

Analysis of Fuel Cell Vehicles Equipped with Compressed Hydrogen Storage Systems from a Road Accident Safety Perspective

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ABSTRACT

The potential impact of real world accident scenarios on fuel cell vehicles equipped with a compressed hydrogen storage system is analyzed from a component point of view. Even though hydrogen compressed gas tanks can sustain very high loads, in this study a simplification is made. It is investigated to what extent different real world accident scenarios with conventional vehicles have caused deformation of the vehicle in the area where a hydrogen tank would have been integrated in a fuel cell vehicle. The study is based on accident data from the GIDAS (German In-Depth Accident Study) database. Deformation matrices for each passenger car in the database are defined over a deformation grid largely independent of vehicle type and shape. The matrices are combined to statistically analyze the occurrence of deformations in selected regions of a vehicle. The concept of cumulative frequencies is extended to two dimensional deformation matrices defined over a set of accident cases and

a new algorithm is applied to calculate the cumulative frequency matrix which is discussed for the GIDAS sample. In addition, accidents which resulted in an intrusion up to an area where the compressed gas tank would likely be located are further investigated with respect to the situation in which they happened.

INTRODUCTION

Due to the rising importance of vehicles with alternative propulsion systems ([Figure 1](#)), fuel cell vehicles using gaseous hydrogen as a fuel gain in importance and can potentially replace all vehicles with internal combustion engines. For fuel cell vehicles, common storage technology of the hydrogen fuel is a compressed storage system with pressures as high as 70MPa. Many safety aspects of the hydrogen technology have been discussed in great detail, from fueling to day-to-day usage. This study will examine

one aspect of the crashworthiness of fuel cell vehicles in real world crashes.

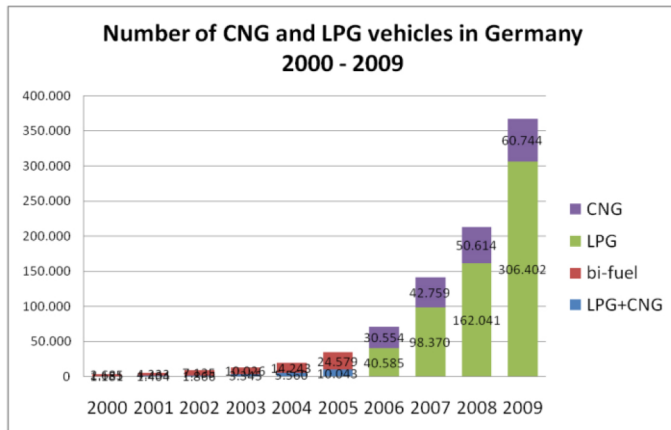


Figure 1. Number of registered gas-powered vehicles by year in Germany, source: Federal Motor Transport Authority (Kraftfahrt-Bundesamt KBA).

Historically, a great part of crashworthiness analysis has focused on vehicle structure and safety systems to protect occupants in a crash. While occupant protection remains important, an additional area of focus for fuel cell vehicles is protection of components such as high voltage batteries and compressed gas tanks. As these components can sustain very high loads, the focus of research questions shift to new accident situations and there is a need for new methods and tools. We have developed the concept of deformation matrices which can be used to analyze the spatial occurrence of deformations by postprocessing real world accident data. Due to low market share, only few accidents with compressed gas tanks are known. To extend the data source and to take real world experience of accidents into account, we assume that all vehicles of an accident sample with conventional vehicles are equipped with compressed hydrogen tanks. Under this assumption, the impact of potential real life accident scenarios on vehicles equipped with compressed hydrogen gas tanks can be investigated.

Vehicle integration of compressed gas fuel tanks is important. In a specific crash, the performance of the fuel system is in part affected by the chosen location within the structure. For the placement of compressed gas tanks in a vehicle, several concepts and strategies are available. Especially in aftermarket solutions there is a great variation of tank placements, be it under-floor, low-floor, in the trunk, behind or in front of the rear axle. For our analysis, we have focused on integration concepts of compressed hydrogen gas tanks as they are currently realized by GM/Opel and Daimler. However, future integration concepts are possible that deviate from the vehicle location investigated in this analysis.

DATA SOURCE

The analysis in this paper is based on accident data provided by the GIDAS (“German In-Depth Accident Study”) project. GIDAS is a cooperative research project of the Research Association for Automotive Technology (Forschungsvereinigung Automobiltechnik e.V., FAT) and the Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BAST) (see [3,4] for more details). It was founded in 1999. Since then, in-depth documentations of accident data for more than 2000 accidents per year have been collected in two research areas - the areas surrounding Hanover and Dresden (Fig. 2). For an assessment of an accident by the GIDAS team, the following criteria must apply: (1) The accident happened on public roads, (2) the accident happened in one of the research areas, (3) the accident had occurred when a team was on duty in a defined time frame, and (4) at least one person was injured in the accident, regardless of severity (see [5] for more details).

Depending on the type of accident, each case is described by a total of 500 to 3,000 variables, containing for example, accident type and environmental conditions (the type of road, number of lanes, width, surface, weather conditions, time of the day,...), surroundings of the accident scene, vehicle type, vehicle specifications (mass, power, tires, ...) and configurations (primary and secondary safety measures), documentation of damage on the vehicles, injury and medical treatment data for all persons involved. The investigation of all cases is “on the spot” to ensure the best visibility of traces for the best possible reconstruction. Each accident is reconstructed in detail including the pre-collision-phase. Available information includes initial vehicle and collision impact speed, deceleration as well as the speed sequence of the collision. The great advantage of this database is that: (1) the number of cases is high enough to provide statistically significant results, (2) each accident is documented in great detail, including in-depth analyses and reconstructions of the course of the accidents including the pre-crash phase, and (3) most of this database is confirmed to be representative for German National Accident Statistics.

The following study is based on a sample of the GIDAS data from the years 1999 - 2007 containing 16,102 accidents and 28,592 vehicles. Basically, all passenger cars with the necessary information available were selected. In detail, the selection criteria are shown in Figure 3. The resulting data set consists of 8,612 passenger cars.

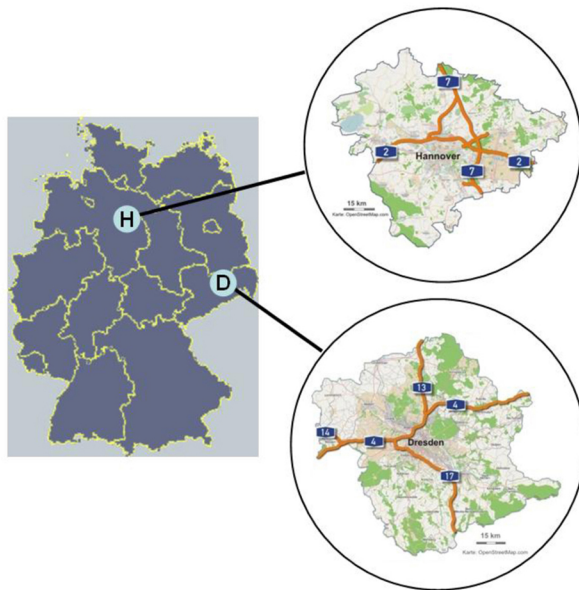


Figure 2. Investigation areas of the GIDAS project are the surroundings of Hanover and Dresden.

Despite GIDAS being representative compared to the federal statistics, there are situations where it is recommended to apply weighting factors to the data. This is due to the fact, that some variables may be biased compared to the corresponding variables in the federal statistic. When it comes to the maximum injury severity of an accident, GIDAS tends to contain slightly more severe accidents than the federal statistic. Focusing on very severe accidents in the further analysis the end result will be more accurate though the difference between weighted and non-weighted data is not very big.

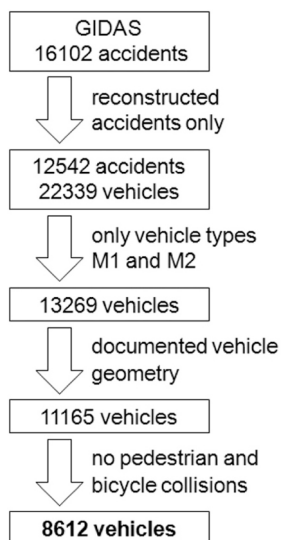


Figure 3. Selection criteria for the GIDAS data sample used for the deformation analysis.

METHODOLOGY

ASSUMPTIONS

As we want to study the possible impact of the use of hydrogen tanks in the car fleet in a variety of real world crash scenarios, our first assumption is that all 8,612 passenger cars in the data sample were equipped with a hydrogen tank. Furthermore, a categorization of the different shapes in the car fleet is needed to be able to compare deformation characteristics between different car types. The deformation characteristics depend strongly on the stiff parts of the vehicle. So, placement of the axles and length of front end and body rear end play an important role. Therefore, the data sample is divided into four categories of car shapes which are shown in Figure 4.

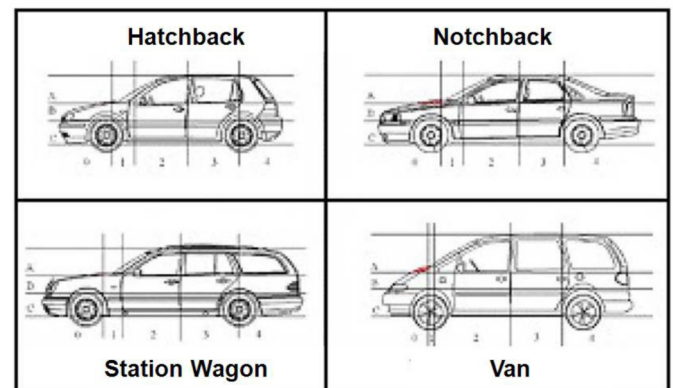


Figure 4. The data sample is divided into four categories of car shapes.

DEFORMATION GRID AND DEFORMATION MATRIX

The GIDAS data sample contains information on the maximum deformation in different zones of each vehicle. The number of the zones differs in each spatial direction: in x-direction the vehicle is divided into five zones, in y-direction into four zones, and in z-direction into three zones. The layout of the zones is shown in Figure 5. As the current hydrogen tank concepts place the tank in the under-floor, only the lowest zone in z-direction is evaluated. This zone covers the region from lower edge of the door sill up to half the height of the door. Therefore the deformation characteristic of each vehicle can be reduced from a three-dimensional geometry to a two-dimensional grid.

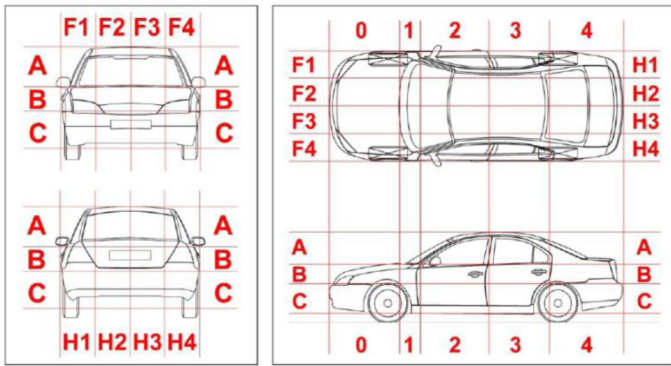


Figure 5. GIDAS deformation zones

Based on the points of maximum deformation in each zone, a deformation characteristic for each vehicle is derived. This is accomplished by linear interpolation of points of maximum deformation, as shown in Figure 6.

The vehicle is divided at the axles into the three sections: car front, passenger cell, car back. Because of differing length proportions of the sections between car models, cell sizes differ from section to section and from shape to shape.

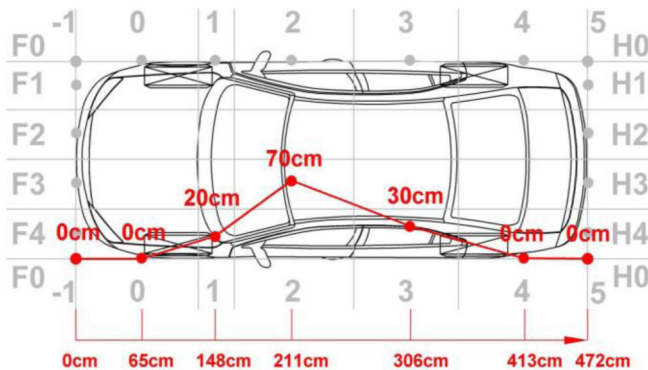


Figure 6. Vehicle deformation characteristics expressed as the linear interpolation of points of maximum deformation in each deformation zone.

However, the position of the axles in the grid formed by these cells and the cell count in x and y (and thus the overall cell count) is fixed for all vehicles: 121 cells in x-direction and 40 cells in y-direction. The grid and the position of the axles are shown in Figure 7. Marking each cell covered by the deformed area with 1 and all non-deformed cells with 0, the resulting matrix is denoted the “deformation matrix” of a vehicle. The deformation matrix spans a discrete coordinate system in the outline of the vehicle, where each cell can be geometrically addressed within the vehicle and has a comparable location in different vehicles with respect to the reference points, independent of the vehicle's shape.

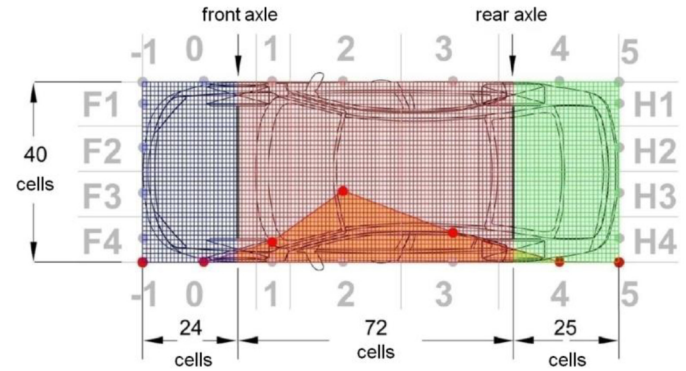


Figure 7. vehicle independent grid and one deformation matrix.

CELL FREQUENCY MATRIX

The deformation matrix of one vehicle is a binary matrix, that is, every cell contains either the value 0 or 1. When taking a set of vehicles in account, for example the whole GIDAS data sample, the binary matrices of each vehicle in the set can be combined into a frequency matrix. This is simply accomplished by adding the values of the cells with the same coordinates over all matrices in the set. Each cell of the resulting frequency matrix is mapped to the number of cars whose structure was deformed up to or beyond the geometric location of the cell. Figure 8 illustrates the calculation of the frequency matrix by assigning different colors to different frequencies. On the left side, top views of the deformed vehicles in the accident can be seen. The corresponding deformation characteristics are shown in the middle.

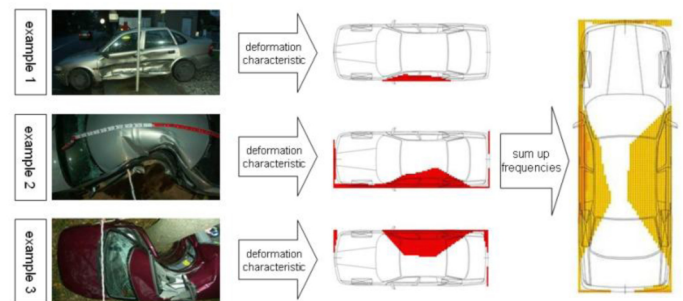


Figure 8. Calculating the cell frequency from the deformation characteristic of several vehicles.

Applied to the whole data set, the resulting cell frequency matrix is shown in Figure 9. The frequencies are mapped to a heat color spectrum with red for the highest frequency and light blue for the lowest frequency. Some basic observations are: