized for engine design, because the model should be used in the stage of trial manufacturing, and designers would need results of parametric studies quickly. At the latest stage of manufacturing, fine design should be performed by experimental results.
- Using rational simplifying assumptions in the physics is okay; however, all relevant processes must be represented.
- The effort should be concentrated on understanding the variables that have the most effect on the model. The assumptions of what are the most important variables should then be checked with experimental results.
- Engine modeling should be used to find dominant factors and optimum variables of an engine for an objective output (power and exhaust emissions). In the current computer situation (in terms of cost and performance), the engine model which includes several models of each engine process, such as intake-air and exhaust-gas dynamics, fuel supply combustion, heat transfer, and so on, should be simplified, since the integrating detailed each process model requires huge memory storage and very fast calculation speed by the computer.
- Only include variables which have a significant effect. Second-and third-order effects should be avoided when possible.
- The variables that are of primary importance have to be considered first, neglecting the variables with secondary importance. But the important variable cannot always be measured!
- A model should be more simplified in nature. It should be oriented to the user.

- Model complexity should be kept to a minimum level necessary to address specific technical problems. "General" models are not welcome, since they tend to unfocus attention.
- We should always try to include the main physical variables. If we do not, we are in grave danger of incorrect prediction of trends, etc., as fundamental interactions are not modeled.

Complex Models:

- There should be an ever-growing level of complexity and detail driven by our increasing knowledge and growing power of computers.
- All models are approximate, but as they become validated, they can include more detail. All models should have balanced assumptions and details. A more detailed approach is favored whenever it is justified by the questions, and if it is affordable.
- We need to continue moving toward complexity to fully define phenomena and possible solutions.
- Models are still not able to capture much of the fundamental physics of engine behavior. Thus, we need to push them to be as complex as possible. At the same time, they need to be usable with calculations taking minutes of computing time. Otherwise, the usefulness in the design process is greatly reduced. Thus, there is a need for multilevel models – complex, computationally intensive, and very simple guides for designer's use.
- In an ideal sense, it is better to conduct modeling with as many variables as you can. People can design and develop in the computer a "whole new engine."
- Engine modeling is a highly complex task by its own nature. The constant growth in computing power and efficiency and reliability of software modeling applies to engine models which will involve many different aspects, turbulent combustion and fluid-structures interaction, to cite but a couple. More complex models are needed because the engine itself is complex.
- Models will become more and more detailed including more and more realistic effects. This includes modeling of external engine components.
- Concentrating efforts in understanding the variables mostly affecting the models is first priority. When this problem has been solved, adding more variables can help to better simulate the reality.

Hybrid/Both Models:

- There are different tools necessary in the different stages of the design process. The range to be covered is from first conceptions of vehicle/ powertrain/engine interaction all the way up to detailed chemistry using 1,600 equations to discover the soot mechanisms.
- Both — simple for "order of magnitude" studies and complex for "fine tuning" and advance design.
- I am a big believer in hybrid models. You use extensive complexity for only small parts of the problems. Actually, the current state-of-the-art of engine models is quite adequate for engine design. Belief in models is what is needed!
- For fuel economy simulation, models need to be more global and less detailed. For combustion study, one needs detailed finite element model (with many variables). Both are needed.
- Models are required to be both simple and highly accurate — at this stage, it's one or the other. Existing codes (i.e., wave) can cope with this by allowing different levels of detail (low to high) with corresponding levels of accuracy (low to high).
- The issue is one of turnaround time. If simulation time is less than 30 minutes, we can run an optimizer. If it is less than 24 hours, we can choose design alternatives. If it is greater than 2 weeks, modeling is used to diagnose broken prototypes.

- Models should be simple for first-trend analysis, but they must also have the capacity for detail analysis, with all influences factors incorporated.
- Both sides are right. Very simplified models are sufficient for some purposes, and the most complex models available are still inadequate to describe the physics in other cases. Engineers must use sound judgment in choosing the right model for the application.
- Both: a) for insight; b) for real design.
- Phenomenological models have a place when working within known boundaries. Highly detailed models are the only way to explore new operating regimes.
- The complexity in modeling engines depends on what you expect. For a design engineer who expects simulation results quantitatively (e.g., NOx (nitrous oxide) is predicted to go down 1% from 5.0 g/bhp-hr to 4.95 g/bhp-hr), the second argument is relevant, concentrating on the variables that have the most effect on the model. On the other hand, for a research engineer who expects simulation results qualitatively (e.g., simulation results indicates that NOx formation is related directly to the adiabatic flame temperature, the first argument, incorporating as many as variables as when defining a model, is appropriate.
- If simulations are going to be used to evaluate new concepts, i.e., to simulate complete engine system (performance studies, control studies, etc.), the second approach will be more efficient. The first approach is needed for detailed studies of more fundamental nature.
- There is room for models of varying complexity. One should use the simplest tool consistent with the level of detail sought.
- The basic flow and temperature distribution under the hood can be obtained without much detail. In-cylinder flows, especially combustion, require high levels of detail, and thus are intractable today.
- There is increase complexity during design phase. In the concept phase, few variables better guide the answering of general questions. In the detailed design phase, more variables available increase the possibility of detailed modeling and prediction.

"It Depends....":

- Requires judgment between computing power today and tomorrow and use to which model is to be put.
- Design time schedule dictates complexity of a model. Model has to simulate reality as well as possible in a given time frame.

Summary

The dominant theme among panel responses seemed to be one of pragmatism over theory. Although 22 percent of respondents feel that emphasis should be placed on developing complex, comprehensive models employing perhaps hundreds of thousands of variables, a greater number (32 percent) express the opinion that simpler, perhaps less precise but better understood, models would be of greater practical value. Still, the plurality (41 percent) believes that there is a role for both types of models, depending on what is being examined, and that development work on both – either in the form of a hybrid model or separate submodels – should continue.

Comparison of forecasts: Dynamics -6

The Dynamics panelists responded almost identically to the Engine panelists with the majority noting many different situations that demand a flexible view of modeling.

Strategic considerations

Continued development of complex models, such as those simulating engine performance, have spurred a controversy regarding the level of detail needed to adequately capture and describe the phenomena occurring within the engine. Three schools of thought have arisen around this issue. One camp, led largely by academics, prefers to describe such phenomena as friction by employing hundreds of thousands, or even millions, of data points in order to fully predict its source and effects. These data must necessarily include such factors as geometry, materials, motions, etc. — a daunting task that remains years away from possible fruition. The opposing camp, spearheaded primarily by end-users in the automotive industry, asserts that while this level of detail would be useful to have, not only would an enormous amount of effort be needed to develop the software, but also the man-hours needed to measure and input the necessary variables and the CPU required to run the model would make it prohibitively expensive and time-consuming to use. Instead, they propose a simplified model that would utilize some degree of real-life experimental data to supplement the predictive functions, thereby reducing model complexity. However, this would require either physical prototypes or older data based on previous engines in order to obtain the experimental data, which would require more time and materials, and possibly introduce more error into the system (see ENG-10). The third camp favors a compromise approach: a model that has the capability to perform detailed theoretical analyses with a minimum of experimental data, but that can also be "switched" to perform in a faster, less detailed, more streamlined mode as desired. This would allow the end-user to decide upon the most efficient use of the software, although it will place greater strains on software developers to refine their products to permit this flexibility.

ENG-7. One of engine modeling's potential uses is to reduce reliance on physical prototyping for development and validation purposes. Please indicate how much of a reduction in physical prototype iterations should be expected in the short term (1996 to 2001) compared to presimulation days, and the long term (2002 to 2006) relative to the present.

Scale: 1 = close to a 100% reduction 3 = about a 50% reduction 5 = very little reduction

Reduction in Prototyping Activity	Mean Rating	
	Short Term 1996-2001	**Long Term 2002-2006**
Prototype Iterations for Validation	3.5	2.8
Prototype Iterations for Development	3.8	2.9

Selected edited comments

Round 1

- As the models develop better, all the knowns are accounted for. The prototype iterations and developments are for the "known-unknowns" and "unknown-unknowns." Therefore, there will be very little reduction.
- As confidence is gained in the results of models, fewer iterations will be built for development. Due to complexities beyond engine models (i.e., process variation, tolerance stack-ups), models will never replace validation testing.
- Prototype iterations strictly for "validation" are very rare.

Round 2

- The models will be sophisticated in the future. However, drastic reduction in physical prototype iterations should not be expected, because new technology will be introduced.
- There are certain engine phenomena which are not quite understood today. These areas need much more research before reliable, predictive models become acceptable to designers.
- While the number of iterations has reduced, the number of confirmatory tests has, if anything, increased. The overall number of prototype units required for programmers has not reduced in proportion to the number of iterations.

Summary

For Validation: There is a strong opinion that, in the short term (1996 to 2001), there will be only modest reduction in the number of physical prototypes used for validation. Among the respondents, nearly 96 percent provide answers of "3" ("about 50 percent reduction") or "4." Over the long term, however, there is a distinct upward shift, with three-quarters of respondents answering "2" or "3." The consensus opinion is that, by 2006, the reduction in prototypes will be greater than 50 percent compared to 1996 levels.

For Development: Although the degree of consensus isn't quite as uniform, the panel's opinion is also for great improvement in the reduction of physical prototypes needed for engine development. Although short-term reductions are seen as limited, they are predicted to total over 50 percent of 1996 figures over the long term.

Comparison of forecasts: Dynamics - 9 / Structures - 10

Although the Dynamics and Structures sections of this survey also addressed the issue of prototype reductions, it focused on the reduction of prototypes of the full vehicle while this question considered only the engine.

Strategic considerations

According to the panel, by the year 2006, the number of engine prototypes needed during design and development will be only one-third to one-quarter the number used at the beginning of this decade. In practical terms, this translates to a minimum of one prototype per engine model (manufactured near the end of the design cycle) to prove out design concepts and validate the design. This result holds the potential for significant reductions in the time and cost required for engine development, as prototypes are relatively time-consuming endeavors (see ENG-8).

ENG-8. **Please give your expectations of current and future development cycle times (in months) — from concept approval through production initiation — for both new and redesigned engines.**

Development Cycle (months)	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
New engines	48	36	30	48 / 48	36 / 36	27 / 30
Redesigned engines	24	18	16	24 / 24	18 / 20	16 / 18

Selected edited comments

Round 2

- Absolute program timings are heavily influenced by individual vehicle platform requirements.

Round 3

- Redesign time depends heavily on program content.
- As time goes on, powertrains will be required to do more and more (performance, fuel economy, emissions). So more time will be required even as we become more efficient.

Summary

Simulation is predicted to have a profound impact on product development cycle times for both completely new and redesigned existing engines. For new engines, average development time is foreseen as falling from 48 to 30 months, a reduction of 37.5 percent. Similarly, redesigned engines are expected to require 33.3 percent less time, going from 24 to 16 months. Obviously, these numbers represent composite figures, with times for individual engine models varying slightly or greatly, depending on features.

Comparison of forecasts: Dynamics - 3 / Structures - 3

Though the Dynamics and Structures panelists answered this question in terms of overall vehicle development cycles instead of engine development cycles, their responses show a strong positive trend in the reduction of future development cycles (See DYN-3 and STR-3).

Strategic considerations

One of the issues that arises in discussions of outsourcing of components and systems to suppliers is that the manufacturers see the powertrain as a domain that will continue to be one of their strengths in terms of adding value to the vehicle (whether the consumer sees value in this proposition is still being debated in the industry). Nevertheless, the vehicle manufacturers are using the same process for designing engines as they are with vehicles, where they develop fewer stand-alone platforms and more variations off of a standard base. Fewer platforms of engines make it simpler to adapt new technologies across fewer engines, but it also makes it easier for modelers to optimize performance, fuel economy, and emissions.

As overall vehicle development cycle times shrink, pressures to shorten engine design cycles have increased commensurably. Simulation not only allows faster, more efficient design, but also a reduction in the time and cost required to be allocated for prototype manufacture along the way (see ENG-7). However, these advantages may be offset by ever-increasing demands upon engines (greater fuel economy, livelier performance, lower emissions, smaller size, etc.) requiring more novel approaches to design and, to some extent, exploring more alternatives in order to achieve performance goals.

Nonetheless, use of simulation is expected to reduce the time required to design a completely new engine by over 35 percent. This scenario permits car manufacturers to respond more quickly to shifts in consumer tastes or to react expeditiously to competitors' new offerings.

In the case of "freshened" existing models by the year 2006, engines will require the same amount of time to be updated as the rest of the vehicle structure (16 months), permitting the introduction of a "completely redesigned" engine every year-and-a-half if manufacturers think they will gain a competitive advantage with consumers or if the redesign better incorporates new emissions and fuel economy technologies that meet or exceed new regulations.

ENG-9. **Some modelers see a trend toward focusing on generic engine simulation models as a way of commonizing and simplifying the engine modeling process. What is the likelihood of expanding the use of generic engine models in the short term (1996 to 2001) and the long term (2002 to 2006).**

Scale: 1 = very likely 3 = somewhat likely 5 = not very likely

Generic Models	**Mean Rating**	
	Short Term 1996-2001	**Long Term 2002-2006**
Likelihood of expanded use	3.7	3.3

Selected edited comments

Round 1

- I'm uncertain about your definition of generic.
- I don't know the meaning of generic model.
- What is the meaning of generic in this case?
- I'm unsure of what generic engine simulation is, but if it is the elimination of detail and complexity in a model, it will not be a step forward.

Summary

This question was intended to explore the feasibility of a generic model using standardized engine component representations as a means of speeding the development process. However, as the comments above indicate, the question failed to adequately convey what was being sought, and thus no meaningful information can be derived.

ENG-10. Some modelers also see a trend toward extensive use of experimental and statistical data as a way of simplifying the engine model. What is the likelihood of expanding the use of experimental and statistical data in the short term (1996-2001) and the long term (2002-2006)?

Scale: 1 = very likely 3 = somewhat likely 5 = not very likely

Experimental/Statistical Data	Mean Rating	
	Short Term 1996-2001	**Long Term 2002-2006**
Likelihood of expanded use	3.7	3.3

Selected edited comments

Round 1

- Depends on the level of understanding of relevant physics.
- Incorporating test data in a model (i.e., hybrid modeling) has been done and is a valid way to improve accuracy and reduce complexity. If large amounts of test data are required, then the value of the model is lost (as a prediction tool).
- Experimental data is most useful to synthesize subsystem and component performance requirements. It is unlikely to be useful as a model, beyond calibrating physical constants.
- We have a race between fundamental and empirical. Whatever works best will be used at any point in time. We may assume that gradually empiricism will be reduced, but the demands on the modeler will increase.
- Models must be predictive!

Round 2

- Experimental data are necessary in order to improve accuracy and to simplify the models. Use of experimental data and statistical data are a practical way.
- Use of data can be used to validate developing models, but eventually this connection must be severed if one wishes to have predictive capability.
- Experimental results to represent the engine as a subsystem of a more complete vehicle model are often used.

Summary

The results regarding the issue of expanded use of statistical data in order to simplify an engine model are surprisingly uniform throughout the time frame in question. For both the short and long terms, panel members expect to see only limited likelihood for an increase in the use of such data, with the majority ranking the likelihood as a "4" – not out of the question, but not very probable.

Strategic considerations

As discussed in ENG-6, there continues to be a debate as to whether engine models should try to capture and describe performance entirely internally, requiring vast amounts of CPU and raw data, or whether "short cuts" in the form of experimental data obtained from prototypes or assumptions based on earlier engine models might be used to simplify models and, in the process, possibly yield both better and more timely results. As one panelist expressed it, "We have a race between fundamental and empirical."

Because of the sheer size of any model needed to predict, for example, friction, most industry respondents believe that use of experimental data is necessary to make such models manageable. However, use of such data does come at a cost: Physical prototypes must be built in order to obtain the data, countering the time savings used to justify the use of simulation, or else less accurate data from earlier versions must be massaged and used, reducing the simulation's accuracy. Further, the more experimental data must be relied upon, the less useful modeling becomes as a tool to reduce the need for experimental data.

Despite efforts of many software designers to enhance simulation's predictive capabilities, the panel actually foresees a slightly greater reliance on the use of experimental data. This is not as surprising as it might seem. As more knowledge is incorporated into these models and their complexity increases, more experimental data will be used to try to keep the models simple and less CPU-intensive.

ENG-11. What techniques do you feel offer the most potential for incorporating experimental data into engine models?

Techniques for Incorporating Experimental Data	Percentage of Responses
Use of experimental data for optimization and/or validation	31%
Expert systems/artificial intelligence/neural nets	17%
Database management	10%
Finite element analysis	6%
Enhanced statistical methodologies	4%
Cycle-to-cycle variation modeling	4%
Turbulence modeling	4%
Port/valve flow coefficients	4%
Optimum matching techniques	4%
Random or "semi-random" processes	4%
Identification model	4%
Correlation functions based on fundamental principles	4%
Detailed measurements	4%

Selected edited comments

- Using experimental data as a validation of model, some empirical correlations, such as friction, heat transfer, etc., may always be needed in the model. I see models as a way to reduce tests, not eliminate them.
- Incorporating experimental data into a model is just an attempt to make up for shortcomings in the model. Personally, I don't believe in the approach, but recognize that for some phenomena, like HC (hydrocarbon) emissions, it is all that is possible now.

Summary

Panel members suggested a virtual shopping list of techniques for incorporating experimental data into engine models. The single most popular idea appears to be to limit the use of such data to tweaking and validation of the model, rather than as a primary driver. Also mentioned often was the use of some form of expert system or artificial intelligence component to aid the designer, and the use of better database management techniques. Beyond those suggestions, respondents have their own individual perspectives, yielding the wide variety of answers listed above.

Strategic considerations

While many panel members expressed the opinion that the incorporation of experimental data into simulation models is necessary to keep the process manageable, there appears to be little consensus as to the best way to accomplish this. Some form of expert system, artificial intelligence, or neural network to help "learn" from experience was most often suggested, although advanced database management techniques and the expanded use of finite element analysis to help interpolate or extrapolate from experimental data also had their proponents. Nevertheless, the lack of a clear consensus suggests that methods to incorporate such data remain a vital issue requiring the attention of model developers.

ENG-12. Of the following process submodels for use in a phenomenological model, please rate how accurately each captures reality today.

Scale: 1 = highly accurate 3 = acceptable accuracy 5 = unacceptable accuracy

Current Accuracy of Phenomenological Submodels	Mean Rating 1996
Flow Rates	2.6
Thermodynamic Properties	2.8
Cylinder and Valve Geometry Effects on Engine Performance	3.3
Combustion Rate: Spark Ignition	3.3
Friction	3.5
Heat Transfer	3.8
Noise/Vibration/Harshness (NVH)	3.8
Turbulence	3.8
Combustion Rate: Diesel	3.9
Transient Behavior	4.1

Selected edited comments

Round 1

- Friction modeling is perhaps where a major effort should go.

Round 2

- Currently, combustion models are not too effective for predicting actual fuel burning rate.
- Inaccuracy for NVH is predicated on 1-D codes incapable of capturing turbulence-generated flow noise.

Summary

Depending on the phenomenon trying to be simulated, accuracies currently achieved by each of these submodels, in the opinion of the panel, vary greatly. At the higher end of the scale, flow rate models earn moderately good marks (84.4% of respondents rate them at either "2" or "3," indicating accuracy significantly above merely acceptable), as did thermodynamic models (80.3 percent at either "2" or "3"). At the opposite end of the scale are models predicting transient behaviors, with 82.7 percent of panelists giving scores of either "4" or "5" – clearly unacceptable accuracies. In the middle, with average scores ranging between 3.3 and 3.8 (indicating marginally acceptable accuracy, at best) were models describing cylinder and valve geometry, heat transfer, combustion rates for both spark ignition and diesel engines, turbulence, friction, and NVH.

Strategic considerations

The general theme revealed by the results from this question is that the current use of phenomenological modeling is constrained by achievable accuracy. Although models for describing flow rates and thermodynamic properties are considered at least acceptably accurate for some applications, the others still fall below this level. This question was designed to find out where the most work needs to take place in phenomenological modeling, and the following question looks at the specific challenges for each of the areas.

ENG-12a. Of the process submodels listed in ENG-12, please list the most important specific problems remaining in the modeling of each.

CYLINDER AND VALVE GEOMETRY:

- modeling of fuel droplet breakdown and evaporation process
- three-dimensionality of valve flow
- in-cylinder and valve flow interaction
- calculation of sub-sonic flow surrounding valves
- adequate empiricism for calculating the turbulent flow developed in the intake process
- wall effects in the cylinder
- manifold dynamics
- prediction of air motion, such as swirl, squish, and turbulence
- accurate valve motion dynamics
- accurate representation of combustion chamber geometry
- efficient mesh generation
- the effect of combustion chamber shape and flow field on spray penetration and impingement in diesel engines
- friction of piston components and valvetrain
- lubrication and wear of piston components and valvetrain
- thermal effects, including cooling
- a quicker way to create the geometry in the model flow structure (i.e., swirl, tumble) not predicted phenomenologically
- direct (CAD to engine simulation) modeling of cylinder head and combustion chamber geometry and effects on fuel economy, burn rates, heat transfer, emissions
- The problem for phenomenological models is not accuracy but the range of applicability. For very well-defined cases, phenomenological models can be very accurate, but they cannot be used far from their domain of validation. This is true for every submodel.

THERMODYNAMIC PROPERTIES:

- to define precise geometry of combustion chamber and piston in order to model boundary conditions
- properties of exhaust gases
- exhaust stream species thermodynamics
- fuel injection systems
- knock models suited to real fuels
- evaporation and mixing of fuel
- coupling of thermal, fluid, and mechanical models
- multi-species fuels
- combustion chemical kinetics

- thermodynamic properties of in-cylinder contents at high pressure and high temperature (especially fuel properties around and above the critical condition)
- direct injection (spark ignition and compression ignition)
- fluid mechanics
- distortions
- heat transfer
- relations with noise and vibration characteristics and thermodynamic properties
- liquid fuel wetting of walls

FLOW RATES:

- intake port and valve geometry simulation
- a priori knowledge of pressure losses of various elements
- model of in-cylinder pressure and temperature
- the behavior of complex components like turbo charger, heat exchanges, etc
- flow losses in bends/branches/Y's
- three-dimensional wave models
- multiphase flow
- heat transfer effects
- influence of dynamic discharge coefficients
- discharge coefficient models for multi-valve engines
- turbulence models
- cold start, transient conditions
- unsteady manifold flow
- cross-runner feedback

HEAT TRANSFER:

- cylinder head and bore cooling models
- turbulence models
- calculation of turbulence heat transfer
- heat transfer with in-catalyst converter
- fluid flow motions
- experimental temperature data in combustion chambers
- a very good boundary layer description is necessary
- local temperature and flow conditions
- experimental techniques are inadequate for good model validation.
- definition of boundary conditions (specifically, in-cylinder)
- accurate description of combustion chamber geometry
- simplifying mesh generation

- for diesel engines, heat transfer among air, fuel film impinged on combustion chamber wall, and cylinder liner wall
- high-temperature material properties
- accurate account of thermal environment exterior to engine (i.e., location of other hardware)
- the effect of swirl and tumble
- cylinder liner deformations
- surface roughness effects
- heat transfer between gas and cylinder wall as well as droplet-wall
- relationship between NVH characteristics and heat transfer
- Heat transfer does not dominate thermal consideration on the gas side, but does dominate cooling design through the flux from the combustion gas. We don't have good formulas for either peak values or for the flux spatial distribution. Spark ignition is in better shape than diesel. The models for the boundary layer are not reflecting the correct physics for highly turbulent cases. Minicooling can't be done without knowing the flux distribution. The flux distribution depends on the combustion model.

COMBUSTION RATE:

- effect of complicated flame geometry
- flame kernel growth
- turbulence effects on flame propagation
- chemical kinetics, including formation of various kinds of hydrocarbons
- fluid flow and temperature distribution
- spray dynamics and mixing for diesels
- air entrainment into sprays
- wall impingement effect on air entrainment
- accurate turbulence model
- heat transfer model
- accurate description of combustion chamber geometry
- fuel jet mixing and evaporation
- the effect of swirl and tumble on turbulence and flame front shape/position
- efficient mesh generation

TRANSIENT BEHAVIOR:

- intake port wall flow
- calculation of gas exchange process when the throttle valve is open/closed
- influence of rapid changes in environment of combustion; e.g., chamber metal temperatures
- simulation of temperature rise (intake manifold, cylinder head, exhaust manifold, catalyst, and coolant)
- cold-temperature kinetics
- wall wetting in parts

- wall wetting in cylinder
- knowledge of localized engine conditions
- fuel distribution in the combustion chamber
- fuel transport injection
- heat transfer
- fuel variation predicting combustion of poorly vaporized fuel/air mixtures
- vehicle load model
- boundary conditions
- ignition and quenching of fuel-air mixture
- heat flow to different components/fluid (heat distribution)
- stresses/deformations during warm-up

TURBULENCE:

- effects of turbulence on heat transfer
- turbulence's dependence on induction flow pattern
- dissipation model
- turbulence validation and distribution validation of fuel concentration should be considered to predict cyclic validation
- effect of turbulence on burning rate
- compression/expansion effects not captured
- spatial/temporal effects not well captured
- knocking simulation
- encompassing mixed models — flows with turbulent and laminar regions
- numerical schemes in engine simulation are still only of low order (first-order or sometimes a little bit more). The potential of K-epsilon is still not known
- difficult, if not impossible, to measure in engine; therefore can't correlate K-epsilon type models accurately
- This is a killer problem which may not ever be solved for engines to a point where reliable predictions can be made. We need new concepts from fundamental fluid mechanics.
- It's fundamentally not understood; turbulence is now where electromagnetism was before Maxwell.

FRICTION:

- movement of oil film
- local oil film temperature
- heat transformation of cylinder bore and piston
- understanding of flexibility/clearances in the entire system
- knowledge of hydrodynamic lubrication condition or boundary friction condition
- the effect of temperatures on friction losses, e.g., under cold start conditions
- piston ring friction — distortion and oil shear

- piston ring force — bore distortion
- valvetrain/cam lifter interface
- bearings — oil shear and distortion
- deformation of shafts
- EHD (Elastohydrodynamic) – contact and elastic understructure
- modeling of piston group/cylinder liner friction with respect of ring behavior, cylinder deformation, piston design
- too complex for phenomenological modeling; better to use experimental data from similar engines
- too complex to be simulated
- art, no science

NVH:

- model to predict cavitation onset, growth, and the influence on spray formation
- tailpipe-flow generated noise turbulence
- noise: numerical accuracy and resolution
- techniques for modeling complex components (e.g., mufflers)
- transient mixture behavior of catalysts
- better crevice flow models for hydrocarbons
- adsorption/desorption of unburned hydrocarbons processes downstream of the cylinder
- coupling of structural and acoustic dynamics models
- detailed cell effect
- engine-structure linkage
- influence of tolerances; e.g., beamings
- materials/limiting properties
- prediction/knowledge of damping levels
- valve gear noise together with engine mount and covers
- abnormal engine idle vibration

Summary

In most cases, numerous different responses were provided for each model category. In some cases, some generalities could be discerned. For cylinder and valve geometry, issues included accurate descriptions of turbulence, friction, and thermal effects, as well as better computing techniques, such as more accurate mesh generation. For thermodynamic properties, many responses centered on the properties of fuels (and how they affect mixing, evaporation, wall wetting, etc.), combustion kinetics, and the properties of exhaust gases. Heat transfer models require accurate definition of boundary conditions, description of materials properties (including deformability), and prediction of turbulence, as well as better experimental data. The major areas for concern for combustion rate models are chemical kinetics, spray dynamics, turbulence prediction, and flame behavior. For transient behavior models, the areas of concern center on fuel distribution and wall wetting, the effects of sudden temperature changes (especially regarding deformation), and boundary conditions. Problems with turbulence models include inductive and dissipation flow patterns, burn rate modeling, and the difficulties associated with obtaining experimental data, particularly figures for K-epsilon. No consensus could be formed from the results of the other model types.

Strategic considerations

When this question was posed, it was expected that responses to each category would center on perhaps two or three problems associated with each. Instead, respondents supplied numerous areas for improvement, indirectly verifying their consensus opinion in ENG-12 that most phenomenological models remain unsuitably inaccurate for use. These areas offer modelers significant opportunities to improve and add value to the engine development process. These challenges also offer both the ARC and other consortia the opportunity for collaboration with the manufacturers to solve some of these complex problems. In particular, the ARC and other consortia may be involved in pre-competitive research on these issues that will be of value to all modelers before they reach the competitive stage of development. In much the same way that the Automotive Composites Consortium under the USCAR (United States Council for Automotive Research) umbrella has developed the use of composites in vehicles, a modeling and simulation consortium could guide the study of phenomena to be modeled that are of particular interest to all manufacturers.

ENG-13. For phenomenological models, please rate the probability of having the following factors accurately simulated and effectively integrated into the design process in the short term (1996 to 2001) and in the long term (2002 to 2006).

Scale: 1 = high probability 3 = moderately probability 5 = low probability

Accuracy of Simulating	Mean Rating	
	Short Term 1996-2001	Long Term 2002-2006
Burn Rate (Diesel)	3.3	2.6
Burn Rate (Spark Ignition)	2.9	2.2
Friction	3.1	2.4
Mixing (Diesel)	3.6	3.0
Mixing (Spark Ignition)	3.6	2.8
Turbulence	3.8	3.1

Selected edited comments

Round 1

- The usefulness of phenomenological models is declining, and will continue to decline in the next decade. It is not justifiable to continue to develop these models, which, due to their global nature, are necessarily too limited to address the detailed flow processes of interest in the next decade.
- When used close to their validation domain (i.e., mainly for slightly redesigned engines), phenomenological models can already be used.

Round 2

- Heavy instrumentation in phenomenological models has a diminishing return in many areas, such as chamber and port design.
- There is slow progress in phenomenological models, due to the emphasis on CFD (computational fluid dynamics) or 3D models.

Summary

In the case of all the various phenomenological models listed, notable, if limited, developmental progress is expected over the coming decade. Particularly noteworthy is the rather high probability associated with development of an effective submodel for friction (a rating of 2.4 by 2006, with 52 percent of respondents giving a "2"), considered a key element for a larger, unified model. Other models believed to have moderately high probabilities for successful development include those for spark ignition burn rate (a 2.2 rating for the year 2006) and diesel burn rate (2.6 for 2006). Those given a moderate probability include fuel/air mixing for spark ignition (2.8 for 2006), fuel/air mixing for diesel (3.0 for 2006), and turbulence (3.1 for 2006).

Strategic considerations

Each of these listed factors represents a critical and complex aspect of engine performance. Although each is expected to advance to some degree over the next ten years, the fact that most are given only a moderate probability of being fully integrated into the design process by the end of this time reflects the difficulties associated with fully capturing all the effects taking place, as listed in question ENG-12a.

One explanation suggested by panel members for this rather unexpectedly low perception of progress may be the emphasis being placed on computational fluid dynamics modeling. Because many simulation developers view industry demand for CFD to be of paramount importance, resources for development of the more limited-capability phenomenological-based models may be diverted, slowing their progress. If this explanation is correct, it is reasonable to expect that further development will continue to decelerate beyond the forecast period, and may be abandoned altogether at some point.

ENG-14. Below is a series of process submodels for use in a CFD-based model. Please rate how accurately each of these models captures reality today.

Scale: 1 = highly accurate 3 = acceptable accuracy 5 = unacceptable accuracy

Current Accuracy of CFD Submodels	Mean Rating
	1996
Flow Rates	2.8
Thermodynamic Properties	2.9
Combustion Rate: Spark Ignition	3.4
Heat Transfer	3.5
Cylinder and Valve Geometry Effects on Engine Performance	3.5
Combustion Rate: Diesel	3.7
Turbulence	3.7
Transient Behavior	4.2

Selected edited comments

None

Summary

In general, panelists think that the accuracies of most process submodels for a CFD-based model still leave much to be desired. Although ratings for flow rate and thermodynamic submodels are marginally above "accurate," the remainder scored 3.4 or lower, all indicating levels of unacceptable accuracy. Submodels describing transient behavior rated worst of all, with nearly 90 percent of respondents giving them scores of "4" (59 percent) or "5" (31 percent).

Strategic considerations

Comparison of the results of this question, which examines the future of CFD submodels, with those of question ENG-12, which looks at phenomenological submodels, yields an unexpected observation: As of 1996, there is little difference in the accuracy of results between these two types of models (see table, next page). On the one hand, it may be said that since CFD is a more complex approach, it might better capture some of the nuances of engine performance; while on the other, since phenomenological models are simpler and have been around longer, it may be argued that this advantage should lead them to better results until development of CFD models progresses further. Perhaps what panelists believe they see is that 1996 represents an equilibrium point along the way to presumed CFD dominance in these applications.

The lone exception of any significance is the status of heat transfer modeling. In this instance, the panel actually rated the accuracy of CFD submodels superior to that of the phenomenological counterparts. However, it should be noted that both fell well below the threshold of acceptable accuracy, so this disparity is of little consequence.

Current Accuracy of Submodels	Mean Rating Phenomenological	Mean Rating CFD
Combustion Rate: Diesel	3.9	3.7
Combustion Rate: Spark Ignition	3.3	3.4
Cylinder and Valve Geometry Effects on Engine Performance	3.3	3.5
Flow Rates	2.6	2.8
Heat Transfer	3.8	3.5
Thermodynamic Properties	2.8	2.9
Transient Behavior	4.1	4.2
Turbulence	3.8	3.7

ENG-14a. Of the process submodels listed in ENG-14, please list the most important specific problems remaining in the modeling of each.

CYLINDER AND VALVE GEOMETRY:

- grid generation process
- accurate, automatic moving meshes
- reduction in the number of required grid points
- moving grid technology for valves and pistons
- fine geometric details in the context of a complete cylinder model aren't well resolved
- cyclic variability
- two-phase flow (air and liquid fuel) in an intake port and a cylinder
- detached flows
- wave action effects on flow fields
- moving valves
- crevice modeling
- reliable, simpler combustion models
- validation of CFD models
- computational power available
- computational costs for time domain solutions remain prohibitive
- time required to build models
- relatively high expertise required

THERMODYNAMIC PROPERTIES:

- thermal properties of various fuel species in vapor state
- near-critical properties, especially in liquid state
- thermodynamic properties of in-cylinder contents at high pressure and high temperature
- kinetics submodels
- combustion models
- evaporation process
- fuel composition and additive effects
- database for adjustment for new engine types
- better chemical analysis functions

FLOW RATES:

- automatic mesh generation
- very accurate boundary layer simulation
- detailed flow separation effects
- wave action effects in fuel injection

- pulsed flow effects in a turbocharger turbine
- flow details near the valve seat
- transient flow rates (time constraints for typical strategies can be prohibitive)
- multiphase flow
- cavitation effects
- compression/expansion effects
- cycle-to-cycle variation
- heat transfer in manifold runners
- turbulence modeling
- better empirical wall friction factors to improve pressure-loss prediction
- transient condition models (e.g., cold start, acceleration, deceleration, etc.)
- computing resources
- manpower resources to create/refine models

HEAT TRANSFER:

- mesh resolution near walls
- boundary layer combustion
- non-equilibrium boundary layers
- unsteady boundary layers typically smaller than mesh size
- mesh resolution near walls
- better wall models
- wall temperature data as a function of time
- conjugate heat transfer
- core heat transfer properties
- for diesel engines, heat transfer among air, fuel film impinged on chamber wall, and liner wall
- relationship between NVH characteristics and heat transfer
- surface condition modeling (e.g., materials, roughness, etc.)
- effects of knocking conditions
- turbulence modeling
- Coupling fluid/structural models
- for diesel combustion, radiation heat transfer model
- modeling of the duct air flow regime
- resolution
- solving the corrective CFD subproblem

COMBUSTION RATE:

- basic combustion/emission behavior
- spray modeling
- modeling of fuel droplet split, collision, and evaporation
- flame initiation
- flame propagation
- effects of burnt gases on local flame propagation
- flame quenching
- chemical kinetics
- for diesel engines, non-homogeneous combustion
- spark plug modeling
- auto-ignition
- modeling of very first period during and after spark
- wall films
- multiphase flow (i.e., wall wetting) and combustion effects
- simulation of gasoline wall flow during cold start and warm-up
- better resolution of boundary layer details
- turbulence/flame interactions
- turbocharger performance at low flow/pressure ratios
- condensation
- resolution
- computing resources
- faster CPUs required

TRANSIENT BEHAVIOR:

- turbulence induced by liquid fuel injection
- effect of turbulence on burn rates and emissions
- compressed transient turbulence
- Resolution of boundary layer details
- chemistry and chemical kinetics
- heat transfer (nonequilibrium)
- flow problems with mixed regions (part laminar and part turbulent)
- wall functions that apply to a wide variety of flows (impinging, shear, separating)
- better estimates of K-epsilon and Reynolds stress
- high Reynolds numbers (>106)
- finding alternative models (to K-epsilon) that are not vastly more CPU-intensive
- computer resources

TURBULENCE:

- catalysts: acceptable accuracy on flow distribution
- resolution of boundary layer details
- surface roughness
- influence of hot spots on coolant
- turbulence modeling currently adequate for engineering purposes

Summary

In most cases, numerous different responses were provided for each model category. In some cases, some generalities could be discerned. For cylinder and valve geometry, issues included accurate descriptions of flow characteristics and surface textures, as well as better computing techniques, such as moving mesh generation. For thermodynamic properties, responses centered on the properties of fuels (evaporation, composition, etc.), as well as combustion kinetics. Heat transfer models require accurate definition of boundary conditions, prediction of turbulence and its effects, and multiphase heat transfer characteristics. The major areas for concern for combustion rate models are flame-related behaviors (e.g., initiation, propagation, quenching), transient condition modeling, and multiphase flow descriptions, as well as the need for greater computing resources to handle the complexity. For transient behavior models, key areas of concern center on the effects of turbulence and the handling of a variety of flow types and conditions, along with computing resources once again. For the other model types (flow rate, turbulence), a variety of answers were supplied, but no strong patterns could be discerned.

Strategic considerations

As with question ENG-12a, the responses to this question are numerous and varied. The answers to question ENG-14 indicated that few CFD-based submodels are up to the tasks desired of them today; the lengthy list of challenges demonstrates clearly why this is so. But as was stated in ENG-12a, these challenges represent opportunities for developers as well as possible collaborations with research consortia and universities to help solve these problems in a precompetitive atmosphere that will aid all parties before they reach the competitive stage of developing programs that model the phenomena of interest. In much the same way that the Automotive Composites Consortium under the USCAR umbrella has developed the use of composites in vehicles, a Modeling and Simulation Consortium could guide the study of phenomena to be modeled that are of particular interest to all manufacturers.

ENG-15. Please rate the probability of the following model categories offering an economical way of developing new and/or redesigned engines in 2001 and 2006.

Scale: 1 = high probability 3 = moderately probability 5 = low probability

Designing New Engines	Mean Rating	
	Short Term 1996-2001	**Long Term 2002-2006**
CFD-based	3.0	2.0
Phenomenological	2.6	2.1

Selected edited comments

Round 1

- Phenomenological models by definition cannot address engines outside their "calibration" range, so they cannot be used to develop new engine concepts without very large risk.
- The needs of the phenomenological model might be less important in 2006, if the capacity and speed of computers become 1000 times the current values.
- One should not look at these two models as one or the other, but to be used together – one for details and combustion, the other for systems aspects and economy.
- Regarding the combustion process, a CFD-based model is still under development and a phenomenological model requires modification constants.
- Phenomenological models are useful only for slightly redesigned engines.
- Simulation tools provide understanding and cannot replace "traditional" development procedures.

Round 2

- Phenomenological models operate well within their range of interest and do not model the fundamental processes. We must try to do the latter.

Round 3

- Phenomenological models already do, and will continue to, offer an economical analysis tool, but they cannot "stand alone" — they must be supplemented with physical models.
- Phenomenological models can consider fundamental processes, but limited.
- Phenomenological models will always be used, at least at the concept level, because of their relative simplicity and ease of use.
- There appears to be a trend of the use of simple models (quick and dirty) at the early design process to compare general design alternatives. It is a very important tool to reduce the cost, etc., in the early design phase and get a 90 percent result in a short time. In an early phase, this is often better than a 3-D calculation in which the boundary conditions are not totally clear.
- These types of models will fade away.

Summary

Panel members indicate that, in the short term, phenomenological models will be slightly more likely to aid in the economical development or redesign of new engines, with an average rating of 2.6 as compared with CFD's 3.0. However, by 2006, CFD models are predicted to catch up to phenomenological models in terms of likelihood of usefulness, with both receiving average ratings of around 2.0 to 2.1. These scores indicate that both have a significant probability of helping reduce the cost of engine design.

Strategic considerations

The panel clearly holds the expectation that, over the course of the next ten years, simulation will provide an economical means of designing new engines. In fact, the panel believes that, by the year 2006, the development of CFD models will have progressed sufficiently to be as likely to achieve this goal as the simpler phenomenological models.

This result is consistent with those of questions ENG-2 and ENG-3, which estimates long-term efficiency improvements in the engine design process of 40 percent and cost savings of 30 percent through the use of simulation. But in some ways the optimism of this question must be tempered by the numerous challenges noted by respondents for both types of models. Though engines will continue to be designed over the next ten years, the challenges noted in previous questions show that much work needs to be done in order to reach optimum engine models.

It should also be noted that, in conjunction with the results of question ENG-16, these results most likely depend strongly upon the continued development and adoption of steady-state models rather than more complex transient models.

ENG-16. **Please rate the probability of having accurate CFD-based and phenomenological steady-state and transient models (in order of seconds; e.g., change in load) in the short term (1996 to 2001) and in the long term (2002 to 2006).**

Scale: 1 = high probability 3 = moderate probability 5 = low probability

Accuracy of Simulating	Mean Rating	
	Short Term 1996-2001	**Long Term 2002-2006**
STEADY-STATE:		
CFD	3.0	2.2
Phenomenological	2.5	2.2
Friction	3.0	2.5
TRANSIENT:		
CFD	4.2	3.3
Phenomenological	3.0	2.4
Friction	3.8	2.9
Emissions*	4.1	3.3

* "Emissions" not relevant in steady-state modeling.

Selected edited comments

Round 1

- One-dimensional CFD is there on transients now. Full 3-D will take more time.
- Regarding CFD modeling capabilities, much will depend on computer power development.

Round 2

- Friction modeling will have to be based on statistics.

Summary

Steady-State: Over the short term, there appears to be a better-than-even probability that an accurate phenomenological model for steady-state applications will become available. At the same time, there appears to be only a moderate chance of an accurate CFD-based or stand-alone friction model. However, in the longer term (2002 to 2006), accurate versions of all three types of models appear to have a good probability of development and availability, although the situation for a friction model is a bit less optimistic than for the others.

Transient: Reflecting the greater complexity in developing usable, accurate transient models are the much lower probabilities associated with their availability over the next five years. Only phenomenological transient models are seen as having even a moderate probability of achieving acceptable accuracy, with CFD, friction, and emissions models lagging much further behind in development. Over the longer term, transient friction models are also seen as moderately probable of demonstrating a reasonable degree of precision, while CFD and emissions models still show only marginal likelihood of doing so.

Strategic considerations

Steady-state models, which are useful for "snapshots" of an engine, are comparatively simpler constructs, and thus their likely robust state of development by 2006 is unsurprising. Even an accurate steady-state friction model is seen as quite likely by many panelists. This will provide a useful tool in actually constructing a new engine on the computer, but will allow only limited testing of performance characteristics.

More comprehensive transient models, in which the dynamics of a working engine can be examined on-line, are viewed as significantly less likely to be operating efficiently within the next ten years. Simpler phenomenological models are more likely to find acceptance by that time, but more complex CFD models, along with friction and emissions models, are only moderately likely to provide accurate analyses.

ENG-17. Please list what you feel are the advantages and disadvantages of moving from steady-state to transient (in the order of an engine cycle) boundary conditions as inputs to detailed models (e.g., cylinder wall temperatures near top dead center as a function of crank angle).

Steady-State to Transient Boundary Conditions	
Advantages	**Percentage of Responses**
Better accuracy/precision	34%
More realistic simulations	22%
Better prediction of effects of engine design changes	8%
Permits combustion analysis	8%
Permits design of better emission control systems	8%
Permits analytical calibration	4%
Better guidance for experiments	4%
New insights gained	4%
No advantages	8%
Disadvantages	
Increased computational resource requirements	34%
Added complexity of model/difficulty of building model	18%
Difficulty in defining boundary conditions	12%
Results more difficult to interpret	9%
Not necessary for structural/thermal analyses	6%
Post-processing must be streamlined	3%
Predictiveness only as good as least accurate submodel	3%
Uncertainty	3%
How could you ever know what values to use?	3%
No disadvantages	9%

Selected edited comments

Round 1

- One advantage is that it is highly specific, which is very important for pressures and flow rates, unimportant for wall temperatures.
- Transient boundary conditions are only needed for fluid temperatures and pressure; wall conditions don't respond fast enough to matter.
- For "accurate" models, only transient conditions are of interest.
- The disadvantages are small; complexity improved through better GUIs (graphical user interface), and run-time is continually falling with faster CPUs and parallel processing.

Summary

As might be expected, the main tradeoffs associated with a shift from steady-state models to transient models appear to be enhanced accuracy and realism (56 percent of all responses) in exchange for added model complexity and associated computer CPU time needed to run the model (52 percent of all responses). Other advantages included the ability to perform more types of detailed analyses, while other disadvantages center on the difficulty of defining boundary conditions and variables.

Strategic considerations

As expected, panelists identify the main trade-off in going from steady-state to transient models as better accuracy versus increased model complexity and greater CPU demands to handle it. Thus, given the expected difficulties in the development of transient simulation (see ENG-16), the single most important expediter of a shift toward greater use of transient models may be the continued improvement in computing hardware.

The other issue that will continue to challenge modelers for both steady-state and transient models lies in determining when models become "good enough" to facilitate the design process. What modelers have found is that they can take one engine and one situation and accurately model it, but they can't make the model predictive for other engines and other situations. Designers will need predictability as well as accuracy in order to feel confident with using the results of modeling in their designs.

ENG-18. **Please rate the probability of having accurate phenomenological and CFD-based multicylinder models that include the intake and exhaust manifold in the short term (1996-2001) and in the long term (2002-2006).**

Scale: 1 = high probability 3 = moderate probability 5 = low probability

Accurate Multicylinder Models	Mean Rating	
	Short Term 1996-2001	Long Term 2002-2006
CFD-based	4.4	3.0
Phenomenological	2.6	2.0

Selected edited comments

Round 1

- Accurate CFD multicylinder models will come with improvements in CFD accuracy and advancements in computer power (speed, memory).
- A multicylinder phenomenological model already exists.
- Such models already exist, but they are not 100 percent complete. They are pretty good, however.
- Phenomenological models can be accurate only close to their validation domain.
- Assumption: These models are used for performance and manifold/duct tuning. Details of combustion and emissions are unimportant. If so, we have these models today. If the question is whether we will be able to predict cylinder-to-cylinder variations (e.g., in emissions) crank angle by crank angle while the car is warming up and accelerating.... Never!

Round 2

- 3-D for a few cycles is done today. For inlet/exhaust manifolds, it could be done in-cylinder as well, but it would take a long time. We could not do cycle-to-cycle variations practically.

Round 3

- Full 3-D simulations are difficult to spread in short term because of calculation time. But a 3-D model combined with a 1-D multicylinder model will be used by many engineers in the short term. This technology is very important to estimate not only engine performance but also emissions of each cylinder.
- Phenomenological models have severe accuracy limitations for futuristic work. Progress with CFD based models is impressive and rapid.
- “Accurate” is impossible. “Usefully accurate” is probable.

Summary

As the panel has noted in other questions, development of capable CFD models is expected to lag that of simpler phenomenological models in both the near and longer terms. Predictions indicate a fairly strong probability (2.6) that useful phenomenological multicylinder models will be available over the short term (1996 to 2001), and becoming increasingly strong (2.0) in the long term (2002 to 2006). On the other hand, the probability of a CFD-based multicylinder model is seen as extremely low (4.4) within the next five years, becoming moderate (3.0) over the course of the next decade.

Strategic considerations

Consistent with the results of other questions, the panel sees a relatively strong likelihood that phenomenological models will be able to accurately model multicylinder simulation by the year 2006. Several individuals noted that such models may already exist. However, it has also been noted that while these models are or will be useful tools for standard phenomena, they tend to fail when trying to handle cycle-to-cycle variations, and thus cannot handle more detailed areas such as combustion and emissions.

Also as noted earlier, development of CFD models, while progressing over the next decade, will likely remain incomplete by the year 2006 and therefore, only modestly useful for engine design.

ENG-19. For diesel modeling, please rate the level of current and future modeling difficulty presented by each of the listed factors.

Scale: 1 = extremely difficult 3 = somewhat difficult 5 = not difficult at all

Use of Models, by Application Area	Mean Rating		
	1996	2001	2006
Boundary conditions at the end of the orifice (for combustion)	1.8	2.4	3.4
Friction	2.9	3.6	4.1
Fuel droplet breakdown and mixing	2.1	2.6	3.2
Injection and spray of 2-phase flow into the cylinder	1.8	2.2	3.2

Selected edited comments

Round 1

- It is not feasible at all to model the details of the injection process because 1) the exact-model is difficult both in terms of physical modeling and in terms of computation difficulty, and 2) any model is not verifiable. Thus, appropriate empiricism has to be employed.
- Modeling the two-phase cavitation flow in a nozzle is required for diesel design modeling.
- Since 1981, progress has been very slow, and most of the problems existing then remain today. Very little useful progress is being made in the area of spray modeling, let alone droplet combustion.

Round 2

None

Round 3

- Friction is important for the engine's fuel consumption during city driving operation. Due to this, the modeling is very helpful for the design/redesign of future diesel engines.

Summary

Panelists view the difficulty of modeling many aspects of diesel engines as quite difficult today. Models for examining injection and spray of two-phase flow into the cylinder, boundary conditions at the end of the orifice, and fuel droplet breakdown and mixing all received difficulty ratings ranging from 1.8 to 2.1, indicating a rather high degree of difficulty to model using today's technology and development work. By the year 2006, all three are expected to see improvement, but all still receive ratings of from 3.2 to 3.4, still indicating a moderate degree of difficulty to model even ten years from now.

Friction modeling is viewed a bit more optimistically. Currently, it receives a difficulty rating of 2.9 (moderately difficult), but this falls to 4.1 (little difficulty) by 2006, indicating strong progress over the next decade.

Strategic considerations

All of these application areas are listed in questions ENG-12a and ENG-14a as important areas needing to be addressed in simulation of engine performance, with each unable to be adequately described using phenomenological modeling techniques. In many cases, the physics of a phenomenon may be imperfectly understood (e.g., boundary conditions), while in others, the level of detail required to adequately capture the phenomenon may be forbidding (e.g., friction). Each of these areas also interacts to some extent with the others, compounding the complexity problem.

Nonetheless, the panel has expressed optimism that each of these four areas will surmount many of the difficulties in capturing them adequately in a model of diesel engine performance. Admittedly, diesel engines are somewhat less complex in their design than their spark-ignition counterparts, but combustion modeling for diesel engines is more complex than spark-ignition due to the non-homogenous charge that has the burn rate and ignition occurring in numerous places in the cylinder compared to the homogenous charge of a spark-ignition engine that has an equal distribution of air and fuel entering the cylinder and igniting near the spark plug.

ENG-20. Please rate the probability of having accurate models for each of the listed emissions components in both spark-ignited and diesel engines in the short term (1996-2001) and in the long term (2002-2006).

Scale: 1 = high probability 3 = moderately probability 5 = low probability

Accuracy in Simulating Emissions	Mean Rating	
	Short Term 1996-2001	**Long Term 2002-2006**
SPARK IGNITION:		
Hydrocarbons	3.7	2.8
NOx	2.5	1.8
Carbon monoxide	3.2	2.3
Particulates	4.1	3.0
DIESEL:		
Hydrocarbons	4.1	3.2
NOx	3.1	2.0
Particulates	4.3	3.4
White Smoke	4.2	3.4

Selected edited comment

Round 1

- All the above depend very much on spray and combustion simulations.
- If the question is: Will we have models which will predict compliance with emission regulations for a paper engine? Never. But, for example, will we have a ring pack model which will simulate blow-by and other flows, allowing us to infer which designs will have lower hydrocarbon emissions? Absolutely.

Round 2

- All emissions models' output depends on combustion models' performance.

Summary

Spark Ignition: Strong progress is foreseen for the accurate modeling of gaseous emissions for spark ignition engines by 2006. NOx emissions are seen as already having a somewhat high probability of accuracy (2.5) in the short term, rising to a fairly high probability (1.8) by 2006. Carbon monoxide and hydrocarbon emissions modeling is also expected to rise from a somewhat low probability of accuracy over the short term to a moderately high probability by the end of ten years. However, particulate emissions modeling appears to be a more difficult problem, with a quite low probability of accuracy in the short term, rising only to a moderate probability in the longer term.

Diesel: As alluded to in the previous question, diesel engine modeling is seen as being less fully developed today, and thus will probably continue to lag spark ignition engine modeling throughout the forecast period. NOx emissions modeling is viewed by the panel fairly optimistically, with a fairly strong probability (2.0) of an accurate model for diesel engines by the year 2006. However, short-term development of accurate models for hydrocarbon, particulate, and white smoke emissions is seen as very unlikely (average ratings ranging from 4.1 to 4.3), rising only to less-than-moderate probability by 2006 (average ratings of 3.2 to 3.4).

Strategic considerations

In this age of consumer concern with, and government regulation of, pollution, emissions represents an important area of engine simulation.

For spark ignition engines, the panel believes the simulation of simple, non-hydrocarbon gases (e.g., NOx, CO (carbon monoxide)) should be handled relatively routinely by 2006. Hydrocarbon compounds, with their more complex chemistry and variety, will require a more sophisticated chemical kinetics component to the model in order to adequately simulate their formation. Nevertheless, panelists see a moderate probability that this problem, too, will be solved by the end of the forecast period. Throughout the survey, the difficulty of modeling particulate formation has been suggested as one of the more difficult areas to solve.

In the case of diesel engines, experts see an equally great amount of progress in modeling emissions, but, with the exception of NOx, are much more pessimistic about the overall level of accuracy to be achieved by 2006. This may be due to the greater complexity of the compression-ignition internal processes. With forecasts predicting wider sales of diesel-powered vehicles in the future, as well as the military's reliance on diesel engines, this represents an important area for additional research.

ENG-21. Please rate the difficulty of incorporating each of the listed factors into a predictive emissions model in the short term (1996 to 2001) and in the long term (2002 to 2006).

Scale:	1 = extremely difficult
	3 = moderately difficult
	5 = not very difficult

Incorporation into Predictive Emissions Model	Mean Rating	
	Short Term 1996-2001	Long Term 2002-2006
Compression ratio	4.1	4.3
Cycle-to-cycle variations	1.9	2.0
EGR	3.3	4.0
Knock	2.3	3.2
Mixing	2.7	3.1
Spark advance	3.0	3.6

Selected edited comments

Round 3

- We may be able to come up with a model, but I'm skeptical about proving its accuracy.
- There appears to be no clear trend in progress toward this goal.

Summary

Panelists appear to lump the factors listed above into three general categories of difficulty in terms of incorporating them into a comprehensive predictive emissions model. Compression ratio appears to be the easiest to model and include, receiving an average rating of 4.1 (only somewhat difficult) in the short term, lowering to 4.3 over the long term. Spark advance and EGR elements of such a model appear to be somewhat harder to develop and incorporate, receiving average ratings of 3.0 and 3.3, respectively, in the short term. However, by the long term, strong progress for each is foreseen, with both receiving ratings in the "only somewhat difficult" area. Finally, cycle-to-cycle variations and knock appear to be the most difficult to resolve, receiving ratings indicating that they are quite difficult to incorporate. While knock modeling is predicted to make significant progress by 2006, cycle-to-cycle variation modeling is seen as making virtually no headway during this time, remaining a very difficult problem even after another decade of work.

Strategic considerations

In general, the panel is rather optimistic regarding the comparative lack of difficulty in resolving most of the potential problems to emissions modeling over the longer term. With the exception of cycle-to-cycle variations, which in other questions has been cited as both a critical and a thorny issue, respondents see the remainder as ranging from moderately difficult (mixing, knock) to rather easy (EGR, compression ratio) to resolve. In the case of mixing and knock modeling, the main limitation to date appears to be sufficient knowledge of the physics (in particular, chemical kinetics) involved; for the "easier" areas, it appears that evolutionary progress in simulating these phenomena is the primary need.

Not surprisingly, cycle-to-cycle variation is seen as a continuing difficult problem for emissions modeling throughout the forecast period. Accurate modeling draws upon virtually all the disciplines employed in other model areas, including those that are not yet fully understood. In addition, some believe that this may be among the most computer-intensive applications, requiring advances in hardware as well as software. Thus, even beyond the scope of this study, this area of simulation may be among the most resistant to effective resolution.

ENG-22. Concerning zero-dimensional phenomenological models, please rate the probability of having predictive capability for pollutant formation for a generic engine in the short term (1996-2001) and in the long term (2002-2006).

Scale: 1 = high probability 3 = moderately probability 5 = low probability

Pollutant Formation	**Mean Rating**	
	Short Term 1996-2001	**Long Term 2002-2006**
Predictive capability	4.0	3.4

Selected edited comments

Round 1

- A zero-dimensional phenomenological model has very low probability as a predictive tool for an advanced combustion system.
- A generic model may not be very engine-specific. Thus, it may be of little use, except for teaching.
- This is just not possible.

Summary

The panel rates the probability for the development of a predictive model for pollution formation as remaining rather unlikely (3.4) throughout the ten-year forecast period.

Strategic considerations

Although as a group, the panel foresees modest progress toward a zero-dimensional phenomenological model to predict pollution formation, the consensus among individuals commenting on this question is that the goal is nearly unattainable. In any event, a universal phenomenological model for this should not be expected over the next ten years. This may be due in large part to the panel's view of the generic engine model as lacking ability to model the individual characteristics of each engine.

ENG-23. Concerning heat rejection models, please rate the probability of having accurate heat rejection models for each of the listed items in the short term (1996-2001) and in the long term (2002-2006).

Scale: 1 = high probability 3 = moderate probability 5 = low probability

Heat Rejection Rates	Mean Rating	
	Short Term 1996-2001	**Long Term 2002-2006**
Coolant flow	2.1	1.8
Heat-to-cooling system	2.6	1.7
Inclusion of catalyst in temperature tracking	3.0	2.2
Tracking of temperatures in gas path	2.9	2.1
Transient effects	3.4	2.7

Selected edited comments

Round 1

- This is a 3-D transient problem. The "science" of heat transfer is relatively silent with respect to time-dependent phenomena. That means fundamental science needs to be developed.

Round 2

- Three-dimensional steady-state models for coolant flow and heat loss are already here.

Summary

There appears to be a good deal of optimism for the development of accurate heat rejection models over the long term, and, for some aspects, even within the next five years. By 2001, panel members see a fairly high probability of accurate models for heat-to-cooling systems and coolant flow, and moderate probability for gas path temperatures and inclusion of catalyst in temperature tracking. By 2006, all four of these areas are viewed as having fairly high probabilities for accuracy, with transient effects modeling holding better-than-moderate promise.

Strategic considerations

The tracking of heat generated during combustion appears to be a task relatively easily accomplished by simulation, both within the cooling system and in the exhaust. It should be noted that prediction of radiant heat transfer was not included in this list, although some have suggested that this should be a relatively straightforward issue. Transient effects, most often associated with engine warm-up or sudden acceleration, are seen as offering more difficulty, which is consistent with the previous responses concerning the modeling of transient effects. These issues are particularly important for emissions modeling and represent an important area of research for vehicle manufacturers faced with tougher emissions regulations for their vehicles.

ENG-24. How close, at present and in 2001 and 2006, are models of direct-injection spark-ignition engines to being useful and implementable design tools?

Scale 1 = very close 3 = somewhat close 5 = not very close

Direct-Injection Spark-Ignition Engines	Mean Rating		
	1996	**2001**	**2006**
Models for use as design tools	3.8	3.0	2.3

Selected edited comments

None

Summary of results

Direct-injection spark-ignition engine models appear to be increasingly likely to exist by 2006, but are by no means assured, according to the engine panel. As of the present, such models appear to remain quite far from being useful and implementable design tools; however, by 2001, they are expected to be "somewhat close" (average rating: 3.0) to implementation, and "rather close" (average rating: 2.3) by 2006.

Strategic considerations

Despite advances being made with regard to alternatives to homogeneous charge, spark-ignition engines (direct-injected spark-ignited, compression ignition, electric vehicles, etc.), it appears quite probable that they will continue to predominate over the coming decade. Thus, the forecast of a significant likelihood of accurate spark ignition engine modeling by the year 2006 substantiates earlier questions (e.g., ENG-2 and ENG-3) examining quantifiable benefits in terms of efficiency improvement and cost reduction.

ENG-25. **How close, at present and in 2001 and 2006, are moving (or flexible) grid techniques for CFD models to being useful and implementable design tools?**

Scale: 1 = very close 3 = somewhat close 5 = not very close

Moving (or Flexible) Grid Techniques	Mean Rating		
	1996	2001	2006
Techniques for use as design tools	2.8	2.0	1.6

Selected edited comments

Round 2

- This technique already being implemented.
- At present, moving grid is mostly designed for specific applications. In the future, a more generalized moving grid can be implemented in CFD codes.
- We already invariably use moving piston/valve calculations -- speed is the problem. We are aiming for a one-to-two-day turnaround for intake and compression.

Round 3

- The moving value problem is being used — speed of computation may be a computer speed problem more than a computational technique issue.
- It is important to use the right model in the right stage of engine design. CFD-type models are expected to be useful in the early stage of engine design. Phenomenological models are expected to be useful in the latter stage of engine design.

Summary

Moving grid techniques for CFD models are viewed as already somewhat close to implementation today (average rating: 2.8) and becoming even more likely to be used over the next ten years (average rating for the year 2006: 1.6).

Strategic considerations

Several earlier questions (e.g., ENG-12 and ENG-14) revealed concern among panelists over the need for improved moving grid techniques. Although variants of the technique are already being implemented, by as soon as 2001, effective and usable versions should become relatively common, and by 2006, the panel expects them to become fairly standard tools in simulation. These techniques will help particularly for modeling processes occurring within the cylinder of the engine where the grid will expand and contract as the piston moves up and down in the cylinder.

ENG-26. Do phenomenological models offer a feasible approach to turbulence modeling within the cylinder, especially for swirl and tumble-like motions?

Response	Percent of Respondents
Yes	36.4%
No	54.5%
Maybe	9.1%

Selected edited comments

- Phenomenological models that are tuned will work.
- Phenomenological models offer a "gross" but useful turbulence representation.
- Are they feasible? Yes. Are they useful? They are of limited value.
- Phenomenological models are for basic layout.
- The main effects can be found with phenomenological models.
- Phenomenological turbulence models are okay for global entities such as heat transfer or bulk mixing, but unacceptable for localized entities such as NOx, HCs, or particulates.
- I don't think phenomenological models can tell you much about turbulence.
- Phenomenological models are not feasible for modeling and hence not for performance prediction.
- Phenomenological models are not for local analysis (CFD is better).

Summary

Even though there appears at first glance to be a fairly even split between panel members who see phenomenological models as a feasible approach to turbulence modeling and those who don't, a closer reading of the comments reveals that even the proponents tend to concede that phenomenological models in this application have limitations and may not always be sufficient.

Strategic considerations

See the Strategic Considerations for all the turbulence modeling questions in ENG-26b.

ENG-26a. Will CFD models offer a better solution to turbulence than phenomenological models?

Response	Percent of Respondents
Yes	100%
No	0%

Selected edited comments

- CFD can come closer to a more comprehensive description of turbulence.
- CFD offers a better solution.
- CFD is required. Low Reynolds number, no spatial or temporal homogeneity; conventional modeling (Reynolds averaged) are unlikely to succeed; large-eddy simulations are more appropriate.
- CFD offers the only solution.
- To my knowledge, the best way to describe a turbulent flow is a direct solution of the Navier-Stokes equations; however, it's not practical for the time being. Therefore, we have to resort to models, and each model is somehow restricted to some flow configuration. Accordingly, CFD models should offer a better solution.
- CFD model should be used as guideline and for local variations. Intelligent combination of experience and CFD can lead to simple and useful phenomenological "models" of in-cylinder turbulence.

Summary

All respondents to the question agreed that, despite inevitable difficulties during development of a CFD-based approach, the results of such a model for turbulence modeling will be significantly superior to those of a phenomenological model.

Strategic considerations

See the Strategic Considerations for all the turbulence modeling questions in ENG-26b.

ENG-26b. What are the stumbling blocks impeding progress on turbulence modeling?

Difficulties in Turbulence Modeling	Percentages of Responses
Computer resources required	33%
Lack of basic understanding of gas dynamics	33%
Lack of understanding of large-scale fluid modeling	17%
Insufficient resolution	17%

Selected edited comments

Round 2

- CFD could be architecturally limited by technology advance. Within CFD models there are numerous constants which are changed according to operating conditions — this needs to be resolved.
- If the interest is in turbulence, there is a need for a wider database and you must use CFD. If the interest is in performance/need transfer, phenomenological is okay.
- Progress on practical use of turbulence modeling will come when either a detailed RSM (response surface model)-type model becomes easy to use and wall layer reduction ceases to be a problem or better modeling techniques are available and there is a good understanding outside the experts of why RSM is unnecessary for in-cylinder flows.

Summary

The panel was unusually uniform in its appraisal of the use of phenomenological versus CFD modeling for the simulation of turbulence. The majority expressed the opinion that, due to the complexity of the process, phenomenological modeling simply wasn't a powerful enough tool to capture the effects adequately. Many of the remaining panelists went on to hedge their responses in the comment section, noting that while such modeling might be feasible, it would probably not be very useful. Others broke down the overall turbulence phenomenon into subcategories, and identified which would be suitable for phenomenological modeling and which would not.

When asked if CFD modeling offered a superior approach to turbulence simulation, the answer was a unanimous "Yes." Therefore, the impediments to this superior type of model are similar to the list provided for CFD modeling in general, specifically a lack of sufficient computing power and incomplete knowledge of the physics involved.

Strategic considerations

The results of this question serve to reinforce the perceived superiority of CFD modeling for highly complex phenomena, such as turbulence. Although phenomenological models might be able to capture some aspects adequately for some purposes, a truly thorough engine model that looks at 3-D effects will necessarily require the development and refinement of CFD simulation technology using moving grids.

ENG-27. Please indicate significant new technologies that are likely to emerge within the next decade that will affect how powertrains are modeled.

ENGINES:

- catalyst chemical models integrated into CFD
- conjugate heat transfer
- dynamic gas flow models
- combustion model that includes turbulence, fuel spray, chemical reactions, and emissions formation
- thermal and structural simulation
- progress in mixture formation using wall-impinging spray
- knock modeling
- fuel injection modeling
- very flexible, perhaps camless, valve actuation systems
- two-stroke-cycle engine equipped with an electronically controlled fuel injection system
- air/exhaust systems becoming more complex to handle EGR (exhaust gas recirculation)
- very high injection pressures for compression ignition engines
- electronically controlled fuel injection system for variable injection rates and pressures for diesel engines
- direct-injection, spark-ignition engines; i.e., various new stratified charge concepts
- alternative-fuel engines, like CNG (compressed natural gas) -powered gas engine
- hybrid (gasoline/electric) powerplants
- progress in developing true CFD
- digital physics "EXA" software to model flows
- CAD software integration with analysis tools
- P-element and boundary element codes
- finite element analysis with multibody analysis features
- unstructured grids
- improved grid generation
- parallel computing
- more powerful computers
- virtual reality technologies
- no new technologies, but evolutionary changes

TRANSMISSIONS:

- electric powertrain to replace gas and diesel powertrains (up to about 7 percent at the end of the next decade)
- CVT belt system
- integration of engine/drivetrain/vehicle control algorithms
- torque converter submodels
- powertrain control model
- no new technologies, but evolutionary changes
- New technology is probably not needed.

Selected edited comments

Round 1

- Apart from computer power, there will not likely be other possible contributions of new technologies to engine/powertrain modeling. Continuous effort, experimentation, diagnostics, and understanding of the physical processes are the main serious contributors to advanced modeling.
- There will be new technology, too, in software methods: more design optimization, more automatic programming for fast algorithms, more parallel programming, more graphics for input and output.

Summary

For engine technologies, most responses tend to fall into four broad categories. The first is the development of specific application simulation modules (e.g., heat transfer, combustion, etc.). The second focuses more on anticipated developments in engine technology itself, including direct-injection spark ignition, variable injection, and alternative fuel engines. The third category cites development of more powerful analytical software features (e.g., improved grid generation, boundary element codes, integration of CAD software, etc.). And the final section covers computer hardware advances, including parallel computing and virtual reality.

The list for powertrains is considerably shorter, focusing on technological developments in the powertrain itself. Several respondents foresee no significant developments in this area at all.

Strategic considerations

Given the wide variety of new technologies seen as likely to emerge over the next decade, it is clear that simulation developers are facing a quickly moving target with unpredictable zigs and zags. These developers will have to work closely with their customers in order to keep abreast of current industry needs and trends, and will have to react quickly to address them. In order to maintain the flexibility needed, emphasis will likely be placed on plug-in modules to an overall software system, rather than constantly revising the entire software package periodically, which would be much too cumbersome to be of help to designers.

ENG-28. What modeling and simulation issues will present the most significant challenges or opportunities to the vehicle manufacturing industry in the coming decade?

- aerodynamics modeling
- automatic grid construction
- automatic model adaptation to experimental results
- catalyst modeling
- combustion modeling
- development of automated CFD modeling
- development of really predictive powertrain models
- direct-injection gasoline spray modeling
- driveability modeling
- emissions modeling
- heat transfer modeling
- incorporation of locally complex models (e.g., cylinder CFD) into globally accurate ones
- integration of three-dimensional CAD and simulation software to define detailed shapes of engine parts
- materials properties database
- modeling degradation of sensors
- modeling of compression ignition fuel/air mixing
- modeling of fluid-structure interactions
- modeling of new materials (composites, adhesives)
- modeling of wall wetting
- moving sophisticated software down to the engineers who design engines (by use of object-oriented software)
- multiphase CFD
- NVH modeling (powertrain, vehicle)
- rationalizing the selections of speed versus accuracy for a spectrum of models suited to various users
- simulation of fuel spray dynamics, including cavitation flow inside a nozzle, breakup of injected liquid, and coalescence of droplets
- simulation of long-term durability
- simulation of manufacturing processes
- simulation of vehicle/driver interactions
- system approach instead of component approach
- system integration
- training development engineers to use new simulation technologies effectively
- transient emissions modeling

- use of a broader database (experiment, diagnostics, simulation)
- use of artificial intelligence and expert systems for optimization
- virtual reality

Summary

In answering this question, respondents tended to focus on the need for specific modeling modules; hence, many answers ranged from "aerodynamics modeling" to "simulation of vehicle/driver interactions." Beyond this list, a number of panel members zeroed in on the need for more complete and extensive databases, more efficient means to incorporate experimental results into the model, better methods to determine the tradeoffs between speed and complexity, more computing power and display options, and better user interfaces and designer training programs.

Strategic considerations

Although this question was intended to focus more on hardware, user, or overarching control software issues associated with the use of simulation for engine design, many panelists used the opportunity to reinforce the results of Question ENG-27: More and better simulation modules covering a variety of specialized topics are still required. Of the remaining responses, nothing stood out as a major roadblock to the effective use of simulation. These answers represented more of a wish list of items that would improve performance, rather than a series of enabling technologies or developments.

II. VEHICLE DYNAMICS MODELS

DYN-1. To what extent do present dynamics simulation models meet the needs of vehicle manufacturers, and will future dynamics models in 2001 and 2006 meet the needs of vehicle manufacturers?

Scale:	1 = needs met completely 3 = needs met somewhat 5 = needs met not at all

Vehicle Dynamics Models	Mean Rating		
	1996	2001	2006
Meeting the Needs of Manufacturers	3.0	2.7	2.4

Selected edited comments

Round 1

- As computation power increases, allowing more realistic simulations, the main bottlenecks will be in model construction and data interpretation.
- Frequencies above 20Hz are not handled well by current models. Catastrophic local failures are not recognized in crash simulations. Dummy/Crush interaction needs development.
- We introduced ADAMS, but we do not use it effectively in the development of a new car.
- The current evaluation items meet our needs pretty much. However, for the past several years, the number of evaluation items has tended to increase to narrow the gap between functional evaluations and quantitative tests. We expect that this will create a period when the analytical capability will not meet the needs.
- The models themselves currently meet our needs. However, the way that we utilize them, and our pre- and postprocessing techniques, need continued development.
- I felt that the ADAMS vehicle modeling at our company was very accurate in many areas of steering and handling. The usefulness of the models was growing everyday. However, as the models become more useful, new ideas are generated as to how they can be applied to the design process. Therefore, the companies needs are never totally met. (3)
- The prediction is based on whether there will be efforts on IPPD (Integrated Product and Process Development).
- Structural dynamic simulation is far better developed than vehicle system dynamic simulation for load history determination and durability prediction at a design level of fidelity.
- Real-time simulation for driver-in-the-loop virtual proving ground simulation is only now emerging. Much development is required to achieve potential.

Summary

Currently, our dynamics modeling experts are somewhat divided about whether dynamics models meet the needs of manufacturers. Half of the experts believe that the models only somewhat meet the needs of manufacturers today, about 30 percent of the experts think the models are meeting manufacturers' needs, and about 20 percent of the experts believe the models are not meeting manufacturers' needs. But concerning the future, the experts are much more certain that dynamics models will come closer, but will not completely meet the needs of manufacturers in 2001 and 2006.

Comparison of forecasts: Engines - 1 / Structures - 1

Our engine modeling experts also feel that engine models only somewhat meet the needs of manufacturers today. But they believe engine models will come closer to meeting the needs of manufacturers in 2001 and 2006, with responses that fall halfway between the more optimistic Structures experts and the less optimistic Dynamics experts.

Engine Models	Mean Rating		
	1996	2001	2006
Meeting the Needs of Manufacturers	3.1	2.6	2.2

Our vehicle structure modeling experts also feel that structures models only somewhat meet the needs of manufacturers today, but they believe structures models will come closer to meeting the needs of manufacturers in 2001 and 2006 than do the Engine and Dynamics experts.

Structures Models	Mean Rating		
	1996	2001	2006
Meeting the Needs of Manufacturers	3.0	2.4	1.9

Strategic considerations

This question leads off a series of questions that look at the general effects of improved dynamics modeling and simulation techniques. Though the experts do not agree about how well dynamics models are meeting the needs of manufacturers currently, over time, many experts believe dynamics modeling will improve in meeting the needs of the vehicle manufacturers. However, the improvement in how the models are used in the near future, including the integration of modeling and simulation into the design process, will determine how successful they will be in meeting the needs of the manufacturers. Another issue concerning meeting the needs of the manufacturers focuses on the idea that as the models begin to meet the current needs, the expectations of the manufacturers will also continue to increase, thus making their "needs" a moving target that will be harder to satisfy.

DYN-2. What percentage improvement do dynamics simulation models add to vehicle process design efficiency currently compared to presimulation days, and what improvement over the current state should we expect by 2001 and 2006?

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	35%	50%	25%/30%	30%/38%	40%/55%

Selected edited comments

Round 1

- Design efficiency would relate to future test vehicle and test count reduction, lead time reduction, and product change count reduction.
- At least in our division, vehicle dynamic models have almost no contribution to the efficiency improvement.
- More developments in shock modeling and NVH ride models are needed to push the envelope further.
- Fifty percent means that the conceptual design time is divided by two, but it does not mean that the technological design can be reduced as much.
- The above are round estimates. We tend to judge our success by our customers' ability to solve problems that have eluded them in the past.
- These improvements are based on time saved by eliminating test and prototype machines.

Round 2

- Round 1 response results are higher than I thought. I think the main purpose of a vehicle dynamics model is to clarify the phenomena and to get a better measure through qualitative analysis.
- We hope that in the future, the use of models and simulation will become a habit for technological designers.

Summary

Our dynamics panelists see a 30 percent improvement in design efficiency due to dynamics simulation models over pre-simulation days, but they feel design efficiency will improve 35 percent in five years over the current state and 50 percent in the next ten years over the current state. The interquartile ranges for each of these time periods show a very tight range of response (i.e., consensus) on each time period.

Comparison of forecasts: Engines - 2 /Structures - 2

Our Engine panelists are the least optimistic about the effects improved engine models will have on engine design efficiency in the future, though their responses are in agreement with those of the Structures experts regarding the effect their models have on design efficiency in 1996 and the effect they will have in 2001.

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	30%	40%	25/30%	25/30%	30/40%

Our Structures panelists are also not as optimistic as Dynamics panelists about the effects improved structures models will have on vehicle design efficiency in the future, though they agree on the effect their models have on present design efficiency.

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	30%	45%	30/43%	25/33%	37/50%

Strategic considerations

The move to using modeling to improve design efficiency has already yielded a significant increase in efficiency, but over the next ten years, the Dynamics panelists see substantial improvement in design efficiency because of improved dynamics models. The improvements may come because the models or the modeling tools will improve, or because the designers will improve how they use the models and modeling tools. But possibly, the experts also see these improvements occurring because of improved integration of other types of models into a system that will be able to accommodate models from vehicle structures and engines in order to better balance all of the tradeoffs inherent in designing vehicles.

DYN-3. Please give your expectations, in months, of current and future development cycles from concept approval through production initiation for new and redesigned vehicles.

Dynamics Panelists Expectations of Development Cycles (Months)	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
New Vehicle	38	32	24	36/40	30/33	24/27
Redesigned Vehicle	22	18	16	21/24	18/20	14/18

Selected edited comments

Round 1

- From concept approval to launch. Redesigned, to me, means you carry over the platform, chassis, powertrain, etc.
- I think the period shorter than one year is ideal but this may be impossible within ten years. Secondary target at present is two years.
- The main driver for 20 months is flexibility – not a new product every 20 months.
- Enhanced capabilities are needed to achieve potential. Integrated simulation with vehicle CAD (computer-aided design) systems will yield greatest payoff in development time reduction, especially for vehicle redesign.

Round 2

- I think, in 2006, 12 months may be the best case. The shorter, the better. But if it will be possible to develop within one year, I think the lifetime of a car will be also shorter. So "the shorter the better" may not be right.
- Even if CAE (computer-aided engineering) technologies improve significantly, at least one prototype lot will remain. Considering the time required for prototype building, testing, and design feedback, it will be extremely difficult to reduce development cycles under 12 months, for redesigned vehicles.

Round 3

- Basically, I think the shorter it is, the better. When 12-month development cycles will be possible, the main part of it may be the time for product preparation. In this situation, we'll have a very short time for (dynamic) analysis activities. We'll need a new procedure or method for this.

Summary

Our Dynamics panelists see the current development cycle from concept approval through product initiation to be 38 months for a new vehicle and 21 months for a redesigned vehicle. They see a 16 percent reduction (to 32 months) compared to the current state in the time it will take to develop a new vehicle by 2001 and a 14 percent reduction (to 18 months) in the time it will take to develop a redesigned vehicle in 2001. By 2006, they see a 37 percent reduction (to 24 months) compared to the current state in the time it will take to develop a new vehicle and a 24 percent reduction (to 16 months) in the time it will take to develop a redesigned vehicle. All of these responses represent a consensus view based on the tight interquartile ranges for each time period.

Comparison of forecasts: Structures - 3

Dynamics and structures modeling experts are in general agreement about the time it takes to develop new and redesigned vehicles presently and in the future. The only disagreement comes in the time it will take to develop new vehicles by 2001, where the Structures experts believe the manufacturers will be able to reduce the number of months by 37 percent, and the Dynamics experts feel the manufacturers will not reach that level until 2006.

What is curious is that the Structures experts do not see any improvement in new vehicle development in 2006 relative to 2001. The interquartile ranges show 75% of the experts reporting a 24 month development cycle for 2001, but by 2006, 50% of the respondents report a range of 19 to 26 months, with 25% predicting a development cycle of 19 months or less.

Structures Panelists Expectations of Development Cycles (Months)	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
New Vehicle	36	24	24	32/38	24/30	19/26
Redesigned Vehicle	20	18	16	20/26	17/22	14/18

Strategic considerations

The following is a summary of some of the larger issues concerning shortened development cycles:

For vehicles that manufacturers believe are meeting the customers' needs, development will focus primarily on continuous improvement of the original design. This evolutionary approach will yield to a revolutionary technological push when a manufacturer feels the need to create a paradigm shift in industry or consumer thinking (e.g., the electric or hybrid vehicle). The revolutionary approach will probably be used exclusively in low-volume vehicles as a way of displaying a company's technological competence or as a market test to measure high volume potential.

Decreased design time and shortened product development cycles will not mean a proliferation of platforms, but it will mean a proliferation of models based on fewer platforms as manufacturers compete to create the "must have" buyer niche based on product differentiation at a variety of levels such as cost (price), quality, type of vehicle (such as a minivan ,SUV (sport-utility vehicle), EV (electric vehicle), hybrid), buying experience (Saturn), options, safety, and whatever new differentiators may appear. One area of consumer research that can feed into the development cycle will be to measure consumer wants and needs within a segment and translate that knowledge into the product development cycle for that segment.

More models in the product mix will challenge manufacturers to find ways of making a profit on low-volume production runs. But the incorporation of flexible and agile manufacturing into the shortened product development equation will allow manufacturers to adjust output to meet the needs of the market by shifting production from models consumers are not buying to new or redesigned models that may attract buyers. The 50-to-60 month development cycles of the past could not make these adjustments. By the time a manufacturer found a mistake in a model (or a potential new niche), designed a replacement, and produced the new model, four or five years had passed.

Within the platform environment, increased component sharing will reduce cross-platform complexity of models. There will be a standard set of variables with fixed ranges that will help modelers complete complex vehicle models in time to be usable in the early stages of vehicle design.

Decreasing development time allows personnel to move around within the limited number of platforms. This helps to solve one of the problems of platform teams that are learning from other platform teams, but are working somewhat in isolation from each other (though there still needs to be some dissemination of knowledge gained on a project).

The managerial challenge will be to balance development time on improving parts of the vehicle that the customer actually sees, feels, touches, hears, and smells with improvements on the parts the consumer does not see yet expects to perform flawlessly.

DYN-4. What percentage improvement in cost savings do dynamics simulation models add to vehicle process design efficiency currently compared to presimulation days and what improvement over the current state should we expect by 2001 and 2006?

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Cost savings	20%	25%	37%	15/20%	23/25%	30/40%

Selected edited comments

Round 1

- Many savings are compensated for by higher demands for completeness, coverage, and accuracy, and by more complexity.
- I think cost savings by dynamics simulation modeling is very small compared to the structural simulation modeling.
- Companies are only now beginning to believe in and act upon reducing prototypes in the design process. This will continue in the future. Companies cannot afford to build three to four levels of prototypes.
- These savings are based on reduced test time. Development phase is greatly shortened by eliminating the need for long drawn out test programs. (2)

Round 2

- At least by means of a vehicle dynamics model, the number of test cycles needed for performance verification was reduced to a certain extent. But the contribution to the cost savings is not so large.
- Numbers are given assuming that the level of complexity and performance stays unchanged.
- Even though the cost of prototype building and testing is expected to decrease, when you consider the development cost and manpower needed for CAE, it should be estimated lower than the previous estimates.
- Simulation will aid intermediate cycle of design by reducing physical prototypes, but design standards continue to evolve.

Round 3

- I think cost savings by all CAE activities will be more than 50 percent. But the contribution of dynamics simulation may be half of it at most.
- Use of Cray supercomputers and expensive, high-end work stations along with expensive CAE engineers will somewhat offset the reduction in prototypes.

Summary

The Dynamics panelists believe that dynamics modeling has reduced vehicle design costs by 20 percent over pre-simulation days, and they feel these costs will be reduced another 25 percent over the current costs by 2001, and 37 percent over the current costs by 2006. But a number of comments suggests that these efficiencies are qualified by the costs incurred with personnel and equipment needed to perform the modeling, as well as increased expectations and model complexity.

Comparison of forecasts: Structures - 4

Structures panelists are not as optimistic about how much cost reductions will be achieved in the future from improved structures modeling as Dynamics experts are about the effects of improved dynamics modeling. They agree that there has been a 20 percent reduction in design efficiency costs over presimulation days currently, but they believe costs will only be reduced by another 20 percent over the current costs by 2001, and 30 percent over current costs by 2006.

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Cost savings	20%	20%	30%	15/28%	20/25%	30/40%

Strategic considerations

A 37 percent reduction in vehicle design costs associated with improved dynamics modeling by 2006 is a significant savings in total vehicle costs. It will be interesting to see how these savings will be reflected in the final cost of the vehicle, and if there will be other areas of design, materials, manufacturing, or distribution that will absorb this savings. Also, the increased costs of employing these techniques may absorb some of the savings.

One issue that is not addressed in this question concerns how increased levels of performance, complexity, and accuracy will affect modeling and design costs over the next 10 years. Will increasing levels of performance, complexity, or accuracy decrease potential cost savings due to modeling because of the need to increase the time to program the models, add personnel, or purchase new equipment or software to reach these higher levels? Or will the manufacturers continue, as they do now, to test new models, but only use models that offer a clear reduction in time and costs?

DYN-5. What is the level of dynamics software modeling expertise needed by users to design vehicles now, and what will it need to be in 2001 and in 2006?

Scale: 1 = High level of expertise 3 = Medium level of expertise 5 = Basic knowledge

Dynamics Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	1.5	2.0	2.4

Selected edited comments

Round 1

- When we analyze vehicle dynamic behavior we must represent the phenomena exactly. This is the engineer's job. Easy operation and user-friendly software may help it, but it cannot replace the engineer's expertise.
- Part of the success of the tools is in reducing the expertise required to use them.
- The trend should be directed towards users who have expertise in vehicle dynamics and not to require expertise in the software modeling end.

Round 2

- Design could be achieved without this expertise, but the more expertise the better.
- Our needs for modeling expertise for the current dynamics software are not very high. However, for the future, even though their operation will become more user-friendly, as models become more complicated, the need for modeling expertise is expected to become higher. (3)
- Knowledge of the problem or system at hand should enable the engineer/analyst to decide on a level of complexity required to answer a given question.
- Globally, people involved in the design process will need this expertise.
- If modeling expertise needs to be higher than medium by 2006, then the CAE community will have failed.
- There is a need to automate model size/complexity selection so that less expert users can use correct models.

Summary

The Dynamics panelists, in general, see a continued need to have a relatively high level of dynamics modeling expertise over the next 10 years, though they do see a reduction from the high level of expertise currently needed to a medium level of expertise in 2001 and 2006.

Comparison of forecasts: Engines - 5 / Structures - 5

All three sets of experts agree generally that there is now, and will continue to be in the future, a need for a relatively high level of modeling expertise necessary to design engines and vehicles. There are two places, however, where the Structures experts disagree with the Dynamics and Engine experts disagree. The Structures experts, unlike the Engine and Dynamics experts, believe that there is currently, and will continue to be, a lower level of expertise needed to design vehicles.

Engine Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	1.9	2.3	2.3

Structures Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	2.0	2.2	2.7

Strategic considerations

Though modeling programs may become more user-friendly over the next 10 years, the expertise needed to perform vehicle dynamics modeling will continue to be focused on the ability of the engineer to understand the issues and solve the dynamics problems he or she is faced with. The issue of increased model complexity also expands the base knowledge the modeler must have to use a modeling program. The assumptions each program makes in solving complex physics problems must be well understood by the user in order to interpret and apply results correctly.

DYN-6. There's a debate in the modeling community about the need for complexity in vehicle modeling. One side argues that vehicle modeling should be integrated and complete and must incorporate as many variables as can be measured when defining a model. Another side says that a model should be more simplified in nature, focusing only on particular engineering problems, while yet another side argues that models should be large but with only significant complexity in those areas seen as important by engineers. What do you feel is the necessary level of complexity in modeling, and why?

Response	Percent of Respondents
Simplified	18%
Complex	23%
Both / Hybrid	59%

Simplified Models:

- Use simplified model focusing on particular engineering problems to reduce run time and provide answers on multiple alternatives.
- I think a model should only be as complex as is necessary to provide the information desired so that resources are not wasted (data requirements, computer time, users time).
- As long as the demand for the model is satisfied, it is not necessary to make up the large model.
- A model should be simplified and just complicated enough to describe the physical conditions which are part of the engineers' research and development process.

Complex Models:

- With the increasing speed and efficiency of computers, more details are highly desirable. The arguments suggesting that we only need moderate complexity might be of value for short term objectives; however, our knowledge is still limited and what we think, at this time, might not (will not) be acceptable in 5 to 10 years.
- I feel it is driven by readily available computer power. When more power is cost effective, more complexity in the models will follow.
- We expect that future models will become increasingly complicated for the following two reasons: Discussions on tradeoffs between functionality will become increasingly important, and in order to narrow the gap between functional evaluations and quantitative indices, the number of evaluation items focusing on minute differences are increasing. In response to this trend, models are becoming increasingly complex.
- From a current design perspective, simpler models are required, but may bear little resemblance to the end product. Future design capabilities will enable more complex models to be used for greater design variation.
- Simple models are only good for simple ranking exercises. Full vehicle models demand more complexity.

Hybrid/Both Models:

- I support the third view, that models should be large, but with significant complexity only in those areas seen as important by engineers.

- If we don't care about the model consistency, we should use many simplified models that are purposely designed for a particular task. But, if we want to reduce overall cost of the entire design process and get consistent design for all the products, I believe we need to have a complete model that everybody uses. It (the model) may be overkill for some tasks, but it is needed for IPPD.
- The right level of modeling is determined by the task at hand. Adaptive and semiautomatic model construction is the right approach, together with interactive model refinement. Far more flexible user interfaces and model construction capabilities are required.
- All three views are valid in different phases of the design cycle.
- There is not a single level for all purposes. It would be useful to be able to assemble a large "complete" model and to derive many simpler, specialized models.
- The level of complexity should be based on phenomena to be simulated and the time of use in the design cycle. Simple models can be very useful and cost effective early in the design process to address global issues. More detailed models are often required later on as the emphasis shifts to more specific and refined issues. (2)
- For concept design and selection, the models are simple and focused. They are partly detailed (in relevant areas) in parameter and system design and optimization. In sign-off/integration, they need to be fully detailed.
- It depends. Often one is interested in a particular subsystem. A high level of detail is necessary sometimes. There is no "one size fits all" type of model.
- The large simulation packages make nice pictures but are not useful for design. Models should always be formulated to answer engineering questions and aid in design. Some models can be quite simple, while others might be complex. It depends on the need. My experience has always been that reasonable models answer virtually all of the questions.
- The level of model complexity depends on the goal of your model. For simulation purposes, it is interesting to have a model as precise as possible – a "knowledge model." For a control design purpose, it is often necessary to use a simplified model. For engine control, you need fairly simple models.
- My feeling is that a great level of component level detail, plus accurate loads data, is an absolute necessity. For full vehicle models, "concept level" seems to be best for dynamics.
- Simulation needs to follow a "value added concept." That is, early concept needs are simple models, and as decisions are made models need to define more realism. The last step includes a "complete" model used to assure a robust product that meets quality goals and customer wants.
- All sides are correct. You need different models for different situations. In some problems you need a very complex and comprehensive model, but for some other problems a comprehensive model may be not only inefficient and time consuming to use, but also less able to demonstrate the response as clearly as a simple model could.

Summary

Our Dynamics experts believe that there is no one way to deal with complexity of models. There are nearly equal opinions about the need for simplified and complex models, but a majority of respondents think that different levels of complexity are needed in a variety of ways throughout the whole design process.

Comparison of forecasts: Engines - 6

The Engines panelists responded almost identically to the Dynamics panelists, with the majority noting many different situations that demand a flexible view of modeling.

Strategic considerations

The issue of model complexity is a serious one in terms of a modeler's ability to influence the design process. Models that are too complex to complete within the time frame dedicated to the design process are of little use, while models that are too simplistic to give the detail necessary to accurately measure component performance are also of little use.

Good design engineers using models to create a new component or improve an existing component must be able to balance the use of simplified and complicated models where necessary. Understanding the modeling needs of each of the components of the system under consideration will be a necessity if good decisions about the use of modeling resources and time are to be made. One area where manufacturers may decrease time while increasing complexity is in developing common databases for all engineers and designers to use in the modeling and simulation process. The manufacturer who most efficiently uses modeling to support the design process will also be the most able in reducing costs and developing superior products.

DYN-7. When constructing models, is it immediately obvious what components and level complexity are appropriate?

Obviousness of Components and Level of Complexity	Percentage
Yes	6%
Depends/Sometimes	29%
No	65%
Total	100%

DYN-7a. Can automated component and complexity selection programs such as MODA (Model Order Deduction Algorithm) accurately automate the selection of components and complexity now or in the future?

Use of Automated Component and Complexity Selection Programs	Percentage
Yes	12%
Maybe	38%
No	42%
Don't know	8%
Total	100%

Selected edited comments

Round 1

- A good experimental database from which to derive correlation between test result and analytical results will always be an effective means of determining the level of complexity necessary in a model/simulation.
- If I've solved similar problems before, I can give you a good idea of the needed complexity. If I haven't then I won't know until I've uncovered the root cause.

Summary

The majority (65 percent) of the Dynamics respondents believe that they do not immediately know what level of complexity is appropriate before beginning the modeling process, but they are less certain (12 percent "yes," 38 percent "maybe", 42 percent "no") whether automated complexity selection programs will be able to accurately determine the components and complexity necessary at the beginning of the modeling process. The engineers involved in the process of modeling feel their input into the modeling process will be very hard to eliminate, though they believe improved tools will help them work through problems more quickly.

Strategic considerations

These results mirror the uncertainty the dynamics experts expressed about the level of model complexity needed to solve automotive modeling problems in the previous question. The respondents, in general, believe there may be some time saved through automated component and complexity programs, but there will still be a strong need for experts in the field of research to guide the programs before, during, and after the modeling process.

DYN-8. Some modelers also see a trend towards extensive use of neural networks, expert systems, and artificial intelligence systems as playing an increasing role in vehicle simulation. What is the likelihood of expanding the use of these systems in the short term (1996 to 2001) and the long term (2002 to 2006)?

Scale: 1 = Very likely 3 = Somewhat likely 5 = Not very likely

Use of Neural Networks, Expert Systems, and Artifical Intelligence	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Neural Networks	4.0	3.5
Expert Systems	3.4	2.8
Artificial Intelligence Systems	3.9	3.3

Selected edited comments

Round 1

- Some participants have illusions about these technologies. AI (artificial intelligence) or neural network-like technologies will be possible to utilize, but these may reduce some parts of modeling at most.
- It will never effectively and efficiently replace human experts and natural intelligence, if we are after good end results (vehicles) and not after impressive high-tech tools for their own sake. They may help in clearly defined, narrow areas, and for inexperienced users. (3)
- These technologies will gradually gain opportunities to be introduced. However, I do not believe them to be key technologies for forecasting vehicle performance.
- AI technology is necessary for user interface and utility, not modeling only. This is perhaps where it will have the biggest impact.
- Given the lack of progress in AI systems and expert systems, I am skeptical of their usefulness. Neural nets do have some application, even currently, for generating "look-up table" types of models. (2)

Round 2

- AI techniques offer great promise in automating model construction, hierarchical reasoning, and data and model evaluation.
- I don't think these technologies will be completed in ten years. Presently, I do not expect them at all.
- Tasks for automatically searching for solutions that satisfy target performance as well as testing conditions will become increasingly demanding.
- AI and databasing are the current MBA buzzwords. Just wait until companies find out how expensive it is to log data, store data, and make sure it's accurate. Engineers rarely find a need for data on a five-year old vehicle.
- Neural nets are a useful automated data-fitting tool. However, they can be much worse than regression models outside the data envelope. Regression models can be designed to perform reasonably outside the data domain (although they often are not) but nets cannot be.
- The "artificial intelligence" community contributing to automation of vehicle dynamics modeling and simulation needs to stay close to the real world. The "devil is in the detail" of modeling and simulation, not in abstract computer science.

Round 3

- AI has potential and is making, in a quiet way, big contributions. It is not always called AI though.
- We are seeing definite benefits now and expect benefits to increase.
- When we use the AI or neural network-like technologies, we must arrange and prepare the underlying procedures the way a human being does. This work needs a lot of effort and labor to develop these technologies.

Summary

As the data and the comments of our respondents show, the experts are relatively skeptical about the expansion of these systems to support modeling and simulation in the short term and the long term. They see the use of expert systems expanding more than AI systems and neural networks, but only in the long term do they see expert system expansion as slightly more than somewhat likely.

Comparison of forecasts: Engines - 5a / Structures - 6

The panelists are fairly divided in their visions of when expanded use of these advanced techniques will occur. In the short term, of all three techniques, only the Engine experts believe that expert systems are likely to play an expanding role in vehicle simulation. In the long term, all three panels feel that expert systems are more likely to play an expanding role, and the Structures and Engine panelists both think neural networks and artificial intelligence are at least somewhat likely to play an expanding role in vehicle simulation.

Use of Neural Networks, Expert Systems, and Artificial Intelligence	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Neural Networks	3.4	2.5
Expert Systems	2.1	1.8
Artificial Intelligence Systems	3.4	2.7

Use of Neural Networks, Expert Systems, and Artificial Intelligence	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Neural Networks	3.7	2.6
Expert Systems	3.2	2.5
Artificial Intelligence Systems	3.4	2.8

Strategic considerations

These higher order techniques seem to be in their infancy in terms of their applicability to the automotive industry. Though some experts believe these techniques will be helpful in the future, many experts will need to see direct applicability to their processes as well as proven effectiveness before they will relinquish what they see as core engineering decision-making.

DYN-9. One of dynamics modeling's potential advantages is to reduce reliance on physical prototyping for development purposes. How much of a reduction in physical prototype iterations should we expect in the short term (1996 to 2001) compared to presimulation days and the long term (2002 to 2006), relative to the present?

Scale: 1 = Close to a 100% reduction 3 = About a 50% reduction 5 = Very little reduction

Physical Prototype Ilerations for:	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Validation	3.4	3.2
Development	3.5	2.7

Selected edited comments

Round 1

- Both iteration reduction and quality of result should be considered. Optimization will become more difficult.

Summary

Dynamics panelists see close to a 50 percent reduction in reliance on physical prototypes for both validation and development. For validation, they see little reduction in reliance on physical prototypes from the short term to the long term, but for development, they see a move from less than a 50 percent reduction to slightly more than a 50 percent reduction in reliance on physical prototypes.

Comparison of forecasts: Structures - 10

Structures panelists were asked what the effects of structures modeling would have on the reduction in reliance on physical prototypes. They see more of a reduction in reliance on physical prototypes due to structures modeling than Dynamics panelists see due to dynamics modeling. For validation, they see less than a 50 percent reduction in reliance on physical prototypes in the short term and an even 50 percent reduction in the long term. For development, they see close to a 50 percent reduction in the short term and nearly a 75 percent reduction in the long term.

Iterations for Structures:	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Validation	3.6	3.0
Development	3.1	2.3
Testing	3.1	2.4

Strategic considerations

A 50 percent reduction in the reliance on physical prototypes is one of the major goals for increasing the use of modeling and simulation, and manufacturers hope it will translate into significant cost savings in the product development process. Considering the time saved of iterating prototypes, the total product development process should be shortened, thus allowing manufacturers to design and redesign in a way that may make them more responsive to their customers.

DYN-10. In the short term (1996-2001) and long term (2001-2006), do you see any reduction in model calibration and validation requirements, such that extrapolation of the model for design work may be carried out more reliably and easily?

Scale: 1 = Close to a 100% reduction 3 = About a 50% reduction 5 = Very little reduction

Calibration Validation	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Reduction	4.0	3.5

Selected edited comments

Round 1

- Model calibration and validation are the basis of the studies afterward. Some software or technologies may help reduce some work, but model calibration and validation will not vanish.
- What we've already achieved (i.e., kinetics) and are continuing to achieve in reduction in some areas is (possibly) compensated by modeling more detailed and other criteria requiring validation on that new level.
- Some reduction will be obtained if libraries of validated models, well organized and documented, exist in companies.
- Design work use of models can be achieved without calibration and validation; final product must be validated by physical test.

Round 2

- Physical calibration and validation will always be necessary, but will be confined to the hardest, most novel problems. (2)
- In general, models need not be validated to be useful. If properly formulated, models are very accurate for comparative studies. In other words, a model need not be absolutely accurate in order to accurately predict trends.
- Model validation is still crude and not done as thoroughly as needed. I see no significant change in this in the foreseeable future.
- Complex, full system models will continue to require large amounts of data and validation for the foreseeable future. Smaller, simpler models will require less data — but only because we don't expect answers that are as precise.

Summary

Our Dynamics panelists see about a 25 percent reduction in model calibration and validation requirements in the short term and about a 40 percent reduction in the long term. Though this difference may seem like a lot in real terms, our panelists see reasons why this change will not be more dramatic. New, more detailed models, which will replace past models that no longer needed to be validated, will themselves need to be calibrated and validated; completely new models will continue to need validation; and the uniqueness of each system in the vehicle will demand that validation occur.

Strategic considerations

As one of our panelists noted, well-documented libraries of validated models may lead to a reduction of validation, but this suggests that this process may not be occurring at present. This is in conjunction with the increasing detail of modeling and broadening of the scope of modeling across the entire development process, such that calibration and validation will remain essential. Based on these issues, companies that have well-organized and well-documented modeling research organizations may have a competitive advantage over companies that do not.

DYN-11. Ground/tire interactions, as well as higher resolution models of tire dynamics themselves warrant continued research. Please rate how accurately aspects of ground/tire interactions capture reality today.

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Aspects of Ground/Tire Interactions	Mean Rating
Handling	2.9
Ride Quality	3.4
Friction (for steering)	3.7
Ground/Tire Contact	3.8
Durability	4.3
Off-Road Behavior	4.3

Selected edited comments

Round 1

- We collaborated to create a good tire model with a tire maker and got acceptable accuracy. But the number of cases where it can be applied are few, so the profit from it is unclear.
- In my opinion, this is the weakest link in a vehicle model for dynamic simulations. This subject needs more research.

Round 2

- We have models that are accurate enough for our uses.
- Big questions we're helping clients answer include kinematic effects, generation of accurate road loads data, and nonlinear vehicle behavior.

DYN-11a. Please list the most important specific problems remaining in the modeling of any of the above.

Unresolved Ground/Tire Interaction Issues

- ground/tire contact (4)
- mid-frequency NVH (noise, vibration, and harshness) problems; durability load predictions (3)
- tire/soil interactions for off road vehicles (3)
- tire models for ride (greater than 4Hz) (3); quick and accurate (and reliable /robust) integration for durability and ride; realistic friction models (2)
- On-center feel model precision needs improvement.
- measure and setting the dynamic properties of rubber bushings; nonlinear properties of the damper; treatment of friction and hysterisis of components
- position on friction circle dynamics of lateral force and lengthwise force, when considering the dynamic characteristics of tires (whether static position is acceptable)
- generation of surface contact rather than point contact tire models; representation of tires' tendency to envelope road surface irregularities; creation of durability tire models with nonlinear radial rates to represent sidewall compression over severe inputs (pothole; washout; etc.)
- self aligning torque (poor modeling); in the condition of large slip angle; in the condition that lateral and longitudinal forces simultaneously act; lateral force characteristics depending on vertical load; longitudinal force characteristics depending on vertical load; micro friction characteristics (depending on velocity)
- A list of difficulties arises when dynamic systems modelers have to communicate with people from other technical areas (material science for example) because of a lack of a common language.
- Effect of surface coefficient of friction on tire force and moment capability. Effect of tire pressure on tire force and moment capability. Effect of tire wear on tire force and moment capability. Ride and durability tire model that is simple to use and directionally accurate. Steering system friction modeling techniques that don't make the integrator crash.

Summary

Currently, our panelists see acceptable accuracy only in the modeling of handling, and close to acceptable accuracy in the modeling of ride quality. Durability, off-road behavior, friction, and ground/tire interactions all have unacceptable modeling accuracy currently. The problems our panelists identified indicate exactly where the most work is still needed, particularly in ground/tire contact models, friction models, durability models, and ride quality models.

Strategic considerations

Ground/tire interaction modeling and general tire modeling offer excellent opportunities, at present, to effect significant change in the field of vehicle dynamics. Within the context of the results of this survey, these issues offer the greatest modeling challenges as well as the greatest opportunities.

DYN-12. Durability models include such intensive events as tire/pothole interactions, suspension compliance, and bushing behavior. Please rate the accuracy of these models (both quantitatively and qualitatively) currently, in 2001, and in 2006.

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Accuracy of Durability Models	Mean Rating		
	1996	2001	2006
Quantitatively	4.2	3.4	2.7
Qualitatively	3.7	3.1	2.3

Selected edited comments

Round 1

None

Round 2

- We have models accurate enough for our uses.
- Current durability models comply with suspension requirements fairly well. Model/test verifications of tires are likely to be time consuming.
- There is a lot of work needed in this field.
- Without extensive efforts in increasing the complexity of vehicle system models as well as tire/terrain models, I don't expect to see major improvement in durability models.
- Regarding the use of hybrid systems, recording actuating test benches associated with theoretical modeling seems to be the way. High accuracy is not necessary considering the actual production diffusion.

Summary

This question was designed to further develop the discussion of the complexity of models by looking at how experts look at or use two versions of the same model, a quantitative one and a qualitative one. One could hypothesize that in some cases modelers would use a qualitative solution to a problem if an acceptable quantitative one was not available. But despite some of the contradictions noted in comments by Dynamics respondents, the Dynamics panelists generally do not see large differences between quantitative and qualitative models. Also, they don't see quantitatively acceptable accuracy for durability models being reached until 2006, but they do see qualitatively acceptable accuracy for durability models being reached by 2001.

Strategic considerations

Obviously, durability models have not reached acceptable accuracy either quantitatively or qualitatively, though some of our respondents believe the models they currently use are "good enough" for their purposes. Considering the importance of the effects durability models have on the consumer, it seems likely that a competitive advantage will be gained by the group that can bring quantitative or qualitative models with acceptable accuracy to market before the turn of the century.

DYN-13. Please rate how advanced tracked vehicle dynamics models are currently, and how advanced they will be in 2001 as well as in 2006.

Scale: 1 = Very advanced 3 = Moderately advanced 5 = Not advanced at all

Tracked Vehicles	Mean Rating		
	1996	**2001**	**2006**
Advance	3.0	3.0	2.4

Selected edited comments

Round 1

None

Round 2

- We have some simple tracked vehicle models and some complex tracked vehicle models. In the future we will have more complex tracked vehicle models.
- There are some very advanced but not very useful track models in existence today. I believe that will still be the case in 2001 and 2006.
- Efforts continue to make improvements. Complete field application load histories can now be measured.
- Achieving their potential will require concerted and coordinated effort of both vehicle dynamics and soil mechanics specialists.

Summary

A number of our respondents did not feel comfortable answering this question because they do not use or design tracked vehicles, but those who do use these models believe they are currently moderately advanced. They do not see much improvement in the near term, but they do see substantial advancement over current models by 2006.

Strategic considerations

Because there is a limited market for tracked vehicles, modeling dynamic behavior of these vehicles becomes even more important than nontracked vehicles due to costly prototypes. Any reduction in the number of prototypes in this case will greatly contribute to cost reductions for the whole project. Also, though the emphasis of concern for modelers of tracked vehicles may be different in some ways from modelers of nontracked vehicles, many of the models used for vehicle dynamics apply to both types of vehicles, which may explain why tracked vehicle models seem to be following the same path of development as nontracked vehicles.

DYN-14. What is the probability of effectively integrating flexible components into simulation models in the short term (1996-2001) and in the long term (2002-2006)?

Scale: 1 = High probability 3 = Moderate probability 5 = Low probability

Flexible Components	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Probability of Integration	2.7	1.6

Selected edited comments

Round 1

None

Round 2

- This requires massive computational power, which will become more available as time goes by.
- I think the probability is low, but the demand for this type of analysis is high.
- The added complexity of flexible components should only be introduced when absolutely necessary.
- You can currently do it, but it really slows down run time.
- Customer acceptance is somewhat of an issue, but the technology is currently available.

Summary

Our panelists are relatively confident that they will be able to effectively integrate flexible components (i.e., moveable components) in the short term, but they are even more confident they will be able to effectively integrate flexible components in the long term. The roadblock seems to be time as measured by a lack of computing power rather than the theoretical models necessary to model component behavior.

Strategic considerations

The point that most of the components of the vehicle move in some way and are thus considered flexible is an important issue in modeling and simulation. Many of today's models assume components are rigid, thus when the model does not accurately reflect the flexible nature of a steering or safety design, for example, it must be re-engineered at a substantial cost in order to "get it right." Being able to accurately model flexible components the first time will reduce costs and product development time.

One of the main issues that confronts the integration of flexible components into simulation models is the need to centralize and unify the vehicle databases that the programs draw on to run simulations. As these databases become more unified and centralized, computers will be able to run the simulations faster and be better able to incorporate flexibility into the models.

DYN-15. Please rate the probability of modeling nonlinear behavior of components, as well as modeling components using continuous mass nonlinear finite element analysis (FEA) in the short term (1996 to 2001) and in the long term (2002 to 2006).

Scale: 1 = High probability 3 = Moderate probability 5 = Low probability

Dynamics Panelists' Ratings	Mean Rating	
	Short Term (1996-2001)	**Long Term (2002-2006)**
Nonlinear Behavior	2.5	1.6
Continuous Mass Nonlinear Finite Element Analysis	3.0	2.3

Selected edited comments

Round 1

- To what extent the nonlinearity is considered is important. In doing this it is also necessary for us to get the equivalent test data. If there is no test data, it is meaningless to model it.
- Nonlinear behavior of components is currently modeled, even if the associated characteristic laws are often linearized for analysis purposes.

Round 2

- To represent the nonlinear behavior, we developed a special in-house program to use.
- I can currently model nonlinearities although some are harder than others.
- Existing methods can model some components very well. Because of the lack of validation data, it is unclear how well existing methods model the others.

Summary

Panelists see a slightly higher than moderate probability of modeling the nonlinear behavior of components in the short term, and good probability of modeling the nonlinear behavior of components in the long term. They are slightly less confident in the probability of using continuous mass nonlinear finite element analysis to model nonlinear behavior.

Comparison of Forecasts: Structures - 14

Though Structures experts are optimistic about their ability to model nonlinear behavior in the short and long term, they see a lower probability of modeling nonlinear behavior in the short and long term, relative to Dynamics experts. However, relative to Dynamics experts, they see a higher probability of using continuous mass nonlinear finite element analysis to model nonlinear behavior in the short term and the long term. These results may be due to structures models being, in general, more complex than dynamics models, and thus more challenging nonlinear models.

Structures Panelists' Ratings	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Nonlinear Behavior	3.2	2.2
Continuous Mass Nonlinear Finite Element Analysis	2.8	1.9

Strategic considerations

Though the Dynamics panelists did not comment on the reason for the high probability of being able to model nonlinear component behavior, a number of the Structures panelists mentioned that as computing power expanded, these types of models will be more readily available to designers.

Being able to model nonlinearities will give dynamics modelers important information in the modeling of tires and shocks, as well as modeling tires and handling at high lateral acceleration. It will give them the ability to better model both the component and the system. By feeding this information into the early stages of the design process, designers will have a more robust model that will cover a wider variety of operating circumstances and will allow them to design vehicles with superior ride and handling.

DYN-16. **What is the importance of each of the following factors in helping to develop real-time models?**

Scale: 1 = Extremely important 3 = Moderate important 5 = Not important at all

Factor	Mean Rating
Significant Increase in Computing Power	1.9
Refinements of Existing Codes	2.3
Reduction in Model Complexity	2.2

Selected edited comments

Round 1

- Why do I need a real-time model? (2)
- Considering the use of real-time simulation, the capabilities of the work stations, rather than the clay model need to improve dramatically.
- parallel processing or faster vector processors

Round 2

- more Cray capacity
- Validation is a key bottleneck also.
- Current real-time simulation methods and computer codes are fundamentally limited by the available numerical integrators.
- specialized hardware (IC's (integrated circuits)) design

Summary

Based on what respondents have commented on prior to this question, it is no surprise that they believe that a significant increase in computing power will be important to developing real-time models, but it is also significant that they see a reduction in model complexity and refinements of existing codes as important to developing real-time models. The importance given to all three of these issues leads one to suspect that a lot of work is still necessary in this field if real-time models are to be used for design purposes.

Strategic considerations

Today's modelers and designers probably do not feel real-time models are that important to their process (though it would be nice to complete simulations faster). But in the areas of driver-in-the-loop studies and virtual reality battlefields and highways, real-time simulations are critical. Because of the need for more computing power, refined codes, and reduced model complexity in order to run real-time models, driver-in-the-loop and virtual reality studies may lead the way to future gains in the three areas mentioned.

The use of real-time models for general vehicle design purposes may be limited because of current computing power (which vehicle manufacturers have little control over), but manufacturers and suppliers do have the ability to reduce model complexity and refine existing codes. When the computing power becomes available, modelers who have succeeded in reducing model complexity and refining existing codes will have an advantage over other modelers in implementing real-time models if they think these models will aid in the design process.

DYN-17. How long will it be before a design fidelity simulation can be run in real-time?

Real-Time Design Fidelity Simulation	1-2 Years	3-5 Years	6-10 Years
Percentage	0%	29%	71%

Selected edited comments

Round 1

- I checked "6-10 years" but I doubt that it can be done within 10 years
- The answer is "1-2 years" or "3-5 years," depending on the level of complexity you wish to model (4).
- "Real time" is not necessarily the main issue in improving design.
- The need for design fidelity in real-time is only driven by the need to speed up design; faster than real-time would be great!

Round 2

- We need to define what "design fidelity" is, since we are not fully utilizing dynamic simulations in design phase yet!
- Handling and active controls only. Does not include NVH, ride.
- It is important to focus on design issues that are influenced by the driver, for example, handling, ride quality, automatic control, etc. Real-time is not required unless there is a driver or un-modelable hardware interaction.

Summary

This question begins to get to the heart of the problem of using real-time simulations. Though the respondents clearly do not see design fidelity real-time simulations occurring in the near future, their comments begin to flesh out the discussion of the level of complexity needed to properly design vehicles.

Strategic considerations

Though many of the comments of the respondents note that real-time simulations are already being performed, the main consideration that needs to be addressed is whether the models they are currently running in real-time give them the answers they need for design, or are these real-time models actually a compromise of what modelers would really like to have, but cannot have because of the lack of computing power. Have they had to compromise their codes and model complexity to get the simulation to run at all with the results being less than optimal? Is "less than optimal" acceptable for designing vehicles, or is this a result of compromises due to a lack of computing power?

What will be the effect of being able to run real-time models on the complete vehicle? As noted in the previous question, real-time models will be of particular use to driver-in-the-loop and virtual reality studies, but this also raises a number of questions about the effect of these models on complete vehicle models. Will there be an advantage gained by using real-time simulations when running complete vehicle simulations? Though modelers currently solve their problems by running subsets of the complete vehicle simulation, will these subsets fit into the real-time framework when it becomes available? Will there be significant gains made in full vehicle simulation when the computing power necessary to run real-time models becomes available, or will the submodels be so well designed that there will only be a small gain made by complete vehicle simulation using real-time models?

DYN-18. Given that full real-time driver-in-the-loop simulations are possible, what results do you feel you could obtain from them that you cannot obtain from an off-line simulation?

SPACE

- It will be easier to instrument more fully.
- better exploration of the design space; speed-up the control of the type of output and its amount.

DRIVER

- driving behaviors/trends; fatigue and failure
- interaction; event feedback
- limit handling stability in transients; straight ahead stability/path following
- subjective feel, audible feedback, tactile feedback;understanding of transient response
- responsiveness of driver; responsiveness of other crew members (tank); accurate fire on the move models
- driver response handling; human reaction to ride quality
- desktop simulation of ride comfort comes true
- bench evaluation of controller; functional evaluation using drive-simulator; human factor research
- driver seat-of-pants reaction
- subjective driver assessment; understanding of true range of driver inputs; understanding of driver reactions/behavior in emergency situations
- operation tactile feel; operator reaction to response of controls/systems; sound
- Driver's feel of the car and his/her intuition cannot be easily transformed to numbers, plots, equations, etc. Off-line simulations cannot provide that intuitive response.

MULTIPLE USES

- overall system performance under more realistic operations; human's perception of the system performance; impact of transportation safety regulations
- We could evaluate handling quality. We could get information about evasive maneuvers. The design process could become simpler.
- Make the link between quantitative and qualitative criteria of performance evaluation. Take into account the human body reactions under some solicitations.
- ability to tune the design to the intended driver population; ability to tune design to ranges of uncertainty in unmodelable components/effects
- With a simulator, the CAE analyst could actually feel how well the new design handles, before hardware prototypes are built. Also, the usage (duty cycle) of the model would be more representative of real life.
- driver responses to vehicle changes; safe limit handling; driver training; prototype vehicle development

NEGATIVES

- I see no real benefit, except for research studies.
- I do not think real-time driver-in-loop simulations are necessary. Spend the money and time instrumenting a real car, and drive it.

Selected edited comments
None

Summary
Without the restrictions placed on what is possible now, respondents see a wide variety of possible uses of driver-in-the-loop simulations, including ride, handling, driver interaction and response in emergency situations, design of interior space, and sound.

Strategic considerations
Three very interesting driver-in-the-loop issues that show the potential value of these models emerged from comments from respondents: being able to see the impact of safety regulations before they are legislated, being able to better judge the usage/duty cycle of a vehicle, and being able to tune the design cycle to a particular driving population.

Despite the limitations of current computing power, the advantages of developing driver-in-the-loop models clearly offer competitive advantages to the manufacturer who can develop usable models. Being able to see the impact of safety regulations before they are implemented could lead to a collaboration between government and industry on driver-in-the-loop models, which may spur development through a pooling of resources and knowledge before a competitive advantage for any one manufacturer is reached.

DYN-19. With regard to ride quality perception by the driver and passengers, how accurately do models incorporate the following currently, and how accurate will the models be in 2001 and 2006?

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Accuracy of Aspects of Ride Quality	Mean Rating		
	1996	2001	2006
Higher Frequency Vibrations	4.3	3.4	2.8
Dynamics of the Human Body	4.2	3.5	3.1
Load Path to the Driver & Passengers	4.3	3.6	2.9

Selected edited comments

Round 1

- Driving simulator development is important.
- These NVH models are all linear approximations of a highly nonlinear and complex vehicle. A lot of work is needed in this area.

Round 2

- We may clarify the load path and dynamics of the human body, but it may be difficult to solve relations between human feelings and human dynamics.
- There isn't enough knowledge of this area right now.
- Human body response to dynamic loads and human volitional control thereof is poorly understood even in lab conditions. Simulation in field conditions is problematic.

Summary

The Dynamics panelists see models focusing on higher frequency vibrations, dynamics of the human body, and the load path to driver and passengers as unacceptable currently, reaching near acceptable accuracy by 2001, and reaching acceptable accuracy by 2006.

Strategic considerations

Ride quality is an important consumer and vehicle performance measure. Current design techniques are not able to predict ride quality consistent with consumer preferences. Therefore, a huge benefit is afforded the manufacturer who develops the capability to design (without prototypes) for ride quality. These challenges also apply generally to modeling subjective human responses because of their complexity and nonlinearity.

Because of the amount of time manufacturers have already spent developing ride quality through physical testing and retesting, in some ways modeling issues like this begin to reach the "icing on the cake" stage of product development. Yet despite the extensive work done in this area, in the future small differentiators that can be gained by improved ride quality as well as reduced product development time will potentially make modeling a valuable aid for designers and engineers.

DYN-20. What problems do you currently resolve exclusively (or mostly) by test rather than modeling? What problems do you foresee in 2006 being resolved exclusively (or mostly) by test rather than modeling?

1996

- ride comfort; sound quality
- shock absorbers, tuning
- durability (collision, fatigue, stress under unusual environment), safety
- inconsistency between the quantitative evaluations and sensory evaluations; insufficient accuracy of the computational models; unreliability of the tire models
- on-center feel; tire noise
- reliability and durability; survivability, gun and fire control accuracy
- reliability, durability; live fire testing
- vibration, wear and tear, tolerancing
- reliability testing
- vehicle/tool/ground interaction; sound measurements; mission levels (engine)
- component specifications, tire force and movement, ride
- durability testing for both components and full systems [16]; durability testing for full complex vehicle systems
- Human body response to dynamic loading – for example, at the hands – is a very tough problem.
- proving grounds durability

2006

- ride comfort; sound quality (especially high-frequency)
- engine emissions, tire design
- shock absorbers, tuning
- durability
- The inconsistency between the quantitative evaluations and sensory evaluations is a difficult problem to resolve.
- subjective evaluations of customer performance
- reliability and durability; survivability, gun and fire control accuracy
- vehicle "feel", crash models
- emission levels (engine)
- component specifications, tire force and movement, ride
- durability testing for full complex vehicle systems

Selected edited comments

Problems between phenomena and feelings of humans will be solved to some extent, but will remain forever.

Summary

The three main areas that currently are resolved mostly by test are issues related to the driver's subjective, sensory perceptions (e.g., ride and comfort, sound, and vehicle "feel"), issues of the vehicle's durability and reliability, and other certain nonlinear phenomena. Respondents believe that these same issues will continue to be resolved mostly by test in ten years, though fewer of the current issues will be resolved by test.

Strategic considerations

This question highlights three of the greatest challenges in dynamics modeling and simulation, being able to model the wide range of subjective driver perceptions, being able to model tires, shock absorbers, bushings, and other nonlinear phenomena, and being able to simulate the effects of the environment and wear on components or systems over a long period to time. These issues offer substantial opportunity to modeling and simulation suppliers to provide manufacturers with tools to overcome these challenges as well as providing a competitive advantage to manufacturers who best use these tools.

Having solutions to these challenges folded into the ARC (Automotive Research Center) full vehicle model would offer manufacturers value that they do not even see themselves being capable of creating ten years from now. But the general challenge of being able to accurately quantify subjective driver responses may create a level of complexity that limits the ARC's ability to provide the ultimate full vehicle model.

DYN-21. Does modeling get utilized constructively and in a timely fashion in the design process? Ideally how would you see modeling placed in the vehicle design process? If so, at what point(s) in the design process has modeling been most successful and/or useful? If not, what have been the roadblocks?

Modeling Used Constructively and in a Timely Manner in the Design Process:

- Modeling does not get used constructively or in a timely manner in the design process. This is because the models are too complex to initiate design, and model complexity requires large amounts of time to program. I believe reliance on computers has made it possible to use modeling in the design process, but has also encouraged the user to go overboard, thus defeating the original purpose.
- Modeling is being constructively utilized and is most effective when it leads design activity and addresses key issues prior to design deadlines.
- Modeling is used constructively, but not always in a timely manner. Designing models can take as long as designing and building hardware. It is useful to establish vehicle concept, and it is useful when a design is similar to past designs.
- Most modeling efforts today are on existing vehicles rather than on future and new designs. I consider the present modeling a success compared to two decades ago. More emphasis should be placed on modeling in designing new vehicles

Ideal Use of Modeling in the Design Process:

- Yes, modeling must be done as early as possible.
- I think the most important role of modeling and any kind of analysis is to clarify the vehicle phenomena. If we know the phenomena we can manage to take measures to improve performance and to make better structures or properties. This is a job of design engineers. The main role of our CAE engineer is to propose good information and enough information for design engineers to do their work.
- Modeling is most successful when active components (suspension, steering) have to be defined and controlled
- With the exception of the last test, modeling could replace actual test vehicles for prototype and evaluation testing. It will become very important to determine what should be evaluated with the prototype vehicle, as well as what should be evaluated based on the computational data. In order to develop products in short development cycles, a number of existing issues must be cleared up.
- Modeling is key to working concurrently. All functional groups must define requirements at start. Proper modeling depends on "solid model." The supplier link to modeling is key. The model must drive manufacturing.
- Targets should be set and models should tell the design engineer how to make the vehicle. Models are used to quickly and easily evaluate design changes.
- Currently, models have a fixed place in the design process. I believe that the models and the modeling process should occur throughout the design process. These models should have several levels of complexity, while maintaining the correct information in all the models. A combination of concurrent engineering and level of detail is needed.

Where Has It Been Most Successful/Useful:

- It is most successful in the first one-third of a program and for resolving specific test problems.
- Modeling is best used early on, when vehicle subjective targets are set and objective vehicle targets need consideration, which continues until the first prototype phase.

Roadblocks:

- The association of CAD data and FE(finite element) models is a key to successful implementation
- Modeling has an important place in the concept part of the design process. Many problems remain for using the model in the development stage. Research engineers trust modeling, not development engineers.
- Time to create vehicle systems models is excessive, and sometimes we are not able to stay ahead of design, as a result. Setting targets and arriving at the proper tradeoffs for a given customer are still troublesome
- The roadblocks are a lack of a validated methodology for building models that would allow models to replace physical testing of prototypes, and the reluctance of old-fashioned project managers to use modeling. But the main problem is money. Without money, we cannot develop new methodologies to get validation, and until modeling is useful, it is hard to get the money.
- The most difficult modeling stage, conceptual design model fine-tuning, is unusual; we must provide tools for better model construction and fine-tuning.
- Ease of use and ability to interpret results are roadblocks to use of simulation.

Selected edited comments

None

Summary

This question simultaneously asked a variety of questions and received a variety of answers. The respondents see the ideal use of modeling and simulation as tools for understanding vehicle phenomena, helping to see the ramification of design changes quickly, decreasing the number of physical prototypes to only one, and working as part of concurrent engineering by creating models with varying and sufficient levels of complexity.

The respondents feel that modeling and simulation are most successful when they are used early in a program and when subjective targets are set but objective targets are still under consideration.

Finally, they are conflicted about the timely use of modeling and simulation. Some respondents believe modeling works well in its present form while others see it being used effectively when doing simulations on past designs, but not used effectively when used in future designs. Others do not see modeling being used effectively at all, citing issues of the time needed to program complex models in order to get results in time to incorporate into designs, the challenge of setting targets and arriving a proper tradeoffs, and the length of development time needed to create vehicle systems models as roadblocks to improving the successful use of modeling.

Strategic considerations

The variety of responses to this question shows dynamics experts using modeling at different levels. There are simplified models that modelers use to help solve basic problems successfully. Within a fixed framework of using what has worked well before (and gradually extending the use of new models) they feel satisfied with how they are using modeling. But there are other dynamics experts who believe the process of employing modeling and simulation in the design process is not being managed effectively. They see the complexity of models as not fitting well into the goal of reduced development cycles because of the time needed to program complex models and even more challenging is the idea of programming full vehicle system models. Though manufacturers may believe the internal expertise they have in modeling and simulation may offer them a competitive advantage, the ARC full vehicle simulation model may offer a quicker (and less internally biased) solution to incorporating complex models into full vehicle design.

DYN-22. Do you have any general comments about the role of modeling in industry today, and how it is being utilized in the design and research process? For example, are engineers being trained effectively, and is the information that simulations output being used constructively and efficiently?

The Role of Modeling in Industry Today:

- Engineers could be trained much better in the proper use of modeling for design. I have seen excellent uses of modeling in industry, and I have seen terrible uses in other industries. Training is probably the key issue in taking advantage of this marvelous tool.
- Modeling allows the capitalization of the know-how, and the expectation of the company. Modeling's increasing role has led to the need for model libraries. Engineers are trained, continuously, and it is shown to them that models have to be used not only for simulation but also for analysis, fault diagnosis, and control design.
- Systematic and prompt evaluation of tradeoff regarding noise and vibration, ride comfort, driving controllability and stability, reliability, and cost factors will be the key focus. A significant reduction of development cycles should be achieved by addressing the production process-related issues simultaneously with performance at the time when the layout and shape are designed. Failing to do so will cause one to be left behind the crowd.
- We say "do not have blind faith in modeling." Judgment and experience should also be consulted. All models are an idealization of reality. The offer the only predictive tool that is compatible with reduced lead time.
- Modeling is being used extensively. However, creative engineers can go beyond the intelligence put into the model. We do good in modeling what we have done before, but not so well for something we are doing for the first time.
- Engineers are not being trained in modeling effectively. When the information that simulations produce is generated by and interpreted by expert modelers, and is not ignored, then it is very helpful. Unfortunately, it is usually generated and interpreted by nonexperts, who draw incorrect conclusions or it is ignored by decision makers.
- In particular in the past ten years, I have seen a drastic shift towards more modeling and analysis in industry. This trend must continue. Unfortunately, some industry top managers do not yet have a clear understanding of the power of modeling.
- We must have more significant effort in modeling.
- Training is very, very weak. Engineers are not trained to think 3-D solids.
- Every company does it differently. Many modelers are not properly trained. There is a tendency to put the "new kids" at the computers. Some companies have a process; they just model to impress management.
- Modeling is quickly becoming the most favored way to "test" designs. As computer technology increases, the complexity of the models will increase. Due to this, I believe engineers are well-trained at putting together these models, but are not well-trained to determine if the complexity is required.
- The modeling process is not very well taught and not well understood. There is too much emphasis on application. Specific codes disguise the problems due to lack of fundamental understanding.

Selected edited comments

- It is realistic to model a whole system as one analysis model or combined model. But initially it is difficult to do so. It is an engineer's job to divide a whole system into some modules or subparts and make things easy to understand.
- It is important to notice that models are used also for control purposes.

Summary

A number of issues were brought up in this question that were not previously addressed. The issue of the knowledge and training of modelers elicited a number of comments dealing with their training. Respondents see the need for libraries of models to help engineers learn more quickly and apply what has already been learned, but these models need to be continually re-evaluated to meet the best level of model complexity. One respondent also mentioned that relying on specific codes for modeling may disguise the lack of fundamental understanding of the process being modeled, which also argues for continual training of engineers and updating of models based on new knowledge.

Though it makes sense that modelers are better at redesigning previous models than first time models, the focus of reduced lead time may be hindering the further development of new models because new model development cannot keep up with the demands of reduced lead time. Managers who do not see the power of modeling may relegate it to a "stretch goal" that may or may not have an impact on development, and because of this they may not adequately support model development.

The other issue brought up by this question is the possible cost savings potential of modeling production related issues at the same time performance issues are being addressed in the layout and shape design phase.

Strategic considerations

Our Dynamics experts have covered a wide range of issues involving modeling and simulation, and this question offers some new areas of concern as well as reiterating some of the issues previously addressed. A concern about the proper use of modeling, the training necessary to perform modeling and simulation, the technical and knowledge barriers to future modeling, managing the knowledge gained from the process, and the expanded use of modeling for production offer significant challenges to industry as it continues to expand its use of modeling and simulation.

DYN-23. What expectations and desires do you have for the ARC integration efforts?

Expectations of the ARC Integration Efforts:

- reducing the cost of analysis tools; reducing the time needed in making system-related decisions while keeping performance tradeoffs in mind [7]
- Identify what can be done. Identify what is possible over next 10 years. Demonstrate the value of an integrated vehicle model. Demonstrate the value of having man in the loop. [9]
- focus the community on modeling and integration; standards and testing committee; liaison between researchers and designers [12]
- refinement of all simulation technology; simulations to eliminate all tests [14]
- I don't think we need to integrate all models. [15]
- Provide an environment, at least at an educational level, to simulate complete vehicles. [18]

Selected edited comments

- I'm sorry, but I don't have a real image of the ARC model. [3]
- I believe integration strategies represent a competitive advantage and outside efforts to help this strategy along may have a tough time gaining acceptance. [8]

Summary

Though there were few responses to this question, the responses touched on all the reasons the ARC was created: to develop an integrated model that reduces the time needed to make system-related decisions, to create liaisons between researchers and designers, and to refine simulations to reduce the number of physical tests needed to develop vehicles.

Strategic considerations

The issues involved in the creation of the ARC may be in conflict with what manufacturers see as a potential competitive advantage for their companies. But what this study and the ARC in general shows is that the world of modeling and simulation of vehicles is very complex, and knowledge is too distributed throughout the world for any one company to manage it all. Companies may be strong in particular areas or have overly simplified models that they believe serve their purposes, but the value to be gained from a well-integrated vehicle model could far surpass what any one company could develop on its own in the next ten years. The value of having an organization oversee the combined efforts of researchers throughout the country with the input of industry to help lead the way will, in the end, offer manufacturers advantages that individually they cannot acquire in the short period of time the ARC has as its goal.

DYN-24. What advances in dynamics modeling in the next 10 years will lead to significant improvements in the following areas?

WEIGHT REDUCTION
- identification of parts that are not needed; identification of parts that don't need to carry high loads
- size and mass reduction; improved functionalities
- improved road load analysis
- tire models; better load characterization
- composites modeling
- flexible multibody system design
- dynamic loading/behavior of materials
- consideration about elasticity components
- taking into account material characteristics for dimensioning; modeling the chassis
- flexible body capability; better load profile information
- accurate prediction of loads, stresses, and NVH for design; dynamics and structural design sensitivity analysis and optimization for weight minimization subject to quality constraints
- topology optimization
- design sensitivity analysis; flexible body modeling
- durability analysis

RIDE AND COMFORT ENHANCEMENT
- better modeling of nonlinear components; customer-oriented objective criteria
- tire models; ergonomic models, targeting
- active suspension
- relation between driver/passengers and vehicle dynamics
- Modeling of human factors is important for ride comfort. Accuracy of high frequency estimation must be improved for vibration.
- nonlinear body (bushing models); durability tire model
- mid- and high-frequency vibration methods; human body modeling
- consideration about distributed mass system; consideration about elasticity components
- suspension
- tire modeling in ride (vertical) response; bushings and body flexibility
- human model enhancement
- accurate prediction of NVH for design optimization; real-time simulation at design level of fidelity for virtual proving ground simulation and design
- more development of objective metrics that relate to subject assessments
- faster (real-time) simulation
- tire models; body flexibility

HANDLING ENHANCEMENT
- tire-to-road model; better maneuver models
- active suspension
- soft soils;track model
- improved performance under wet or uneven road conditions; technologies will narrow the gap between vehicle rigidity and functional evaluations are important

- suspension design
- friction models; bushing models
- nonlinear property of tire dynamics
- Servo power steering
- ground/track/wheel-interaction model improvement
- real-time virtual proving simulation for handling design optimization with the driver-in-the-loop
- simple ways to handle nonlinear flexibility; use of design-of-experiments and design sensitivity analysis to interrogate models more efficiently and accurately
- faster (real-time) simulation

SAFETY ENHANCEMENT

- emergency maneuvers
- collision avoidance
- significant improvement due to advancements in hardware development for VDC(vehicle dynamics control), etc.; improvement resulting from human factor research
- design of crush mechanisms
- dynamic loading/behavior of materials
- driver-in-the-loop real-time simulation
- active safety
- crash prediction and design sensitivity analysis; real-time simulation to support design for crash avoidance
- integral controls; deformable flex bodies

IMPROVEMENTS THAT AFFECT ALL AREAS

- speed of analysis turnaround; simplicity of the tools
- Input estimation under various driving conditions will be more accurate and better.
- better accuracy
- model enhancement
- use of design of experiments and design sensitivity analysis to interrogate models more efficiently and accurately
- feedback control methods offer much hope here
- Technologies to narrow the gap between vehicle rigidity and functional evaluations are important.
- more efficient modeling methods

Selected edited comment

- Tolerancing and manufacturing will also benefit significantly.
- If the resolution to the level of brain or perception is not done, significant improvement will not be achieved.
- The tools are already available. It just requires clever people to use them.
- All these issues will benefit from new tools which will enable the modeler to focus on modeling (conceptual) decisions, while keeping clear links between model properties and design parameters.

Summary

The Dynamics panelists see a wide variety of areas where advances will lead to significant improvement in vehicle dynamics models. For weight reduction they see load analysis, material analysis, flexible body analysis, and design optimization as some of the main areas. For ride and comfort, the main areas are human factors modeling, tire models, bushings/body flexibility models, suspension models, real-time simulations, and customer-oriented objective criteria. The main areas for handling include human factors modeling, tire-to-road models, suspension models, real-time simulations, and nonlinear models; while for safety, human/mechanical avoidance modeling, crush behavior, and real-time simulations are some of the main areas where advances will lead to significant improvement.

Strategic considerations

Dynamics models that focus on weight reduction, ride and comfort, handling, and safety each have their own modeling challenges for the future, and they represent some of the overarching issues that need to be dealt with if dynamics modeling is to progress. Some of these issues are directly connected to a logically connected area of interest such as materials analysis for weight reduction, tire-to-road analysis for ride and comfort as well as handling, and crush behavior analysis for safety. But other issues can be seen as basic modeling issues that affect all the areas such as improvements in design optimization, real-time simulations, developments in nonlinear models, and developing objective customer-oriented criteria to use as an endpoint in the modeling process. Decisions about allocating resources to work on these challenges, some of which are formidable and could take up one's whole career, may force manufacturers to channel some of their research to specialists outside their companies or industries thus creating collaborations between manufacturers and suppliers or manufacturers and academia, the military, and the national labs that provide the impetus to solve these challenging issues.

One of the major challenges of these working relationships centers on how they are to be managed. Manufacturers, suppliers, and academia all have their own priorities and timetables as well as their own views of when a usable solution is ready for implementation. How these issues are negotiated and managed between the parties will determine in some ways how successful these cooperative efforts will be.

DYN-25. What areas in dynamics modeling need more fundamental research work that will lead to more accurate modeling or new capabilities?

Fundamental Dynamics Research Work Yet to be Performed:

- better ways to define model specifications; better ways to derive simpler models from a large, complex one
- elastomer representation
- multiple contact kinematics and dynamics; tolerance analysis and synthesis; conceptual design
- handling of stiff matrices (friction); subsystem behavior models (e.g. bushings)
- how stiff is stiff enough for body structure reaction to suspension inputs; temperature affects on bushings
- dynamics in soft soil; durability model; reliability models; shock and vibration models; more efficient models and computers
- the vehicle-to-ground interface, such as tire-road or track-soil interaction
- relation between the performance index and brain or perception
- progress of tire models (activities on uneven roads, dynamic characteristics, accurate analysis of the point of application of force); understanding the human factors for accuracy of closed models; quantifying the functional evaluations of driving stability (understanding accurate evaluation indices)
- durability tire model; nonlinear bushings with hysterisis and creep; friction models
- Simulation programs will become more and more simple to use, but modeling decisions will always have to be made by the user to obtain useful engineering information.
- tire/road interactions; flexible joints in dynamics models
- validation studies; mid- and high-frequency vibration methods; nonlinear behavior of components/systems; modeling of the human body
- tire dynamics
- distributed parameter systems; delay systems; efforts to go from finite elements models to simplified macrophysics localized models; rubber and composite models for tire and engine mounts
- a systematic approach of modeling decisions and multiple view representations; robust numerical tools; hierarchical modeling
- friction; all elastomeric components
- statistical energy methods, p-elements, automatic error estimators/mesh, and p-level refinement
- flexible bodies and nonlinear response
- tire-end track-soil interaction modeling; extension of kinematics and dynamic simulation formulations and computer codes to support design sensitivity analysis and optimization; real-time modeling and computational methods for a design level of fidelity virtual proving ground with the driver/operator-in-the-loop
- more realistic modeling of kinematic joints inside elastic bushings; model analysis of flexible bodies in a multibody environment; inclusion of friction; more realistic analytical tire model

Selected edited comments

None

Summary

The Dynamics experts offer an array of needed improvements in dynamics modeling from the general, like improved nonlinear behavior models, hierarchical models, statistical energy models, and distributed parameter systems, to the specific, like models for vehicle/tire-to-road interaction, friction, bushings and flexible joints and bodies, human interface, and shock and vibration. Of the specific models that need improvement, vehicle/tire-to-road models were mentioned most frequently, followed by bushings and flexible joints and bodies, friction, and models involving a human interface.

Strategic considerations

Both the specific and general modeling issues described all offer substantial opportunities for manufacturers and suppliers to gain a competitive advantage, and academia to gain support for research projects. The challenge for every manufacturer becomes managing their R & D (research and development) function and concentrating on which areas are most in need of research dollars and which areas will deliver the best return on investment.

In general, our Dynamics experts are confident that many of the modeling challenges will reach acceptable accuracy over the next ten years, but there are certain areas such as human interaction models that will demand more basic research to develop the parameters (measurements) that can be used as input for these models. For most or all of the other models discussed the basic physics have been resolved but the challenge becomes one of managing the details and results of the modeling procedure.

DYN-26. Do you have any general comments about vehicle dynamics modeling that you would like to share with us?

General Comments About Vehicle Dynamics Modeling:

- Vehicle dynamics modeling needs to add value.
- You need integration to design (CAD) system.
- Tire models are capable of recreating uneven roads.
- We need to put more efforts into integrating "dynamics models" into system modeling, which should couple FEM/CAD dynamic control.
- Closed-loop modeling should be advanced.
- It is of fundamental importance to use an integrated design approach, including beginning the study of the control architecture (actuators and sensors) and the monitoring system for fault detection (safety).
- The complexity of models is usually far too high for the purpose of the model.
- The field has evolved significantly over the past two decades. With industry involvement/commitment, the ARC can greatly accelerate the process.
- The bottleneck in the system is not the computer hardware or software, it is the human users. The learning curve in CAE is very steep and better training is needed. Also, computers can create data faster than humans can evaluate it. More work needs to be done to allow humans to analyze the CAE data faster in more human-friendly forms.

Selected edited comments

None

Summary

Two issues not mentioned prior to this question concern the integration of modeling results into the CAE/CAD systems and having better trained people to evaluate and use the information received. These issues were not raised prior to this question, and if they are looked at in concert with the need for faster computers, both sides of the modeling equation of users and tools need to advance in order to improve the use of modeling and simulation.

Strategic considerations

Two major areas need to be considered: 1) Educational: Undergraduate and graduate programs should focus more on modeling and simulation for design; 2) Research: Model formulation, interpretation (design changes implied), and model reformulation are important research areas. Also, the incorporation of multimedia and virtural reality into the presentation and analysis of data may be of help in the future. Lastly, the use of powerful macro languages to get data into the analysis program as quickly and easily as possible may also help speed up the analysis process.

DYN-27. What modeling and simulation issues will present the most significant challenges or opportunities to the vehicle manufacturing industry in the coming decade?

The Most Significant Challenges/Opportunities in Modeling and Simualtion:

- verified and accessible (i.e., reusable) component models used by suppliers and assemblers.
- accuracy, speed, ease of use.
- adaptive/hierarchical modeling; multiphysics problems; ergonomics and user-interface issues for design engineers.
- modeling techniques to support efficient analysis-driven design; deciding on minimum modeling complexity to achieve a prescribed output accuracy.
- consistency and compatibility
- represent nonlinear behaviors; relationship of vibration/shock/temperature inputs and durability/reliability; interaction of human and models.
- With regard to the dynamic simulation, the treatment of nonlinearity (friction, hysterisis, etc.), and research for solving the relation between the performance index and brain or perception may be important. Easily making up the model is also important.
- systematic tradeoff evaluations on noise and vibration, ride comfort, driving stability, reliability, cost and weight; verify rigidity and strength in suspension assembly; simulation of manufacturing processes, such as presses, and consolidating the evaluation of shape, layout and performance.
- well-trained engineers who like their job; accurate and available testing facilities for validation
- improvements in modeling nonlinearities such as friction; knowledgeable management that lets the modelers do what they know is right, not what idealistic managers want
- Computer modeling will continue to simplify the incremental engineering necessary to improve next year's fleet. In my area, the big challenges are in the control of major aspects of vehicle dynamics. Integration of sensors, actuators, algorithms is where the action is.
- The integration of new modeling and simulation tools into existing design environment is more crucial than developing "new and better" simulation methods. Unless we incorporate simulation into design specification and design procedure, the simulation will always be the after checking tools only.
- validation; development of simplified models
- nonlinear dynamics in handling enhanced area; modeling of human operating behaviors
- dynamic models; model reduction for control purposes; modeling of distributed phenomena by simplified localized elements (e.g., tires); taking into account the recycling problems at the design level to fix the technological choices.
- structured, hierarchical modeling on the basis of reusable submodels.
- The biggest challenge appears to be one of developing techniques/technologies that will allow accurate dynamic analysis for relatively detailed complex models without undue CPU penalties, while providing multidisciplinary analysis and design optimizations.
- flexible body, nonlinear
- developing staff oriented toward simulation based design, empowering them to use the technology, and keeping pessimistic managers off their backs
- tire modeling with higher frequency information; flexibility modeling for vehicle dynamics
- user-friendliness of simulation software; accuracy of simulation results; faster computation time.

Selected edited comments

None

Summary

The Dynamics panelists see significant challenges and opportunities for both general modeling and specific modeling issues in the coming decade. The general modeling issues include better incorporating modeling and simulation into the design process, and general reuseability, ease of use, speed, and increased accuracy of models. Two of the more often noted areas concerned reducing model complexity and tradeoff analyses that help balance the multitude of issues in dynamics modeling including NVH, ride comfort, handling, reliability, cost, and weight.

The specific modeling issues that elicited the most comments include the representation of nonlinear behaviors, and human interaction models. Modeling tires with higher frequency information, verifying rigidity and strength in suspension assemblies, and using hierarchical models and being able to solve multiphysics problems also were considered both challenges and opportunities for the modeling community in the coming decade.

Strategic considerations

The issues of model complexity and the tradeoff evaluations necessary between the numerous models available for each area within the vehicle will offer considerable challenge and opportunity to both the manufacturers and their modelers. The overall management of these processes and management support for the modeling effort will determine which companies will be able to best take advantage of what these models will provide in terms of vehicle improvement and development time reduction.

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III. VEHICLE STRUCTURE MODELS

STR-1. To what extent do present structural simulation models meet the needs of vehicle manufacturers, and will future structural models in 2001 and 2006 meet the needs of vehicle manufacturers?

Scale: 1 = Needs met completely 3 = Needs met somewhat 5 = Needs met not at all

Structures Models	Mean Rating		
	1996	2001	2006
Meeting the Needs of Manufacturers	3.0	2.4	1.9

Selected edited comments

Round 1

- It is true that the present level of simulation modeling is not satisfactory, but we manage to meet the requirements within present resources. I expect progress in hardware may help to solve these problems to some extent.
- Current capability/deliverables are not as good as they need to be. Process/people issues cause deployment to delay technical capability by several years.

  I am not sure if the needs will be completely met by 2006. I would say 80 to 90 percent.
- "Needs" are a moving target. From our standpoint we see customers' expectations are always on the increase, thus I don't ever foresee a complete satisfaction of needs. (3)

Summary

Currently, Structures experts believe structures models somewhat meet the needs of vehicle manufacturers, but they see steady improvement being made by 2001 and 2006, though they do not see their needs being completely met by 2006.

Comparison of forecasts: Engines - 1 /Dynamics - 1

Our engine-modeling experts also feel that engine models only somewhat meet the needs of manufacturers today, but they believe that vehicle structure models will come closer to meeting the needs of manufacturers in 2001 and 2006, with responses that fall halfway between the more optimistic Structures experts and the less optimistic Dynamics experts.

Engine Models	Mean Rating		
	1996	2001	2006
Meeting the Needs of Manufacturers	3.1	2.6	2.2

Our vehicle-dynamics-modeling experts also feel that dynamics models only somewhat meet the needs of manufacturers today, and they agree that dynamics models will better meet the needs of vehicle manufacturers over the next 10 years. But they are less optimistic than Structures experts about how well their respective models will meet the needs of manufacturers in 2001 and 2006.

Dynamics Models	Mean Rating		
	1996	2001	2006
Meeting the Needs of Manufacturers	3.0	2.7	2.4

Strategic considerations

This question leads off a series of questions that look at the general effects of improved structures modeling and simulation techniques. Over time, the experts believe structures modeling will improve in meeting the needs of the vehicle manufacturers, but the improvement in *how* the models are used in the near future will determine how successful they will be in meeting the needs of the manufacturers. Another issue concerning meeting the needs of the manufacturers focuses on the idea that as the models begin to meet the current needs, the expectations of the manufacturers will also continue to increase, thus making their needs a moving target that will be harder to satisfy.

STR-2. **What percentage improvement do structural simulation models add to vehicle process design efficiency currently compared to presimulation days, and what improvement over the current state should we expect by 2001 and 2006?**

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	30%	45%	30/43%	25/33%	37/50%

Selected edited comments

Round 1

- I interpret efficiency improvement as [Cold-Cnew/Cold] x 100% where Cold = old cost of given design procedure or decision.
- As time goes on other aspects of criteria and design become more complex, so it is hard to establish a baseline.
- We had nine development stages in presimulation days. Today we have reduced that to two stages, using primarily simulation technology, and one more stage will be deleted within five years.
- This is hard to quantify because today's vehicles are more refined, complicated, and meet higher demands than vehicles built before simulation.
- We tend to judge our success by our customers' ability to solve problems that have eluded them in the past.

Round 2

- Hardware capacity and efficiency improvements are assumed to be linear from 1996 to 2006. Equation solving algorithms will be improved substantially. Simulation (modeling) time must decrease by a big factor.

Summary

Our Structures panelists see a 30 percent improvement in design efficiency due to structures simulation models over presimulation days, but they believe design efficiency will improve 30 percent in five years over the current state and 45 percent in the next 10 years over the current state.

Comparison of forecasts: Engines - 2 /Dynamics - 2

Our Engine panelists are the least optimistic about the effects improved engine models will have on design efficiency in the future, though they agree with the Structures experts on the effect their models have on design efficiency in 1996 and the effect they will have in 2001.

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	30%	40%	25/30%	25/30%	30/40%

Our Dynamics panelists are the most optimistic about the effects improved dynamics models will have on design efficiency in the future, though they agree on the effect their models have on present design efficiency. These differences may be due to the relative advanced nature of some dynamics models over structures and engine models.

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Efficiency	30%	35%	50%	25/30%	30/38%	40/55%

Strategic considerations

The move to using modeling and simulation has already yielded a significant increase in design efficiency, but over the next ten years, the Structures panelists see further substantial improvement because of improved structures models. The improvements may come because the models or the modeling tools will improve. This model improvement may occur through some form of artificial intelligence that will allow models to "learn" from past modeling experience. Improvement may also occur because the designers will improve how they use the models and tools.

The experts also see these improvements occurring because of improved integration of other types of models into a system that will be able to accommodate models from vehicle dynamics and engines in order to better negotiate all of the tradeoffs inherent in designing vehicles. Simulation models will continue to become more sophisticated and will further reduce (but not eliminate) the need for tests, thereby reducing design and analysis costs.

STR-3. Please give your expectations, in months, of current and future development cycles from concept approval through production initiation for new and redesigned vehicles.

Structures Panelists' Expectations of Development Cycles (Months)	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
New Vehicle	36	24	24	32/38	24/30	19/26
Redesigned Vehicle	20	18	16	20/26	17/22	14/18

Selected edited comments

Round 1

- I think the period shorter than one year is ideal but this may be impossible within 10 years. The secondary target at present is two years.
- On redesign, it will take 10 months for a plastic body and 20 months for steel.

Round 2

- No customer would like to see his car outdated in 1.5 years or less. Business will drive the development cycle, not engineering.

Summary

Our Structures panelists see the current development cycle from concept approval through product initiation to be 36 months for a new vehicle and 20 months for a redesigned vehicle. They see about a 33% reduction (24 months), relative to the current state, in the time it will take to develop a new vehicle by 2001 and about a 12% reduction (18 months) in the time it will take to develop a redesigned vehicle in 2001. By 2006, they see a 33% reduction (24 months) in the time it will take to develop a new vehicle and a 25% reduction (16 months) in the time it will take to develop a redesigned vehicle. A noted difference can be see in the respondents' feeling that there will be no reduction in new vehicle development time from 2001 to 2006.

Comparison of forecasts: Dynamics - 3

Dynamics and structures modeling experts are in general agreement about the time it takes to develop new and redesigned vehicles presently and in the future. The only disagreement comes in the time it will take to develop new vehicles by 2001, where the Structures experts believe the manufacturers will be able to reduce the number of months by 37%, and the Dynamics experts believe the manufacturers will not reach that level until 2006. What is curious is that the Structures experts do not see any improvement in new vehicle development in 2006 relative to 2001.

Dynamics Panelists' Expectations of Development Cycles (Months)	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
New Vehicle	38	32	24	36/40	30/33	24/27
Redesigned Vehicle	22	18	16	21/24	18/20	14/18

Strategic considerations

Some of the larger issues concerning shortened development cycles include the following:

For vehicles that manufacturers believe are meeting the customers needs, development will focus primarily on continuous improvement of the original design. This evolutionary approach will yield to a revolutionary technological push when a manufacturer feels the need to create a paradigm shift in industry or consumer thinking (e.g., the electric or hybrid vehicle). The revolutionary approach will probably be used exclusively in low-volume vehicles as a way of displaying a company's technological competence or as a market test to measure high volume potential.

Decreased design time and shortened product development cycles will not mean a proliferation of platforms, but it will mean a proliferation of models based on fewer platforms as manufacturers compete to create the "must have" buyer niche based on product differentiation at a variety of levels, such as cost (price), quality, type of vehicle (such as a minivan, sport-utility vehicle (SUV), electric vehicle (EV), hybrid), buying experience (Saturn), options, safety, and whatever new differentiators may appear. One area of consumer research, as defined within the role of the brand manager, that can feed into the development cycle will be the measurement of consumer wants and needs within a segment and the translation of that knowledge into the product development cycle for that segment.

More models in the product mix will challenge manufacturers to find ways of making a profit on low-volume production runs. But the incorporation of flexible and agile manufacturing into the shortened product-development equation will allow manufacturers to adjust output to meet the needs of the market by shifting production from models consumers are not buying to new or redesigned models that may attract buyers. The 50-to-60-month development cycles of the past could not make these adjustments. By the time a manufacturer found a mistake in a model (or a potential new niche), designed a replacement, and produced the new model, four or five years had passed.

Within the platform environment, increased component sharing will reduce cross-platform complexity of models. There will be a standard set of variables with fixed ranges that will help modelers complete complex vehicle models in time to be usable in the early stages of vehicle design.

Decreasing development time allows personnel to move around within the limited number of platforms. This helps solve one of the problems of platform teams learning from other platform teams that are working somewhat in isolation of each other (though there still needs to be some dissemination of knowledge gained on a project).

The managerial challenge will be to balance development time on improving parts of the vehicle that the customer actually sees, feels, touches, hears, and smells with improvements on the parts the consumer does not see yet expects to perform flawlessly.

STR-4. What percentage improvement in cost savings do structural simulation models add to vehicle process design efficiency currently, as compared to presimulation days, and what improvement over the current state should we expect by 2001 and 2006?

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Cost savings	20%	20 %	30%	15/28%	20/25%	30/40%

Selected edited comments

Round 1

- They provide improvements to quality and performance for the same cost.
- It is difficult to estimate cost savings and weight reduction directly compared to presimulation days, because regulation requirements for crash safety are very severe at present day. Cost savings estimation is especially difficult.
- This is hard to say because the use of modeling is mostly to get more design work done, rather than save money.
- About 80 percent of cost savings issues are verified by structural simulation.

Round 2

- About half of the total efficiency improvements for each period are assumed. Cost and quality have to go hand-in-hand. Optimization techniques for complex structures will definitely improve to provide at least 15 percent in cost savings per phase.

Summary

The Structures panelists believe that structures modeling has reduced vehicle design costs by 20 percent over presimulation days, and they feel these costs will be reduced another 20 percent over the current costs by 2001, and 30 percent over the current costs by 2006.

Comparison of forecasts: Dynamics - 4

Dynamics panelists are more optimistic about how much cost reductions will be achieved in the future because of improved dynamics modeling than Structures experts are about the effects of improved structures modeling. They agree that there has been a 20 percent reduction in design efficiency costs over presimulation days currently, but they believe costs will be reduced by 25 percent over the current costs by 2001, and 37 percent over current costs by 2006.

Percentage Improvement	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Cost savings	20%	25%	37%	15/20%	23/25%	30/40%

Strategic considerations

A 30 percent reduction in vehicle design costs associated with improved structures modeling by 2006 is a significant savings in total vehicle costs. It will be interesting to see how these savings will be reflected in the final cost of the vehicle, and if there will be other areas of design, materials, manufacturing, or distribution that will absorb this savings. Some of the potential cost savings may be used, as one of our panelists suggested, to do more design work rather than to save money on design. Also, the increased costs of employing these techniques may absorb some of the savings.

The use of simulation models in vehicle design directly reduces costs by eliminating the need for extensive testing. An indirect but as valuable an effect of simulation is the improvement in performance and quality. One issue that is not addressed in this question concerns increased expectations for improved levels of performance, complexity, and accuracy, and how they will affect modeling and design costs over the next 10 years. Will increasing expectations for higher levels of performance, complexity, or accuracy decrease the potential cost savings due to modeling because of the need to increase model programming time, add personnel, or purchase new equipment or software? Or will the manufacturers continue, as they do now, to test new models, but only use models that offer a clear reduction in time and costs?

STR-5. What is the level of structural software modeling expertise needed by users to design vehicles now, and what will it need to be in 2001 and in 2006?

Scale: 1 = High level of expertise 3 = Medium level of expertise 5 = Basic knowledge

Structures Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	2.0	2.2	2.7

Selected edited comments

Round 1

- As a particular technique matures, the level of expertise needed tends to decrease, but simultaneously new techniques appear which require higher levels of expertise.
- The simpler the model, the more expertise is needed. As finite element method (FEM) models become more precise and large in the future, we will not need a high level of expertise.
- Modeling is not push-button yet. It requires experience and well-grounded modelers.
- I believe it is a mistake by the industry to assume that good engineers are a commodity. Companies that succeed will always be pushing the limits.

Round 2

- Modeling expertise is always desirable regardless of software sophistication.
- As time passes, multidisciplinary models will become more complex requiring higher expertise to understand and relate to the physical world. The focus will shift from just construction to expected behavior.

Summary

The Structures panelists, in general, see a continued need to have a relatively high level of structures modeling expertise over the next 10 years, though they do see a reduction from the moderately high level of expertise needed currently to a medium level of expertise in 2001 and 2006.

Comparison of forecasts: Engines - 5 /Dynamics - 5

All three sets of experts agree generally that there is now and will be in the future a need for a relatively high level of modeling expertise necessary to design engines and vehicles. But there are two places where the Structures experts and the Dynamics and Engine experts disagree. The Structures experts, unlike the Engine and Dynamics experts, believe that there is currently and will be in 2006 a lower level of expertise needed to design vehicles.

Engine Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	1.9	2.3	2.3

Dynamics Modeling Expertise	Mean Rating		
	1996	2001	2006
Level of expertise needed	1.5	2.0	2.4

Strategic considerations

Though modeling programs may become more user-friendly over the next 10 years, the expertise needed to perform vehicle dynamics modeling will continue to be focused on the ability of the engineer to understand the fundamental issues (e.g., the physics of a problem) that govern the structural problems he or she is faced with. The issues of increased model complexity, new model construction and adaptation, as well as multidisciplinary models, also expand the base knowledge the modeler must have to use a modeling program. The assumptions each program makes in solving complex physics problems must be well understood by the user in order to interpret and apply results correctly.

STR-6. Some modelers also see a trend towards extensive use of neural networks, expert systems, and artificial intelligence systems as playing an increasing role in vehicle simulation. What is the likelihood of expanding the use of these systems in the short term (1996-2001) and the long term (2002-2006)?

Scale: 1 = Very likely 3 = Somewhat likely 5 = Not very likely

Likelihood of Increased Use of Alternative Systems	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Neural Networks	3.7	2.6
Expert Systems	3.2	2.5
Artificial Intelligence Systems	3.4	2.8

Selected edited comments

Round 1

- I am pessimistic because these methods have existed for over a decade and have yet to make a significant impact.
- I do not think these technologies will be completed in ten years. I do not see them at all at present.
- Because such methods have not proved out, early significant efforts to develop such systems are being cut back.
- More pre- and postprocessing and more degrees of freedom (i.e., the size of a structural model) will reduce decision-making.

Round 2

- Some very complex systems will require these systems. There are too many attributes (parameters) playing roles, and it is very difficult to form a unique response surface model (RSM).

Summary

As the data and the comments of our respondents show, the experts are skeptical about the expansion of these systems to support modeling and simulation in the short term and only slightly less skeptical about the long term. In the long term they see all three systems as slightly more than somewhat likely with expert systems with the highest ranking followed by neural networks and artificial intelligence (AI) systems.

Comparison of forecasts: Engines - 5a /Dynamics - 8

The panelists are fairly divided in their visions of when expanded use of these advanced techniques will occur. In the short term, regarding all three techniques, only the Engine experts believe that expert systems are likely to play an expanding role in vehicle simulation. In the long term, all three panels feel that expert systems are more likely to play an expanding role, and the Structures and Engine panelists both think neural networks and AI are at least somewhat likely to play an expanding role in vehicle simulation.

Likelihood of Increased Use of Alternative Systems by Engine Panelists	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Neural Networks	3.4	2.5
Expert Systems	2.1	1.8
Artificial Intelligence Systems	3.4	2.7

Likelihood of Increased Use of Alternative Systems by Dynamics Panelists	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Neural Networks	4.0	3.5
Expert Systems	3.4	2.8
Artificial Intelligence Systems	3.9	3.2

Strategic considerations

These techniques seem to be in their infancy in terms of their applicability to the automotive industry. Though some experts believe these techniques will be helpful in the future, many experts will need to be shown direct applicability to their processes as well as proven effectiveness before they will relinquish what they see as core engineering decision-making. More fundamental work may be needed before these methods can be applied in an industrial automotive environment, except perhaps for very specific applications.

STR-7. Taking uncertainties into account is important, as deviation in the parameters will cause a deviation in the response, especially at higher frequencies where the wavelengths can be in the order of small defects (e.g. thickness of a weld). What methods or approaches are used to account for these uncertainties?

Methods of Accounting for Uncertainties:	Percentage of Responses
Hardly any/None	21%
Statistical Energy Analysis	17%
Monte Carlo Methods	17%
Design of Experiments/Design Sensitivities	12%
Calibration by comparing the simulation results to experimental results	8%
Use of extremes to bracket performance	8%
Model refinement	4%
Optimum sensitivities	4%
Power Flow Analysis	4%
Energy Finite Elements	4%

Selected edited comments

Round 1

- We now have no effective methods or approaches to account for these uncertainties. The only method may be a design sensitivity analysis.
- At high frequency, discrete models are discarded in favor of statistical energy analysis.
- We need to adopt robust design procedures that reflect ensemble instead of individual case design methodology. We must simulate variability with the intent to reduce.

Summary

Structures panelists are divided on what they use to deal with uncertainties. Some feel that there are hardly any or no methods for dealing with uncertainties, stating that there is very little being done in this area. Others believe that statistical energy analysis, Monte Carlo methods, and design-of-experiments procedures are being used to deal with uncertainties.

Strategic considerations

Traditionally, uncertainties have essentially been ignored because designs were not as sensitive. But new, structurally more flexible vehicle designs demand an account for uncertainties and the corresponding mid- to high-frequency vibrations. The division of responses among the panelists shows that modelers are still not clearly addressing this area. Even the panelists who suggested methods for dealing with uncertainties would first say there is little being done in this area, as if to suggest that the methods mentioned are not the best methods, but the best methods available at the moment. New techniques are being developed but are currently somewhat in their infancy and are being tested on specific test cases. Large-scale implementation in an industrial setting will be a long-term process.

STR-8. How successful are current order reduction methods you are familiar with in helping to reduce complexity, while still maintaining all the important physics of the problem? Also, how successful will future order reduction models be in 2001 and 2006?

Scale: 1 = Very successful 3 = Somewhat successful 5 = Not very successful

Order Reduction Method	Mean Rating		
	1996	2001	2006
Modal Analysis	2.0	2.1	1.8
Component Mode Synthesis	2.3	2.1	1.8
Mesh	3.3	2.1	1.3
Guyan	2.8	2.6	3.1

Selected edited comments

Round 1

- Most current activity uses discrete field equation methods (which reduce from molecular or atomic models). Practitioners use reduction techniques, such as replacing a weld by a rigid bar or spring, only because they don't have the resources (modeling or computer time), not because they think it is an efficient way to get a reasonable answer. Most practitioners would represent the entire structure with elements if possible.
- The Building Block Approach (BBA), a very simple substructure synthesis method, is useful. A lumped mass model is also useful to understand the various phenomena of the vehicle.

Round 2

- Current frequency extraction capability is adequate in auto industry. Only marginal improvement is expected by 2006.
- Order reduction methods used will depend upon what attribute one is looking for. For example, the quality of the output will depend upon displacements, loads, and stresses and how they are used. Most reductions are good in ascertaining displacements. Non-linearity assessment needs a lot more development.
- Guyan is good for statistics only.

Summary

Structures experts listed modal analysis, component mode synthesis, mesh, and Guyan as current order reduction methods. Currently, they feel that the modal analysis reduction method is successful and the component mode synthesis is nearly successful in helping reduce model complexity, but the Guyan method is seen as slightly better than somewhat successful and the mesh method is less than somewhat successful. By 2001, panelists see the modal, component mode synthesis, and mesh methods all becoming successful in reducing model complexity with the Guyan method as slightly better than somewhat successful. And by 2006, our Structures experts see the modal, component mode synthesis, and mesh techniques as improving over their 2001 predictions and becoming slightly better than successful in helping reduce model complexity, while the Guyan method continues to be seen as only somewhat successful in helping reduce model complexity.

Strategic considerations

Our Structures experts see the current methods of order reduction as successfully helping reduce order complexity in the future, but they also see some of the compromises currently made to use these methods as possible stumbling blocks in the future. Modeling and computer time, as well as extremely complex structures and nonlinearity will also challenge the current methods used to reduce model complexity. These issues can be seen as the differentiators between using the current methods in their present forms and adapting the current methods to deal with the method's limitations, thus giving the company that can successfully overcome these limitations a competitive edge in modeling.

More fundamental work is needed on these issues (joint modeling, complex structures, and nonlinearities) before the corresponding modeling techniques can be implemented in the vehicle design process. It would be difficult for one company alone to develop a satisfactory solution to these challenges. It is much more likely to be a slow evolutionary process between researchers in academia, industry, and government.

STR-9. How reliant are your present structural models on calibration against some form of physical prototype and how reliant will your models be in 2001 and 2006?

Scale: 1 = Very reliant 3 = Somewhat reliant 5 = Not reliant at all

Physical Prototypes	Mean Rating		
	1996	2001	2006
Reliance on	3.0	3.2	3.3

Selected edited comments

Round 1

- The trend here is toward reliance on more fundamental (and more generic) prototypes.
- Crash models are very reliant, while stiffness models of components are less so.
- It is now very difficult to get a model that is valid for quantitative analysis.
- It is necessary to have empirical evidence to track model capability. This will continue. Model checking will move later and later in the development process, possibly to production initiation in the distant future.
- There will always be some reliance, due to new methodologies in manufacturing.
- It is more important to validate the methodology than it is to calibrate a specific model.

Round 2

- Physical prototypes will exist very late, perhaps 12 to 18 months before production initiation or may not exist at all by the year 2006.

Summary

Panelists believe they are somewhat reliant on calibrating their vehicle structure models against some form of physical prototype now and will only become slightly less reliant in the future.

Strategic considerations

Our experts offer some very good reasons why they feel they will continue to be somewhat reliant on calibration of their structures models against some form of physical prototype. Vehicle structure models concerned with crash are very reliant on physical prototypes, the effects of new manufacturing methodologies demand physical prototypes be produced, and the methodology used to create a specific model needs to be validated through prototypes. But the experts also believe the process of building the prototype will be pushed later and later in the development cycle, to within 12 to 18 months of Job 1, thus reducing the costs of developing multiple prototypes.

Our respondents also see reliance continuing to be based on more generic prototypes that will allow quicker development time because many of the fundamental processes will have already been modeled in advance.

STR-10. One of structural modeling's potential advantages is to reduce reliance on physical prototyping for development purposes. How much of a reduction in physical prototype iterations should we expect in the short term (1996-2001) compared to presimulation days and the long term (2002-2006) compared to the present.

Scale: 1 = Close to 100% reduction 3 = About 50% reduction 5 = Very little reduction

Structures Panelists Expectations of Physical Prototype Reductions	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Prototype Iterations for Validation	3.6	3.0
Prototype Iterations for Development	3.1	2.3
Prototype Iterations for Testing	3.1	2.4

Selected edited comments

Round 1

- Crash models are very reliant, while stiffness models of components are less so.
- At least, final validation is necessary.
- Reduction in the number of prototypes is a moving target, and is based on the public's perception of acceptable noise, vibration, and harshness (NVH) characteristics. My personal feeling, however, is that some auto makers' goals (e.g., only one prototype) are unreasonable.

Round 2

- Physical confirmation test is still required because of product liability concerns.

Summary

In the short term, Structures panelists see close to a 50 percent reduction in reliance on physical prototypes for both development and testing, and about a 30 to 40 percent reduction for validation. In the long term, they see a 50 percent reduction in reliance on physical prototypes for validation, and about a 60 to 70 percent reduction for development and testing.

Comparison of forecasts: Dynamics - 9

Dynamics panelists were asked what the effects of dynamics modeling would be on the reduction in reliance on physical prototypes. They see more of a reliance on physical prototypes due to dynamics modeling than Structures panelists see due to structures modeling. For validation, they see about a 30 to 40 percent reduction in reliance on physical prototypes in both the short and long term. For development, they see about a 45 percent reduction in the short term, and nearly a 60 percent reduction in the long term.

Dynamics Panelists Expectations of Physical Prototype Reductions	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Prototype Iterations for Validation	3.4	3.2
Prototype Iterations for Development	3.5	2.7

Strategic considerations

A 50 percent reduction in the reliance on physical prototypes is one of the major goals for increasing the use of modeling and simulation, and manufacturers hope it will translate into a significant cost and time savings in the product development process. Considering the time saved of iterating prototypes, the total product development process should be shortened, thus allowing manufacturers to design and redesign in a way that may make them more responsive to their customers and bring more optimized products to market. The challenge for the manufacturers will be to reallocate the cost savings in a way that not only increases profits, but also contributes to the improvement of processes and products as well as reducing prices.

STR-11. For durability and fatigue models, please rate their accuracy currently, in the short term (1996-2001) and in the long term (2002-2006).

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Durability and Fatigue	Mean Rating		
	Current (1996)	**Short Term (1996-2001)**	**Long Term (2002-2006)**
Model Accuracy	3.8	2.9	2.3

Selected edited comments

Round 1

- Currently, we believe an order of magnitude improvement in accuracy is achievable.
- At present, experimental results are indispensable to estimate the durability and fatigue level of the vehicle.
- Models are good, but load cases are questionable.
- It is highly dependent upon computer resources and quality of available information for simulation.
- We're making more progress in this area, from a software development standpoint, than almost any other.
- The weak link here is a shortage of good data on material variability.

Summary

Our Structures experts believe that current durability and fatigue models do not have acceptable accuracy, but they feel the models will reach acceptable accuracy within the next five years, and will continue to improve (though not as dramatically) in the following five years.

Strategic considerations

Manufacturers and suppliers must have confidence in models that predict performance, durability, and fatigue if they are to shorten the testing and validation process. These models, in particular fatigue models, are particularly important for a number of vehicle components. A very large amount of research is being carried out in this area, and the problems are plentiful (multiaxial fatigue models, materials behavior, etc.). The development of improved models is critical if fatigue life is to be predicted accurately. Though the Structures experts believe they will have acceptable models in the future, their comments describe significant data and computer challenges in this area. These challenges may contribute to the uncertainty the respondents show in the slower progress they predict for these models in the five to ten year time frame.

STR-12. Modeling component flexibility due to high frequency excitation, as well as loading, can be important in certain applications. How accurate will component flexibility models be in the short term (1996-2001), and in the long term (2002-2006)?

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Component Flexibility	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Accuracy	3.4	2.5

Selected edited comments

Round 1

- A large number of modes in this range reduces accuracy.
- Due to the limitation of the hardware, especially in our company, modeling component flexibility may not be treated for daily use. In this region (high frequency phenomena) experiment itself is very difficult.
- High accuracy models are possible now, but need to be weighed against the high central processing unit (CPU) costs. Most customers are pleased with acceptable levels of accuracy.

Summary

Our panelists do not see modeling of flexible components reaching acceptable accuracy within the next five years, but they do see the models exceeding acceptable accuracy over the next five to ten years.

Strategic considerations

Like durability and fatigue, modeling flexible components is currently limited by computer-related issues such as CPU time because of the complexity of trying to model parts that bend under different stresses and situations. Advances in this area may be aided by advances in computing power, but they may also be advanced by developments in modeling that incorporate experimental data, as well as from data reduction methods that reduce the number of parameters by combining parameters into groups. It will be important to solve these issues because new vehicle designs are much more flexible structurally and thus are much more prone to mid- and high-frequency vibrations.

STR-13. Challenges of lighter vehicle structures include a wider range of frequencies to be modeled, as well as more flexibility to contend with. Are the existing tools adequate for modeling these structures? If not, what tools will be needed?

YES	NO
89%	11%

TOOLS NEEDED:

Round 1

- Finite element analysis (FEA) methods for composite structures will be needed.
- Flexible mesh size/ P-elements are needed.
- We need faster computers to handle more detailed models.
- We need a better approach to simulate non-frontal collision.
- Much faster but accurate modeling tools are needed.
- A large and efficient solver (10^6 Degrees of Freedom in one hour) is needed.
- Intelligent post-processing and display is needed.
- We need model builders to easily include details that are important at higher frequencies.
- Better material models are needed.
- Statistical energy analysis is not currently adequate.
- Mid-frequency 100-250Hz models are needed.

Round 2

- An auto mesher with flexibility in simulating connections between components for optimum spot-welding configurations is needed, as are fast, easy, and quality modeling tools. Fine to course and vice versa meshing is also needed.

Selected edited comments

Round 1

- I don't think this is a significant issue because the basic criteria probably won't significantly change.
- No new tools are required; better application of existing tools would be sufficient.
- Lighter vehicles may exhibit lower frequency ranges.

Round 2

- Modeling time must be reduced by the provision of appropriate tools. The quality of mesh must be maintained when modifying automatically (course to fine and vice versa).

Summary

Overall, respondents believe the tools currently available are sufficient to model lighter vehicle structures, but they also reported a number of improvements to current techniques they feel would help model these types of structures.

Strategic considerations

The respondents' emphasis on refinements of current techniques, rather than the need for completely new techniques, suggests a good scenario for the future modeling of lighter vehicle structures. Though some respondents noted the need for better materials information, the bulk of the reported needs focused on more computing power which will most likely be fulfilled in the near future. Two issues that may pose a challenge in the future are the simulation of nonfrontal collisions and simulations using composite materials. These issues, combined with the role of uncertainty, may potentially invalidate many of the existing techniques or at least increase their complexity.

STR-14. **Please rate the probability of modeling nonlinear behavior of components, as well as modeling components using continuous mass nonlinear finite element analysis in the short term (1996-2001) and in the long term (2002-2006).**

Scale: 1 = High probability 3 = Moderate probability 5 = Low probability

Modeling Nonlinear Behavior: Structures Respondents	**Mean Rating**	
	Short Term (1996-2001)	**Long Term (2002-2006)**
Nonlinear Behavior	3.2	2.2
Continuous Mass Nonlinear Finite Element Analysis	2.8	1.9

Selected edited comments

Round 1

- Accuracy of nonlinear continuous mass elements is probably not achievable in the foreseeable future at acceptable accuracy and mesh refinement level.
- Due to the progress in hardware, analysis for nonlinear behavior will be improved to some extent.
- Given elastomeric properties, modeling is very good. Modeling (predicting) the elastomeric properties is difficult.
- User-interface and modeling issues (e.g., gap elements, contact) are the current limiting factors, and not really core technology.
- It is not a probability issue; it is here. We are doing it.

Round 2

- As computer simulation cost comes down, a 1,000,000 element finite element (FE) model should be able to capture any spot welds, separation, and slip.
- I predict a high probability due to the future availability of efficient computer resources.

Summary

Respondents believe modeling nonlinear behavior has a moderate probability of success in the short term and a good probability of success in the long term, though they feel continuous mass nonlinear finite analysis has a higher probability of success in the short and long term relative to using general nonlinear modeling tools.

Comparison of Forecasts: Dynamics - 15

Though Dynamics experts are also optimistic about their ability to model nonlinear behavior in the short and long term, they see a higher probability of modeling nonlinear behavior in the short and long term compared to Structures experts. They also see a lower probability of using continuous mass nonlinear finite element analysis to model nonlinear behavior in the short term and the long term than do Structures experts.

Modeling Nonlinear Behavior: Dynamics Respondents	Mean Rating	
	Short Term (1996-2001)	Long Term (2002-2006)
Nonlinear Behavior	2.5	1.6
Continuous Mass Nonlinear FE Analysis	3.0	2.3

Strategic considerations

In general, both sets of experts see a good probability of modeling nonlinear behavior in the long term. The comments of a few experts noting that nonlinear modeling of some components is already being done shows that significant development has already occurred in this area.

The challenges to modeling nonlinearity seem to be a lack of computing power (which is a common theme throughout this report), a general need for good models, and the lack of validation data for some components. The good probability experts believe about their ability to model nonlinearity in the future shows their confidence in overcoming these challenges.

STR-15. Are there any simple, yet sufficiently accurate methods available to include non-linear behavior into FEM? If so, what are they?

Methods for Including Nonlinear Behavior into FEM:

- lumped parameter models for crash using crush test data for spring rates
- Geometric nonlinears are relatively easy; material nonlinears are relatively difficult.
- ADAMS-FEA (expensive); ABAQUS
- use of finite-segment (multibody) dynamics
- Nonlinear methods are not simple. Neubar's rule for plasticity calculations is one method, and others include design-of-experiments and probabilistic methods.
- Crash worthiness is based on nonlinear behavior of the vehicle. The tools that we are using are DYNA-3D, RADIOSS PAM-CRASH, and in-house codes.
- crash simulations

Selected edited comments

Round 1

- As well as linear analysis, a simple lumped mass model may be available.
- There is no such thing as "perfect" in nature. Variability and nonlinearity are built in. Therefore, one needs to design for 99% or so for customer use, considering all variability.
- A more effective and stable solver for nonlinear equations is needed. Accurate modeling methods for nonlinear elements are also needed.

Summary

There is no unanimous choice by Structures experts for including nonlinear behavior into FEM models.

Strategic considerations

This area may be a sensitive one for experts because they noted having in-house codes written specifically for this purpose. By extension, it may be a strong competitive advantage for a company to quickly and inexpensively model nonlinear behavior with FEM (though most commercial FEM codes have a built-in nonlinear capability).

STR-16. **Please rate the probability of accurately modeling medium and high frequencies, including noise, vibration, and harshness, as well as the probability of using statistical energy analysis for very high frequencies in the short term (1996-2001) and in the long term (2002-2006).**

Scale: 1 = High probability 3 = Moderate probability 5 = Low probability

Probability of Modeling:	Mean Rating	
	Short Term (1996-2001)	**Long Term (2002-2006)**
Medium and High Frequencies	3.3	2.4
Very High Frequencies (Statistical Energy Analysis)	2.6	2.3

Selected edited comments

None

Summary

In the short term, Structures experts see a moderate to good probability of accurately modeling very high frequencies using statistical energy analysis, but a slightly less than moderate probability of accurately modeling medium and high frequencies. In the long term, the experts see a moderate to good probability of accurately modeling very high, high, and medium frequencies.

Strategic considerations

Experts seem to be more confident in their modeling of very high frequencies than high and medium frequencies currently. Statistical energy analysis has been mentioned in a number of other areas of this report as the method of choice for modeling high frequencies. If this technique can be used for all high-frequency levels, modelers will need to focus only on improving the techniques used to model medium-level frequencies, which currently are not available in a satisfactory form. The confidence the experts show in being able to model these frequencies suggests a developing expertise in one of the crucial customer satisfaction areas: noise, vibration, and harshness.

STR-17. What are the key issues in noise, vibration, and harshness (NVH) modeling?

Key Issues in NVH	Percentage of Responses
Nonlinear effects (e.g. friction/contact boundary conditions/excitation models/connection models)	17%
Damping	12%
Total Nonlinear	29%
Accuracy	2%
Accuracy vs. ease of use	5%
Accuracy vs. design maturity	2%
Total Accuracy	9%
High frequencies/SEA (statistical energy analysis) development	7%
Understanding the human (customer) perception of noise and vibration /human sensual evaluation	7%
Variability	2%
Production variability	2%
Testing variability/non-stationary	2%
Total Variability	6%
Acoustic absorption	2%
Pass-by noise	2%
Sound quality	2%
Total Noise-Related	6%
System simulation	5%
Model Size/Density	5%
Objective targets	5%
Computer turnaround time/costs	5%
Soft component modeling	2%
Accurate modeling of materials used for interior (trim, carpeting, etc.), headlamps, etc.	2%
Representation of physics for components	2%
Human resources	2%
Design optimization	2%
Mid-frequencies	2%

Selected edited comments

Round 1

- Currently, the manpower required for modeling is enormous.

Summary

Reflecting the numerous challenges in NVH modeling, our Structures experts noted over 40 key issues in NVH modeling. The challenge most often mentioned is modeling nonlinearity, especially damping. Issues dealing with accuracy, modeling of high frequencies, human sensual evaluation, variability, and noise also were mentioned as key challenges.

Strategic considerations

This question gives some good indications of what the challenges will be for NVH modeling over the next 10 years. Though our Structures experts showed optimism about modeling nonlinearity in the future in previous questions, they still see them as the biggest challenge in modeling NVH. Computer resources and costs, which have been noted as challenges in other questions, received much less response in this question. By placing less emphasis on computer challenges in this open-ended question, respondents may be assuming the solution to this problem is inevitable, and thus focused their thoughts on the most challenging aspects of NVH modeling.

STR-18. Although individual component FE models can be very detailed and give accurate results, currently how accurate is an assembly model, including, for example, bolted joints? How accurate will assembly models be in 2001 and 2006?

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Assembly Model Accuracy	Mean Rating		
	1996	**2001**	**2006**
Accuracy	3.4	2.6	2.0

Selected edited comments

Round 1

- The limitation on improvement is based on complexity and absence of data rather than computer power. There are so many parameters at this level that it is difficult to do validation.
- This is mostly a user interface issue, which depends on development of a priori applications. The trend is towards improvement, however.

Summary

Our Structures experts do not believe assembly models currently have acceptable accuracy, though they think these models will achieve acceptable accuracy by 2001 and approach a level of high accuracy by 2006.

Strategic considerations

The information needed to build and validate assembly models needs to continue to be gathered and tested in order for modelers to develop full, accurate models. The lack of computing power that is mentioned so often as a limitation in other modeling questions is a secondary issue in assembly models. Focusing on developing and validating these models will give manufacturers or suppliers a competitive advantage in an area where the models themselves are considered still under development (though models as complex as these may develop in a slow, evolutionary manner such that no one manufacturer will have this capability).

STR-19. What methods could lead to an improvement in these FE assembly models?

Methods for Improving FE Assembly Models	Percentage of Responses
Improved modeling methods	5%
Nonlinear elements modeling	5%
Automation of remeshing with "quality indicators"	5%
Improved meshing techniques	9%
Damping models	14%
Connection models (contact, friction)	18%
Material models (e.g. spot welds, plastics)	27%
Total Improved modeling methods	81%
Better computer speeds	9%
Model library of various types of fasteners/hardware	5%
Validation of subassembly models	5%

Selected edited comments

Round 1

- More detailed mesh, good contact treatment, and also a high-performance supercomputer may be necessary.

Summary

Of the possible methods that could improve FEM assembly modeling, our Structures experts felt that improving materials, connection, and damping models were the key issues in improving assembly models.

Strategic considerations

The focus on improving particular models continues the ideas noted in previous questions, particularly the need for improved damping models. The need for improved materials and connection models adds to the list of model improvements that modeling supplier companies and universities can focus on to aid manufacturers and suppliers.

STR-20 **How accurate are crash models currently, and how accurate will they be in 2001 and 2006?**

Scale: 1 = Highly accurate 3 = Acceptable accuracy 5 = Unacceptable accuracy

Crash Models	Mean Rating		
	1996	2001	2006
Accuracy	3.4	2.6	2.0

Selected edited comments

Round 1

- We need to develop better material models and properties -- for example, strain rate effects. They need to include more and more detail, hence new solution algorithms or faster computers. There also needs to be an improvement in dummy/structure interactions.
- Improved accuracy will be highly dependent on the rate of hardware improvement since explicit transient dynamics is highly CPU- and space-intensive.
- We need faster computers to handle model complexity – for example, dummy-car interaction.

Summary

The Structures experts see crash models currently as approaching acceptable accuracy, and they see these models exceeding acceptable accuracy by 2001 and reaching very accurate levels by 2006.

Strategic considerations

Based on the comments of the panelists, faster computers as well as improved materials models will determine how accurate crash models will be in the future. Since the speed and capacity of computers continue to increase at a very high rate, it is reasonable to expect the improvement that the experts predict for these models. But the need for better materials models may be more challenging because it seems to demand both more computational power and increased knowledge of how materials respond to the diverse dynamic situations of vehicle structures.

Also, though increased computing power is generally thought of as the main hurdle for increasing model complexity, the increased demands that will be made on modelers to refine or expand models will make decisions about when to cut off modeling activity more challenging. The push to reduce development cycle time acts as a control for modeling because the need to finish a product determines when modeling can no longer take place. The challenge of improving modeling within the strictures of the reduced development cycle will raise decision-making about what and how to model to a managerial art form. The goal throughout the process will be to have the government perform the first crash test with the manufacturer knowing the vehicle will pass the test because of the prior modeling.

STR-21. Please rate the percentage increase or decrease crash simulation has had on the following factors in 1996 compared to presimulation days, and the percentage increase or decrease crash modeling will have on the same factors in 2001 and 2006 compared to now.

Percentage Increase or Decrease Due to Crash Simulation	Median Response			Interquartile Range		
	1996	2001	2006	1996	2001	2006
Costs	-10	-15	-25	-10/-5	-20/-10	-26/-20
Development Timelines	-7	-10	-22	-10/0	-20/-10	-26/-20
Number of Prototype Iterations	-10	-20	-35	-20/-7	-30/-10	-50/-30
Quality of Design	18	20	30	10/20	20/23	24/33

Selected edited comments

Round 1

- A large portion of the prototype cars is for crash tests. If we had no crash simulations, we would have more cost and weight, and quality might go down.
- There is no change due to increased computing costs.

Summary

The Structures panelists see a 10 percent decrease in costs due to crash simulations currently (over presimulation days), and they see continued decreases of about 15 percent by 2001 and 25 percent by 2006 (compared to the current state).

On average, the experts believe that development times have currently decreased about 7 percent due to crash simulations (over presimulation days), and by 2001 they see a decrease of development times of 10 percent over the current state and a 22 percent decrease by 2006 over the current state.

The number of prototype iterations will undergo significant change over the next ten years according to the Structures panelists. They currently see a 10 percent decrease in prototype iterations over presimulation days, and they predict a 20 percent decrease over the current state by 2001 and a 35 percent decrease over the current state by 2006.

The Structures experts believe that, due to crash simulations, the quality of design has increased about 18 percent over presimulation days. They predict a 20 percent increase in quality of design, relative to the current state, by 2001, and a 30 percent increase in the quality of design by 2006.

Strategic considerations

Though these estimates are probably very rough because of the complexity of the design and development process, the trends in the responses are clear. Crash simulations have had and will continue to have significant positive effects on all areas of the design and development process, including costs, development timelines, prototype iteration and quality of design.

One issue noted by one of the experts is the cost of increased computing power, which he felt would absorb the savings others thought would be gained from using the simulations. Though the computing power issue is a continuing theme throughout this study, it seems unlikely that the cost of increased computing power will reach the magnitude of savings gained through the simulations themselves primarily because of the man-hours saved through the reduction of prototypes.

In general, the biggest gains noted by the experts will occur in the 6-to-10 year span. Their caution in making higher predictions about the next five years may be based on their view of the time it will take to develop faster computers, but it may also be based on their knowledge of how long it takes to make significant changes in large organizations, where resistance to change can only be overcome through clear proof of the promised gains.

STR-22. Within the next 10 years, will there exist real-time crash simulations? Will these real-time simulations be worthwhile?

Exist?		Worthwhile?	
Yes	54%	Yes	54%
No	38%	No	38%
Maybe	8%	Maybe	8%

Real-Time Crash Simulations:

- They will not be real-time. They will be worthwhile when used with man-in-the-loop simulation.
- Very unlikely at anything approaching acceptable mesh refinement.
- Real time simulations would be very beneficial. However, model complexity will increase and computer software hardware will decrease time required. A 10-to-1 reduction would seem do-able.
- Full vehicle crash analysis within one hour will exist.
- Since crash phenomena are on the order of milliseconds, real-time simulation will be very difficult. But it will be preferred to have faster simulation tools to analyze different prototypes.
- It currently takes three to six months to build a FE crash model that runs in 10 to 30 hours. The real payoff will be in improved FE mesh/model generation.
- Yes, real-time simulation is definitely worthwhile!
- No! Even if it existed, it would be used only at the test-piece level.
- Yes, if one can manage analysis of data volume.

Selected edited comments

Round 1

- Currently crash simulations take 20 to 40 hours, and initial model development and validation can take three to six months. Unless the model development time is reduced significantly it doesn't matter how fast the simulation is.
- I think full vehicle crash analysis within one hour will be possible, but an analysis method for the calculation result such as design sensitivity is necessary for real-time simulation.
- Models will expand in detail, preventing worthwhile real-time models.

Summary

Structures experts are divided about their views about whether real-time simulations will exist within 10 years and whether they are worthwhile, though a few more experts believe they will exist and will be worthwhile.

Strategic considerations

Structures experts continue to see significant challenges to real-time simulations in both computer time and model development time. Increased model complexity, the need for improved mesh/model generation, and the potential addition of driver-in-the-loop into simulations all contribute to the challenge of real-time simulations. These views are in contrast to experts who feel useful real-time simulations as possible and worthwhile. The difference between the two groups may be in the level of detail each group believes is necessary in modeling real-time simulations. Deciding on the appropriate level of model detail will be the area where modelers and managers will bring a competitive advantage to their companies, and will make real-time simulations a hope or a reality.

STR-23. What problems do you currently resolve exclusively (or mostly) by test rather than modeling? What problems do you foresee in 2006 being resolved exclusively (or mostly) by test rather than modeling?

1996

- crash test; fatigue-like test
- engine noise radiation; road noise of 100-500 Hz
- seat belt (FMVSS 209); seat and seat belt anchorage (FMV85 207/210) tests, fatigue tests
- road loads for durability; brake design and development
- transient noise events; most durability problems (2)
- highly nonlinear, high-frequency and other safety related items
- studying the body mounts and calculating its properties
- transient powertrain events (clutch engagement, shift feel)
- structure-borne noise; nonlinear noise (squeaks, squeals, etc.)
- damping properties and other material parameters

2006

- none/almost none (4)
- fatigue analysis/life predictions
- verification of prototypes for all attributes (vehicle level); highly nonlinear system response attributes

Selected edited comments

- There is too much detail required to eliminate all above problems.

Summary

Durability, fatigue, safety, and noise are the most frequently noted areas where structures experts today rely almost exclusively on test rather than modeling. In the future, though these same areas were mentioned as needing more testing and less modeling, some experts are hopeful that modeling will be all that is needed to resolve these problems.

Strategic considerations

The measured optimism of some of the structures experts and the view by some of the experts about the need for testing in the future shows the uncertainty of modeling completely replacing testing procedures in the future. In some ways, the issues of durability, fatigue, safety, and noise represent the experts' views of where modeling suppliers (and by extension the Automotive Research Center (ARC)) can offer manufacturers models and processes that may give them a competitive advantage in the area of modeling and simulation.

STR-24 Does modeling get utilized constructively and in a timely fashion in the design process?

Constructive Use of Modeling?		
YES	NO	SOMETIMES
40%	30%	30%

- Not yet - it is still too imprecise and not used efficiently.
- It is very people dependent. Not all car lines are equally staffed, and not all customers are open to CAE (computer-aided engineering).
- Ninety percent is done in a timely fashion.
- Usually, but it could be more timely in some instances, as design changes rapidly.
- Yes, but other constraints drive design changes faster than FEA (finite element analysis)/CAE simulation.
- Sometimes building the model might take more time than expected, but it is used constructively provided that the model is delivered ready for analysis before the deadline of the design process.
- It needs improvement. Until modeling improves, analysis will lag behind design.
- body structure - yes (dynamic and crash); engine combustion -- yes; powertrain mounting - no

Selected edited comments

None

Summary

Experts are almost evenly divided about the constructive and timely use of modeling in the design process. Some believing that modeling is used in a constructive and timely fashion, while others believe it isn't or is only sometimes used in such a fashion.

Strategic considerations

The lack of consensus on the constructive and timely use of modeling in the design process accentuates the misunderstanding among experts about how modeling is or should be used in the design process. The theoretical side of the argument about usage says that complete models must be ready in time to be incorporated into design, while the practical side of the argument says that any improvements in previous modeling that can be added incrementally design by design will suffice.

Of course, the discrepancy of views may be a function of the experts' experiences at companies that actually do not use modeling in a constructive and timely fashion in the design process. These companies will be at a distinct competitive disadvantage in the near future as they try to compete against companies who have a well-defined process for incorporating modeling into the design process. Companies may be able to purchase off-the-shelf modeling packages from modeling supplier companies, but the knowledge of how to best incorporate the results from modeling into the design process that comes with experience cannot come off the shelf. Attempts to use a plug-and-play methodology with off-the-shelf modeling packages may not yield the expected results if the modelers on staff are not thoroughly familiar with the strengths and weaknesses of a particular model or package and how to best fit the results of modeling into the current design. Therefore, companies will need to develop the core competency of using models as opposed to building models.

STR-25. **Do you have any general comments about the role of modeling in industry today, and how it is being utilized in the design and research process? For example, are engineers being trained effectively, and is the information that simulations output being used constructively and efficiently?**

General Comments on the Role of Modeling in Industry:

- It is far less effective than it could be.
- CAE is emerging to lead design. We need good measurement tools to make CAE accountable for predictions. We cannot continue to run CAE in an open loop mode.
- Our company uses computer simulation to guide design process extensively. Still, we verify by using physical tests for final confirmation in almost all cases. We use simulation results constructively but we don't test them 100%.
- Historical reliance on hardware is a major inhibitor. Capability is moving ahead rapidly.
- There is too much time spent in the modeling effort.
- I think the engineers in this area are not well prepared to cope with CAE demands in the auto industry. It is better to have courses at UM (University of Michigan) that deal with some of the issues concerning CAE in auto industry (meshing, judging the results).
- Entry level engineers know analysis tools but need a better understanding of the basic physics of automotive problems.
- CAD (computer-aided design) programs (UG, CATIA, IDEAS, etc.) have modeling capabilities which engineers normally don't take advantage of because these software packages are considered to be for "designers," not engineers. Progress is being made, though, in directly importing CAD data into "engineering" packages such as Patran. Auto meshing routines must then be utilized to use this CAD data effectively. Such auto meshing capabilities, however, are not very robust and need much improvement, especially for quads and hexes.
- Modeling is used much more successfully than it was 10 years ago. Modeling creates fewer disasters (no unexpected problems lurking). But there is no good modeling career path. It is seen as an entry-level training ground.

Selected edited comments

- I believe there is a general consensus that computational methods are not used as efficiently and in as timely a manner as we would hope. In most cases, the elapsed time between when information is requested and when it is produced is greater than the time allowed to make the decision. The problem is usually not with the length of execution, but with the length of model building and validation time (usually one to two orders of magnitude greater). We still have many situations where we generate physical and mathematical information in parallel, but with little chance of using them to reinforce each other.

Summary

Respondents, in general, do not think modeling and simulation are being used as effectively as they could be because of hardware restrictions, and conflicts between designers and engineers. They also think entering engineers need more background in modeling as well as a better defined career path.

Strategic considerations

In general, the Structures experts see progress in modeling and simulation and the improvements modeling and simulation have made in vehicles compared to presimulation days, but they definitely see room for improvement. Managing the interface between modeling, design, and testing and development appears to be an area that will need some concentrated effort by the manufacturers in order to take full advantage of modeling and simulation. They will also need to further support modeling to improve the timeliness of results, which would facilitate their incorporation into the design of vehicles.

STR-26. What expectations and desires do you have for the ARC integration efforts?

Expectations for the ARC Integration Effort:

- I expect it to be general enough to handle vehicle simulation.
- I would like to see work on automating the machining process. Another idea would be to work on software that creates a "give (adaptive) mesh" which could save us a lot of time.
- I expect it to create a modeling shell that does not require any customer specific customization.

Selected edited comments

- The goal of integration of tools and skills spans industries, universities, and vendors. If the integration efforts don't figure out a way to create and work with larger teams, and identify their unique contributions, I suspect they are doomed to failure.

Summary

Though there are few responses to this question, some of the issues relate directly to the goals of the ARC, including the development of models general enough to do full vehicle simulation without the need for customization and the ability to develop custom additions to the shell.

Strategic considerations

The issue of fitting the ARC model into the information infrastructure is an issue that has been given little attention but addresses a basic need of how to integrate a method such as the one the ARC is proposing into a company's engineering and business processes. Though one can argue that the potential barriers to change should be addressed within the company culture, having a program that documents the inputs from all parties in a full vehicle simulation might be seen more as a facilitator to change rather than a barrier.

STR-27. What advances in structural modeling in the next 10 years will lead to significant improvements in the following areas?

WEIGHT REDUCTION

- shape/size optimization (6)
- better understanding and idealization of material behavior – for example, fatigue; parameterization of complex structures; better understanding of operating conditions
- multifunction optimization
- improved, lighter weight materials
- improved boundary conditions definitions; composite simulation
- better optimization tools for solid finite elements (2); better environment models
- optimization - design sensitivity analysis across all attributes
- having an automatic meshing tool that produces the optimum mesh to where "war page" and "skew" are minimized

RIDE AND COMFORT ENHANCEMENT

- frequency optimization
- better understanding and objective targets for a currently subjective assessment
- better sound quality
- simulation of ride and comfort depending on age, person and other human factors
- improved seating and suspension
- simulation technology – simulators; human sensory evaluation
- better definition of component characteristics. Inclusion of flexibilities/compliances
- better environment models; improved subjective-objective understanding
- improved nonlinear suspension models; models of active and semi-active suspensions
- mid-frequency modeling; quantify customer perceptions and usage

HANDLING ENHANCEMENT

- better understanding and objective targets for a currently subjective assessment
- lower mass center location
- dynamics with nonlinear element; man-in-the-loop simulation
- better definition of component characteristics; inclusion of flexibilities/compliances
- better environment models
- improved system-based nonlinear dynamics models
- simulation of compliant components (i.e., rubber mounts), directly from material behavior

SAFETY ENHANCEMENT

- crash analysis technology (2)
- occupant model fidelity (2)
- hardware performance (e.g., supercomputer improvements)
- degree of nonlinearity

- ability to model the test during accelerating; ability to model the restraint system (i.e., belt, air-bag, etc.) (2)
- side-impact air bags; improved seats and seat belts; improved structural integrity
- gap/interference simulation
- larger (more detailed) models; simulation of other failure modes (punctures, efforts, separations, etc.)
- having an automatic meshing tool that produces the optimum mesh where "war page, skew" are minimized; better shell element suitable for crash; no cheap, minimum problems with zero energy modes; good models for spot welds
- coverage of all safety-related events

Selected edited comment

- Incremental advances are likely in all areas.
- Except for crash safety, I think it is almost sufficient to analyze these issues with the present technology. I think advancement in experimental technology is more important in these areas.
- For all of the main areas, there is a need for design optimization, model analysis techniques, and the ability of the users to easily substructure full vehicle models.

Summary

The Structures panelists see a wide variety of areas where advances will lead to significant improvement in vehicle structures models. For weight reduction they see multifunction optimization including shape, size, and general structural optimization, as well as a better understanding of composites and material behavior. For ride and comfort, the main areas are customer-oriented objective criteria, and improved suspension and sound models. The main areas for improvement of handling models include simulation of compliant / flexible components, and general improvement in nonlinear models, while for safety crash analysis they see modeling the full safety system including restraint system analysis as some of the main areas where advances will lead to significant improvement.

Strategic considerations

Structures models that focus on weight reduction, ride and comfort, handling, and safety each have their own modeling challenges for the future, and they represent some of the overarching issues that need to be dealt with if structures modeling is to progress. Some of these issues are logically connected to each area such as shape, size, and materials analysis for weight reduction, suspension analysis for ride and comfort, models of compliant / flexible components for handling, and crash-and restraint-system analysis for safety. But other issues can be seen as basic modeling issues that affect all the areas such as improvements in multifunction optimization, developments in non-linear models, and developing objective customer-oriented criteria to use as an endpoint in the modeling process. Decisions about allocating resources to work on these challenges, some of which are formidable and could take up one's whole career, may force manufacturers to channel some of their research to specialists outside their companies or industries. These collaborations between manufacturers and suppliers or manufacturers and academia, the military or the national labs to may help to resolve these challenging issues.

One of the major challenges of these working relationships centers on how they are to be managed. Manufacturers, suppliers, and academia all have their own priorities and timetables as well as their own views of when a usable solution is ready for implementation. How these issues are negotiated and managed between the parties will determine in some ways how successful these cooperative efforts will be.

STR-28. What areas in structural modeling need more fundamental research work that will lead to more accurate modeling or new capabilities?

Areas of More Fundamental Research in Structures Modeling:

- penetration mechanics; material deformation, characterization (2)
- reduced order modeling, particularly of nonlinear effects (2)
- benchmark studies with experimental validation
- ride and comfort; durability and fatigue (3); handling
- simulating variability/statistical FEM
- noise and vibration performance (primarily in the high frequency range)
- adaptivity, p-version elements
- connection failure: welds failure particularly during crash simulation
- damping; transition range from FEA to SEA
- seats, doors, seat belts, occupant dynamics
- more accurate nonlinear element modeling methods (including tire, etc.) (3)
- spot weld material (heat affected zone); probabilistic modeling
- damping models
- mid-frequency NVH
- simulation of fastening techniques, variability; balance of all the above with the need for raw speed of the simulation task

Selected edited comments

- The entire discussion misses the point, I think, because there appears to be an assumption that accuracy is the primary question. While that is important, in my opinion, it is not the major problem with engineering for the next 10 years. Three issues in particular are of prime importance, in my opinion. First, structural simulation methods do not produce answers in the time frame that they are required, primarily because of the initial construction and validation of the model. This suggests that a greater effort on automated and adaptive modeling is necessary. Second, as an engineering community, we have concentrated on discipline accuracy as opposed to multidisciplinary design, to the extent that simulation practitioners rarely address the process. That is, we don't use our existing simulations for effective designs, so it is unlikely that more accurate simulations will have much effect. Third, we have not developed practical efficient ways to integrate test and simulation.

Summary

The Structures experts offer an array of needed improvements in structures modeling, from general models like improved non-linear behavior models, model reduction methods, and simulations of variability to specific models for durability and fatigue. From the specific models that need improvement, connection/weld models were mentioned most frequently, followed by damping and material characterization.

Strategic considerations

Both the specific and general modeling issues described offer substantial opportunities for manufacturers and suppliers to gain a competitive advantage, and also for academia to gain support for research projects. The challenge for every manufacturer becomes managing its R & D function and concentrating on which areas are most in need of research dollars and which areas will deliver the best return on investment.

In general, our Structures experts are confident that many of the modeling challenges will reach acceptable accuracy over the next ten years. However, there are certain areas, such as the integration of structural and fluid dynamics, the integration of simulations into the design, and the integration of test results into simulations, that will demand more interdisciplinary communication and support between functions to reach higher levels of design efficiency.

STR-29. Do you have any general comments about structural modeling that you would like to share with us?

General Comments on Structures Modeling:

- At present, except crash simulation, we generally get many output results when analyzing vehicle phenomena. I think, at present, we make insufficient use of them.
- Modeling is still not used enough. It is too slow, and is always behind the design, that is, the CAD model.
- It has improved greatly over the last ten years, but may still be improved.
- The finite element models are currently too inaccurate, inefficient, and difficult to use.
- Stronger bonds need to be created between the auto industry and universities. University graduates seem to be less interested in simulation technology. They need to work in a real work environment during their college years to understand and appreciate industry needs.
- My biggest hope is that executives of the auto companies to see analysis as a useful design tool when in the hands of capable engineers. The view of a "push-button" future is, in my opinion, a dangerous one.

Selected edited comments

None

Summary

- The general theme of the responses to this question – the inability of simulation to fit easily into the design process because models take too long to analyze – is counterbalanced by the assertion that executives need to 1) understand the advantage of allowing capable engineers the time to use the available tools to aid designers, and 2) have a realistic understanding of the capabilities and potential of the models.

Strategic considerations

- The responses to this question show one of the disconnects that are a part of the modeling and simulation discussion. Engineers believe that they need time to make good decisions based on the output from modeling and simulation, while executives are focused on reduction in the development cycle and feel modeling and simulation will give "push button" results that will reduce development time. Faster computers and more efficient models will probably reduce some of the time engineers need to perform simulations, but the interface between the modelers and the designers needs to be examined. This interface seems to be a critical point of the design process that can leave both sides frustrated. The designers become frustrated because the models take too long and cannot be incorporated into the development cycle in a timely manner. The modelers become frustrated because the tools they are using slow down their work, and they then feel pressured to present results that are not yet properly optimized to fit the timeline for the development cycle.

STR-30. **What modeling and simulation issues will present the most significant challenges or opportunities to the vehicle manufacturing industry in the coming decade?**

Most Significant Modeling and Simulation Issues in the Future:

- translation of graphics; high-fidelity performance evaluation models
- Optimization methods are needed to continuously improve designs. Improve concept-level design tools such that "analysis drives design." (2)
- integration across traditional disciplines (2)
- At present, except for crash simulation, we generally get good output results analyzing vehicle phenomena compared to the presimulation days, but we don't make sufficient use of them.
- modeling and simulation of human factors in different qualities, such as noise and vibration, safety of occupant, comfort and so forth
- The greatest opportunities come from integration of meshing/modeling with CAD models.
- Full integration of occupant with car in crash simulation with good accuracy is a challenge. (2) Because engineers only need to specify line data, I would like to take results directly to crash simulation (bypassing FE modeling) if possible.
- modeling nonlinear and damping effects
- Safety/collision analysis is important. Current engineering means integration of design, testing, and prototyping through a common database. New modeling and simulation for new material (such as composites), as well as electric vehicles and combustion, will be key.
- Fast and easy (automatic) modeling to meet timing requirements; CAE training for new graduates (they will need more physics, chemistry, and mathematics background); nonmetal modeling and analysis situations
- nonlinear effects; optimization techniques; parallel processing
- As technical capability advances, it will be a challenge to train engineers and assure capability of usage.
- roles and responsibilities of engineer/analyst/designer/testing; balance of technique and process requirements

Selected edited comments

None

Summary

Structures experts describe some very specific modeling challenges including human factors modeling, driver-in-the-loop modeling, safety / collision analysis, as well as modeling new materials. But a common theme throughout the responses to this question is the issue of integration of knowledge and people across disciplines. The experts see a challenge composed of integrating results of modeling into the design function to create analysis driven design as well as integrating different disciplines into the modeling function. As one respondent noted, the roles and responsibilities of employees include those of the engineer, analyst, designer, and tester, and the goal for this employee will be to balance technique with process requirements. They believe this will happen through cross-training between disciplines, and developing a common database that is used for design, simulation, testing, and prototyping. They also believe there is a need for new employees to have more training in a variety of disciplines.

Strategic considerations

The views of our Structures experts, in general, show a convergence around the concept of the integration of functions within an organization. This issue has begun to be addressed at some of the vehicle manufacturers with their move to cross-functional platform teams in building a vehicle, but it seems that this concept must continue to be driven down farther into the organization. Our experts believe the integration of design and analysis is an issue that will challenge the industry most likely because each group seems to be working on a different timetable. The design team, as part of the platform team, must meet deadlines in the product development cycle in order to bring a vehicle to market. But the analysis/simulation team, being limited in some respects by the time it takes to run computer models and the time it takes to learn and understand new materials and the physics of interactions between components, has a difficult time bringing the results of their analyses to support design in a timely manner. Because the results of modeling and simulation are used across platforms, rather than for just one specific design, the integration of their results into a company's complete vehicle design process will be a significant challenge for all companies in the future.

IV. VEHICLE INTEGRATION MODELS

INT-1. Concerning the complete engine model, the complete powertrain model, and the all encompassing vehicle model, please rate the likelihood of having accurate models in the short term (1996-2001), and in the long term.

Scale: 1 = Very likely 3 = Somewhat likely 5 = Not likely at all

Likelihood of Having Complete, Accurate Models (Mean Rating)						
System	Short Term (1996-2001)			Long Term (2002-2006)		
	Engines	Dynamics	Structures	Engines	Dynamics	Structures
Complete Engine	3.3	3.4	3.1	2.4	2.6	2.1
Complete Powertrain	3.4	3.3	3.3	2.6	2.4	1.9
Complete Vehicle Dynamics	Not Asked	2.8	2.8	Not Asked	1.9	1.9
Complete Vehicle Structure	Not Asked	3.4	2.7	Not Asked	2.4	1.7
Complete Vehicle	3.5	4.0	3.3	2.4	3.1	2.5

Selected edited comments

Round 1 Engine

- A system using some experimental data will be more accurate.
- There are already tools in use for every point of view and different granularity. They have to be improved. There is a problem with the words "accurate" and "satisfying." Today's tools are used, but still have to be improved.
- Complete powertrain and vehicle models incorporate zero-dimensional engine models, which are sufficient for predicting fuel economy, performance, and driveability.
- Complete vehicle models will evolve as software and hardware skills develop. But there will probably be more detailed models of both engine and powertrain coexisting.
- Today, given an engine map and a transmission map, we have models for vehicle performance. With measured emissions maps, we can "predict" FTP (Federal Test Procedure) emission. Predicted emissions are not available now and are unlikely in the future.
- A huge integration model, like a complete vehicle model, has a low possibility in terms of limitation of computation memory storage and speed, even in the long-term future.
- A complete engine and powertrain are done routinely now.
- The engine is the most difficult of these models.

Round 2 Engine

- Developing a complete vehicle model is not effective for the improvement of design efficiency.
- If you can model pre-engine accuracy, you can probably model the rest.
- We already make extensive use of "black box" engine and transmission models in our total vehicle models – improvements will come in transient models.

Round 1 Vehicle Dynamics

- These models exist and are used.
- The efforts in developing a design fidelity model for operator-in-the-loop will push the development of a complete vehicle model.
- The problem is the word "complete." I can imagine excellent models for many areas of the problem, but they are unlikely to be complete in the sense that they contain all of the interesting physics of the real system and can duplicate all the interesting behaviors.

Round 2 Vehicle Dynamics

- I doubt the necessity of this type of model. Benefit from this model may be small.

Round 3 Vehicle Dynamics

- I think complete vehicle structures or vehicle models can be made and used even at present. But considering the effort and labor needed, the gains are very small. Limit analysis or small component analysis are more beneficial for real design activities.
- If accomplished, it will be "gee whiz," but not too useful.

Round 1 Vehicle Structure

- What do you mean by accurate enough for design? You "design" using all levels of accuracy. Do you mean no component tests, and no vehicle tests until final validation of prototype? Is a material test a component test?
- Assume "complete" model refers to an integrated single-physics model.

Round 2 Vehicle Structure

- Current integrated simulation is limited by computer hardware capability and cost.
- Technology will allow a move toward better micro- and macro-level models. Models are constructed, but what useful information can be obtained is more important.

Round 3 Vehicle Structure

- I think after 10 years, progress will be gained somewhat, but I think what is important is the necessity of such a modeling technique. A complete engine model is somewhat more necessary than a complete vehicle model.
- In general, more and more system simulation is coming in the near future. Boundary conditions for subsystem/components will be used by component engineers. But this addresses only one or two kinds of loadings and boundary conditions[, those at the macro level]. At the micro level, the conditions may be different, requiring micro and macro levels of loadings/boundary conditions.

Summary

In general, respondents from all three panels see improvements in modeling complete systems in the short and long term. In the short term, they generally see complete system modeling as being somewhat likely, and in the long term they see these types of modeling as likely. Structures experts are the most optimistic about the possibility of modeling complete systems, Dynamics experts are the least optimistic, and Engine experts fall between the Structures and Dynamics experts concerning the possibility of modeling complete systems in both the short and long terms.

In the short term, both the Dynamics and Structures experts feel a complete vehicle dynamics model is somewhat likely, and the Structures experts think a complete vehicle structures model is somewhat likely. This optimism of the Dynamics and Structures experts also appears in their long term predictions, where both agree that a complete vehicle dynamics model is likely, and the

Structures experts think that a complete vehicle structure model is likely.

As one would expect, the complete vehicle system is the system the experts think is least likely to be developed in the short and long term, where the experts think this system is in the somewhat likely range of development. But the complete engine and powertrain models are also viewed by the experts as similar to the complete vehicle system in their likelihood of development.

Strategic considerations

This question leads off a series of questions asked of all respondents across all three panels about their thoughts concerning the issue of integrating complex analyses within large systems such as engines, powertrains, vehicle dynamics, and vehicle structures. Not all of the questions in this section were asked of all three panels. The tables that accompany each question lists which panels were asked each question.

This series of integration questions comes after the detailed questions for each panel have been asked, and it asks respondents to broaden their thinking about the whole issue of modeling and simulation by asking about the likelihood of having "complete" system models in the short and long term. The problem some of the respondents had with the word "complete" in this context was intentional because it allowed respondents to decide for themselves what it means, and didn't set any boundaries on what they think is possible. This question gives a good overview of what respondents from all panels think about integration models in general, and it also shows, through the comments section, how far along they think they are in developing what they consider "complete" system models, as well as some comments on the value of model integration.

As the summary section states, respondents are somewhat optimistic about the idea of developing complete system models, yet a number of comments focus on the overall utility of such models. These cautionary comments combined with the somewhat optimistic numeric responses represent well the industry's thinking on the subject of complete system models. The auto industry has jumped on board the movement that hopes to integrate all information needs within a company, including modeling and simulation. But this movement is in its early stages and, for the most part, the employees are cautiously optimistic about the final result. They see the potential rewards of such a system, but they also see the need to manage the value proposition of balancing the return on the investment with the rewards to be had from this integration movement.

INT-2. In general, how valuable is the concept of the integrated vehicle model?

Scale: 1 = Very valuable 3 = Somewhat valuable 5 = Not valuable at all

Value	Mean Rating		
	Engine	Dynamics	Structures
Integrated Vehicle Model	1.9	2.4	1.9

Selected edited comments

Round 1 Engine

- It is valuable if it is useful.
- It depends on the specific use of the model (driveability, fuel consumption, emissions, NVH (noise, vibration, harshness), etc.)
- Specific models address specific problems. A "universal," complex integrated model is not very useful because the complexity would confuse everything, and exercising it carelessly would only lead to wrong conclusions.
- It is valuable if it is credible.
- If a lot of limitations due to a computer's ability are not considered, the integrated vehicle model is very desirable.
- The model would be so large that building it would be impossible for a single person to do and maintain.
- There is a big need for all three models (engine, powertrain, and vehicle)!
- Unless there is a strong coupling between phenomena, an integrated model has little value.
- In the near term, it is impossible to do.

Round 2 Engine

- It is valuable if it responds properly.
- Most valuable if coupled between phenomena.
- The real vehicle is an integrated system. The model must reflect this.
- It is valuable but not desirable because of cost.

Round 1 Vehicle Dynamics

- It is valuable, provided proper model integration is done.
- It is valuable to some, but not to others.
- It is not necessary to integrate all the models in order to check system response to various sub-system inputs.
- These models are broken apart since they can be studied separately. Combining them would really slow run times and would add errors since untrained engineers will run them (i.e., there is no modeler I know who is an expert in every discipline).
- As any engineer knows, high frequency and low frequency can be modeled separately. While it is possible to integrate a high-frequency structural model and low-frequency powertrain model, one must ask why.
- It strongly depends on the problem to be solved, and the question to be answered.

- This is still worth doing. What you gain are not necessarily correct answers but insight into how the various subsystems interact.
- In spite of the value, the role of ARC (Automotive Research Center) in creating an integrated modeling system should be critically considered. Most effort required for integration is hard application work. ARC's role should be limited to research in methods to enable integration and their demonstration.

Round 2 Vehicle Dynamics

- I think "not valuable at all" is not true, but, at present, we don't confront such situations.

Round 3 Vehicle Dynamics

- I don't deny the value of these kind of integration models, but necessity or benefit may be small.
- The benefits of integrated modeling and simulation are yet to be realized or understood, but will be significant.

Round 1 Vehicle Structure

- It is not valuable in any area.
- The big issues are interface definitions for all situations, resources, and the fact that intelligent investigative tools do not exist.
- The primary benefit of this integration is for RWD (rear wheel drive) and AWD (all wheel drive) applications.

Round 2 Vehicle Structure

- Evaluation of such a large model will be very difficult. One will need a group of engineers evaluating the same model for various loads.
- It is especially valuable to extreme events: hard shifts, hard braking and turning, ABS (antilock braking system).

Summary

All three panels see an integrated vehicle model as valuable, but the comments of the respondents show a real caution about the issue.

Strategic considerations

Having asked respondents about the likelihood of having complete system models in the short and long term in the previous question, this question focused on what respondents feel is the overall value of integrated models. Though all the respondents think integrated models are valuable, members from all three panels listed a number of caveats to this optimism in the comments section, illustrating some of the issues facing integration modeling. Respondents see integration modeling as valuable if it is truly useful, if it gives insight into how the systems interact, or if it gives insight into extreme events. Some of the possible negatives include the complexity of such a model, which could lead to wrong conclusions; the need for a large group of engineers dedicated to maintaining and interpreting the models; and the fact that most problems can be solved by just looking at subsystem models.

INT-3. When looking at the submodels of the "black box" type, how complex do these models need to be while still being realistic and predictive, that is, how many parameters are necessary to predict effects (e.g. pressure and temperature changes) with a reasonable degree of accuracy?

Needed Complexity of "Black Box" Submodels:

- It depends on the question. In a conceptual stage, it is not necessary to know the pressure distribution in the cylinder. For intake optimization, you don't have to simulate the whole vehicle.
- They need to have significant fidelity; steady-state is currently done. We need transients to do control system development.
- Pressure, temperature, load, load (transient) are needed.
- The number of "state" parameters needed is about six; for example, speed, fuel rate, temperatures (about three), turbo speed. The number is much greater if nonstandard environments are involved.
- It depends upon their intended use. If you want to use a vehicle model to look at fuel economy and acceleration, etc., then they don't need to be highly complex. But if you want to investigate transmission gear rattle or tip-in/tip-out drive dynamics, much more detailed models are needed.
- It depends entirely on what use of the model is contemplated.
- It all depends on what you want out of them. The more complex, the better, as long as the user can understand them and generate values for unknown parameters based on experience, guidance, and other analyses/measurements.
- Appropriate number of parameters for each submodel should be considered under relations in terms of complexity among submodels in the integrated model. If only one submodel has many parameters as compared with other submodels, that submodel is too complex. In other words, it has unnecessary accuracy.
- Predictiveness is proportional to the number of parameters up to a point; that is, the number of constants that need to be calibrated must not increase too much. If it does, model complexity might not increase predictiveness. Number of parameters can be up to 50 (this does not include the look-up tables that might also be used).
- It depends on what you are looking for. Cycle integrated quantities, such as power and economy, are easy to predict relative to, say, soot or hydrocarbons, where detail of local conditions and how they vary with time is essential.
- It depends on the effect.
- As chassis manufacturers, we only require simple engine models. We need to estimate torque on driving wheels for a given driver input to within ± 2%.
- It depends on intended use of them. They must be very complex to be realistic. For general features they can be simple.

Selected edited comments

None

Summary

This question was asked only of Engine panelists, and their responses can be summed up in two phrases: "It depends" and "Complex on some issues and simple for others."

Strategic considerations

Respondents to this question show the specificity needed to determine the number of parameters of a "black box" model, as well as the knowledge experts must have in their particular subsystem. These models will have to be examined and tested carefully to see what the true requirements are for specifying each model. This also means that experts from a number of different disciplines will need to interact in order to test and better understand the effects of their model within the context of the larger integrated model because what might have been true for the subsystem alone may not be true when the subsystem is one of many within an integration model. Thus, the issue of combining subsystem "black box" models becomes one not only of the technical expertise of the modelers and the power of the software, but also of the integration of engineers into a group that will work together to solve some extremely complex integration modeling problems.

INT-4. **Within the context of an integrated powertrain model, what is required to go from a steady state map of the engine to a transient simulation, that is, how many and which components should be modeled to see the transience?**

Requirements to Move From Steady State to Transient Engine Simulation	Percentage of Responses
Heat Transfer	20%
Inertia	15%
Turbo-compression / charger	10%
Air flow	10%
Combustion	10%
Fuel flow	5%
Friction	5%
Torque converter	5%
Transmission shift	5%
Load	3%
Moments	3%
Governor model	3%
Engine control module	3%
Cold start model	3%

Selected edited comments

None

Summary

This question was asked of Engine respondents only, and it shows them putting priorities on a variety of issues for moving from an integrated steady state to an integrated transient engine model. The most important issues listed included heat transfer, inertia, combustion, and air flow. Though issues such as air flow and fuel flow could be considered part of heat transfer and combustion respectively, they were not combined to allow the reader to see some of the details experts felt were important to the move from steady-state to transient engine modeling.

Strategic considerations

In the Engine Modeling and Simulation section of this report, the issue of moving from steady-state to transient modeling of engine processes was discussed extensively for both phenomenological and CFD (computational fluid dynamic) models. This question was asked to elicit from Engine experts their insight into what they think are the most important challenges to address in the larger picture of fully integrated transient engine models. Though respondents were not asked to rank order their responses, issues of heat transfer, inertia, combustion, and air flow were noted most often and show where the experts think more research is needed if the move to transient engine models is to occur.

INT-5. **What is the probability of taking each of the following fundamental models and incorporating them as system level submodels into a seamless powertrain system model in the short term (1996-2001), and in the long term (2002-2006)?**

Scale: 1 = High probability 3 = Moderate probability 5 = Low probability

Probability of Submodels in Powertrain Model	Mean Rating	
	Short Term	Long Term
CFD	4.5	3.6
Phenomenological	2.7	1.8
FEA (finite element analysis)	3.6	2.6
Dynamic models	2.6	2.0

Selected edited comments

Round 1 Engine

- To integrate detailed models, you need a lot of number-crunching power.
- CFD and FEA are too complex to produce results in a realistic time frame.

Round 2 Engine

- We currently have piston, block, head, valve in an engine performance model to solve for heat transfer, component temperature, and engine performance. It is not routine, though.

Summary

This question was asked only of Engine experts, and looks at the type of models they think will be able to be incorporated into a complete powertrain model. In the short term, phenomenological models and dynamic models show the most promise with a better than moderate probability of being incorporated. In the long term, phenomenological and dynamic models again show the most promise, but the experts also think FEA models will also have a better than moderate probability of being incorporated into a powertrain system model.

Strategic considerations

The comments for this question touch on one of the issues that is part of the complete integration discussion, the computing power necessary to complete an integrated system analysis. These analyses take an enormous amount of computing power, which is the reason for the comments on the problems with the timeliness of these types of analyses. The lack of computing power is also most likely the reason for the lack of enthusiasm by the engine experts for the use of CFD models in the short and long term, though the improvement of moving grids in CFD models as noted in the Engine section of this report may make it easier to incorporate them into an integrated model in the long term.

INT-6. **What level of fidelity of full-vehicle integration is being achieved currently, and what level of fidelity do you see being reached by 2001 and 2006?**

Scale: 1 = High fidelity 3 = Moderate fidelity 5 = Low fidelity

Level of Full-Vehicle Integration	Mean Rating		
	Current (1996)	**2001**	**2006**
Dynamics	4.0	3.3	2.3
Structures	3.8	2.7	2.0

Selected edited comments

Round 1 Vehicle Dynamics

- Computing power is needed as an "enabler."
- I see more fidelity in the future.

Round 2 Vehicle Dynamics

- It may be possible in the future, but we don't feel the merit in it.

Round 1 Vehicle Structure

- Define fidelity degrees by percent deviations from experimental results. For example, high fidelity has less than 5%.
- At present, no integrated full-vehicle model exists.

Round 2 Vehicle Structure

- For a multidisciplinary approach at micro and macro levels, the fidelity needs have to go up.

Summary

This question on the fidelity of full vehicle integration models is one the Structures and Dynamics experts tackled, and though both groups see only moderate fidelity being reached by 2001, they both see good fidelity being reached by 2006.

Strategic considerations

This question presupposes a full vehicle model is available, and opens the discussion of the issue of what types of full vehicle models are currently in place. In a number of comments throughout this report, respondents commented that they already had full system or full vehicle models in place. This question allowed these people and others who have seen current attempts at full vehicle integration models to rate the fidelity of these models. The below moderate fidelity noted by both sets of experts shows the current state of full vehicle, integrated models, which are most likely used in a very simplistic form.

Though some respondents, based on their comments, undoubtedly see little merit to full vehicle models, the potential for these models has not yet been tapped. Some manufacturers are working on this issue because the ability to measure and predict the interactions of a number of large systems can bring valuable information that will improve the performance of the vehicle as a whole. Ultimately, the model is expected to help engineers create optimized designs quickly. To do this, the model probably does not need to be perfect, just good enough. There is generally a balance between simplicity and complexity, but this balance may be different for different vehicle systems as well as for different engineering organizations.

INT-7. How well configured and integrated are current simulation codes to allow for useful design work, and how well configured and integrated will they be in 2001 and 2006?

Scale 1 = Very well 3 = Sufficiently 5 = Insufficiently

Configuration and Integration of Simulation Codes	Mean Rating		
	Current (1996)	2001	2006
Dynamics	4.1	3.3	2.6
Structures	4.0	3.0	2.2

Selected edited comments

Round 1 Vehicle Dynamics

- This progress will depend on the development of IPPD.

Round 1 Vehicle Structure

- By 2006, "1" is our goal.

Summary

Both Structures and Dynamics experts responded to this question and both think the current simulation codes are not sufficiently configured and integrated to allow for useful design work. However, they believe that codes will be sufficiently configured and integrated by 2001 and well configured and integrated by 2006. As is the case for a number of these integration questions, the Structures respondents are more optimistic than the Dynamics respondents.

Strategic considerations

The issue of having well configured and integrated codes to allow for useful design work can be looked at from the perspective of having models that give results that can then be used by designers to improve their designs, as well as having results from models that are delivered in a timely manner that will give designers time to use the results. The issue of timeliness of results of models has been mentioned a number of times in this report as one of the negatives of the current modeling being performed by the auto manufacturers. But the issue of the quality of results, in terms of having codes that fit well into the design framework, shows another area of concern for the interface between modelers and designers. As modelers take on larger roles within the design process, the demand for the skills needed to interface with designers, on both a software and personal side, will increase and may determine how successful the use of modeling will be in a company.

INT-8. **How well do current simulation codes handle multiphysics problems (for example combination fluid dynamics, structural dynamics, and heat transfer problems), and how well will they handle these type of problems by 2001 and 2006?**

Scale: 1 = Very well 3 = Sufficiently 5 = Insufficiently

The Ability of Simulation Codes to Handle Multiphysics Problems	Mean Rating		
	Current (1996)	2001	2006
Dynamics	4.4	3.9	3.0
Structures	4.5	3.5	2.4

Selected edited comments

Round 1 Vehicle Dynamics

- Once again, modeling advances are key.
- We came to see the simulation codes which can handle multiphysics problems in this several years. They need a large computer resource, so it takes long time to be able to use it daily.
- It depends on the model.

Round 2 Vehicle Dynamics

- I have some concern about multiphysics problem code. It needs a large computer resource, so I think it will be not realistic within 10 years.
- The bond graph methodology is very useful in dealing with multiphysics problems.

Round 1 Vehicle Structure

- Progress will depend on the perception of need at the software development level. At present, we write custom codes for these problems.
- We're currently making great strides in these areas (e.g., heat transfer, acoustics), but wide acceptance will probably be up to individual companies' business practices.

Summary

The issue of simulation codes that handle multiphysics problems was asked only of Structures and Dynamics experts. The experts think that while simulation codes do not handle multiphysics problems well at all at present, nor will they in 2001, they will improve and sufficiently handle them by 2006.

Strategic considerations

Multiphysics problems within the modeling and simulation context are some of the most complex and challenging issues facing complete system integration. The respondents' prediction of having codes that sufficiently handle multiphysics problems (but not handle them very well) by 2006 shows the lack of confidence they have in being able to overcome this challenge. There is no doubt a lack of computing power in solving these types of problems, but when a lack of computing power combines with problems of defining the basic processes involved in a system, experts realize it will take a much longer time before these type of problems will be solved within a system level analysis.

INT-9. Flexibility of the ARC integration shell is important to ensure its usage without major modifications to the user's existing databases and component models. Is this increased flexibility in the short term (1996-2001) likely to lead to decreased efficiency of the integration effort? Is it likely to lead to decreased efficiency in the long term?

Scale: 1 = Very likely 3 = Somewhat likely 5 = Not likely at all

Decreased Efficiency of Integration Due to the Need for Flexibility of ARC Shell	Mean Rating	
	Short Term (1996-2001)	**Long Term (2002-2006)**
Dynamics	3.1	3.1
Structures	2.8	3.1

Selected edited comments

Round 1 Vehicle Dynamics

- Maybe.
- Efficiency is likely to be achieved due to domain/application/company specific integration, rather than due to a general purpose integration shell.

Round 1 Vehicle Structure

- If it is less efficient, then unless some overall efficiencies are identified it won't be used.
- The question may be, "is it worth it?"
- I think what is important is the necessity of its technology.
- If we can address major structural requirements in ARC integration shell simultaneously which will allow optimization, layout and other architectural changes (macro-level) before a "go for one" type of decision, it will give a big boost to the auto industry.

Summary

Both the Structures and Dynamics experts who responded to this question think that the necessity of making the ARC shell flexible will make it somewhat likely that it will decrease its efficiency as an integration tool in both the short and long term.

Strategic considerations

Though all respondents were sent a brochure detailing the proposed effort by ARC to develop a flexible shell to be used as a tool by industry to develop complete integrated system models, a number of respondents were not aware of what the effort was about and therefore didn't respond to the question. Some who did respond see the challenge of a shell for integrated system models as a daunting task and question the value of it. Others see the shell as a potential aid to industry if it can be adapted to company specific codes or if it can help sort out the larger issues of integrating complex submodels. If the ARC shell is to find strong support within industry, ARC must make the effort more visible, either through public relations or through continuing demonstration projects that show the value and progress made by ARC toward reaching its goal.

INT-10. How willing will your organization be to adapt any legacy codes you might have to an integrated shell concept?

Scale 1 = Very willing 3 = Somewhat willing 5 = Not willing at all

Willingness to Adapt Legacy Codes to an Integrated Shell Concept	Mean Rating	
	Dynamics	Structures
Adaptation to Integrated Shell	2.7	2.6

Selected edited comments

Round 1 Vehicle Dynamics

- Integrated shell in-house is currently happening.
- This is the best way to enhance capability especially in the short term, but will not necessarily optimize efficiency.

Round 1 Vehicle Structure

- It will be willing, if the cost is low.
- Very few [legacy codes] are left anyway.

Summary

The Structures and Dynamics experts who were asked this question both see a willingness tempered with a small amount of caution to adapt their internal legacy codes to an integrated shell concept.

Strategic considerations

A willingness to cooperate with ARC in its integrated shell is a very good sign for the program. Of course, the shell must be seen as having value to the companies. The biggest challenge for the ARC shell will be the need for it to be adaptable to the various in-house information and modeling technologies that the manufacturers are developing to integrate their product development, design, and manufacturing groups. These in-house programs also extend down through the supply chain where suppliers send and receive information about part design, orders, and deliveries. Almost all the manufacturers are committed to particular programs to deliver this seamless interface between internal functional departments and their suppliers. But though the software has been chosen, implementation is still in progress, and the ARC shell has an opportunity to provide a valuable part within the modeling and simulation area that needs a program that will be able to integrate full system models as they become available.

INT-11. **What major changes do you foresee in the methods (software or hardware) you use to visualize and interpret your output data over the next decade?**

Changes in Methods to Visualize and Interpret Data Over the Next Decade	Percentage of Responses
Integration of results from all models and formats including CAD (computer-aided design) /CAM (computer-aided manufacturing) /CAE (computer-aided engineering) /CIM	20%
Improved speed / animation speed	15%
Virtual reality	12%
More user-friendly graphics	7%
Fidelity of display	7%
Rapid 3-D visualization environment	7%
More realistic models / visualization	4%
Graphics animation	4%
Models that design and reduce the need for visualization	3%
Parallel processing	3%
Common graphical environment	3%
Simplification of graphics	3%
More sophisticated data analysis	3%
Data more readily available	3%
Better cross-platform analysis packages	3%
Graphical preprocessors for building models	3%

Selected edited comments

Round 1 Vehicle Dynamics

- Visualization is very important and will be developed much more over the next decade.

Round 1 Vehicle Structure

- I hope we see less visualization and more automated ways (sensitivities, neural nets, formal approximations) to interpret data. History, however, doesn't support this.

Summary

The Dynamics and Structures panelists who answered this question offered a panoply of methods to visualize and interpret data over the next decade. The areas most often mentioned include the easy integration of all models and formats including CAD/CAM/CAE/CIM; increased speed in terms of response from model building and increased animation speed; and the use of virtual reality to visualize and interpret data.

Strategic considerations

Visualizing and interpreting data based on modeling and simulation of integrated models is considered by many to be a very important part of the modeling process. The results of this question show the need for a program that will provide the graphical interface to the results being generated by modeling and simulation programs now and in the future. The most frequently noted responses show where most people see potential help, but some of the lesser noted responses also offer some very good ideas. In particular, using graphical preprocessors for building models, parallel processing, and models that design and reduce the need for visualization all offer very good ways of looking at visualizing and interpreting data over the next decade. The last suggestion is particularly intriguing because if designers can receive the information they need for design without the need for visualization, they will save an enormous amount of time and money currently spent trying to develop visual displays of the results of models.

INT-12. How well do you feel present design and analysis codes currently integrate the different levels of model description across the entire design process, and how well do you feel they will be integrated in 2001 and 2006?

Scale: 1 = Very well 3 = Somewhat 5 = Not at all

Integration of Models Across the Entire Design Process	Mean Rating		
	Current (1996)	2001	2006
Dynamics	4.0	3.2	2.6
Structures	4.3	3.2	2.1

Selected edited comments

Round 1 Vehicle Dynamics

- Room for improvement.
- It is completely unrealistic to think of modeling phenomena of totally different dynamics within the same environment.
- I do not see much work in handling models with differing levels of obstruction in a unified way.

Round 2 Vehicle Dynamics

- I think present code is insufficient and there is room for improvement. But I do not feel the necessity for such code and analysis anyway.

Round 3 Vehicle Dynamics

- Recently, such codes (structure, fluid, etc.) have begun to be used, but they need very large computer resources and are still in the development stage. I think it may be difficult to use them in the short term.

Round 1 Vehicle Structure

- This will not happen without a major shift in thinking away from looking at increasing accuracy of the next detailed analysis methods.
- This is a big challenge: It is not a problem a lot of people can get excited about, from a theoretical standpoint, as it is more of a legacy, data handling, and user interface problem.

Summary

The Dynamics and Structures respondents who answered this question think present design and analysis codes currently poorly integrate the different levels of model descriptions across the design process. They see improvement by 2001 where codes will integrate different levels of model description somewhat, and by 2006 they think the codes will integrate the different levels of model description well.

Strategic considerations

As the questions within this integration section have shown, there are a number of complex, thorny issues that face programmers and designers in their attempts to develop full system, integrated models, and the experts who responded to this survey agree there is much work needed over the next ten years to reach the goals they have set for themselves. The issue of integrating different levels of model description also falls within the category of "areas that need work." This particular area is seen as a "show stopper" for some experts because of the complexity of modeling such different phenomena within the same context, while others see it as just another hurdle to get over.

These complex issues bring to the fore a number of comments that have noted that there is little interest in solving some of these issues. A number of experts seem to think that if a company dedicated itself to solving all of these complex issues, it would never be able to design any vehicles. They recognize and understand the weaknesses of their system and set priorities to deal with complex issues they feel will be worth the investment in the long term, while at the same time using what is currently available to solve what can be solved and build the best vehicles they can.

The disconnect between the modeling and simulation engineers and the product designers comes from the need for modeling and simulation to constantly justify its existence by showing the value of working on complex, long term solutions to what some might label "esoteric" problems that will not add value relative to the commensurate time and money needed to solve them. In order for modeling and simulation to prosper within such a competitive environment, it must have a long-term plan that shows what has been gained from past long-term research, as well as what will be gained based on the current long term research plan. This is an example of the kind of cost/value time tradeoff that is evident throughout the industry today.

INT-13. How well integrated are suppliers who play a role in the design process into your information resources, such that the design process is more effective and efficient? How well will they be integrated by 2001 and 2006?

Scale: 1 = Very well integrated 3 = Sufficiently integrated 5 = Insufficiently integrated

Integration of Models Across the Entire Design Process	Mean Rating		
	Current (1996)	2001	2006
Dynamics	4.1	3.3	2.7
Structures	4.6	3.3	2.5

Selected edited comments

Round 1 Vehicle Dynamics

- Secrets/sharing of proprietary codes is a big issue.
- The tire suppliers are the best, but cost reductions reduce the workforce and therefore the number of modelers.

Round 2 Vehicle Dynamics

- Some are better than others.
- How willing are the players to share resources?

Round 1 Vehicle Structure

- Suppliers will be integrated better and better with better simulation of system loads and boundary conditions and better electronic exchange of information.

Summary

Currently, our Dynamics and Structures panelists see a very low level of integration between the manufacturers and suppliers. They think suppliers will be approaching a sufficient level of integration by 2001, and they think suppliers will be reach a level of integration slightly above sufficient by 2006.

Strategic considerations

This section of the report has focused mostly on the integration of submodels into full system level analyses within the design process. However, this question broaches an issue that is in the process of being addressed as I write this sentence: the expectation of the manufacturer that suppliers in the future will be more responsible for the design of the part or system they deliver. As the manufacturers continue to outsource more to their suppliers, part of that arrangement may mean suppliers may need access to the modeling resources the manufacturers have traditionally maintained, or they may have to develop those resources themselves.

The role of modeling and simulation in design is a critical factor in the growing concerns with supply chain management. As the manufacturers improve their ability to use math-based engineering in their design process, some of the time bottlenecks that have been housed within the manufacturer's domain could shift to the supply base. This will dramatically increase the urgency of suppliers to quickly enhance their modeling and simulation capabilities, which could prove to be very difficult for many suppliers.

There is another possible disconnect between the manufacturer and supplier in terms of the responsibility for modeling and simulation, because the supplier, for the most part, is concerned with a subsystem or single part, not the complete vehicle. Will the manufacturer continue to model parts or systems that are being completely outsourced to suppliers? Will manufacturers and suppliers create a free flow of modeling data and results that will be shared between the companies? Will the manufacturers have access to supplier modeling data that they will include in their full vehicle, integration models? Will the manufacturers have to create shadow modelers to represent what the suppliers may or may not be doing in order to have data to feed into their integration models? As these questions indicate, modeling and simulation represents a particularly challenging issue in this move to outsource more parts and systems to suppliers. But one answer that may prove worthwhile pursuing is the ARC shell that could be shared between manufacturers and suppliers and offer a common platform for analyzing integrated models. Also, as has been stated before, the issue of a modeling and simulation consortia similar to the ones now operating under USCAR (United States Council for Automotive Research) may offer the industry, including suppliers, an opportunity to work in precompetitive areas within modeling and simulation that may head off some of the possible disconnects between the manufacturers and suppliers in the area of modeling and simulation.

KEY WORD INDEX

Key Words	Question Number			
	Engines (ENG)	Vehicle Dynamics (DYN)	Vehicle Structures (STR)	Vehicle Integration (INT)
Complexity - model	1,3-6,9-10,14a, 16-17,19-20,26b, 28	3-7a,12,14,16-17, 19-22,26,27	3,4,8,12-13,18,20	2-3,6,12
Component mode synthesis	-	-	8	-
Component thermo loads	4	-	-	-
Compression ignition engines	27	-	-	-
Compression ratio	21	-	-	-
Computer / supercomputer / Computing power / CPU (Central Processing Unit)	1,3,5a,6,10, 14a-18,21,25, 26b,27-28	1,4,6,14-16, 17-18,21-22, 25-27	8,11-14, 17-22, 24-25,27,29-30	1-2,5-6,8,11-12
Condensation	14a	-	-	-
Connection models	-	-	17,19	-
Continuous mass nonlinear finite element analysis	-	-	14	-
Coolant flow	23	-	-	-
Cooling requirements	4	-	-	-
Cost / cost savings	2-4,6-8,10, 14a-15,24	3-4,6,9,13-14, 22-23,27	2-4,10,12,14,17, 21	1,2,10,12-13
Crash models / simulation	-	1,20	9-10,15,20-24, 27-30	-
Cycle-to-cycle variation	11,14a,18,21	-	-	-
Cylinder and valve geometry	6,12-12a, 14-14a,17-19, 25-26b,28,	-	-	-
Damping	12a	-	17,19,23,28,30	-
Database / Information	3,11,14a,26b,28	6,7a,14	11-12,18,25-26, 30	1,6,9-11,13
Design efficiency	2-3	2,4	2,4,28	1
Design of Experiments (DOE)	-	24	7	-
Design process	2,4,5a-6,13,15, 17	1,4-6,15-16,18, 21,27	8,24-25,29,30	7,12-13
Design quality (quality of design)	-	-	(21)	-
Design tools	24-25	-	29	-
Design fidelity simulation	-	17	-	1
Development / cycle time / development cycles / design cycle	2-3,7-8	3,6,18,21-22	2-3,9-11,17-18, 20-23,25-27, 29-30	1,3,7-8,10,12
Diesel engines	12-12a,14a, 19-20,27	-	-	-

Key Words	Question Number			
	Engines (ENG)	Vehicle Dynamics (DYN)	Vehicle Structures (STR)	Vehicle Integration (INT)
Digital physics	27	-	-	-
Direct injection / Direct injection engines	12a	-	-	-
Driver-in-the-loop	-	1,16-18,24	22,29	-
Dissipation model	12a	-		-
Durability	28	1,11a-12,20, 24-25,27	11,12,28	-
Dynamic models	12a-13	2,20,24-27	1-2,27	1
Dynamics of human body	-	-	-	19
Education / training / learning	2-3,28	3,18,22-23,26	3,25,30	-
EGR (Exhaust Gas Recirculation)	12a,21,27	-	-	-
Emissions	1-2,6,8,11,12a, 14a,16,18,20,21, 23,27-28	20	-	1,2
Engine model	1,6,7,8,9,10,11, 15,20,22, 24,26b	1-2,5	1-2,5	3-4
Ergonomics	-	27	-	-
Evaporation	12a,14a	-	-	-
Exhaust	6,12a,18,23,27	-	-	-
Experimental data	6,10-11,12a	-	12	1
Expert systems	5a,11,28	8	6	-
Fastening	-	-	28	-
Fatigue	-	18,20	11,12,23,27-28	-
FE (Finite Element) / FEA (Finite Element Analysis) / FEM (Finite Element Model)	6,11,27	15,21,25-26	5,13-15,18-19, 22,24,27-28,30	5
Fidelity	-	1,24-25	27,30	1,3,6
Flame initiation	14a	-	-	-
Flame propagation	12a,14a	-	-	-
Flexible components	6,12a,27,	3,14,24,27	12-13,27	9
Flexible grid techniques	-	-	-	-
Flow rates	12-12a,14-14a, 17	-	-	-
Friction	4-6,10-12a,13, 14a,16,19	11-11a,24-25,27	17,19	-
Fuel consumption analysis	1,19	-	-	2
Fuel distribution	12a	-	-	-
Fuel economy	6,8,12a	-	-	1,3
Fuel injection modeling	27	-	-	-

Key Words	Question Number			
	Engines (ENG)	Vehicle Dynamics (DYN)	Vehicle Structures (STR)	Vehicle Integration (INT)
Fuel spray	27-28	-	-	-
Fuel flow	-	-	-	-
Full vehicle model / integrated vehicle model / full vehicle integration	-	6,17,20,23		2,6
Gas dynamic flow model	-	-	-	-
Generic engine	9,22	-	-	-
Graphics	27		30	11
Grid / mesh generation	12a,14a,25-28	-	-	-
Ground / tire interactions	-	11-11a	-	-
Guyan analysis	-	-	8	-
Handling	14a	1,11-11a,15, 17-18,24-25,27	27-28	12
Heat rejection models	23	-	-	-
Heat transfer	6,11-12a,14-14a, 23,26,27-28	-	-	4,5,8
Hierarchical modeling	-	25,27	-	-
Higher frequency vibrations	-	19	-	-
Horsepower analysis	-	-	-	-
Human factors	-	24,25	27,30	-
Hybrid modeling	6,10	6,12	-	-
Hydrocarbons	12a,20	-	-	3
Inertia	-	-	-	4
Intake flow	1	-	-	-
Integrated vehicle model	-	23	-	2
Integration	1,27-28	1-2,6,11a,14,23, 26,27	2,26,28,30	1-3,5-9,11-13
Knock modeling	21,27	-	-	-
Legacy codes	-	-	-	10
Limit analysis	-	-	-	1
Load analysis	-	24	-	-
Load path to the driver and passengers	-	10	-	-
Lubrication	4,12a	-	-	-
Manufacturing	3,6,28	3-4,21,24,27	3-4,9,30	10-11
Materials	6,12a,14a,28	4,24	4,11,13,17,19-20, 27,30	-
Mechanical Loads / Stresses	4	-	-	-

Key Words	Question Number			
	Engines (ENG)	Vehicle Dynamics (DYN)	Vehicle Structures (STR)	Vehicle Integration (INT)
Mixing (Diesel)	13	-	-	-
Mixing (Spark Ignition)	13	-	-	-
Modal analysis	-	-	8	-
Model library	-	-	19	-
Modeling expertise	5	5	5	-
Mufflers	12a	-	-	-
Multicylinder models	18	-	-	-
Multiphysics problems	-	27	-	8
Neural networks	5a	8	6	-
NOx	5a,20,26	-	-	-
Nonlinear models	-	11-11a,15,24-25, 27	8,14-15,17,19,23, 27-28,30	-
NVH (Noise, Vibration, and Harshness)	4,12,12a,14a,28	2,11a,17,19,24, 27	10,17,28	2
Object-oriented software	28	-	-	-
Off-road behavior methods	-	11,11a	-	-
Operating conditions	26b	-	27	-
Optimization	11,27,28	6,9,24-25,27	17,27,30	3,9
Order reduction methods	-	-	8	-
P-element	27	25	-	-
Parallel programming / computing	17,27	-	25,30	-
Particulates	20,26	-	-	-
Performance estimation	4	-	4,7,11,28,30	-
Phenomenological model	6,12-16,18-19, 22,26,26a,26b	-	-	5
Pollutant formation	22	-	-	-
Powertrain model	27-28	-	23-24	1-2,4-5
Prototype	6-8,10	2-4,9,13,18-19,21	9-10,21-23	1
Real-time models / simulations	-	1,16-18,24-25	22	-
Redesigned engine	8,13,15	-	-	-
Ride quality	-	11-11a,17-19	-	-
RSM (Response Surface Model)	26b	-	6	-
Safety	-	3,14,18,20,24	3-4,23,27,30	
Shock absorbers	-	2,15,20,25,27	-	-
Sound	-	18,20	27	-
Spark advance	21	-	-	-
Spark ignition	1,12,12a,13, 14,20,24,27	-	-	-

Key Words	Question Number			
	Engines (ENG)	Vehicle Dynamics (DYN)	Vehicle Structures (STR)	Vehicle Integration (INT)
Spray dynamics / formation	1,12a,28	-	-	-
Statistical data	10	-	-	-
Statistical Energy Analysis (SEA)	-	-	17,28	-
Steady-state models	15,16,17,23	-	-	3,4
Structure(s) / structural Models	-	1-5,9,15,24	1-6,9-10,27-29	1-2,8-9
Submodel(s)	4,6,12-13, 14-14a,17	17,27	-	3,5,9,13
Subsystem	10	6,25	-	1-3,13
Suppliers	8	16,20,24-25,27	11,18-19,23, 27-28	10,13
Suspension	-	12,21,24-25,27	27	-
Swirl	12a,26	-	-	-
Testing	3,7,10,11,16	1-4,7a,8-10,12, 15,19-23,27	2-4,7,10-11,15, 18,20-23,25, 27-28,30	1,3,13
Temperature	6,12a,14a,17, 23,	25,27	-	3,5
Thermodynamic properties	12-12a,14-14a	-	-	-
Timeliness in design process	10	21	24-25,29-30	5,7
Tire models	-	11-11a,20,24-27	-	-
Tracked vehicles	-	13	-	-
Transient models	15-17	18	20,23	1,3-4
Transmissions	27	-	-	1,3-4
Tumble	12a,26	-	-	-
Turbulence	11-14a,26-27	-	-	-
Uncertainties	-	7,18	7,13,23	-
Validation	7,11,12a,13, 14a,18	7,9-10,15-16, 21,25	10-11,14,18-19, 22,25,28	1
Vehicle load model	12a	-	-	-
Vibration (mid- and high-frequency)	12a	11a,19-20,22, 24-25,27	7,12,16,28	2
Virtual reality	27,28	16,18	-	11
Visualization	-	-	-	11
Wall layer reduction	26b	-	-	-
Wall wetting	12a,14a,28	-	-	-
Weight reduction	-	24	4,27	-
White Smoke	20	-	-	-
Zero-dimensional phenomenological model	22	-	-	1

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