Virtual Manufacturing for Zero Defects

Quality issues are a significant problem for the automotive industry. We estimate that in the past as much as 60% of warranty claims resulted in “no trouble found” after the problem had been investigated: the cause of the issue was probably due to random component interactions that were impossible to replicate at the time.

The root causes of quality issues are often the designs that do not account for sources of variation, including component tolerance, environmental conditions, component aging and so on. Unfortunately, we cannot perform any statistical analysis using traditional approaches (such as physical prototyping) to complex automotive subsystem design. Statistical analysis using actual parts is economically prohibitive due to the size of the systems involved. We needed a new approach to solve the problem.

Compounding the quality challenge is the proliferation of electrical subsystems. The electrification of vehicles has made them increasingly complex such that traditional design approaches don’t achieve performance and design goals. This trend is driving an increase in projects requiring simulation and analysis.

On top of these challenges, the automotive industry has had to deal with horrendous economic pressures in recent years. Reductions in engineering budgets have led to an increase in

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workload that has to be managed by the same—or sometimes reduced—levels of staffing. Competition from global players has intensified, which puts more pressure on development timescales as manufacturers strive to bring their products to market faster. Therefore, we must identify quality problems as early as possible—when it is cheaper and faster to fix them.

In order to respond to these management issues, we recognized that as an engineering team we needed to adopt methods that produce robust designs, improve productivity and quality by increasing our confidence that components and systems can meet all performance requirements under all conditions for a range of vehicle types.

**Robust Design Methods**

Robust design methods require that we test multiple subsystem prototypes. Taking a manual approach, we would have to test hundreds or even thousands of individual units to achieve statistically significant test results. Building and testing this many subsystems within a finite development cycle and budget is just not possible. We have been able to address the quality, economic and complexity issues created by the rise of electrification by adopting virtual manufacturing, where the benefits of virtual prototyping of physical systems and distributed processing are combined to effectively build and test multiple subsystems.

In order to make our design process more robust we created a high-performance computer (HPC) distributed processing environment (Figure 1). This supports the use of advanced simulation tools that allow us to create multiple virtual physical system prototypes for testing, where each differs only by a change in parameters within tolerance ranges. This technique parallels a real-world manufacturing line, replacing real systems with accurate simulation models that allow parameter changes between simulation runs. Where hardware prototyping allows only a few systems to be built and tested within a finite development cycle, virtual manufacturing makes it possible to effectively build and test thousands of individual prototypes, which provide a statistically representative sample size.

Figure 1: Key elements of the HPC network methodology
This statistical information gives us detailed data on component interactions. We use the information gathered to predict specific problems that might occur during actual subsystem manufacturing. We aim to achieve zero defects from the adoption of a virtual manufacturing methodology using our HPC network.

Project Example: VVT
The first project that involved developing new technology using the HPC demonstrated the value of taking a virtual approach to manufacturing. The variable valve timing (VVT) subsystem (also known as Cam Phaser) improves engine performance by dynamically adjusting the timing for an engine’s intake and exhaust valves. Because the subsystem is fairly complex, even executing a moderate statistical analysis on a single CPU may take several hours or days to complete, depending on design complexity, the number of statistical simulation runs, the range of analyses, and the CPU configuration. A properly configured distributed processing environment enables us to perform this same statistical analysis in a fraction of the single-CPU time. As a result, we could identify and correct issues associated with sources of variation early in the design process, which resulted in the subsystem working first time and a significant reduction in warranty-related issues.

Boosting Quality and Productivity
We had already adopted virtual prototyping of physical systems and had used simulation or virtual robust design for years on projects like VVT. We reaped the benefits of this on project after project. However, there were limitations when running all of these simulations on a single computer. Using the old way of working, we would typically complete the analysis of one subsystem every eight weeks. Given the growing complexity of the systems we were analyzing, we estimated that we would need to double our productivity at least, and without additional staff, just to keep up with our projected workload.

Using the HPC network significantly boosted our productivity with one of our team of five engineers completing four projects in the first two and a half weeks of use, achieving some 60,000 simulation runs. The new methodology enabled each of our engineers to become about 400% more productive. The HPC runs 24 hours a day, seven days a week, and doesn’t take rest breaks, holidays or sick leave!

We have applied the new methodology to other projects that require the analysis of a large population of components or systems. For example, we are currently using it on a number of “Design for Six Sigma” (DFSS) projects. The DFSS project teams are tasked with increasing quality, and therefore, reducing warranty-related problems. The virtual manufacturing methodology is ideally suited for such projects, including those within the battery, powertrain, signal delivery subsystem and EM groups.

Today, the advent of hybrid and electric vehicles (EVs) is raising a whole new set of issues not encountered before. Alongside advanced infotainment systems, EVs bring completely new propulsion systems and requirements, such as battery management, that present new challenges to my current assignment in EMC engineering.

Combining Systems
Even with the widespread electrification of the automobile, the systems we analyze still combine multiple domains including mechanical, hydraulic and software subsystems. The methodology that we apply to DFSS projects takes this into account by integrating tools and models that allow us to bring together mechanical and electrical analysis into one model for execution on our HPC network.

It was important that the simulation environment we chose to use on our HPC network fulfilled our need to:

- analyze complex, multi-domain design,
- access a large library of parts and subsystems,
- import data from many other tools, and
- have advanced, post-processing capabilities.

The tools that support the HPC methodology fulfill all of these needs. However, running multiple simulations generates a lot of data, so we have been working with our EDA partners to further improve the tools’ post-processing capabilities to help us to assimilate simulation output.
The Importance of Partners
We worked closely with our third-party partners to create the HPC network, and they have become an incredibly important part of our design teams. Their expertise has been critical to the success of many projects over the years. Another vital role that they fulfill is to help (within the company) to evangelize new technologies and methodologies, especially by elevating the business case for investment in infrastructure to board-level executives. When it comes to getting the best out of new methods, partners can provide knowledge continuity, which otherwise might get lost because of staff reorganizations.

By working with our partners, we have been able to introduce new methodologies to help us analyze EMC for increasingly complex mechatronic and electrical systems across a range of vehicle types. We are aiming for quality improvements that result in zero defects, which will significantly reduce warranty claims. We have already substantially exceeded our productivity targets.

If we look back to the 1980s, electronics comprised 5% of the content of a vehicle; today, it’s 40%, and, in just a few years, it will reach 50%. The 2011 GM Chevrolet Volt EV depends on over 10 million lines of software code, and it has been developed in less than five years. To achieve and surpass these levels of sophistication and productivity, we will look to software simulation and virtual manufacturing more than ever.

Solution Summary
Our multidomain virtual prototyping platform enables us to address many of the quality and productivity issues that we face in the light of the increasing electrification of vehicles. In summary, using HPC for statistical analysis allows us to:

- Analyze complex systems in a fraction of the time compared to using a single PC
- Analyze statistically significant sample sizes, comprising hundreds of units, in a few minutes
- Achieve our performance and design goals
- Increase production and achieve design goals with a smaller workforce
- Achieve a 400% increase in productivity, which exceeded all expectations
- Achieve a significant reduction in development time

Project Profile
- **Multidomain Virtual prototyping platform:** Synopsys Saber
- **Multidomain models of physical components:** Synopsys Saber
- **Control algorithm models:** MathWorks Simulink
- **Finite element tools:** Ansys

About the Author
William C. Goodwin received his BSEE and MSEE from Michigan State University in 1985 and 1990 respectively. He initially held positions in the aerospace industry where he designed aircraft avionic systems. Upon completing his MSEE, he held contract positions specializing in the design and development of automation and data acquisition systems. Since 1994 Mr. Goodwin has been employed with General Motors Powertrain involved in mechatronics simulation for the engine, transmission, and electric vehicle groups. His present assignments at GMPT are focused on the development of EMI/EMC modeling and simulation techniques. He has published 7 articles in professional journals and conferences. He holds one U.S. patent with two others pending.
Virtual Design and Verification Solutions for e-Mobility

The electrification of vehicles is the key to innovation for carmakers. David W. Smith, Synopsys Scientist, takes a look at the challenges for design teams and the key qualities they need in a platform for virtual design.

The electrification of the automobile is the most fundamental change within the industry since the beginning of the 20th century. We have witnessed the proliferation of electronic subsystems within conventional vehicles over the past 10 years or so, and the growth forecasts for hybrid and pure electric vehicles will give the market for automotive semiconductors a significant boost.

The market for electronic control units (ECUs) alone stood at just under $48 billion in 2010, some 29% higher than 2009. Overall, electronic vehicle content is forecast to grow by just under 8% annually to 2015. Some application areas will show exceptionally high growth (in excess of 50%). These include pure EVs, head-up displays, drowsiness detection, LED lighting, stop/start, lane departure warning and blind-spot monitoring.

By 2010, electronic systems and software comprised 30% of the cost of conventional (gas) vehicles and 65% of the cost of hybrid and electric vehicles.

Key Electrical Connections

Driver experience (including safety, comfort, ecology, economy)—the connection between the car and its passengers—has become as important as the cars purpose as a means of transport. The industry has focused on how to make vehicles more people-friendly for the last 20-30 years. As a result, electric subsystems feature in many of the car’s systems. Some of the key connections between people and vehicles (both in production and in research) include:

- electrification of driver comfort and entertainment,
- electrification of the drive train to reduce emissions,
- navigation, GPS, cloud navigation giving immediate access to information,
- electric power infrastructure and minimizing power,
- ‘platooning’ vehicles together, sign/pedestrian/road line recognition, and
- autonomous vehicles, where the driver becomes unnecessary.

Implementing the kinds of connections above makes cars more complex—just how much more complex can be seen in the amount of software that automotive engineers produce.

Automotive systems are starting to approach the same level of software complexity that modern operating systems contain—anything from a staggering 50m to 300m lines of code.

System Challenges

At the 2010 SAE International conference, top engineers from Honda, GM, Ford, BMW, Chrysler, PSA and Toyota took part in a “Carmakers Speak” panel session, which identified the main system challenges for automotive design. These were:

- **Function and software allocation, and verification**: This activity is central to car design today. It involves identifying the functions on the vehicle, and allocating them to hardware and software resources.
- **System engineering and simulation**: Automotive engineers must redesign every system in the vehicle for electrification.
- **Power generation, management and distribution**: The core system of the vehicle is still the generation, management, and consumption of electricity, and is being expanded to include the drive train.

We look at these three challenges in more detail below.

Function and Software Allocation, and Verification

The key challenge for automotive systems engineers is that rather than increasing reliability, software makes the problem harder. Making cars that don’t crash, that serve up driver...
information without distraction, and that don’t pollute, are among the greatest system engineering challenges that the industry faces. On top of that, success in the industry depends on there being sufficient demand for cars, which means that design teams are constantly under pressure to find the latest “cool factor”.

The essence of system design is to design a distributed computing system that interacts with physical systems, and then defining and mapping the software onto this distributed system.

This task was more straightforward when every ECU in the vehicle mapped to a single function and the ECU/software was delivered as a black box—an approach that means it’s now common to find over 100 ECUs in high-end vehicles. In order to reduce the number of ECUs, the technology now exists to consolidate multiple functions into a single ECU. The complexity of functions has also increased so that multiple ECUs must cooperate to implement a high-level function. Tasks like automatic parking or collision avoidance must communicate with and control multiple subsystems.

A big challenge in integrating systems is that components invariably come from multiple suppliers. This compromises safety and quality. At the start of ECU-software integration, there may be thousands of errors present. The later that someone identifies the problems, the more it costs to fix them. Problems that manifest themselves once the car is in the customer’s hands become very expensive to fix. Business Week reported that Toyota’s 2009-10 recalls cost the company more than $2 billion, including legal costs, lost sales and warranty payments.

**System Engineering and Simulation**

So how can automotive design teams conquer the system design challenges that come with vehicle electrification? The problem scope is not limited to software and electronics—design teams must also consider mechatronics. Potential solutions need to support detailed physical modeling, conceptual design and implementation, and concurrent, multiple tiers of modeling and verification.

The history of car electronics has gone from simple power generation and distribution, through electronic control systems, to electronic drive systems. The cost of electronics has increased from 10% to 60% of the car for electric hybrids. The cost is not in software (manufacturing of software is mostly free) but in the electronic, electrical, and electro-mechanical components that make up the vehicle.

**Model-Based Embedded Systems Engineering (MBESE)**

Carmakers need models for multiple purposes:

- for analyzing/verifying the product need,
- to define software applications of the EE system, and
- to support simulation and verification of the plant/multi-physics/car system models.

Consequently, modeling requires the use of many different frameworks:

- AUTOSAR—software running on a virtual processor,
- EAST-ADL2—software running in an environment (plant included),
- VHDL-AMS/MAST—mechatronics modeling and electrical systems,
- SystemC/SystemC-AMS—system-level description of SoCs and interconnection of SoCs,
- SystemVerilog/Verilog-AMS—SoC implementation, and
- SPICE—IC analog.
Bringing together all of these elements requires a platform that is capable of modeling and simulating physical systems, which enables full-system virtual prototyping for applications in analog/power electronics and electric power generation, conversion distribution and mechatronics (Figure 1).

Semiconductors are the basis of all automotive electronics systems, while software runs on all the ECUs, mechatronics is what makes the software do something useful. To be useful, a platform must incorporate an electrical system architecture that links these key system components together.

**Power Generation, Management and Distribution**

The core function of the vehicle is still the generation, management, and consumption of electricity. This is even more pronounced with electrification since the power train is now a factor in all of these areas. All of the electrical systems need to make use of low-power techniques so that the amount of electricity used by the vehicle can be reduced, and so, too, the battery size.

We can reduce the electrical load on the battery by optimizing 12/24/48V loads, by reducing the amount of wire in the vehicle, and by designing more efficient HVAC (heating, ventilation and air conditioning) systems.

Compared to automotive, other sectors, like the mobile phone industry, have a lot more experience of applying low-power techniques. Battery life plays a large part in determining the success of mobile software platforms like Android. And in turn, software has a large part to play in determining battery life. For example, an application that wakes up the phone every 10 minutes for just eight seconds to perform updates can cut its stand-by time by half. Any software power inefficiency or malfunction can quickly cause a drop of 5x or more in standby time.

The complex, highly distributed software entities for power saving and management must be vertically integrated and cooperate to guarantee an efficient use of the battery in a mobile phone. The phone’s usage scenarios play an important role as they define how it interacts with the environment. However, how can you debug your phone while it is locked in your pocket? How can you make sure that scenarios are deterministic to compare different implementation options?

Debugging power defects comes with another major issue. In low-power modes such as “suspend”, the embedded debug service is likely to be suspended as well. In addition to that, any debug interaction with the device is intrusive and severely tampers the power figures. Furthermore, expensive lab equipment is required to perform a sufficiently fine granular power profiling to determine which of the components is the most critical.
In many ways the challenges that designers face, whether they’re working on mobile phones or electric vehicles, are converging.

**Solutions for Automotive Engineering**

Synopsys’ design automation solutions help to address many of the emerging engineering challenges that carmakers now face. We have solutions for the design of the silicon itself (system on chip—SoC), provide leading solutions for virtual platform verification of software (Virtual Prototyping) and we partner with the leading solutions for creation of the software. We also have the market-leading tool (Saber) for mechatronics design, and lead the creation of the standard languages used, including MAST and VHDL-AMS. Saber is also the leading solution used in electrical power systems in the vehicle and has powerful capabilities for enterprise-level wiring design.

**Virtual Solutions for Function and Software Engineering**

Virtual prototypes help vehicle designers to overcome function and software allocation, and verification challenges. They provide excellent debug visibility at the right level of abstraction, such as OS process traces. They can also be instrumented with information that characterizes power usage. Their execution is controlled via deterministic scenario scripts that drive the I/O of the virtual prototypes, such as generating user input via a touchscreen controller, setting GPS coordinates through a UART, initiating a phone call, etc. During simulation, power analysis data is collected, alongside other hardware and software traces, to enable root-cause analysis and debugging that ultimately allows engineers to optimize the software. Increasingly, automotive design teams are shifting from a traditional to a virtual approach (Figure 2) to manage the growth in system complexity.

A virtual prototype of an automotive system provides a fast, fully functional software model of the interacting subsystems, executing unmodified production code and providing higher debugging analysis efficiency.

**System Engineering Solutions**

All systems are subject to sources of variation including component tolerances, environmental stresses, or aging. Automotive system engineers want to reduce the effects of variability on system performance by designing systems that are less sensitive to these sources of variation. Saber helps engineers to apply robust design methods, such as Taguchi or DFSS (Design For Six Sigma) and to optimize their mechatronic systems for quality and cost.

**Power Management Solutions**

The Saber links to TCAD (transistor-level CAD) tools from Synopsys enable engineering teams to achieve faster product design for power electronic systems. By abstracting device-level physics to physical systems, designers can work with accurate, compact Saber models of power components. The abstracted models support behavioral circuit simulation that can be hundreds of thousands of times faster than device-level mixed-mode simulation.
Q: FPGAs are increasingly being used in automotive applications, but their cost per part is typically much higher than an ASIC/SoC. What can be done to keep FPGA part cost down?

A: These days, performance requirements for most Automotive electronics applications can be achieved using either FPGA or ASIC/SoC technology. ASIC/SoC devices tailored for the particular application can reach part cost levels that no FPGA can match. However, be sure to consider the total cost for the volume of parts expected to be required. The significant extra development, testing and fabrication cost necessary to design and manufacture a custom IC must also be included in the part cost calculation. Typically, volumes in the tens of thousands are best implemented in FPGAs, volumes in the millions are best as custom ICs, while volumes in the hundreds of thousands could go either way. For higher volume FPGA designs, be sure to use the best design tools available. Synthesis, placement and routing tools have the most impact on resource utilization (and resulting part cost) for the design. In particular, a logic synthesis tool that can implement the required functionality and performance using fewer FPGA resources can often fit the design in a smaller, less expensive device. True timing-driven synthesis technology that optimizes for area reduction after meeting the performance requirement specified by the user is key to minimizing cost. Part cost savings for using the next smaller FPGA device is significant, ranging from 15% to 30%.
Today, automotive systems are getting too complex to assess their reliability with our current methods. What simulation-based techniques are available for verifying our mechatronic system reliability?

Many powerful and accessible techniques can be used to predict the reliability of mechatronic systems. Monte Carlo simulation, for example, commonly serves as a basis for understanding the effects of uncertainty in complex systems, and combined with data reduction and analysis. Physical Modeling provides the ability to describe the uncertainty throughout the system—in system inputs, in component parameters, or in the ambient environment—and, combined with Monte Carlo, simulation can develop a statistical picture of the effects and interactions that impact reliability.

Additional techniques are also available that complement the “brute force” nature of Monte Carlo simulation. These “guided” approaches employ highly efficient and intelligent optimization algorithms that search the parameter space and identify the worst case conditions and boundaries of system performance that jeopardize overall reliability. Finally, physical modeling and simulation provides a platform for injecting faults into a mechatronic system and evaluating the impact on reliability—from inducing unanticipated component stresses to triggering more catastrophic failures.

Contact Synopsys to learn more about the statistical analysis, worst-case analysis, and fault injection capabilities of the Saber Physical Modeling and Simulation tools.

We are upgrading to quad-core machines. Can I run Saber on all four processors to increase the simulation speed and if so, by how much?

It depends on what you are simulating. For a single simulation, the process cannot be spread across multiple cores (multi-threading). However, using all four cores can be a great benefit for iterative analyses. For iterative simulation runs such as Worst Case Analysis, Monte Carlo, Sensitivity, and Pareto, this works by distributing the multiple simulation runs across the available processors. The performance boost is slightly less than a 1:1 improvement for each additional processor (there is a small overhead to parallelization). Keep in mind that this will consume additional licenses (1 per core). We offer specific Saber Runtime licenses to make this easier for adoption.
We need to start Embedded ECU software development earlier. What strategy can I apply?

Today, traditional software development, integration and test for embedded automotive ECUs starts when the physical hardware is available. However, several factors are making this serial approach more challenging. These include the emergence of multicore MCUs, the need for greater testing of software used in safety critical application, and so on. A simple strategy would be to consider approaches that enable software development to start earlier, thus resulting in more time available for testing. This objective can be achieved using simulation-based approaches enabling developers to execute the actual production software on a representation of the hardware. This approach called, virtual prototyping, enables companies to start development early, have a higher debug cycle turn-around and perform system testing without risks. “Today, the ECU is the most important device in automobiles based on performance and cost. We need virtual prototyping not only to accelerate ECU development time while lowering cost, but also to ensure that our ECUs are safe and reliable,” said Mr. Hisayoshi Naito, General Manager, Vehicle Development Division at Mazda. Contact Synopsys to learn more about Virtual Prototyping and its application to the automotive ECU software development.

Marc Serughetti
Director, Virtual Prototyping Solutions

Have Questions?

Have a burning question you want answered? Submit questions to our panel of experts. Please send your email to atb@synopsys.com.
Additional Resources

Saber website:
www.synopsys.com/saber

SaberRD Student/Demo Edition
FREE software download:
www.synopsys.com/saber-sw-demo

SaberRD Datasheet:
www.synopsys.com/saber-ds

Virtual Prototyping website:
www.synopsys.com/virtualprototyping

Virtualizer Datasheet:
www.synopsys.com/virtualizer-ds

FPGA Design website:
www.synopsys.com/fpga

Synplify Premier FPGA Brochure:
www.synopsys.com/synplify Premier-fpga

Automotive Solution website:
www.synopsys.com/automotive

Automotive Solution Datasheet:
www.synopsys.com/automotive-ds

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Upcoming events

Japan Automotive Solutions Seminar
May 16, 2012
Nagoya

SNUG Germany, Automotive Track
May 23, 2012
Munich

Pictured is Jim Patton, Saber CAE Manager, with Chevy Volt at the Automotive Solutions Seminar in Detroit.