Chapter 2
State of Scientific and Technical Knowledge on Pre-crash Evaluation

2.1 Methodological Aspects of Evaluation

The recent development and market introduction of various active safety functions within the context of integral safety have generated a demand for evaluation methods (see Chap. 1). The key research question for the evaluation of integral safety, using the paradigm of Fig. 1.6, is:

How well does a given function perform regarding safety during the pre-crash phase at the characteristic or functional level?

As this question is often asked in this manner, two vital aspects are not explicitly named or are missing. The reference situation (i.e., the baseline of comparison) for the question as well as the validity of the expected answer (which directly depends on the method used) must be included in the question. No generally accepted definition of "safety benefit", as stated in the question, exists (neither for its meaning nor for the metrics). Examples of possible interpretations are:

- Performance of a given component in a specific test or a variety of tests.
- Performance of a measure regarding a particular accident constellation.
- Performance of a measure regarding specific injuries.

Considering the introduction and discussion about new measures of integral and active safety as a background, the safety performance generally refers to the benefit in the field. The "field" is a commonly used term for the traffic system as a whole (in markets and countries where the measure will be available). As a consequence, all possible safety effects (both positive and negative) within the traffic system as a whole have to be evaluated. The answer to the question should include a trade-off between both kinds of effects rather than the magnitude of positive effects alone.

However, for practical reasons, evaluations are often limited to accidents as reference groups (instead of traffic in general). Possible negative effects, such as aspects of controllability are excluded from analysis and only possible positive effects are

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assessed. The problem with many measures and studies cited below is that the questions as well as limitations are not stated precisely enough.

In order to answer (parts of) the question stated above, a variety of methods and procedures have been developed and discussed in recent years. This chapter summarizes the most important ones together with their advantages and challenges (as far as they are generally known).

Two aspects are of special importance in this context:

1. The validity of the method with respect to the research questions it is intended to answer.
2. How the method deals with uncertainty.

Although the first point seems to be obvious when setting up or choosing a method, it is of vital importance when drawing conclusions. In the discussion that follows, "validity" refers to comparison of the results, e.g., a method or process model, with observed empirical data; therefore validation does not directly confirm that every detail is correct. "Verification" refers to the confirmation of the correctness of each individual detail, e.g., in a laboratory setting. Generally speaking, it is only possible to verify some parts of a method in detail, for example, models of reaction sequences, which have been studied quite thoroughly in the literature [1]. Other processes such as pedestrians' reaction in acute situations are understandably difficult to verify in a laboratory setting. However, in order to improve the confidence in, e.g., modeling details, one performs validation of a large spectrum of statistics which can be measured; as the number of validated relationships increases, the sensitivity of the validation procedure to possible modifications of the detailed microscopic models increases.

The second point is more subtle: Every evaluation method either uses data sources, contains modeling to some extent, relies on assumptions, or draws conclusions using some kind of extrapolation. Each of them is subject to various kinds of uncertainty (e.g., within the assumed parameter values). This inevitably brings uncertainty into the answer (or results). The degree of uncertainty is thereby dependent on the least accurate part of the method. In other words, it is nearly never helpful to test one aspect with the highest degree of validity while others with the same sensitivity for the analysis have a lower degree. Measures of quality (such as error intervals) should be given with the final results, or at least the validity of them should be assessed together with the results.

In order to categorize different methods with respect to the subject of evaluation, the model of driver, vehicle, and environment (see Sect. 1.1) can be used. The vehicle is further analyzed using the structure of active safety as given in Fig. 1.6. In practical terms this means that the smallest entity for evaluation within the vehicle is a component. The next level is a system (or some part of a system, here referred to as subsystem). Especially when testing different vehicles, as it is the case, for example, with consumer protection agencies, the levels "function" and "characteristic" are of importance.

As many active safety systems do have a human-machine interface, the driver can also be in the focus of evaluation. The surroundings of the vehicle constitute important influences during development and testing. Evaluation methods refer to multiple possible combinations of different parts of this model (e.g., testing the driver *and* the vehicle or a single component).

The driver with his vehicle and its immediate surroundings form one entity in traffic, but this entity is not isolated. Evaluations often analyze the driver/vehicle entity (or parts of it) as if it were isolated. If the interaction with other participants in traffic is essential to answer the research question given, more than one of those entities must be taken into account.

Once the effects of a measure on (parts of) the system "traffic" (i.e., involving more than one entity), are under investigation, two main approaches can be distinguished:

- *Accident*-based evaluation. The effect of a measure in one or many accidents is investigated. The effect on the whole accident occurrence in a particular area, e.g., a country, can be assessed.
- *Traffic*-based evaluation. In this case, the effects on traffic are evaluated, either in a specific subset or, for example, one country. Depending on the sample size and method used, this procedure includes the evaluation of accidents, as they form a subset of traffic.

The main difference, as explained above, is that a representative evaluation on the sum of both positive and negative safety effects is only possible using traffic-based testing. This point will be discussed in its special meaning with every method further below in this chapter.

2.2 System Responses Available for Evaluation

The evaluation of measures, which are active during the pre-crash phase, includes all possible system responses. As those systems are subject to a variety of uncertainties (e.g., due to limitations of the sensors, variability in the situation when making predictions, etc.) they will not work ideally [2]. That means they will produce unintended side effects; together with the intended effects they can be visualized using a classification matrix [3] as given in Table 2.1.

There are two categories of intended as well as unintended responses with respect to the *objective* danger of the specific situation. The intended actions are the following:

Table 2.1 Categorization of possible system responses

		System response	
		Yes	No
Objective danger	Yes	True positive	False negative
	No	False positive	True negative

- *True-positive* action (TP): The system acts accordingly to its specification[1] in a dangerous situation.
- *True-negative* action (TN): The system does not act in a non-dangerous situation according to its specifications.

The *intended* actions are explained straightforward regarding the objective of the system. If necessary, it should do what it is specified to do (i.e., true positive) and otherwise should not act (i.e., true negative). The *unintended* actions are grouped into:

- *False-positive* action (FP): The system acts like in a hazardous situation while in a non-dangerous situation.
- *False-negative* action (FN): The system does not act in an objectively dangerous situation.

The unintended system actions have different consequences: A false-negative action means, the situation is dangerous and the system should act, but does not. This results in a loss of safety benefit in that situation regarding the specification of the system. A false-positive action is not related to a dangerous situation but can provoke a new critical situation, either if the driver reacts incorrectly to the system action or if the surrounding traffic is endangered (e.g., by massive automatic interventions or incorrect driver actions). In this context, false warnings can be regarded as less dangerous, as they need an incorrect driver reaction to be effective for the surrounding traffic; whereas automatic interventions regarding the vehicle controls have to be considered as potentially more critical [4].

The quality of a measure with respect to traffic safety can thus be evaluated using this abstract scheme. The sensitivity (also called right-positive rate (RPR)), defined in Eq. 2.1, gives the conditional probability that a positive (i.e., objectively dangerous) situation is treated by the system accordingly [3].

$$p\,(\text{positive reactions} \mid \text{positive situations}) = RPR = \frac{TP}{TP + FN} \tag{2.1}$$

The specificity, defined in Eq. 2.2 (also called right-negative rate (RNR)), describes the conditional probability that a negative situation is treated correctly by the system.

$$p\,(\text{negative reactions} \mid \text{negative situations}) = RNR = \frac{TN}{TN + FP} \tag{2.2}$$

The complementary quantity to specificity is the false-positive rate (FPR):

$$p\,(\text{positive reactions} \mid \text{negative situations}) = FPR = 1 - \frac{TN}{TN + FP} = \frac{FP}{TN + FP} \tag{2.3}$$

[1] The specification of the system includes the definition of “dangerous” as well as the activation thresholds. “Objectively dangerous” refers to the criteria set within the specification. No generally accepted or universally applicable definition of “dangerous” exists.

The complementary quantity to sensitivity is the false-negative rate (FNR):

$$p\,(\text{negative reactions} \mid \text{positive situations}) = FNR = 1 - \frac{TP}{TP + FN} = \frac{FN}{TP + FN} \tag{2.4}$$

Other important rates give information on all correctly (i.e., definition of accuracy) or incorrectly treated situations:

$$p\,(\text{correct reactions}) = \frac{TP + TN}{TP + TN + FP + FN} \tag{2.5}$$

$$p\,(\text{incorrect reactions}) = \frac{FP + FN}{TP + TN + FP + FN} \tag{2.6}$$

When evaluating the overall safety impact of a measure, the medical term "number needed to treat" (NNT) [5, 6] can be adapted:

$$NNT = \frac{TP + FP}{TP} \tag{2.7}$$

The NNT describes the number of necessary system actions per correct action. Combined with the consequences of false positives, a trade off regarding the overall safety effects can be made. Obviously, NNT is always > 1, but should be as small as possible.

Two concurring ways of optimization are generally predominant during the development of active safety functions and are known as "warning dilemma". The first aims for the highest safety benefit. That requires early system actions as well as high sensitivity. As described, this leads inevitably to an increased number of false system reactions (resulting in lower acceptance as well as possibly new critical situations), as evident in the false-positive rate [7, 8]. The second aim is a low NNT. Optimization which brings down unintended system reactions usually also affects intended system reaction negatively, e.g., more conservative activation thresholds minimize false activations but also lead to later and/or fewer activations. The optimization must thus aim for an optimal trade off with respect to safety benefit, acceptance of the measure, and negative consequences due to false system actions while defining the operating point of the system.

If the consequences of false-positive warnings as well as of false-positive interventions of a specific deceleration could be quantified (e.g., by subject experiments), a factor comparing warnings and interventions could be constructed. For illustration of the methodology, the coefficient "effective intervention" is defined as sum of interventions and warnings, combined by a factor resembling the severity of the "consequences" of each measure. The NNT using effective interventions gives the overall functional "costs" of a system including a combination of warning and automatic intervention. It can be calculated for every desired outcome category (e.g., effective intervention per avoided accident).

The overall functional costs of a specific system configuration as characterized by NNT is one important parameter for optimization. Usually, these costs are intended to remain within a given range. The change in overall costs depending on the optimization parameter is often non-linear. For example, an increase in the time-to-collision, as one defining parameter for intervention by the system, usually leads to an accelerated increase in overall costs, as more and more false-positive interventions will occur per true-positive intervention.

The well-known concept of marginal benefit describes the maximum amount someone is willing to invest for an additional unit of benefit. The marginal functional costs can be interpreted as the derivation or slope of the overall NNT curve. In the case of preventive pedestrian protection, marginal costs refers to the additional cost for another increment of the optimization parameter. In combination with the overall functional costs, a stakeholder or group of them (e.g., manufacturer, driver, society) could set a limit for the overall costs as well as for the marginal costs. The overall functional costs thus narrow down the potential range of the optimization parameter. The optimum within this range could be a minimum NNT (as described above) or an incremental search for the best operating point using marginal functional costs. The parameter is incrementally increased within the range until the marginal costs (i.e., the costs for each additional increment) reach their limit.

An optimized development therefore takes these metrics as criteria for optimization and considers both expected safety benefit as well as possible negative consequences. In order to test false-positive rates or calculate NNT, adequate testing methods with respect to real traffic and its variability are needed [9, 10].

2.3 Retrospective and Prospective Evaluation

Methods for evaluating vehicle-based safety measures can be categorized into *prospective* and *retrospective* [11–15]. The main difference is the time of the evaluation regarding the development process and/or life cycle of the measure in question [12]. Prospective analysis can be used from very early stages of development on (without the necessity of having a fully developed measure), and retrospective analysis can be used once a measure has been developed (and usually has already been in the market for a given span of time) [15].

Retrospective analysis mainly uses real accident data and evaluates existing measures with respect to a safety statistic. A common procedure is to define two groups in the accident data, one with the measure in question and the other without. The two groups are then compared searching for changes in characteristic values of the statistic [14, 15].

There seems to be a consensus in the literature concerning the "power" of this approach as being both very important [14] and impressive [9]. Analysis of existing real-world accident data is even sometimes regarded as "[a]n ideal method to assess the safety impact of advanced safety technologies" [10]. The most prominent example for retrospective evaluation is the Electronic Stability Program (ESP)

[9, 16]. A summary on available studies is included in [16]. Besides the obviously striking approach of using accident data retrospectively for evaluation, past studies also indicate the challenges coming with this method. It took years before the effectiveness numbers regarding ESP turned out to be stable, while other (common) systems like Antilock Braking System (ABS) are still being discussed regarding their actual effectiveness [16].

The retrospective approach in general has a number of constraints:

- The measure must be frequent enough in the market to have a sufficient market penetration and thus produce visible effects in accident data [9, 14, 16–18]. This often takes years as market penetration is dependent on the take rate of a measure (if optional) [10, 11, 15, 16]. The positive exception was again ESP; rapid and broad market introduction lifted this measure quickly above the statistical noise in accident data [9].
- The presence of the measure in a vehicle must be identifiable in accident data [16] in order to group the accidents. The information as to whether an active safety system was active during an accident is rarely available in nearly all accident data sets (this applies only to measures which can be deactivated by the driver). (The limitations of accident data bases in general are discussed further below.).
- Statistical similarity of case and control group must be assured [16].
- Long term behavioral effects may change results over time [16] (see also previous points).
- The retrospective statistical analysis of accident data tests mainly for correlations. The observed effects need therefore not be causally related. A causal relationship has still to be proven, e.g., by controlled experiments [16].
- The baseline or reference group may be biased by avoided accidents, as they are not included in accident statistics [12–14, 16, 17]. Although the opinion exists that only accident mitigation can be evaluated by a retrospective approach [12], newer research indicates that the avoidance potential of measures of active safety may be accounted for by statistical means like odds ratios and thus making this constraint less severe [19].
- Probable interaction effects with other measures can mask the investigated effect: To this end, possible confounders have to be known and controlled (e.g., belt-use rates, presence of other systems with similar functions and/or effects) [16, 19]. The control of confounders is only possible, if those are available in the data sets used. Interaction effects and confounders are even harder to control for, if the data cover a large span in time and the internal influences on traffic and/or accidents may change in that period [12].

The importance of controlling confounders and interaction effects shall be pointed out by an example. Using the retrospective approach, one study evaluated the effects of xenon headlamps on accidents in Germany [20] on basis of the federal accident statistics. As a result, introducing xenon in 100 % of passenger vehicles would lead to a decrease in 6 % of all accidents and 18 % of all fatalities. The study claims that all possible confounders were taken into account and do not bias the results [20]. The possible confounders cited, such as exposure time of vehicles, driver behavior etc., are not part of the federal data, thus cannot have been accounted for in the study. The results found may not be attributed to xenon headlamps as stated but could be causally connected, for example, to differences in driver behavior (as xenon was introduced in upper class vehicles first, they could have a different driver population). The vehicle groups could be very inhomogeneous if differentiated by xenon, as the comparability of drivers and vehicles cannot be assured in the groups used. All other safety features of vehicles introduced during the 10 years of data considered (coded in the federal statistics or not!) were not explicitly taken into account. This example should highlight the importance as well as the difficulties considering the challenges while performing retrospective analysis as described above.

The necessity to evaluate safety measures *before* market introduction regarding their safety benefits is the driving force behind *prospective* analysis and evaluation [12, 21]. In this case, only one group is selected from the data instead of two. This group is then evaluated on a theoretical basis with and without the measure in question [14].

The advantages of prospective analysis in general are the following:

- Applicable from early on during development of a measure [9, 14].
- Using one group only eliminates several problems stated above for retrospective analysis (e.g., comparability of the two groups) [14].
- Possibility to compare different variations of a measure during development [21].

The limitations of prospective analysis are not that easy to generalize, dependent to a large extent on the method used. These methods have a wider variation than the retrospective ones. Different examples are given in the following sections together with their specific advantages and challenges. The main challenge for any method is its validity with respect to the question it tries to answer.

2.4 Data Sources for Evaluation

As both retrospective and prospective evaluation methods are based in many cases on accident data, a short summary concerning possibilities and limitations of accident data as well as other data sources is given in the following. These general findings have effects on the validity of each method discussed below and are not dependent on the specific method used.

There is a variety of different accident data bases available for evaluation. Two main criteria for categorizing accidents data bases are representativity and level of detail [12, 21]. The representativity is directly but not entirely linked to the number of cases available in the data set. Another factor is the representativity of the sampling scheme used. As a consequence, two categories of accident data are in-depth and national (or international) data collections.

National statistics are regarded as being most representative for their specific country. For example, the German Federal Statistics, provided by the Federal Statistical Office (Statistisches Bundesamt), collects all police reported traffic accidents connected to driving traffic. That means that police reported accidents involving only pedestrians are excluded from this statistics. As the police are mainly contacted in case of personal injury or high property damage, accidents with slight injuries or minor property damage may be underreported [21, 22]. The federal statistics have high case numbers, but also a low depth in the data, as all information is taken from police reports. Access to disaggregated data is limited [16, 21]. Especially information regarding the genesis of an accident, the course of events during an accident, the vehicle damage in detail, and the injury mechanisms are not included [21].

Also on national level, the German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft e.V., GDV) runs its own accident data base. It contains detailed documentation of a sample of all accidents followed by insurance claims. The main sampling criteria are personal injury and a property damage greater than €15,000 [23, 24]. Around 700 cases are added each year [24]. Access to the database is limited to the members of GDV [13]. Although the representativity for accidents with insurance claims within these criteria is given [23], a further extrapolation of the findings is difficult due to the biases induced by the sampling scheme [13].

In-depth accident investigations include more details but contain by far fewer cases [16, 21]. One example is the German In-Depth Accident Study (GIDAS). As a combined industry and government effort, about 2,000 cases are collected and documented with a high level of detail each year [25] (see also Sect. 5.2.1 for a general description of GIDAS). The main sampling criteria are accidents with at least one injured person in road traffic. The sampling area is confined to two German cities and the surrounding areas; the sampling itself follows a shift schedule [25].

As a consequence, some restrictions apply when discussing the validity of findings based on in-depth accident data. The restrictions given in the following refer to GIDAS as an example, but can be transferred to other studies with respect to their internal structure and sampling criteria:

- Only accidents with personal damage [14, 21]; thus severe accidents are over-reported.
- No accidents with property damage only or non-collisions (i.e., critical situations) [21].
- No information about participants in traffic who were not directly involved in the accident [21].

Other biases may be induced by low case numbers as well as other sampling criteria [16].

The results based on accident data are only valid for the area of the data set [16]. Nevertheless, generalization of the findings, for example, to national level, is facilitated using weighting procedures. Based on parameters available in the national statistics, a weighting scheme tries to correct biases in the GIDAS data and thus make them more representative for Germany. The most commonly used scheme relies on type of the accident, accident severity, and location of the accident (urban or non-urban). A description of the procedure can be found in [14]. In order to gain representativity, this weighting or very similar approaches are widely used [7, 13, 16, 25].

Officially, weighting ensures that GIDAS is mainly representative for the areas its data is collected in as well as for most aspects of passive safety, if free from regional influences [25]. However, the benefits of weighting as well as the validity of the results are still subject to discussion. On the one hand, this procedure is believed to ensure representativity [26]. On the other, studies show that weighting does not solve these problems and is not able to correct all biases in the data set. Even sophisticated methods still leave distortions in the data [27, 28]. As the representativity for the country of the in-depth study itself has to be questioned, an extrapolation on other countries seems even less valid; in this case, the use of accident data directly collected in that country is recommended [21].

Another example for an in-depth accident data base is the Pedestrian Crash Data Study (PCDS) from the US [29] (which is also described in Sect. 5.2.1) or accident investigations carried out by vehicle manufacturers. The latter ones have a very high level of detail but suffer even more from biases due to low case numbers, model selection criteria or geographic effects [16].

For more information and the description of different accident data bases, also on an international level, the following literature provides a good starting point in form of summaries [13, 14, 30, 31].

Comprehensive and detailed knowledge of all factors relevant in accident genesis are a prerequisite for an evaluation of safety during the pre-crash phase [32]. A variety of factors is available in accident data bases (see above), but many factors—especially relevant during the genesis of an accident—are not part of accident data bases [32, 33]. As a consequence, detailed conclusions about the pre-crash phase and the genesis of an accident, especially with respect to critical combinations of mistakes and the course of events following the phases of an accident, are only possible in a very limited way [32]. Thus, the understanding of the mechanisms and processes involved is also bound to these limitations [33]. As many parameters, especially concerning the persons involved (e.g., the driver), are not available in accident statistics (and cannot be gathered by methods applied in accident data collection) [34], a distinction of different accident causes is very difficult [35].

The reliability and validity of the accident data proves to be a difficult issue as the data collection is always a sample and not a census in the sense of an absolute "true" number [33, 35] (see also abstract description of different accident bases and sampling schemes above). Furthermore, even the data available most of the time include inconsistencies and uncertainties due often to the process of reconstruction and the assumptions necessary therein [35].

Although accident statistics are able to give valuable information about accidents as well as influencing factors (at least to some extent), the findings must still be interpreted with care, as their true meaning is only revealed when related to exposure [32]. Many studies using accident data do not consider risk exposure or discuss the correct measure for exposure with respect to the research question [34].

Accidents are statistically rare events [17, 32] and represent only partly the complexities of traffic. As discussed in Sect. 2.1, they cannot be regarded as being sufficient for every possible evaluation of safety in traffic [33], especially of the pre-crash phase. The events leading up to a possible accident are by far more frequent than the accident itself [36] (see also Sect. 1.2). From the whole course of events from "normal" driving, mistakes, failed corrections, contributing factors, and finally a collision [37], only the last part is recorded in accident statistics. Consequently, no data on avoided accidents or very slight accidents are in the data bases [17]. The evaluation of safety benefits using accident data as the only data source is thus regarded as incomplete [17]. The evaluation of overall safety effects with respect to false activations etc., as explained in Sect. 2.2, is also not possible solely on the basis of accident data.

Directly linked with the "systematically missing" information in accident data bases is the importance of the human behavior for the accident genesis and thus for the evaluation of measures of the pre-crash phase. In most cases, human behavior is by far more important than driving performance of the vehicle [17]. The driver has a highly variable behavior and is the decisive element during the pre-crash phase (as well as during "normal" driving) [38]. Measures that interact with the driver—by direct means of a human machine interface (HMI) or indirectly via their interventions in vehicle controls—require a driver model for their theoretical (i.e., not subject-based) evaluation [13]. In case an HMI is present, it has to be evaluated, too [23]. Due to the importance of the driver [39] an over-simplification of the driver model leads to invalid results. The complexities of human cognitive modeling are avoided in some studies using a "perfect" driver (often with fixed (re)actions, not distributed stochastic behavior) which constitutes a severe assumption [23, 24].

In this context, not only the driver in view of his actions and decisions is of interest, but also regarding his acceptance of different measures [39] (see Sect. 4.3 for more on acceptance and its connection to safety). During the use of a system of active or integral safety, changes in behavior due to adaption or compensation effects can occur and must be accounted for when evaluating safety benefits [32]. To draw a conclusion, a "full forecast of their [i.e., active safety systems; author's note] potential is only possible with respect to the complete relation of driver-vehicle-system-environment" [9] (see also [40]). These and various other aspects of evaluation of active safety systems have also been subject of discussion in European Union funded projects; an overview is, for example, given in [41].

The limitations and boundary conditions connected with *accident-based* testing lead directly to the approach of *traffic-based* testing, based on the control loop of driver, vehicle, and environment with its processes on the way to an accident [42] (see also Sect. 2.1). The main advantage of traffic-based testing over accident-based testing is that exposure can be taken into account [43]. The usage behavior of the driver regarding active or integral safety systems can also only be reliably tested in real traffic [44]. Different methods considering the variability of traffic and its consequent testing are discussed below. Traffic-based testing does not necessarily mean driving on public roads but also can involve simulation [10]. In addition, traffic-based testing is capable of evaluating all four possible categories of system responses (see Table 2.1), where accident-based testing is mainly restricted to evaluating true positives and false negatives. As false positives as well as true negatives are of high importance while finding the optimal operating point for a system, traffic-based testing is the method of choice and is able to close that gap.

2.5 Methods of Prospective Evaluation

This section discusses a variety of rather "theoretical" methods of prospective evaluation: fault tree, traffic conflict technique, operational field and effectiveness in the field, and scenario technique. Section 2.6 focuses on case-by-case prospective methods.

The basic idea of analyzing the traffic system with respect to the genesis of mistakes, conflicts, and accidents is structured in the *fault tree* method [45], see Fig. 1.1 (p. 3). This scheme follows a process-oriented approach as displayed in Fig. 1.2 (p. 4). The basic concept of Reichart was thus extended beyond the basic elements of driver, vehicle, and environment to include, for example, driver assistance systems [42, 46]. One advantage of a fault tree is that once a critical set of probabilities is known, the calculation of the other probabilities is straight forward using the Boolean connections in the tree.

In this context, the top event in a fault tree can be an accident or a conflict [45]. The probabilities for accidents can come from classic accident analysis [42], the corresponding ones for conflicts or mistakes (being at the other end of the tree structure) are not generally known and hard to extract [35, 42]. An example of such calculations as well as further information, for example, on validity of the method, can be found in [45]. The method seems to be able to generate sound results, especially on the connections between conflicts and accidents, although many assumptions are basically needed during evaluation [36].

As conflicts can be top events in fault tree analysis or generally constitute rather high level events, the probabilities and nature of conflicts is regarded an important issue within the literature. One way to assess conflicts in traffic is the so-called *traffic conflict technique* [35]. A traffic conflict may be characterized by considering approaching object trajectories which, extrapolated in time, would exhibit an increased probability for collision unless one of the participants changes his current state of motion [35]. This definition could be extended on non-observable situations and single vehicle conflicts.

The objectives of this standardized observational technique are risk assessment as well as effectiveness evaluation of traffic facilities, not estimations regarding the quantity of accidents [35]. Thereby, conflicts have a probability to become accidents, which does not mean that accidents can be predicted with the method [35]. The transition probabilities between conflicts and accidents, as needed, for example, in the above-mentioned fault tree analyses, can be assessed [42]. Compared to accident analysis, investigating conflicts has the following advantages [35]:

- Conflicts occur with higher frequency and thus provide more statistical power.
- Conflict data can be collected with more completeness and better controlled reliability.
- They allow for a more "objective" collection, as legal liability is not considered.
- Conflicts have still sufficient frequency even for low accident frequency at that point.

- Regional boundaries as well as other requirements of data collection can be well defined and documented.
- Conflicts can be collected as a controlled sample.
- Many additional factors can be collected.

The studies done show that conflicts have a good correlation to accidents and thus can be considered as "dangerous" [35]. Therefore, the results (respectively the probabilities) can be included, for example, in fault tree analyses. However, the traffic conflict technique itself requires a high effort in data collection and analysis [45]. Further combined research on mistakes, conflicts, and accidents is strongly recommended in the literature [45].

Which specific factors can possibly be investigated using traffic conflict technique, depends on the technology used (in general, a large variety of factors are well observable in traffic). A *static* traffic observation from a fixed location may adequately record all macroscopic traffic effects as well as environmental parameters, but has its limitation regarding the precise measurement of dynamical properties of individual participants as well as their specific configurations (i.e., presence of specific safety measures, such as ESP). The technique of traffic observation from the view of one specific participant will be discussed in connection with Naturalistic Driving Studies (NDS) and Field Operational Tests (FOT) further below (see Sect. 2.7).

Another possible evaluation uses the *operational field* and the *effectiveness in this field* of a measure as a metric. Two commonly used definitions exist:

- The operational field (OF_1) is defined as the number of accidents, where the measure can potentially show an effect:

$$OF_1 = \frac{\text{potentially affected accidents}}{\text{all accidents}} \tag{2.8}$$

  The effectiveness (EF_1) within this operational field is then defined as the quotient of real effectiveness to the number of accidents [13]:

$$EF_1 = \frac{\text{affected accidents}}{\text{all accidents}} \tag{2.9}$$

- Another definition is given by the following equations [14], where $OF_2 = OF_1$.

$$OF_2 = \frac{\text{potentially affected accidents}}{\text{all accidents}} \tag{2.10}$$

  The effectiveness is given as:

$$EF_2 = \frac{\text{avoided accidents}}{\text{potentially affected accidents}} \tag{2.11}$$

Considering all accidents (e.g., in one country or area) as baseline, the *overall effectiveness* [14] is given by the product of 2.10 and 2.11:

$$\text{effectiveness}_{overall} = OF_2 \cdot EF_2 = \frac{\text{avoided accidents}}{\text{all accidents}} \tag{2.12}$$

The advantage of the first definition of effectiveness (Eq. 2.9) is that it includes all possible effects of a measure, also negative ones. The second definition (Eq. 2.12) refers to positive (intended) effects only. The effectiveness in general is assumed to be smaller than the operational field, as no system works perfectly in the sense of an ideal system [14].

The advantages of this method are that it allows a fast application with limited effort. The operational field can be estimated quite exactly (e.g., using accident data) whereas the effectiveness estimation is a challenge and is often facilitated by assumptions, resulting in low validity [13]. Although this method has become a common practice in the last years, the procedure itself was used decades before.

One example is a summary report on the research that led to the introduction of the center high mounted stoplamp from 1985 [47]. The overall effectiveness in the sense of Eq. 2.12 for the center high mounted stoplamp was determined by operational field and effectiveness. The operational field was defined as the number of all rear end accidents. The effectiveness was estimated from different studies (most of them FOTs) and has to be regarded as much more valid than, for example, an expert opinion. The average effectiveness was found to be 50 %. In addition, an overall monetary benefit was calculated, first on the basis of avoided accidents, secondly using a cost-based (monetary) approach for both avoided and mitigated accidents. As a result it was possible to give a cost benefit ratio for the measure, which was found to be 0.1 [47].

In line with the previous approach is the *scenario technique*. It describes the possible benefit of a measure regarding accidents of relevance [13]. An exact effectiveness is not determined, but the true effect is approximated using two scenarios as upper and respectively lower boundary. The scenarios are defined using an optimistic and pessimistic approach with respect to the benefit [13, 14]. The analysis is commonly conducted using accident data and assumptions on the effect of a measure.

The methods mentioned above can rely on assumptions to a particular extent. One very common form of making assumptions are expert opinions. Although the general value of expert opinions should not be a matter of doubt in this work, the validity regarding the effectiveness of complex systems in complex (and highly variable) traffic or accident situations has to be doubted. Depending on the extent and severity of the assumptions used, the validity of a study has to be questioned. For example, if the whole effectiveness of a measure is based on expert opinion alone and is not backed by any empirical evidence, then this constitutes a severe assumption. In order to demonstrate a method [14], this can be regarded as uncritical, but in real evaluations this should be avoided, at least regarding sensitive parts or models of the evaluation process.

2.6 Methods of Prospective Case-by-Case Analysis

The accident-based methods described in the previous sections use aggregated data. That means that coded values of many accidents are used to define, for example, an operational field for a measure without considering each single case in detail. These procedures have the disadvantage that subtle effects (e.g., interactions between a system and a driver or the perceptibility of an object by a given sensor over time) can be considered only in very general means on a meta level. The potential of a future measure can thus be evaluated at a very early stage of development. However, optimization and evaluation of minor system changes are not possible on that level but require more detailed analysis with respect to the time-bound interactions in each single case.

Although single-case analysis is not new and has been conducted for decades in different ways, modern calculation capabilities together with corresponding detailed data sources allow a very detailed analysis which is not limited to a few cases any more [13]. As a result, a large number of cases can be analyzed automatically with reasonable resources [13, 14]. This kind of analysis solves the problems of time consuming and complicated hardware testing in many different situations and thus is reproducible without danger, quantifiable, and controllable [48]. Ideally, a flexible and universal tool would fulfill those characteristics instead of an inhomogeneous world of incompatible tools [11]. All relevant parameters should be adjustable and the boundary conditions variable in order to enable sound testing and evaluation of the safety effects [11].

Considering simulation as a method, the validity of the findings is a key aspect. The simulation itself must be validated regarding the research question it is used for [49]. In addition, a validation and, of course verification, if possible, of the findings against field data (e.g., accident data) can also be recommended [11].

The following part of this section briefly introduces different methods that can be categorized as prospective case-by-case analysis. Case-by-case evaluation is explained using the injury shift method as example. Different methods including case-by-case simulation are described:

- Simulation by Busch
- PreEffect-iFGS
- rateEffect
- VUFO Simulation
- PreScan
- Bosch simulation
- ACAT simulation

The first one focuses on the evaluation of passive safety measures and is called the *injury shift method*. The basic idea is that a passive safety measure has a positive effect on the severity of injuries sustained at a specific component. The assumption is that below 40 kph, optimized components result in a reduction of one level on the abbreviated injury scale (AIS) [50] (for a detailed description of AIS see Sect. 5.1,

p. 91). As a consequence, this may lead to a reduced overall injury severity. The benefit of a given measure is thus evaluated on the level of single injuries and corresponding components in each single case [14, 51]. The method has been used in a couple of studies [14, 30, 51–54].

The injury shift method has been used, for example, for the evaluation of secondary safety measures for pedestrians at passenger cars. The maximum impact speed considered is 40 kph. The results of Euro NCAP crash tests are transferred to the vehicle in question, and the impacting body parts are mapped to the test grid. The metric includes assumptions leading to an optimistic and a pessimistic approach. In the optimistic case, if the zone was tested green, the injury severity is shifted down to AIS 1 (pessimistic: by two AIS levels). If the zone was tested yellow, the injury is shifted by two AIS levels (pessimistic: one AIS level). A red zone does not lead to a shift in either approach. No injury is shifted below AIS 1, meaning the method does not predict avoided injuries [53].

The injury shift method is computationally efficient: The assumptions used lead to an algorithm, which is simple and fast to calculate and can be applied to a table of injuries and corresponding vehicle components. Each case is thus evaluated, and the overall injury severity of every person is recalculated. As a result, the safety benefit for every person can be evaluated in comparison to the original severity distribution.

However, several severe assumptions underlie this estimation method: As detailed Euro NCAP test results are not available for the majority of (rather old) vehicles in databases such as GIDAS, each vehicle is considered as zero points (i.e., being totally red). In reality, also older vehicles do have a good protection potential in some zones and the overall safety benefit of a measure is thus overestimated by the underlying assumption [21]. The second challenge is that a color in the Euro NCAP test stands for a bandwidth of actual dummy readings. That means a color distribution is a rough estimate of the real stiffness (protection potential) of a vehicle. The three-color categories used for the injury shift method can be regarded as rather crude approximation to a stiffness distribution. In addition, all AIS levels are treated in the same way without considering that AIS is a non-metric scale. It is unclear whether a given measure has the same effect on an AIS 2 as on an AIS 5 injury [21, 52]. Considering pedestrians, only the impact on the vehicle is evaluated, not the secondary impact.

The next level in automated single-case analysis is the actual simulation of the dynamics over time for each accident. The focus is on the pre-crash phase of an accident. In 2005, Busch described a simulation of single accidents, each with and without the measure of active safety in question [13]. The main procedures are: selection of relevant accidents, simulation with/without system, translation into injury severity, and calculation of the effectiveness. The input data for the simulation are the values coded in the GIDAS data base. As the sequence of the accident is described there via characteristic parameters but not as time series, the simulation provides a kind of automated reconstruction of the pre-crash phase and a subsequent simulation of it. By comparing the results for each accident and summarizing them, the effectiveness is calculated. The first stage is a physical assessment (i.e., impact speeds, impact locations, etc.). These data can be translated into physiological data using, for example, the injury shift method for passive safety and injury probability models for active safety (for the later see also Chap. 5). The results gained from the simulated accidents are then weighted to the national statistics to gain representativity for Germany [13].

The advantages of this approach are a degree of representativity as well as the opportunity to model a system in detail and take system modifications into account by simulating each single case. A drawback of the method is its reliance on the information available in the data base used. As many relevant pre-crash parameters are not coded (and especially not coded as time series) in in-depth data bases (such as lane markings, positions of the vehicles in the lanes) and thus are not available for the simulations, only a limited subset of functions can be evaluated (e.g., automatic braking, but not lane departure warning). The method does not include behavioral driver modeling, i.e., models of driver perception, response, performance under extreme condition, etc. These are required for an evaluation of a system with an information or warning component. Thus, this method is limited to evaluation of automatically intervening systems [21].

The next evolution of the method presented by Busch is called PreEffect-iFGS. It is a prospective method for evaluating the field effectiveness of integral pedestrian protection systems [21]. The main procedures of Busch, i.e., selection of relevant accidents, simulation with/without system, translation into injury severity, and calculation of the effectiveness, stayed the same with some additions. The improvement is an incorporation of test results for active and passive safety systems derived from hardware testing [54]. The initial version also includes an automated backwards simulation of each accident based on the values available in GIDAS. The results are then transferred into the commercial software PC-Crash and are then simulated forward with and without the measure in question.

The simulation can be run in two modes: open-loop and closed-loop. The *open-loop* variant calculates key parameters for automatic interventions with different parameters per accident. These key parameters are then filtered using the specific system configuration in question. The advantage is that a variety of system configurations can be compared without running the simulation again. The disadvantage is that the results do not include a feedback loop of the measure on the situation itself, for example, the reaction of a driver to a warning. The *closed-loop* simulation includes the feedback on the situation and thus is able to evaluate all kinds of effects, e.g., the driver's reaction to a warning. The higher level of detail and the inclusion of a probabilistic driver model increase the computational effort [21].

One main disadvantage for the simulation methods described above is the inherent limitation regarding depth of information of the data used. In order to make more information during the pre-crash phase available and thus enable other functions to be evaluated, a project has been launched within the GIDAS consortium. The so-called *pre-crash matrix* is a digital and machine readable description of the pre-crash phase [55, 56]. The information falls into the categories *static* and *dynamic*. The *static* part contains information on the street layout, the lane markings, and accident relevant objects (e.g., parked vehicles). The *dynamic* part contains the trajectories of the participants as a time series, going back about 3 s before the first collision.

The information ends at the point of the first collision [55]. This data base provides a uniform basis for simulation of a subset of the GIDAS accidents, thus making the backwards simulation of accidents as used in the method above obsolete. In addition to the pre-crash matrix, values from the GIDAS data base, such as vehicle characteristics, weather conditions, etc., can be used.

The next version of PreEffect-iFGS, called rateEffect, is able to import the pre-crash matrix and use these data [57–61]. Whereas rateEffect as well as a comparable approach from Spain [62] use PC-Crash as software package, other solutions are available, too. PC-Crash is able to calculate the crash phase and thus rateEffect provides key parameters of the crash (if still one occurs) as additional input for an evaluation metric.

The Verkehrsunfallforschung an der TU Dresden GmbH, which is one of the data collecting partners in GIDAS, developed a pre-crash simulation using a commercial driving dynamics simulation as core together with proprietary Matlab® and Simulink® functions [55]. The latest version changed the driving dynamics simulation from CarSim™ to CarMaker™ [63]. The idea is again to simulate single accidents automatically and to compare a system effect to a baseline without system. Also in this simulation, no predefined field of operation or estimated effectiveness is needed [55].

The Netherlands Organization for Applied Scientific Research TNO has developed another simulative approach called PreScan®. It includes the complete road situation, vehicle sensors, system controls, and vehicle dynamics [64]. Based on Matlab®, Simulink®, and Stateflow®, PreScan® claims not only to simulate the pre-crash phase, but also to calculate the crash consequences via a link to MADYMO® [48].

The Robert Bosch GmbH developed a Matlab®-based simulation working with GIDAS accidents [39]. One essential part (especially for systems with a human machine interaction, such as warnings) is the modeling of the driver in terms of cognitive processes. The cognitive modeling of the driver is also capable of revealing findings about system acceptance and thus effectiveness (see also Chap. 4).

All methods described above can be categorized as automated case-by-case simulations based on accidents. There are two more aspects which are of importance for a sound system evaluation during the pre-crash phase. Many processes involved are deterministic, e.g., the participants dynamics, the technical functions implemented, as well as many physical boundary conditions. However, some of the key processes do have a stochastic nature; for example, the driver action and reaction as well as some characteristics, e.g., of the sensors modeled. Due to the sensitivity of the results to those processes, stochastic elements are an important feature of any representative evaluation (see also Sect. 3.4).

For example, the driver reaction is important for the genesis of an accident as well as the interaction with a safety system and the possible impact of a safety system. As a consequence, stochastic driver modeling is also included in some approaches [15, 65]. Stochastic elements are not limited to processes within an accident but are of importance also in uncritical traffic situations. As mentioned before (see Sect. 2.2), an overall estimation of possible safety effects should include the evaluation of positive effects within accident scenarios as well as undesired potentially hazardous side effects in normal traffic. The only data source used in the approaches discussed above, i.e., accident data, does not provide normal or critical situations which would not have resulted in an accident. There are several ways to incorporate this traffic-based evaluation into a simulation.

As classical data collections are limited to accidents, one way to get data on non-collision events is a stochastic variation of accident reconstruction data in a way that the single event does not necessarily result in an accident anymore. These non-collisions are then used in the simulation in order to assess the balance between desired and undesired effects of a measure in traffic [15]. As a consequence, validating the non-collisions regarding the distribution of key parameters and their representativity for overall traffic is vital. The basic data concerning exposure are not as well known as accident related data.

Another simulative method is introduced in the following in order to highlight the use of other data than accident data. Within the Advanced Crash Avoidance Technologies Program[2] (ACAT), initiated by the National Highway Traffic Safety Administration (NHTSA), a standardized Safety Impact Methodology (SIM) has been developed [10, 66, 67]. The main objective was to develop a tool that evaluates the effectiveness of crash avoidance technologies in a US context. Combined with that is the development of objective tests capable of verifying the safety impact of a real system [10].

The basic idea again is to conduct time domain-based simulations of the driver-vehicle environment with and without an ACAT system. The available data include crash cases from accident data bases, such as the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) or the Pedestrian Crash Data Study (PCDS) (for a detailed description see Sect. 5.2.1, p. 93). The difference to the approaches discussed above is that normal driving situations from Naturalistic Driving Studies (NDS), for example, provided by Virginia Tech Transportation Institute (VTTI) as well as synthesized crashes are also used for evaluation; the technique thus allows for an assessment of non-critical situations [10]. Again, the driver reaction can be varied, e.g., using Monte-Carlo techniques, and the simulated physical outcomes are translated into physiological parameters. The results can be transferred to national US level [10, 68]. The ACAT framework is thus an example for an accident as well as traffic-based approach.

2.7 Methods for Modeling Different Parts of Driver, Vehicle, and Environment

This section introduces typical methods for investigating the control loop of driver, vehicle, and environment or different parts of the latter (see also Sect. 1.1, p. 1). Although the methods are not able to assess overall effectiveness of a measure of

[2] Extensive information in form of publications and project reports is available on the NHTSA homepage.

active safety, they provide valuable findings that can be incorporated into modeling as needed for the simulative approaches discussed above. This section is not meant as a complete compilation but aims at giving an overview about the different levels of testing in the traffic system as well as typical examples of current methods. Included in this overview are:

- Hardware and component-based testing
- Vehicle Related Pedestrian Safety Index (VERPS)
- Vehicle Hardware In The Loop (VEHIL)
- Test track
- Test track target: Experimental Vehicle for Unexpected Target Approach (EVITA)
- Subject experiment: Driving simulator
- Vehicle in the Loop (ViL)
- Real traffic
- Naturalistic Driving Study (NDS)
- Field Operational Test (FOT)

The smallest unit under testing in the context of active or integral safety is a *component*. This method is usually applied for measures of passive safety, such as deformation spaces, active bonnets or airbags. This "classical" testing can be based on hardware (like the Euro NCAP tests for pedestrian safety [69, 70]) or virtual testing using, for example, multi-body or finite element simulation. These methods are not discussed here in detail (examples can found in [48, 71, 72]) but are relevant for active safety, since the concept of integral safety (see Sect. 1.1) includes a comparison of the effectiveness of active and passive safety. Some of the methods discussed below also incorporate component-based testing.

One example of a component-based testing method is the *Vehicle Related Pedestrian Safety Index* (VERPS) [73, 74]. This index utilizes a linear scale for both active and passive safety measures. The pedestrian head impact in frontal passenger vehicle collisions is assessed using the Head Injury Criterion (HIC) as metric. The method delivers specific results for a given vehicle and pedestrian combination. The evaluation process includes accident data analysis for relevant scenarios, kinematic analysis (via multi-body simulation), hardware component testing, and a procedure to obtain the VERPS index [73, 74]. The VERPS index takes only the probability for AIS3+ head injuries due to impact on the vehicle into account, since this probability can be derived from the HIC measurement.

As an addition to the VERPS method, the (here slightly generalized) *VERPS*$+_k$ index considers the effect of active safety, as different impact speeds lead to different kinematics and impact locations as well as changed HIC values.

$$\text{VERPS+}_k = P_{impact}(v) \cdot \sum_{i=1}^{m} \sum_{j=1}^{n} R_{i,WAD}(v) \cdot R_{j,front} \cdot \left(1 - e^{-\left(\frac{HIC_{ij}(v)+500}{1990}\right)^{4.5}}\right) \tag{2.13}$$

- $P_{impact}(v)$ gives the dependency of the impact probability for the pedestrian's head on impact speed v.
- $R_{i,WAD}(v)$ and $R_{j,front}$ are relevance factors with respect to the impact probabilities derived via analysis of accident data: $R_{i,WAD}(v)$ refers to the relevance in longitudinal direction, depending on impact speed, and wrap around distance (WAD). $R_{j,front}$ gives the corresponding relevance in lateral direction.
- $HIC_{ij}(v)$ characterizes the pedestrian's head loading, depending on impact speed and the area on the vehicle front, as specified by i and j.

The secondary impact is not assessed, but is assumed to improve with decreasing impact speeds [73, 74]. The actual performance of an active safety system together with the driver (if a driver-relevant component is included) is estimated by weighting the different $VERPS+_k$ indices for different speeds according to the performance of the active safety system (including avoided accidents and the probability of avoided head impact on the vehicle). Averaging over all drivers in the population in question and all relevant accident situations, the resulting VERPS+ index is able to quantify the effect of an active safety system [73, 74] once the primary effect of the active safety system (i.e., the reduction of vehicle speed) has been assessed properly. An example for the use of the VERPS index as well as an addition for leg injuries can be found in [75].

An advantages of the VERPS method is that both active and passive safety can be assessed on a common linear scale. A drawback is that only pedestrian head injuries in primary frontal passenger vehicle collisions are evaluated, while secondary impacts are not taken included [73, 74].

Clearly focused on active safety functions is the *Vehicle Hardware In The Loop* (VEHIL) facility of TNO in Helmond, Netherlands [49, 77, 78]. The basic idea is to connect a traffic flow simulation with a chassis dynamometer for testing active safety systems as hardware including the whole vehicle. The surrounding traffic is represented by moving platforms as in Fig. 2.1, which can be fitted with shapes and materials suitable for the specific sensors used. As the vehicle under investigation is on a dynamometer, the moving bases just have to perform the relative movements to the (not moving) vehicle. VEHIL is intended for testing, for example, Adaptive Cruise Control (ACC), collision warning systems or functions based on car-to-car communication [77]. The advantages of VEHIL are the possibility for safe, reproducible testing with real objects. In addition, the actual state of all participants is known and can be analyzed [49]. The limitations are, for example, a minimum time-to-collision about 0.5–0.2 s and a maximum relative speed about 50 kph [49].

A *test track* is a "classic" environment for testing and evaluation of different functions [79]. A experiment on a test track can reproduce very different aspects of various traffic systems, such as different kinds of road classes, road surfaces or traffic situations. As test tracks are not open to normal traffic, full experimental control [44] together with a quite realistic environment [80] including real vehicles and their dynamics is available [79]. Another advantage is that test tracks are available on many locations around the world which makes testing geographically flexible [80].

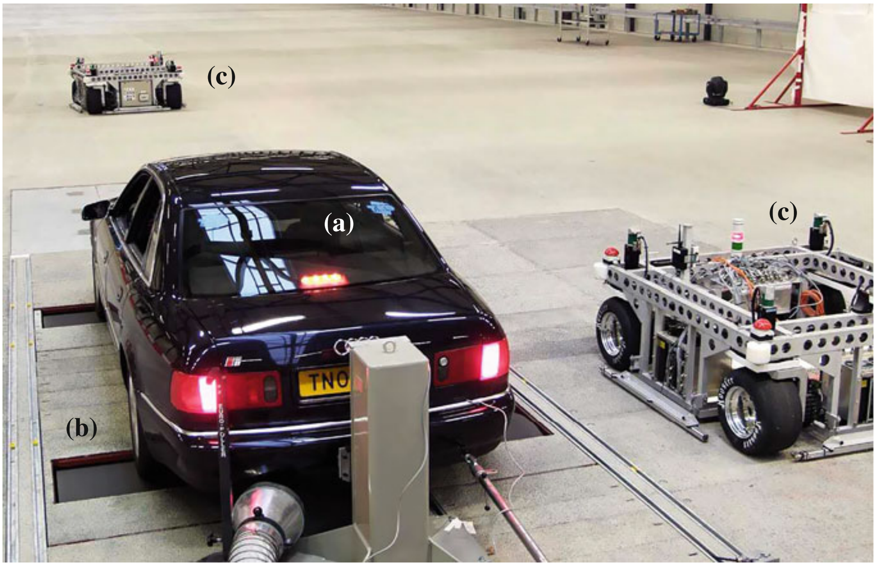

Fig. 2.1 VEHIL test facility: **a** vehicle under investigation on **b** dynamometer together with **c** moving bases [76]

The challenges come with the construction of specific traffic situations on a test track. Some situations are hard to build (such as complex ones with many participants) or are dangerous (especially for safety related functions) [49]. This leads to two consequences: First that it requires a high effort on a test track to build a subjectively critical situation which is objectively safe; and second that scenarios have to be kept quite simple and perhaps must be within a limited speed range [80]. As test tracks lack normal traffic situations, testing can be less diverse and realistic than in road traffic [44].

Although test tracks provide a valuable environment for development and testing, "a test track test alone will not be sufficient" [9]. Concerning the possibilities on a test track it can be concluded that "it is not realistic that [...] overall functionality and performance [can] be evaluated on basis of a limited number of tests" [9]. For overall effectiveness of a measure of active safety, track testing alone does not seem to be sufficient [10]; thus statistical methods or field tests seem to be more promising [9].

Due to the importance of hardware testing on test tracks during development, a common practice for the evaluation in safety-critical situations is introduced here. In order to achieve a subjectively realistic but objectively uncritical situation for active safety functions, so-called *targets* are used on test tracks instead of real traffic participants. Whereas most targets are designed for sensor or system testing, some are also suitable for behavioral studies. Many targets represent vehicles, or what a sensor or driver can perceive of a vehicle. For radar this means that a triple reflector made of

Fig. 2.2 EVITA: lead vehicle and trailer [86]

the right material can be sufficient, whereas for a mono-camera, a picture of a vehicle is sufficient. Important features are the possibility of self-propulsion, the ability to be crashed (without damage to target and vehicle) and the sensor characteristics of the target. Descriptions of a large variety of different targets are found in the literature [8, 49, 81–84]. Not only vehicles, but also, for example, pedestrian dummies (targets) fitting specific sensor requirements are available [8, 10, 85].

Representative for the variety of targets used in research and development, a more advanced target capable of performing system as well as subject experiments (including behavioral as well as acceptance studies) is introduced in the following. The *Experimental Vehicle for Unexpected Target Approach* (EVITA) has been constructed for testing critical rear-end situations and aims for a high degree of reality [82]. Figure 2.2 shows the trailer with an original vehicle rear-end connected to a lead vehicle via a cable and a winch in the lead vehicle. The trailer is comparably lightweight and can be braked independently of the lead vehicle, thus suddenly reducing the gap to the following vehicle with the system and/or subject on board. The trailer looks realistic for the subject (including full brake lights, etc.) as well as for many common sensors. If the time-to-collision (TTC) reaches a defined value (measured by a backward radar sensor in the trailer), the winch closes, and the trailer is accelerated away from the following vehicle [83]. This allows safe and reproducible testing under quite realistic circumstances [82]. EVITA is limited to rear-end situations and is not impact resistant, allowing a minimum TTC of about 0.8 s and a maximum relative speed of 50 kph. Its velocity is limited to about 80 kph [83].

The importance of *subject experiments* (or behavioral studies) is founded on the fact that for active safety, driver behavior is more important than the driving characteristics of the vehicle [17]. However, human behavior is subject to a large variability [43], which can be modeled, e.g., on the basis of experiments [87]. The findings from many experiments can then be used to develop behavioral models [87] which, for example, are used in simulations as described in the preceding section. The EVITA target for use on a test track is one possibility for assessing driver behavior in particular situations.

A common practice for the evaluation of active safety is use of *driving simulators*. A driving simulator provides an environment for subject experiments with the aim of assessing usability and ergonomics, for example, of advanced driver assistance systems (ADAS), investigating driver behavior with (and without) a system in different situations, and generating findings on acceptance [79]. Driving simulators can have a variety of setups and functions. They range from simple static mock-ups (which basically include a display and human-machine interface) to dynamic simulators, which can simulate limited motion with respect to six axes, allow a full range of view, and provide the look and feel of a real vehicle for the subject [44, 49, 79].

The main advantages of driving simulators are high reproducibility of experiments [18, 79, 80] together with very good experimental control [80]. The possibility of collecting detailed data (including, for example, the surrounding artificial traffic) provides the basis for comprehensive analysis [18].

Experiments in the driving simulator can be conducted during a very early stage of product development [18]. The safe testing of critical situations without endangering the subject allows the investigation of functions which are in early development phases and which thus are not sufficiently safe, e.g., for test track experiments with subjects [18, 79, 80]. One important limitation is that only simulated environmental sensors can be used in driving simulators [18]. As the environment and the surrounding traffic are virtual, these data are used as input for the system algorithms. Experiments regarding the sensor performance itself can thus not be conducted in a driving simulator. This can be an advantage, if no highly developed sensors are available or if any uncertainty due to the (imperfect) sensing equipment should not distort the results of the experiment.

However, several important points have to be considered if driving simulator experiments are conducted or the results interpreted. Depending on the technological level of the simulator, an experiment can be very complex and can end up at high costs [80]. Many simulators, especially the more advanced ones including dynamics simulation, are immovable and thus result in geographic inflexibility of the experiment, which can also influence the structure of the subject sample [80]. Even highly advanced dynamic simulators have limited abilities concerning realistic driving dynamics [79]. On the contrary, motion simulation comes at the possible price of motion sickness [79, 80], which results in loss of data for a fraction of the sample affected. As the environment, and so to say the "world", the subject is in are virtual, specific motivational aspects relevant for driver behavior can be distorted; consequently behavior can differ from that of real traffic [18]. The sometimes "clinical" look and feel of situations can also lead to a lack of perception regarding criticality and can produce other behavioral artifacts [80]. Therefore, the validity of the simulation should be proven for every research question [49]. Driving simulator experiments are always restricted to a limited number of situations [18]. As a consequence, overall effects of a measure cannot be assessed in driving simulators [65],

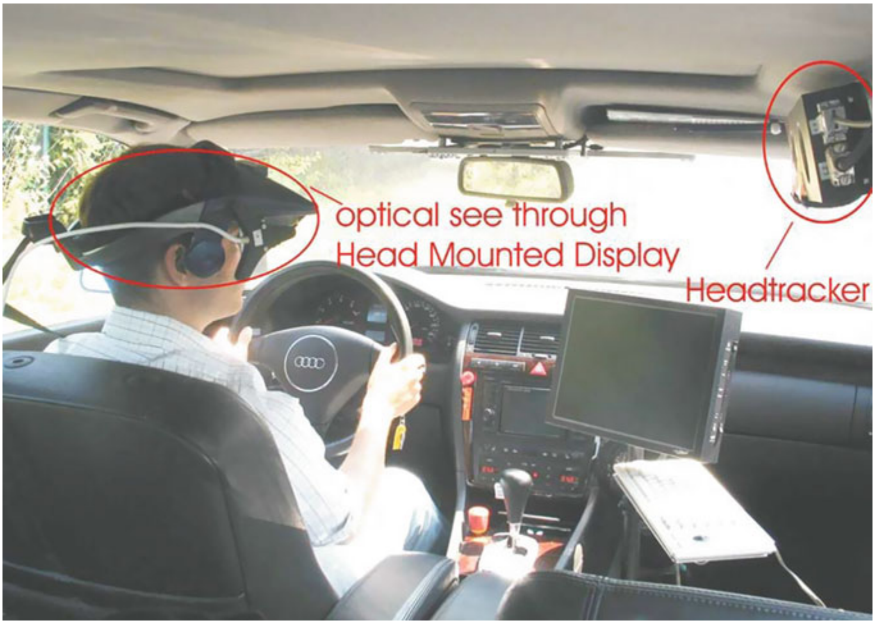

Fig. 2.3 Vehicle in the Loop: Vehicle, head-mounted display, and head-tracking [79]

and experiments can hardly be regarded as representative, for example, in the sense of overall effectiveness in a traffic system [2].

The limitations imposed on subject studies by test track as well as driving simulators have inspired a new approach. The idea of *Vehicle in the Loop* (ViL) is a combination of the advantages of track testing with driving simulators while avoiding some of their limitations [49, 83, 88, 89]. The basis is a real vehicle in combination with a virtual environment (see Fig. 2.3). The vehicle drives on a test track, but critical objects in the environment (e.g., other traffic participants) are virtual. The information for the vehicle system under investigation thus comes from the virtual environment, but triggers real system responses within the real vehicle. The subject wears an optical head-mounted display. Virtual objects are projected in an appropriate way into the real spatial environment according to the contact analogue paradigm. In the *augmented* mode, *some* virtual objects are projected into the real environment. In the *virtual* mode, *everything* the subject sees is virtual [49, 83].

The striking advantage of ViL is the real vehicle including obviously realistic movement and vehicle responses. The experiments are nevertheless safe, even in subjectively critical situations. The reproducibility is high. The method has its strongest advantages in safety critical situations when realistic driving dynamics are of importance [49]. Reported drawbacks are dimension and weight of the head mounted display, which can result in changed driver behavior and headache, whereas motion sickness has not been observed [49]. As in every method, validity is of high importance. Several aspects of driver behavior have been investigated and compared to responses in "normal" vehicles on a test track. For example, the following distance to lead vehicles, several reaction times, and general driving patterns were found to be similar. Acceleration in curves and recognition of the lane of distant vehicles were found to be not exactly comparable [49].

Another possibility for the testing of both driver as well as system behavior are studies in *real traffic*. Obviously, the whole surrounding is realistic and thus provides a maximum of validity in this respect [80]. Testing is geographically very flexible and allows an investigation of "normal" driving behavior under various circumstances. It is also possible to test false-positive system reactions, triggered by a variety of (random) influences [80]. This can be done with a deactivated system (i.e., open-loop), which means the system works in the background and its output is recorded, but no interaction with the driver or vehicle is allowed [9]. This kind of testing can only be carried out rather late during development [9], as functions and components must have approval for testing in traffic. Depending on the function in question, additional safety measures must be included to ensure safe testing [80]. One main deficit of testing in real traffic is that specific conditions or scenarios can hardly be triggered and cannot be reproduced easily [49, 80]. A systematic variation of conditions, such as in driving simulators, requires a high effort [80]. The true-positive reaction of safety systems cannot be tested at all, as testing must always be safe for every participant involved [49].

There are several techniques for the analysis of driving behavior in its natural environment, i.e., real traffic [44]. They are summarized under the term *Naturalistic Driving Study* (NDS). An NDS is "[...] the observation of drivers in naturalistic settings (during their regular, everyday driving) in an unobtrusive way. The essential driver behavior is what is of interest in these studies, usually in relation to crashes" [44]. If a system is included in the observation, it is called *Field Operational Test* (FOT). An FOT can include quasi experimental methods and is focused on behavior in combination with a system in the field [44]. Examples for NDS are the 100-Car Naturalistic Driving Study [90] and The Second Strategic Highway Research Program (SHRP2) [91]. Some examples for FOTs are euroFOT [92] or the Integrated Vehicle-Based Safety Systems: Light-Vehicle Field Operational Test (IVBSS) [93].

The consideration applying to testing in real traffic with regard to subjects also apply to NDS and FOT. The advantages of these observational methods in real traffic are that they provide the only way of discovering unexpected behavioral patterns, especially in combination with a safety system [44]. Over an extended observational interval, they provide a very reliable source of information on driver behavior [44] and also generate knowledge on traffic and environment. One crucial point is that these studies allow for an estimation of exposure in various forms, which is not feasible in the methods described above [43]. The downsides are that experimental control is extremely limited, that different methods have been applied in nearly all studies conducted so far, and that these studies require extremely high efforts and costs [44]. Although these methods are the only ones presented in this section which are capable of capturing "real-world effectiveness", the information derived is in the context of this thesis rather used to derive models.

2.8 Summary and Conclusion

This chapter has summarized the state of scientific and technical knowledge concerning the evaluation of the pre-crash phase. With respect to the fundamentals of traffic as given in Chap. 1, basic methodological aspects of evaluation have been discussed. The difference between *accident-* and *traffic*-based testing and the subsequent meaning of possible findings are discussed. Validity of findings is an overall issue that is of high importance regardless of the method used.

The evaluation of safety functions, especially of active and integral safety, is not limited to true-positive system responses. The second section has elaborated on all possible system responses, classified in true positive (or negative) and false positive (or negative). The importance of these terms for system development regarding the operating point as well as system optimization and the implications for evaluation are discussed.

The review of existing methods of evaluation includes a general description of retrospective and prospective testing and data sources available. For new systems of active safety a prospective approach seems nearly always to be most promising. However, the data sources available have deficits regarding the amount of data as well as depth of information and quality. Different methods of evaluation have been introduced; especially their advantages and challenges with respect to validity have been discussed.

Given the objective of prospective evaluation regarding the overall effectiveness of a measure of active safety representative for a traffic system, the methods discussed above—ranging from analysis of accident data bases to sophisticated case-by-case simulations—do not seem to be adequate. Mass simulations covering all relevant varieties (e.g., due to human behavior) as well as uncertainties in different situations offer an approach to meet this objective.

As mass simulation seems to be the method of choice for representative evaluation of the effectiveness of systems of active and integral safety, substantial modeling and input data are necessary. The last section has introduced different methods used to gain knowledge needed for implementation in such a simulation. Starting with methods focused on single components or subsystems, examples of different techniques and expected results have been given. The next level is the testing of whole systems, for example, on test tracks or in subject studies. Research on driver behavior is also a vital part, often conducted in driving simulators, on test tracks, or in real traffic. Exposure and long term studies can be conducted as FOT or NDS in real traffic and provide valuable input for modeling different parts of the driver, vehicle and environment system in a simulation or enable validation or even verification of different parts of a process model, especially for critical situations.

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