A Systems Engineering Approach to Occupant Protection System Design and Optimization through Modeling and Simulation

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ABSTRACT

Occupant Protection Systems (OPS) have become a very important part of today’s automotive systems. The extensive government regulations and consumer information programs make the design and optimization of the OPS a complex and challenging task. A Systems Engineering (SE) approach is implemented throughout the OPS design and optimization process. The SE process includes customer requirements analysis, system concept design, system design, analysis and optimization, and system verification and validation. To fully evaluate the performance of the OPS and ensure its compliance of government regulations, the system needs to be tested in a large number of crash scenarios. Using physical tests alone to develop the OPS is cost-prohibitive. Therefore, computer modeling and simulation are utilized as one of the primary tools in the process. A frontal impact OPS design and optimization example is presented in the paper to demonstrate the process. © 2004 Wiley Periodicals, Inc. Syst Eng 8: 51–61, 2005

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1. INTRODUCTION

**Occupant Protection Systems.** Occupant Protection Systems (OPS) have become a very important part of today’s automotive systems. A typical OPS is composed of, but is not limited to, airbags, seat belts, knee bolsters, and crash sensing systems. Since there are different types of crashes in the field, such as frontal impacts, side impacts, rear impacts, and rollovers, some OPS components are designed to address the safety concerns for specific types of crashes. For example, driver and passenger airbags are designed mainly for frontal impact protections, while torso airbags and side curtain airbags are developed for side impact protections. On the contrary, some OPS components such as seat belts are intended to provide protection for occupants in all crash scenarios.

Besides the varieties of crash types, occupants are also diversified. In the automotive industry, the adult population is classified into three typical occupant sizes: (1) the 5th percentile female, representing the small females of the USA adult population, (2) the 50th percentile male, representing an “average” of the USA adult male population, and (3) the 95th percentile male, as a representation of the large males of the USA adult population [TNO Automotive, 2003]. Children at different ages are treated separately. The OPS is supposed to provide adequate protections for occupants of all sizes without introducing serious injuries to any occupant. Sometimes the requirements for various occupant sizes can be conflicting. For example, the 95th percentile male tends to require a powerful airbag to absorb a big amount of energy due to his large mass, but an overpowered airbag can induce inflation-related injuries to small females and children, as reported by National Highway Traffic Safety Administration [NHTSA, 2003]. Children at different ages are treated separately. The OPS is supposed to provide adequate protections for occupants of all sizes without introducing serious injuries to any occupant. Sometimes the requirements for various occupant sizes can be conflicting. For example, the 95th percentile male tends to require a powerful airbag to absorb a big amount of energy due to his large mass, but an overpowered airbag can induce inflation-related injuries to small females and children, as reported by National Highway Traffic Safety Administration [NHTSA, 2003].

**OPS Computer Modeling and Simulation.** To fully evaluate the performance of the OPS and ensure its compliance of government regulations, the OPS needs to be tested in a large number of crash scenarios. Using physical tests alone to develop the OPS is cost-prohibitive. Therefore, computer modeling and simulation have become one of the primary tools for OPS development.

OPS computer modeling and simulation started in early 1970s. The rapid improvement of the computer calculation power brought the simulation from research labs to the industrial application environment in the following decades.

A typical OPS model consists of two major parts: the vehicle interior including occupant restraint components and the occupant. Each part can be modeled as either rigid/flexible multibodies or finite elements (FE), or the combination of both. Rigid/flexible multibody models simulate the structures or occupants by a number of rigid or flexible bodies, such as planes, ellipsoids, and cylinders, connected by joints to control the relative motions of the bodies. Rigid/flexible multibody models are very efficient in their requirements for computer memories and computation time. But they have limited capability to simulate the details of the OPS and the occupant responses. In contrast, FE models can replicate most details of the physical systems, including the geometries, material properties, and system constraints. Therefore, more reliable simulation results can be achieved. As a tradeoff, large computational power is usually required for a pure FE model. In industrial applications, the objectives and requirements of the analysis decide the type of models used in the simulation. Worthy of mention, the cost of computer power has been dramatically reduced in the last few decades, and the trend is continuing. Therefore, the concern about computational power will become less important than simulation accuracy in the future.

While occupant restraint components vary from vehicle to vehicle, the occupant models have been standardized. Both rigid/flexible multibody models and FE models of occupants of different sizes are available as ready-to-use packages in the automotive industry. Many efforts are being invested to improve the biofidelity of these occupant models.

Currently three major software packages are widely used in the automotive OPS analysis: LS-DYNA, PAM-CRASH, and MADYMO. LS-DYNA and PAM-CRASH are FE-based solvers, with limited rigid/
flexible multibody functions. MADYMO started as a rigid/flexible multibody dynamics solver, but more and more FE modules have been added to the software to simulate components that require more details, such as airbags and seatbelts. The combination of both the rigid/flexible multibody model for the occupant and the FE model for the key occupant restraint components gives sufficient details of the system responses within quick turnaround time. Therefore, MADYMO has been utilized as the major modeling tool for system level simulation and optimization in the automotive safety industry. This is also the package chosen in the current study.

2. SYSTEMS ENGINEERING DESIGN AND INTEGRATION PROCESS

The Systems Engineering (SE) design and integration process can be considered as a series of decisions made in light of the knowledge obtained through modeling, testing, and engineering experience [INCOSE, 2000]. To fully evaluate the performance of an OPS and optimize the final design, an extensive matrix of the OPS design and optimization ranging from several hundreds to even thousands of sled/barrier tests and computer simulations are often required. This is definitely a prohibitive schedule and cost requirement. An SE approach has been developed to design and optimize the OPS with minimum material cost and program timing. Here computer modeling and simulation are the primary tool to explore the whole design space and search for the optimal designs, while physical tests are used to correlate the baseline computer simulation models and validate the final designs. A number of possible design and optimization strategies for the OPS are discussed.

The OPS design and optimization process follows the general SE procedure shown in Figure 1, known as “V” Diagram [Rohr, Austin, and Ma, 2003]. On the left portion of the “V” diagram, the system requirements are allocated to subsystem requirements and then component requirements. Product designs are based on the detailed component requirements. This is a top to bottom process. The bottom of the “V” diagram represents the product design. On the right portion, the components and subsystems are verified and validated according to the requirements at the corresponding levels, and then integrated into the system. At each level, the designs are verifiable. The integration process is a bottom to top approach.

The application of this general SE approach to the OPS design and integration process is demonstrated in Figure 2. It starts from the customer requirements analysis. A clear customer requirements document helps to understand the system requirements, eliminate ambiguities, and clarify the responsibilities. A system design concept is then developed based on the system requirements. Some analysis tools such as feasibility study and Design Failure Mode and Effects Analyses (DFMEA) can be used to direct the concept design. Afterwards, initial component and subsystem design is performed according to the component and subsystem requirements. With the information from the initial design, the computer simulation model is created and correlated with physical test data. A well-correlated baseline model makes a solid foundation of the further system and component design and optimization. The quality control of the baseline computer simulation

![Figure 1. Systems engineering “V” diagram.](http://www.interscience.wiley.com)
model is vital to the success of the whole procedure. An extensive exploration of the design space, including multicriteria tradeoff studies and system robustness analyses, is performed on the correlated baseline model to establish the optimal system configuration. As an essential part of the OPS integration process, system verification and validation evaluate the performance of the complete OPS and its subsystems and components, and ensure the compliance of the optimized system to the system specifications. If the system does not pass the validation tests, system concept design, model analyses and optimization are reconsidered and improved until all system requirements are satisfied [Ma et al., 2000]. The four critical steps of the process, customer requirement analysis, computer model correlation and validation, design space analysis, and system verification and validation are elaborated in the following sections. An example of an advanced frontal OPS design and optimization is presented throughout the paper to demonstrate the process.

3. CUSTOMER REQUIREMENT ANALYSIS

System requirements come from a variety of sources, including customers, government regulations, and certain industrial entities. The system requirements form the basis for the design, analysis, test, manufacture, and operation of the OPS. In general, the requirements consist of system performance requirements, functional requirements, environmental requirements, and manufacture and service requirements. The system requirements analysis is a complex process that employs performance analysis, tradeoff studies, constraint evaluation, and engineering cost/benefit analysis. It is essential that a complete, but minimum set of requirements be established and analyzed early in the program.

An advanced OPS is required to meet the legislative requirements, nonlegislative performance goals, and test conditions for the target vehicle platform. A frontal impact protection system, for instance, has to meet the mandatory regulation Federal Motor Vehicle Safety Standards (FMVSS) 208 for OPS designs [NHTSA, 2004] with a predetermined design margin, and at the same time achieve the customer performance goals including the highest star ratings in US NCAP [NHTSA, 1978] and Euro NCAP [EuroNCAP, 2001]. In other words, FMVSS 208 requirements are the constraints of the OPS design, while NCAP performance is the optimization goal. FMVSS 208 requirements are comprised of multiple crash scenarios and occupant sizes as shown in Figure 3. The occupants are 50th percentile male and 5th percentile female with and without seat belt usage. The crash profiles include frontal rigid barriers, 30° left and right angular impacts and 40% Offset Deformable Barrier (ODB) tests with various impact speeds. The main occupant injury criteria in these requirements take account of Head Injury Criterion (HIC), Neck Injury Predictor ($N_{ij}$), neck tension and compression, chest deflection, chest acceleration, and femur load [NHTSA, 2004]. They were derived from numerous biomechanical studies with animal and
human test subjects and have evolved over the last few decades [Atkinson, 2003].

**Head Injury Criterion (HIC)**—a mathematical integration of the resultant acceleration of the center of gravity of the dummy head over time. According to the new FMVSS 208, within the time window of no more than 15 ms, the HIC value should not exceed 700.

**Neck Injury Predictor ($N_{ij}$)**—a measure of the injury due to the load transferred through the occipital condyles. It combines the neck axial force and the flexion/extension moment about the occipital condyles. An $N_{ij}$ value less than 1.0 is required.

**Neck Tension and Compression**—the peak neck tension and compression forces during an impact. The maximum allowable values vary with different occupant sizes. For the 50th percentile male dummy, the maximum allowable neck tension value is 4170 N and the neck compression value is 4000 N.

**Chest Deflection**—the maximum compressive deflection of the occupant’s sternum relative to the spine. A maximum chest deflection of 63 mm is allowed for the 50th percentile male dummy.

**Chest Acceleration**—the acceleration measured in multiple of $g$’s at the center of gravity of the dummy thoracic region. For the 50th percentile male dummy, the maximum allowable value of chest acceleration sustained over a 3 ms period is 60 g.

**Femur Loads**—compression loads transmitted axially to the upper part of the legs. For the 50th percentile male dummy, it is required to be lower than 10,000 N.

The above Injury Assessment Reference Values (IARVs) are legislative requirements. To add a design margin, most automotive manufacturers set internal requirements of 60–80% of IARVs.

Besides the design regulations, another constraint to the OPS design is the vehicle structure crashworthiness characteristics. A vehicle with optimal crashworthiness structural design absorbs most crash energy by the deformation of the vehicle body structure in a premediated manner. The crash energy transferred to the occupant compartment is minimized. In contrast, a vehicle with harsh crashworthiness characteristics transfers a large amount of crash energy to the occupant compartment. In some cases it is very challenging to design an OPS that meets all system requirements without improving the vehicle structure design. The vehicle structural crashworthiness performance is mainly reflected in its crash pulses (acceleration vs. time curves) measured in the occupant compartment. Numerous studies show that the effect of the vehicle crash pulses is significant in the overall occupant dynamic responses [Ma and Zhang, 2004]. Even a small variation from pulse to pulse can lead to a large difference in the occupant IARVs. Figure 4 illustrates two similar crash pulses from the same vehicle. Crash pulse B is slightly “softer” than crash pulse A. Such a small improvement in the crash pulse improves the occupant HIC value by 28%.

Obviously, the frontal OPS is a complex system with multiple and even conflicting requirements. Among the requirements, there are some critical ones that drive the design directions. Take the design of passenger air bag volume (size), a key design parameter for frontal restraint system, as an example. Generally, a large deep bag is preferred for a large size unbelted occupant. On the other hand, a small shallow bag would be more

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**Figure 3.** FMVSS208 Frontal Barrier Crash Test Matrix. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
proper for a small female occupant to avoid the inflation-induced injuries. Additionally, the airbag size affects the energy absorbing capability of the restraint system that needs to be adjusted for different crash velocities and profiles. System requirement analysis is essential to understand the intrinsic relationship of the system requirements among these cases and identify the controlling cases for the OPS design and optimization. It helps the Systems Engineer to resolve conflicting requirements and arrive at a design that represents an optimal balance of all the requirements.

4. COMPUTER MODEL CORRELATION AND VALIDATION

Mathematical modeling and computer simulation have evolved to the stage of performing scientific research and engineering analysis by complementing experiments and theories. Mathematics-based OPS models provide engineers with a powerful, flexible, and less expensive tool to explore design alternatives and optimize systems before the physical part fabrication. Figure 5 shows a typical MADYMO simulation model as well as the physical test set-up for the frontal OPS. Before any parameter study and optimization can be performed on the simulation model, the model needs to be validated with physical test data. Model validation confirms that the predictions of a numerical model approximate the underlying physics of the application being modeled to an acceptable degree of accuracy. The evaluation of the correlation quality is essential to estimate the confidence level of the predictive results and decide an appropriate design margin.

Worthy of mention, all the OPS design requirements, including legislative requirements and market-driven requirements, are based on laboratory tests with physical
cal dummies. Therefore, the computer models are built to reflect such physical models and are only validated to these physical models. In other words, the computer model validation at the system level compares a physical model of the OPS system, including the vehicle OPS and the occupant, with its mathematical version. The correlation of computer models to field accidents is beyond the scope of this paper.

Traditionally, correlation quality is assessed by visually comparing the characteristics of the occupant response time history curves from the simulation model outputs and from the physical tests, then scored based on an engineer’s modeling experience and engineering judgment. This approach is often inaccurate, subjective, and inconsistent. Recently, a more objective statistics-based correlation grading methodology has been developed by Ma et al. [2004].

This grading system is composed of two key parts, the overall kinematics evaluation and the dynamic response assessment. A single overall kinematics score is granted according to the kinematics similarity between the model animation and the physical test videos. The kinematics variables of a typical OPS model include, but are not limited to, vehicle interior intrusions and movements, restraint system performances, and dummy kinematics responses.

Dynamic responses are evaluated based on the complete time history curves of each variable from both the simulation results and the test data. Among the full range of statistical measurements of two curves, several representative measurements are selected in the correlation grading system to draw a comprehensive picture of the relationship between the curves.

When the dynamic responses of a computer simulation model are considered close enough to those of a physical test, the following criteria need to be satisfied:

1. The overall shape and trend of the two time history curves are similar.
2. The peak values and their timing of the response curves and the corresponding occupant injury measurements are close.
3. The total areas under the curves are alike.

To quantify the above three criteria, two major parts are included in the dynamic response evaluation, peak value comparison and statistical analysis. For peak values, both the magnitude and the time when the peak value is reached are assessed. The statistics analysis is utilized to measure the overall shape and trend of the dynamic model response time history curves, as well as the total areas under the curves. Average residual, standard deviation, correlation coefficient, and 0th–2nd moment relative differences are the main statistical variables considered in the correlation grading system. The average score of all these variables becomes the general dynamic response score of the model.

The grading criteria of the measurement variables are another important component of the correlation grading system. The criteria vary from case to case. For example, for a relatively simple component model, the criteria are more stringent, while for a complex system model, the criteria are looser. Even among system models, the criteria for frontal systems and side systems are different. A whole set of criteria for each scenario were developed in the correlation grading system based on the engineering experience with the reliability and predictability of each category of models. Once decided, the grading criteria are applied constantly to all the models in the same category to ensure the consistency of the methodology.

The correlation grading system has been tested and improved through several OPS design programs and integrated into the SE process.

5. DESIGN SPACE ANALYSIS

An OPS mainly consists of airbags, seat belts, knee bolsters, crash sensing systems, etc. Advanced OPS may include more sophisticated components such as a Passive Occupant Detection System (PODS), seat track sensors, seat belt usage sensors, seat belt pretensioners, and load-limiters. The complexity of the OPS varies significantly. Therefore, various analysis tools are employed to address different system analyses needs. Two major methodologies are discussed in this section: the algorithm-based optimization [Zhang et al., 2003], as shown in Figure 6, and the Design-Of-Experiments (DOE)-based optimization [Rohr, Austin, and Ma, 2003], depicted in Figure 7. For relatively simple and specific product design problems with limited number of design parameters, the algorithm-based optimization methodology has its advantage. To study the interaction among a large number of system design parameters, and thus analyze and optimize the performance of a complex system, the DOE-based optimization methodology is more suitable.

Generally, there are two classes of optimization methods: analytical and direct. The analytical method calculates the first and second derivatives of the objective function to get the minimum value while the direct method compares the objective function values at different points directly [Evtushenko, 1985]. For an OPS model with both the vehicle interior and the occupants involved, it is very difficult, if not impossible, to calculate the derivatives of the objective function. So the direct method becomes the choice. Both the algorithm-
based optimization methodology and the DOE-based optimization methodology fall into this category. However, their theories and processes are very different.

The algorithm-based optimization methodology was developed in-house for OPS design and optimization. An integrated optimization system combines the optimization algorithms with computer simulation models, integrating the model preprocessing, solving, and postprocessing into a single system. Users only need to input the range of the design parameters. The integrated optimization system searches the whole design space and output the final optimal design.

The Exterior Penalty Function method is applied in the optimization system to address design constraints (e.g., geometry constraints and legislative performance requirements) in the optimization process. A few penalty terms are added to the original objective function (e.g., performance index in customer designated tests) to construct a penalty function. For any point falling inside the feasible set, the penalty function value is set equal to the original objective function value, while for any infeasible point, the penalty function is increased by a large positive term to keep the algorithm away from those points. The minimum value of the penalty function corresponds to the optimal values of the independent variables, i.e., optimal system design.

The optimization algorithm used in this integrated optimization system is the SWIFT algorithm [Wu, 1989]. It is based on the Simplex algorithm, one of the well-established direct methods for unconstrained optimization problems, combined with the Exterior Penalty Function algorithm for constrained optimization problems. Every iteration follows the basic procedure of Simplex algorithm, but the penalty factor in the Exterior Penalty Function algorithm is based on the results of the previous iteration. The information in the last iteration can be used to choose a reasonable penalty factor for the next iteration and accelerate the convergence. The SWIFT algorithm does not require the calculation of the derivative of the objective function, the number of calculations of the objective function is also relatively small, and convergence rate is relatively fast; thus it is very suitable for the engineering optimization problems with less than 20 parameters.

The algorithm-based optimization approach is fairly easy to use. The computer resource requirements and user interaction are minimum. As a tradeoff, the information output from the integrated optimization system about the OPS is limited. This approach is more applicable as a product design tool rather than a generic parametric study tool.

The DOE-based optimization methodology is often used for more general design space analysis. It helps to provide essential information for design variable screening, assess design variable impacts, and identify significant design variable interactions. The DOE-based analysis usually starts at the construction of a full factorial design matrix, including all the possible combinations of the design parameters. Such a full factorial matrix can easily reach a few hundreds or even thousands of simulations, which are cost and schedule prohibitive. Statistical tools such as D-optimal and Central Composite designs are utilized to reduce the full factorial design matrix to a fractional factorial matrix without losing the most important information about the system. For example, in the typical frontal occupant
protection system shown in Figure 5, eight MADYMO input parameters corresponding to systems performance are chosen as design variables (control factors). A list of these variables is given in the Table I.

A three-level full factorial design with 8 factors requires 6561 runs. To reduce the number of computer runs and construct an approximate functional relationship between the OPS responses and the design variables for system optimization, the Response Surface Method is used in this application. The methodology includes approaches for selecting data points where the analytical experiments should be evaluated, techniques for solving the unknown coefficients of a response surface approximation, and methods for evaluating the accuracy of the resulting response surface model.

D-optimal designs are particularly useful for selecting data points for computer runs when resources are limited or there are constraints on factor settings. They use criterion of minimizing the variance in the regression coefficients of the fitted model. D-optimal designs can be used regardless of the type of model to fit or the objective specified for the experiment. To fit a quadratic response surface model on the eight design factors using D-optimal designs, the minimum number of experiments required is 45 for D-optimal designs (8 × 7/2 = 28 for the interaction terms, 2 × 8 = 16 for the main effects and 1 for the constant term). To ensure a good fit, two to three times the minimum number of experiments are normally conducted for the OPS optimization. Given the total number of runs for a design scenario and a specified model, the computer algorithm chooses the optimal set of design runs from a candidate set of possible design runs. This candidate set of runs usually consists of all possible combinations of various factor levels that the designers wish to use in the analytical experiments.

After simulations for all the selected data points are performed, the results are processed and analyzed to create the response surface model. This approximate model is typically constructed in the form of a low-order polynomial based on a subregion from a D-optimal subset of analytical experiments. Once the response surface is constructed, multiple response optimization is performed to help identify the combination of input variable settings that jointly optimize a set of system responses. This method allows compromise among the various responses and helps manage conflicting requirements. As a result, optimal system performance can be achieved. Specialized knowledge of the OPS product in the study is often required during the analytical DOE process.

Compared with the algorithm-based approach, the DOE-based optimization methodology provides more information about the design space and draws a more comprehensive picture about the whole system. However, the computer CPU time and storage resources requirements are much higher, and more user involvement is necessary. This is a general full system analysis and optimization tool instead of a specific product design and optimization tool.

### 6. SYSTEM VERIFICATION AND VALIDATION

System verification and validation are to ensure that the system designs, processes, and products are fully compliant with the system requirements, including the functional, behavioral, performance, configuration, reliability, and maintainability requirements. The functions performed for system verification and validation consist of tests, analyses and simulations, inspections, and demonstrations.

Throughout the SE process as shown in Figure 1, verification and validation are integrated into each level of the system design. At the component design level, static tests are often conducted to verify the integrity and performance of the components. Afterwards, sled and vehicle barrier tests are required to confirm the optimal OPS design and test the robustness of the system. Verification and validation are an inseparable part of the SE process.

A typical vehicle design process is usually divided into a few major phases such as pre-prototype, prototype, pilot I, pilot II, preproduction, and production phases. The OPS engineering process is basically an iterative process of system design, modeling, testing, and technical evaluation and leads to a validated OPS design. During the iterations many concept alternatives are proposed, analyzed, and evaluated in tradeoff stud-
ies. At each phase, the OPS design improves as vehicle design evolves. For example, an optimized OPS design based on the inputs and constraints from the prototype vehicle structure provides a solid baseline for the pilot I phase design. The OPS design is then modified and reoptimized according to the pilot I phase vehicle structure and moves to the pilot II phase. The verification tests at the prototype phase not only verify the system performance of the prototype phase OPS design, but also help to correlate the mathematical models for the pilot I phase design and optimization. The OPS system is further improved at each of the following phases until its finalization.

7. DISCUSSIONS AND CONCLUSIONS

Increasingly complex OPS design has driven the needs for the SE approach. The SE process is a logical, systematic, comprehensive, iterative problem solving process selectively used to accomplish the SE tasks. It is implemented throughout the OPS design and optimization process, including customer requirements analysis, system concept design, system design, analysis and optimization, and system verification and validation. It helps to

- Understand and analyze the system requirements completely
- Set-up and correlate computer simulation models consistently
- Explore the design space systematically
- Integrate the verification and validation into the system design process effectively.

In summary, it helps to deliver better products to meet customer requirements. The continuous development and improvement of the SE approach to complex OPS design and optimization are still an ongoing process.

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