

An Approach for the Development and the Validation of Generic Simulation Models for Crash-Compatibility Investigations

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ABSTRACT

Global emission targets and high fuel costs encourage manufacturers to produce ultralight vehicles. This and the low range of electric cars have resulted in new vehicle concepts and reuse of the quadricycles classification for microcars in Europe.

Because of their lightweight and small size, microcars face crash-compatibility problems in car-to-car collisions, which are not considered in current safety assessment approaches. Therefore, new assessment approaches must be developed for crash-compatibility of microcars, whereupon a common method is using generic simulation models to avoid test dependencies on special vehicle models.

In this study, an approach for development and validation of generic simulation models for compatibility investigations of microcars is introduced. This approach defines minimal requirements for reliable application of generic simulation models in crashworthiness studies.

Two groups of requirements are defined for the generic vehicle model: conceptual requirements for representability of the generic model for microcars and safety requirements for the generic model to have an adequate safety level. Based on these requirements and relying on the vehicle concepts developed within the projects Mute and Visio.M, a generic simulation model is developed. The model is verified regarding geometry generation, mesh quality, contact stability, energy balance and time step issues. Using real crash test data from NHTSA database, typical crash behavior of light passenger cars is driven for occupant load criterion, intrusions and crash pulse in both full-width and offset tests. The generic simulation model is validated with these criteria. Finally, model robustness is demonstrated by additional test scenarios.

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1. INTRODUCTION

Microcars are small vehicles that are classified as heavy quadricycles in Europe. Challenging emission targets and high fuel costs (or low capacity of the battery for electric vehicles) encourage manufacturers to reuse this car classification for ultra-light passenger cars in Europe.



Figure 1. Car-to-car collision, SUV vs. Microcar [2]

Microcars face crash-compatibility problems in car-to-car collisions with larger vehicles due to their lightweight and small size. According to European vehicle market statistics [1], the market share has increased in opposite extremes relative to values of 2001. This increase of both minicars and off-road vehicles (SUV) is a warning

for more incompatible collisions in the future. The situation is further exacerbated as there are still no safety regulations that consider the special requirements for efficient, ultralight microcars.

In recent years, several assessment approaches have been proposed for crash-compatibility and safety of microcars [3], [4], [5], [6] and [7]. To study these approaches and calibrate test parameters, some microcar models should be simulated or crashed in different scenarios. However, due to the lack of necessary safety regulations, current microcar models provide a much lower safety level than regular passenger cars [8]. Therefore, using current microcar models for investigation and calibration of the proposed assessment approaches would result in inadequate safety level for this car segment in the future.

The development of a generic simulation model of microcars is essential for crash-compatibility investigations. Generic in this case is defined by a vehicle model that is not a model for prototypical vehicle, instead represents typical properties for the desired car classification in the intended application. Generic simulation models are particularly necessary for crash-compatibility investigations to avoid test dependencies on special vehicle models.

The novelty of this work is the investigation of an approach for the development and the validation of a reliable generic simulation model. The developed generic simulation models with this approach fulfill some minimum standards. Therefore, it is hoped that the use of them for crashworthiness studies becomes more reliable.

2. CRASH-COMPATIBILITY INVESTIGATIONS

This section explains intended applications and objectives of the development of a generic simulation model.

A study of current test approaches [4], identified a test concept with a moving deformable barrier, representing the larger adversarial vehicle as having the highest potential for the assessment of crash-compatibility of microcars. This has been confirmed the results of [5], [9]. However, these studies show no agreement on type of the deformable barrier, assessment metrics and other test parameters like the barrier weight, offset value and test velocity.

Generally, two barrier concepts are proposed in the community: Advanced European Mobile Deformable Barrier and variations of Progressive Deformable Barrier [5], [7]. The first step to find the most proper barrier is conducting a sensitivity analysis for the most important compatibility parameters: compartment strength, restraint systems and structural interactions. If a barrier is sensitive to variations of these compatibility parameters, then it will be tested if the relevant metrics can assess the crash-compatibility properly. For both of these analyses, generic simulation models of microcars are necessary.

After finding the most proper barrier, other test parameters should be calibrated. Barrier weight, collision speed and offset-value will be set to represent the severity of car-to-car collisions in the reality. Therefore, a generic simulation model is necessary, which represents a regular safety level for microcars.

Finally, the developed assessment approach should be validated with a generic simulation model. For that, the generic model will be optimized for the developed assessment approach and its crash performance will be analyzed in different car-to-car collisions. The proposed assessment approach is validated, if the optimized model has a better crash performance than the original model in the studied crash scenarios.

3. REQUIREMENTS OF THE GENERIC MODEL

To assure the representability of the simulation model for microcars, some requirements are defined. The requirements are classified into two groups: requirements for the vehicle concept and passive safety requirements.

3.1. Vehicle Concept

The concept of microcar can be registered in different approval classes. This study focuses on microcars in terms of heavy Quadricycles (L7e) in Europe. Furthermore, it is considered that the vehicle concept of the generic simulation model should be compatible with a range of other car classifications:

- proposed class M0 from VDI for safe microcars [10]
- low-speed vehicles (LSV) in USA [11]
- Japanese Minicars (Kei-cars) [12]

The vehicle concept of the generic simulation model should represent a typical microcar. According to [13], microcars are designed as commuter vehicles and normally the second vehicle of a family. These vehicles are intended for urban areas and the limited net power restricts their use on highways. Electro microcars have a limited range of about 100 km and, therefore, are not proper for long-distance commuters.

Vehicle concept of the generic model is based on projects MUTE and its successor Visio.M [14], [15] to assure the consistency of the generic model and prevents unrealistic designs. The Visio.M vehicle is an electric car developed by a consortium containing 16 industrial, governmental and academic partners. The objective of the safety task force within the Visio.M project, funded by German Federal Ministry of Education and Research, was to draft, implement, and test a concept that resolves the conflicting interests and provides sufficient protection for ultra-compact vehicles [16]. Table 1 summarizes some technical information of the vehicle concept with some slight changes to Visio.M to be compatible with further car classifications.

Table 1. Technical information of the generic vehicle concept

Registration class	Europe: L7e heavy quadricycle or M0 USA: low-speed vehicle Japan: Kei-cars
Power	Net power ≤ 15 kW
Curb weight	≤ 450 kg without batteries
No. Seats	2
Powertrain	Electric & rear-wheel drive
Top Speed	120 km/h (40 km/h for low-speed-vehicles)
Range	150 km (NEDZ)
Energy Storage	Lithium-ion battery, Capacity 13.5 kWh
Wheel base	2100 mm

3.2. Passive Safety Requirements

To have a generic simulation model with adequate safety level, all relevant passive safety requirements for registration classes of Table 1 should be considered.

In Europe, the passive safety requirements for L7e are limited to stipulating three-point seatbelts for all seats including the location of the effective anchorage points to the H-point [17]. No requirements for performance of the vehicle in a crash are established. However, Euro-NCAP defined a test scenario for heavy quadricycles to require a regular safety level of normal passenger cars. According to this test protocol [6], the vehicle should be tested against a deformable barrier (FWDB) at 50 km/h. In the United States,

low-speed vehicles are regulated under the safety standard FMVSS500. In terms of passive safety, the vehicle equipment required by the FMVSS500 standard is a Type 1 (lap belt) or Type 2 (lap and harness belts) seat belt assembly conforming to Sec. 571.209, Federal Motor Vehicle Safety Standard No. 209 [18]. In both Japan and Australia, microcars are not identified as a particular case and approval requirements are those of upper categories, and are, thus, more demanding [18]. The tests consist of the full-width rigid barrier (FWRB) test at 50 km/h, the offset deformable barrier (ODB) test at 56 km/h, and the side impact test at 50 km/h. In all of the aforementioned tests, dummy measurements and door opening after the crash decide about the crash performance of the test vehicles.

The generic simulation model should have an acceptable crash performance in all of these tests to be representative for microcars with regular safety level of passenger cars. The dummy injuries depend on restraint systems and their specifications. However, crash performance of a generic simulation model should be decoupled from the performance of a specific restraint system. Therefore, occupant load criterion (OLC) [19] and intrusions in the compartment are considered as criteria for crash performance analysis of the generic simulation model in frontal impact tests. Generally, a car with low OLC values and intrusions can protect the occupants from injuries with the help of proper restraint systems.

According to [19], an OLC limit of 42 restricts head injuries for occupants to be under the determined limit in frontal impact test protocols. Therefore, OLC values less than 42 are considered as an acceptable crash performance in frontal impacts. According to [20], intrusion on A-pillar should be less than 50 mm to assure the compartment strength, which avoids injuries due to direct contacts with intrusions. Therefore, intrusions less than 50 mm on A-pillar are considered as an acceptable crash performance in frontal impacts. Table 2 summarizes the test scenarios and their relevant criteria for the passive safety requirements of the generic simulation model.

Table 2. Passive safety requirements for the generic simulation model

#	Test Scenarios	Criteria
1	Full-Width Rigid Barrier (FWRB) at 50 km/h	OLC < 42 Intrusions on A-Pillar < 50 mm
2	Offset deformable barrier (ODB) at 56 km/h	
3	Full-width-deformable-barrier (FWDB) at 50 km/h	

4. DEVELOPMENT OF THE MODEL

The basis of this generic model for microcars is the Lightweight Extruded Aluminum Frame (LEAF) developed by [21] within the framework of the projects MUTE, Visio.M and Transregio 10 [22] to serve as an parameterized demonstrator for structural design optimization. Both type and material of the selected frame are representative for microcars:

- A space frame body is economic for small series vehicles due to the lower tool costs and is used in many microcar models like Renault Twizy, Buddy electric, Aixam eCity, CLEVER, VW Nils, etc.

- Aluminum is a lightweight material, which is common for the frame of modern light vehicles. Use of fiber-reinforced polymer is not proper for a generic simulation model. On the one side, these composites are expensive and their production costs cannot be justified for microcars. On the other side, simulation tools are generally not mature enough to represent the behavior of models using fiber-reinforced materials in crash simulations.

The development of the model is done in two steps: development of the space frame and assembling of other components to the space frame.

4.1. Development of the Crash Structure: LEAF

The requirements of a vehicular structure stem from multiple disciplines. Economical and manufacturing aspects lead to the decision of an aluminum space frame of readily available materials and cross-sections. As the designated vehicle class requires a maximum mass of 450 kg, lightweight design is critical. The foremost structural-mechanical requirements are those related to passive safety. These include the consideration of frontal impact (100% and 40% offset), side impact, rear impact and roof crush load cases. Beyond these load cases, driving comfort and handling put requirements on static and dynamic stiffnesses. General chassis loads set further strength requirements.

As a first step to the development, topology optimization was used with quasi-static replacement loads representing the impact loads. This resulted in information to where the most efficient load paths through the design domain are located (Figure 2). From the result of the topology optimization, a space frame Lightweight Extruded Aluminum Frame (LEAF) was conceptualized (Figure 3). For more details on the development process see [21].

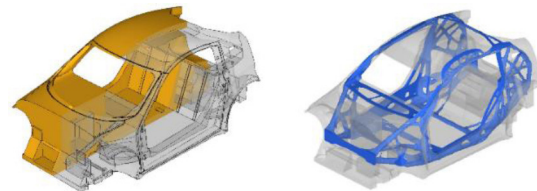


Figure 2. Design domain and results for the topology optimization [23]

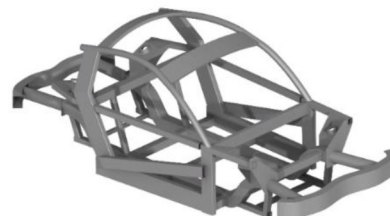


Figure 3. The concept LEAF [21]

As shown in Figure 4, the structure is divided into four functional assemblies:

- The floor assembly provides a stiff basis structure for static and dynamic stiffness as well as the occupant safety cell.