Executive summary
It is increasingly important to incorporate safety systems into vehicles. With advancements in vehicle electrification and autonomous vehicles (AV), the automotive industry is undergoing a transition that is safer and more environmentally friendly. This white paper discusses the transitions occurring in the automotive industry and what considerations for integrated safety system designs are relevant today or are expected to gain relevance in the coming years. The role of robust, fast and accurate numerical simulations in the development process of integrated safety systems is emphasized in this white paper.

J.M.A. Melvin, K. Chatrath, K. Shienmar, Siemens Digital Industries Software
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The use of biofidelic human/dummy simulation models with good predictive capabilities is of great value. Simcenter™ Madymo™ software, which is part of the Xcelerator™ portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, offers a wide range of such models and allows users to simulate a variety of safety-critical scenarios and design an appropriate safety system. To more conveniently facilitate integrated safety system design with Simcenter Madymo, the Framework for Occupant Restraint Testing and Evaluation (FORTE) application has been made available to users of the software. This application offers a simulation environment that is user-friendly, modular, versatile, numerically robust and time-efficient in setup as well as execution.

Automotive safety systems of today have a complex multilayer approach to ensure occupants’ safety. There are two classes of safety systems: passive and active. The active takes action to avoid or reduce the size of the impact; for example, electronic stability control. A passive system reduces the injuries sustained when a crash occurs; for example, seat belts. An integrated safety system combines these two systems. For more information on these systems, you can consult our previous blogs:

- Autonomous vehicles enter a validated future
- The evolution of integrated occupant safety systems

This white paper looks at the state-of-the-art and investigates the future of integrated safety systems.

Electrification and driverless cars

The automotive industry is in a transition phase. Although combustion-powered vehicles remain common on the roads, there is growing popularity and demand for hybrid-electric and electric vehicles (EVs). This evolution in powertrain concepts has an impact on the design of vehicle interiors and dynamics. In a safety-critical situation, the vehicle occupant’s motion depends on their initial posture, activities, environment and the vehicle’s kinematics. Changes to the vehicle’s internal environment and motion have implications for safety system designs.

According to Bellona Foundation, the 2020 pandemic has shone a light on the changes occurring in the automotive industry. EV sales increased across Europe by 107 percent during this period, while internal combustion engines (ICE) had a large drop in sales. Despite the decline in sales, conventional combustion road vehicles continue to be the most widely used powertrain type. The increasing...
The popularity of alternate powertrain solutions has led to a wider variety of vehicles running on the roads. This variety presents an interesting challenge for vehicle safety system manufacturers. There is a need to develop designs that are effective for each vehicle type, be it combustion, hybrid or electric.

The need for improved safety and comfort has made vehicle manufacturers think of automating the task of driving. The road to complete vehicle automation has been a work-in-process (WIP) for several years now. The progress made and anticipated in vehicle automation is quantified in the SAE J3016 taxonomy. Apart from many other details, the document lists six stages of vehicle automation ranging from level 0 to 5. Level 0 is no automation while level 5 is complete automation requiring no human intervention. The state-of-the-art of automated driving is one where vehicles are increasingly equipped with functionalities like cruise control, lane-keeping assistant, etc. These functionalities assist the driver in maneuvering a vehicle but still depend on the driver to perform most driving tasks (levels 1 and 2).

Vehicles that are capable of automating motion but require human intervention when it functions outside its operational design domain are still rare on the roads today, but developments are ongoing in this area. Although leaders in the field are optimistic about achieving level 4 and 5 autonomy (little or no human intervention in driving tasks) in vehicles, the date of arrival to markets remains difficult to predict. This uncertainty is due to the challenges yet to be overcome, including the occupant’s safety needs and those of other road users.

Considering new developments in vehicle powertrains and advancements in automated driving, the variety of vehicle types on roads have increased and will continue to do so. Therefore, it becomes necessary to equip each vehicle type with a suitable safety system. It has become essential to develop a framework for simulating the variety of vehicle powertrain and automation level combinations for safety system development.

### Tasks of occupants

#### The recent past

Safety systems of the early 2000s worked on the principle of saving the occupant in the most likely crash scenario, and the requirements used to fire an airbag highlight this, including: The vehicle must be moving at more than 25 kilometers (km)/per hour (h), the angle of impact must be within approximately 30 degrees of the car’s centreline, airbags are designed only for adults and, therefore, children should not occupy the front seat. Furthermore, drivers of 4 feet, 6 inches or less are allowed by National Highway Traffic Safety Administration (NHTSA) regulations to fit their car with an airbag off switch because the airbag poses an increased risk of injury to them.²

Safety engineers have become skilled at developing rules of thumb to design their safety systems. They have been able to do this because:

- There are many fixed requirements for the safety systems, such as those listed above for the airbag
- The driver has to maintain a consistent position to reach the pedals and steering wheel

Fixed requirements reduce the number and variability of the parameters that define the environment in which a safety certification test is conducted. Reducing the number and variability of a small number of parameters can significantly reduce the complexity of any system under investigation, such as a car and occupant in a crash test. At the same time, maintaining a consistent position for the occupant further reduces the number and range of potential variables in the system under observation.
Introduction of electronic safety systems

Although the requirement for the driver’s airbag to only be for adults has changed little, this is not true for many other safety features. With the continued development of electronic systems that have become much more reliable and sophisticated, they are now an integral part of safety systems. In 1999 Mercedes-Benz introduced the electronic stability control system (ESC), which many safety experts believe to be the most important advance in vehicle safety since the seat belt. It is thus unsurprising this feature has become compulsory in many territories, including Australia, in 2011. Antilock braking systems (ABS) and ESC were the first of many more advanced active safety systems to ensure the occupant’s safety.

The advancement of sensors has significantly increased the number of possible advanced driver assistance systems available such as lane-keeping assistance, adaptive cruise control, lane-change assistance and pedestrian detection.

Looking toward the future

Tools such as collision avoidance systems, autonomous emergency braking and lane-keeping assistance work as safety features and have the potential to reduce the burden on the driver. In fact, if a car had all three of these systems, it would already be considered a level 2 autonomous car (per SAE J3016). With such functionalities already available, it is not hard to imagine a future without a driver (level 5). However, before we reach a driverless safety utopia, there are still several steps. The next development is a semiautonomous car (conditionally automated) that can switch between driver and driverless modes depending on the environment in which they are traveling (level 3). The following section will look at some of the integrated safety developments and related projects required to reach a safe autonomous future.

Figure 1. Intelligent digitalization of road networks is of critical importance for economic growth and quality of life. This is why Siemens Mobility has developed the Vehicle2x technology, which is a secure, cooperative technology for communication between all kinds of vehicles and infrastructure. Vehicle2x is part of the growing Internet of Things.
If in an autonomous vehicle the need for a driver’s seat becomes obsolete, designers may consider removing all the seats. Perhaps for pods operating for short commutes, say between the station and your office, one would only need to stand. Standing room only will get more people in shared pods, lowering the cost of running routes and thus making more routes viable. However, all occupants standing is likely only the case for pods and is not so likely for privately owned vehicles where owners may wish to have fully flat beds to snooze their journeys away.

To accurately predict future trends and safety requirements, engineers and researchers need data to establish and validate their simulation models. Since there are no fully reclining seats on most public highways because they are generally not recommended for safety reasons, there is little accident data. Some countries in Asia and South America allow sleeper buses but accident data for these is also limited. Therefore, researchers have to develop their models on conceptual ideas and test likely design concepts for practicality, user experience and safety.

Initial investigations have found that reclined seating positions result in the lap belt being placed above the pelvis, increasing the risk of submarining during frontal collisions. Submarining occurs when the occupant’s pelvis slides under the lap belt and loading is transferred from the pelvis to the abdomen, increasing the risk of serious injuries that are sometimes fatal.

Seat belts are not the only piece of safety equipment that is inhibited by reclined seats. When the occupant is seated upright, a large area of the occupant’s body moves forward vertically. This occupant position offers up a large surface area that can contact the airbag at a relatively predictable distance, especially when the seat belt is working optimally. When the occupant is reclining, the airbags will likely completely miss the occupant, either passing over the top of them or not extending far enough to have any benefit. Additionally, knee bolsters that would ordinarily prevent large displacement of the legs by blocking their motion, may never contact the legs.

The changes in seat belt loading and the reduced effectiveness of the airbag and knee bolsters will significantly affect the injuries observed. New neck and lower back injuries may become prevalent as the loading on these regions substantially changes.

Rear-facing seats
To better understand what someone may experience in a rear-facing frontal impact, researchers began investigations. One of the first design constraints observed was the position of the D-ring. The D-ring is typically located on the B-pillar. Researchers observed that if the seat swiveled from front to rear-facing, a belt connected to the B-pilar would either come off the shoulder or wrap around the seat and neck of the occupant. To prevent this belt issue, tests have been conducted with the D-ring fixed to the seat. Like in forward-facing seats, rear-facing seats of the future may also need to consider how much seat recline users would like to have – investigations into this subject produced exciting results. Studies have found the belt attached to the seat generated fewer injuries than those attached to the B-Pillar. Investigating the effects of rear-facing seat inclination found that when reclined to 45 degrees, more injuries are sustained than at 25 degrees.
Increasing test complexity
Above we have covered one of the many complications that can occur when changing seat designs. However, there are many more variables that engineers need to tune before seats are safe to use in autonomous vehicles, such as:

- Seat pan angle
- Occupant age
- Size and gender
- Potential new airbag and safety system designs
- Reclining seats

All these changes are happening while groups such as New Car Assessment Program (NCAP) and NHTSA are increasing the number and complexity of the standards they expect to be met. Therefore, the future car designer is confronted with a level of complexity and a volume of variables far greater than ever before. It is likely engineers will need to perform an extensive range of tests to validate their safety systems for every seating position configuration.

Problems that engineers face
The engineering problem of designing better safety systems in any form of transport is essentially a highly nonlinear multi-objective optimization problem. Broadly speaking, the objectives are minimization (ideally, elimination) of incidents of transport-related accidents and the maximization of the quality and robustness of the designed systems. What complicates this optimization problem even further are the constraints. From a business perspective, these constraints are budget and time. There is also a constraint generated by the market forces that continually change the problem’s parameters with the constantly evolving state-of-the-art of transportation. As highlighted previously, two of these rapidly evolving development areas are the influence of automated driving functionalities and powertrain electrification of road vehicles. Moreover, as vehicle technologies and occupant activities evolve, each variation needs to be considered.

Arriving at optimal designs is also a time-consuming exercise. Physical crash testing, although providing insight, is a tedious process and testing all possible safety-critical scenarios is not the most cost-effective route. This is where a numerical simulation framework becomes necessary. Such a framework requires accurate modeling of human occupants, vehicle interiors and restraint systems. This solution has indeed been recognized and explored by the market. Finite element analysis (FEA) has been one of the modeling techniques. However, exploring many design possibilities in a time-efficient manner becomes a challenge with FEA.
Safety engineers need a simulation framework that conveniently allows users to model all aspects of any transportation safety-critical scenario. To ensure this framework is used correctly, it is necessary to have ease of modeling as well as modularity. Furthermore, the simulations should be robust and accurate from a numerical standpoint and completed in a relatively short amount of time. This would allow engineers to perform several iterations of the designs.

In addition to the numerical robustness and accuracy, engineers must anticipate the future needs of the market. Being able to simulate a wide range of situations is an essential step. They could range from frontal or lateral impacts, different seating postures, seat orientations, vehicle interiors and motions, as well as numerous restraint system types, etc.

Siemens continues to seek the globally optimal solution to this complex optimization problem. With this in mind, the following sections describe such an integrated safety simulation framework.

**Solutions**

Simcenter Madymo is a software solution meant for occupant and vulnerable road user safety simulation. The concept of multi-body dynamics coupled with a multi-physics solver facilitates modeling of safety simulations. The software comes equipped with a wide range of human and dummy multi-body models that are used to analyze various safety-critical scenarios. Studying the biomechanical response of human and dummy models allows engineers to design safety systems in a time-efficient manner due to the computational speed advantage offered by multi-body dynamics compared to FEA.

Keeping in mind the points discussed in earlier sections of this white paper, the Simcenter 3D software team has worked on an integrated safety application for use with Simcenter Madymo. The application is called FORTE.

FORTE can be used to offer the following benefits:

- **Versatility**
- **Reduced learning curve**
- **Modularity**
- **User friendliness**
- **Quick to set up**
- **Short run time relative to FEA**

**Versatility**

When using the FORTE application, various scenarios can be simulated by first positioning a dummy or human model inside a generic vehicle environment. Users then prescribe the motion of this generic vehicle multi-body model. The prescription of vehicle kinematics allows users to simulate different situations such as crash events, evasive maneuvers, emergency braking events, etc. User-defined scenarios can also be conveniently created by prescribing vehicle motions of interest. Using a similar simulation setup for different dynamic driving scenarios allows safety system designers to assess the performance of restraint systems under various circumstances.

**Modularity of FORTE**

Depending on the need, the vehicle interior environment, including the seat, belt systems and airbag systems, can be conveniently replaced with one of the user’s choice. The models are segmented into subsystems and parameterized to enhance user-friendliness. Moreover, the user can easily choose from a range of dummy and human models. Seating postures and configurations can be modified to the appropriate predefined parameters. Such a modular and parameterized simulation setup makes the application suitable for extensive parametric or optimization studies.
**User-friendly and quick setup**
The modular features of the FORTE application are designed to enhance user-friendliness. Ease in defining a specific load case by varying the appropriate parameters spares the user from setting up simulations from scratch.

**FORTE addresses the needs of integrated safety simulation**
With the constantly evolving safety needs of the automotive market, the FORTE application delivers a reliable and adaptive solution. Dynamics of any vehicle can be modeled by quickly changing the prescribed motion. With the automotive landscape slowly transitioning toward higher levels of automation, simulating seating positions and human/dummy postures is convenient and straightforward in this integrated safety framework.

The models in FORTE are best suited for analyzing the kinematic response in various safety-critical situations. In addition to kinematics, various injury criteria, such as head injury criterion (HIC), brain injury criterion (BrIC), etc. can be quantified. These injury criteria are a function of kinematic quantities. Dynamic quantities (such as joint/constraint forces, forces due to active and passive elements) can also be quantified, providing insight into human/dummy motion. The models available for use within FORTE are validated using experimental data collected at the TASS International Test Center and university research labs.
Conclusion

The developers of the FORTE application are constantly thinking of new ways of adding value to this simulation product. Integrated safety solutions do not have a one-size-fits-all answer and it is imperative to arrive at optimal designs that are compatible with humans of varying sizes and populations and both genders to ensure the safety of the entire global population and not just a subset. As a result, one among many things of interest to the team is the option of running simulations using scalable (in terms of mass and dimensions) dummy and human models. In recent releases the team has addressed this by adding scaling to their workspace tool and incorporating scaling from the Jack™ software in the Tecnomatix® portfolio. This scaling tool has significantly increased the number and types of population databases that can be used to scale Simcenter Madymo models. However, the industry as a whole has a long way to go before it is able to provide the same level of safety for all occupants.

References
About Siemens Digital Industries Software

Siemens Digital Industries Software is driving transformation to enable a digital enterprise where engineering, manufacturing and electronics design meet tomorrow. Xcelerator, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, helps companies of all sizes create and leverage a comprehensive digital twin that provides organizations with new insights, opportunities and levels of automation to drive innovation. For more information on Siemens Digital Industries Software products and services, visit siemens.com/software or follow us on LinkedIn, Twitter, Facebook and Instagram. Siemens Digital Industries Software – Where today meets tomorrow.