Digital Testing in the Context of Digital Engineering

"Functional Virtual Prototyping"

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Abstract

As product complexity increases and competitive product development cycle times are reduced, hardware prototype creation and testing become major bottlenecks to successful new product launches. Due to these bottlenecks, leading global manufacturers are feeling increasing pressure to rapidly institute enterprise-wide, simulation-based design and virtual prototyping practices that can insure greater product performance and quality in a fraction of both the time and cost required with traditional build-and-test approaches. How can companies make this transition and develop confidence in virtual prototype modeling and simulation? This paper outlines the requirements for successful virtual prototyping implementations and discusses the industry trends supporting such a shift.

Figure 1. Digital Testing (Functional Virtual Prototyping)

Introduction

The current BMW 3-series sedan came to market amidst a flurry of accolades and awards. "Perfection down to the last detail" was an overriding philosophy throughout the design process used to create this latest version of "the Ultimate Driving Machine." According to BMW Magazine [1], the development process involved five and a half years, 2.6 million man-hours, 130 hand-made system-level hardware prototypes created at a cost of roughly $350,000 per vehicle, and some 2,400 new components. Anti-lock braking systems, traction-control, advanced multi-link suspension systems, state-of-the art safety systems, and a chassis/powertrain combination that operates in perfect unison are just a few of the complex engineering characteristics of this stellar vehicle.

Based on the rate of change in the automotive industry, it is safe to say that the remarkable standard of excellence set by this BMW 3-series vehicle will be surpassed by many new vehicles in a few short years to come. New vehicles will incorporate more advanced technology so that they ride smoother, react faster, have more pleasing sound qualities, last longer, require less maintenance, protect occupants better, and deliver more value to the customer. Moreover, these new vehicles will be developed in roughly half of the development time of the current 3-series. The cost of producing a system-level hardware prototype will probably not substantially change, but the overall development cost for these new vehicles are projected to plummet along with the development time. How can this be? What will facilitate this remarkable advancement? The answer is Virtual Prototyping.

Simulation-based design practices allow product designers, engineers, and analysts to more quickly assess *form, fit, function*, and *manufacturability* of new products throughout concept design, concept refinement, detailed design, release, and production. No longer is it necessary to wait months to build a hardware prototype, instrument it, run tests on it, and make a small number of expensive modifications to it in order to assess proposed design changes. Instead, participants in the design process are able to construct accurate virtual prototypes in less than a week, exercise the models through hundreds of tests with thousands of variations, and optimize the form, fit, function, and manufacturing characteristics in a fraction of the cost of traditional hardware prototype processes.

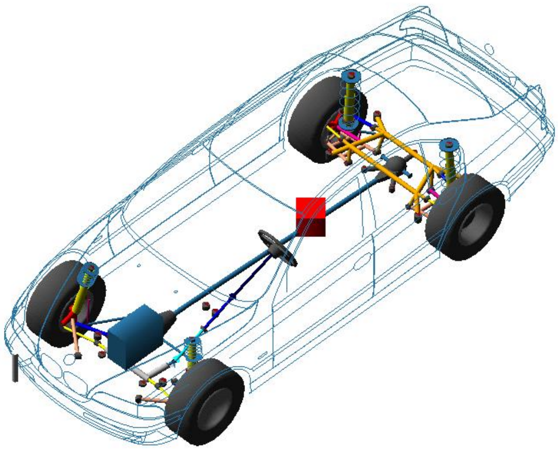


Figure 2. Virtual Prototype of a BMW Sedan

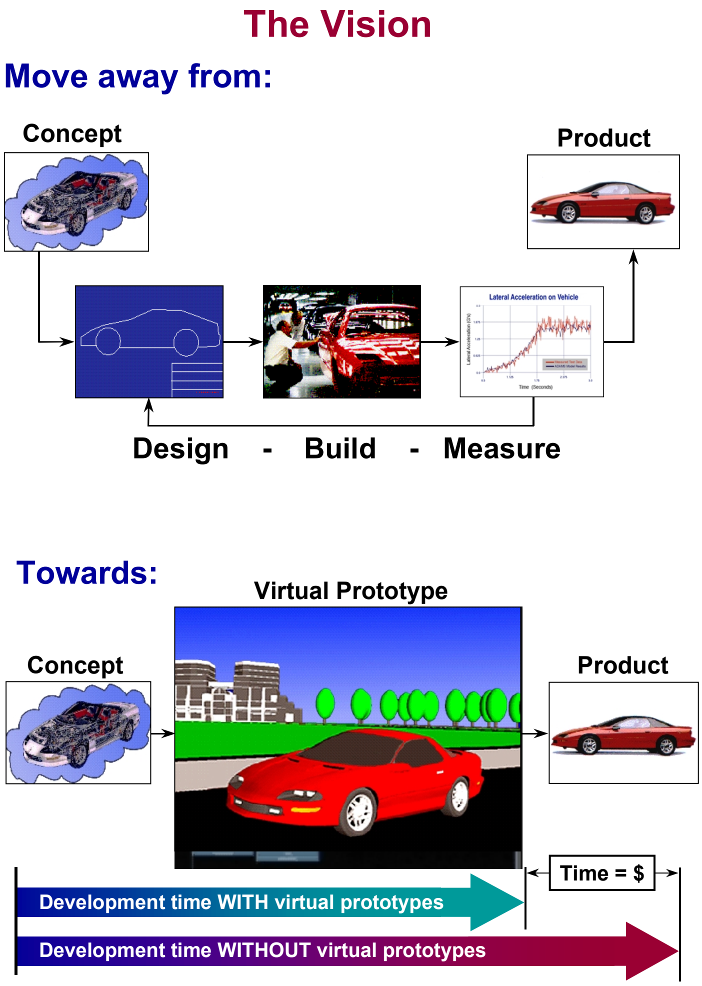


Figure 3. Moving from Physical to Virtual Prototyping

What is required to implement a successful virtual prototyping process? Why hasn't this been done previously? What industry trends are enabling such a transition? What are potential pitfalls and limiting factors? What are the critical success-factors for a truly effective virtual prototyping system? The purpose of this paper is to address precisely these questions and to stimulate action.

Traditional CAD/CAM/CAE vs. System-level Virtual Prototyping

Traditional CAD/CAM/CAE practices throughout the 1970's and 1980's focused on a concept referred to as "art-to-part." Nearly all engineering software activity was oriented toward the design, development, and manufacturing of higher quality parts. Detailed, three-dimensional solid modelers (CAD) allowed for quick part design and understanding of "form." Finite element software (CAE) made it feasible to perform detailed meshing and analysis of structural effects, thermal effects, and vibratory characteristics, or "function," of individual parts. Software aimed at improving "manufacturability" of parts (CAM) provided better control of machine tools, robots, mold procedures, stamping procedures, forging processes, etc.

These traditional CAD/CAM/CAE tools and processes were embraced and implemented throughout major industries, including the automotive, aerospace, general machinery, and electromechanical markets. For the most part, they lived up to their promise of dramatically improving part design. In the automotive industry, for example, automotive suppliers reported a 40% reduction in part defects over a recent five-year period. This significant improvement was accompanied by a corresponding drop in development and manufacturing costs attained through successful implementation of better CAD/CAM/CAE tools and processes.

Unfortunately, during the same five-year period that automotive part suppliers were achieving a 40% reduction in part defects, the vehicle manufacturers (OEMs) who were using these parts to assemble and market full vehicles experienced only a 20% reduction in warranty costs. In some sense, this was a surprise to many OEMs who expected a one-to-one correspondence between part defects and warranty costs. In retrospect, it seems perfectly sensible. ***Optimal part design rarely leads to optimal system design.*** For example, when perfectly good brakes are combined with a perfectly good suspension system and a fine chassis, the resulting combination often performs in a less-than-stellar manner. Clearly, the interaction of *form, fit, function*, and *assembly* of all parts in a product is a major contributor to overall product quality. We may be reaching levels of diminishing return in applying CAD/CAM/CAE technologies to part design. ***The big opportunity to increase quality and reduce time and cost has now shifted to the system level.***

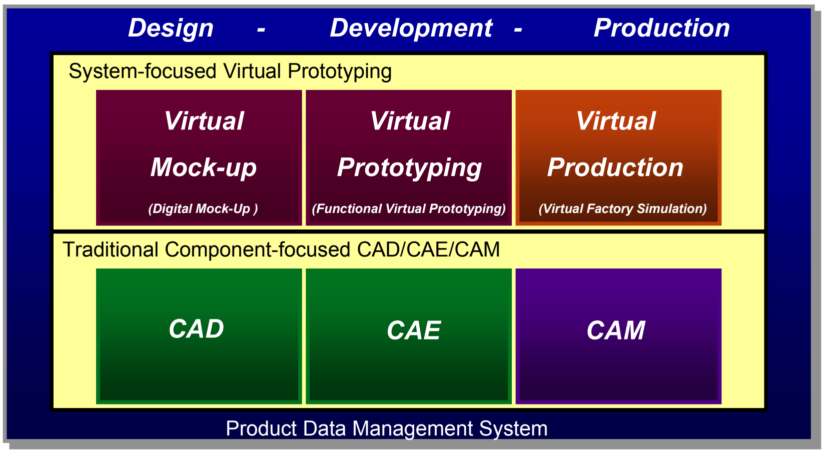


Figure 4. Component- and System-Focused CAD/CAM/CAE

More significant returns on investment can be realized today through the effective use of simulation-based design processes and ***virtual prototyping applied to system-level design***. Manufacturers now need a means to quickly assess *form* and *fit* of entire assemblies of three-dimensional solid models comprising a product (Digital Mock-Up). They need to be able to assess the operating *function* of the entire assembled product (Functional Virtual Prototyping), not just the component parts. And they need to investigate the entire *manufacturing* and *assembly* of the product (Virtual Factory Simulation), not just the creation of the parts. As global product manufacturers began to realize this fact over the last 2-5 years, it was natural for them to look for extensions to their traditional CAD/CAM/CAE systems to address system-level design. Part-focused CAD/CAM/CAE providers hurried to extend their software to address system-level designs with varying levels of success. But simple extensions of part design paradigms to system-level design often lead to impractical software products. For instance, as manufacturers tried to construct large assemblies of solid models to facilitate system-level interference detection and virtual fly-through, the rendering performance of most traditional CAD/CAM/CAE systems became unacceptably slow (e.g., measured in hours). Similarly, manufacturers investigating system level operating performance attempted to combine all of their component finite element models and perform nonlinear finite element system simulations. These typically took Cray-weeks of simulation time to predict only seconds of real operating performance, thus making design trade-off investigations impractical. Similar problems occurred in manufacturing and assembly.

New methodologies, specifically oriented toward rapid system-level design, had to be adopted. The growth in simulation-based design tools has now shifted away from traditional CAD/CAM/CAE software and toward these newer system-focused solutions. Specifically, these system-level solutions include Digital Mock-Up tools to investigate product *form and fit*, Functional Virtual Prototyping tools to assess product function and operating performance, and Virtual Factory Simulation to assess *manufacturability* and *assembly* of the product.

Enterprise-wide, Product Data Management (PDM) is the "glue" that enables these system-focused solutions to be successful by making all of the up-to-date component data readily available and manageable.

Digital Mock-Up (DMU) solutions that make efficient use of tessellated three-dimensional component solid models were pioneered by Tecoplan, Engineering Animation, Clarus, and Division among others. These allow efficient design collaboration, mark-up, fly-through, and interference/collision detection. Integrated with Product Data Management Systems, these Digital Mock-Up products provide an excellent means to insure that all of the parts of the product will fit together properly and that the product will appear as specified.

Functional Virtual Prototyping solutions make efficient use of three-dimensional component solid models and modal representations of component finite element models to accurately predict the operating performance of the product in virtual lab tests and virtual field tests. Mechanical Dynamics pioneered this field with its ADAMS system simulation product line and is expanding its coverage through its partnership with MTS systems, nCode, and the solid modeling and finite element solution vendors.

Virtual Factory Simulation was pioneered by Tecnomatix and Deneb. With these solutions, the entire manufacturing and assembly of products can be simulated, and field maintenance of products can be assessed as well.

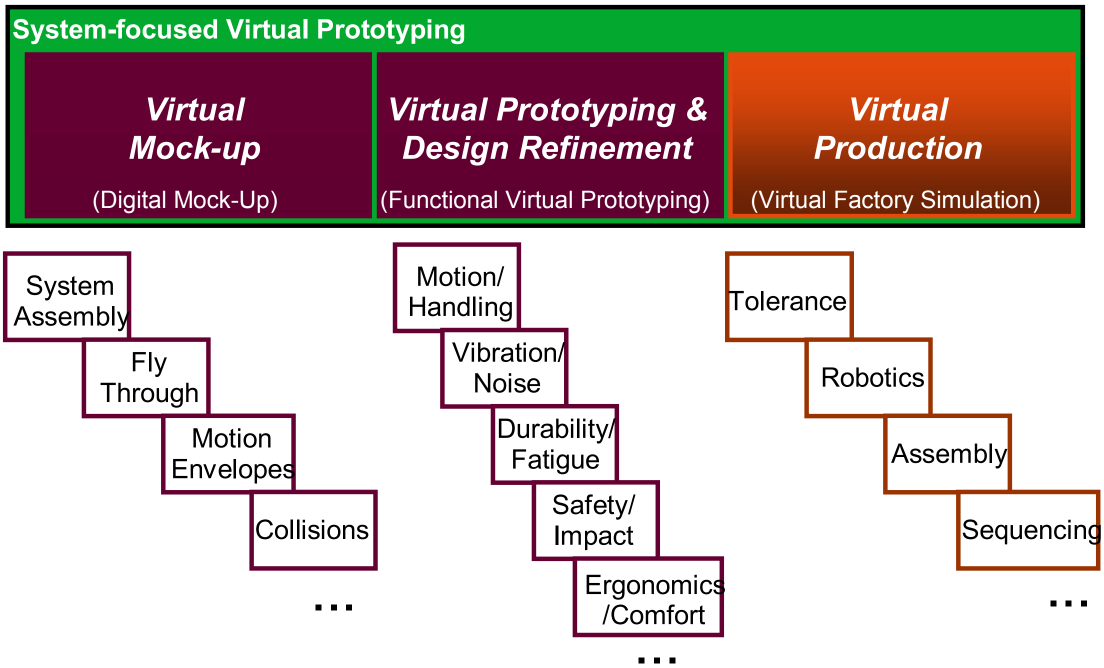


Figure 5. Technology Segments of System-Focused CAD/CAM/CAE

The combination of Digital Mock-up, Functional Virtual Prototyping, and Virtual Factory Simulation provide a means for realizing an effective transition from hardware prototyping practices to software prototyping practices with all of the concomitant benefits. The remainder of this paper will focus on the subject of Functional Virtual Prototyping and how it can be implemented.

Functional Virtual Prototyping

Effective Functional Virtual Prototyping (FVP) allows the full operation of the product to be considered and evaluated early enough in the design process to allow for ‘function” to truly drive “form” and “fit.” It also allows multi-function optimization to be realized, such that a true balance can be obtained between competing functional requirements involving performance, safety, durability, cost, comfort, etc. These two benefits were largely impractical in traditional development cycles involving extensive reliance on hardware prototypes. In addition to these benefits, functional virtual prototyping has proven effective in facilitating tighter and more successful relationships between manufacturers and their lead suppliers.

Deployment of Functional Virtual Prototyping typically involves five phases: *Build, Test, Validate, Refine*, and *Automate*.

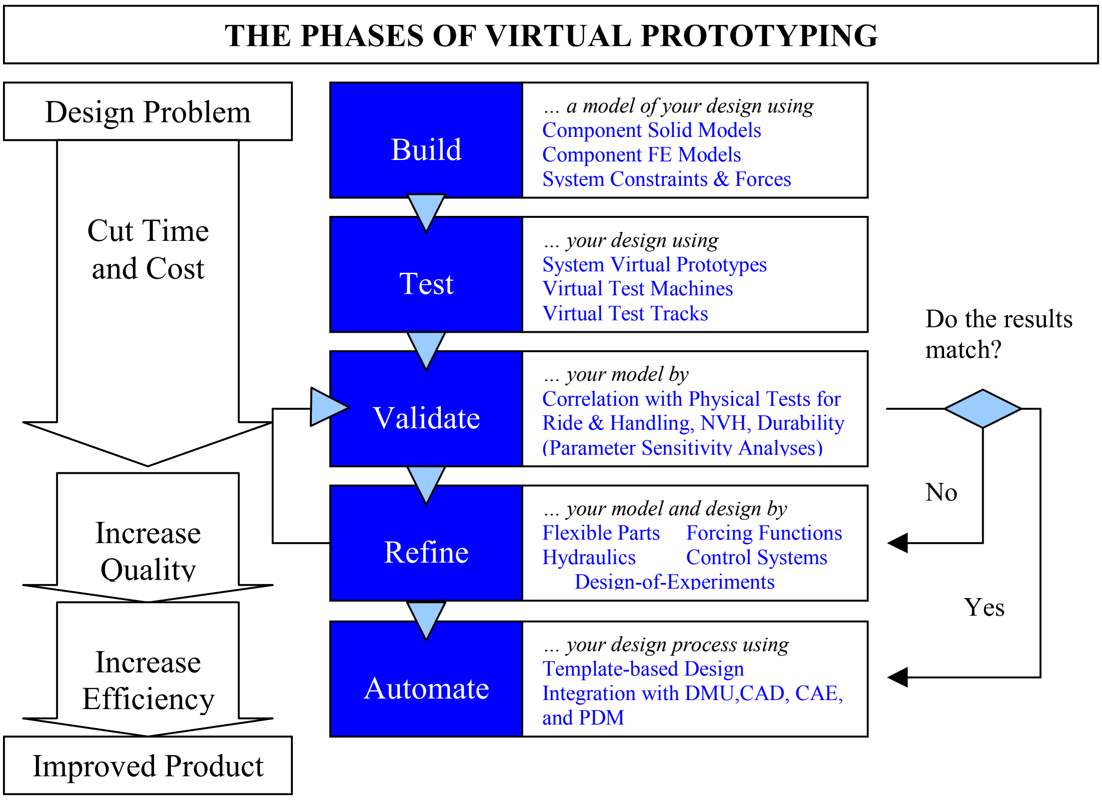


Figure 6. Functional Virtual Prototyping Process

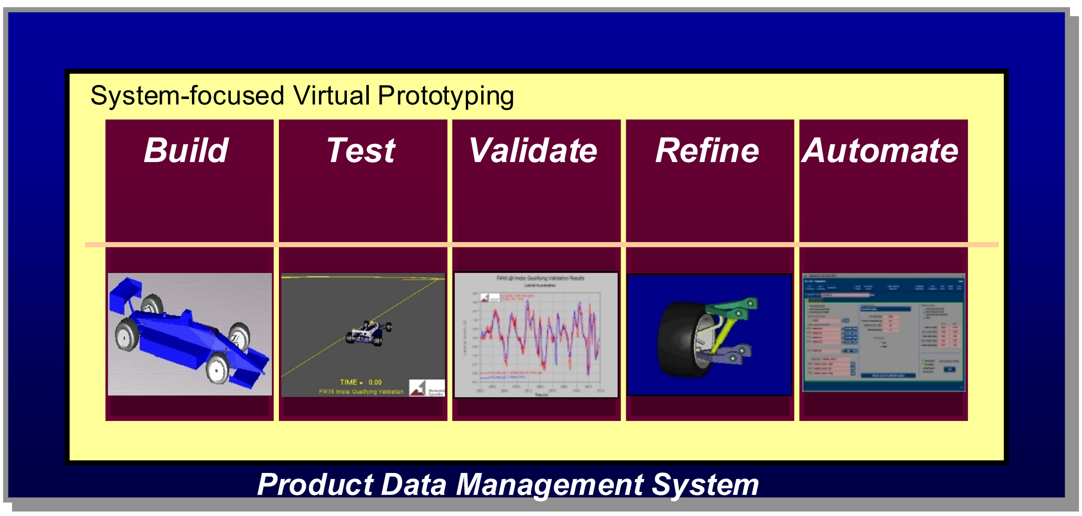


Figure 7. Illustrated Phases of Functional Virtual Prototyping

Build

During the *Build* phase, virtual prototypes are created of both the new product concept and any target products which may already exist in the market. In the early concept stage, the virtual prototype models of the new product concept are kept simple and are most often driven by desired functionality data curves, rather than by specific product topologies. Appropriate target setting is, of course, very important. The desired functionality data curves should be derived from a customer Quality Function Deployment (QFD) study that identifies the desired operating performance. For instance, in the initial design of a vehicle suspension system, the virtual prototype model often involves only the overall vehicle body and a set of vehicle suspension curves that relate the movement of the body to the movement of the wheels. These data curves embody the desired suspension characteristics. During later model refinement, specific suspension topologies are chosen (e.g., McPherson Strut) and the software optimizes suspension geometry and structural properties to yield the relationship described by the chosen curves. Similarly, to create models of target products, the actual target product is physically tested and its characteristics are accurately measured. This data is incorporated into a system-level model of the competitive vehicle to use later during the evaluation phases.

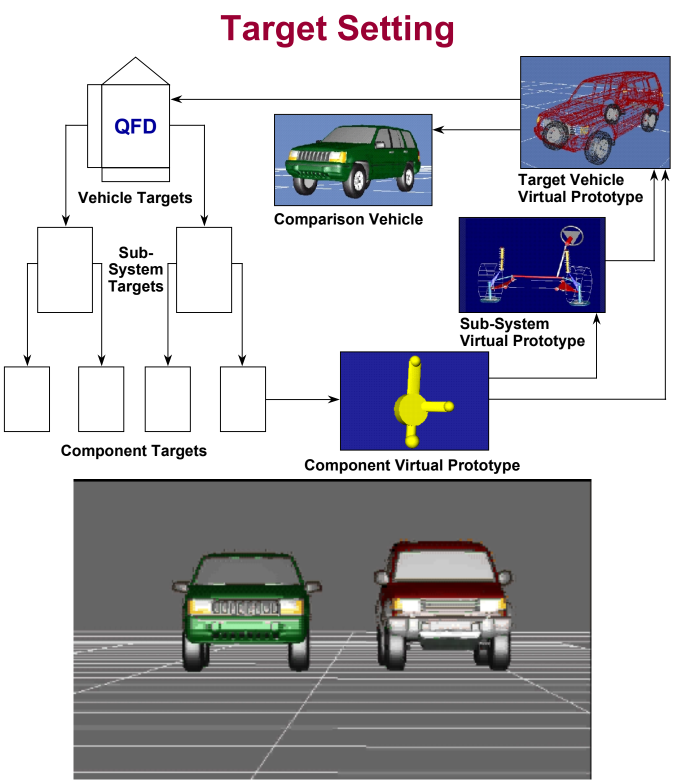


Figure 8. Target Setting via QFD and Comparison Vehicle

A modular system design process facilitates functional virtual prototyping and the manufacturer-supplier interaction. Clear inputs and outputs between various subsystems permit the development of multiple subsystem models with varying levels of model fidelity

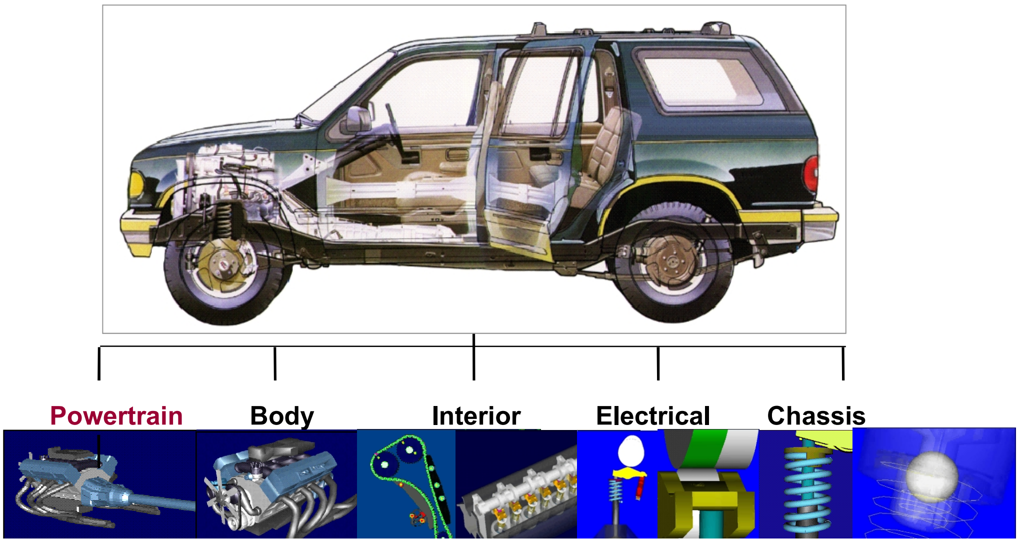


Figure 9. Modular System Design Facilitates OEM-Supplier Relationship

and complexity. These subsystem and system-level virtual prototypes are comprised of rigid and flexible representations of component parts connected through mathematically defined constraints. The geometry and mass properties for the parts are derived from component solid models; while the structural, thermal, and vibratory properties are derived from component finite element models or experimental tests. The most effective implementations of virtual prototyping begin in this Build phase with a close cooperation between engineering analysts and test engineers. Also, up-front planning of what product parameters may be varied in the design cycle, and how manufacturers and suppliers are going to share models, can be tremendously helpful.

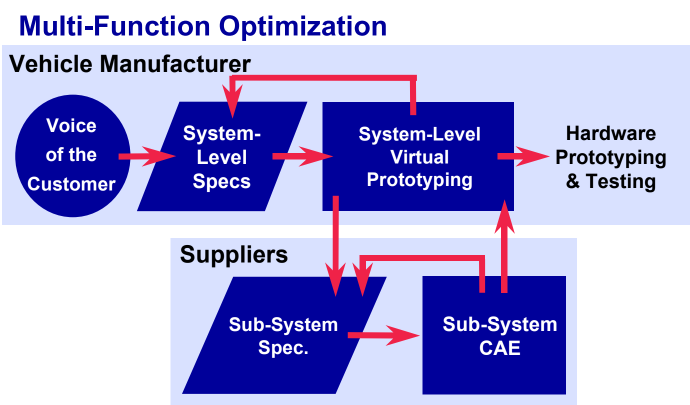


Figure 10. Virtual Prototyping Allows Multi-Function Optimization

Test

Perhaps the single most important axiom for successful functional virtual prototyping is to ***simulate as you test.*** Testing of hardware prototypes has traditionally involved both lab tests and field tests in various configurations. With virtual prototyping, we need to create virtual equivalents of the lab tests and the field tests. By doing this, we greatly facilitate model validation through testing, and we break down the cultural barriers to the adoption of virtual prototyping practices. With regard to lab tests, successful virtual prototyping dictates that we need to construct virtual test rigs that reproduce the test procedures and boundary conditions of the real fixture and machine. With field tests, we need to construct models that represent the actual operating conditions of the product in the field. This may involve virtual test tracks in automotive, virtual landing strips in aircraft simulation, etc.

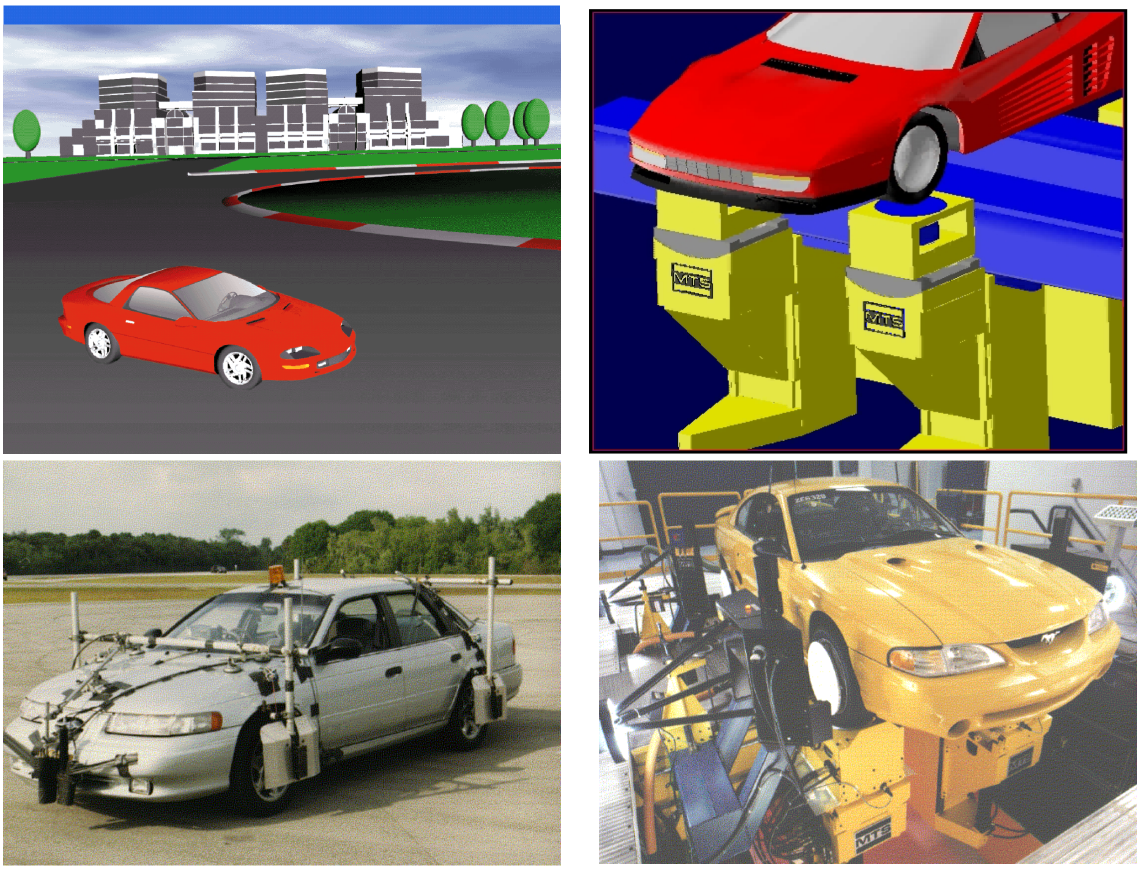


Figure 11. Field & Lab Testing: Virtual and Physical

Effective implementations of Functional Virtual Prototyping require a tight synergy between physical testing of hardware prototypes (components and systems) as well as simulation-based testing of virtual prototypes (components and systems). Testing requirements vary during the different stages of the design process. At the outset of a new product design based on virtual prototyping, hardware testing is instrumental in two ways. First, component tests are performed using various real component alternatives. These tests provide good characteristic data for a complete system-level virtual prototype model. Secondly, full system hardware tests are conducted using target products. This allows for the simultaneous development of virtual prototypes of competing products so that performance comparisons can be made throughout the design and development cycle.

Then, during concept design, virtual testing is used to exercise the new system model through a limited number of actual test scenarios such that performance data can be collected and validation can be performed. For companies that are initiating new virtual prototyping processes, it is imperative that they build a first system-level physical prototype at this stage in order to insure confidence in the simulation model. Companies who have been through this process a number of times have learned how to validate the modeling assumptions such that a physical prototype is unnecessary at this stage.

Once initial validation has been achieved by correlating the test results of the physical and virtual system prototypes, the true value of virtual prototyping begins to become apparent. Thousands of system variations, component choices, parameter choices, and tolerances can be examined through simulation and the results can be used to confidently make design choices about the new product. This will be discussed later in the section entitled “Refine.”

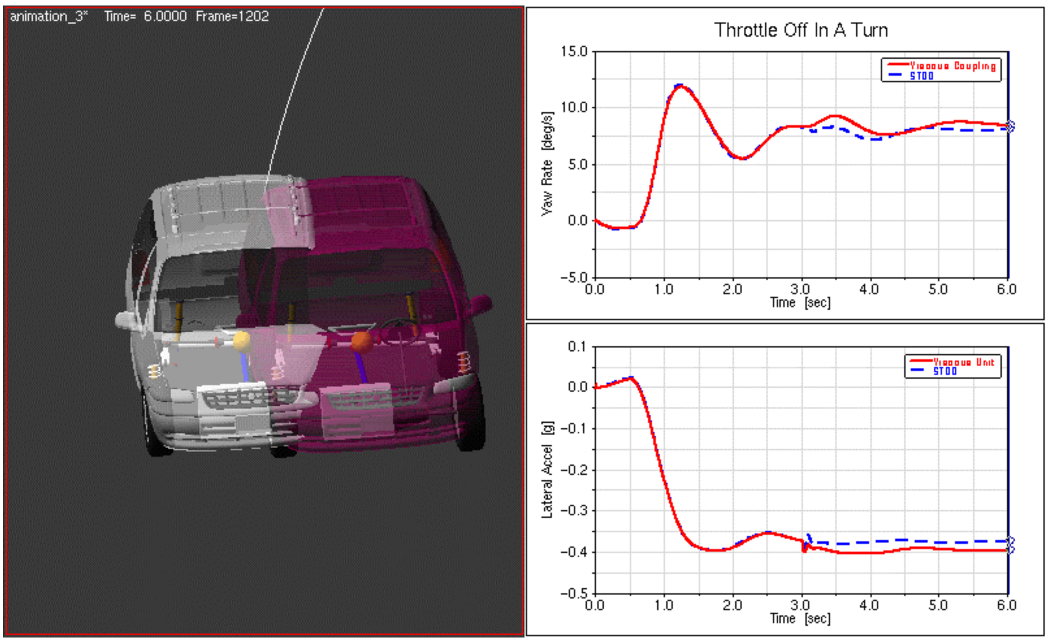


Figure 12. Typical Parameter Study With Virtual Prototype

Testing remains an important part of functional virtual prototyping throughout the design cycle. Virtual testing is conducted continuously. Physical testing is introduced at various stages to either re-validate the model after significant refinement or to test certain configurations of the product containing design parameters outside of those for which the model has been validated.

Validate

The importance of accurate validation of system-level models and modeling assumptions should not be under-emphasized. Functional Virtual Prototyping can yield a wealth of information to support rapid decision-making. It is critical to insure that this information reflects the actual operating performance of the new product. The validation phase is not overly difficult, but often is not approached with as much rigor as is warranted. The companies with the very best records in making effective use of functional virtual prototyping have invested significant time and resources in building a validation library. This library defines how models need to be constructed so that simulation performance results can be easily compared with test results. The library catalogues past validation work and summarizes modeling assumptions that have been validated. And the library is integrated with an internal product data management system so that data and information is readily available.

Good simulation tools and processes can greatly facilitate the validation process. For instance, a simulation software product that provides quick information on design sensitivity to various parameter changes can pinpoint areas of a model to be investigated to improve correlation between experiment and simulation. Also, as stated earlier, it is important to "simulate as you test," meaning that the same testing and instrumentation procedures should be used both in the physical and virtual test process.

In a typical validation process, the physical and virtual models are tested identically and baseline results are derived. The results are compared either manually or in automated computer-based fashion. Discrepancies are noted in specific performance results. Design sensitivity analyses are performed on the virtual model to identify design parameters or model areas that significantly contribute to the performance results that do not correlate. Then, a mixture of manual changes and computerized nonlinear optimization techniques are employed to make changes to the model parameters identified or the test procedures until acceptable correlation is achieved and the model is validated across the different tests.

In a recent validation process, a virtual prototype of a Formula 1 race car was tested on a virtual representation of the Imola race course in Italy. A virtual driver model learned the course and was used to duplicate the behavior of a real race driver. Lap times were compared between the virtual car and a real car driven by a professional driver. The virtual prototype delivered a lap time that was within 0.1 seconds of the real driver. More importantly, a comparison of the vehicle lateral acceleration levels for the real and virtual vehicles showed outstanding correlation.

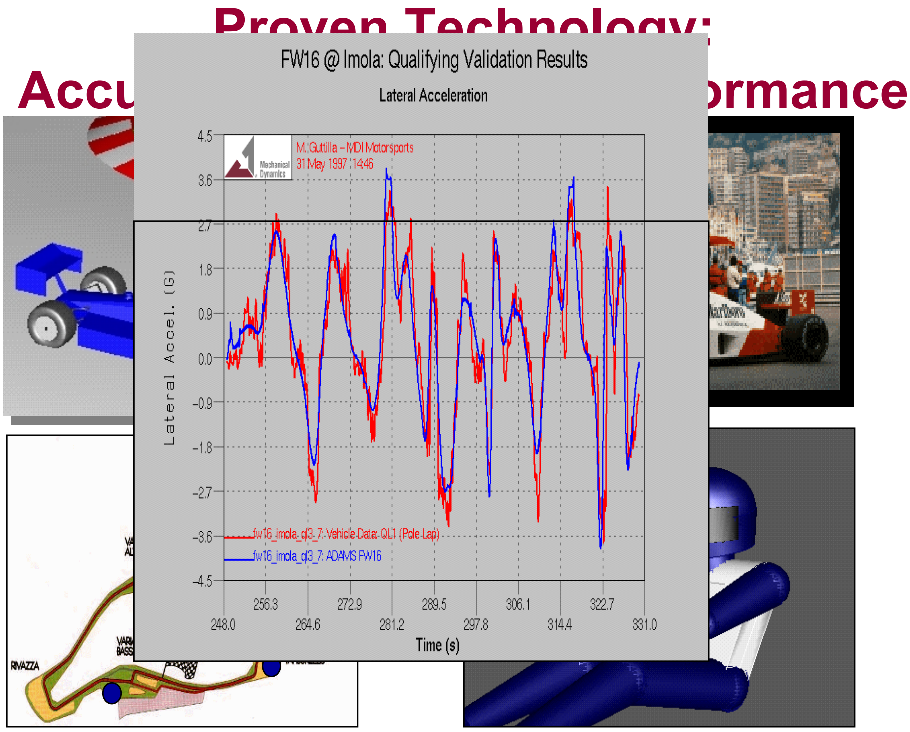


Figure 13. Outstanding Correlation Using Virtual Vehicle, Driver, Roadway

With experience, modeling assumptions can be correlated and catalogued. This allows for the automated creation of new product virtual prototypes that can be utilized with confidence without the need for the construction and testing of an initial physical prototype. Physical prototypes are still needed downstream in the process to verify the design prior to production.

Refine

Refining a virtual prototype involves two aspects, refining the fidelity and breadth of the model, and refining the product design itself. Each of these will be discussed separately here.

As the design process progresses, the virtual prototype models will be relied upon to investigate more and more functionality. Initially, it may be enough to understand speed of operation, the space envelope of operation, the total power requirements, etc. This understanding can help drive component topology selection and overall design parameters. Then, as issues of comfort, noise, vibration, and durability need to be addressed; the virtual prototype model will need to be enhanced. It is important that the virtual prototype can access subsystem models of varying complexity and model fidelity. For investigations of more complex phenomenon, it will be important to enhance the model by replacing more and more of the rigid subsystem models with flexible counterparts. Models of the fluid power systems that interact with the mechanical and electrical components will need to be represented. Automatic control systems that alter the operating performance of the product will need to be accurately represented. These are all natural extensions of the initial virtual prototype. Component and subassembly models of varying complexity must be constructed in such a manner so as to be quickly interchangeable. For instance, when investigating engine performance in a vehicle, it may be important to exercise a fairly detailed engine model that includes a flexible valvetrain with cam-rocker contact. However, if vehicle

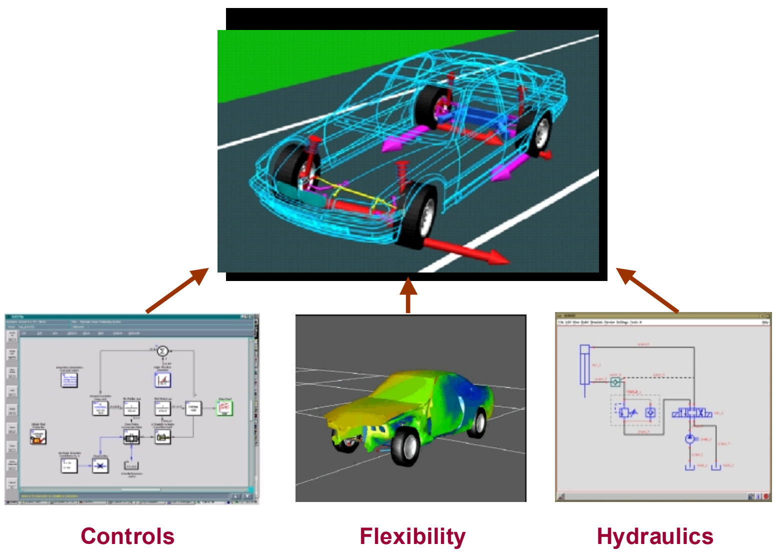


Figure 14. Successive Refinement of Virtual Prototype

dynamics is the main focus, the engine model can be effectively replaced with a much simpler representation. A template-based design system that allows for quick and easy exchange of various subsystem models is of paramount importance for effective design refinement.

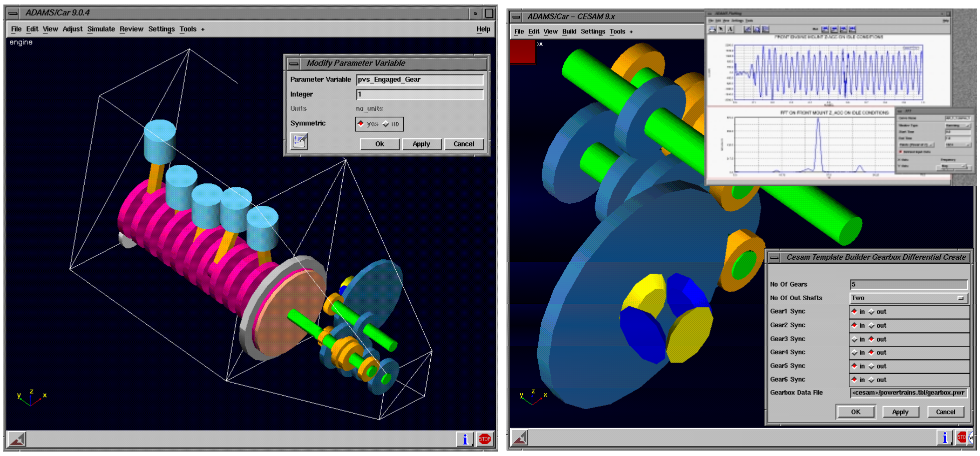


Figure 15. Template-based Engine Mount Design System

Refining the actual product design is where functional virtual prototyping delivers the real value. Once a validated, system-level virtual prototype has been created with interchangeable subsystem models of varying model fidelity, a very rigorous design refinement process is within reach. First, a complete battery of product functional tests are defined and finalized. These will be the virtual tests used to sign-off on the new product design. Next potential design changes are identified in terms of component parameter changes, system topological changes, and potential manufacturing tolerances. Performing the complete battery of selected tests with all combinations of parameters and tolerances is both impractical and unnecessary. Statistics-based, Design-Of-Experiment (DOE) methods are used to consider the entire universe of combinations of these changes and determine what combinations of these parameters must be simulated in the battery of virtual tests in order to give a statistically relevant prediction of the envelope of operating performance. The identified combinations are then simulated using both the virtual prototype and the battery of virtual tests, and the results are exported to a simple spreadsheet. Curve fitting of these results allows for quick spreadsheet assessment of any potential design changes within the specified range. This approach facilitates rapid, knowledge-based decision making in product design review meetings. Requested changes to system design points or parameters can be immediately assessed for their impact on performance, safety, durability, comfort, and cost. Faster decisions and a better balance of competing functional performances result from this approach.

	Factor	Units	Nominal Value	Tolerance	Minimum	Maximum
Upper Control Arm	Front Bushing Y	mm	0	1	-15	0
	Front Bushing Z	mm	0	1	-30	0
	Ball Joint X	mm	0	1	-10	10
	Ball Joint Y	mm	0	1	-2	2
	Ball Joint Z	mm	0	1	-2	10
	Rear Bushing X	mm	0	1	-5	30
	Rear Bushing Y	mm	0	1	-15	0
	Rear Bushing Z	mm	0	1	-25	5
Lower Control Arm	Front Bushing X	mm	0	1	-80	0
	Front Bushing Y	mm	0	1	-15	0
	Rear Bushing X	mm	0	1	-60	0
	Rear Bushing Y	mm	0	1	-30	0
	Rear Bushing Z	mm	0	1	0	10
	Ball Joint X	mm	0	1	-5	5
	Ball Joint Y	mm	0	1	0	10
	Ball Joint Z	mm	0	1	-5	5
	Front Bushing RAD	%	0	1	70	130
	Rear Bushing RAD	%	0	1	70	130
	Rear Bushing AX	%	0	1	70	130
Tie Rod Outer	X	mm	0	1	-20	10
	Y	mm	0	1	0	18
	Z	mm	0	1	-20	20
Tie Rod Inner	Y	mm	0	1	-5	0
	Z	mm	0	1	-5	0
Stabilizer Beam	Front		0	1	-1	1
	Rear		0	1	-1	1

	Responses		Response Value	Nominal Veh	% change
0.2 G Brakestop	Toe change left	deg	0.00	0.00	0%
	Toe change right	deg	0.00	0.00	0%
	Lateral Drift	ft	7.42	7.42	0%
0.5 G Brakestop	Toe change left	deg	-0.04	-0.04	0%
	Toe change right	deg	-0.04	-0.04	0%
	Lateral Drift	ft	3.81	3.81	0%
Stepsteer	Peak Roll Angle	deg	2.79	2.79	0%
	Peak Sideslip Angle	deg	3.71	3.71	0%
	Yaw Rate Overshoot	%	37.74	38.67	-2%
	Sideslip Angle Overshoot	%	21.57	21.57	0%
	Peak Lateral Acceleration	G's	0.68	0.68	0%
	Lateral Acceleration Overshoot	%	6.76	6.76	0%
Sweptsteer	Roll Gradient	deg/G	4.01	4.01	0%
	Sideslip Gradient	deg/G	3.24	3.24	0%
	Steering Sensitivity	g/100 deg	0.91	0.91	0%
	Roll Couple Distribution		1.16	1.16	0%
(Stepsteer)	Peak Lateral Acceleration	G's	0.63	0.68	-7%
	Peak Roll Angle	deg	2.47	2.78	-11%
	Peak Sideslip Angle	deg	2.93	3.71	-21%
	Sideslip Angle Overshoot	%	19.66	21.57	-9%
	Lateral Acceleration Overshoot	%	6.76	6.76	0%
(Sweptsteer)	Roll Gradient	deg/G	3.93	4.00	-2%
	Sideslip Gradient	deg/G	3.27	3.23	1%
	Steering Sensitivity	g/100 deg	0.81	0.91	-11%
	Roll Couple Distribution		1.17	1.16	1%
Test Stand	ACKERMAN	%	33.78	33.78	0%
	RACK_TRAVEL	mm	83.35	83.35	0%
SVC	Anti-Dive	%	11.92	12.26	-3%
	Roll Center Height	in	2.43	1.87	30%

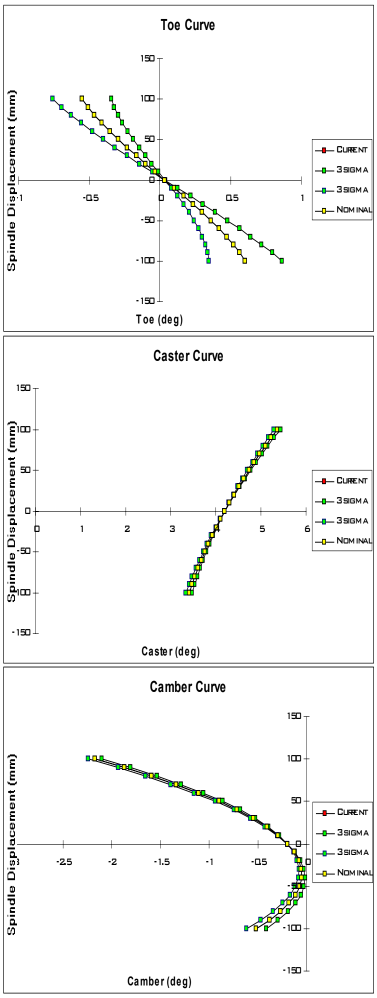


Figure 16. Design-of-Experiments Approach to Virtual Prototyping

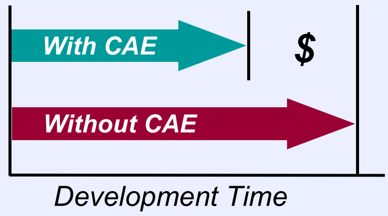
Automate (Publish)

The approach outlined above leads to significantly improved products at lower cost. To simultaneously reduce the overall development time, it is necessary to automate the virtual prototyping process. This phase requires close cooperation between designers, development engineers, analysts, and test engineers. Although this cooperation may not be easy to effect, the payback is significant. Ford Motor Company recently released results of applying an automated virtual prototyping process to three new vehicle programs. They demonstrated $40 million savings in engineering costs and over $1 billion savings in manufacturing changes through reduction of late cycle changes.

Ford Motor Company

Savings from CAE on three major programs:

Engineering Expenses Eliminated		Manufacturing Costs Eliminated
Labor	$17.4 M	> $1 Billion
Prototypes	54.5 M	
Testing	20.3 M	
Tooling	2.0 M	
	$94.2 M	
CAE Costs	$53.0 M	
Net Savings	$41.2 M	



Source: Investigating Virtual Product Development Conference June 4, 1996

Figure 17. The *Real* Benefits of *Virtual* Prototyping

Automating the process can be done very effectively in companies that make the same type of products year after year. It is much more difficult in organizations where radically different products are created over time.

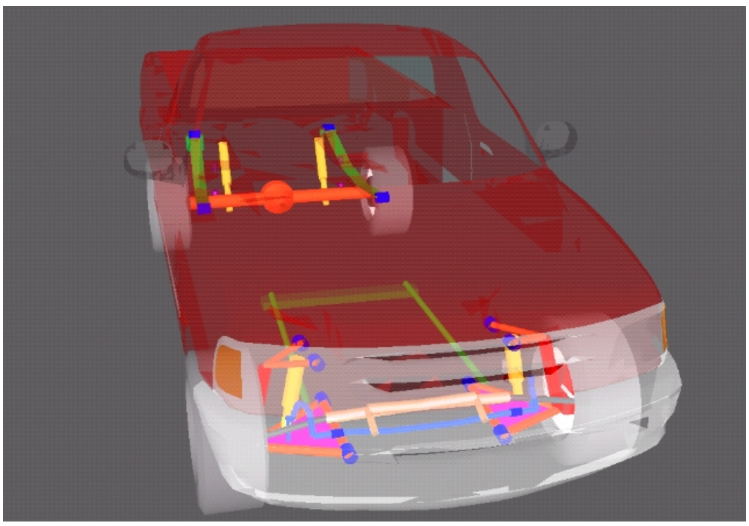


Figure 18. Automated Creation of Vehicle Models & Events

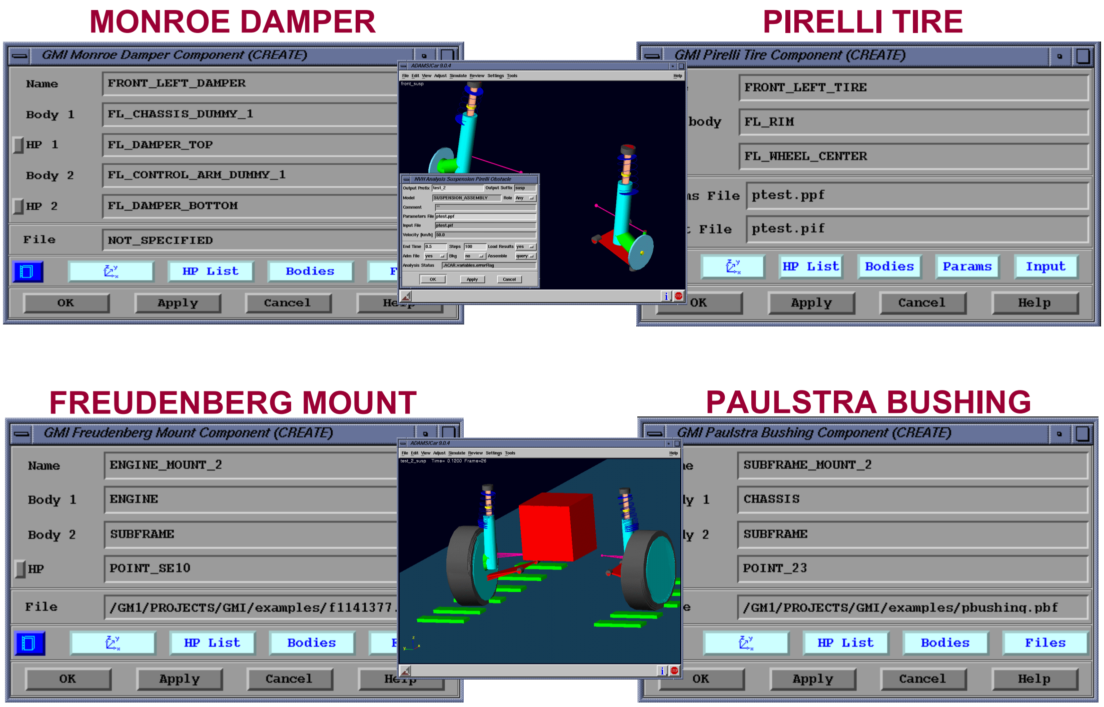


Figure 19. Template-based Subsystem Modeling

Once the engineering analysts have worked through a few virtual prototyping cycles and helped create validated models that can be exercised through the parameter changes requested by the development engineers, the virtual prototyping environment can be automated through the use of a template-based design system. It works as follows. The engineering analysts catalogue: (1) parametric topologies that are normally considered for new products, (2) typical parameters that are varied in the design process, (3) the range of validity of various modeling assumptions, and (4) the different levels of subassembly model representations required for various levels of fidelity.

Then an analyst utilizes a template-based design system to create a series of design templates that can be used by the designers and development engineers to evaluate design changes. These templates automate the creation of the subassembly and system models. They allow input only within the range of the validated modeling assumptions. They hide the complexity of the model by only presenting the parameter changes that have traditionally been varied. And they automate the selection of subassembly representations in accordance with the type of test or performance output that is requested. If this is integrated with a product data management system, it allows for quick comparisons of new design performance with previous designs or competitive target designs. The analysts publish these design templates internally for use throughout the design process and even later in field troubleshooting.

This makes it possible to have an enterprise-wide virtual prototyping process where any engineer in a vehicle manufacturing organization can access a validated model of any previous vehicle or current new vehicle design. They can replace subsystems, alter vehicle design parameters, add automatic control systems, and run the vehicles through standard test procedures to understand the effects of proposed changes. This is extremely powerful in stimulating creative input and capturing corporate design knowledge.

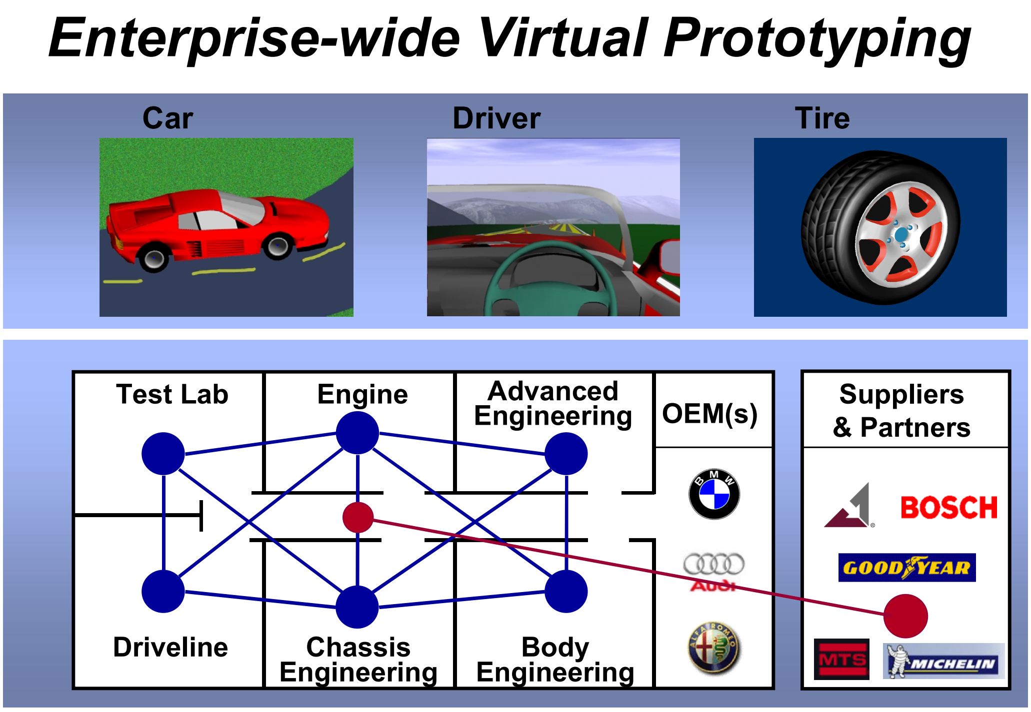


Figure 20. Uniting the Extended Enterprise in the Design Process

<u>**Technology Enablers and Limiting Factors**</u>

An often-asked question is 'why haven't technologies such as Digital Mock-Up (DMU) and Functional Virtual Prototyping (FVP) been applied extensively before now?' To understand this, it is important to look at factors that enable this technology and factors that inhibit it. Key enablers include the fact that three-dimensional solid models and component finite element models are now available for most system components, unlike in the past. Secondly, new technologies have been developed for simplifying the representation of component data so that it can be efficiently processed in large system simulations. Thirdly, fast graphic workstations that can quickly analyze and display system-level models have now become inexpensive and plentiful. Also, Product Data Management systems facilitate system-level design by making vast quantities of data available and current. These four factors make it possible to effectively deploy DMU and FVP today.

A few limiting factors still exist which retard progress in applying these newer technologies. First, very few universities have instituted effective training in these technologies, thus limiting the number of knowledgeable candidates for deployment. Secondly, hardware testing is ingrained in most manufacturing organizations and this newer technology is sometimes viewed as a threat rather than being synergistic. And lastly, effective deployment requires some process change within these large organizations and that requires a significant amount of training and the passage of time for overall adoption.

Success Story

A number of major automotive OEMs and tier 1 suppliers have already made substantial progress in using virtual prototyping to reap cost, time, and quality benefits. One of these is Volkswagen (VW). Starting with a clear set of design performance targets, Volkswagen set out to remake the venerable Beetle into a modern day success, not only in its styling, but also its driveability. To achieve its goal, VW relied heavily on the use of a robust virtual prototyping process throughout their chassis and powertrain development groups. They made extensive use of ADAMS system simulation software to evaluate thousands of design variations for vehicle ride and handling, vehicle durability, safety systems, as well as engine, clutch, and transmission performance.

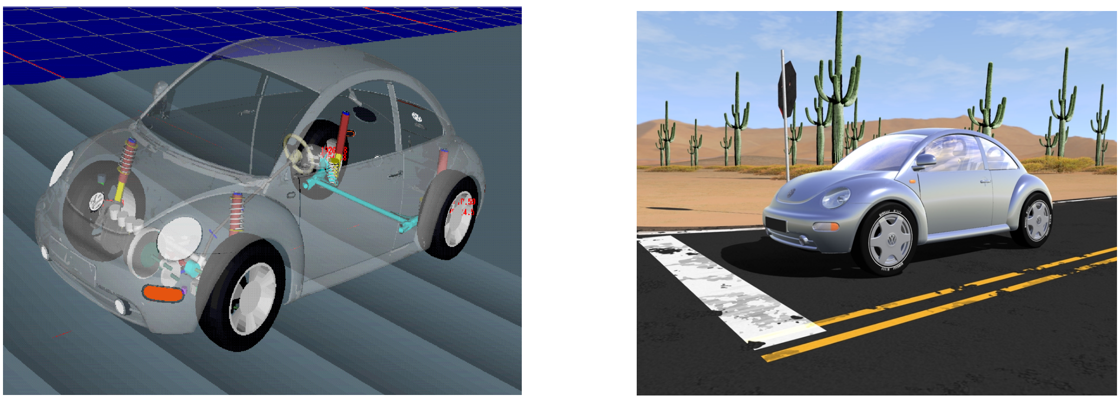


Figure 21. Virtual Prototype Refinements of the New Volkswagen Beetle

The results were outstanding. After thorough design in the *virtual* world, the vehicle behaved splendidly in the *real* world! It was released to wide acclaim in both North America and Europe. Below are just a few of the awards bestowed on this vehicle:

• 1999 North American Car of the Year	*Detroit Auto Show*
• 1999 Automobile of the Year	*Automobile Magazine*
• 1999 Import Car of the Year	*Motor Trend*
• 1998 Most Appealing Car	*J. D. Power and Associates*
• 1998 Grand Prix Award	*European Car Magazine*
• The Best of 1998	*Time Magazine*

David E. Davis Jr., a writer for Automobile Magazine [2], wrote: “The New Beetle is a landmark car.” “The car is a blast to drive.” “Steering, braking, shifting, and clutch operation are, quite simply, a joy.” “[It] is a very safe car…” “More important, for us, is first-rate dynamic performance.” “The New Beetle is definitely a driver’s car.” This is a rather stark contrast to the original Beetle that was very popular, but was never known for its performance. These great improvements were made possible in a cost-effective manner through the heavy reliance on virtual prototyping.

Figure 22. The New Volkswagen Beetle – 1999 Automobile of the Year

Conclusion

A current bottleneck in globally competitive product design is the creation, instrumentation, testing, and modification of system-level hardware prototypes. Traditional CAD/CAM/CAE methodologies do not provide a good means to break this bottleneck. New products in the Digital Mock-Up (DMU) area, Functional Virtual Prototyping (FVP) area, and Virtual Factory Simulation (VFS) provide system-level counterparts to traditional component-focused CAD/CAM/CAE solutions and allow for breakthroughs in speed, cost, and quality for new product design. Key enablers are present in the market to make these technologies practical today.

This paper provides a brief overview of Functional Virtual Prototyping and how it can be successfully implemented in major manufacturing industries. Clearly the need for this technology exists. Rapidly increasing product complexity coupled with declining development budgets and time-to-market pressures mandate an alternative to singular reliance on hardware prototype testing. New computer hardware and software have enabled cost-effective implementations of this FVP technology. What remains is for manufacturers to adopt enterprise-wide processes that fully incorporate virtual prototyping as a mainstream practice and institutionalize the use of virtual prototyping software to improve design and development of new products.

Critical success factors for FVP implementation include:

- *A well-defined process*
- *System-level focus*
- *Effective target setting*
- *Rapid simulation turnaround*
- *High quality CAE infrastructure*

Implementation of Functional Virtual Prototyping on an enterprise level requires a significant commitment of time and financial resources. The benefits of making this commitment are enormous in terms of return-on-investment and global competitiveness.

References

[1] Bidrawn, Les and Kohnle, Thomas, "The New 3," *BMW Magazine,* Vol. 2, 1998, pp. 8-14.

[2] Davis, David, "Volkswagen New Beetle," *Automobile Magazine*, Vol. 13, 1999, pp. 92-95.