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# Experimental investigation of consequences of LPG vehicle tank failure under fire conditions

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ABSTRACT

In case of a vehicle fire, an installed LPG (liquefied petroleum gas) tank with a malfunctioning safety device poses severe hazards. To investigate the consequences in case of tank failure, we conducted 16 tests with toroidal shaped LPG vehicle tanks. Three tanks were used for a Hydraulic Burst Test under standard conditions. Another three tanks were equipped with a statutory safety device and were subjected to a gasoline pool fire. The safety device prevented tank failure, as intended. To generate a statistically valid dataset on tank failure, ten tanks without safety devices were exposed to a gasoline pool fire. Five tanks were filled to a level of 20%; the remaining five were filled to a level of 100%. In order to gain information on the heating process, three temperature readings at the tank surface, and three nearby flame temperatures were recorded. At distances of $l = (7; 9; 11)$ m to the tank, the overpressure of the shock wave induced by the tank failure and the unsteady temperatures were measured. All ten tanks failed within a time of $t < 5$ min in a BLEVE (boiling liquid expanding vapor explosion). Seven of these resulted directly in a catastrophic failure. The other three resulted in partial failure followed by catastrophic failure. A near field overpressure at a distance of $l = 7$ m of up to $p = 0.27$ bar was measured. All ten tests showed massive fragmentation of the tank mantle. In total, 50 fragments were found. These 50 fragments make-up 88.6% of the original tank mass. Each fragment was georeferenced and weighed. Fragment throwing distances of $l > 250$ m occurred. For the tanks with a fill level of 20%, the average number of fragments was twice as high as it was for the tanks that were filled completely.

## 1. Introduction

### 1.1. LPG as fuel for vehicles

Most vehicles in the world use conventional fuels like gasoline and diesel fuel. A variety of alternative propulsion systems also exists. One of the most widely used alternative fuels is liquefied petroleum gas (LPG) (Heidt et al., 2013). The percentage of LPG-powered vehicles differs greatly between countries. For example, nations with a high amount of LPG-powered passenger vehicles in 2016 were South Korea (2.2M, 10%), Poland (3.0M, 14%) and Turkey (4.4M, 40%) (World LPG Association, 2015). In contrast, the percentage in countries like Germany (0.48M, 1.1%) (German Federal Motor Transport Authority, 2016), UK (0.12M, 0.4%) and USA (0.16M, 0.1%) is much lower (World LPG Association, 2015).

There are three different types of LPG-powered vehicles. The first type includes new vehicles with a gaseous propulsion system, ex works. The second type comprises of Bi-fuel vehicles with gasoline and LPG. The last type is comprised of vehicles with converted gasoline-to-LPG propulsion systems. Requirements on fire risk prevention of vehicles are set-out in the UN-ECE R34. However, this regulation only covers systems with a tank suited for liquid fuels (UN-ECE R34, 2015). Regulations concerning LPG retrofit systems are set-out in the UN-ECE R115. This regulation covers mainly system specifications and instruction manuals (UN-ECE R115, 2013). Requirements regarding the approval of equipment of LPG vehicles are part of the UN-ECE R67. This regulation includes a specific test that deals with the fire resistance of the tank and the correct functionality of the PRD (pressure-relief device). For the test, the tank must be completely filled. This corresponds to a fill level of 80%. The tank must be installed horizontally and centrally at $h = 0.1$ m above the fire source. There are no specifications pertaining to fuel type of the fire source. It is only specified that the heat

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**Nomenclature**

*Symbol*

| | |
|---|---|
| A | Area ($m^2$) |
| *D* | diameter (mm, cm, m) |
| d | distance (cm, m) |
| f | frequency (Hz, fps) |
| h | height (m) |
| l | length (cm, m) |
| m | mass (kg) |
| p | pressure (bar) |
| r | radius (m) |
| t | time (s, ms, min) |
| T | temperature (°C) |
| v | velocity (m/s) |
| V | Volume ($dm^3$) |

*Greek*

| | |
|---|---|
| ρ | density ($kg/m^3$) |
| Δ | difference |

*Subscripts*

| | |
|---|---|
| a | ambient |
| c | critical |
| m | mean |
| max | maximum |

impact must be homogeneous at the tank surface over a length of l = 1.65 m, and that a temperature of at least T ≥ 590 °C after t = 300 s at the tank bottom surface must be assured. During a fire test, the inner tank pressure and two temperature points at the tank bottom surface must be measured. The fire test is considered successful, if the PRD is activated and the pressure decrease leads to a safe state of the tank. The test fails if the tank bursts, if the inner pressure increases to p ≥ 37.0 bar or if the tank starts to deform (UN-ECE R67, 2014). In conclusion, the task of this fire test is only the accurate behavior of the PRD. The bursting of the tank is only a shut-off criterion. Investigations regarding the consequences of a tank failure, for example as a result of a faulty PRD, are not part of this test procedure.

### 1.2. Traffic accidents and vehicle fires with LPG-powered vehicles

Malfunction of a PRD can be, for example, due to a vehicle collision. One of the world's most extensive accident studies was conducted in Germany by GIDAS (German In-Depth Accident Study). Since 1999, all traffic accidents with casualties in two, representative German model regions (Hannover, Dresden) were investigated on-scene. Statistics were then collated in a database (Hannawald et al., 2012). Table 1 shows the total number of accidents listed in the GIDAS database, and the number of accidents involving LPG-powered vehicles for the years 2011–2014. In Germany, approximately 1% of all traffic accidents involved LPG-powered vehicles. It is expected that the total number of traffic accidents involving LPG vehicles is higher in countries with a larger proportion of LPG vehicles (e.g., South Korea, Turkey (World LPG Association, 2015)).

A drastic example of such an accident happened in Germany, in 2014, where an LPG-powered car crashed into a tree. Upon crashing, the car started to burn. The driver was trapped and died. Shortly after the beginning of the firefighting operations, the tank failed. Ten firefighters were injured, five severely. The main fragment of the LPG tank was thrown over l = 30 m (Rixen, 2014a). The damage to the car after the fire and the tank failure is shown in Fig. 1.

Another possible reason for an LPG tank failure is a vehicle fire in conjunction with a faulty PRD, without a crash. The PRD could be faulty from the outset, or it could be a PRD that has not been sufficiently sized for the extent of the fire. In 2015, a passenger car started to burn in Davoren Park, a suburb of Adelaide, Australia. Once the car had burned completely, the tank failed. The throwing distance of the fragments was reported to be l = 200 m. The driver suffered burns, another person was injured by a fragment (Dowdell, 2015). Another exemplary accident happened in 2012 on a German motorway near Warburg, North Rhine-Westphalia. A passenger car started to burn, and the tank failed before the fire service arrived on-site. (Fire Department Warburg, 2012a). The car was seriously damaged, but the tank was located in the position at which it was originally mounted. (cf. Fig. 2).

The presented statistics and examples show that it is important for fire fighters and rescue services to understand the consequences of LPG-powered vehicles being involved in traffic accidents and/or fires. The German Fire Service Regulation 500 (Regulations for Fire Services at CBRN/Hazmat Operations) only outlines precautions and control measures for larger tanks (e.g., rail cars, industrial tanks). In this regulation, the danger zone is given as r = 300 m, the shut-off zone as r = 1000 m (AFKvZ, 2012). A consultative document from the German Fire Protection Association (ger.: vfdb) regarding hazards resulting from LPG define the necessary minimum safe distance for fire fighters in the case of a fire as l = 25 m (German Fire Protection Association, 2013). The related Fire and Rescue Manual in UK recommends only a safety distance of l = 20 m in case of a flame from a responsive PRV (pressure relief valve). Furthermore, there is only the comment that fragments can be thrown over a distance of up to l = 200 m (HM Fire Service Inspectorate, 2007). A somewhat detailed description on LPG tanks that are involved in a fire was produced by the ERAFV (The Emergency Response Guide to alternative Fuel Vehicles) of the California Department of Forestry and Fire Protection. If a tank is involved in a fire, the aim is to extinguish the fire from a maximum distance. After the fire is extinguished, the tank must be cooled down. In case of a massive fire, it must be checked whether or not unmanned hose holders or monitor nozzles may be used (Stover et al., 2009). Safety distances are not given in the ERAFV. For this, the ERG (Emergency Response Guidebook) is referenced. The evacuation radius is given as r = 1600 m if a tank, a rail car or a tank truck is involved in a fire (United States Department of Transportation, 2016).

**Table 1**
Extrapolated number of traffic accidents with casualties involving an LPG-powered vehicle.

| No. | Year | 2011 | 2012 | 2013 | 2014 | Ref. |
|---|---|---|---|---|---|---|
| 1 | Total number of traffic accident listed in GIDAS | 1974 | 1768 | 1325 | 1068 | GIDAS, 2016 |
| 2 | Number of accidents involving a LPG-powered vehicle listed in GIDAS | 25 | 16 | 11 | 14 | GIDAS, 2016 |
| 3 | Percentage accidents involving LPG-powered vehicles (2) of the total number of accident listed in GIDAS (1) | 1.27% | 0.91% | 0.83% | 1.31% | – |
| 4 | Total number of traffic accidents with casualties in Germany | 306266 | 299637 | 291105 | 302435 | Destatis, 2017 |
| 5 | Extrapolation of accidents involving LPG-powered vehicles (3) on the total number of traffic accident (4) | 3890 | 2727 | 2416 | 3962 | – |