

Vehicle Hot Surface Ignition and Mitigation Measures of R-1234yf Refrigerant for MAC Systems

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ABSTRACT

The European Commission (EC) as well as the United States Environmental Protection Agency (EPA) published legislations to regulate or encourage the use of low Global Warming Potential (GWP) refrigerants applied to Mobile Air Conditioning (MAC) systems. Europe mandates a GWP less than 150 of MAC refrigerants for new vehicle types. The thermodynamic refrigerant properties of R-1234yf are slightly different from the properties of R-134a, currently used in MAC systems. Although the basic material data show that R-1234yf is flammable, ignition tests performed for an automotive engine under-hood environment reveal design and packaging influences of its ignition behavior. After extensive collaborative research in 2009, the Society of Automotive Engineers Cooperative Research Team (SAE CRP1234) concluded that R-1234yf is suitable for use in automotive applications. Further ignition risk assessment regarding R-1234yf usage in MAC systems was done by SAE CRP1234-4 in 2013. They concluded that "risks are still very small compared to the risks of a vehicle fire from all causes and well below risks that are commonly viewed as acceptable by the general public."

This paper will compare under-hood hot surface ignition behavior of five different vehicles under specific test conditions. Out of these five, two vehicles were further investigated and the engine compartment designs were assessed. A broad range of flammability testing was completed to study release of the R-1234yf and Polyalkylene Glycol (PAG) oil mixture. Both vehicles were equipped with a transverse gas engine, front take down exhaust routing, turbo charger, and single evaporator MAC system. This engine architecture was chosen due to the short distance from a potential condenser leak and the hot exhaust system components in case of a frontal crash. Although the engine architecture was the same for both vehicles, the engine design and packaging were different and were described in this paper. Parameters that were considered include heat shield design, engine packaging, exhaust system surface temperatures during refrigerant release, and the impact on the time to ignition of the R-1234yf/PAG mixture. Mitigation measures were also identified and their potential integration into a vehicle were discussed. As engine coolant will be released in many real-world frontal crash scenarios, the impact of vaporized glycol water mixture on the ignition behavior was assessed. This paper further describes the MAC systems, the test facility used, and the testing procedure applied.

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INTRODUCTION

In recent years, environmentally-friendly vehicles are becoming more and more important to reduce greenhouse gas emissions. 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 Global Warming

Potential (GWP) less than 150 for Mobile Air Conditioning (MAC) refrigerants used in new vehicle types from 01/01/2011 and for new vehicle registrations from 01/01/2017.

The United States Environmental Protection Agency (US EPA) and the National Highway Traffic Safety Administration (NHTSA) have finalized regulations to reduce greenhouse gas emissions in order to reduce global warming. Air conditioning

related credits (13.7 gCO₂/mi for cars) can be earned with the Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards by implementing a low GWP refrigerant in a MAC system [1].

R-1234yf is considered environmentally-friendly due to a significantly reduced GWP compared to the R-134a refrigerant currently used in most vehicle MAC systems.

The thermodynamic properties of R-1234yf are slightly different than the properties of R-134a [2]. This enables a drop-in of the refrigerant without needing to develop new MAC system components (e.g. compressor, lines, heat exchangers). R-1234yf may cause a cooling performance loss of approximately 10%. This performance degradation can be compensated by implementing an internal heat exchanger into the MAC system. As the specific enthalpy difference of R-1234yf is smaller, mass flow must be increased to achieve the same cooling performance [3]. Neither refrigerant provides adequate lubrication to the compressor on its own. Therefore Polyalkylene Glycol (PAG) oil is added to the MAC system. The PAG oil is dispersed in the system circuit and is at least partially dissolved in the R-1234yf.

The main differences of the refrigerant properties of both refrigerants are the Auto Ignition Temperatures (AIT), flammability concentration limits, and the potential for combustion. The Material Safety Data Sheet (MSDS) classifies R-1234yf as extremely flammable in the EU [4] and flammable in the US [5]. R-134a is not classified as flammable in air under ambient conditions of temperature and pressure [6].

In the event of a MAC system leakage, a mixture of R-1234yf and PAG oil can be released into the under-hood or passenger compartment and may ignite if an ignition source is present. SAE International and a number of vehicle manufacturers have performed detailed risk assessments using Fault Tree Analysis. In 2009, the Society of Automotive Engineers Cooperative Research Team (SAE CRP1234) concluded, that R-1234yf is suitable for use in automotive applications [7]. CRP1234-4 has performed risk assessment to evaluate the risk of vehicle fire pertaining to the use of R-1234yf. They assessed the risk of occupant exposure to adverse events based on R-1234yf usage and concluded that "risks are still very small compared to the risks of a vehicle fire from all causes and well below risks that are commonly viewed as acceptable by the general public" [8]. The CRP1234-4 used a lowest hot surface ignition temperature of 700°C for R-1234yf/PAG, which was reconfirmed by this paper.

This paper will focus on under-hood hot surface ignition behavior. A broad range of flammability studies were undertaken for the R-1234yf/PAG oil mixture. Five production vehicles with different engine designs and packaging were used to determine the lowest hot surface ignition temperature of the R-1234yf/PAG oil mixture. More than 800 ignition tests were performed with these five vehicles.

Out of these five, vehicle A with a high temperature to produce an ignition and vehicle B with a low temperature to produce an ignition were selected. Both vehicles were further investigated and the engine compartment designs were compared. The result presented in this study is a summary of the more than 600 ignition tests for these two vehicles.

All vehicle hot surface ignition testing was performed on a chassis dynamometer. The test procedure developed includes moderate and extreme test conditions.

Both vehicles were production intent and represent typical midsized, high production volume vehicles. They were equipped with a transverse gas engine, front take down exhaust routing, turbo charger, and single evaporator MAC system. Although the engine architectures were the same, the engine design and compartment packaging of the vehicles were different. This paper summarizes the systematic investigation of exhaust system surface temperatures during refrigerant/PAG release and its impact on the ignition delay. A further study was done to identify how vaporized coolant affects R-1234yf/PAG oil ignition. Additional studies were completed to understand the influence of exhaust heat shield designs.

In an actual frontal collision, the hood is typically buckled. To assess the impact of the buckled hood, ignition tests were performed with a partially opened hood. Mitigation measures like shut-off valves and engine fan after-run were also evaluated and pros and cons were discussed regarding integration into a typical vehicle engine compartment.

This paper does not cover fire propagation or fire progression through the vehicles. Also this paper does not discuss R-1234yf/PAG ignition in the passenger compartment which was covered in the original SAE Cooperative Research Report on R-1234yf. The influence of engine compartment and heat shield crushing as an ignition mitigation is excluded as well.

BACKGROUND INFORMATION AND THEORY

In today's vehicles, several fluids used under-hood are classified as flammable or combustible. NHTSA and others have created several standards to address vehicle fire safety and fire propagation for flammable fluid usage. The well-known fire tetrahedron requires flammable material, oxygen, ignition source, and self-sustaining exothermic reaction to achieve a distinct and stabilized flame. All four conditions could be available in a frontal crash and post-crash situation.

Under normal vehicle usage, the refrigerant is contained within the MAC system. The condenser is typically located in the vehicle front-end module and is plumbed with the compressor, evaporator, and expansion valve through hoses and lines (see black colored assembly in [Appendix 1](#)). In a frontal crash event the condenser, compressor, and lines could breach, and a

large amount of refrigerant/oil mixture can be released into the engine compartment. Unforeseen events in non-crash scenarios can also lead to a rapid refrigerant release, e.g. hose or line failure.

Ignition Conditions

Figure 1 illustrates flammability and ignition conditions for a typical hydrocarbon fuel. The forced ignition condition is bounded by the saturated liquid curve and the upper and lower flammability limits.

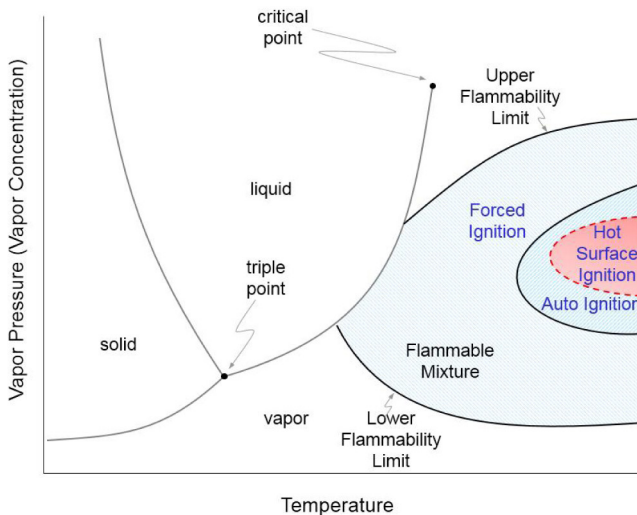


Figure 1. Flammability and ignition conditions as a function of temperature and vapor pressure [10].

As shown in Fig 1, a minimum temperature is required to achieve ignition. The minimum temperature depends on the ignition source and shifts towards higher temperatures when a hot surface is used as an ignition source. Even the flammability limits are contracted in the hot surface ignition condition.

Auto Ignition Temperature

The AIT is known as the lowest temperature at which a flammable material ignites in a normal atmosphere without adding external energy to the system. Usually, the AIT value is measured by using a flask or test chamber under idealized test conditions found in test laboratories. Depending on test methodology, test set up, and volume of a test sample, the AIT values can vary in a broad range [10]. Material, size, surface, and shape of the test set up can influence the AIT value as well. Reference [9] states, that the temperature at which auto ignition can occur is also dependent on the mole fraction, and therefore a series of tests in which the volume of the combustible fluid injected into the flask is varied until the minimum auto ignition temperature is observed.

R-1234yf has an AIT of 405°C, a Lower Flammability Limit (LFL) of 6.2%, and a Upper Flammability Limit (UFL) of 12.3% [4]. The LFL and UFL values have been tested at standard test conditions. But both values are also a function of temperature and pressure.

Depending on the specific formula of the PAG lubricant, the AIT value can also vary. Reference [11] specified an AIT value for PAG oil above 400°C.

Hot Surface Ignition Temperature

Figure 2 compares the hot surface ignition behavior of motor oil, synthetic motor oil, brake fluid, power steering fluid, and transmission fluid [10]. A cast iron crucible and a cast iron hemisphere were used as a hot surface to ignite these fluids. This study revealed how the lowest ignition temperature changes when these fluids were poured onto cast iron hemispheres versus when poured onto cast iron crucibles.

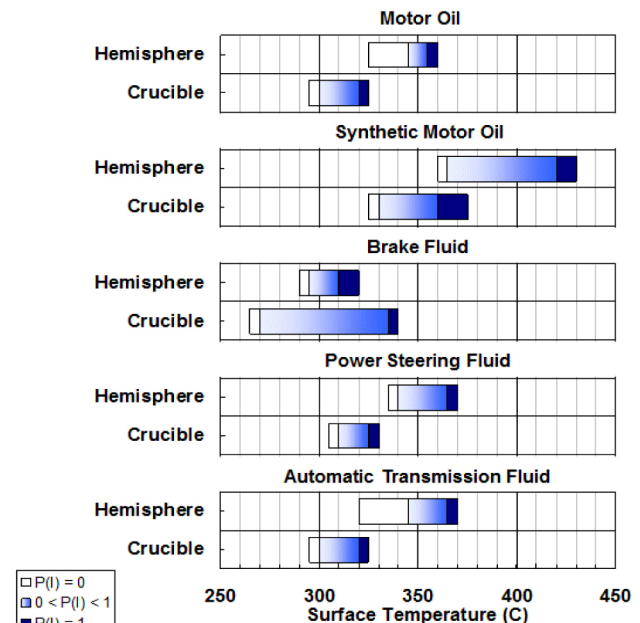


Figure 2. Comparison of hot surface ignition characteristics of fluids used under the hood [10]. An observed ignition probability $P(I) = 0$ means no ignition and $P(I) = 1$ means ignition always occurred.

In a previous study the hot surface ignition behavior of R-1234yf/PAG oil mixture was studied on a vehicle test buck and is summarized in Ref [12]. The lowest hot surface ignition temperature reported was 847°C. Reference [13] described and summarized ignition test results for a different study of R-1234yf/PAG oil mixture done in a laboratory. This testing showed a lowest ignition temperature of 750°C. Further investigations done at the same laboratory and published in Ref [14] identified a lowest hot surface ignition temperature of 710°C. The Kraftfahrt-Bundesamt (KBA) published hot surface ignition investigations of four different vehicles [19]. The minimum exhaust surface temperature for ignition was 694°C.

Parameters which affect the temperature required to achieve ignition by a hot surface include heat loss, exposure time, local air flow, and flow of the combustible fluid [9, 10, 15, and 16]. Relevant factors other than the surface geometry, shown in Fig. 2, include the surface material, fluid spray type, and fluid spray droplet properties [9, 10, 15, and 16].

In an engine compartment, hot surfaces are often exposed. Forced or natural convection moves air and potentially the flammable vapor over the hot exposed surface, which impacts the ignition behavior as well. All these parameters are strongly influenced by the specific engine compartment package and the engine design. The design and packaging of components like exhaust manifolds, turbo chargers, catalytic converters, and heat shields also affect the temperature that is required to achieve ignition. Therefore the lowest observable hot surface ignition temperature can differ from vehicle to vehicle and from the AIT value determined in a laboratory.

Ignition can be influenced by quenching, e. g. through the release of engine coolant, as well as by forced convection, e. g. through engine fan after-run.

These effects were assessed in this report and their influence on the hot surface ignition temperature was determined for the R-1234yf/PAG oil mixture.

Figure 2 also shows the statistical behavior of hot surface ignition for the referenced fluids. Reference [10] defined an intermediate temperature region by surface temperatures that were between the lower and upper temperature thresholds where the vapor generated by the heated fluid spontaneously ignited in some but not all tests. The observed ignition probability (P) for these temperature region is $0 < P(I) < 1$. Reference [15] concluded, that hot surface ignition cannot be described with one single critical temperature that separates the ignition region from non-ignition. For these reason, the actual hot surface ignition temperatures were higher than the published AIT value. More details and test results for hot surface ignition of hydrocarbon based liquids and vapors can be found in Ref [16].

VEHICLE UNDER-HOOD DESIGN

The following section describes the differences between the two selected vehicles (A and B) with regard to their current under-hood design. These differences were determined to highly influence the hot surface ignition behavior of both vehicles.

Heat Shield Design

Vehicle A and B have one heat shield covering the turbo charger and a second one in front of the catalytic converter. Due to specific engine design considerations, vehicle B also has two additional heat shields at the rear of the turbo charger. While vehicle A uses two separate heat shields with a big gap in between, all shields are nearly air-tight to each other in vehicle B, see Fig 3.

The side and top openings of the shields are much larger in vehicle A than in vehicle B. Based on this, vehicle A exhibits enhanced exhaust system ventilation with less retention of heat and vapor under the shield.

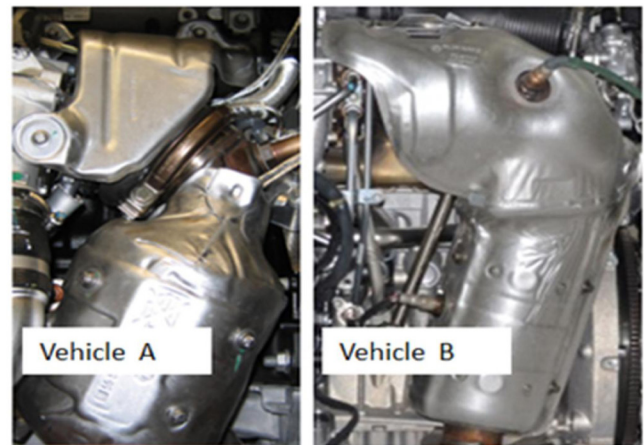


Figure 3. Comparison of heat shield design of vehicle A and B.

The heat shields of vehicle A are also designed smaller. Vehicle B has larger and less ventilated heat shields that are more enclosed around the exhaust surface. This may result in vapor trapping, which could retain, stagnate, and heat up refrigerant/PAG oil fumes underneath the shields.

Turbo Charger Position

Vehicle A has a larger open volume between the closed hood and top surface of the engine compared to vehicle B, see Fig 4a and Fig 4b. The turbo charger is packaged lower in vehicle A than in vehicle B. The distance between the turbo charger and the closed hood is approximately 380mm in vehicle A compared to approximately 130mm in vehicle B.

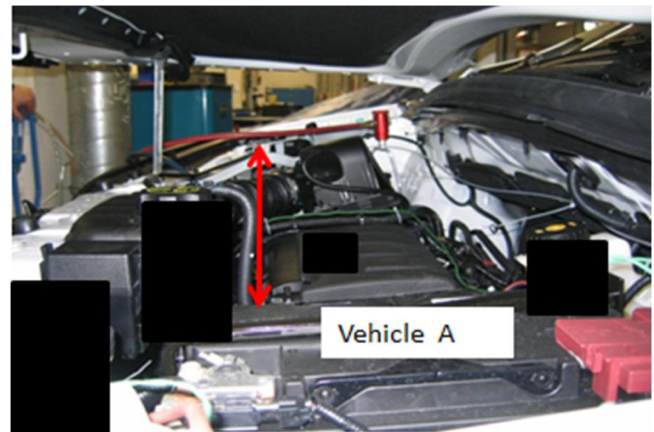


Figure 4a. Turbo charger position and free space below the hood of vehicles A.

The reduced free space above the turbo charger may trap refrigerant/PAG oil fumes more easily near the hot exhaust surfaces and in addition reduce convective flow.

This stagnant zone affects the dilution of the refrigerant/PAG oil-air mixture as well as its exposure time to the hot surfaces and consequently influences the energy transfer from the hot

surfaces to the mixture. As discussed above, these parameters influence the lowest exhaust surface temperature required to achieve ignition by a hot surface.

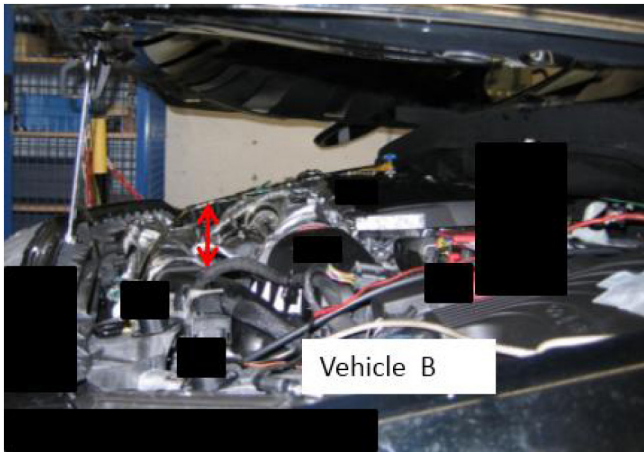


Figure 4b. Turbo charger position and free space below the hood of vehicles B.

TEST APPROACH

The first part of this evaluation was a vehicle screening, an assessment of the ignition behavior of vehicle A and B in the production configuration (baseline), and an assessment of potential ignition mitigating factors.

In the second part of this evaluation, generic engineering design parameters impacting the ignition behavior were studied. This was done by modifying the production under-hood designs of vehicle A and B in order to determine the impact on the lowest hot surface ignition temperature.

VEHICLE TEST SET UP

The following section describes the vehicle preparations, instrumentation and modifications required to perform the hot surface ignition testing.

Vehicle Sub System Preparation

The vehicle sub systems were prepared and modified to enable a defined and controlled release of the refrigerant/PAG oil mixture. Both vehicles were also set up to release a controlled amount of engine coolant and to vary the duration of the coolant fan after-run (electric engine coolant fans are often designed to continue to run after vehicle shut down to help cool down hot components).

MAC System

The refrigerant loop was modified to allow a consistent refrigerant/oil mixture release through the activation of a solenoid valve. A T-junction was brazed into the compressor discharge line, where the refrigerant temperature and pressure

would be highest (worst case - see more detail in [Appendix 1](#) and [Appendix 2](#)). Two different nozzle types were used to assess the ignition behavior in both vehicles.

Nozzle #1

Nozzle #1, see [Fig 5](#), simulates a rupture of an AC line as might be expected by crushing, folding or severing a line in a frontal collision.

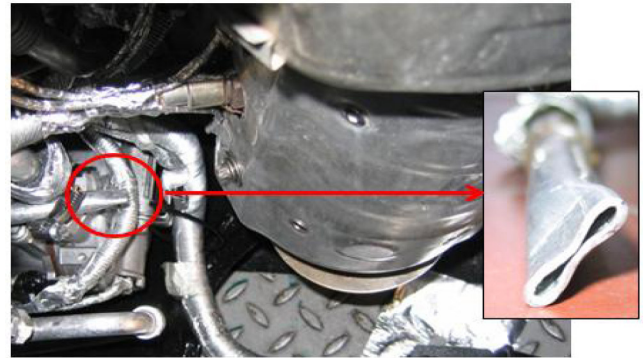


Figure 5. Example of position and spray direction of nozzle #1 with a mean width and height of approx. 18mm by 4mm. Different nozzle positions and spray directions were assessed.

After a distance of approximately 6cm, the refrigerant/oil jet directly hits the hot catalytic converter heat shield, the lower part of the converter, and the engine block, where it disperses into multiple droplets. The droplets are distributed by convection throughout the hot engine compartment.

When the release valve was opened, the high side pressure was approximately 12bar creating a refrigerant/oil jet with relative large forward momentum. [Figure 6](#) shows an example of the refrigerant/oil jet for a nozzle position and spray direction near the turbo charger heat shield.



Figure 6. Example of refrigerant/PAG jet in combination with nozzle #1. This position was selected for illustration purposes of the spray pattern of nozzle #1. Numerous other nozzle locations were studied as well as direct and indirect spray from both sides of the exhaust manifold.

Nozzle #2

A different nozzle type was created by using an open pipe with a deflector plate mounted in front of the pipe, see nozzle #2 in Fig 7. The pipe was not crushed as it was for nozzle #1.

The deflector plate on this nozzle disperses the mixture into droplets (mist) and sprays in a uniformly distributed radial to the pipe.



Figure 7. Example of position and spray direction of nozzle #2 with a gap of 3mm and an inner pipe diameter of 8mm (a temperature sensor was also installed in the outlet area). Different nozzle locations and spray directions were investigated.

The duration necessary to release the majority of the refrigerant charge was in the range of 20 seconds for both nozzles when the system was charged with 50% of the nominal refrigerant amount.

Engine Cooling System

The engine coolant loop was modified similarly to the refrigerant system by implementing a T-junction and a solenoid valve to enable control of the coolant release time and thus, coolant volume released. Figure 8 shows the coolant outlet pipe positioned at the right radiator end tank, one third of the way down from the top edge of the radiator.

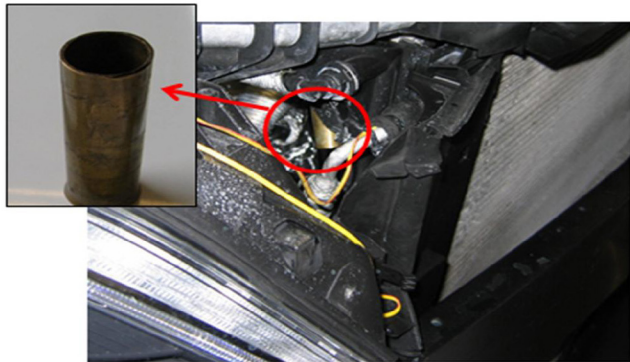


Figure 8. Coolant release outlet with an inner pipe diameter of 14mm. The outlet was positioned at the right radiator end tank due to radiator breach in a frontal collision. Various outlet positions and spray directions were also studied.

This release location was chosen due to the high probability of radiator breach in a frontal crash event. As both vehicles had a pressurized engine cooling system, the coolant was superheated at high load conditions. Once the superheated coolant was released under-hood, a large coolant steam cloud was generated as shown in Appendix 3.

The vehicle operator was able to disconnect the cooling fan power to interrupt any fan operation after engine stop or to enable a defined duration of the fan after-run.

MAC System Segmentation

For an additional study, the MAC system of vehicle B was segmented by adding two shut-off valves. An automatic shut-off valve was positioned at the condenser inlet and a manual operated valve was positioned in the suction line between the evaporator and compressor. In a crash event, the valves could reduce the volume of refrigerant/PAG oil mixture released in the engine compartment.

Similar to an air bag deployment, the valves could be activated automatically in an actual collision.

Under-Hood Design Modification

The following section describes the vehicle under-hood modifications required to perform the hot surface ignition testing for the second part of this evaluation.

Vehicle A

To understand the influence of exhaust system shielding with regard to creating stagnant zones that would encourage lower hot surface ignition temperatures, vehicle A was modified in several steps. The shielding was made increasingly restrictive from no shielding (removal of the production shield) to highly restrictive using spun fiber ceramic insulation (to restrict ventilation) as well as adding an awning over the turbo shield to further restrict the ability of the heated refrigerant/PAG oil mixture to rise away from the hot surface. These changes were executed in five steps, see Table 1 and Fig 9.

Table 1. Test setup used to assess the impact on lowest ignition temperature for vehicle A.

Setup Iteration	Heat Shields	Awning
A1	None	None
A2	Production	None
A3	Production + ceramic insulation	None
A4	Production	Installed (130mm above hot surface)
A5	Production + ceramic insulation	Installed (130mm above hot surface)

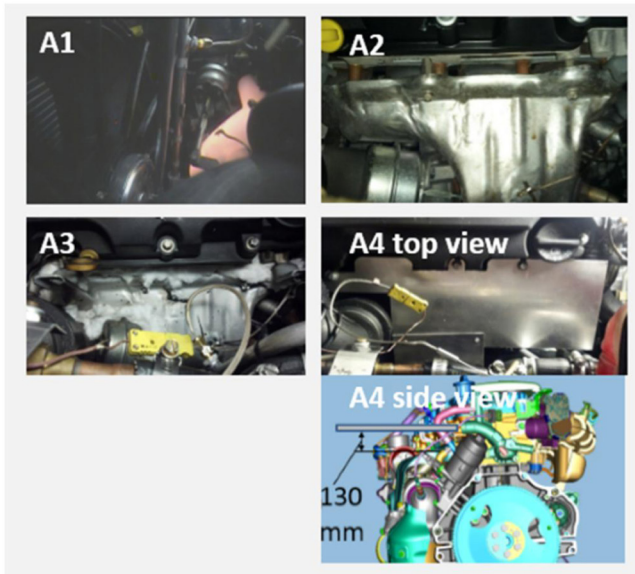


Figure 9. Test setup iterations as described in Table 1 for vehicle A.

Vehicle B

In vehicle B, where the production design heat shields and under-hood configuration was initially more restrictive, the process was reversed to increase the ventilation. Initially, the hood was opened using a spacer of 200mm to increase the distance between the turbo charger and hood to enable increased convective flow of the air and released refrigerant. In the next step the heat shields were trimmed similar to the shields of vehicle A to achieve increased venting. All components, blocking the convective flow above the turbo charger, were then removed, bent aside or rerouted. This included the air ducts, engine cover and air cleaner box cover (these modifications are not a production design solution). Finally all four heat shields were removed in addition to the aforementioned, see Table 2 and Fig 10.

Table 2. Test setup used to assess the impact on lowest ignition temperature for vehicle B.

Setup Iteration	Heat Shields, Air Ducts, Air Cleaner Box Cover, Engine Cover	Hood Opening Front
B1	Production	Secondary hood latch
B2	Production	200mm
B3	Trimmed heat shields, air-ducting removed, respectively bent aside, without covers	200mm
B4	Without heat shields, air-ducting removed, respectively bent aside, without covers	200mm

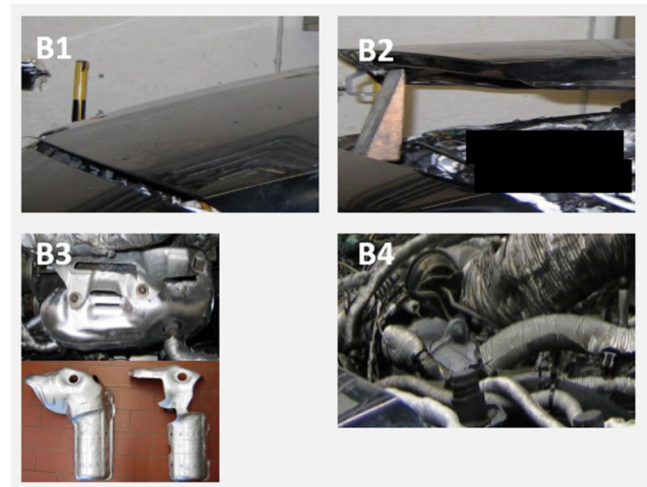


Figure 10. Test setup iterations as described in Table 1 for vehicle B.

Vehicle Instrumentation

Temperature and/or pressure sensors were placed on all relevant locations in the MAC system, the engine coolant system, and the engine exhaust system. All temperature and pressure sensors were calibrated prior to the testing. The most relevant measurement devices are detailed in the following section.

Engine Compartment

Three video cameras were positioned in the engine compartment to locate the ignition source and judge the potential for propagation. The color of the flame and its duration were also discernible in the video. The color of the flame might be an indication of the portion of refrigerant or oil that is burning. Whereas refrigerant is burning with a more blue flame, oil is burning with an orange flame, see Fig 13. In addition, ignition was also monitored by a thermocouple positioned underneath the turbo charger shield in the area of first ignition (see Appendix 5.1). A rapid air temperature increase indicates ignition under the shield which might not be observable in the videos.

All relevant hoses, wiring, and plastic parts were protected and insulated by aluminum sleeves to prevent heat damage in case of ignition and to insure multiple test runs.

A nozzle was placed under the hood and connected to a CO2 gas cylinder to enable fire extinguishing if required.

Once all sensors were in place and all protective measures completed, the heat shields and all other removed parts were reinstalled to ensure a production built state. All sensor wires and pressure lines were routed in such a manner as to not block the released R-1234yf/PAG oil mixture or the convective flow in the engine compartment.