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Vehicle Risk Evaluation in Low Speed Accidents: Consequences for Relevant Test Scenarios

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Abstract**—**Projects of accident research analysis are mostly focused on accidents involving personal damage. Property damage only has a high frequency of occurrence combined with high economic impact. This paper describes main influencing parameters for the extent of damage and presents a repair cost model. For a prospective evaluation method of the monetary effect of advanced driver assistance systems (ADAS), it is necessary to be aware of and quantify all influencing parameters. Furthermore, this method allows the evaluation of vehicle concepts in combination with an ADAS at an early point in time of the product development process. In combination with a property damage database and the introduced repair cost model relevant test scenarios for specific vehicle configurations and their individual property damage risk may be determined. Currently, equipment rates of ADAS are low and a purchase incentive for customers would be beneficial. The next ADAS generation will prevent property damage to a large extent or at least reduce damage severity. Both effects may be a purchasing incentive for the customer and furthermore contribute to increased traffic safety.

Keywords**—**Property damage analysis, effectiveness, ADAS, damage risk, accident research, accident scenarios.

I. Introduction

CURRENT vehicle safety systems and advanced driver assistance systems (ADAS) are mainly developed in order to reduce injury severity in accidents with high initial and collision speeds, as for instance adaptive cruise control using an emergency brake function. This is also reflected in various studies focusing on effectiveness evaluation of ADAS. Most studies merely cover accidents with personal injury [1]. Large-scale projects on accident analysis do similarly. For example, the German In-Depth Accident Study (GIDAS) and a number of accident research units deal mainly with personal damage accidents. Many findings are used for infrastructural development and layouts contributing to the continuous enhancement of vehicle safety [2], [3]. This is mainly reflected in the decreasing number of traffic fatalities during the last two decades since 1994. The number of annual fatalities in Germany dropped over 66% to 3.377 in 2014. Accidents involving personal injury reduced more than 23% to 302.435. The only increasing number of accidents is accidents involving property damage (+12 % to 2.104.250) [4].

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It is not only the absolute number of property damage accidents that is higher than the one of accidents involving personal injury, but also economic costs – up to 30% of all insurance claims for low speed maneuvering accidents [5]. The gap between the different accident categories keep growing further apart as shown in Fig. 1.

A significantly higher number of accidents are not reported to the police. Some are reported to the insurers as third-party liability or own damage claim (in total: 9.7 million cases) [6]. A pilot study on property damage accident analysis by means of insurance data reveals that merely every fourth insurance case (property damage collision) is reported officially [7]. The number of minor damage cases not appearing in statistics and not reported to the insurers add up to 4.8 million cases per year [8]. Hence, official statistics only represent a fraction of real-world accidents involving property damage.

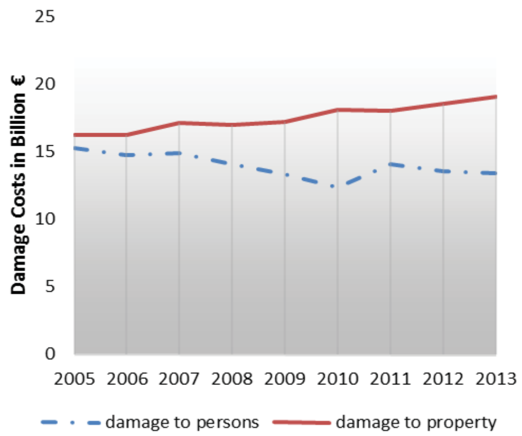

Fig. 1 Economic costs of property damage accidents and accidents involving personal injury in Germany, values according to [9]

Up to now, only few projects, like [7], deal with detailed analysis of accident characteristics and accident causes in the field of property damage. It is here the objective to gain detailed information and knowledge about the occurrence of accidents and underlying conflict scenarios. This will benefit from the development and design of future advanced driver assistance systems.

Characteristics of property damage accidents are entirely different from the accidents involving personal damage. 35% of comprehensive cover accidents occur at low speeds [7]. Therefore, a major potential of ADAS is the reduction or avoidance of current and future property damage accidents. Currently, ADAS equipment rates are low – purchasing incentives for customers' need to be created in order to achieve a higher market penetration rate of these systems. This would also lead to a higher effect on traffic safety, but also requires knowledge of system effectiveness prior to commercialization. Purchasing incentives for the customer can be saved repair costs or a benefit in the insurance premium. Systems would thereby partly or fully pay off in the course of use.

This paper presents a detailed classification and evaluation of vehicle damage risk in low speed accidents based on the methodology for prospective determination of field effectiveness of ADAS focusing on the potential of reducing property damage accidents given in [10], [11]. Low speed accidents are defined as accidents without personal injury within this research. Due to the low speed range damage to outer attachment parts can be investigated. In a GIDAS analysis, the EES (energy-equivalent-speed) for an upper limit of damage to property cases has been conducted. Frontal crashes belong to this definition below 15 km/h, rear crashes below 6 km/h, lateral crashes below 11 km/h for the left side and 9 km/h for the right side [12].

Comparable prospective analysis methods of ADAS in the field of property damage accidents are not available in literature. A prospective evaluation method is indispensable for deriving influencing effects on accident occurrences, because retrospective effectiveness analyses of active systems are elaborate and time-consuming due to comprehensive data collection and low fitting rates. The damage risk evaluation considers various equipment configurations and materials of outer attachment parts (OAPs). Hence, a significant impact on repair costs may be envisaged. In addition, the vehicle class is included.

For evaluating the structure in the repair cost changes by the use of ADAS, appropriate values are needed. In the years to come, this will be emphasized through an increasing number of automated systems, which have an operational field for property damage cases. In the following chapters, the method and data source for a prospective extent of cost evaluation method and test scenarios within property damage accidents will be explained.

II. Methods and Date Sources

For determining the influence of ADAS on property damage accidents, a specific method described in [10] has been developed. This approach requires data collection, reconstruction, and subsequent advanced simulation of accidents, as well as a damage risk function for the evaluation of modified accident parameters resulting from the new simulation.

A. Damage Points (SP)

For providing a comparison of various damages, a standardized description in relation to the volume model is used in [10], [11]. Hence, a non-currency related comparison over a long period of time is possible, and in addition various vehicle models can be compared.

The modular design of the damage risk functions and the use of damage points (SP) facilitate evaluation of individual accidents. Total cost of component replacement is under consideration. This consists of component costs (ET), wages (LW) and paint-work costs (LACK). These costs are subsequently divided by a basic factor α in order to receive a certain number of damage points. Currently, the basis factor represents 25 €. This calculation is performed for all OAP and ADAS sensors.

$$SP_i = \frac{ET_i + LW_i + LACK_i}{\alpha} \tag{1}$$

In order to extract the main influencing parameters on property damage, repair cost for various exterior parts has been calculated by the software Audatex (status as of November 2014). Audatex is a common tool for technical experts to compute damage costs of various manufacturers and models for expert assessments.

The restriction on OAPs is derived assuming that no structural elements are damaged in the low speed range without personal injury. In addition to component replacement, repair methods like smart repair and paint work may be considered as well.

B. Using Matching Coefficients

The calculated damage points are the same for each vehicle model. Matching coefficients are necessary to consider various component materials, vehicle equipment specification, and various vehicle classes [11]. The coefficients β show the ratio of different prices of repair costs for different parts and vehicles. In order to determine the exact repair costs, the software Audatex (status as of November 2014) was used. For the calculation of repair costs, damage points are multiplied with the matching coefficients and all damaged parts are summed up.

C. Damage Units (SE) and Determination of Expected Damage Extent

The product out of damage points and matching coefficient is called damage units (SE) for a specific part i [11]:

$$SE_i = SP_i \cdot \prod_n^m \beta_n \tag{2}$$

$$n, m \in \{class, light, material, rims, dynamic, varnish, ADAS\}$$

In nearly every accident, more than one component is damaged. Therefore, all damaged components (from part i to j) may be summed up for determining the entire damage extent. Basic costs like varnish preparation are added to the total amount of damage units.

$$SE_{sum\ of\ external\ components} = \sum_i^j \left(SP_i \cdot \prod_n^m \beta_n \right) \tag{3}$$

The damage extent in the used currency may be determined at all times. Therefore, the damage units are just multiplied with the basic factor. In the course of time, only the basic factor need to be adjusted for considering higher or lower prices. This approach allows to determine brand and model independent damage costs of accidents. Thus, a methodology has been created for evaluating new vehicle concepts at an early point in time of the product development process in order to evaluate future damage and property behavior based on the input of vehicle class, exterior part material, installed ADAS and sensor types. Furthermore, a prospective estimation for the extent of damage may be implemented for the insurance class relevant test scenario according to RCAR [13]. Based on the expected damaged exterior parts in combination with the selected vehicle class, optional equipment and ADAS sensors the possibility has been created to calculate generally the repair costs. Furthermore, this can be used for the three different (front, rear and side) test scenarios within RCAR tests to compute the extent of damage and the achieved insurance rating, according to [14]. This methodology facilitates a differentiated consideration: ADAS may reduce damage points which have a vehicle individual impact on damage units.

D. Systematic Damage Extent Evaluation Structure

By means of knowledge of the main influencing parameters for property damage, various types of accidents may be considered. Chapter III covers the evaluation of exemplary real world property damage accident scenarios. The methodology of main influencing parameters is based on a standard volume model. Fig. 2 shows the systematic structure of the extent of damage determination. In this paper, damage costs are provided in damage units. Based on the reference vehicle class, here a medium-sized volume model, damage costs for individual property damage scenarios will be calculated. In the next configuration step the damaged parts can be selected in order to determine the expected damage units. On the one hand, affected exterior parts may be selected as well as various materials and optional equipment. On the other hand, ADAS sensors are likely to be damaged in property damage accidents due to an exposed position. Thus, sensors can also be configured to compute the expected extent of damage. This systematic model includes various types of ADAS and therefore various types of sensors, e.g. cameras as well as night vision, ultrasonic and radar sensors. The following step converts the vehicle class based on the medium-sized into the interested vehicle class – from small to luxury class vehicles as well as sport-utility vehicle (SUV) derivatives. Finally, the damage extent for a specific accident configuration is determined in damage units. In addition, the methodology of damage points and units has been already validated with averaged deviation less than 2.9%. Further information about the relevant formulas for the described calculation and a suggestion for deriving a property damage risk score is available in [11]. A risk classification is necessary because resulting repair costs in property damage accidents depend significantly on the equipment of the vehicles and materials of the OAPs shown in the following chapter.

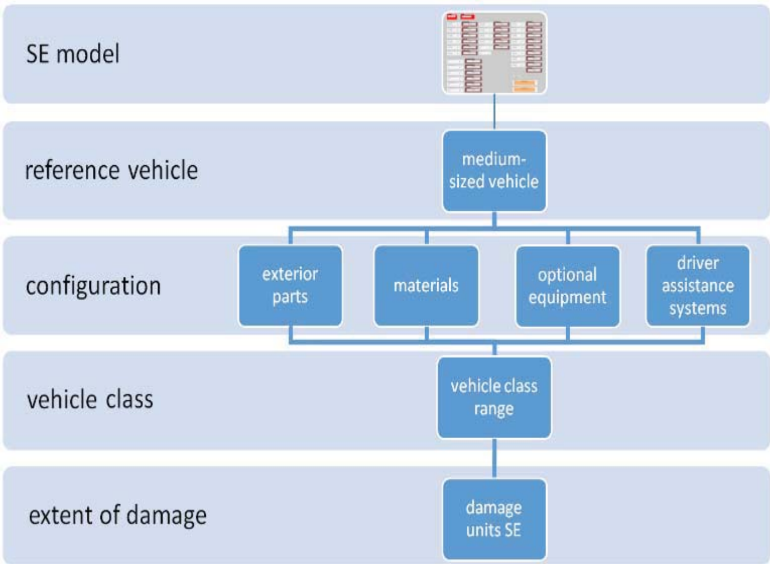

Fig. 2 Schematic structure of the damage unit systematic (SE model)

III. Results

In this chapter, quantitative and qualitative influence of main damage to property parameters are evaluated for the real low speed accident cases.

A. Influence of Material Selection

Repair costs have been determined by means of an appraisal calculation software. Three basic essentials for the cost structure of vehicle repair can be differentiated: wages for replacing or repairing parts, spare parts and vehicle paint. The total extent of damage is computed by summing up this three categories of repair costs. For the calculation, spare part prices need to be considered instead of manufacturing prices. Furthermore, this finding is also valid for the influence of various types of materials for exterior parts. A cost analysis by McKinsey considered the cost effect of various lightweight materials [15]. The expected cost and weight influence of plastics, aluminum and carbon fiber for a fender have been referenced to a commonly used steel version. All versions reduce weight, but have also influence on manufacturing costs, as it is especially the case for carbon fiber. According to an assumed 60,000 units per year, the production of aluminum increases the costs by factor 1.3. Plastics parts are a cost neutral lightweight option (effect factor equals 1.0). Carbon fiber has the highest individual influence with an expected factor of 5.7. In contrast, the spare parts and repair costs analysis supplies one aspect: While manufacturing costs for aluminum and carbon fiber are significantly higher than the ones for steel and at least equal for plastics, the repair costs and spare parts prices show a different situation. For the materials aluminum and carbon fiber the cost factor for damage to property repair is lower, especially for carbon fiber. In a repair cost comparison of a carbon fiber fender for a regular compact class vehicle and its sport version, the influence factor is nearly half than predicted in the product producing cost analysis. Furthermore, the repair costs of plastics OAP will be lower than of the common steel version. Therefore, two main aspects may be inferred: Firstly, for the analysis of the influence parameter on real-world damage to property accidents and their incurred cost consequences for customers or insurances instead of manufacturing prices spare parts and repair costs have to be considered in order to extract the sole influence of the main parameters on damage to property accident costs. Secondly, lightweight materials have extensive influence on repair costs for damage to property accidents. In the next years, this will have negative consequences on insurance rates for new vehicles equipped with lightweight materials for exterior parts in order to achieve further improvements in CO_2 emissions.

Fig. 3 shows the influence on the damage to property risk. Generally, risk is a combination of damage costs and frequency. The dotted lines represent a constant property damage risk. The analysis is based on five different accident cases from Gschwendtner [10].

Fig 3 shows the influence of various material and type of headlights on the property damage risk. The analysis always starts on the referenced vehicle accident assessment. The first discussed accident type is 731. In the expert assessment damage to bumper, fender, hood, doors and headlight have been documented. In the reference case, the vehicle has an aluminum fender and hood. Fig. 3 shows the projected risk for a vehicle with complete steel, aluminum or plastics exterior parts. With aluminum exterior parts (except the plastics bumper) a 5% higher damage cost and risk can be determined in comparison with the version with steel. Furthermore, the application of plastics exterior parts reduces the risk due to lower repair costs around 40% compared to the version with steel. The next sole influence parameter is the type of headlight. The risk increases with LED around 23% and through laser 76% related to the reference case. The influence of the type of lightning has been already further analyzed in [11].

Accident type 861 - involving rear bumper damage: A carbon fiber version would result in a risk increase by 71%.

Accident type 711: in this case a third-party liability claim includes a damaged front bumper and shows the similar effect for a version made of carbon fiber.

Accident type 821: This reference case involves damage to a rear bumper and to a steel tailgate. The risk analysis shows the influence of material for the rear of a vehicle. The highest determined risk is for carbon parts, with an increase of 87%. For the case that the tailgate is made of plastics, the risk score decreases around 25% compared to the reference case.

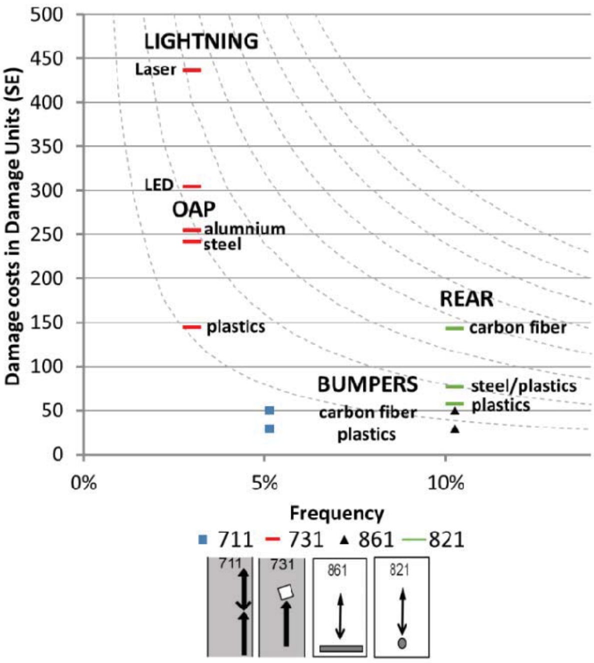

Fig. 3 Material parameter analysis for property damage risk [7], [16]

B. Influence of ADAS Sensors

A further aspect is the influence of ADAS sensor types on damage to property risk. First step is to analyze the repair costs of various sensor types. Various camera, ultrasonic and radar sensors are included. Fig. 4 shows the cost factor of various sensors referenced to damage units of a front radar sensor. Especially, night vision cameras and front radar sensors can have a huge influence on damage to property risk because of high repair costs. A night vision camera causes a more than five times higher damage extent than a front camera for surround view. A complete exchange of six ultrasonic sensors, e.g. for a parking assistant, cause a decrease of cost factor by approximately 36%. Rear radar sensors have similar influence on repair costs as front cameras. The effect of scale costs can be seen by replacing two radar sensors.

In conclusion, ADAS sensors will have an extensive impact on a vehicle's damage to property risk. A further complicating factor is the sensors' installation position – exterior position of vehicle – the replacing rate in damage to property cases is expected to be high. These circumstances are represented through damage risk functions, which indicate the probability of replacing parts depending on the EES [12]. In contrast, the repair model explained in this paper shows the monetary effect of main parameters for damage to property cases.

Further analysis includes the implementation of the sole influence for ADAS sensor types fitting to the damage unit model. In the third section of the schematic structure (Fig. 2), for the damage unit model, it becomes feasible to compute the extent of damage including ADAS sensors.

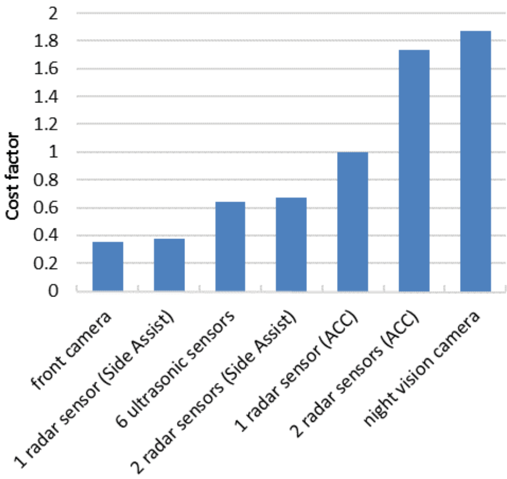

Fig. 4 Repair cost analysis of ADAS sensor types

The influence on the damage to the property risk for real-world accident cases is shown in Fig. 5. The focused accident type is 851. In this particular case, a compact class vehicle was damaged. The specific repaired parts were front bumper, fender, hood and headlight. Based on the reference case the influence of different installed ADAS on the damage to property risk is analyzed. Due to the exposed and outer position of ADAS sensors, the case of replacing the affected parts was considered.

In detail, the installed front camera increases the risk by 14%, ultrasonic sensors by 23%. One radar sensor for an ACC (adaptive cruise control) increases the risk by 45%. For two radar sensors, the resulting increase is 78%, which is slightly smaller than the sole influence of replacing two single radar sensors because of the already explained scale effects. The highest possible effect of ADAS sensors is caused by a night vision camera. In this case, the extent of damage would be raised by 136%. In conclusion, each single type of sensor for current ADAS has an extensive effect on damage to property risk. For a fully equipped vehicle with ADAS (includes all sensor types in Fig. 5 mentioned), the risk increase would be around factor 3. For this exemplary real-world low speed accident, only one third of the costs would be caused by OAP exchange, two thirds are affected due to ADAS sensors.

Due to the fact that only few optional ADAS are available with fully automated intervening functions for the lower speed range in order to avoid automatically and driver independently crashes, the dilemma between increasing comfort and safety features and the real-world damage to property behavior because of vehicle installed ADAS will be emphasized.

A detailed view on the damaged exterior parts in Fig. 5 allows an interpretation for the commonly used insurance rating test according to RCAR [13]. In the front crash the vehicle is impacted at 15 km/h against a non-deformable barrier (40% overlap). The main aim of this test procedure is to review repair friendliness and damage to property behavior of vehicles. For the German insurance rating system, the front RCAR test is weighted with 54% [14]. Thus, the front crash is the most important factor in the insurance rating. Consequently, vehicles with ADAS belonging to the standard equipment may achieve a worse result because of the higher repair costs and risk (Fig. 5).

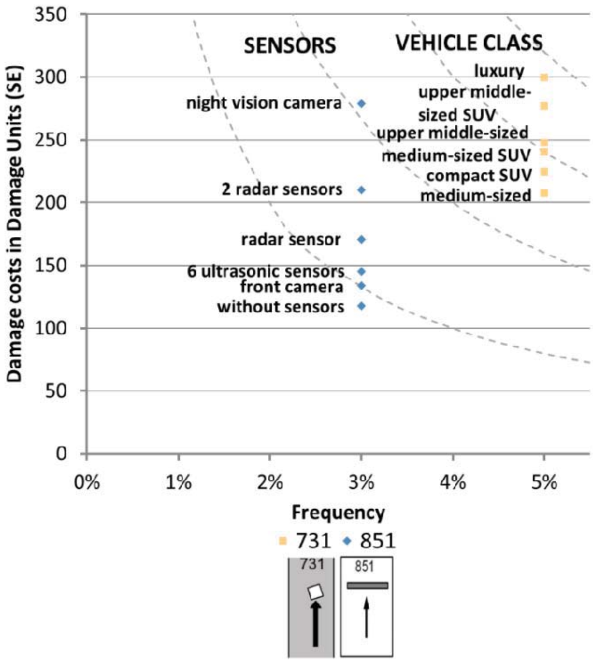

Fig. 5 Vehicle class and sensor parameter analysis for property damage risk [7], [16]

Currently, only few ADAS within property damage operational field, like a reverse auto-brake (Infiniti, Mazda, Cadillac or BMW [17]–[20]), which may mitigate or avoid automatically several accident types within maneuvering, are available. On the one hand, next generation of ADAS may have functionality for several damage to property cases and will reduce the frequency of occurrence in the fleet. On the other hand, this has currently no influence on the insurance rating test according to RCAR. Furthermore, these vehicles may have a worse insurance rating due to the achieved testing result than vehicles without any additional ADAS. For the future, a test procedure for damage to property has to be implemented including the functionality of the specific vehicle's ADAS. There is a possibility to evaluate prospectively the effectiveness in the fleet.

C. Influence of Vehicle Class

A further main influence factor is the vehicle class. The analysis for the damage units systematic includes several classes from small to luxury, including SUV from compact to upper middle size. The repair costs for various OAP and vehicle classes have been analyzed. Generally, for higher vehicle classes involved in low speed accidents the repair costs will increase. Fig. 6 shows exemplary (for one manufacturer) repair costs in damage units for a fender, front bumper and a side panel depending on the vehicle classes – here from small to luxury.

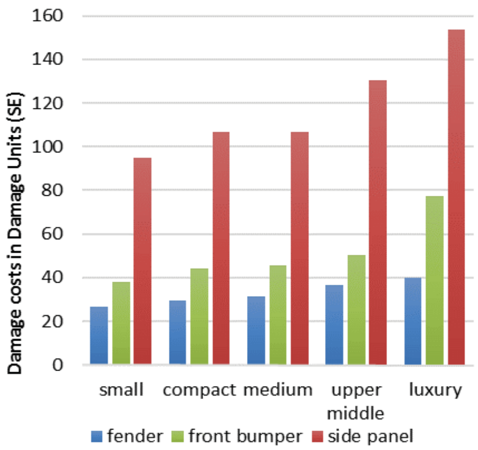

Fig. 6 Exemplary cost structure under the influence of vehicle class

In the further evaluation of the extent of damage, SUVs were analyzed. A risk analysis again based on a real reference case was conducted (Fig. 5). The focused accident type is 731. In the reference case the front bumper, fender, hood, two doors and one headlight of an upper middle-sized vehicle were damaged. Obviously, larger vehicles have a higher risk in damage to property cases. Furthermore, for example, the sole influence for the risk of a SUV in the medium sized class is +15% or the risk of a compact SUV is higher than the larger medium-sized vehicle class. Upper middle-sized and medium sized SUV have a risk value between their basic class and the next higher one. In summary, a higher damage to property risk can be expected of vehicles belonging to the SUV class. Consequently, this implies a higher potential impact of ADAS with fully automated intervening functions for the lower speed range.

D. Further Influencing Factors

Due to the widely possible diversification of vehicles' optional equipment, the damage to property risk can be strongly influenced. These dependencies can be shown with the type of headlights (Fig. 7). Compared to the standard halogen headlights installed in the vehicle model used in the damage units systematic, laser light has an extensive impact on the expected extent of damage. Halogen compared to laser light has a cost factor higher than 16. Even the more established LED or xenon headlights have a cost factor of 5.5 and 2.1.

The consequences for a fleet are obvious: If the percentage of vehicles equipped with these optional headlights increases, the damage to property risk will rise. According to the RCAR test procedure [13], the most common equipped vehicle is tested; therefore, various types of headlights are not included despite their extensive cost influence. Retrospectively, the insurance rating will be adjusted to the fleet data.

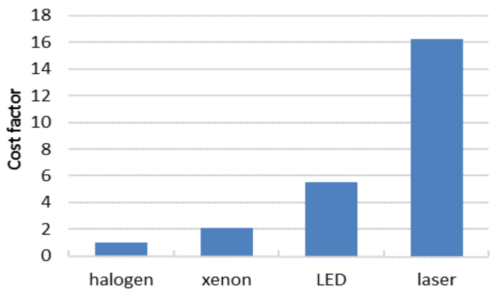

Fig. 7 Repair cost analysis of headlight types

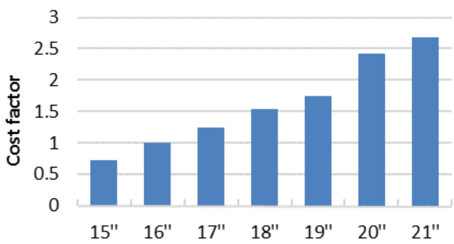

Fig. 8 Repair cost analysis of rim size

A further not yet considered influence factor is the size and type of alloy rims. The used basis standard volume model has 16'' rims. Changing the size up to 20/21'' increases the costs with the factor 2.5 (Fig. 8). Generally, larger rims cause higher repair costs. The increase is caused by higher spare parts prices.

The type of paintwork (metallic and solid paint) has an influence below two percent. On average for all parts, it is around one percent. For parts with larger areas to varnish the effect is slightly higher. In consequence for the damage units systematic this influence parameter will not be pursued further.

IV. Discussion and Limitations

The cost analysis considers current repair costs and dependencies for different technologies. In the future, due to higher installation rates, the influence of certain parameters may change because of scale effects. Through the cost factor structure in the systematic damage unit model, this can easily be adopted to the current status. For example, it can be assumed that in the future the cost impact of carbon fiber, ADAS sensors or laser light will decrease due to a higher market penetration rate.

For the influence of the vehicle class on real-world accident types, a constant frequency of occurrence has been used due to the available small pilot evaluation. It can be expected that as shown above various vehicle classes have varying repair costs as well as diverse frequencies of occurrence for damage to property accident types. This has also consequences for the potential of ADAS and relevant test scenarios. Vehicle classes with higher expected extent of damage in combination with more frequent accident types within the low speed range are suitable for ADAS with fully automated intervening functions.

The analysis of different influence factors on repair costs and the expected damage to property risk for the considered real-world low speed accident cases show that there will be a gap between the prospectively determined risk and the estimated risk through the RCAR test procedure due to the real vehicle configuration. In order to evaluate and test the effectivity of ADAS with automated intervening functions for damage to property accident cases under the aspect of a possible incentives in the insurance rating a test scenario has to be determined. This test has to combine repair costs under the effectivity of the installed ADAS for the most relevant accident types. In contrast to the proposed test procedure by Grover [5], a test scenario according to the extended accident types [7] will be pursued. The reason for using specific accident types is a possible interaction between retrospective data analysis and implementation in new test scenarios. Furthermore, on the one hand the representativeness of each accident type is known through the database, and on the other hand through the achieved results in this specific test possible incentives can be calculated.

The performed analysis for the influencing parameters, realized in this paper, shows that the frequency of occurrence of each accident type for future relevant test scenarios can be determined by means of a retrospective analysis of databases. But for choosing the test scenarios with the highest damage to property risk and thus the most relevant potential for ADAS the expected repair costs have to be considered. This paper demonstrates that different vehicle configurations – like ADAS sensors or optional equipment – will influence the extent of damage. This causes an "accident-type-shift" when determining test scenarios. Due to the specific configuration previously less relevant accident types can become more relevant. Fig. 3 shows these exemplary circumstances. The reference vehicle with steel OAP and bumpers made of plastics for the accident types 731 and 821 have similar damage to property risk. Equipping the specific vehicle in accident type 731 with optional lightning, like LED or even laser headlights, the damage to property risk increases, and the accident type 731 is more relevant for test scenarios than 821 in order to evaluate the effectiveness and a possible impact on vehicles' insurance claims with this specific configuration.

In conclusion, the frequency of occurrence can be determined retrospectively. The extent of damage and thus the risk is depending on the specific vehicle and its configuration. The influence parameters can cause a change of the most relevant accident types for test scenarios.

V. Conclusion

For the determination of the extent of damage regarding the repair costs, two main aspects have to be considered. Firstly, lightweight materials have a negative influence on the damage to property risk. Secondly, especially the economical relevance for lightweight vehicles with modern technology like LED or laser headlights opens a new potential for advanced driver assistance systems extended on a low speed range. Due to the availability of only a small pilot accident data evaluation, accident frequencies and their respective repair costs of each occurring accident type were assumed to be constant within each vehicle class in the first step. In order to raise the significance of the introduced damage to property risk model, the frequencies of occurring damage cases have to be specified more accurately. Frequent accident types can be derived using a real world accident database. Dependencies between accident types, vehicle classes and resulting repair costs can help to understand the natural occurrence of real world damage cases. Ultimately, damaged vehicle parts can be identified and an investigation regarding high risk parts in respect to certain accident types and vehicle classes can be done. A better knowledge of high risk vehicle parts and a better understanding of accident types in relation to the vehicle classes in combination with an accurate method to determine repair costs due to various material choices will increase the quality of vehicle damage risk evaluations. Using these retrospectively determined vehicle damage evaluations, test scenarios can be designed. Test scenarios can help to reconstruct relevant accident types and situations to validate current vehicle damage data and to derive the damage behavior of new vehicle classes prospectively. This approach can also be used to determine ADAS efficiencies, as the prevention and the mitigation of accidents may be quantified by means of ADAS.

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Feig (corresponding author) designed and adopted the concept of the damage unit model in order to evaluate the vehicle risk for low speed accidents and proposed a method for relevant test scenarios.

Dr.-Ing. Gschwendtner contributed to literature review, methods and data sources. He supported and revised the results and manuscript critically.

Schatz contributed to the discussion and conclusion of this paper and is working within the research project. He also revised the manuscript critically.

Dr.-Ing. Diermeyer contributed essentially to the conception of the research project. He revised the manuscript critically for important intellectual content. Dr.-Ing. Diermeyer gave final approval of the version to be published and agrees for all aspects of the work. As a guarantor, he accepts responsibility for the overall integrity of the manuscript.

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