# RECENT ADVANCES IN EFFECTIVENESS ANALYSIS AND VIRTUAL DESIGN OF INTEGRATED SAFETY SYSTEMS

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## ABSTRACT

Design, optimization, and assessment of integrated safety systems (combining active and passive elements) pose considerable challenges. For example, the spectrum of potential situations in the field in which active elements might be triggered is considerably larger than one can achieve under controlled testing conditions.

In this context, it is crucial to evaluate quantitative metrics relating as closely as possible to human risks and benefits, such as avoidance of injuries or reduction of injury severity. The consequences of unnecessary interventions and other side effects on passengers or traffic also need to be quantified. This paper describes a generic approach to assessment of field effectiveness and evaluation of active and integrated safety systems. The approach, based on virtual experiments, is holistic, in that both active and passive safety elements are evaluated using a common metric while seeking the most effective solutions regarding overall improvement of vehicle safety. The complexity of process models and their interactions utilizes an advanced knowledge base. In order to achieve this goal, the whole sequence of events in a hazardous situation is virtually implemented in a tool chain. The tool chain includes stochastic (or "Monte-Carlo") traffic simulation, generating large samples of accident sequences but also near-misses, as well as detailed, high-resolution crash simulations of resulting accidents. The methods are useful not only for assessment of existing integrated safety designs, but also for comparing different system concepts or optimizing performance within a complex design concept. The potential of this approach is illustrated for several key accident scenarios.

## INTRODUCTION

Although prevention of all accidents is still out of reach, integrated approaches, combining elements of active and passive safety, appear quite promising in terms of human benefits. Active safety components are designed to reduce crash severity or avoid a crash entirely in situations with high collision risk, while minimizing unnecessary interventions. In accidents that cannot be prevented entirely by active strategies, it may still be possible to reduce severity of injuries by passive safety elements. However, design, optimization, and assessment of integrated safety systems pose considerable challenges. For example, the spectrum of potential hazardous situations in the field in which active elements might be triggered is considerably larger than one can achieve under controlled testing conditions.

In this context, it is crucial to define and evaluate appropriate quantitative metrics relating (as closely as possible) to human risks and benefits, such as avoidance of injuries or reduction of injury severity. These metrics are generally quite difficult to measure directly in field operating tests (FOT) or naturalistic driving studies (NDS), even retrospectively, because the number of injury accidents required for statistically significant injury probability differences to emerge is typically in the hundreds or thousands; the total accident rate is, for example, a few hundred per billion kilometers on German autobahns. FOT and NDS are appropriate for evaluating the impacts of safety systems on normal driving situations and driving errors that occur with much higher frequency, such as lapses of attention or unintended lane crossings. These observations can play an important role in accident risk modeling, but they do not directly provide the required metrics.

This paper describes the application of a generic safety evaluation algorithm to integrated safety systems. The basic idea is to estimate field effectiveness by virtual experiments carried out on a large sample of representative situations. The experimental design generally compares a safety system to a reference or basis situation without the system; a typical metric for comparison is the relative reduction in frequency and/or severity of accident injuries. The frequency and consequences of unnecessary interventions and other side effects on passengers or traffic can also be quantified in this approach. The virtual experiments are performed in the framework of a tool chain, which is illustrated below for several scenarios and safety systems of interest.

**Knowledge base for virtual experiments on integrated safety systems**

In order to perform virtual experiments, an advanced knowledge base is required. The knowledge base contains detailed models of all safety relevant processes in the traffic scenarios under consideration. In this context, "processes" include vehicle and traffic dynamics, as well as human sensory and physiological performance.

In addition, the possible influences of a proposed safety system on all these processes need to be modeled. To this end, specifications of sensors, algorithms, and actuators are required, as well as models of the human machine interface. The level of detail needs to be adequate to predict if and when a system would trigger during a simulated critical situation and how the system could influence the driver. Active safety modes of influence include acoustic or visual warnings, haptic feedback, pre-filling brakes or changing brake assist thresholds, direct intervention in longitudinal or lateral vehicle control, etc.

For evaluation of integrated safety systems including systems both of active and passive safety (such as pre-tensioning restraint systems or airbag deployment), the approach described below is to implement the knowledge base models within a virtual tool chain for virtual experiments.

**TOOL CHAIN ELEMENTS FOR INTEGRATED SAFETY SYSTEMS**

Figure 1 illustrates the process steps within a virtual tool chain for pedestrian safety systems:

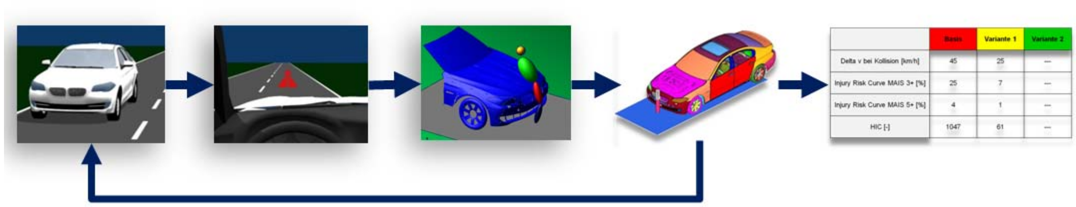


***Figure 1: Virtual Tool Chain (for the case of a pedestrian crossing scenario)***

The virtual tool chain for a typical integrated safety system includes several steps:

1. Stochastic traffic simulation including preventive safety systems
2. Multibody simulations determining precise collision constellations
3. Finite-element simulation of representative collision constellations

4. Surrogate models for injury criteria in collisions (for example support vector machines)

5. Determination of injury risk based on injury criteria, such as Head Injury Criterion (HIC) etc.

The processes represented by the simulation models include behavioral and physical characteristics of all traffic participants, the environment, the vehicle, the safety function, and all possible interactions. A key characteristic of most models in traffic safety is the inherently stochastic nature of the processes, particularly those that depend on human factors. Collisions are generally rare events, even in potentially risky situations. Hence, in order to simulate a sufficiently large sample of "true" virtual accident situations, a correspondingly large number of potential conflicts or hazardous situations need to be simulated, requiring high computational efficiency during the stochastic simulation step.

When evaluating overall safety performance in case of unavoidable accidents, a detailed representation of the vehicle, occupants (dummies, human models) or pedestrians/cyclists (impactors, human models) is necessary. For example, detailed determination of injury characteristics and their improvement due to passive safety systems (e.g., active bonnet for pedestrian safety, reversible belt pre-tensioning during pre-crash phase) usually demand finite-element simulations. The highly dynamic processes during the relatively short crash phase require higher resolution and thus several orders of magnitude more computational time per virtual accident than the pre-crash phase although being significantly longer (usually several seconds of pre-crash phase are followed by only some hundred milliseconds during the crash phase). For virtual statistical evaluation of a particular system configuration, several hundred accidents need to be generated and simulated. Considering the many possible variants within a system, surrogate models, which allow rapid calculations, offer a useful approach to achieving manageable overall computing times.

Regarding kinematic occupant behavior in the pre-crash phase (such as during braking), standard finite element models have only limited validity: first of all, crash test dummies (both, numerical and hardware dummies) are validated for massive crash impacts and are quite rigid under low-g impacts. The second limitation is that under low impacts, the occupants have the ability to actively control their behavior. Therefore, active human models seem to have a more realistic behavior in these scenarios, [KH14].

### CONFLICT SCENARIOS ADDRESSED BY INTEGRATED SAFETY SYSTEMS

In the following, we focus on methods for evaluating integrated systems including automatic emergency braking (AEB) features in three conflict scenarios:

1. Pedestrian/vehicle conflicts (→ AEB pedestrian)
2. Cyclist/vehicle conflicts (→ AEB cyclist)
3. Vehicle/vehicle rear-end conflicts (→ AEB city/AEB interurban)

For these AEB systems, the traffic contexts are different (highway traffic vs. city scenarios, rear-end braking scenarios, lane changing, crossing/turning, occlusion), the driver models are in general similar but may differ regarding their parameterization (e.g., regarding awareness, response times), and also the behavior of pedestrians is completely different from that of cyclists (regarding for example acceleration/deceleration, inertia, evasion). Therefore each traffic scenario needs careful and detailed modeling. The AEB systems under investigation have typical key characteristics which are the similar for all systems mentioned above: sensor opening angles (horizontal, vertical), sensor range, latency, sensor quality, brake ramp, maximal deceleration. Beside these similarities, the algorithms (e.g. the underlying intelligence) are completely different and independent and therefore result in differing behavior.

Regarding cases where the accident cannot be avoided completely or the accidents which happen without an AEB system, the collisions cyclist/vehicle, pedestrian/vehicle, and vehicle/vehicle each have different kinematics and require validated multibody or suitable finite-element models to determine the exact collision constellation and injury outcomes.

In case of an active or integrated cyclist safety system the tool chain itself is identical to the one which is described below for the pedestrian. Evidently, every single module requires different models. The stochastic traffic simulation must be able to reproduce all critical cyclist conflict scenarios (crossing, turning, overtaking…). The multibody models have to be validated for the cyclists (different bicycle geometries, cyclists' body forms (children, adults…)). In addition, the determination of the injury criteria is not trivial, since the model choice is not predetermined (impactors vs. hybrid dummy models vs. active/passive human models). The tool chain for active and integrated cyclist safety systems is under current development.

Similarly, the tool chain for vehicle/vehicle active safety systems is currently under further development. The first module, the stochastic traffic simulation of highway scenarios with and without automatic emergency braking systems is available (highway scenarios including lane change, traffic jams; city scenarios) and presented in this paper. In case of an accident, the injury risks can be estimated based on the resulting crash-constellations (impact speed, masses, impact direction); however, detailed models for vehicle/vehicle crashes at different angles, speeds etc. are still subject of research (available finite-element-models are too time-intensive in computation for this field of application). In the future we will also provide appropriate models for the pre-crash phase (including active safety systems) and surrogate models for the crash phase so that the comparison of passive safety systems is also possible within the tool chain.

## TOOL CHAIN FOR INTEGRATED PEDESTRIAN SAFETY SYSTEMS

### Stochastic traffic simulation of pedestrian crossing scenarios

Effectiveness analysis for preventive safety systems starts with the generation of representative initial conditions for potentially critical situations using appropriate exposure models. An exposure model describes the distribution of key characteristics that are likely to affect the probability of a conflict (and consequently that of an accident or a system response).

Consider for example an inherently hazardous crossing scenario known as the "midblock dash": a pedestrian decides to cross an urban street (from the passenger side) at an unregulated spot between intersections, i.e., without traffic lights, crosswalks, or any other form of infrastructure support, see figure 2. For the example presented in this paper, we consider one-way traffic on a single, straight, one-lane road and assume that there are no obstructions, such as parked delivery trucks, to obstruct the drivers' view of the roadway and the traffic stream. For other applications different street layouts, obstructions etc. are also available.

In the paradigm of virtual testing by stochastic simulation, the aim is to obtain and simulate large, representative samples of virtual sequences of traffic situations. As an example, the pedestrian model consists of various key characteristics; specific parameters are drawn from multivariate distributions, such as:

- Context variables: distribution of pedestrian crossing volume during the course of the day (by age and gender)
- Pedestrian attributes, such as age- and gender-adjusted distributions of height and weight, as well as fatigue and alcohol levels (both related to time of day)
- Distributions of cognitive characteristics, such as alertness, visual and reactional performance (related to age, gender, alcohol, fatigue)

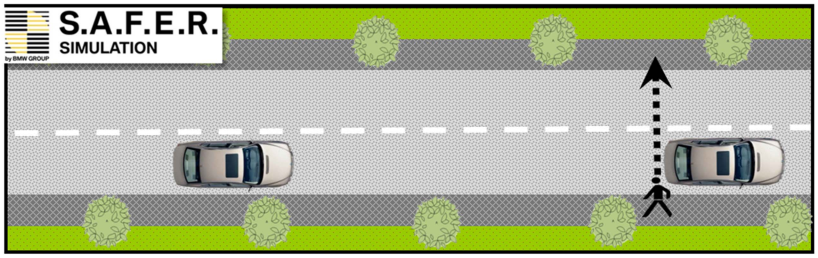


***Figure 2: Stochastic Simulation of a pedestrian crossing: the midblock***

Exposure also deals with generation of realistic traffic contexts and representative drivers, who might be confronted with an unexpected crossing pedestrian. The model distributions involve:

- traffic volume and average traffic flow speed during the course of a day
- speeds and gaps within a traffic stream

Once a representative virtual pedestrian has been "created", processes governing the dynamics of the pedestrian are simulated. These include, for example:

- Gap acceptance to begin crossing of the road
- Decision to walk or run
- Initial walking or running speed
- Initial heading
- Angular gaze distribution
- Possible speed and course correction

The willingness of the pedestrian to wait for an acceptable gap decreases with increased waiting time. As a consequence, the pedestrian "becomes impatient" and will accept smaller gaps. More generally, there are several mechanisms of cognitive error for estimating gaps and crossing times, all of which can contribute to a particularly hazardous crossing. An additional characteristic that needs to be respected is the response of the pedestrian, once he perceived a critical situation: possible reactions include freezing on the spot, jumping forwards, or moving backwards; all responses are associated with cognitive processing demands.

Similarly, driver performance including alertness, visual acuity, perception of hazards, cognitive processing (reactions), and response (such as braking) are also modeled in detail using appropriate probability distributions. These depend in turn on relevant driver attributes, e.g., age or fatigue, but may also depend on context (e.g. lighting conditions). A detailed model description is given in [HSSEK11] and [HNRGKK12].

In the scenarios considered here, available driver responses to a critical situation are limited to braking, but in general, emergency evasive steering would be another option for the driver.

Preventive safety systems – such as AEB systems – have different options for influencing the situation, such as driver information and warning, automatic braking, or rather indirect strategies, such as adaptation of brake assist thresholds. Thus, system safety performance is clearly mediated in many cases by the driver's actions, and these in turn depend on individual characteristics. As a consequence, performance evaluation requires stochastic models that include the relevant individual driver characteristics.

In addition, safety performance is affected by the range of cognitive and dynamic responses of pedestrians: for example, there are two mechanisms for avoiding collisions by braking of the vehicle: The first is obvious, i.e., the vehicle stops before crossing the pedestrian's path. The second is less obvious: even if a vehicle cannot stop before crossing the *pedestrian's* path, some pedestrians might move fast enough to get out of the *vehicle's* path (an extra 300 ms at 3 m/s means 90 cm, or about half the width of a vehicle).

In case of ideal weather and illumination conditions camera systems used for automotive applications show a good performance concerning object detection and classification. Nevertheless in order to ensure a realistic model of the AEB system, probability of failure and limited functionality are also considered.

The possibilities of the virtual simulation are currently extended by considering more crossing scenarios (far side, obstructed), other vulnerable road users (cyclists), other traffic scenarios (turning, oncoming traffic, etc.) and more elaborate preventive safety systems (such as the fusion of camera and radar sensors).

Most active safety algorithms have to deal with uncertainties related to human performance. Effective prevention or mitigation of an accident may require system response before the accident is 100% certain to occur. For example, an acutely endangered pedestrian could jump back at the last minute. The result is that an active safety device can trigger even if no collision would have occurred without it. Because the exposure models generate situations that do not necessarily lead to accidents (even without a safety system), virtual stochastic simulation enables quantification of how often such "unnecessary" responses occur in relation to the "necessary" ones. Moreover, possible side effects of AEB systems, such as secondary rear-end collisions, can be quantified for all responses, not just the necessary ones. In this way, the advantages and disadvantages of a triggering decision under uncertainty can be quantified and incorporated into system optimization.

Since the virtual simulations provide data such as gender, age, height, and weight in addition to collision speed and position, it is possible to model the effectiveness of the AEB systems not only in terms of speed reduction, but also with respect to changes in injury severity. One approach is to interface the stochastic simulation with empirically generated injury probability models. This approach does not require detailed vehicle models and provides a good assessment of the effectiveness of the active system. However, whenever conclusions for specific vehicles and their passive safety systems are required, one has to follow the subsequent steps of the described tool chain.

**Collision constellation via multibody simulation for pedestrian impact**

In cases where the accident cannot be avoided completely, or for the basis simulation without any active safety systems, the collision constellations need to be determined. Stochastic traffic simulation, as described above, calculates the trajectories of involved traffic participants, but is not designed for delivering exact collision details, such as exact points of impact (especially of specific body parts), exact impact speed etc. These parameters can be simulated using fast, multibody simulation models. The pedestrian is modeled by 4 body elements (head, torso, femur, and tibia) joined by 3 joints (neck, hip, knee); the models are scalable for different body heights (children, adults). The pedestrian models have been validated based on available PMHS tests (Post Mortem Human Subjects), [KMDKBC05].

The vehicle is modeled as a rigid surface. Since these models are fast calculating (i.e. few seconds per run), it is possible to determine the exact collision constellation for a considerable number of accidents.

Current developments include enhancement of multibody models for cyclists. In this case, the validation is more difficult, since cyclist data is scarce. It is planned to use the results of finite element simulations for the validation of the multibody kinematics.

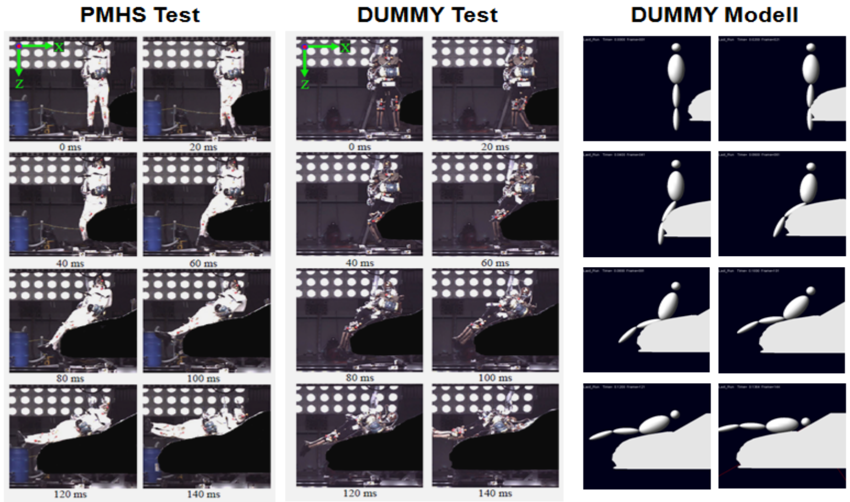


*Figure 3: Kinematics Comparison PMHS vs. Multibody Simulation*

**Injury criteria via finite element simulation for pedestrian impacts**

The next step is the determination of the injury criteria of the pedestrians based on the exact collision constellations. These depend not only on parameters like speed, acceleration or the exact point of impact, but also on the stiffness and geometry of the vehicle and its passive safety features, like active hoods etc.

The finite element models of the vehicle and the pedestrian (THUMS, finite element dummy, head impactor, TRL leg impactor, flex pli …) have the main disadvantage of requiring long calculation times in order to deliver accurate responses. Of course, there are some ways to optimize these calculation times, like reducing the models to the absolutely required model parts and omitting everything which is not needed directly. Nevertheless, depending on the IT-infrastructure, each simulation still requires at least some hours.

For example, considering one million stochastic simulations without preventive safety systems, probably thousands of collision scenarios would have to be simulated using these models (either THUMS Simulation for the whole body or head & leg impact); this would require about 1-2 months calculation times, which is not feasible in this developmental context. To overcome these long waiting times, surrogate models for each vehicle/impactor combination have been developed.

**Surrogate models for injury criteria**

Surrogate models are mathematical, non-physical models describing input/output relations of given data pairs. There are several, well known approaches, such as fuzzy models, linear models, support vector machines, local linear model trees… Since these models are non-physical, one has to calibrate them for each problem and check carefully, if they are truly valid by considering appropriate error measurements, [WBHF15]. When the underlying physical problem changes (e.g., new vehicle geometry), the model has to be rebuilt or at least re-parameterized.

When building surrogate models, the first step is the selection of training data. Beside the appropriate distribution of chosen points, the number of training points is crucial. Too few result in imprecise surrogate models; too many require long calculation times. Regarding the distribution, we found that accounting the problem structure sometimes improves the result quality, for example the use of more training data in areas of higher in-homogeneity. In case of pedestrian protection, all available information has been considered, when choosing training data. For example, in areas with known changes in stiffness, more data have been chosen than in areas with little changes. Our goal was to achieve acceptable results using data of about 100 head-impacts and 100 leg-impacts. The head- and leg-impacts didn't necessarily belong to the same collision. Calibration of the surrogate models can be done using different methods for example by using differential evolution algorithms to find optimal model parameters. We tested different regression methods namely LOLIMOT (Local Linear Model Tree), support vector machines and Kriging. These standard methods are available in different (commercial) optimization and machine learning software. We found that different injury criteria demand different surrogate models.

**Injury risk**

Based on the calculated and predicted injury criteria (in our case HIC-values of the head impactor and leg acceleration, shear- and bending forces of the TRL impactor), injury risk curves are used to determine the risk of injury with and without the integrated safety system or in order to compare different systems.

These impactor values give a first impression of the passive safety performance of a certain vehicle and have the advantage of being established measurement criteria. Further enhancements of the tool chain for cyclists and occupants will also imply the use of biofidelic human models and the deduction of suitable injury criteria.

**Example: Stochastic Simulation of the pedestrian crossing scenario with an integrated safety system**

The next example uses the complete tool chain for effectiveness analysis of an exemplary active pedestrian safety system compared with an active bonnet.

The active pedestrian safety system is camera-based with very limited functionality during night and a maximal automatic deceleration of 4 m/s².

For this example about 1 million stochastic runs of the crossing scenario were performed (pedestrian crosses a single lane street from the right side without traffic signs or obstructions) with and without the preventive pedestrian safety system. The remaining collisions (head to bonnet impacts) were simulated with and without

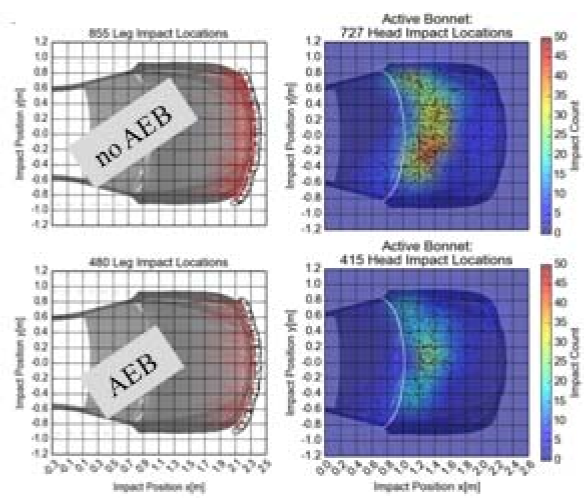


***Figure 4: Impacts on vehicle in pedestrian/vehicle collisions***

an active bonnet.

In order to avoid long calculation times, a surrogate model was used for the prognosis of the injury criteria.

In this example, the preventive safety system succeeds in avoiding 46% of the accidents. In the remaining accidents, the integrated safety system achieves the following injury risk reductions based on HIC15 and lower leg acceleration, bending and shear forces:

- 16% reduced injury risk through the active bonnet
- 29% reduced injury risk through the preventive pedestrian safety system
- 39% reduced injury risk through the combination of both systems

For the interpretation of these figures, one should note that:

- The driver reactions vary due to the underlying probability distributions, so that some drivers show very fast reaction and some show no reaction at all.
- The active bonnet has some effect on the head to bonnet impacts but of course none on the other impact locations (windshield, A-pillar, leg impacts).
- The preventive pedestrian system considered in the stochastic simulation is camera-based and has very limited functionality during nighttime. Additionally, accidents occurring at night are usually with faster vehicle speeds than during daytime.

## EFFECTIVENESS ANALYSIS FOR AEB SYSTEMS DESIGNED FOR VEHICLE/VEHICLE SCENARIOS

### Stochastic Simulation of rear-end conflict scenarios

Another important application of AEB systems is the prevention or mitigation of rear-end vehicle/vehicle conflicts. On highways for example, rear-end conflicts are particularly common when drivers encounter a strong negative gradient in traffic flow speed (a sharp slowdown) that they fail to anticipate. An acutely hazardous scenario can occur for example if traffic flows at a speed requiring a sight distance that exceeds the true visibility distance, for example due to a curve or hilltop, and if a vehicle does not observe the actual braking of traffic ahead. In addition, even if the first driver approaching a slowdown does manage to brake sharply, a second driver who has not been able to observe the primary conflict is also at high risk for a rear-end collision. If there is one collision, then secondary or tertiary collisions become even more likely, for example due to extreme decelerations and loss of control. In either case, avoidance of a collision in an unequipped vehicle (without AEB) depends critically on driver response. The driver must perceive the conflict or the brake lights of a preceding vehicle, properly orient and understand the potential severity, and apply the brakes quickly and decisively. Obviously, if we consider a typical distribution of drivers on a highway, some will not be looking directly forward at the crucial moment. Even without “distractions”, there are many visual cues competing for the driver’s attention.

Under these circumstances, it is intuitively clear that sensor-supported AEB systems could help prevent or mitigate rear-end collisions. The clear advantage is that an AEB sensor (e.g., radar) will not be subject to the same distractions as the driver.

We have developed a knowledge base including stochastic models appropriate for describing traffic flow in rear-end conflict scenarios such as those described above. As in the case of pedestrian protection, the knowledge base begins with appropriate exposition models. For example, an important parameter is the frequency of negative speed gradients as a function of severity – large negative gradients are the most dangerous, but occur less often. Exposition models also describe representative initial conditions for a sequence of vehicles with realistic initial TTC (time to collision) and spatial headways, based on analysis of highway vehicle data. It is also possible to model the effects of traffic context (e.g., traffic volume). The knowledge base further includes observation-based models of the distributions of the key human factors that determine driver braking performance in an acute rear-end conflict. Possible driver swerving will also be taken into account.

A particularly important feature is the percentage of drivers not looking directly ahead. The human factor models take into account the fact that these drivers will tend to have longer reaction times and that they tend to brake more abruptly when they do finally perceive a conflict.

In a typical AEB system, the sensor information can be combined with additional signals from the vehicle. For example, it is an advantage if the algorithm can classify whether the driver is in fact "in the loop" or not. If the driver is in the loop, a delayed system response can avoid unnecessary interventions, [KFS04]. If the driver appears not to be attentive, then an early system response may be advantageous. The stochastic simulation methodology provides a virtual experimental framework for tuning these algorithms and determining an appropriate operating point.

Another key aspect concerns possible secondary or following accidents. It might be assumed that AEB systems will induce more following accidents due to the sharp braking of the system, than would occur without AEB. However, note that in an acute rear-end conflict without AEB, if a rear-end collision does occur, then the effective deceleration is also quite large, and, moreover loss of control can induce a spectrum of additional conflicts. Hence, for a comprehensive analysis, it is important to take following vehicles and their human drivers into account to model the complete situation.

### PERSPECTIVE: EXPANSION OF THE VIRTUAL TOOL CHAIN FOR CYCLIST SAFETY AND OCCUPANT SAFETY

The virtual tool chain including stochastic simulation for the effectiveness analysis of integrated pedestrian safety systems has been designed to provide a valid representation of real-world accident occurrence and system behavior.

The outlined tool chain will be extended for other vulnerable road users, mainly cyclists. The extensions will include a broader spectrum of traffic scenarios for stochastic simulation (turning scenarios…) including several street layouts and a more complex preventive safety system. The cyclist's behavior must be carefully modeled (maximum deceleration rates, swerving). Challenges include validation of the cyclist dynamics and modeling of bicycle-vehicle collisions, including injury characteristics. In addition, surrogate models must be calibrated for each case separately.

Regarding rear-end collision and AEB systems, occupant behavior in these scenarios must also be carefully validated, since it could have a major impact on crash results. Since crash test dummies are too stiff under low g impacts, other models have to be used, such as active human models.

## CONCLUSIONS

This paper has illustrated some recent advances in virtual design and effectiveness evaluation of integrated safety systems, using the example of AEB systems for pedestrians. The approach described above is holistic, in that both active and passive safety elements can be assessed on a common basis. The methods are useful not only for assessment of existing integrated safety designs, but also for comparing different system concepts or optimizing performance within a complex design concept. In order to achieve this goal, the whole sequence of events in a hazardous situation is virtually implemented in a tool chain. The tool chain includes stochastic (or "Monte-Carlo") traffic simulation, generating large samples of accident sequences but also near-misses, as well as detailed, high-resolution crash simulations of resulting accidents. The approach was illustrated in detail for key accident scenarios in pedestrian protection. The virtual-experiment approach using a tool chain generates assessment metrics relating to human risks and benefits, such as avoidance of severe injuries. Comparative evaluation of human-oriented metrics provides important information for stakeholders in safety system development.

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