

# EXPEDITING INNOVATION IN AUTOMOTIVE PASSIVE SAFETY – SAFER DESIGNS IN A FRACTION OF THE TIME

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## Abstract

The use of Computer-aided engineering (CAE) to simulate numerous road vehicle safety-critical scenarios has become common practice. Despite the advancements in CAE and its advantages, the increasing intricacies of simulation tasks present challenges. The inherent complexity of such scenarios, characterized by the interplay of multiple physical principles and nonlinearities leads to simulation models with very large solve times. This results in long product development cycles, which makes meeting customer demands difficult and slows down innovation. Simcenter Madymo - the human safety-centric CAE software addresses this challenge due to its very fast solve times while accounting for all essential scenario details.

## Introduction

The evolution of CAE has been rapid in the last few decades driven by advancements in computers in both hardware and software. This has enabled simulations of more complex phenomena and significant design improvements for passive safety systems. The sooner it is introduced in the product development process, the more impact it can have in shortening its duration. CAE also helps in reducing the cost of conducting many physical crash tests which are significant approximations of realistic scenarios.



Figure 1 – Crash tests require carefully instrumented and calibrated test dummies, multiple vehicle prototypes, advanced, comprehensive sensing, and numerous repetitions. Simulations are a lower-cost alternative.

Physical crash tests are designed to ensure repeatability and regulatory compliance. They require vehicle prototypes, expensive crash test dummies, and specialized testing facilities. Although detailed simulations are less time intensive and expensive than experimental tests, they take a long time to set up, run, and produce a lot of data that needs careful analysis. Solutions to these challenges with CAE significantly shorten product design cycles.

This article explores the emergence of complexity by revisiting some fundamentals in physics and numerical analysis. This understanding will clarify the importance and usefulness of Simcenter Madymo in this life-saving domain.

### **The emergence of complexity and uncertainty in automotive passive safety CAE analyses**

The following sub headers describe each reason behind complexity and uncertainty in simulations.

#### **Multi-physics scenarios**

In safety-critical scenarios, various mechanical factors are at play, including vehicle motion, vehicle structural deformation, occupant biomechanics, mechanical contact, airbag deployment, and external forces like impacts. CAE software uses fundamental laws like Newton's second law, energy conservation, and mass conservation to model each relevant system and their interactions. Different interacting phenomena (or interacting systems) have different mathematical structures, leading to varied numerical treatments and hence, their complex, multi-physics nature. It is essential to account for all these interacting phenomena simultaneously for realistic, true-to-life simulations.

#### **High model order**

In passive safety analysis, simulation models have a high order, which means they have many unknown variables. The higher the model order, the greater the computational resources required to solve them. These high-order systems also produce a lot of output data. The human body, for example, comprises of numerous joints, parts, and deformable tissues capable of multidirectional movement, making it a high order system. Accounting for everything can yield a model order of thousands or higher, thus contributing to computational complexity.

#### **Nonlinearity**

The overall mathematical structure of models, invisible to CAE users determines if they are linear or nonlinear. Nonlinearity manifests in many ways – the geometry of a model, the materials of different components and in the equations governing its time evolution (nonlinear dynamics). Road accidents and crash tests, when modeled, are highly nonlinear phenomena. While nonlinearity is a mathematical concept, it carries significant physical implications.

In linear systems, the principle of superposition applies, meaning the result of a simulation due to multiple inputs equals the sum of results from each input analyzed separately. Nonlinear systems do not adhere to this principle, and the effect of each input cannot be isolated. Understanding this unintuitive behavior of nonlinear systems can challenge even the sharpest scientific minds, contributing to their complexity.

#### **Sensitivity to initial conditions**

The initial conditions are the starting point of any physical/virtual system evolving in time. Nonlinear systems with a high model order can exhibit a phenomenon known as sensitive dependence on initial conditions. Accurate assessment of such systems necessitates precise initial conditions. In such systems, two analyses starting with very small differences in initial conditions (with everything else being the same) can evolve to very different and unpredictable outcomes.

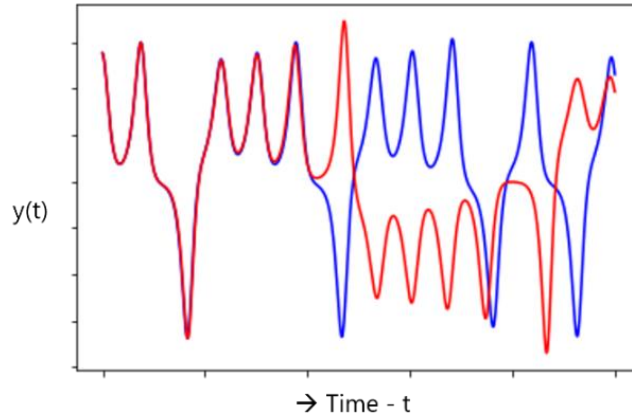


Figure 2: Sensitive dependence on initial conditions - The red and blue curves represent two simulation results each with only slightly different initial conditions. This difference is so small that the starting points for both curves are indistinguishable. As time passes, the differences amplify. The time scale at which these differences become large depends on the system. It could range from a few milliseconds to days.

Hence, specialized crash tests employing calibrated equipment like crash test dummies are conducted in controlled environments to make repeatable predictions. However real-world road accidents pose challenges due to uncertainties in initial conditions, making repeatable predictions with slightly varying initializations difficult. The exact vehicle and occupants' initial postures are always unknown.

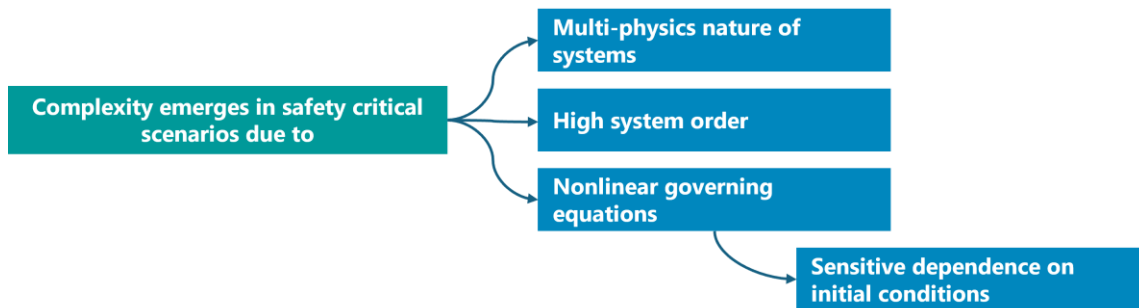


Figure 3: Summary of the reasons behind the emergence of complexity in passive safety analysis

**Imperfections in models**

Simulation models are inherently imperfect. Simplifying assumptions helps to capture essential factors governing a scenario but omit less significant details or elements too random or complex to model accurately. For instance, sudden strong gusts of side wind affecting a moving vehicle could contribute to accidents. Modeling such erratic and uncertain phenomena is difficult. Even if all phenomena are somehow modeled, the resulting very high-order model might render the problem intractable, even with today's powerful computers.

Moreover, numerical approximation of mathematical models for computer handling introduces errors, as numerical solutions are never exact. Consequently, engineers must assess acceptable error levels in their numerical simulations. Generally, higher the approximation higher is the numerical error.

Skilled analysts understand the trade-offs in modeling, knowing when to prioritize certain details depending on the project phase. Analyses early in a project should aim for an optimal design concept by avoiding unnecessary detail and retaining essential considerations, reducing computational demands. This pursuit of the best design requires a fast iterative process.

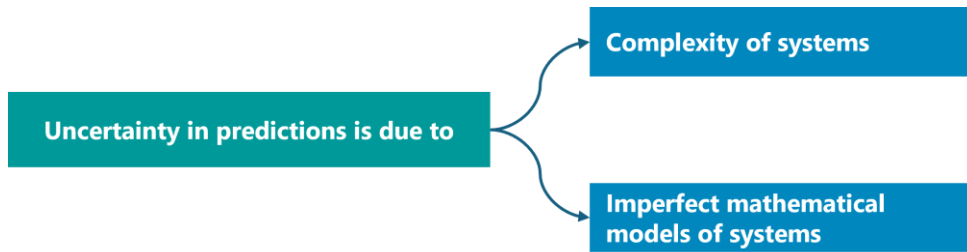


Figure 4: Contributing factors to uncertain predictions of simulation models

### The current way of quantifying injury risk

Relying on a few simulation runs might not fully address passive safety concerns because of the complexity and uncertainty of such models. There is a common approach to address one aspect of uncertainty - the uncertainty around injury risk. This combines biomechanics, crash test data analysis, and statistical methods to formulate so called injury criteria. These criteria allow engineers to assess injury likelihoods based on fewer simulations or tests. Injury criteria are also used as passive safety system optimization objectives – essentially these objectives are minimization of injury risks.

While extremely useful to quantify specific injury risk, injury criteria have limitations: they may overlook certain accidents and injuries, focus on isolated injuries rather than combined ones, and offer a simplified view of crash dynamics. Injury criteria consider specific phenomena and represent it as a single number, but they do not provide a well-rounded understanding of a scenario.

There are other open challenges on injury criteria – for instance, they do not account for changes in injury patterns over time. For example, head injuries in the past were typically skull fractures due to impacts. As safety has developed, other forms of injury like concussions or soft tissue injuries have become more common and new specific criteria have had to be derived to account for these. Additionally, injury criteria are incapable of quantifying long term injury risks. They cannot replace the insights gained from numerous detailed simulations and physical tests, which, although impractical, provide a better understanding of injury risks and in addition to other safety-critical aspects.

### The industry's approach to tackling complexity and uncertainty

The number of accident scenario possibilities is combinatorically explosive. Designing safe cars for all scenarios is a very difficult problem. The industry tackles this problem through regulations. Regulators analyze lots of accident data and define specific scenarios, also known as loadcases. Loadcases represent typical accidents with different types of crashes (frontal, side, or other) at specific speeds with carefully calibrated and positioned dummy models. These steps are taken to minimize the intrinsic complexity and uncertainty of outcomes.

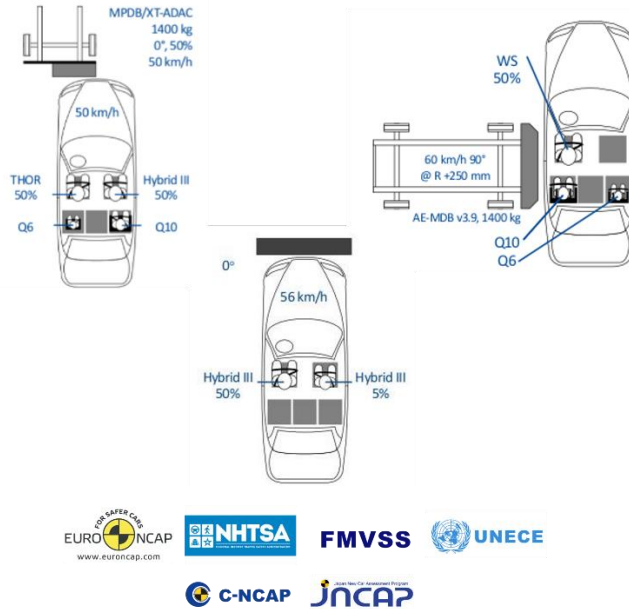


Figure 5: Regulation loadcases' examples involving carefully calibrated and positioned dummy models [7]

Safety systems are designed for such loadcases. Such an approach has led to drastic improvements in road safety. Prior to physical tests, engineers evaluate their vehicle designs using CAE. Improving safety systems under current regulations requires exploration of different design concepts. Reliance on very detailed CAE and a small number of CAE evaluations is not the ideal way to explore many new design alternatives.

To account for the evolving nature of vehicles and the type of road accidents, new loadcases are often added to regulatory requirements. This establishes a need to explore new safety design concepts. **Exploration of new design concepts using excessively detailed and slow CAE is a non-optimal approach. A fast lightweight CAE solution with the right amount of modeling detail is needed.** Such CAE solutions also allow assessments of many realistic accident scenarios that extend beyond specific restrictive loadcases. This creates an opportunity to further improve road safety through innovation.

**An Alternate Approach to handling complexity and uncertainty – A digression from passive safety**

The complexity and imperfections inherent in models, leading to uncertain predictions, extend beyond transport safety to various scientific realms like weather forecasting.

Weather models simulate the complex interactions among atmospheric components, incorporating data from various observations. These imperfect models are multi-physics, high order, nonlinear, and notoriously known to exhibit sensitivity to initial conditions, preventing long-term and precise forecasting.

To address this challenge, ensemble forecasting techniques, akin to Monte Carlo analysis [4], produce a set of forecasts instead of a single forecast. For example, temperature forecasts consider a range of possible initial conditions, resulting in a probability distribution of forecasted temperatures. Similarly, ensemble forecasting aids in predicting precipitation and storm paths, crucial for disaster planning and evacuation strategies. For instance, the statement 'Tomorrow there's a 50% chance of rain', is based on looking at the proportion of multiple predictions that forecast precipitation.

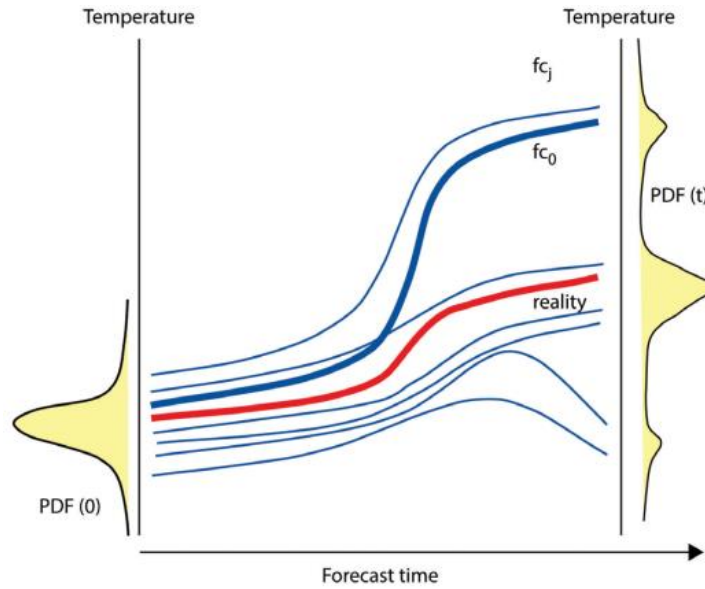


Figure 6: Temperature forecasts consider a range or a distribution of possible initial conditions and multiple simulations using them results in a probability distribution of forecasted temperatures. This helps quantify the uncertainty of predictions. Such an approach is more reliable than simply carrying out a single simulation



Figure 7: The precise initial conditions of a hurricane are unpredictable. Multiple simulations account for a collection of initial conditions (indicated by the red circle) and gives rise to multiple solutions based on which probabilistic forecasts of its trajectory are made

Drawing parallels with simulating safety-critical scenarios, accidents also feature uncertain initial conditions and multiple potential outcomes. Ensemble forecasting offers a natural approach, despite differences in time scale and uncertainty levels between weather forecasting and safety simulations. Moreover, they offer the possibility of gaining a better understanding of injury risks than restrictive and specific injury criteria.

While safety simulation engineers may lack the computational resources of meteorologists, reliance on highly detailed models may impede the discovery of optimal designs. Hence, choosing models or modeling techniques that have fast solve times while still retaining essential details is imperative for efficient assessment of human safety. In other words, a software tool that enables engineers to run a multitude of simulations and make ensemble forecasts about injury risks and accident outcomes.

## Numerical Aspects – The Challenges due to detailed Finite Element Analysis (FEA)

FEA is a necessary method for analyzing safety. It suits detailed biomechanical analysis, vehicle structure deformation, and seatbelt and airbag mechanics, making it favored by engineers worldwide for crash simulations. Despite its importance, running full FEA for studying human safety poses some challenges. Even though safety-critical events unfold in a matter of seconds, one full FEA detailed simulation can take up to days. Relying solely on full Finite Element (FE) simulations to analyze occupant and pedestrian safety can restrict engineers in the following ways:

- The limited analysis runs due to time constraints – slow solve times causes reliance on engineering intuition which is inadequate for high-order, sensitive, nonlinear systems.
- Risk of unreliable results from selecting just-stable time steps, possible neglect of numerical error analysis.
- Slowed parametric studies or optimization for seeking better designs due to excessive modeling details.
- Reliance on material models and possible inaccuracies of those
- A large amount of time spent in meshing and pre-processing – each step in the FE workflow requires specific expertise in meshing, crash analysis, etc.
- The possible sacrifice of numerical accuracy to save time by reducing finite elements.
- Hindered quick design iterations early in the design phase, again, due to excessive modeling details. Design concept optimization is uneconomical using full FE.

The factors above risk limiting innovation. For simulating real-world accidents, numerous unknowns exist, including human variability and imprecise initial conditions. Similarly, for crash tests, while initial condition uncertainties are minimized due to their highly controlled setup, reliance solely on full FE simulations to optimize restraint systems is inefficient.

## Simcenter Madymo - The Solution to these Challenges

Whether it be simulations of real accidents or controlled crash tests, both scenarios require a fast multi-physics solver. The solution offered by Siemens Digital Industries Software is Simcenter Madymo. **Simcenter Madymo is not an alternative to full FE crash analyses but rather a time-efficient complementary solution to it.** Its multi-physics solver is known for its unprecedented speed, encompassing many modeling techniques allowing engineers to account for the most essential details of a scenario. These techniques/methods enable modeling of rigid and/or flexible vehicle components, biomechanics, as well as airbags.

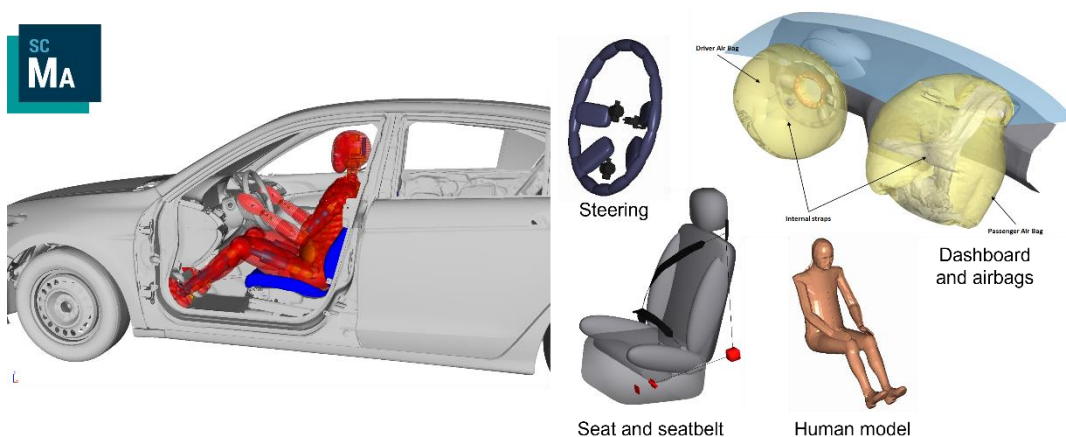


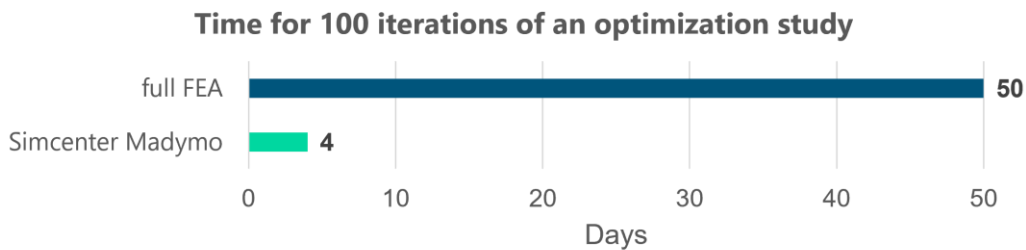
Figure 8: Simcenter Madymo offers unprecedented speed while still accounting for the most essential scenario details. The software can model a multitude of safety-critical scenarios where all relevant subsystems can be modeled, modularly assembled, and parameterized to run several simulations in a time-efficient way.

Simcenter Madymo offers several advantages:

- Quick solve times help engineers run many simulations fast, deepening their understanding of safety-critical scenarios.
- Fast exploration of design options helps create safer designs quickly, getting them to market faster.
- Analyzing sensitivity to initial conditions through multiple analyses or design of experiment studies helps make informed predictions.
- Fast numerical error analysis ensures stable and accurate solutions, boosting confidence in simulation results.

Moreover, its pre-processing and post-processing functionalities are tailored for safety simulations, featuring dedicated tools for easy occupant positioning and passive safety system modeling. The amount of data generated by Simcenter Madymo simulations are non-excessive in comparison to full FE simulations, enabling efficient post-processing and better insights.

Consider a simple example where an engineer is required to find the best combination of parameters for a restraint system through an optimization study. Figure 9 illustrates the superiority of Simcenter Madymo in speed.



- Assuming one Simcenter Madymo simulation takes 1 hour and one full FE solve takes 12 hours
- Conservative estimates. Simcenter Madymo runs can be faster, while a full FE solve can even take days.
- This does not account for the pre-processing effort in full FEA – meshing, material characterizations, etc.

Figure 9: Simcenter Madymo performs a simulation very quickly, enabling the same number of iterations to be completed in much shorter time.

In addition to the software, Siemens provides validated dummy and human body models (HBMs). The dummy model offering includes those used for regulatory compliance. These dummy and human models, including scalable variants, enable engineers to assess occupant interactions with other systems comprehensively, quantify injury risks, and iterate design concepts until optimal solutions are achieved.

Simcenter Madymo enables early design evaluations and iterative assessments to quickly identify and rectify potential issues, thus expediting safety solutions to the market. After conducting many preliminary design evaluations, users can seamlessly transition to detailed FE analyses ensuring a holistic approach to safer design implementation.

Furthermore, Simcenter Madymo facilitates co-simulations with FE solvers including Altair® Radioss™ from Altair Engineering among others, empowering engineers to analyze vehicle structure deformation and human safety comprehensively. Thus, Simcenter Madymo can also be used beyond the initial design concept phase in a project and throughout the simulation lifecycle of a safety solution. Coupled simulations allow users to easily integrate Simcenter Madymo with their existing CAE workflows, without additional effort.



Figure 9: Coupled simulations with Altair® Radioss™ enable users to perform combined assessments of human safety and vehicle structural analysis thus, well-rounded safety assessments.

In addition to facilitating co-simulations with Altair® Radioss™, Simcenter Madymo is a part of the Altair Partner Alliance (APA). By amalgamating multi-physics technology of Siemens with the capacity for detailed analyses, simulation engineers gain the ability to craft safer safety system designs faster.

### Concluding Remarks

Computer simulations as well as physical tests are effective, yet imperfect techniques in improving automotive passive safety. Exclusive reliance on any single simulation technique and unwavering trust in its predictive ability is a suboptimal scientific approach. **Considering multiple modeling approaches and numerical methods for well-rounded understanding as well as time-efficiency is a better alternative.**

Simcenter Madymo is suitable for optimizing early safety design concepts. It complements detailed CAE and seamlessly integrates with existing simulation workflows. It plays an important role in enabling safer designs in a fraction of the time.

### References

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