

Assessment of Technical Requirements for Level 3 and Beyond Automated Driving Systems Based on Naturalistic Driving and Accident Data Analysis

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ABSTRACT

Automated driving systems of SAE Level 3 and beyond allow transferring the driving task and responsibility to the vehicle and its automation systems. A crucial challenge for development and real-world performance is the balance between functionality, availability and safety, as a human driver only needs to be available as a fallback after sufficient lead-time. Consequently, automated driving requires enhanced capabilities of sensors, algorithms and actuators. This paper focuses on improved safety and driving comfort of automated vehicles and upcoming technical requirements compared to driver-only or assisted driving. It uses and adapts the state-of-the-art prospective effectiveness assessment method of ADAS to estimate accident avoidance potentials of automated driving systems. The data sources for this analysis are the Strategic Highway Research Program 2 (SHRP2) and the German In-Depth Accident Database (GIDAS). Exemplary automated driving functionalities for highways are prospectively evaluated and the impact on both traffic safety and driving comfort are presented using crash, near-crash and baseline data. Furthermore, relevant technical requirements for corresponding automated driving systems are derived. For an exemplary use-case, possible impacts on system functionality, availability and safety are presented. Additionally, safety potentials of installing high-performance sensors for automated systems of Level 3 and beyond when driving manually are discussed.

INTRODUCTION

In literature, there are different approaches to define automation levels. Internationally, SAE J3016 [Sae18] is among the most prevalent, and thus used in the following analysis. SAE J3016 outlines six automation levels starting from Level 0 (No Driving Automation) to Level 5 (Full Driving Automation). In this paper, system automation is defined from Level 3 (Conditional Automation) where the Automated Driving System (ADS) performs the entire Dynamic Driving Task (DDT) within the Operational Design Domain (ODD). In Level 3, the ADS sends a transition demand to a fallback-ready user to take over the DDT in the event of a system error or approaching the ODD boundary. In case the driver does not respond appropriately, the ADS might engage a failure mitigation strategy. Automated driving systems in higher automation levels (Levels 4 and 5) incorporate a system response to perform the DDT fallback.

When developing Level 0-2 systems, there are no minimum system requirements due to the instant availability of the driver as a system fallback. Thus, a bottom-up approach can be pursued. The accident prevention potential of active safety systems for manual driving is developed step-by-step addressing more complex scenarios. In contrast, for a Level 3+ automated driving system, the driver/user is not readily available as an instant fallback maneuver. Therefore, a bottom-up approach is not suitable. Using a top-down approach, a corresponding system effectiveness can be determined by restricting the ODD according to system functionalities. For this purpose, the respective system requirements must be derived from different application cases. Hence, a new development process has to be established that is not only based on crash data but also on critical situations (near-crashes) and normal driving situations (baseline).

This paper is structured as follows: to begin with, related work regarding accident prevention potential of ADS and technical requirements are discussed. In the subsequent section, a critical review of literature and research questions of this paper are presented. Section *Methods and Data Sources* introduces the applied methodology to analyze comfort and safety gain based on naturalistic driving and accident data. Section *Results* presents the impact on safety, availability and functionality for different capabilities of ADS. Finally, results and corresponding limitations are discussed and an outlook is offered.

RELATED WORK AND LITERATURE REVIEW

Enhanced safety measurements like improved passive safety and infrastructure have led to reductions in bodily injuries in high-income countries during the previous decades [Who15]. Furthermore, active safety systems such as autonomous emergency braking are increasingly being required by consumer protection, insurance organizations and regulation [Eur19], [Gdv18], [UNa14]. These kinds of systems show significant reductions in accident frequency, bodily injuries and overall losses [Doy15, Fil15, Rat15, Hld11-Hld15b].

Current safety systems, e.g. autonomous emergency braking, are contrived following a bottom-up development process (Figure 1). In this approach, the system functionality and the corresponding real-world accident prevention potential are continuously improved from rear-end vehicle-to-vehicle collision scenarios to current and upcoming functionalities like emergency braking for pedestrians, cyclists and powered two-wheelers, including junction and crossing scenarios. In order to develop automated driving systems (corresponding to Levels 3 to 5) this kind of process is no longer suitable, as the driver is not promptly available as a fallback solution. In this paper, a new approach is developed to evaluate automated driving systems of Level 3 and beyond using a top-down development process. Such a process offers an adjustment of system availability in accordance with previously established technical system requirements of certain driving scenarios.

The typical approach to define technical requirements for future safety systems includes the following steps [Wis13, Wis13a, Edw14, Sei14]:

- Accident analysis of critical real-world collisions
- Clustering and weighting of accident data to scenarios
- Deriving a test scenario and procedure based on clustered accident scenarios
- Developing, testing and real-world validation of a specific function

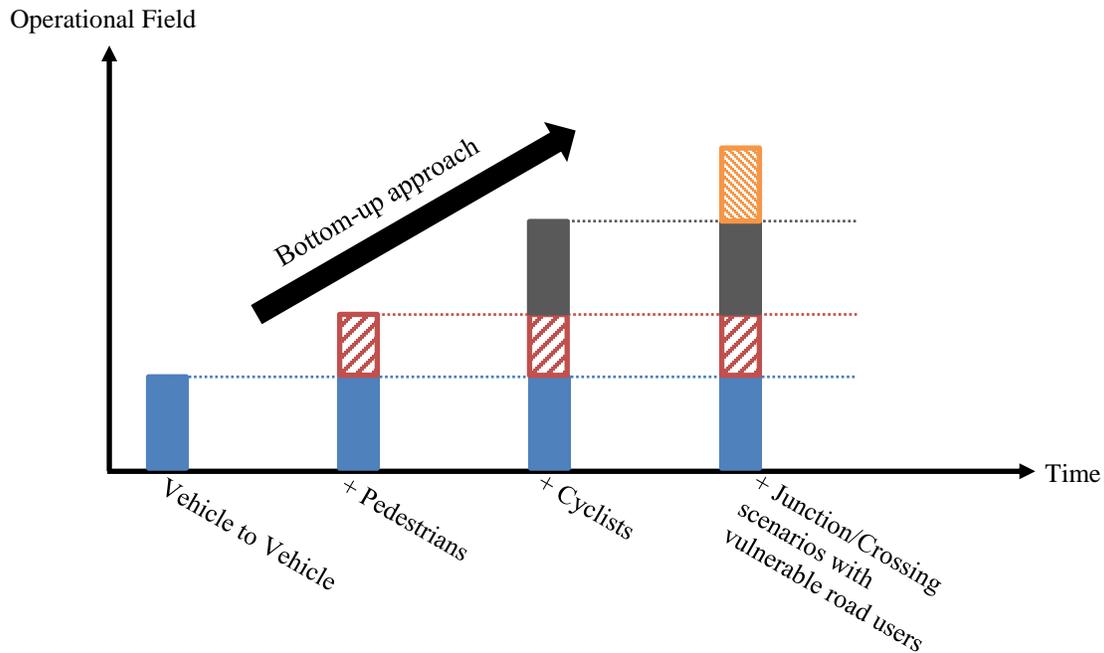


Figure 1. Schematic bottom-up approach for active safety or assistance functions

The German Insurance Association conducted an analysis regarding the impact of automated driving functions on the expected claim expenditure until 2035 [GDV17]. For that study, the monetary reduction of corresponding systems was calculated from system relevance, system efficiency, utilization rate and market penetration rate. The system relevance was determined using accident data and describes the number of crashes a system would be able to address. As not every addressable accident will be a preventable, system efficiency was defined. To take into account that the system might not be active in every driving condition and not present in every vehicle, a utilization rate and a market penetration rate was introduced. Different system functionalities and corresponding requirements (e.g. driving in unfavorable weather condition, performing a lane change etc.) can be addressed by adapting the system efficiency. However, using the method presented, a system efficiency highly depends on expert estimates. To evaluate system requirements regarding the system availability, an analysis of normal driving situation (baseline) has to be conducted as well.

With respect to system requirements of L3+ systems only generic approaches are presented in literature, for example in [Udv18]. Unfallforschung der Versicherer [Udv18] introduces universal requirements for automated driving. However, these do not permit to address the impact on system functionality, system safety and system availability.

AIMS AND OBJECTIVES

Current assessment methods for Level 3+ automation systems have a number of limitations. State-of-the-art effectiveness assessments are based on crash data. Another aspect that should be considered is the additional comfort a driver can gain from using such an automated driving system by transferring the driving task to the system. Thus, drivers' workload may be reduced. Further safety benefit is also to be expected by resolving near-crash situations. A large proportion of near-crashes would show that humans can adequately handle critical situations. These must also be addressed by a Level 3+ automation system. In order to answer these research questions, driving data is needed for baseline events in addition to crash data. As currently used databases only include crash data, an alternative database setup needs to be investigated.

Previous analyses consisted of potential assessments of generic systems without establishing system requirements. An assessment of Level 3+ systems requires a detailed analysis of system requirements for functionality, safety and availability.

This raises the following research questions:

- What is the accident prevention potential of different automated driving functionalities?
- How can the driver comfort be assessed?
- How do various functionalities affect driver comfort?

METHODS AND DATA SOURCES

The data source for our analysis is the Strategic Highway Research Program (SHRP) 2 naturalistic driving database. This data source includes 4,300 years of accumulated driving data, approximately 3,400 participants and 3,300 participant vehicles [Han16]. The study took place in six different cities within the USA. The installed data measurement system stored various time series data, like velocity or steering angle [Vtt16]. Furthermore, manually coded event data and videos of scenarios are available. In total, within the data set 1,465 crashes, 2,710 near-crashes and 20,000 balanced-sample baselines exist.

In the first step, different circumstances, such as locality, crash severity or pre-incident maneuver, are analyzed based on the available NDS SHRP2 data. In this analysis, we focus on automated driving functions for interstates/by-passes/divided highways. Streets with no separated driving directions and traffic signals are hence excluded. An accident prevention potential for a generic highway pilot is determined based on the crash and near-crash events within the SHRP2.

The next steps describe the influence of different technical requirements, their specifications and boundary conditions regarding the impact on functionality, availability and safety. As a human driver is not promptly available for redundancy, a new approach is needed and proposed in this paper. A top-down methodology is applied to determine the influence of different boundary conditions and corresponding technical requirements on the availability of an automated system (Figure 2). In each step, the top-down approach describes the influence of technical requirements on the operational design domain. As not all boundary conditions are manageable, an actual implementation will not cover the operational design domain of a generic highway pilot. Exemplary boundary conditions include:

- weather and surface conditions
- locality, e.g. highway with separated driving directions and no traffic signals
- driving velocity
- use cases, e.g. lane changes, overtaking
- traffic control, e.g. toll gates or police officers

Considering the data from SHRP2 as a baseline, an analysis can be performed whether a specific technical implementation would cover a specific scenario from the database. This allows to judge the comfort advantage of an automated driving function – “how many driving events can be covered by specific functionalities under various boundary conditions?” A similar approach can be taken to analyze the proportion of crashes and near-crashes to establish the accident prevention potential of a specific automated driving system. Thus, the balance between availability and safety has to be considered for different functionalities of a highway pilot – e.g. lane changes, entering/exiting highway or driving under unfavorable weather conditions.

If a current technical solution is not able to handle the baseline scenarios or manage existing crashes/near-crashes, the operational design domain of an automated driving system has to be successively reduced until an acceptable status has been achieved. The influence of various boundary conditions on comfort advantage or safety benefit will be shown for different system specifications of a highway pilot based on SHRP2 data.

To compare SHRP2 data with German accident data the German-In-Depth-Accident-Study (GIDAS) [Erbs08] was used to analyze accidents on German highways. The GIDAS teams have been analyzing and reconstructing approx. 2,000 accidents per year since 1999 in the vicinity of Hanover and Dresden. The advantage of this database is the availability of information about every person involved in the accident. Therefore, an analysis was conducted and required data was extracted for all passenger vehicles involved, meeting specific filter criteria. The GIDAS dataset from June 2018 was used and only reconstructed and fully coded accidents were included.

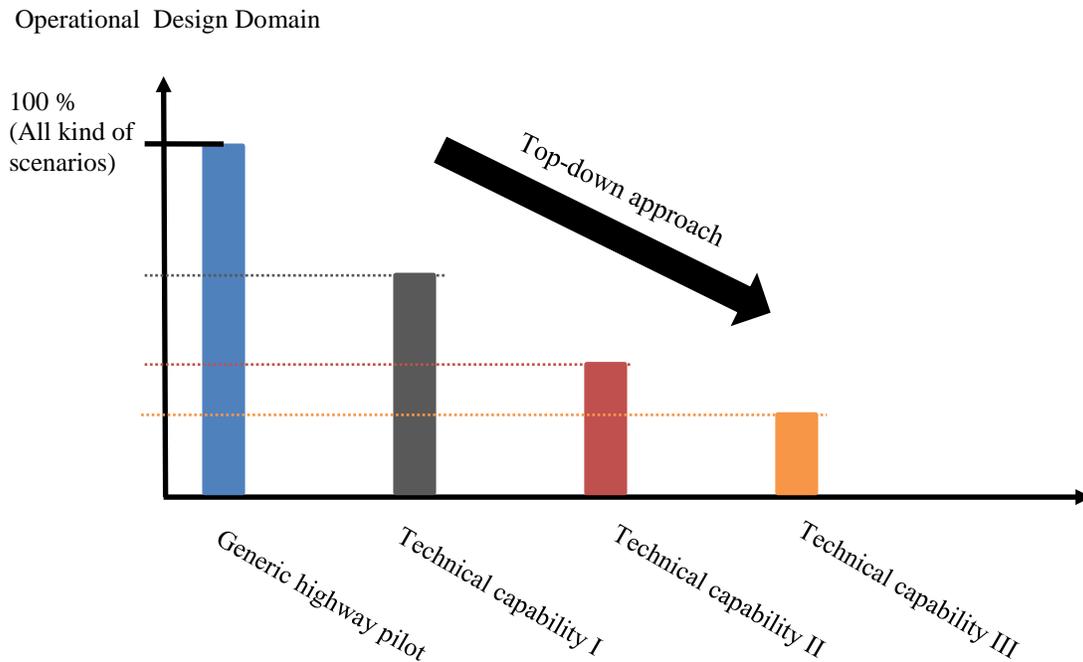


Figure 2. Top-down approach demonstrating the influence of technical requirements on the operational design domain and comfort advantage of an automated driving function

RESULTS

Within the SHRP2 naturalistic driving study, 1,465 accidents, 2,710 near-crashes and 20,000 baseline events are available. Figure 3 a) shows the relative distributions thereof for the respective localities. In this figure, localities are ordered by descending number of crashes. Nearly 48 % of all collisions (including low-risk tire strikes) occurred within business and industrial areas. However, participants only drove within these localities for 32 % of the time. In contrast, only 5 % of all collisions occurred at interstates/bypasses/divided highways with no traffic signals, where a large amount of all near-crashes (21 %) and especially baseline events (27 %) took place. Within this street type fewer collisions occurred, but a large amount of critical near-crash events were mitigated successfully by the human drivers. In addition, a high proportion of baseline events occurred on streets with separated traffic directions and no traffic signals. Consequently, a high comfort advantage may be provided with a highway pilot.

Figure 3 b) illustrates the relative proportion of crash severity under the influence of locality. More severe and police-reportable crashes occurred on interstates/bypasses/divided highways. On streets with no traffic signals but divided driving directions 26 % of crashes were severe and 25 % were police-reportable, while most accidents occurred on business/industrial streets where 12 % were severe and 17 % police-reportable.

In conclusion, on interstates/bypasses/divided highways with no traffic signals fewer accidents occur compared to localities such as business/industrial, residential or school. This result is similar to existing research for a potential safety benefit of a generic highway pilot [Gdv17]. In contrast, this NDS analysis shows that a relatively high proportion of near-crashes occurred on streets with divided traffic directions and no traffic signals. These critical events were handled well by human drivers, thus an automated system needs to perform equally well in these scenarios by avoiding such near-crashes or by predictive driving. Furthermore, collision avoidance for highways/interstates would particularly reduce severe collisions. In general, a large positive influence on critical events, on crash severity, and on accident reduction potential can be established for a generic highway pilot. For the further analyses in this paper we focus on automated driving functions for interstates/bypasses/divided highways use cases excluding streets with no separated driving directions and traffic signals.

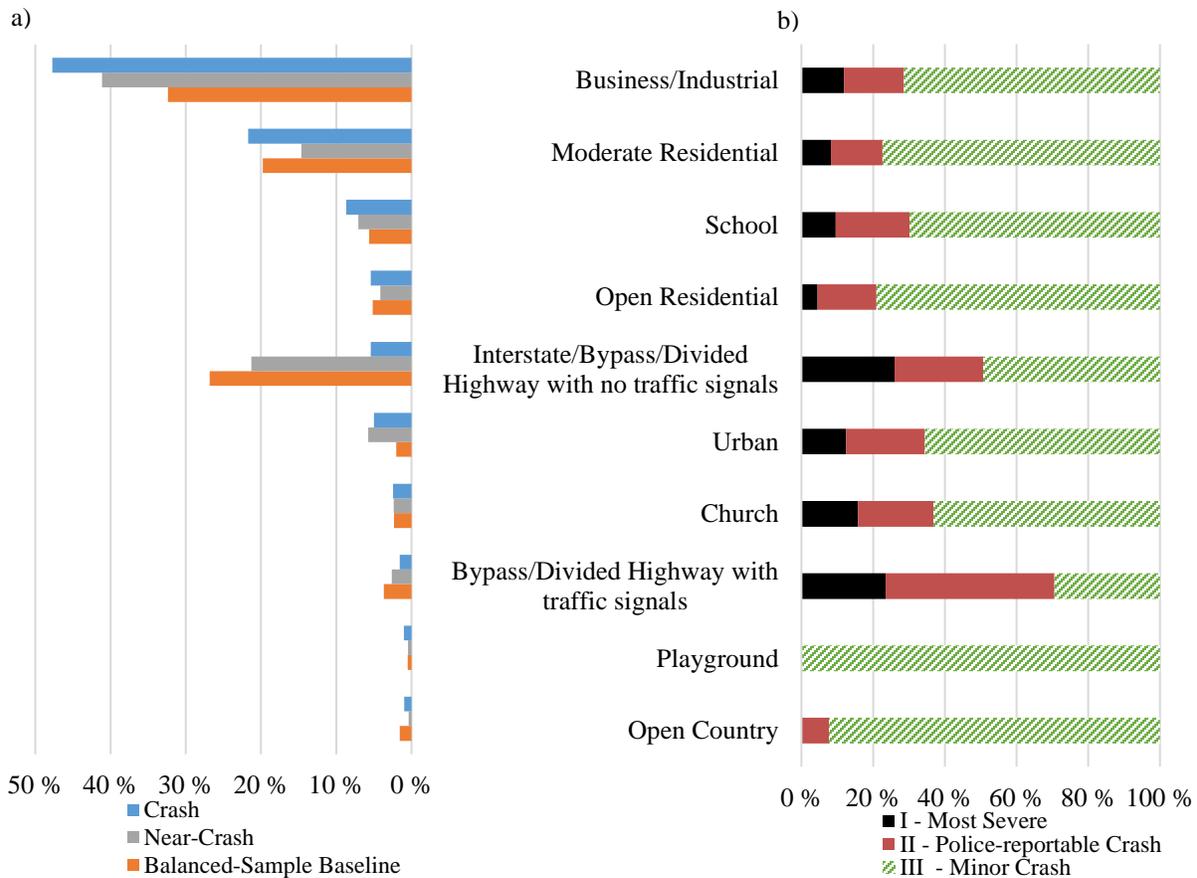


Figure 3. a) Relative proportion of crashes, near-crashes and baseline events depending on locality
b) Relative proportion of crash severity depending on locality

In the next step, we concentrate on pre-incident maneuvers on interstates/bypasses/divided highways with no traffic signals. This variable describes the type of action or driving maneuver just prior or at the time of the event [Vtt16]. Within this category, 79 crashes (5.4 %), 577 near-crashes (21.3 %) and 5,367 (26.8 %) baseline events are included in our data set. Figure 4 depicts the relative proportion of pre-incident maneuvers within crashes, near-crashes and baseline events. 66 % of the time subjects went straight with constant speed. Fewer crashes (43 %) and near-crashes (42 %) occur within this type of scenario. Critical scenarios for human drivers are: going straight while accelerating, decelerating in traffic lane, changing lanes (intentionally and unintentionally), and merging. Therein, the relative proportion of crashes and near-crashes is higher than existing baseline events.

Furthermore, the pre-incident maneuver *decelerating in traffic lane* shows an interesting correlation: in this scenario more near-crashes (19 %) occur relatively compared to crashes (11 %). This may be explained by drivers avoiding an accident through an appropriate evasive maneuver.

Based on the available times series data, the initial velocity of each event is analyzed. Figure 5 shows the velocity distribution under the influence of different event types on interstates/bypasses/divided highways with no traffic signals. Within all baseline events, the velocity was below 60 km/h for 5.7 % of the time, below 100 km/h for 36.8 % of the time, and below 130 km/h for 97.9 % of the time. This analysis includes entering and exit ramps. Thus, if a L3+ system is able to handle all boundary conditions – e.g. unfavorable weather, toll gates, ramps – up to a velocity of 130 km/h, 97.9 % of baseline driving time may be covered. Between 50 to 110 km/h, more near-crashes and crashes occurred compared to the baseline events. This corresponds to the analysis of the pre-incident maneuver (Figure 4): a high proportion of crashes and near-crashes occurred while accelerating, decelerating or negotiating a curve.

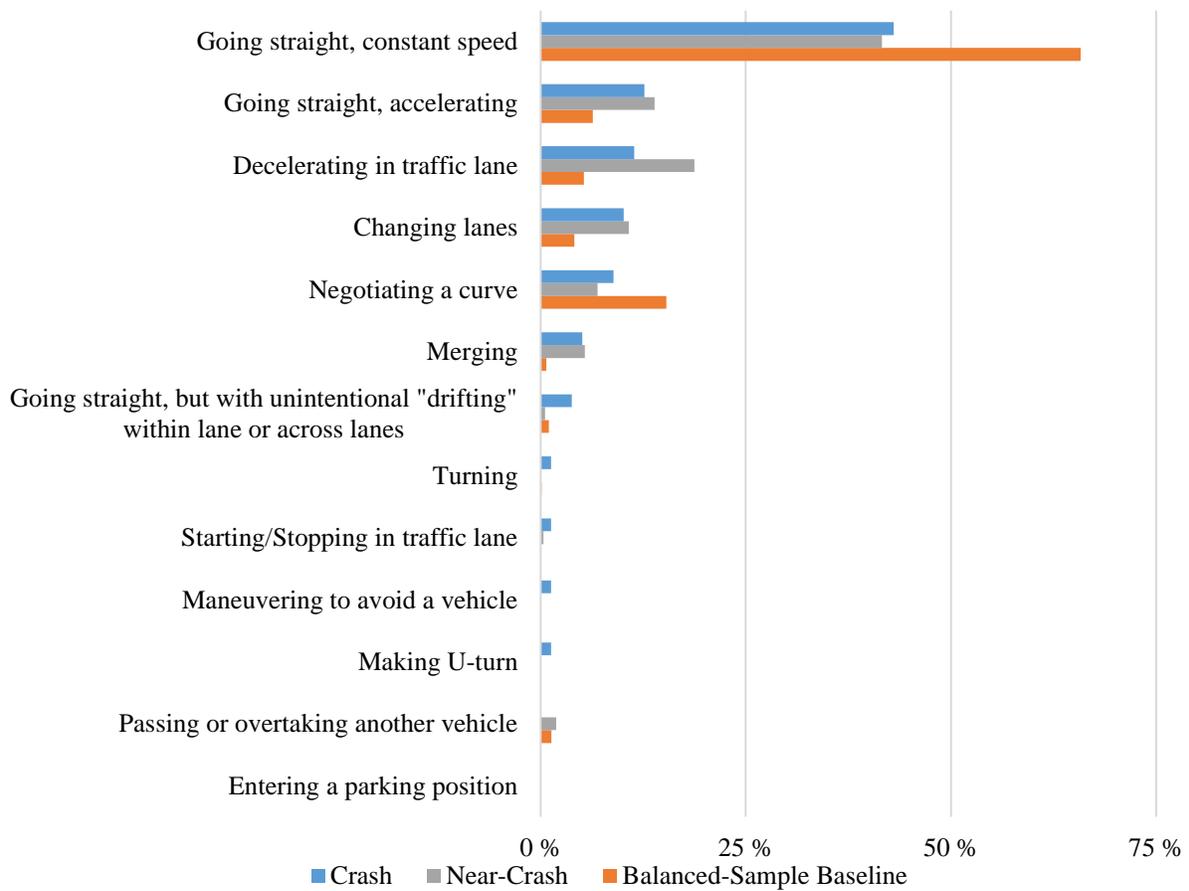


Figure 4. Relative proportion of pre-incident maneuvers for interstates/bypasses/divided highways with no traffic signals

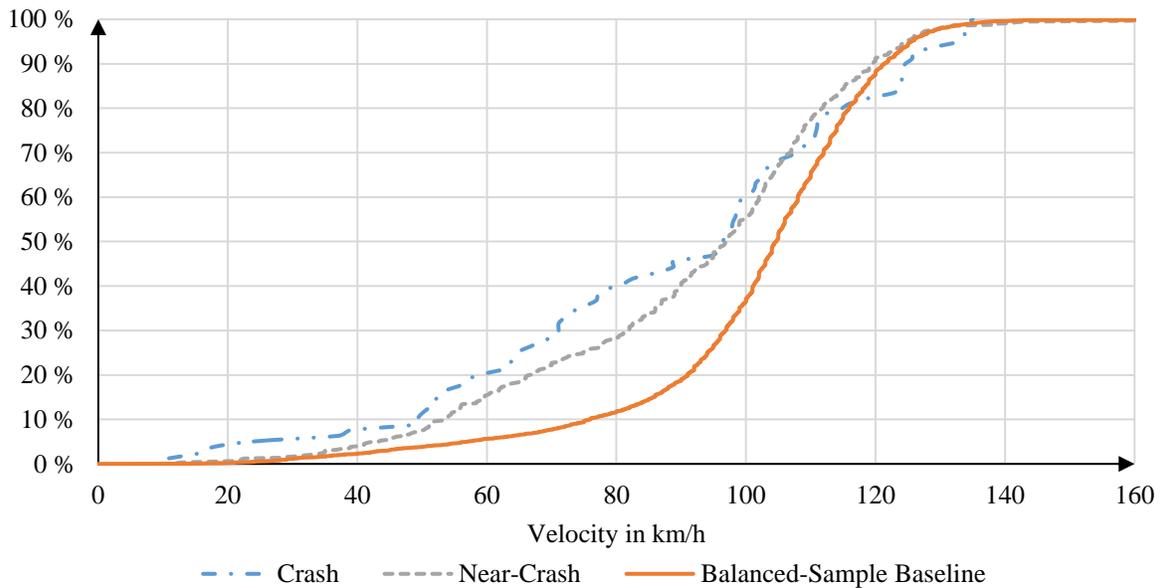


Figure 5. Velocity distribution for interstates/bypasses/divided highways with no traffic signals

Figure 6 shows the availability for different functionalities of a highway pilot and the influence of boundary conditions and technical requirements. Therefore, the baseline events are evaluated starting with a generic highway pilot (=100 %

- all trips within the SHRP2 NDS on interstates/bypasses/divided highways with no traffic signals may be covered by the highway pilot). Accordingly, all kinds of events and circumstances must be handled by a corresponding Level 3+ system, as a human driver cannot be expected to be promptly available as a fallback.

In the following steps, different boundary conditions and technical requirements are analyzed with respect to their influence on availability. Thus the cascade of boundary conditions/technical requirements and the influence on substituting manual driving by an automated system may be analyzed. If a system is not capable to handle situations with a watchman, officers or traffic controls such as toll gates 99.7 % of naturalistic driving time may still be covered. In addition, if the operational design domain is limited by unfavorable weather conditions, the availability is reduced from 99.7 % to 98.5 %. Boundary conditions/technical requirements such as automated driving on exit or entrance ramps, lane changes (detection of rear or side traffic) and construction zones (different/narrow drive paths) show higher influence on a customers' comfort advantage. If these scenarios cannot be managed by the automated system, the comfort advantage due to the automation is still 82.6 % of driving time. If the maximum speed is additionally limited to 130 km/h, the availability reduces to 80.8 %. A further speed reduction to 100 km/h results in a high decrease of availability (27.3 %). A maximum speed of 60 km/h and presence of a leading vehicle – here defined as traffic jam – results in an availability of 3.9 %.

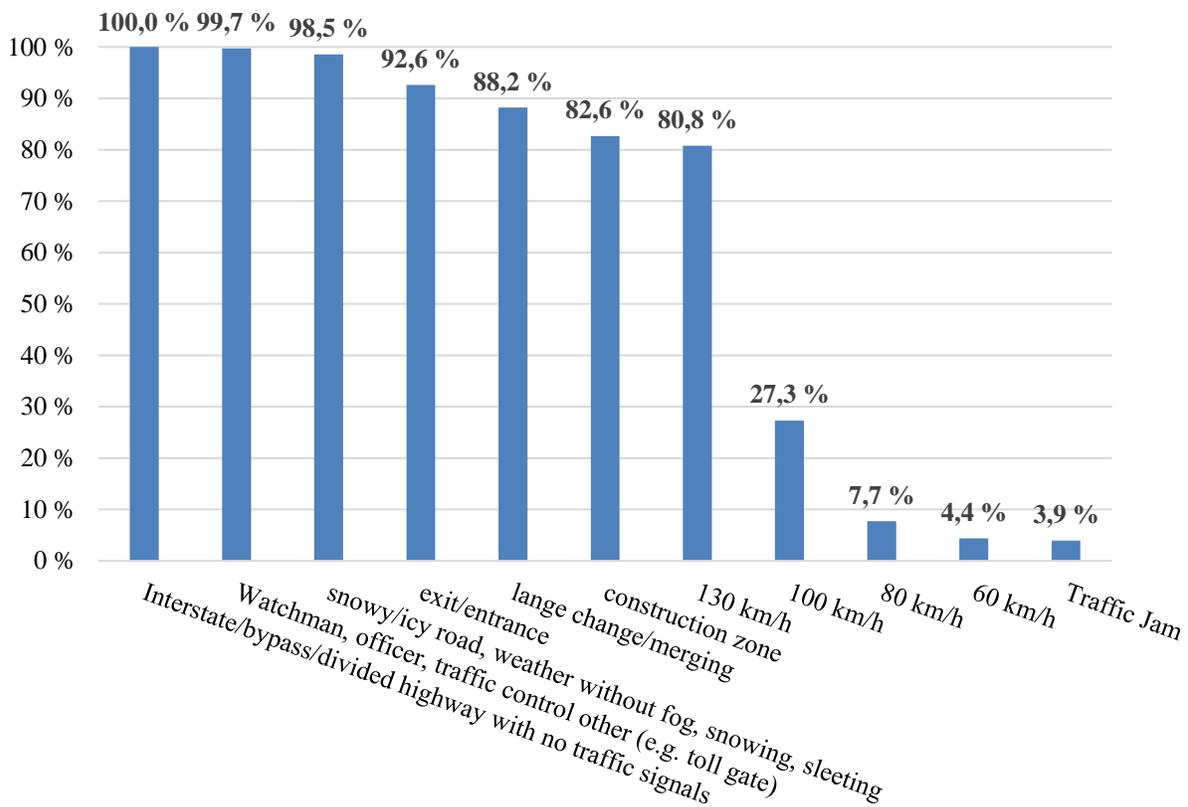


Figure 6. Top-down evaluation of availability for different functionalities of a highway pilot under the influence of boundary conditions and technical requirements

Beyond that, an automated driving function has a potential safety benefit due to avoiding or reducing criticality of (near-)crashes. On interstates/bypasses/divided highways with no traffic signals 79 crashes (5.4 %), 577 near-crashes (21.3 %) and 5,367 (26.8 %) baseline events occurred. For a generic highway pilot, it is assumed that these crashes and near-crashes can be avoided. The impact on safety and availability for different types of the operational design domain are analyzed in Figure 7. This analysis shows that boundary conditions such as weather, exit/entrance or construction zones have a high influence on the safety benefit of an automated driving function. The safety potential drops to 63 % of addressable crashes and 65 % of near-crashes if these cannot be addressed. Compared to the baseline events (83 % of availability) more critical events occurred under such conditions. Furthermore, low velocity automated driving functions (traffic jam, 60 and 80 km/h) have a higher safety potential compared to baseline events. A

traffic jam highway pilot is able to address 9 % of crashes and 8 % of near-crashes while this function will only be offered in 3.9 % of baseline events. Thus, even a generic traffic jam feature has a higher impact on traffic safety compared to availability.

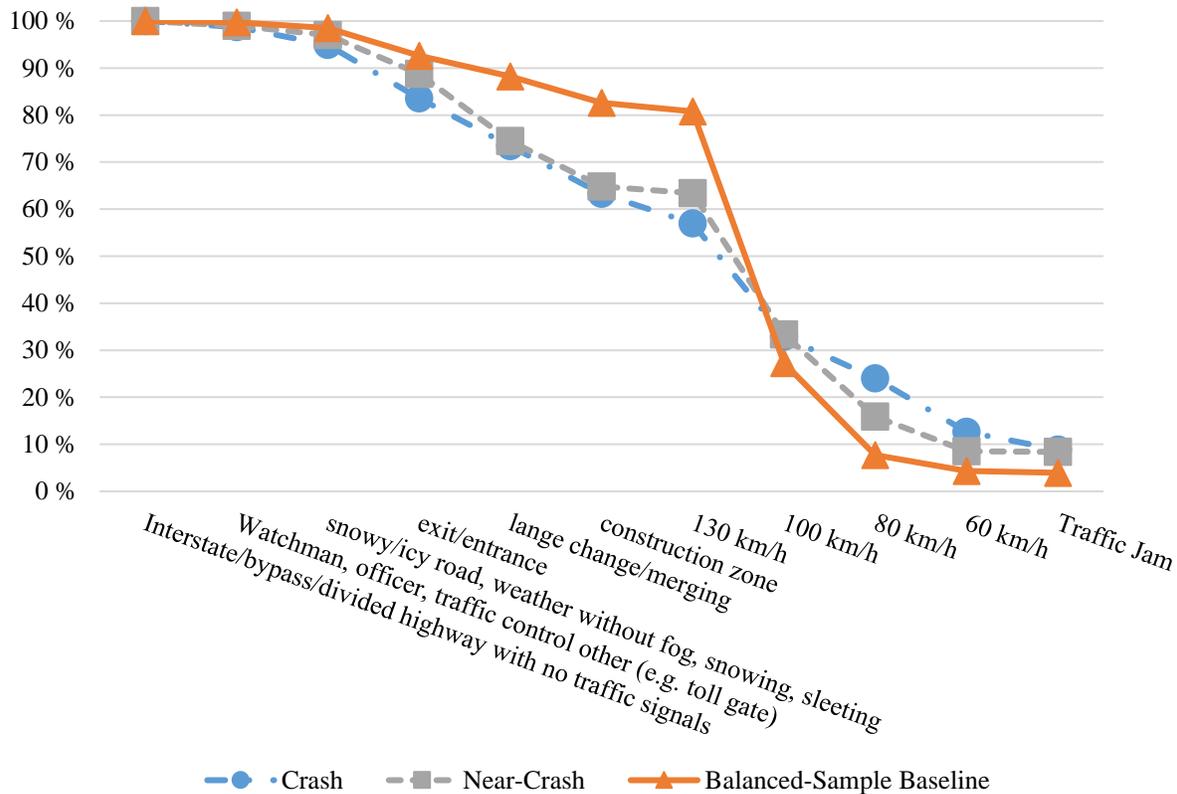


Figure 7. Top-down evaluation of safety potential for different functionalities of a highway pilot

To analyze the impact on collision avoidance, an investigation on GIDAS data has been conducted as well. In total 3,052 passenger vehicles on highways or similar (separated roadways without intersections and traffics lights) were included in our study. The set of all vehicles constitutes 100 % safety potential of a system for highways and comparable roadways. The top-down methodology of different boundary conditions and technical requirements were analyzed with respect to the influence on the safety potential as before. There was no relevant information in the database with respect to situations with a watchman, officer or traffic control such as toll gates. Consequently, there is no reduction in accident prevention potential. Without unfavorable weather conditions, the safety potential is reduced to 94 %. In the next step, vehicles driving on exit/entrance ramps, performing lane changes, merging maneuvers, or passing construction zones were excluded. Hence, the system benefit is reduced to 83 %. When the vehicle's speed prior to the situation becoming critical is below 130 km/h, the gain is 68 %. In traffic jams, with other vehicles present and a system's operating envelope of at most 60 km/h, the associated benefit is at about 9 %. All applied steps are displayed in Figure 8. In contrast to the NDS dataset, for GIDAS all vehicles on the respective type of road are analyzed. This leads to a vehicle-based focus.

DISCUSSION AND LIMITATIONS

The previous section has shown the potential safety benefit of automated driving functions. Additionally, the avoidance of accidents by human errors (e.g. impairment, inattention) during manual driving results in increased safety and comfort.

The high performance sensors installed for Level 3+ functionalities could additionally be used to improve active safety systems for manual or assisted driving. Within the NDS, comparable collisions also occurred on interstates/bypasses/divided highways with traffic signals. Thus, the operational field and performance of state-of-the-art active safety systems could be increased by harnessing these sensors.

By using the NDS's data, some limitations of our analysis need to be considered. On the one hand, only the time series data of the participants' vehicle is known. In contrast, in GIDAS the accident is reconstructed for everyone involved.

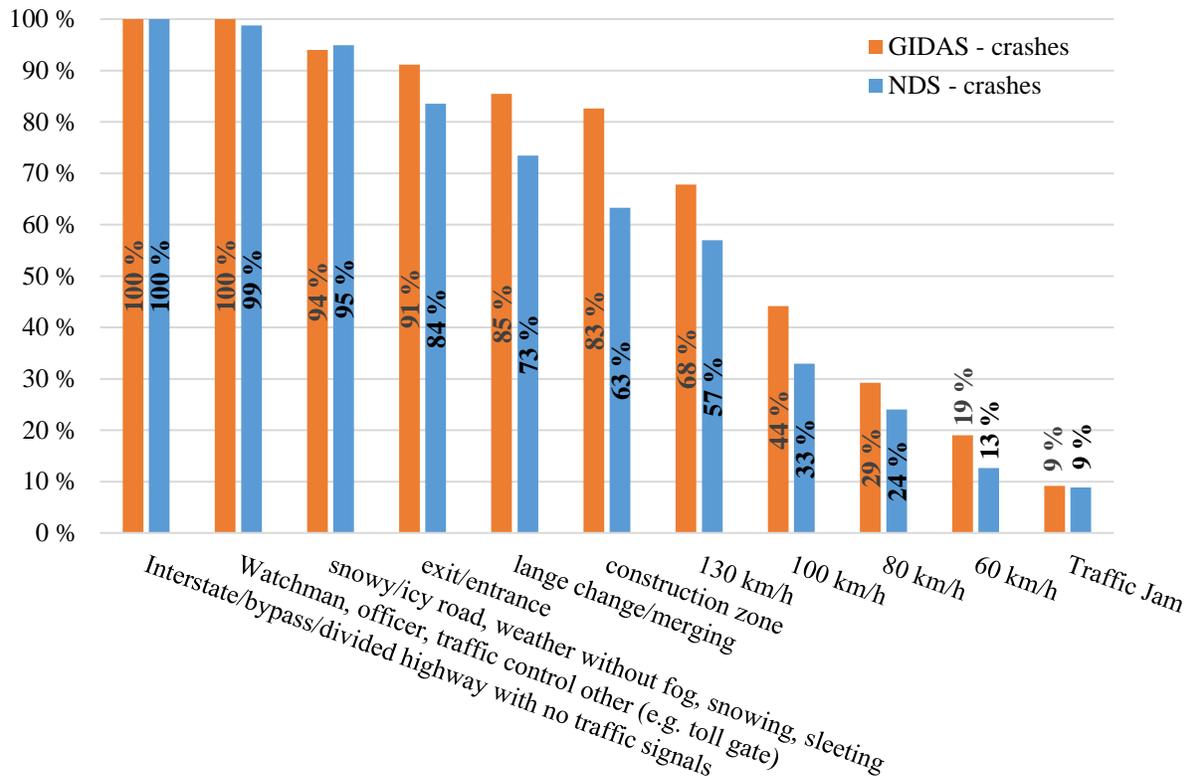


Figure 8. Top-down evaluation of safety potential for different functionalities of a highway pilot under the influence of boundary conditions and technical requirements

On the other hand, for some events specific time series data (e.g. velocity) was not included. In this analysis, events with missing data were excluded.

To investigate safety and comfort gain, it has been assumed that the automated driving function can consider crashes, near-crashes and baseline events. Furthermore, the NDS database is fairly limited with respect to crashes on interstates/bypasses/divided highways with no traffic signals (n=79).

Beyond that, misbehavior of other traffic participants has not been included in our analysis. An example could be a collision during a lane change that is caused by the speeding of the approaching vehicle.

CONCLUSION AND OUTLOOK

For automated driving systems, the balance of functionality, availability and safety is a crucial real-world deployment challenge. Consequently, this paper presents a prospective effectiveness assessment based on naturalistic driving data. For a top-down development process of Level 3 and beyond systems, an evaluation of technical requirements for upcoming automated driving functions is essential.

In this paper, a new method to assess and quantify this impact has been presented. The conducted analysis shows that a generic highway pilot can significantly improve driver comfort, since 26.8 % of the analyzed baseline events are highway driving. Especially the prevention of severe highway crashes leads to a high safety potential. Furthermore, a high proportion of near-crashes on the highway indicate a rather demanding driving task even for human drivers. An analysis of crashes in the GIDAS database shows comparable results and allows to create a range of safety benefits of highway pilots.

In conclusion, the conducted analysis enables a differentiation of various operational design domains on customers' comfort and reduced criticality due to avoided crashes or near-crashes.

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