**PROSPECTIVE EFFECTIVENESS ASSESSMENT OF ADAS AND ACTIVE SAFETY SYSTEMS VIA VIRTUAL SIMULATION: A REVIEW OF THE CURRENT PRACTICES**

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## ABSTRACT

The automobile industry, universities, and automotive research institutes in Europe have started an initiative for cooperative research regarding assessment of real-world safety benefits of advanced driver assistance systems (ADAS) and active safety systems. A ‘Harmonization Group’ was established in 2012 whose motivation is the development of a comprehensive, reliable, transparent, and thus accepted methodology for quantitative assessment of these systems by virtual numerical simulation. One aim of this group, so-called P.E.A.R.S. (Prospective Effectiveness Assessment for Road Safety), was to provide a review of the current practices for this prospective effectiveness assessment of ADAS and active safety systems. This paper’s objective is to present this review.

As a complement to a literature review, five workshops were held with a dozen of P.E.A.R.S. members to collect qualitative in-depth information about their approaches concerning the effectiveness evaluation of ADAS and active safety systems via simulation. During the workshops, non-directive interviews and discussions were held to gather information on the research questions, metrics, methods and simulation techniques employed by the P.E.A.R.S. members. Subsequently, the approaches for prospective effectiveness assessment were classified into four levels according to their use of simulation. Finally, criteria for evaluating the approaches were identified.

The overall evaluation approach consists of: 1) identifying the target accident situations (TS) that the system could potentially address (usually by using crash databases), for example pedestrian crashes; 2) establishing, for each TS, reference situations (RS) such as driving, pre-crash or crash situations in which the system was not present, for example all configurations of pedestrian crashes or critical situations involving a vehicle and a pedestrian; 3) adding the system to the reference situations in order to establish what would have happened if the system had been present,

generating potentially modified situations (MS); and 4) comparing the outputs of the two situations to estimate the effectiveness of the system in terms of crash avoidance and injury mitigation.

Additionally, approaches were classified in four levels depending on their sparse, limited or intensive use of numerical simulation to establish the reference situations and the modified situations. The zero level uses expert opinion instead of simulation to roughly estimate the safety benefit of a system on crash situations. The first level uses simulation to add the system (and simulate its effect) to reference situations that are usually real-life crashes recorded in crash databases. The second level uses simulation to modify parameters of real-life situations and generate more reference situations, and also to add the system and generate the modified situations. The third level characterizes the processes involved in the target situations, then uses simulation to generate reference situations (which are not exclusively based on real-life situations), and the modified situations.

Lastly, fourteen evaluation criteria were identified to assess the performance of the different approaches: Thoroughness and exhaustiveness, completeness, understandability and interpretability, operation capability usability, degree of automation, generalizability, flexibility, fidelity, accuracy, time consideration and ability to go back in time before the collision or critical situation, required resources, validation, and granularity.

This paper provides a taxonomy of approaches and use of simulation to estimate the safety benefits of ADAS and active safety systems but does not provide quantitative evaluation on the performance of the different approaches. Future work focuses on applying various approaches on a same case study (Round Robin) in order to compare them relative to their effectiveness assessment outputs and the evaluation criteria.

This review offers insights into the categories of current approaches for estimating potential benefits of ADAS and active safety systems via simulation. In order to develop a harmonized methodology, stakeholders acknowledge that simulation can be used at several levels with various degrees of data description. Moreover, the evaluation criteria can be used to determine which approach is more suitable for a specific need.

## INTRODUCTION

The automobile industry, universities, and automotive research institutes in Europe have started an initiative for cooperative research regarding assessment of real-world safety benefits of advanced driver assistance systems (ADAS) and active safety systems. A 'Harmonization Group' was established in 2012 with mostly European participants from automotive industry, research institutes, insurances and universities, whose motivation is the development of a comprehensive, reliable, transparent, and thus accepted methodology for quantitative assessment of these systems by virtual numerical simulation. The first aim of this group, so-called P.E.A.R.S. (Prospective Effectiveness Assessment for Road Safety), was to provide a review of the current practices for prospective effectiveness assessment of ADAS and active safety systems [1].

## METHOD

The compilation and description of such elements are the basis for the subsequent definition of a harmonized evaluation process/method. To this end, a template was sent to the P.E.A.R.S. members and an inquiry was sent to over 30 participants of the P.E.A.R.S. group. It gave a good but not sufficiently detailed overview of current practices regarding evaluation.

In order to complement what has been achieved with this first step and to add further details, an additional in-depth review of RQ's, used metrics, and applied methods was needed. For this purpose, five workshops were held with P.E.A.R.S. members. The aim was to collect qualitative information on current methods concerning the effectiveness assessment of ADAS and active safety systems.

The objective of the paper is to present a summary of the findings so far notably on research questions and the process to generate them, the overall process for prospective assessment including different approaches to perform it, and the metrics used to quantitatively assess effectiveness. To have a clearer understanding, definitions of relevant terms are given specifying their intended meaning.

## DEFINITIONS

### Safety versus safety benefit

Traffic safety is usually regarded in terms of "lack of safety" [2]; when talking about road safety, the quantitative measures nearly always focus on the amount of departure from an absence of harm instead of safety itself and therefore safety is usually referred to as the number of fatalities or injuries resulting from traffic crashes [3]. As a consequence, the safety benefits i.e. safety impacts, are represented as the reduction of crashes, injuries or property damages that a system (or a counter-measure) can bring.

Examples of safety benefit definitions:

- How many lives could be saved if x% of the fleet is equipped with the y safety package compared to a baseline fleet;
- How many injuries of Abbreviated Injury Scale (AIS) “i” or Injury Severity Score (ISS) “j” could be mitigated if x% of the fleet is equipped with the y safety package compared to a baseline fleet;
- Reduction in risk to be fatally injured if x% of the fleet is equipped with the y safety package compared to a baseline fleet;
- Reduction in risk to be injured AIS “i” or ISS “j” if x% of the fleet is equipped with the y safety package compared to a baseline fleet over n years.

**Effectiveness assessment of safety functions**

The objective of the effectiveness assessment of ADAS and active safety systems is to estimate the safety benefit of such a function or system (or a combination of them). For systems that have **already been introduced into the market** this can be done by a retrospective analysis; safety benefits are quantified by computing crash statistics (or other direct measurements of mortality and injury impacts) of vehicles equipped and non-equipped with the safety device under study with a breakdown by relevant and non-relevant crash types (for a full description of the overall method, see for example [4] and [5]).

However, there is especially a need for reliable effectiveness assessment of **safety functions that are under development** or functions with a low market introduction rate. Such systems have to be assessed by a prospective analysis that estimates the expected safety benefits of current and beyond state-of-the-art application i.e., the expected safety benefits that could be obtained thanks to a system. Commonly used methods for prospective analyses are Field Operational Trials (FOT’s), subject studies in driving simulators, on closed test tracks or on public roads and analyses by means of virtual simulation. Currently, input for an assessment by virtual simulation is obtained either from reconstructed real-world crashes or from synthetic scenarios derived from real-life distributions of pre-crash conditions and traffic. Simulations allow for a large number of cases and thus are capable of fulfilling the requirements posed by a sound sample size calculation. Simulation is certainly not a sole generic solution for all kinds of research question, but it represents an integrative method to combine different knowledge areas in order to achieve an overall effectiveness result; it offers a promising combination of speed, flexibility, reproducibility, and experimental control.

The methods considering virtual simulation is the core interest of P.E.A.R.S.

## RESEARCH QUESTIONS

A research question can be a simple question raised by anyone who would like to have a straightforward answer regarding safety of systems (for example, what is the safety benefit of Advanced Cruise Control?). It can also be a more complex question (e.g. what are the top five safety systems that could, within 10 years, bring the greatest safety benefits at the lowest cost?). A research question is generally expressed very briefly and without details by a stakeholder and needs a profound ‘reformulation’ to be workable.

One example is the following: a question such as ‘What are the safety benefits of ESC?’ needs further exploration and specification before analyses can be performed to formulate an answer. When? Where? For whom? What are the safety benefits? What kind of ESC? Etc. See [6] for examples.

**Criteria for the construction of research questions**

A research question is normally structured according to a series of comprehensive criteria which make them clear, precise and understandable:

- Motivation: who wants a response to the question, and for what purpose? Is it a matter of estimating the safety benefits of a system, of doing a benchmark comparing the safety benefits of different systems, or of searching for the best parameters of triggering a system?
- Effect: the safety effect needs to be quantified by a metric. How is the effect measured?
- Function: What is the type of functionality or the package of functionalities being evaluated?
- What is the type of technology behind the functionality, which is to be evaluated?
- Scenario: Description of the situations that are being addressed. e.g., maneuver, accident types, traffic participants, type of road, geographic region, etc.
- Time horizon of prediction: What is the time horizon that is being considered? Short-term, mid-term, long-term?

- Sometimes, also the penetration rate of systems needs to be considered.

Considering these criteria will provide questions that are sufficiently explicit, even parsimonious, to be considered as long and precise research questions. Examples are given below:

- Relative change in crashes due to pedestrian AEB (100% penetration rate in passenger vehicles) in urban pedestrian situations in Germany (short term = 2 years in the future).

- Absolute reduction of MAIS3+ injuries due to AEB (50% penetration rate in cargo vehicles) in highway rear-end accidents (excluding two-wheelers) in France (mid-term = 5 years in the future).

There is also a need to be clear about the accuracy of the expected answer, its applicability, its confidentiality and relevance/consistency with the question.

As a part of the inquiry that was disseminated, participants were questioned regarding their interest and focus on several general research questions. Participants were asked to rate the importance of prescribed research questions with a number between 1 (low) and 6 (high).

Table 1 shows some results of the inquiry, which indicate that there is a higher interest in short-term effects compared to long-term effects. Moreover, table 1 also displays that economic aspects seem to play a minor role in the effectiveness assessment compared to the quantification of safety effects.

The intention of the inquiry was to identify the overall interests and general questions that are currently being considered by the participants. Nevertheless, these research questions can be revised to be more precise, for instance by defining the metric that quantifies the "safety benefit" or the specific cause=function under evaluation instead of ADAS and safety systems in general.

**Process to generate the Research Questions**
The discussions held during the various workshops helped to identify the two types of processes that participants use to generate research questions. Some of the participants use both type of processes.

- **Bottom-up process**: Someone (a "client" from product development, suppliers, the government, public or industrial projects, etc.) contacts the person or the team in charge of doing safety assessments and asks to estimate the safety benefit of a defined system X – it can be an idea or description, a developed concept, a product under development or a product that is already in the market. The question is usually very wide and imprecise. Therefore it has to be divided into various questions and needs rephrasing. The main characteristic of this process is that the research questions are linked to a demand to evaluate a more or less defined system.

- **Top-down process**: It involves looking at what is happening today on the roads, the existing or expected safety problems that have been identified and thinking about the kind of scenarios that need to be addressed. The research questions are not linked to a particular system but to a general safety problem and next generation systems i.e., possible solutions to the safety problems, are anticipated upon.

**Table 1. Examples of interest in research questions (outcome of the P.E.A.R.S. inquiry)**

| Research Questions | Mean Rating |
|---|---|
| What are the potential safety benefits of ADAS and safety systems in short term (<5yrs) considering that there are a lot of other road safety actions? | 5.0 |
| What are the optimal parameterizations of technical aspects of ADAS and safety systems if we wish to reach the maximum safety benefits? | 4.9 |
| What re the potential safety benefits of ADAS and safety systems in mid-term (5-10yrs) considering that there are a lot of other road safety actions? | 4.8 |
| What are the externalities (side effects) linked to the development of ADAS and safety systems? | 4.2 |
| What re the potential safety benefits of ADAS and safety systems in long-term (>10yrs) considering that there are a lot of other road safety actions? | 4.1 |
| What are the societal and economic benefits of ADAS and safety systems in short term (<5yrs)? | 3.6 |
| What are the societal and economic benefits of ADAS and safety systems in mid-term (5-10yrs)? | 3.3 |
| What are the societal and economic benefits of ADAS and safety systems in long-term (>10yrs)? | 2.9 |

## METRICS

The changes and safety impacts due to a system can be expressed using various absolute or relative measures.

The direct quantification of effectiveness looks at critical situations, accidents, accidents with injuries, injury severity (such as AIS, Maximum AIS (MAIS), ISS, Head Injury Criteria (HIC), fatalities), Economic/health aspects (i.e., property damages, health care costs, societal costs, insurance costs, functional life years lost, quality life years lost, etc.). The indirect quantification of effectiveness is all the other metrics that are needed to draw conclusions for effectiveness or insight serving as an enabler for effectiveness analysis.

The most frequently used metrics are the **number** (or reduction in the number expressed as **percentage**) of avoided accidents and the **number** of avoided injuries (or similarly, reduction in **percentage**). Another metric used is the reduction in risk to get involved in a crash, or sustain an injury or an injury of a certain level of severity. The changes in injury severity distribution are also used to quantify effectiveness.

Finally, the changes in health aspects are the least used metric to measure effectiveness (see Table 2 for a summary of the inquiry about this topic).

**Table 2. Examples of metrics used (outcome of the P.E.A.R.S. inquiry)**

| **Method** | **How often is the metric used by partners?** (Mean value; 1:never used …5:6 always used) |
|---|---|
| Avoidance of accidents | 5.2 |
| Avoidance of injuries | 4.9 |
| Avoidance of critical situations | 3.9 |
| Changes in injury severity distributions (MAIS, fatality, ISS, etc.) | 4.8 |
| Changes in health aspects (e.g. functional years lost, etc.) | 1.2 |
| Changes in economic aspects (property damage, economic costs, etc.) | 2.1 |
| Percentage of triggered (critical) events | 3.3 |

There are also some Prospective Effectiveness assessments of ADAS and active safety systems in property damages: Since personal damages are the main focus of accident investigators, there is a high number of property damage accidents that are not reported in crash databases even though the data generally is available for insurance companies. The authors of [7] assessed the benefit of ADAS and safety systems in property damage accidents by the reconstruction and simulation of accidents and the construction of a damage risk function.

## APPROACHES, METHODS AND PROCESS

### Overall Process

The process starts from considering driving, pre-crash or crash situations in which the system to be assessed is not present, i.e. establishing the reference situations (RS). Then the system is added to the situation to establish a potentially modified situations (MS) to compare the outcome of the RS and the MS. As specified in the metrics section, outcomes are usually compared in terms of crash reduction and injury severity reduction:

- **Crash reduction**: To estimate the potential for crash reduction the outcomes of the RS (without the system) and the MS (with the system) are compared in terms of trajectories of the vehicles and/or other road users involved in the crash [8]. Then, parameters like the lateral and longitudinal positions, speeds and accelerations of the vehicles (and other road users), the distance needed for braking and the distance needed for performing an evasive maneuver, etc. are used to determine whether or not the accident is avoided.

- **Injury mitigation**: In case an accident is not prevented by the system, but its consequences are mitigated, the extent of the mitigation can be calculated. To estimate the potential for injury severity reduction—including fatality reduction— the outcomes of the RS and the MS are usually compared using injury risk functions. Injury risk functions describe the relationship between the risk of injury and some parameters such as closing speed, speed reduction from emergency braking Δv, collision angle, impact zone, energy equivalent speed, etc., based on a particular sample of casualties and injuries. Therefore, the injury risk functions are not universal; they depend on the sample which was used to build the them.

For passive safety systems that have different protection capabilities, the level of risk is not the same when comparing two systems and thus there will be different injury risk functions for different passive safety systems.

Nowadays, the most urgent need is to evaluate ADAS and active safety systems that intervene before the accident takes place. When comparing ADAS and active safety systems, the risk relation is the same —

with or without implemented system. But the system will influence a parameter such as Δv, lowering the associated level of injury.

Figure 1 shows two fictitious injury risk curves (red and blue) that indicate the probability of injury as a function of Δv (given that there might be additional parameters impacting the probability of injury).

When evaluating passive safety systems, the two functions corresponding to two different systems that have the potential to change the level of risk have to be compared. For the same value of Δv, there would be a different level of injury (ΔP Passive systems) and therefore, the probability of injury of the blue curve would be lower than the one of the red curve. In contrast, for the case of active systems there is no change in the risk relation, thus there would only be one injury risk function. The ADAS or active safety system plays a role on the pre-crash conditions, which ultimately would change the parameters that describe the collision, such as Δv, impact angle, or impact location. As a result, for the same crash there would be a difference in Δv with and without the ADAS or active safety system (ΔP Active systems), changing and possibly decreasing the probability of injury.

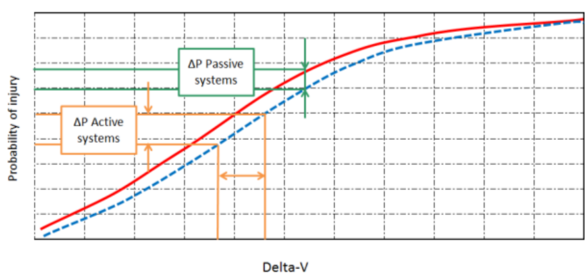


***Figure 1. Example of injury risk curves as a function of Δv***

Therefore, the overall evaluation process consists of establishing RS and MS and comparing their outcomes in terms of crash reduction or injury mitigation. As illustrated in Figure 2, this process includes four main steps: (1) Identification of the target situations (TS), (2) Establishing the reference situations (RS), (3) Establishing the modified situations (MS) and (4) Comparison and safety assessment. The red dotted lines indicate the steps of the process that can involve the use of accident simulations.

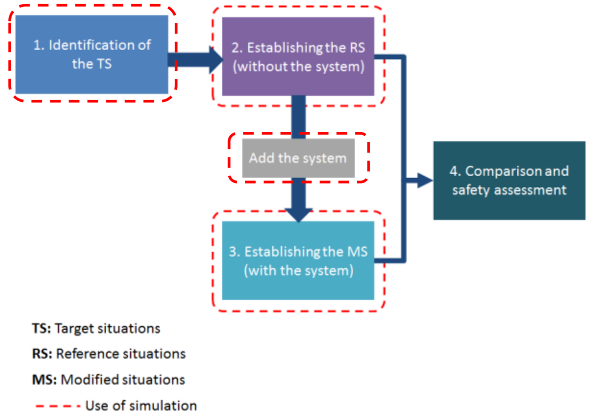


***Figure 2. Overall steps in the effectiveness assessment of ADAS and safety systems***

**1. Identification of situations of interest or target situations** involves looking at the accident databases and performing statistical analyses to identify the type of accident situations that the system could potentially address. In other words, identifying the TS that could be positively affected by a proposed safety system. Furthermore, it can also involve looking beyond the accident databases and identifying critical driving situations that can potentially lead to a crash.

For example, ESC is supposed to address loss of control crashes (lateral dynamics only), Lane Departure Warning may support the driver in lane-off or road-off crashes, and low speed AEB may intervene when the driver is not capable to avoid low-speed rear-end crashes. What is out of the scope of the ADAS and active safety systems has to be stated and might be disregarded (for example intersection crashes for rear-end AEB systems), depending how the effectiveness is defined. The degree of detail of the target situations depends on the degree of detail of the databases used for identifying these situations. For example, in the case of low speed AEB, if in-depth crash databases are used, low speed rear-end crashes could be the target situations. In case a less detailed crash database is used, rear-end crashes in urban areas could be considered as relevant target situations.

**2. Establishing the reference situations (without the system):** Once the TS have been identified, the RS have to be established. The RS represent the concrete situations to which the system is added in the next step of the process. They usually involve situations in which an accident has already happened or defined critical driving situations that can potentially lead to a crash. Most of the systems that are currently being evaluated address warnings, corrections or avoidance manoeuvers that are activated in critical situations, a few seconds before a potential crash. Systems like speed limiters which act for longer periods of time and not especially during a critical situation are less often in the scope of current practices.

In this step there are some studies that establish RS without the use of simulation to modify real accidents or real critical situations. In this case, the RS correspond to the reconstruction of real accidents or real critical situations without changes in the variables that characterize what happened. Some other studies involve the use of simulation to modify real accidents (investigated and coded in crash databases) or critical situations (investigated in other databases than crash databases) and generate RS that do not necessarily correspond one-to-one to the initial real situations for instance by using stochastic simulation to vary some of the parameters of real accidents in order to dispose of more RS or to alter the exposure distribution of RS. Furthermore, simulation is also used to recreate the relevant processes that intervene in TS and literally generate virtual RS i.e., situations that do not have their origins in crash situations that have already happened in real life. For example, simulating a collision between a vehicle and a pedestrian crossing the street in which the relevant processes such as street geometry, the vehicle trajectory, pedestrian trajectory and kinematics, and etc., are generated rather than taken from accident databases. It involves simulating pedestrians crossing a street and vehicles circulating that street and literally waiting for the accident to happen.

According to this, the following three general ways of establishing RS were noticed:

a) No simulation involved to modify or to generate more RS.
b) Simulation used to modify or to generate RS from real accidents.
c) Simulation used to generate RS from the understanding and modeling of the relevant processes that intervene in the TS.

**3. Establishing the modified situations (with the system):** Simulation is used by all participants to perform the third step, to estimate what the outcomes of the RS would have been with the safety system present i.e., modified situations (MS). Since the simulation of the MS encompasses adding the system to the representation of RS, the level of simulation complexity and the level of details depend on the way the RS have been represented in the second step.

**4. Comparison and safety assessment (including interpretation of results):** The last step of the overall process consists of estimating system effectiveness by quantifying the potential for crash avoidance and injury mitigation. For this purpose, the outcomes of the RS and MS are compared in terms of trajectories and parameters describing the pre-crash and crash phases as explained at the beginning of this section.

**Categories and classification of specific approaches**
Although the overall approach is very similar for the interviewed parties, there are some differences when it comes to the use of simulation and specific approaches. In an effort to generalize such differences, four types of approaches were categorized according to the use of simulation to establish RS and generate MS (figure 3). Please note that some of the methods and processes might be between two categories or might involve some deviations.

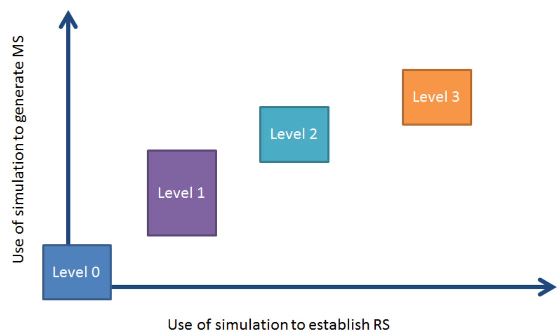


***Figure 3. Classification of the different levels of effectiveness assessment according to their use of simulation***

**Level 0: Use of expert opinion to estimate the potentially addressed situations**
P.E.A.R.S. focuses on the assessment of ADAS and safety systems effectiveness by virtual simulation. However, the effectiveness is sometimes done based on sole experts' opinion. In this approach, experts analyze accident data and estimate the safety benefit of a given system by roughly calculating the percentage of crashes that could be potentially addressed by the system. It mostly relies on experience, and experts do not employ virtual simulation nor are they interested in having a very accurate number on the safety benefit. This approach can be considered as the level 0 of the use of virtual simulation.

**Overall method:** In this method, the objective is to find rough estimations of the share of accidents that are potentially addressed by a system. It starts by identifying the target situations that could be potentially addressed by the system which is done based on the experts' opinions and personal experience. If the system seems promising, the expert looks into accident databases and comes up with rough estimations of the maximum benefit of the system i.e., a percentage of the addressed accidents that could be prevented or in which injuries could be mitigated by the system.

This level 0 might be sufficient in case the target population is very low. In this case, it is also a low cost approach as it consumes little time.

**Level 1: Use of simulation to establish the MS**
In this approach, the first step consists of having an expert look at the accident databases to identify the situations that could potentially be addressed by the system (TS).

In the second step the RS correspond to the real accidents that have been reported in the accident databases; the number of RS is the same as the number of reported real-world accidents. At this point, the RS are represented and modelled in terms of parameters that can be found in the accident databases such as collision speed, Δv, collision angle, and so on. Some studies go further and introduce these parameters into a model of vehicle dynamics to do a simplified reconstruction of the RS. One could argue that there is some simulation involved to perform the reconstruction. However, simulation is not used to modify and generate more RS but to reconstruct and recreate real accidents in order to have a more detailed description of the RS—which is useful for the third step.

In the third step, the system is added to the RS and simulation is used in order to generate the MS and estimate the outcome i.e., what would have happened if the system had been in place. Necessary inputs to simulate the addition of the system include, but are not limited to: (1) the system's description which can be simple at a conceptual level or more complex at a technical level including information about the sensors, the real algorithms, and the actuators of the system, (2) the driver model which represents the driver behavior during the situation. The level of complexity and sophistication of the simulation of the MS can vary, it usually depends on the way the RS have been modelled and represented.

In the final step, the outcome parameters of the RS and the MS are compared, and the safety assessment is completed. In order to estimate whether collisions are avoided, the trajectories of MS are compared with the original trajectories of the RS. To estimate if collisions are mitigated (reduction of injury severity or fatalities), the outcome parameters of both situations such as Δv and their corresponding values in the injury risk function are compared.

The four steps of this approach and their use of simulation is shown in Figure 4.

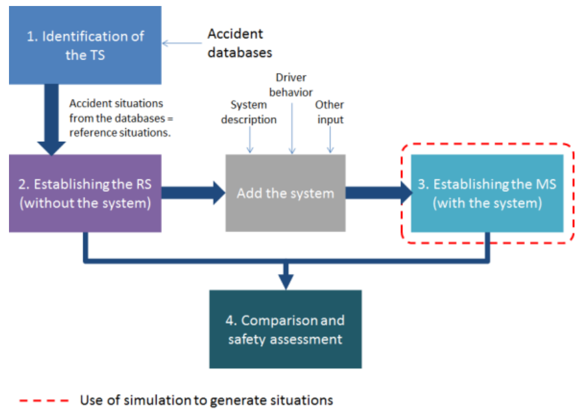


***Figure 4. Level 1: Use of simulation to establish the MS***

**Example:** The SIMPATO Safety IMPact Assessment TOol developed for the interactIVe project is an example of this type of approach [9].

**Overall method:** In SIMPATO, the target situations are the crashes taken from a representative set of accident scenarios derived from the German In-Depth Accident Study (GIDAS) in which the system to be assessed is not present. The RS are represented by the reconstructions of the pre-crash phases of the vehicles involved in the target situations in terms of initial conditions and driver interventions before collisions provided by GIDAS. To determine what would happen if an ADAS or safety system had been present and to establish the MS, the data from technical and user-related tests on the ADAS and safety system, and models that describe the vehicle dynamics and driver behavior are used. The final step consists of comparing the RS and MS and determining the potential effectiveness of collision avoidance and collision mitigation by an ADAS and safety system.

**Specific application:** SIMPATO has been used to assess the expected safety impacts of several ADAS and safety systems that play a role in rear-end collision, i.e., CS (continuous support), RECA (Rear end collision avoidance), CMS (Collision mitigation system and ESA (Emergency steer assist). The target situations comprise 360 accidents reported in GIDAS in which the front passenger car had exactly one collision with the rear of another passenger car. The reference situations are represented by the reconstruction of the pre-crash phase and some other data provided by GIDAS, such as the trajectories of the two vehicles without the ADAS and safety system, the speeds of the two vehicles just after collision, layout and severity of the accident.

To establish the MS, a model is used to simulate and calculate the dynamics of the rear vehicle with the ADAS or safety system present. For a warning system, the probability that the driver reacts to the warning, the driver reaction times to the warning, and the strength of the driver reaction—in this case braking action—are determined with interactIVe user tests. For an intervention system, the moment when the ADAS or safety system intervenes and the strength of the system intervention are determined with interactIVe technical tests. Then the effectiveness of collision avoidance and collision mitigation by each ADAS or safety system is evaluated. The model allows evaluating if the collision is avoided (if the rear vehicle with the ADAS or safety system comes to a standstill before hitting the lead vehicle).

Figure 5 shows the results for a rear-end situation without and with RECA, showing the longitudinal (a) and lateral (b) positions of both vehicles against time, and the warning and intervention time points. In this case the RECA system intervenes by steering and avoids the accident. The longitudinal motion is unchanged as no braking has been applied.

When the warning/intervention of the system still leads to a collision, the change in injury severity (potential effectiveness of collision mitigation) is evaluated using the relationship between injury risk functions and ΔV and comparing the ΔV of the RS and the ΔV of MS. For interactIVe, the change in severity was modelled as an ordered factor response -from uninjured to fatally injured. Hence the ΔV observed in testing were used to predict the changes in injury levels for the specific rear-end population.

Figure 6 illustrates the outcomes of accident situations for rear end collision by every ADAS or safety system under consideration in the interactIVe project. As it can be seen, there is a high potential for accident prevention, especially for ADAS or safety systems that intervene.

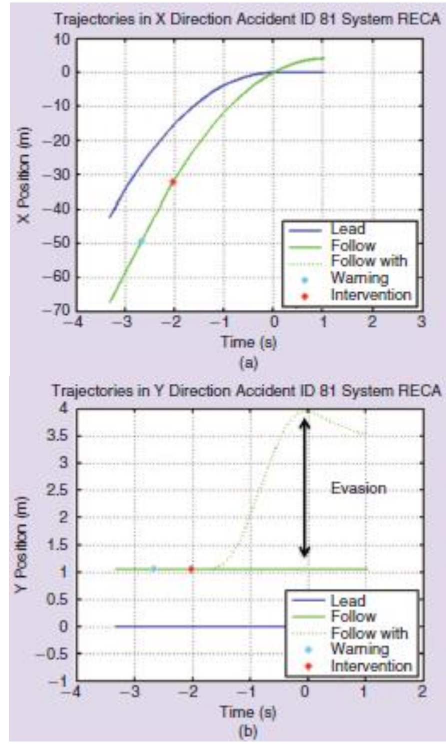


***Figure 5 Results of for a rear-end collision situation without and with RECA taken from (SIMPATO, 2015)***

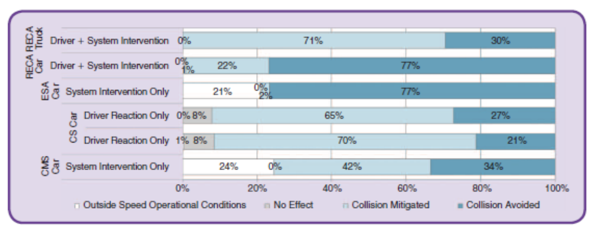


***Figure 6. Results of SIMPATO assessment for rear end collisions by ADAS and safety systems (SIMPATO, 2015)***

**Level 2: Use of simulation to generate RS and MS based on real accidents**

As in all categories, the first step starts by looking at the accident databases and identifying the situations that could potentially be addressed by the system. The main difference in this category is in the second step in which simulation is used to modify the real accident situations, in order to generate RS. For this purpose, some evaluators use the GIDAS based Pre-Crash-Matrix (PCM) database. In the PCM database, which consist of a subset of GIDAS cases, up to five seconds before the crash is coded in time-series format. This allows reproduction and simulation of pre-crash-sequences in virtual simulation.

To establish the RS some of the participants start by increasing the level of safety of the real crashes involving “old fleet” in order to achieve the current safety level of modern fleet for all the real accidents reported in the database. Others directly start by using stochastic or “Monte-Carlo” simulation to create random scenarios based on marginal distributions from real accident samples. In this step “virtual” RS are generated based on real accidents. The number of “virtual” RS can be higher than the number of real accidents from the databases; it can also happen that the simulation procedure leads to the fact that no longer all of the simulated situations end up in a collision.

The third step in which the system is added to the RS to generate the MS is basically the same as in the previous category. However, the participants that use the PCM have a very detailed description of the RS and consequently their modelling and simulation of the MS is more sophisticated.  The final step is the same as in the previous category (figure 7).

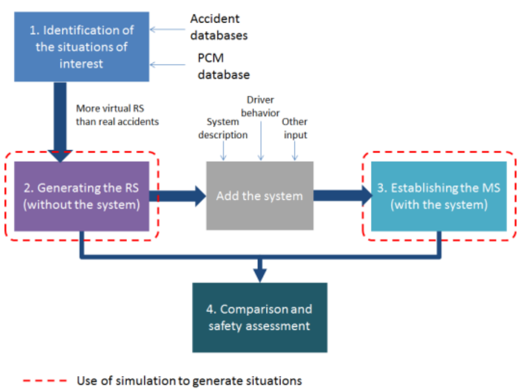


***Figure 7. Level 2: Use of simulation to generate RS and MS based on real accidents***

**Example:** The PRAEDICO (PRediction of Accident Evolution by Diversification of Influence factors in COmputer simulation) methodology developed by Autoliv is used for the estimation of how much (present and future) active and passive safety measures will reduce the risk of sustaining accidents and injuries [10]. It is given here as an example of level 2 even though it is to a certain extent also close to level 1.

**Overall method:** The target situations are also taken from the real accidents—involving vehicles in which the system is not present— reported in the GIDAS database. This method also uses accident situations from PCM. The major difference is the use of simulation to generate RS. Here, a driver model directs a vehicle dynamics model along a given trajectory. This allows to modify driver behavior or to generate variations of given scenarios. By investigation of variations, confidence levels of simulation result can be determined. Moreover, near-crash scenarios can be derived. Relevant scenarios are selected as the RS which represents the baseline data. Then, the system is added to the RS and simulation is done to establish the MS. The final step consists of comparing the RS and MS and determining the potential effectiveness of collision avoidance and collision mitigation by an ADAS or active safety system

Figure. 8 shows the overall method as presented by Autoliv.

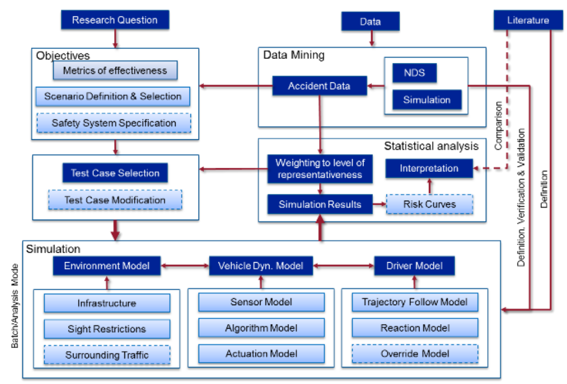


***Figure 8. PRAEDICO method for effectiveness assessment according to Autoliv***

**Specific application:** the use of PRAEDICO to assess the expected safety impacts of a warning system and Automatic Emergency Brake (AEB) in intersection situations (left turn across path and straight crossing path [11],[12]). As an example, for left turn across path, system effectiveness was calculated when: 1) the turning vehicle is equipped with the system, 2) the oncoming vehicle is equipped with the system and 3) both vehicles are equipped with an ADAS or active safety system (see Figure 9).

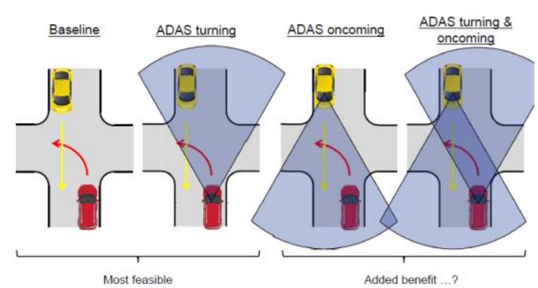


***Figure 9. Left turn across path situations analyzed by the PRAEDICO method***

The definition of the TS also starts by looking at the real accidents reported in accident databases. Real accidents from databases are reconstructed and parameterized. In the next step the system(s) are added to the RS and simulations are completed to establish the MS. For the effectiveness assessment, (1) collision avoidance and (2) collision mitigation by the system(s) are evaluated by comparing the trajectories of the RS and MS and by comparing injury functions and both $\Delta v$ respectively. Moreover, the car fleet penetration equipped with the system is also taken into consideration.

**Level 3: Use of simulation to generate RS and MS from the understanding and characterization of processes**

As in the previous approaches, the first step also begins with the identification of TS that could be positively affected by the system. An additional stage in this step is to analyze accident data, studies on driver behavior, and other relevant data to generate plausible hypotheses that consider how the system can mitigate or avoid collisions in the TS.

Opposed to the previous methods, the second step is not exclusively based on accident situations reported in databases but on the understanding and the characterization of the relevant processes and contributing factors involved in the TS. Once such processes and factors are understood, the situation is modeled and simulated to generate RS. Stochastic (Monte-Carlo) simulation is used to vary the characteristics of the simulations (driver and vehicle characteristics, vehicle trajectories, traffic characteristics and environmental variables) and generate different contexts. When the simulations for generating situations are performed, only a small minority of situations end up in a collision. The RS can then be defined as the situations in which a collision occurs but they can also be defined as critical situations only, without any subsequent crash (Figure 10).

**Example:** BMW's holistic vehicle safety methodology [13-16].

**Overall method:** The first step in this method is to identify the target scenarios that could be positively affected by a proposed ADAS or safety system. It involves prioritizing target scenarios based on statistics from existing databases and generating plausible hypotheses concerning how a proposed system would avoid or mitigate collisions in the TS. Moreover, it helps to understand the mechanisms and the processes that intervene in these situations. In the second step, all (if possible, otherwise some) important processes that contribute to accident risk and that can be influenced by the system within the TS are characterized, modelled and reconstructed. The third step is what distinguishes this method the most; it consists of using stochastic simulation to generate the situations based on the understanding and modelling of the processes that intervene in the TS. These TS situations that are not exclusively based on real accident situations as it is the case for the previous approaches. Like in the previous method, the generated situations include collisions and non-collisions and thus the RS have to be selected from the whole range of generated situations. The system is then added to the RS and stochastic simulation is once again used to generate the MS. The final step is the integration of supporting and classical analyses to calculate the collisions avoided, collisions mitigated, and newly created crashes. One advantage of using these "virtual experiments" is the possibility to address false-positives and true-negatives.

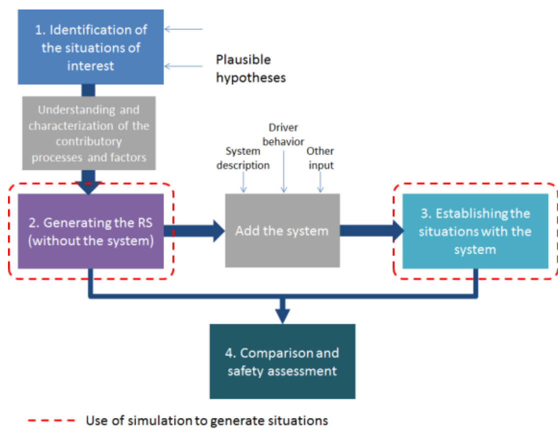


***Figure 10. Level 3: Use of simulation to generate RS and MS from the understanding and characterization of processes***

**Specific application:** The use of BMW's holistic method to assess the effectiveness of pedestrian protection devices in a mid-block crossing from right to left by a single pedestrian. The type of situation is illustrated in Figure 11.

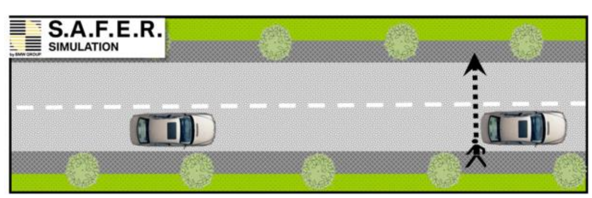


***Figure 11. Mid-block crossing from right to left by a single pedestrian [16]***

Once the TS have been defined, the next step consisted of identifying all the processes (at least some) that intervene in the situations, characterizing them, and modeling them as a sequence of states subject to both deterministic interactions and stochastic influences. The following elements are needed [13].

- Street and scenario: Sidewalk geometry, number/width of lanes in each direction, speed limit, infrastructure, visibility restrictions, crosswalks and road curvature.
- Traffic context and traffic state: The traffic context is generated from an exposure model which includes time of day and day of the week. The traffic state is generated from a traffic model and includes traffic volume, mean and standard deviation speed, and percentage of inebriated drivers.
- Pedestrian attributes: age, gender, fatigue, and alcohol level.
- Pedestrian modeling: The pedestrian is assumed to observe the traffic stream and decide when to cross depending on traffic volume, level of alcohol and etc. Some of the processes that use stochastic models include pedestrian perception of distance and the speed of approaching traffic stream, pedestrian gap acceptance, pedestrian trajectory and kinematics, and pedestrian monitoring of approaching vehicles.
- Driver modeling: Some of the processes include driver perception and reaction to a pedestrian, the spectrum of possible actions taken by the driver in response, the efficiency of these actions, and the probability that braking assistance systems will be triggered.
- Vehicle modeling: For this situation, the vehicle is assumed to travel in a straight line and the dimensions are the ones of a typical midsized vehicle.
- System modeling: The model considers the probability that the system will detect a potential collision and warn the driver. Also the range of possible effects of the warning on the driver's perception reactions processes and the spectrum of possible actions taken by the driver in response are taken into account.

A first step in the validation of the overall simulation fidelity was done by comparing the RS with the gold standard of empirical data from accident databases. The RS are 3042 collisions that resulted from 1 million simulated crossings. They were compared with a subset (n=110) of GIDAS vehicle-pedestrian frontal collisions. Figure 12 compares the cumulative distributions of the initial vehicle speeds of the 3042 simulated collisions that represent the RS with the initial speeds of the GIDAS subset.

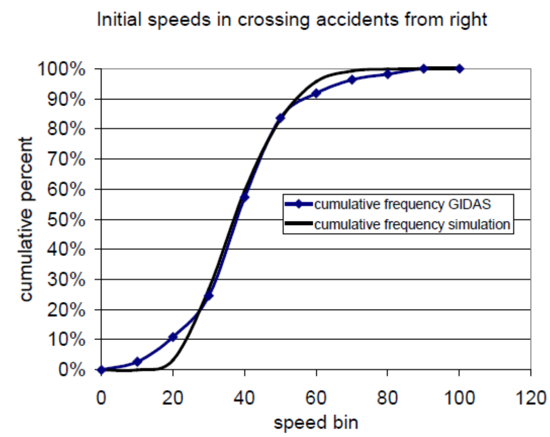


***Figure 12. Comparison of cumulative frequencies of initial vehicle speeds in pedestrian crossing collisions from Monte-Carlo simulation and GIDAS database [13]***

Figure 13 compares the cumulative distributions of collision speeds of the 3042 simulated collisions that represent the RS with the collision speeds reported in GIDAS.

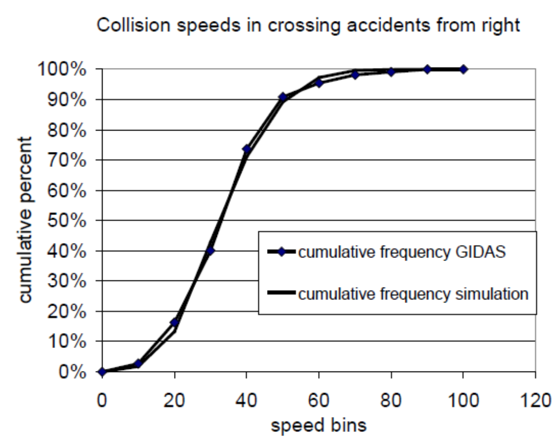


***Figure 13. Comparison of cumulative frequencies of collision speeds in a subset of pedestrian crossing collisions from Monte-Carlo simulations and GIDAS database [13]***

**DISCUSSION**

Each of the different approaches for the process of effectiveness assessment via virtual simulation offer advantages and drawbacks i.e. some of them might be less time consuming also but less realistic. To determine which approach is more appropriate for a specific need, an evaluation of the approaches is needed. The following criteria to help this evaluation have been identified:

- **Thoroughness and completeness**: Criterion that considers if the approach includes or deals with all or nearly all elements or aspects of the target situations; it evaluates if the approach is fully comprehensive.

- **Understandability**: Criterion that considers if the approach itself is clear and easy to understand. Can people that have never used the approach before understand the process of the approach?

- **Interpretability**: Criterion that considers if the results of the approach are clear and easy to interpret. Can people that have not done the effectiveness assessment look at the results and understand the relevance?

- **Operation capability**: Criterion that evaluates the degree of operation capability of the approach. Can people that have never used the approach easily be trainind to use it? Are there specific conditions for the use of the approach for instance specific software, specific data, etc. Is there enough guidance and a defined structure?

- **Usability**: Criterion that considers how easy and pleasant the approaches are to use. It covers whether or not the user finds the approach efficient and easy to learn.

- **Degree of automation**: It evaluates the level of automation of the whole process. Are the difference steps automated? Or do they need a lot of manual work?

- **Generalizability**: Can the approach that was developed for specific cases (situations) be generalized and used for other situations?

- **Flexibility**: Criterion that indicates whether the general approach is rigid or can be adjusted according to available data, used statistical techniques, and used driver-vehicle-road-traffic models.

- **Fidelity**: To what extent do simulations in the approach are close to reality.

- **Accuracy**: Criterion that evaluates the extent to which the values obtained with the approach match the true values. Are they biased? Are they precise or bound with a large confidence interval?

- **Time consideration** and **ability** to go back in time before the collision/critical situation: As we move from passive systems to active systems, preventive systems, connected systems, and automated vehicle systems, the need to go back in time before the crash-phase (or critical situation) becomes essential. This criterion considers the ability to go back in time and to account for behavioral adaptations and the effect of systems that play a role in safety for longer periods of time rather than just a few seconds prior to the impact (or road-off).

- **Resources** required: Criterion that considers the resources needed by the approach. Such resources include: (1) amount time invested by the person(s) doing the assessment, (2) amount of running time required to perform computational processes, (3) amount of money necessary for the approach associated to software licenses, to tests, the acquisition of specific databases, etc. At this point, it is important to take into account the ratio between resources invested and results obtained.

- **Validation**: Criterion that evaluates the way the processes and the results of an approach are validated.

- **Granularity**: Level of detail in the data, the situations under examination, the models, the statistical techniques, etc.

The evaluation of all approaches according to these criteria have not been performed and will constitute a next step in the analysis. It should allow identifying the best practices depending on objectives, research questions, and customer's expectations.

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