

Crash Test with a Hot Operating Engine and R-1234yf MAC System

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ABSTRACT

As part of the launch of the refrigerant R-1234yf there were a number of studies done regarding the ignition behavior of this new refrigerant in passenger cars. These tests were conducted by a number of automobile manufacturers, component suppliers, and the refrigerant supplier under laboratory conditions at the component and vehicle level. In November 2009 the international automotive industry concluded that the R-1234yf can be used safely in automotive air conditioning systems.

Further tests were conducted by different automobile manufacturers, suppliers, and the refrigerant supplier under various laboratory and vehicle operation conditions means hot surfaces in the engine compartment. A number of vehicle manufactures have conducted full vehicle crash tests.

In this paper, real world accidents are analyzed using the German In-Depth Accident Study (GIDAS) database as well as the thermal parameters for ignition of R-1234yf, i.e. concentration and surface temperature to create a worst-case scenario. These parameters were considered while conducting a frontal impact test with a hot 1.4 liter turbo gasoline engine with a critical overheated exhaust surface temperature and an operating R-1234yf Mobile Air Conditioning (MAC) system. The test was conducted with an ECE R95 deformable moving barrier at a test speed of 50kph.

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INTRODUCTION

The European Commission (EC) as well as the United States Environmental Protection Agency (EPA) published legislation to regulate or encourage the use of low Global Warming Potential (GWP) refrigerants in Mobile Air Conditioning (MAC) systems. In Europe, direct and indirect emissions relating to MAC systems were regulated in Directive 2006/40/EC and Directive 70/156/EEC. Europe mandates a GWP less than 150 for MAC refrigerants in new vehicle types from 01.01.2011 and for new vehicle registrations from 01.01.2017. R-1234yf is a refrigerant that fulfills these legal requirement, with a GWP significantly lower compared to R134a refrigerant currently used in most vehicle MAC systems.

Although basic material data shows that R-1234yf is a potentially flammable gas, the international automotive industry concluded in 2009 that R-1234yf can be used safely in automotive air conditioning systems. Tests were conducted by a number of automobile manufacturers, suppliers, and the refrigerant supplier under various laboratory and vehicle operation conditions. Further a number of vehicle manufactures have conducted additional research to evaluate the risk of vehicle fire with R-1234yf.

This paper will focus on possible under-hood hot surface ignition behavior in the event of a simulated frontal crash. In a frontal crash the MAC system may be damaged, resulting in leakage of the mixture of R-1234yf and Polyalkylene Glycol (PAG) oil into the hot under-hood area, which could be ignited. Therefore a frontal crash test was performed with a production vehicle using R-1234yf/PAG. The same crash test was then repeated with a second vehicle of the same type to confirm the result. The vehicle was equipped with a transverse gasoline engine, front take down exhaust routing, turbocharger, and single evaporator MAC system. The hot surface temperatures used at the impact were artificially increased through a modified engine calibration. The temperature selected was chosen based on vehicle testing at max speed as well as laboratory hot surface ignition tests of R-1234yf.

This hot crash test configuration is more representative of a real world scenario than the laboratory or vehicle tests without any frontal impact based dynamics or deformation of the vehicle. Other crash test scenarios using a different approach are discussed e.g. in reference [1]. Several vehicle tests were performed with running engines and operating MAC systems and no ignition was observed. The setup of this test was selected to ensure that the critical surface temperature of

710°C [2] was well as exceeded at the time of impact and thus not allowed to cool down during the final collision test preparation.

MAC Package in the Engine Compartment

The A/C system components for these full vehicle crash tests were designed for a compact vehicle and are representative of a broad spectrum of vehicles and performance levels. The vehicles inclusive A/C system used for these crash tests were taken directly from production. The A/C system components were comprised of: a compressor (w/ PAG oil); an evaporator; a condenser with an integrated receiver/dryer and a sub-cooling section; a thermal expansion valve; an internal heat exchanger and plumbing as diagramed in Fig. 1.

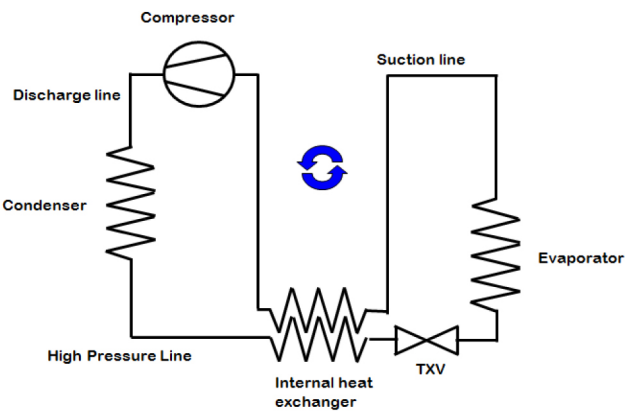


Figure 1. Generic layout of the MAC system.

Due to the position of the condenser in the vehicle front end, see Fig. 2, it may be breached in a frontal collision and the refrigerant may leak e.g. from the damaged condenser into the hot engine compartment. The lines connecting the condenser and compressor may also breach as they are positioned in the crush location of the crash test chosen for this test.



Figure 2. Condenser position in front of the radiator

Refrigerant R-1234yf

The refrigerant used in this vehicle exists as a gas at atmospheric pressure and is considered a pure compound (100% 2,3,3,3-Tetrafluoroprop-1-ene). This medium is classified per its Material Safety Data Sheet as ‘extremely

flammable’ in Europe and as ‘flammable’ in US because it is gaseous at normal ambient temperatures and atmospheric pressures.

The auto-ignition temperature under laboratory conditions is 405°C. The flammability limits have between been reported as 6.85vol-% and 12.00vol-% at 20°C in dry air [3]. UFL and LFL are dependent on the temperature of the fuel air mixture, and slightly dependent on the humidity in the air. At 100°C in dry air, LFL = 5.80vol-% and UFL = 12.70vol-%. [4].

In the case of ignition or thermal breakdown of R1234yf, as with all fluorinated molecules, decomposition products may include hydrogen fluoride.

Ignition Conditions

There are many possible vehicle driving conditions but very few pose a risk for refrigerant ignition. In general, there are the following relevant ignition parameters:

- Flammable substance => refrigerant/PAG oil within flammable range for mixture
- Heat => exhaust surface temperature
- Oxygen

Table 1. Parameters for ignition and potential fire

Parameter	Relation
Refrigerant concentration	Refrigerant leakage
	Release pressure
	Free space volume
	Engine design and packaging
Surface temperature	Driving scenario
	Engine design and packaging
	Ambient air temperature
Oxygen	Engine package
	Free space volume
	Absence of disturbance like air flow or vapor

It may be a significant difference regarding the ignition parameter between a deformed and undeformed engine compartment. Free space volume near the hot surface depends on the location, shape and deformability of the impacting surface and the impact speed. The deformation of the vehicle's engine compartment plays a key role in achieving ignition of an R-1234yf/PAG leak. As such, analysis must be done on vehicles in a real world crash event.

GIDAS

The test configuration chosen for this study was selected after analysis of real world information found in one of the largest accident databases. The German In-Depth Accident Study (GIDAS) was founded by the Federal Highway Research Institute (BAST) and the Research Association of Automotive Technology (FAT). It is a database documenting real world accidents with involving injuries that have been studied for more than 10 years. Specifically, accidents are studied and documented in Germany around Hanover by the Hanover Medical School (MHH) and around Dresden by the Traffic Accident Research Dresden (VUFO).

Currently there are over 20,000 different events documented and available for review. Each accident is analyzed regarding impact situation, environment, vehicle, passengers, damage, all in all over 200 parameters are available. The database is sufficient to use for impact reconstruction on new collisions or extensive statistical research.

TEST SETUP

Accident Research

The GIDAS analysis in this study began with specification of relevant vehicle types. It was focused on small SUVs and small MPVs as well as small and compact cars with comparable front end packages.

In a second step, the free space for possible ignition was transformed into the GIDAS parameters of frontal collision overlap and grade. Collision vehicles were identified using the picture archive to sort for serious damage and leakage of the MAC system. These vehicles were then analyzed for collision type, overlap and relative impact speed to establish a laboratory crash test condition and configuration.

The final conclusion regarding the critical ignition parameters identified a test speed range of 40kph to 50kph depending on the type of impact barrier (rigid or deformable). It was also confirmed that an overlap of 40% with a deformable barrier simulates the most frequent type of frontal impact configuration. This result was not surprising as GIDAS statistics were used to confirm the current European legal crash requirements for occupant safety.

Feasible Crash Test Configuration

The resulting choice was a 40% overlap - 0° frontal impact with a deformable barrier (ODB). This barrier is identical to the European Union (EU) legally mandated deformable barrier for occupant safety crash tests and is representative of a wide variety of consumer vehicles. This was in line with another different study executed by the Kraftfahrtbundesamt (KBA) [5]. In this study it was used this configuration with a test speed of 40 kph with four vehicles, but it was not sure that a leak at the MAC system will be occurred.

To generate a leakage in the MAC system and to avoid a decrease in temperatures of the engine compartment, turbocharger, and exhaust surface during the impact event, further it was decided to use a moving barrier according to ECE R95 and not to run the vehicle against the barrier. The movable deformable barrier (MDB) helps to enable a running engine with operating A/C during the impact and comes closer to a real world crash scenario shown in GIDAS.

The weight of the barrier is adjusted to account for the test vehicle curb weight while considering the comparable impulse of the equipped vehicle.

Table 2. Calculation of test impulse

	ODB test	MDB test
Calculated test weight	1785kg	1411kg
Calculated test speed	40kph	50kph
Calculated impulse	19.8kNs	19.6kNs



Figure 3. Test buildup during final test preparation



Figure 4. Test buildup during final test preparation

Definition of Impact Temperature

The exhaust and turbocharger surface temperature at impact was chosen based on actual extreme driving conditions. The intent was to create a realistic crash scenario which achieves all relevant ignition parameters, even under extreme conditions.

To reach the maximum achievable temperature, the vehicle was driven at max speed. A surface temperature of approximately 805°C was measured at the manifold and 790°C at the turbocharger at 25°C ambient. Afterwards the vehicle was decelerated from max speed to impact speed with the highest possible braking deceleration. In this time the surface temperature decreased to 750°C, which represents the target temperature for the impact.

The targeted overheated surface temperature is significantly higher than the critical temperature of 700°C reported in ref. [2].

VEHICLE PREPARATION

Vehicle Instrumentation

The vehicle was equipped with several accelerometers to evaluate the vehicle crash pulse. Several thermocouples were installed at the turbocharger and exhaust manifold. The thermocouples were attached to the surface, where the hot spots occur under high load conditions. The coolant temperature and the AC high side pressure were also measured. The coolant pressure was measured in a separate test since the pressure sensor is not crash safe.

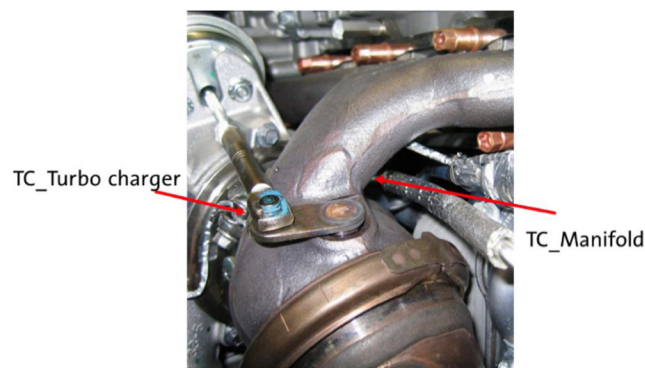


Figure 5. Thermal measurement, thermocouples at exhaust manifold and turbocharger

It is important to identify the hottest surface areas realizing that they can shift under varying engine load conditions. The positions of the thermocouples were chosen according to results obtained in the wind tunnel. Two hot spots were identified by under hood thermal evaluation in a wind tunnel

and shown in Fig. 5. One of the hot spots was identified at the manifold in front of the turbocharger and the other on the turbocharger surface.

The measurement equipment was put into two categories. The crash-safe sensors like the accelerometers were used during the actual test. The thermal measurement equipment was located away from the vehicle to be able to monitor the relevant data prior to impact. The data cables were disconnected automatically after impact.

Additionally there were two onboard cameras mounted in the engine compartment. One was located in the lower area in front of the engine and one in the upper area above the engine block. Both cameras were used to allow for further analysis after the collision (See Fig. 6).

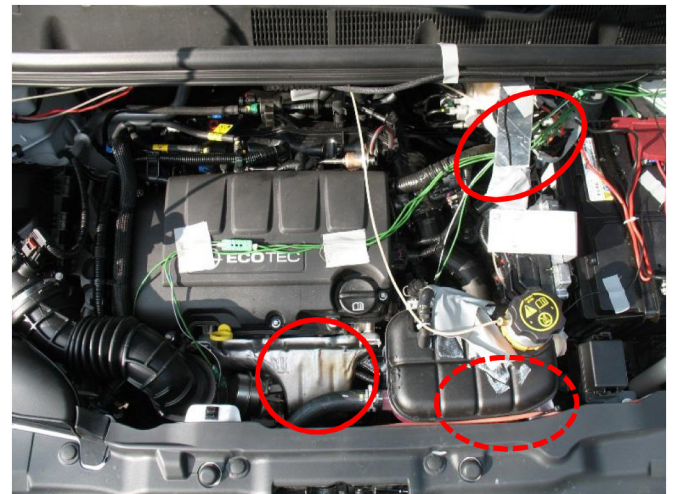


Figure 6. Engine compartment inclusive measurement and onboard cameras

Re-Calibration of Engine Control Unit

The exhaust surface temperature identified above had to be achieved at idle conditions in the crash test lab prior to the collision. To get the required high temperature the Engine Control Unit (ECU) was recalibrated. This recalibration included incomplete combustion and lean air fuel ratios as well as fuel cylinder selection at an increased idle speed. With these modifications it was possible to achieve stable and constantly high surface temperatures during the impact event.

General Remarks

The current NHTSA and EU regulatory crash tests for occupant safety require the removal of vehicle fluids prior to testing because the intent of the testing is to establish vehicle structural integrity and air bag performance under standard conditions.