

# **PREDICTIVE SAFETY: TOWARDS HOLISTIC TOP-DOWN SYSTEMS ENGINEERING FOR PRE-CRASH SYSTEMS**

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## **ABSTRACT**

Since the first equipment of vehicles with environmental sensors for driver assistance systems more than 20 years ago, engineers are working on employing this data to improve or enable the activation of existing or envisioned passive safety systems. This task is motivated by potential benefits in occupant safety. In particular by an increased robustness of activation logic or by innovative actuators which promise to enable more degrees of freedom for new vehicle interior designs and the positioning of occupants. New regulations for ADAS functionalities lead to high equipment rates with environmental sensors which can foster the integration of active and passive safety technologies. Signals with an appropriate quality can be used smart to improve occupant safety in holistic safety strategies combining active and passive safety systems still offers big potentials (see e.g., ref. [1]). In this paper we aim to detail challenges in the multidisciplinary field of “Pre-Crash”, the field of using environmental sensing to improve occupant safety. This requires considering the whole functional chain: sensor – perception – prediction - function logic - actuator, and further system properties like functional safety (including SOTIF topics) or validation strategies. As an example, throughout this paper, we will use a new functionality of a reversible pretensioner to reposition a forward leaned occupant by seatbelt retraction, called Active Occupant Repositioning. By getting into details, the complexity and mutual influences becomes apparent. Discontinuous relationships and dependencies on scenario details exist. The challenge is to divide the problem into manageable tasks. To get a clear understanding and a basis for communication we classify Pre-Crash systems in different base architectures and elaborated principal differences to assess the suitable next step for Pre-Crash system development. Methodologies are reflected to develop Pre-Crash systems, and strategies are derived to adjust the variety of dependent system parameters. Therefore, properties of an electromechanical actuator are analyzed to come towards a holistic Pre-Crash system development.

## **HOLISTIC SAFETY STRATEGY COMBINING PASSIVE AND ACTIVE SAFETY**

Passive safety, active safety, regulations, safety education, safer infrastructure among other disciplines did and will contribute to road safety. In Germany, the traffic fatalities have been reduced to 1/10 in the last 50 years although three times more motorized vehicles take part in traffic nowadays. Due to innovations, stricter regulations and a change in awareness, accidentology does not show these statistically noticeable accident use cases any more. With accident reconstructions specialists are able to analyze details on how accidents could have occurred. But complete details of the situation in the interior are highly complex to reconstruct. Preparing an occupant to be best protected and get the best performance out of the restraint system is reasonable but statistically benefits are still hard to prove with statistics from accident database. Reacting before an accident comes with a lot of other challenges.

Different studies show tremendous potential to reduce the injury risks for the driver using adaptive restraint systems in real world accident scenarios assuming it can e.g., be adapted to specific relative velocity and occupant position (by e.g. 20% to 50% [2]).

Since July 6th 2022 all new developed vehicles in Europe have to be equipped with advanced driver assisted systems. From 2024 all new registered vehicles in Europe have these additional systems. These regulations lead necessarily to a 100% equipment rate for new vehicles with environmental sensors. This opens up potential for a quick market penetration using standardized sensor sets for new functionalities.

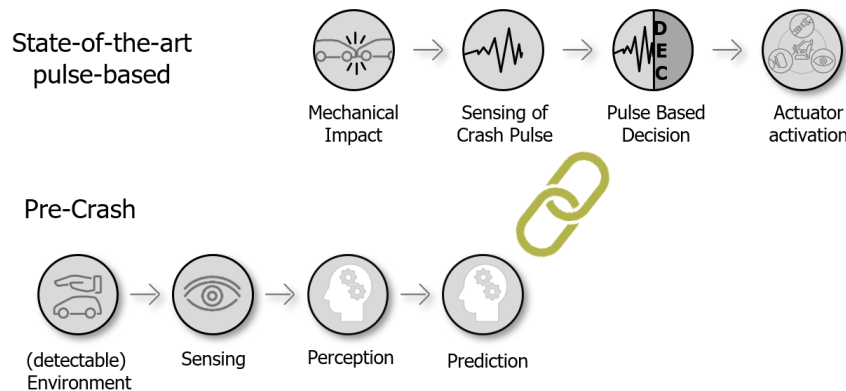
## **CHALLENGES FOR PRE-CRASH**

When a crash is unavoidable the goal is to protect the vehicle occupants, to mitigate the crash consequences. We define Pre-Crash systems as systems which use the information of environmental sensors before a crash to improve the occupant protection system performance. State of the art pulse-based or in-crash decision logics measure the mechanical impact and derive the decision logic for an actuator (Figure 1, pulse and pressure). The information which is collected with environmental sensors can be used with different strategies to improve occupant safety. Basic additional elements of a Pre-Crash systems are a perception and a prediction module. A perception is combining the sensor information to interpret the environment and abstract it in a model. A prediction is necessary to be able to react before something is happening or to offset latencies, depending on the application the information

is used for. With Pre-Crash systems the goal is to develop occupant safety beyond the standard load cases which leads to challenges in different fields when compared to pulse-based systems. We are working on fundamental critical challenges to enable system development

- to make the systems objectively assessable,
- to derive complete requirements,
- to develop methodologies to handle multiple result influencing parameters with complex interdependencies and uncertainties and
- to enter new ground in functional safety depending on the system parameters.

These fundamentals are further described in the following subchapters.



**Figure 1 Basic understanding of Pre-Crash compared to state-of-the-art pulse-based decisions**

### Performance Assessment

The performance assessment of state-of-the-art passive safety systems only takes in-crash decisions in defined standard-load cases into account (pulse or intrusion based). To develop robust triggering algorithms a combination of fire, no-fire and so-called misuse events was established and further developed over decades with field experience. Misuse events in the field of deployment algorithms is an expression for test cases which are used to prevent unintended firing due to misinterpretation of the accelerometer-based decision. Examples are situations which result in a high acceleration peak at the beginning of pulse but do not justify a triggering signal like curbstone override or shopping cart impacts. Environmental sensing enables a safety strategy prior to an imminent collision. As the situation before the crash is not taken into account yet in legal or consumer rating test strategies, not only the system, but also the effectiveness assessment and the proof of concept has to be developed. The potential to improve vehicle safety with information gathered with environmental sensors is also in focus of consumer rating organizations. First not yet specified incentives for Pre-Crash systems are planned in the Euro NCAP Roadmap 2030 for the year 2026.

### Requirement elicitation

To derive requirements for occupant safety beyond the standard load cases is a basic challenge. The relevant field of action and respective measures of effectiveness (MOEs) have to be defined. Fields of action can be defined differently, from broad and comprehensive improving restraint performance in the field to very specific improving occupant safety in defined load cases. Also, the MOEs vary from improving occupant safety for the average driver, increasing robustness to addressing specific groups like elderly driver (an example from the Euro NCAP Roadmap 2030 Milestone M7: Senior protection: low severity testing with sled). The existing standard load cases are developed for conventional in-crash systems. Pre-Crash signals are not allowed in the specification of these standard load cases and cannot be taken into account. The Pre-Crash maneuver or Pre-Crash situation e.g., influencing the occupant's position are not taken into account because the real benefits cannot be shown in the existing standard load cases. In addition, acceptance criteria for unnecessary or unintended activations are crucial aspects to be developed as well.

### Enhanced system design complexity

As described conventional pulse-based decision logic, calibration and validation tests were developed and optimized over several decades. The multiple effects which can reduce the quality or level of information of environmental sensors exceed the number of cases for conventional impact pulse measuring. For existing pulse-based decisions, the pulse evolution during the impact is not completely known at the time of an activation decision, nevertheless due to established calibration methods the severity of the impact can be judged robustly. In comparison, limits, tolerances and uncertainties for environmental sensors are numerous and the risks of misinterpretations are higher and have to be taken into account for a holistic system development. In addition, some object parameters which are necessary for crash severity estimations like e.g., mass, stiffness or fixation cannot

directly be measured and have to be estimated in advance (e.g., with object classification and corresponding accuracy). To react early enough before an impact and to compensate latencies, the vehicles trajectory and the possible bullet trajectory have to be predicted with an accuracy which is limited as any given situation can result in different impact constellations or even near misses.

### **Safety assessment methodology**

If missed/delayed activation or unintended activation are rated “safety relevant” in terms of functional safety, a property which depends on the specific action and further actuator characteristics of the specific system, these limitations must also be regarded in the context of product safety. The well-known standard ISO 26262 addresses failures inside the (electrical control) system and will not handle performance limitations. The new standard 21448 for “safety of the intended function (SOTIF)” focuses on such safety issues which arise from “situational awareness, derived from complex sensors and processing algorithms”. The application of this standard to Pre-Crash brings some further challenges. The standard was originally developed for ADAS/AD systems which take over a dynamic driving task. In its current state, SOTIF aligned to a limitation of the Operational Design Domain (ODD). The standard and specifically the idea of an ODD must be adapted for systems mitigating crash consequences. The SOTIF standard requires a full scope description of the intended function. Currently, crash mitigation systems are defined by reference load cases representing statistically relevant scenarios and describing minimal requirements extended with specific OEM requirements. A full scope specification presents uncharted waters for the field of occupant protection. Direct acceptance criteria are not defined in the SOTIF standard but must be derived with basic principles like GAMAP (Globalement Au Moins Aussi Bon), ALARP (As Low As Reasonably Practicable) or MEM (Minimum Endogenous Mortality) which are challenging to apply and break down to specific performance goals.

### **STRATEGIC NEXT STEP PRE-CRASH SYSTEMS**

To structure the variety of possible Pre-Crash systems, we define three main base architectures (Figure 2). With “Assisted Systems”, we describe systems which use the information of the environmental sensors as additional input for the decision logic to optimize in-crash activation times (after the first contact) or activation logic robustness. The weighting of the perception inputs vs. the pulse thresholds, in other words the responsibility of the perception signals can be used in a wide range. “Add-On systems” have two separated decision paths, one relying exclusively on the signals of the environmental perception with a second ‘state of the art’ decision path relying on conventional crash pulses as a fallback option. This architecture allows for systems with a reduced field of action comparable to an ODD for ADAS/AD systems when focusing on true positives. In the third base architecture, the decision path solely relies on environmental sensors to activate before the first contact and is “fully responsible” for any activation of the restraint system.

Most common in the market are Add-on systems with actuators bringing minimum risk of harm if activated inadvertent and bringing benefits within their limits. To minimize risks, velocities and forces of actuators are limited and the actuation like chassis lifting to improve compatibility of vehicle structures are limited to defined velocities.

ZF has already Pre-Crash assisted systems in serial production. In so-called truck underride scenarios, when the front energy absorbing structure is not in direct contact with the crash opponent, the accelerometers mounted in the front crumple zone may measure reduced deceleration levels in the early impact phase as compared to typical car-to-car crashes, introducing trade-offs in restraint deployment performance. This is a principal problem of poor crash compatibility with impact-sensing accelerometers, which can be improved by an assisted system. To recover more optimized restraint system performance, information from the environmental sensing technology is used to assist in the contact-based crash detection judgment, thereby improving deployment timing and reliability in underride impacts, while maintaining robustness in all other scenarios.

Similar strategies are being employed to assist pedestrian impact judgement in Vulnerable Road User Hood Lifter systems, to improve performance in the challenging uses cases specific to these systems. These are among the first steps being taken to integrate pre-crash sensing information into state-of-the-art restraint control systems, to further improve the safety value provided for occupants and pedestrians. ZF continues to evaluate further Pre-Crash assisted solutions across the operational domain of traditional contact-based restraint control systems, as well as for Fuel / Battery Cut Off and Emergency Call functions.

To further develop assisted systems, market entry and penetration is important to follow an evolutionary development strategy. The reasonable evolutionary next step to tackle challenges of decisions relying solely on environmental sensors is the transition to Pre-Crash actuators with fallback or also called add-on architecture. If the actuator is non-safety-relevant for unintended firing, the requirements from product safety during the development process of add-on functions are comparably low. One serial product out of this category is the ZF Active Controlled Retractor with the ability to reversible retract the seatbelt independent of the pyrotechnical activation. Its actuation is, e.g., based on vehicle dynamics information during a pre-crash phase, which has a high signal reliability.

But once an add-on function is potentially safety-relevant an adjusted development methodology is required. There it is essential to understand the parameters influencing the safety relevance and to understand the benefits and disadvantages when crossing this border in detail. To reduce complexity and to go step by step, the actuation should be flexible in timing. The actuation triggering time should be flexible in timing as well as in duration, in time of effectiveness of the actuator. In this paper we will further use a new add-on function for active controlled retractors: the Active Occupant Repositioning is a function that brings an occupant into a nominal position before an imminent collision. With the possibility to adapt force limits, define force progression and hold forces the flexibility is given to take this as an example. Details on the relevant parameters for appropriate next Pre-Crash system properties and an analyze of the pretensioner function system concept will be presented in the following.

**Understand influencing parameters and effects on threshold for functional safety relevant actuation**

For safety critical actuators, the requirements for the functional chain from sensing to decision logic changes. Depending on risk of harm or distracting a driver in case of a “false positive”, the requirements differ compared to state-of-the-art systems like e.g., AEB. As described in SOTIF Annex C with the example of an AEB, the risk for this system to end in a hazardous event after a false positive is reduced due to the dependency of the following traffic usually keeping enough distance, and if not, it does not necessarily end in a hazardous event. If missed/delayed activation or unintended activation are rated “not safety relevant” clear testable requirements have to be derived from user acceptance criteria to be able to balance performance versus false positive rate. If a safety relevant actuation is necessary to fulfill the overall goals, then the decision is made to break new ground in several disciplines like safety, validation and beforehand requirements elicitation in a balanced development process which we describe in the next chapter.

Depending on the system requirements and the corresponding safety relevance the Pre-Crash base architecture is defined (Figure 2). There are categorical differences in these architectures with different advantages and disadvantages. As described, depending on the necessary responsibility of the perception in an assisted system also the safeguarding efforts can vary in a wide corresponding range. In an Add-On architecture, safeguarding intended activation is not necessary, because errors can be compensated by a fallback (described in the next chapter). If safeguarding unintended firing gets relevant depends on the actuator. If an actuator is rated safety relevant, a defensive decision strategy is obligatory and reduces the triggered scenarios and thus the true positive rate. For fully responsible systems safety requirements for unintended activation and intended activation exist per definition and errors in crash prediction are difficult to compensate. The parameters influencing the safety rating have to be analyzed and understood in detail and the effects on the development process and the function below and above the safety thresholds need to be known to prepare a basis for strategic decisions.

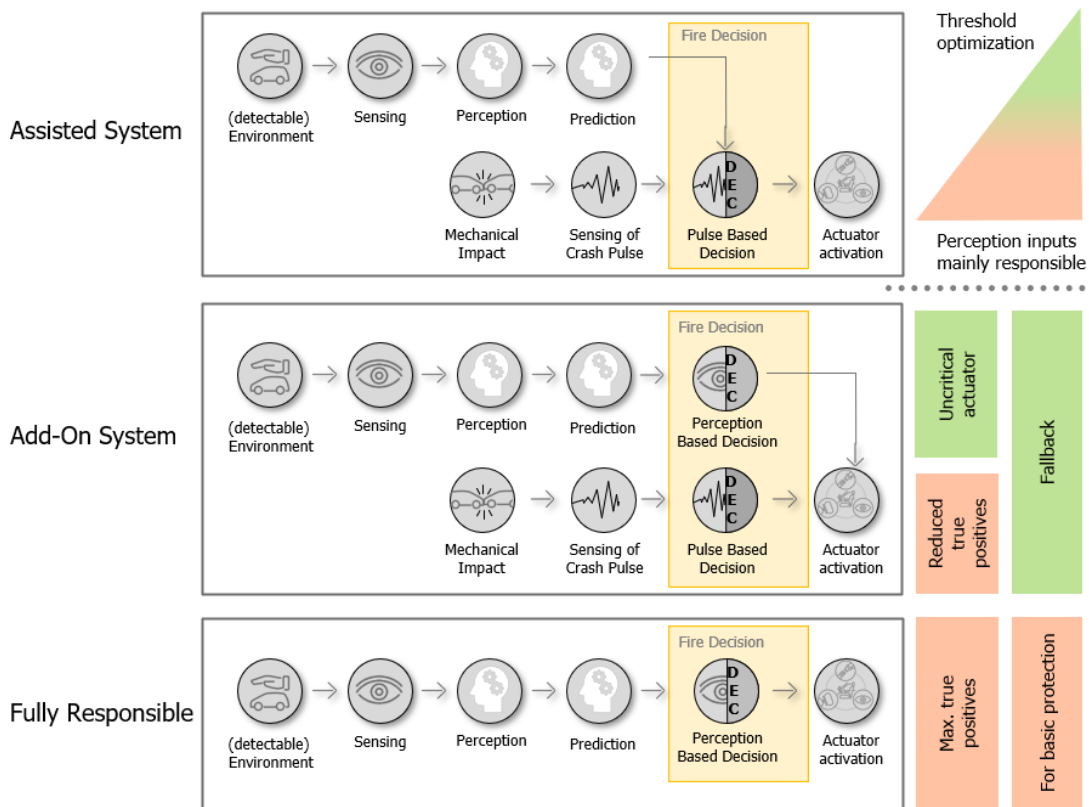


Figure 2 Pre-Crash base architectures and their categorical safety rating

### **Why with fallback / add-on architecture?**

Pre-Crash with fallback means a system guaranteeing a basic occupant safety level even if the activation is not triggered by the Pre-Crash detection. The fallback solution can be realized with different concepts. Possible solutions are triggering a time flexible actuator with a pulse-based system if the Pre-Crash signal was not detected or triggering a different actuator with the fallback path. A special exception is guaranteeing enough basic protection (e.g. defined by legislation) without triggering a function, e.g. by the vehicle structure and interior. An occupant safety system without a fallback would end in a Pre-Crash system with the highest complexity, the fully responsible architecture (Figure 2). The challenge would be to achieve the system goals while handling the tolerances of sensing, perception and prediction while fulfilling the safety requirements.

When looking at the Active Occupant Repositioning there are no minimal safety requirements based on e.g., legislation which must be fulfilled even without a Pre-Crash detection, so no fallback for this function is necessary. On the other hand, when adding a strong electromechanical pretensioner to a belt system, the idea is obvious to try to replace the functions solved with the pyrotechnical pretensioner. This replacement leads to the requirement to ensure the same safety level in any situation, which would get challenging to prove in open world context (any scenario which can be imagined out there). Furthermore, depending on vehicle the benefits of the pyrotechnical pretensioner are necessary for legally required load cases where Pre-Crash information cannot be used nowadays, leading to further unknown requirements and validation specification until regulations are adapted.

### **Why an actuation that is flexible in time?**

Environmental sensors are subject to tolerances and uncertainties. Prediction adds additional variations to triggering times. Some passive safety elements, for example front airbags are time critical and therefore difficult for Pre-Crash activation. They are optimized to be positioned very fast in a relevant severe impact and vents help to reduce the maximal load in the contact with the occupant to decelerate the occupant as soft as possible. That means, if an airbag is triggered too early it cannot support the occupant protection optimal. Exact triggering times are critical. Therefore, we selected the electromechanical belt pretensioner as a Pre-Crash actuator which has a higher tolerance for triggering times compared to airbag systems to further investigate principles of Pre-Crash systems. The force can be applied for a long period, disregarding dynamic effects like elevations inertias in the pretensioning system. And the belt system can be equipped with fallback solutions for basic safety requirements. Due to this flexibility and adjustability this actuator was chosen to analyze the effectiveness and the benefit with different operating strategies.

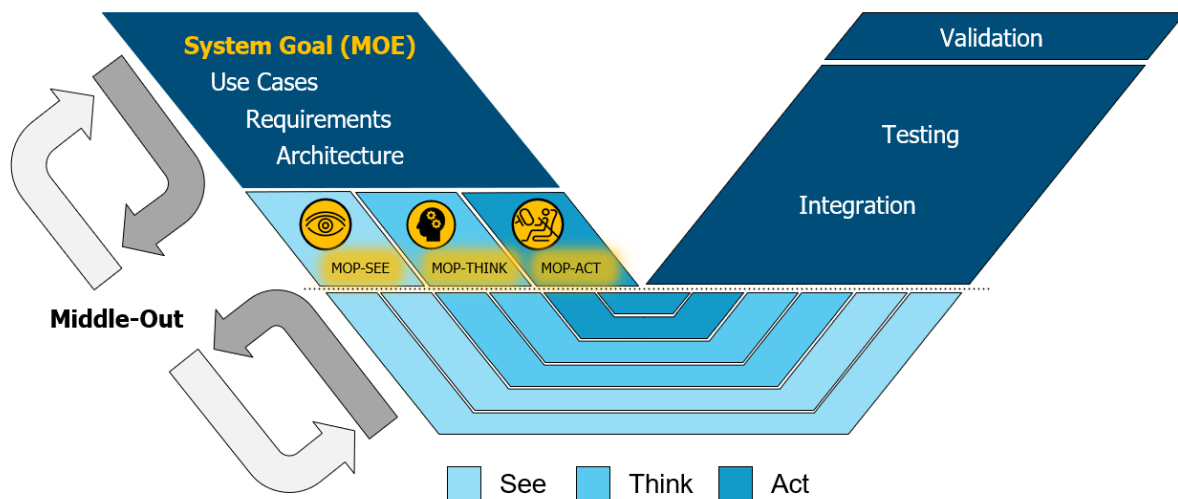
To be able to handle the development of complex systems with interdependencies between multiple domains different methodologies were analyzed according to their suitability for Pre-Crash development. Methods to include safety already in an early stage of development were applied [3]. The tailored approach based on fundamentals of systems engineering will be shown and outcomes described in the following.

## **MIDDLE-OUT METHODOLOGY TO DEVELOP AFFORDABLE AND EFFICIENT PRE-CRASH SYSTEM**

Development of complex Pre-Crash Systems must be supported by a systems engineering process. Basis for clear top-down systems engineering are detailed system requirements which can be derived from use cases. Especially when working with environmental sensors, an unreflected application of the approach can lead to unaffordable or even not viable requirements for sensing and perception. Tolerances and insufficiencies of environmental sensors have to be reflected in the process to not derive unrealistic precise requirements. To follow the approach of bottom-up would mean to take an existing system and find out how good a function can be implemented within the given limits. The bottom-up approach will not lead to a well performing system because the development of existing components like sensors, perception and prediction was based on other system goals.

When constraints do not allow to develop all system components from scratch and the goal is to improve a system the appropriate approach is called Middle-Out in literature (e.g., [4]).

In the development approach, the already existing functions of the system (bottom up) are compared to potential beneficial field of new functions (top-down) in an iterative process (compare Figure 3). The Measures of Performance (MOP) of subsystems have to be sufficient to achieve relevant Measures of Effectiveness (MOE) of the complete system. Identified gaps can be analyzed. After a feasibility check the development effort can be estimated and discussed with stakeholders if with reasonable effort MOPs for subsystems can be improved to increase the overall MOE.



*Figure 3 Middle-Out process in relation to the V-Model*

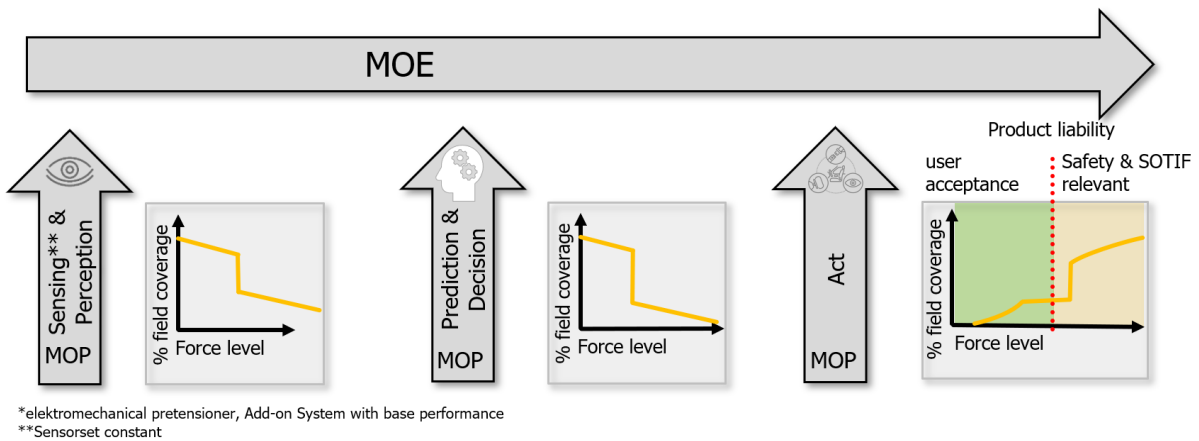
## CHALLENGES AND OPPORTUNITIES IN DEVELOPMENT STRATEGY WITH A HOLISTIC VIEW

When it is possible to map a system MOE to defined MOPs, next subsystem level development can start. However, when having a holistic view on the overall system effectiveness and the characteristics of one subsystem influences the MOPs of other subsystems it gets complex. If these relationships are not linear but have discontinuous jumps with different effects depending on the scenario, a holistic understanding is important. A clear understanding can only be achieved by applying the methodology to a first example otherwise it is too theoretical. For the Active Occupant Repositioning the interdependencies and discontinuities of the different subsystems - Sensing & Perception - Prediction & Decision and Act are schematically described (Figure 4).

### Basic principles for discontinuous jumps

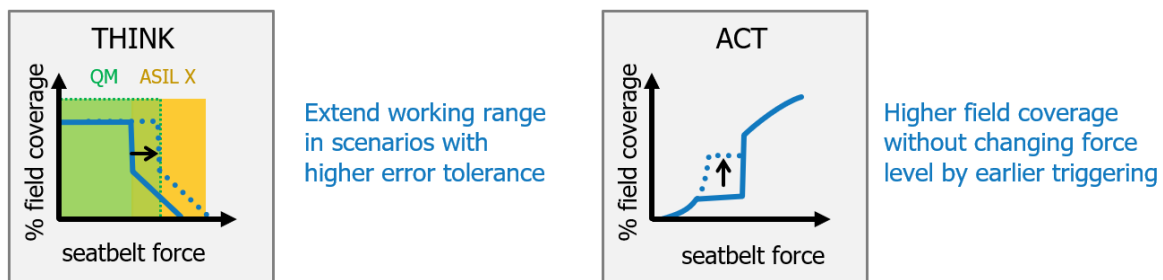
For Active Occupant Repositioning more situations in the field can be addressed (e.g., late detection times) when the actuator has the capability to provide higher forces. So in principle the field coverage over the force level is increasing (right schematic graph Figure 4). A discontinuity can be expected when the required force for Active Occupant Repositioning reaches the level necessary to overcome deceleration forces due to breaking maneuvers (simplified view excluding effects due to occupant or vehicle specific properties). Breaking before an accident is and will be an even larger proportion of remaining accidents when advanced driver assisted systems cannot completely avoid an accident or the driver is reacting too late. What must be considered is that depending on the force level, the criticality of the actuator increases. Below the distraction level, the acceptable rate of unintended activation (false positives) for the sensing - perception – prediction to decision path is defined by user acceptance. Above the distraction level the functional safety is the main stakeholder for false positive rates and SOTIF gets relevant. A defensive design strategy for sensing and perception gets necessary to achieve minimal false positives rates. For example, if difficult weather conditions might lead to a false activation these scenarios must be actively suppressed. This is one reason for the drop of the field coverage over the requirements due to force level (left schematic graph Figure 4). Not only sensing and perception strategies are influenced by functional safety ratings also uncertainties tolerated in the prediction logic is strongly dependent on the safety rating. For an actuator with a high risk of injury in case of an unintended activation, the accident must be physically unavoidable, otherwise activation could take place also in non-collision scenarios. Compared to a prediction with the most probable trajectory (this includes allowing activation in evasive maneuvers), the scenarios which can be declared as a true positive drop significantly (middle schematic graph Figure 4). The challenge is to find the right balance, the tradeoff between these divergent effects.

In general perception of objects and the prediction of their behavior cannot be executed perfectly fault free due to inevitable uncertainties. The performance of perception and prediction can be described on a statistical basis according to the “confusion matrix” by false positives (FP) and false negatives (FN). In such a constellation there is an inherited tradeoff between FPs and FNs as decreasing the one will increase the other. So there is an inevitable tradeoff between the two for all systems incorporating perception and prediction – including Pre-Crash systems [5].



**Figure 4** Simplified principles of divergent discontinuous jumps in MOPs

The next dimension to this optimization problem is that the effects of the relationship are different, depending on the scenario. One example thesis is, that in a breaking or steering maneuver, higher forces are possible before distracting a driver from the driving task (Figure 4) compared to driving on narrow lanes on construction sites. These different theses have to be proven to be included in a final function. Obviously most important for this optimization problem is the dimension of time. When reacting before the deceleration of a breaking maneuver, lower forces are able to bring an occupant in a nominal position.

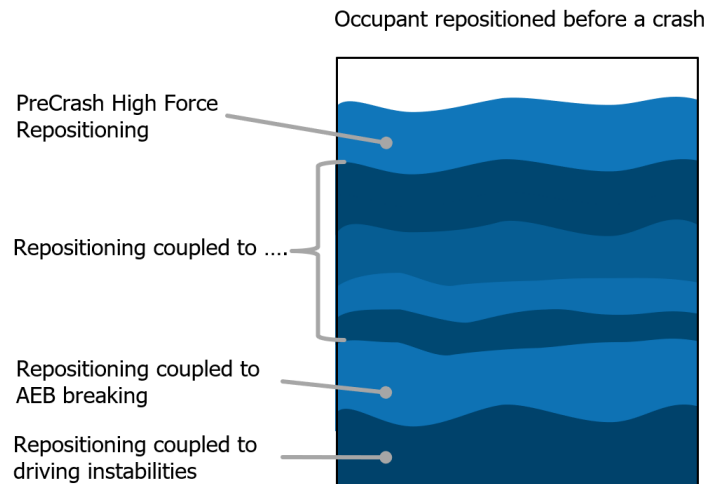


**Figure 5** Parameter relationships and strategies to improve field coverage

**Benefits and disadvantages of different levels supporting a common goal**

The selected goal to have the occupant in a nominal position before an imminent collision cannot solely be achieved by a pure Pre-Crash function. Early, softer solutions with less side effects can support the goal. Reacting early, not even before a crash but already in critical situations are state of the art functions which contribute to the same goal to have an occupant in a nominal position before a collision. To avoid unnecessary work in developing solutions for sensing, perception and predictions on scenarios which can be detected with other sensors and furthermore be solved with different actions the first task is to understand the functions which contribute to the goal (Figure 6). It is necessary to exclude these scenarios from the Pre-Crash prediction development process but to include them into the development process of the decision logic. Their interdependencies and the effect on field coverage for the overall goal is to be considered. Typical examples are accidents which occur after driving instabilities. These scenarios do not have to be solved with a solely environmental sensor-based decision. When losing control is detected, state of the art pretensioners retract the webbing with a limited force and support the occupants to get or to stay in nominal position. Limits of this functions can be identified, and solutions must be implemented to combine vehicle sensor data and environmental sensors to address missing scenarios with a robust decision. Scenarios with driving instabilities are very challenging for state-of-the-art perceptions because they were developed for stable driving, but also are rare due to electronic stability controls systems (ESC) and anti-lock braking system (ABS). The possibility to solve these scenarios beforehand reduces the effort for the Pre-Crash function and improves the overall occupant in-position rates.





**Figure 6 Functions contributing to the goal to reposition an occupant before a crash**

After identifying the gap between the potential beneficial area and the already solved scenarios identifiable without a special Pre-Crash perception and prediction, a tool chain is necessary to be able to understand the complex interdependencies and the effects of decisions made for the different subsystems. Ideal is a tool chain, which helps to estimate the field coverage. Methods, the developed chain and an example what gets possible to analyze will be described in the next chapter.

### **TOOL CHAIN TO ESTIMATE FIELD COVERAGE AND OPTIMIZE SYSTEM PARAMETERS OF SEE THINK AND ACT**

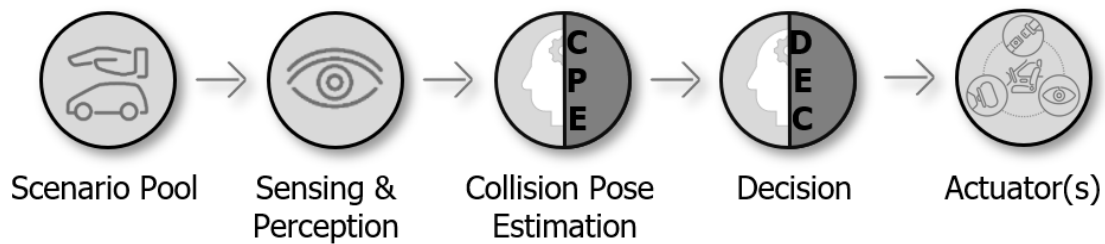
To assess the effectiveness of an innovative system with benefits in a complex environment in an early stage of development is a research discipline in itself, which is addressed by different collaborations. One collaboration ZF is also involved is called Prospective Effectiveness Assessment for Road Safety (P.E.A.R.S.). P.E.A.R.S. suggests four baseline approaches for the safety performance assessment (source [6]). All approaches are based on real-world scenarios. In the first approach directly, the real-world scenarios are taken to analyze the effectiveness of new or changed functions. The second approach is to add variations to this real-world scenario pool. The third and fourth approaches are based on synthetic generated cases based on parameter statistics from real world accidents with and without variations.

In accordance with the suggested second approach, we extracted relevant scenarios from GIDAS and made variations to get further scenarios ending in a crash and further near miss scenarios. These scenarios help to assess and determine the robustness of the decision logic. Further details see ref. [7].

When evaluating complex systems with several components which contribute to a final function, it is helpful to start with an ideal assumption for the components. This process was e.g., described by [8]. This process helps to learn about fundamental upper limits of components and finally assesses the performance of the complete system. The idea is to improve the assessment in the development process by adding more accurate representations in the approach. Starting with idealizations representing the different involved components in a tool chain and going over different modelling accuracies and prototype stages to the final component. This methodology can also be used to understand the effects of the discontinuous jumps described in the section “basic principles for discontinuous jumps”.

We divided our system chain into sensing and perception going over into the prediction, our so-called Collision Pose Estimation, leading to a decision and finally the action of the passive safety system. The idealization of sensing and perception helps to better understand the fundamental limits of crash prediction (also shown by [9]).





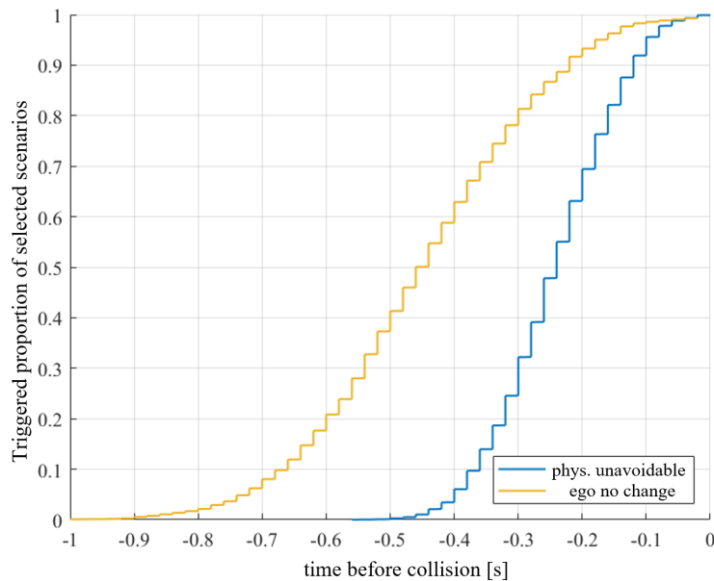
*Figure 7 Main parts of involved components represented in the tool chain to analyze system performance*

A big challenge is the definition of an appropriate scenario pool to assess statistically meaningful results (our approach see ref. [7]). It is challenging to include enough and the correct parameters addressing the performance limitations of the sensing and perception component. Here a reasonable approach is with the assumption of rates for example how often adverse weather conditions occur where limits of sensors are reached. Challenging no-fire scenarios must be generated and specifically selected with the knowledge on a sensor set and its limitations. To estimate the field coverage, it becomes particularly challenging when the performance assessment of the actuator is included. The evaluation of current passive safety systems is based on standard load cases representing statistically relevant accident scenarios. This is helpful to have a testable and evaluable amount of load cases but not necessarily applicable to Pre-Crash as discussed in Chapter “Challenges for Pre-Crash”. For real life safety, the most appropriate choice is to define desired performance rates for the field. This definition leads to a complex assessment of the restraint system performance. The parameters to derive these rates are numerous and vary strongly. Besides the pulse direction, intensity and profile, the triggering time due to detection time is a key influencing factor for the MOP of the restraint system. Surrogate models based on carefully selected FEM simulations are an effective approach to get the number of results which are required to get to field rates [10]. Much more convenient would be to agree in collaborations on standardized procedures to judge on performance and to validate systems [11]. Due to the variant diversity and the wide range of benefits these procedures do have to be flexible enough and the fundamental knowledge on how to estimate the effectiveness in the field beforehand has to be build up.

To be able to react before an imminent collision the vehicles trajectories of the ego and the possible bullet vehicle have to be predicted. Different approaches to predict the trajectories are available with different advantages and disadvantages. Examples are suitability for time frames, needed computing power or false positive rates. To reduce false positive rates to a minimum, an accident has to be physically unavoidable. Such restrictive requirements might get important depending on the safety rating, discussed in the Chapter “Challenges for Pre-Crash”.

Comparing this logic to a logic with reduced hypotheses, e.g., a no change assumption for the ego vehicle while keeping all hypotheses for the potential accident opponent. This strategy leads to much earlier actuation times. For example, in 70% of the selected scenarios the physically unavoidability of the accident is estimated 200 ms before the impact, based on ground truth. A function which could be activated already when breaking or steering and would get necessary 200 ms before the impact, would be triggered in 92% based on ground truth (Figure 8). Latencies and sensor uncertainties are possible to consider in our tool chain, but are not included in this ground truth analysis.

For the development strategy for a function and the components it is essential to get a good understanding of the consequences in the complete chain due to parameter changes in one component (see Chapter “Basic principles for discontinuous jumps”). The difference of the two prediction strategies and their effect on the triggering rates on the selected scenario pool was analyzed to give some principal insights in the possibilities with our tool chain. The comparison on detected scenarios over time shows in how many scenarios triggering of a function based on the two different defined decision parameters is possible. The change from physically unavoidable to the prediction with a reduced number of hypotheses leads to a drastic increase of the rate of early detection (Figure 8) along with not compulsory or even unintended activation. The challenge is to find the right balance for the complete system (Chapter “Basic principles for discontinuous jumps”).



**Figure 8 Influence of prediction strategy on triggering time based on ground truth information**

With a reduced area of action, the true positive rates are adjustable. The area of action describes crash constellations where an action is required. For example, a minimal overlap and a May-Trigger overlap area is defined. The May-Trigger area describes the grey area where a crash or a driving constellation does not require an activation but is also not rated as a false positive. The overall number of activated scenarios of the complete selected pool can be reduced by this process, and results in a clear understanding and description of the activation characteristics of the function.

The minimum overlap for standard load cases is 25 % between barrier and the vehicle (IIHS Small Overlap). With No-Fire and misuse load cases, the lower thresholds are defined. A similar approach has to be established for environmental sensing-based restraint system triggering. The agreement on acceptance criteria is only possible in collaborative working groups.

## CONCLUSION AND LIMITATIONS

We detailed the different levels and interdependencies leading to the complexity in realization of advanced Pre-Crash systems. Classifications help to understand fundamental differences and challenges in a specific system development. Active Occupant Repositioning was used to describe in detail the discontinuous relationships of different influence factors by taking safety requirements into account. We outlined a process to develop a holistic system-design for affordable and efficient Pre-Crash systems on basis of a full scope system development. On this foundation, the following basic developments steps of methodology, standards and technologies for validation, functional safety, legal and regulatory requirements as well as sensing were discussed. The complexity of this field requires collaborations to jointly develop acceptance criteria addressing performance and false positive acceptance rates. ZF actively supports these collaborations and working groups and is open for further exchange.

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