The Motor Vehicle in the Post-Crash Environment, An Understanding of Ignition Properties of Spilled Fuels

Stephen M. Arndt and Don C. Stevens
Safety Engineering & Forensic Analysis, Inc.

Mark W. Arndt
Transportation Safety Technologies, Inc.

Reprinted From: Advances in Safety Technology 1999
(SP-1433)
The Motor Vehicle in the Post-Crash Environment, An Understanding of Ignition Properties of Spilled Fuels

Stephen M. Arndt and Don C. Stevens
Safety Engineering & Forensic Analysis, Inc.

Mark W. Arndt
Transportation Safety Technologies, Inc.

ABSTRACT

To date, the flammability of common automotive fluids under real-world conditions has not been well characterized for general use in the automotive community. This paper presents the results of a research program aimed at providing a greater understanding of the potential fire hazards of common fluids carried on board today's vehicles. A literature review was conducted to define the ignition properties of common automotive fluids as determined very precisely in the lab environment. A test program was then established to gain insight into the ignition properties of common automotive fluids under some real-world conditions. Automotive engine and exhaust components were used to create a test mechanism which realistically represented the environment, temperatures, and surfaces to which vehicle fluids may be subjected. The reported laboratory results are compared to the test data. Tests were conducted on twelve fluids with and without ignition sources present. The results of the project state whether each of these fluids was found to ignite under the test conditions. For each of the fluids which did ignite, the lowest temperature at which ignition occurred is listed. Results show that for the variety of potentially spilled automotive fluids, a wide range of ignition properties exists.

INTRODUCTION

The three components of the fire triangle, fuel, oxygen, and an ignition source, must be present for a motor vehicle fire to initiate. All of these components are available in the crash and post-crash environment of modern automobiles.

It is desirable to reduce the probability of increased occupant harm that can result from a post-collision fire. Under normal driving conditions as well as following a collision, a vehicle's design should work to keep flammable fluids away from potential ignition sources. Given that flammable fluids must be carried on board modern day automobiles, it would be useful to know the properties of these flammable fluids and the conditions under which they will ignite. This data could then be used during the design process of the automobile to improve a vehicle's post crash fire safety.

The ignition properties of common automobile fluids under laboratory conditions are fairly well understood and documented in scientific literature. This is not true for the ignition properties of these same fluids under real-world conditions. This poses a problem for the automobile designer who is interested in minimizing post crash fires in automobiles. This is because the flammability of a fluid under laboratory conditions does not provide an adequate description of how and when the fluid will ignite in a real-world environment. The purpose of the research presented in this paper is to begin to investigate the ignition properties of common automotive fluids in a real-world environment and compare them to those found in the published literature.

This paper presents the integrated results of a literature review and test program. The literature review was undertaken to compile and study the published ignition properties of modern day automobile fluids. This data was used to identify and compare the level of post-crash fire threat posed by each fluid. The data was also used for comparison to the results of the testing phase of this program. The second part of this program subjected a series of common automotive fluids to hot exhaust components while the temperature was varied from 100 °F to 1200 °F in 50-degree increments. The results of the project state whether each of these combustible fluids was found to ignite under the test conditions.

LITERATURE REVIEW

For a car crash to cause a fuel fed fire, the fuel must be in the vapor state because liquids do not ignite [1]. For ignition to take place the concentration of fuel vapor must be greater than the Lower Flammability Limit (LFL) and less than the Upper Flammability Limit (UFL) [2]. These
Flammability Limits measure percent volume of fuel in the air and differ for each fuel. For example, to ignite gasoline there must be at least 1.4% (LFL) fuel vapor by volume in the air and not greater than 7.6% (UFL) or the mixture will be too lean or too rich in fuel respectively [1].

Vapor pressure measures a liquid's ability to vaporize. This is the pressure a vapor exerts on the surface of a liquid at equilibrium [3]. The higher the vapor pressure, the more easily the liquid vaporizes. The vapor pressure of liquids depends on the temperature and the liquid's intermolecular force [3]. Increasing temperature raises vapor pressure, which results in faster vaporization [4]. For example, gasoline, modeled as hexane, at 77°F (25°C) has a vapor pressure of approximately 2.94 psi (0.2atm). At a temperature of 122°F (50°C) its vapor pressure rises to 8.82 psi (0.6atm) [2]. In contrast, liquids with strong intermolecular force have lower vapor pressure, which requires more energy to break the intermolecular bonds for vaporization to occur [4]. For example, at 77°F (25°C) water (having strong intermolecular bonds) has a vapor pressure of 0.44 psi (0.03 atm) [3].

The ratio of a fluids vapor pressure to its vapor pressure at the LFL is the Flammability Index (FI) [2]. The temperature when FI equals one is called the flash point. This is the minimum temperature at which sufficient vapors are generated at the surface of a liquid to just form a mixture that can ignite and propagate a flame through the mixture [2]. For example, 100 octane gasoline, diesel fuel #2D, and fuel oil #1 have flash points of – 45.4°F (–43°C), 127.4°F (53°C) and 100°F (38°C), respectively [1].

An introduced energy source can ignite vapors. Examples of introduced ignition energy sources are sparks (electrical and mechanical), flames, and hot gases [2]. An electrical spark can generate much more energy than is required for vapor ignition [2]. For example, gasoline at its LFL requires only 0.28 mJ of energy for ignition [1].

Vapors can also self-ignite when the temperature of the vapor-air mixture is raised to a point (autoignition temperature) in which an exothermic (heat producing), self-accelerating reaction occurs and propagates throughout the mixture [2]. Autoignition temperatures (AITs) vary greatly between substances and within substances. The variation of AITs between substances results from the differences in chemical structure [5]. AITs decrease with an increase in carbon chain length and also tend to be higher for branched chain hydrocarbons than for straight chained ones [5]. The variation of AITs within substances results from the test apparatus and procedures. The AITs will vary with vessel size and shape, fuel contact time prior to ignition (delay), fuel and oxygen concentrations, mixture pressure and fuel injection pressure [5]. For example, one test proves the autoignition temperature of gasoline to be 536°F (280°C) [6] while another autoignition test for gasoline gives a temperature range of 430 °F to 797 °F (221 °C to 425 °C) [7]. Another example of autoignition temperature is diesel at 444 ±7 °F (229 ±4 °C) [2]. The fuel form in a crash will affect ignition. Fuel in a crash takes the form of vapors (mist or droplets) and pools [2]. Vapors are most likely to ignite and often play a large role in post-crash fires. Gasoline vapors are four times denser than air. These vapors sink to the ground and spread, sometimes reaching warning flares or other ignition sources [1]. Mist or droplets can take on properties of vapors and become a source of fuel in a post-crash fire. This is a function of the high surface area to volume dimensions [2]. Mist or droplets form in different ways. A crushed fuel tank under high pressure causes a high fuel exit velocity resulting in shearing of the liquid into mist or droplets [2]. Also, a liquid will shear into mist or droplets as it enters a moving airstream [2]. Pools of some fluids are the least likely to ignite, requiring large inputs of heat energy to raise the temperature of the fluid for vaporization [2].

Gasoline is chiefly comprised of isomers (molecules of the same chemical formula but possessing different structures) of pentane, hexane, and octane. At the same time, lubricating oils, such as motor oil or transmission fluid, are comprised mostly of hexadecane and/or octadecane. All of these organic molecules are products of crude oil refinement. The properties of these molecules are not the same. For example, they differ with regard to their heats of vaporization [8].

The amount of energy required to change a substance from its liquid to its gaseous state is known as the heat of vaporization. The energy needed to vaporize the components of gasoline is considerably less than the energy needed to vaporize the components of motor oil or transmission fluid. [9].

TEST SETUP

Fluid flammability tests were conducted using a four-cylinder engine from a 1980 model year passenger car. The engine was removed from the vehicle and mounted onto a test stand. The catalytic converter was used as the hot element onto which various flammable automotive fluids were sprayed. The exhaust system was routed through a steel fire wall to protect the engine from burning fluids. A schematic of the test setup is provided as Figure 1. The temperature of the catalytic converter was modulated by changing engine speed and by routing part of the engine exhaust through a bypass exhaust pipe. A valve placed at the end of the bypass exhaust pipe controlled the quantity of bypass engine exhaust. The temperature of the catalytic converter could be varied from 400 (204 °C) to 1200 °F (649 °C) using this technique.

The catalytic converter temperature was monitored by five Type J thermocouples. The thermocouples were placed on the catalytic converter as shown in Figure 2. The control temperature for each test run was evaluated by thermocouple 3, which is located in the center of the catalytic converter.
Figure 1. Equipment Configuration for Test Performed on Catalytic Converter Surface (Top View)

Figure 2. Thermocouple Placement on the Catalytic Converter
Three test configurations were evaluated:

1. Each of the fluids was sprayed onto the catalytic converter to determine if the surface temperature alone was enough to ignite the fluid.

2. The tests were repeated while friction sparks were thrown onto the catalytic converter from a distance of five feet. The sparks were created by a grinding disk applied to a block of mild steel.

3. The tests were again repeated while a single Estes model rocket motor ignitor was energized at a distance of approximately one inch from the surface of the catalytic converter.

In each test, the fluid was dispensed onto the test surface of the catalytic converter for approximately one second. In the third test configuration, the rocket motor ignitor (seen in Figure 2) was fired approximately one second after spraying of the test fluid began. This timing allowed a portion of the sprayed fluid to vaporize so that the ignitor was energized in the presence of both liquid and gaseous fuel. The lowest surface temperature which could be achieved by the catalytic converter was 400 °F (204 °C). A flat steel plate was used to evaluate the fluids at temperatures below this point. The temperature of the flat plate test surface was increased using radiant heat from the sun to temperatures of 130 °F (54 °C). Temperatures between 130 °F (54 °C) and 200 °F (93 °C) were reached by heating the surface with a small amount of burning fuel then allowing it to cool to the target temperature. A single thermocouple was used to gauge the flat plate temperature prior to testing. This thermocouple was placed at the center of the fluid spray’s target area. A schematic of the flat plate test setup is shown in Figure 3.

FLUIDS TESTED – The 12 automotive fluids tested were:

1. 91 octane gasoline (summer & winter) – distributed by Texaco.
2. 89 octane gasoline (summer & winter) – distributed by Texaco.
3. 87 octane gasoline (summer & winter) – distributed by Texaco.
5. Prestone High-Temp Brake Fluid. DOT#3 – manufactured by Prestone Products Corporation, Danbury, CT.
6. Prestone Power Steering Fluid – manufactured by Prestone Products Corporation, Danbury, CT.
8. Valvoline Dexron III/Mercon ATF – manufactured by The Valvoline Company, a division of Ashland Chemical, Inc., Lexington, KY.
10. Prestone Anti-freeze/Coolant – manufactured by Prestone Products Corporation, Danbury, CT.
11. Mixture of 50% water and 50% Prestone Anti-freeze/Coolant – Manufactured by Prestone Products Corporation, Danbury, CT.

PROCEDURE

The catalytic converter test surface was heated to the target test temperatures by exhaust from the running engine. Each temperature in the test matrix was reached and maintained by adjusting the engine rpm and by using the bypass valve to proportion the hot exhaust gases between the pipe attached to the catalytic converter and the bypass exhaust pipe. Once the test surface temperature was steady at a given target value ±5 °F, all five of the thermocouple temperatures were recorded in addition to the ambient temperature.

A real-time video camera and, for some tests, a high-speed video camera (1000 frames/sec) were started to document the event. The fluid sprayer was pressurized to 90 psi then used to spray the test fluid onto the center of the catalytic converter from a distance of three feet. The spray was continued for a duration of one second. The fluid dispenser was weighed before and after each test run so that the volume of fluid sprayed onto the test surface could be calculated.

When friction sparks were used during a test, they were sprayed onto the catalytic converter during the entire time that the fluid was being dispensed and for a couple of seconds after the fluid spray was discontinued. When the ignitor was used, it was fired approximately one second after the fuel spray started.

If an ignition did occur during a test series, another run was completed at a lower temperature. This process was repeated until no ignition occurred. If an ignition did not occur, another run was completed at a higher temperature. This process was repeated until ignition did occur. This process established the range of temperatures that would produce an ignition of the subject fluid under the three test conditions.

Following each test run, the test fluid in the spray container was weighed. This was subtracted from the pretest weight to determine the weight of the fluid that had been sprayed.

Similar procedures were used for the flat plate experiments. The only differences were the heating source and the number of thermocouples.

TEST RESULTS

The results of the ignition tests are presented in bar charts as Figures 4 through 18 throughout this section. Theses bar charts show the minimum ignition temperatures for the fluids tested under the test conditions described. They also provide a good general overview of the test results and a relative comparison of the fluids.
tested. However, these charts do not tell the full story of how the fluids performed and should not be taken literally without an examination of the raw data. This data is provided in tabular format in Appendix A.

Figure 3. Equipment Configuration for Tests Performed on Horizontal Flat Plate (Side View)

WITHOUT IGNITION SOURCE – Each of the studied fluids was tested to determine the lowest temperature at which it would ignite on the test surface without any additional ignition sources (i.e. friction sparks or electronic ignitor.)

The minimum ignition temperature (MIT) range for six of the test fluids (brake fluid, power steering fluid, engine oil, automatic transmission fluid, CV joint grease, and engine coolant) was established without an external ignition source. Ignition did not occur for any of the other six fluids within the range of temperatures tested. The results for these tests are shown in Figure 4.

FRICITION SPARKS – Seven of the twelve fluids in this study were tested to determine their MIT in the presence of friction sparks. The MIT was identified for three of the test fluids on the catalytic converter test apparatus (diesel fuel, power steering fluid, and engine coolant) while the other four fluids which were tested did not ignite. The three grades of gasoline ignited in the presence of friction sparks on the flat plate test apparatus. The results of these tests are shown in Figure 5.

IGNITOR – The MIT for each of the twelve fluids in this study was investigated with an Estes model rocket motor ignitor used as an external ignition source. The MIT under these conditions was established for all but two of the fluids in this study. The 50/50-coolant/water and windshield washer fluid did not ignite at temperatures to 1100 °F (593 °C) and 1200 °F (649 °C), respectively.

Figure 4. Ignition Test Results – Ignition Source: None

Figure 5. Ignition Test Results – Ignition Source: Friction Sparks

The MIT for five of the fluids (power steering fluid, engine oil, automatic transmission fluid, CV joint grease, and engine coolant) was determined using the catalytic converter test device. The catalytic converter test device had a minimum test temperature of 400 °F (204 °C). This necessitated the use of the flat plate apparatus to test the other five fluids, which all ignited at 400 °F (204 °C). The flat plate device could be utilized at temperatures as low as 100 °F (38 °C). The results of this test series are shown in Figure 6.

Figure 6. Ignition Test Results – Ignition Source: Ignitor

COMPARISON BY FLUID TYPE

Gasoline 91 Octane – Ignition of this fluid did not occur at any of the temperatures evaluated on the catalytic converter test apparatus regardless of the ignition source used. This was true for both summer and winter blends of gasoline sold in Phoenix, AZ. Test temperatures ranged from 800-1200 °F (427-649 °C). Ignition of this fluid did occur on the flat plate apparatus in the presence of an electronic ignitor and friction sparks. Ignition
occurred at temperatures as low as 100 °F (38 °C) in the presence of both ignition sources (Figure 7). Temperatures below 100 °F (38 °C) were not evaluated. Ignition of this fluid without the presence of an ignition source was not achieved under any of the test conditions. An MIT for this fluid under any of the test conditions was not established.

Figure 7. Ignition Test Results – Gasoline 91 Octane

Gasoline 89 Octane – Ignition of this fluid did not occur at any of the temperatures evaluated on the catalytic converter test apparatus, regardless of the ignition source used. This was true for both summer and winter blends of gasoline sold in Phoenix, AZ. Test temperatures ranged from 800-1200 °F (427-649 °C). Ignition of this fluid did occur on the flat plate apparatus in the presence of an electronic ignitor and friction sparks. Ignition occurred at temperatures as low as 100 °F (38 °C) in the presence of both ignition sources (Figure 8). Temperatures below 100 °F (38 °C) were not evaluated. Ignition of this fluid without the presence of an ignition source was not achieved under any of the test conditions. An MIT for this fluid under any of the test conditions was not established.

Figure 8. Ignition Test Results – Gasoline 89 Octane

Gasoline 87 Octane – Ignition of this fluid did not occur at any of the temperatures evaluated on the catalytic converter test apparatus, regardless of the ignition source used. This was true for both summer and winter blends of gasoline sold in Phoenix, AZ. Test temperatures ranged from 800-1200 °F (427-649 °C). Ignition of this fluid did occur on the flat plate apparatus in the presence of an electronic ignitor and friction sparks. The electronic ignitor MIT was determined to be 125 °F (52 °C) (Figure 9). Note that this fluid failed to ignite when tested at 100 °F (38 °C) in the presence of an electronic ignitor or an overloaded 16-amp fuse. However, it did ignite with friction sparks at a flat plate temperature of 100 °F (38 °C). Temperatures below 100 °F (38 °C) were not evaluated.

Figure 9. Ignition Test Results – Gasoline 87 Octane

Diesel Fuel – This fluid did not ignite at any temperature tested on the catalytic converter test apparatus when no ignition source was present. Diesel fuel was found to have an MIT of 1200 °F (649 °C) in the presence of friction sparks. Ignition was also achieved in the presence of an electronic ignitor on the catalytic converter surface at 400 °F (204 °C) (the apparatus’s lowest temperature), and an MIT of 200 °F (93 °C) was established on the flat plate test apparatus (Figure 10). Diesel fuel could not be ignited with friction sparks at a flat plate temperature of 100 °F (38 °C). No friction spark ignition tests were conducted below a temperature of 800 °F (427 °C) with one exception on the flat plate at 100 °F (38 °C).

Figure 10. Ignition Test Results – Diesel Fuel
Brake Fluid – This fluid had an MIT of 700 °F (371 °C) established on the catalytic converter test surface without an ignition source and an MIT of 750 °F (399 °C) in the presence of friction sparks. Ignition was also achieved in the presence of an electronic ignitor on the catalytic converter test surface at 400 °F (204 °C) (the apparatus's lowest temperature), but did not occur on the flat plate at 200 °F (93 °C) (Figure 11).

Power Steering Fluid – The MIT of this fluid was established on the catalytic converter test surface at 850 °F (454 °C), both without an ignition source and in the presence of sparks. An MIT of 450 °F (232 °C) was achieved in the presence of an electronic ignitor on the catalytic converter surface (Figure 12).

Engine Oil – This fluid had an MIT of 950 °F (510 °C) on the catalytic converter test surface without an ignition source and an MIT of 900 °F (482 °C) in the presence of an electronic ignitor (Figure 13).

Automatic Transmission Fluid – An MIT of 900 °F (482 °C) was established for this fluid on the catalytic converter test surface without an ignition source. An MIT of 450 °F (232 °C) was also achieved in the presence of an electronic ignitor on the catalytic converter test surface (Figure 14).

CV Joint Grease – This viscous lubricant could not be sprayed. It had to be applied to the test surface of the catalytic converter using a small scoop. The CV joint grease began to flow quickly when placed in contact with the hot surface. The MIT was determined to be 1050 °F (566 °C) without an ignition source and 1000 °F (538 °C) in the presence of an electronic ignitor (Figure 15). It was not tested in the presence of friction sparks.
Engine Coolant – This fluid has an MIT of 950 °F (510 °C) on the catalytic converter test surface without an ignition source. The MIT is 800 °F (427 °C) in the presence of friction sparks, and 450 °F (232 °C) in the presence of an electronic ignitor (Figure 16).

![Figure 16. Ignition Test Results – Engine Coolant](image1)

Engine Coolant with Water (50/50) – This fluid was tested on the catalytic converter test surface at temperatures as high as 1200 °F (649 °C) without an ignition source and 1100 °F (593 °C) in the presence of an electronic ignitor (Figure 17). It could not be made to ignite under either condition. No MIT was established. This fluid was not tested using sparks as an ignition source.

![Figure 17. Ignition Test Results – Engine Coolant with Water (50/50)](image2)

Windshield Washer Fluid – This fluid was tested to temperatures as high as 1200 °F (649 °C) under all three ignition source conditions (Figure 18). It could not be made to ignite under any of these conditions. No MIT was established.

![Figure 18. Ignition Test Results – Windshield Washer Fluid](image3)

DISCUSSION

EXTERNAL IGNITION SOURCES

Steel Friction Sparks – Friction sparks were sprayed onto the test surface for some of the runs to simulate the sparks that can be generated when vehicle components contact each other, the roadway surface, or roadside obstacles. Reference [10] states that a typical steel will begin to glow red at temperatures as low as 932 °F (500 °C) changing to orange at about 1652 °F (900 °C) and finally becoming white at approximately 2462 °F (1350 °C). The specific temperature that generates a corresponding color of any given steel is a function of its composition and heat treatment.

![Figure 19. Ignition Test Results – Steel Friction Sparks](image4)

Applying a grinding disk spinning at high rpm to a block of mild steel generated the friction sparks used in this testing. These sparks tended to be yellow to orange as they left the grinding disk. They cooled off as they flew the three feet through the air to the test surface becoming orange to red upon impact. This observation implies that the temperature of the friction sparks was likely in the range of 932 °F to 1652 °F (500 °C to 900 °C) at the time they impacted the test surface.

The friction sparks added only a small amount of thermal energy to the fluid spray when compared to the radiant energy added by the test surface. This is because the sparks are small in mass and the temperature of the sparks was not significantly higher than that of the test surface.

Model Rocket Engine Ignitors – Estes Model Rocket Ignitors were used in some of the test runs to simulate the effect of an external ignition source that has more energy than friction sparks (e.g. light bulb filaments, electrical shorts, etc.). Discussions with Estes technical representatives revealed that the rocket motor ignitor will develop temperatures of approximately 1200 °F (649 °C) when energized with fresh batteries. A fresh battery was utilized for all of the experiments conducted.

The rocket motor ignitor consists of two nickel-plated steel lead wires of 0.0159-in. nominal diameter. The lead wires connect to a bridge wire of 0.0063-in. nominal diameter that is of the nichrome family. The bridge wire is coated with approximately 0.009 grams of a composite material consisting of 60-65% potassium nitrate, 5-10%...
Carbon, 5-10% Corn Starch, and 25-30% Hide Glue. The energy generated by the ignitor has been estimated to be 25 J during the first second that it is energized.

TEST CONDITIONS – The tests presented in this paper were designed to be representative of conditions which could exist in a vehicular collision. The combustion of vehicle fluids is controlled by numerous variables in the post-crash environment, including but not limited to fluid flammability, fuel/air mixture ratio, and the presence, temperature, and location of a heat source within the fluid’s vapor cloud. Each such variable can take on a wide range of possible values, yielding an unlimited number of potential fuel combustion scenarios. For example, when the ignition source was an electronic ignitor in the test series presented, it was placed close to the catalytic converter and energized near the end of the fuel spray. This presented a localized ignition source for a short period of time at a single position in space during the complex process of fuel mixing with air. It is possible that ignition sources placed and energized at different points in space and different times would produce different minimum ignition temperatures, even if all other test variables were held constant.

It is important to recognize that the series of tests discussed in this paper were intended to characterize a variety of fluids under the same set of conditions. The results for the group of fluids which were tested can be compared to one another, providing insight into their relative levels of flammability. The test results are not intended for use as a predictor of the minimum ignition temperature of these fluids under different conditions.

RESULTS FOR GASOLINE TESTS – Three grades of gasoline were tested on the catalytic converter surface at temperatures from 800 °F (427 °C) to 1200 °F (649 °C). Regardless of the presence or absence of an external ignition source, none of the gasolines ignited during any of the catalytic converter tests. This is an interesting result because the temperature range of these tests undoubtedly covers the range of gasoline autoignition temperatures determined by ASTM methods [11] and because the flat plate tests resulted in gasoline ignition at temperatures as low as 100 °F (38 °C).

At first glance, these results might seem contrary to intuition and the published laboratory autoignition temperatures for these fluids. However, three possible explanations for these results should be considered, each of which likely contributes to the test results in some degree:

First, fuel vapor and air must exist in a combustible ratio in the presence of a sufficient heat source before ignition can occur. Gasoline is a relatively volatile fluid (possessing a high vapor pressure and low heat of vaporization). Therefore, near the catalytic converter surface, where the fuel is being rapidly vaporized, the proportion of fuel vapor in the fuel/air mixture may be too great to support combustion (e.g., the mixture may be too rich). This explains the absence of combustion when gasoline was tested on the catalytic converter with an ignitor. Because the ignitor was placed approximately one inch from the test surface and energized for a short period of time near the end of the fluid spray, the fuel air mixture around the ignitor could have been too rich for ignition to occur. There are most likely alternate ignitor positions or energizing times for which a combustible vapor cloud would exist near the hot ignitor leading to fire.

Second, a proper fuel/air mixture must remain in residence near a heat source long enough to absorb thermal energy sufficient for combustion. The currents of free convection near the heated test surface, combined with the normal air currents of the outdoor test facility may have carried away the fuel/air mixture before it could be heated to the ignition point.

A third explanation for the gasoline test results may also lie in gasoline’s high volatility. The test fluid spray was at low pressure and had insufficient mass to absorb the latent heat of vaporization and contain the boiling fuel on the test surface. This allowed the boiling phenomenon to proceed so violently that it quickly forced the fluid away from the hot surface. The sprayed fuel was unable to attain a combustible fuel/air mixture while remaining adjacent to the hot surface (and/or the ignitor) long enough to absorb the energy required for ignition.

When gasoline was sprayed on the 100° F (38° C) flat plate beneath the position of a rocket ignitor, a less volatile vaporization process occurred. Unlike the gasoline tested using the catalytic converter at higher temperatures, the fluid in these tests did not boil and was therefore able to remain on the surface long enough to generate a combustible volume of fuel/air mixture in the vicinity of the ignitor.

COMPARISON OF RESEARCH AND TEST RESULTS – The minimum ignition temperatures of four of the fluids that were tested without an external ignition source are compared to the published values obtained during the literature review [1] in Table 1.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Minimum Test Ignition</th>
<th>Published MIT</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Oil</td>
<td>950 °F (510 °C)</td>
<td>600 °F (316 °C)</td>
<td>58%</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>950 °F (510 °C)</td>
<td>775 °F (413 °C)</td>
<td>23%</td>
</tr>
<tr>
<td>Gasoline (Regular Grade)</td>
<td>none</td>
<td>700 °F (371 °C)</td>
<td>n/a</td>
</tr>
<tr>
<td>Diesel Fuel (#2D)</td>
<td>none</td>
<td>494 °F (257 °C)</td>
<td>n/a</td>
</tr>
</tbody>
</table>

* Median value of published range
The test results showed that the ignition temperatures were 58% higher for motor oil and 23% higher for ethylene glycol, when compared to the published values. Note that no quantitative comparison could be made between published values and test results for gasoline or diesel fuel because autoignition did not occur in any of the tests performed on these fluids.

CONCLUSIONS

Based on the MIT results from this testing, the fluids can be ranked in order of increasing potential to start or contribute to a post-crash fire. The fluid rankings, in order of decreasing ignition potential, are given below both without an external ignition source and with one:

Without External Ignition Source
1. Brake fluid
2. Power steering fluid
3. Automatic transmission fluid
4. Engine oil
5. Engine coolant (full strength)
6. CV joint grease

In the Presence of an External Ignition Source
1. Gasoline, 91 octane
2. Gasoline, 89 octane
3. Gasoline, 87 octane
4. Diesel fuel
5. Brake fluid
6. Power steering fluid
7. Automatic transmission fluid
8. Engine coolant (full strength)
9. Engine oil
10. CV joint grease

The fact that gasoline was not in the rankings without the presence of an external ignition source is an artifact of the particular test conditions evaluated. It is probable that gasoline would be ranked as having the greatest ignition potential under different test conditions without an external ignition source.

The inclusion of an ignition source tended to decrease the MIT for a given fluid compared to the MIT with no ignition source. The application of friction sparks caused a slight reduction in MIT for several of the tested fluids, and the use of an ignitor caused a greater reduction in this value for all of the fluids which were ignitable under the test conditions.

The function of an ignition source is to add thermal energy to the test environment. Based on the changes in MIT among tests of a given fluid at the same temperature but using different ignition sources, it appears that friction sparks, as generated and applied in this testing, are a relatively low-energy ignition source when compared to rocket igniters.

Two of the test fluids (50/50 mixture of engine coolant/water and windshield washer fluid) were not ignitable, even in the presence of an ignitor, at temperatures as high as 1200 °F. These fluids do not represent a significant fire threat compared to the other fluids that were tested.

The three grades of gasoline and the diesel fuel were all capable of igniting at temperatures of 200 °F or below in the presence of an external ignition source. These MIT results are at least 200 °F below that of all other fluids tested. This implies that vehicle fuels pose a potentially greater fire threat than other fluids when an ignition source, such as an exposed light bulb filament or a shorted electrical wire, is present.

This test methodology attempted to simulate a realistic disbursement of combustible fluids onto a heated vehicle component surface that might be found in the post-crash fire environment. The discrepancy between tested and published ignition temperatures suggests that, when exposed to real-world hot vehicle component surfaces, these fluids are less likely to ignite than published data would indicate.

Significant differences have been shown between the published results of laboratory testing (i.e. reproducible measurement of autoignition temperature) and tests designed to represent a potential post-crash environment. These differences reveal the complexity of the autoignition process outside of the controlled laboratory environment. The differences also support the previous statements that these test results are useful in comparing the relative flammability of fluids but should not be interpreted as the minimum ignition temperatures under different conditions.

ACKNOWLEDGMENTS

Thanks to Pete Baray and Ambrose Hubbard of P.E.B. Consulting and Gary McDowell and Fred Arndt of SEFA, Inc. for their support in the conduct of the test program.

REFERENCES


**CONTACTS**

Stephen M. Arndt
Safety Engineering & Forensic Analysis, Inc. (SEFA)
3022 S. 52nd St.
Tempe, AZ, USA 85282
(602) 438-2004
E-mail: sarndt@sefainc.com

Steve Arndt is currently the president of Safety Engineering & Forensic Analysis, Inc. (SEFA). His interests include consulting in the fields of automotive and aviation crash safety. Steve received his BS in Aerospace Engineering from the University of Arizona in 1984. He spent the first eight years of his professional career working at Simula Inc. where he conducted R & D programs in the fields of aviation crash safety, aircrew protection, and structural composites. He spent the next six years working for Arndt & Associates, Ltd., specializing in automotive and aviation crash safety technology. Steve has continued his work in these fields over the last year at SEFA, Inc. Steve lives in Phoenix, Arizona with his wife and daughter.

Don C. Stevens
Safety Engineering & Forensic Analysis, Inc. (SEFA)
3022 S. 52nd St.
Tempe, AZ, USA 85282
(602) 438-2004
E-mail: don@sefainc.com

Don Stevens is a consulting engineer employed by SEFA Inc. He received his MS in Mechanical Engineering in 1992 and has since pursued a career as an automotive crash safety researcher and analyst for Simula, Inc, Arndt & Associates, Ltd, and SEFA Inc.

Mark W. Arndt
Transportation Safety Technologies, Inc.
P.O. Box 30717
Mesa, AZ, USA 85203-0717
(602) 964-9266
E-mail: marndt@syspac.com

Mark Arndt is president of Transportation Safety Technologies. His primary interest and consulting work is in motor vehicle safety. Mark lives in Mesa, Arizona with his wife and two children.

**APPENDIX A, TEST DATA**

**Automotive Fluid Flammability Test Matrix**

**Ignition Source: None**

<table>
<thead>
<tr>
<th>Fluid / Temp °F (°C)</th>
<th>400 (204)</th>
<th>450 (232)</th>
<th>500 (260)</th>
<th>550 (288)</th>
<th>600 (315)</th>
<th>650 (343)</th>
<th>700 (371)</th>
<th>750 (399)</th>
<th>800 (427)</th>
<th>850 (454)</th>
<th>900 (482)</th>
<th>950 (510)</th>
<th>1000 (538)</th>
<th>1050 (565)</th>
<th>1100 (593)</th>
<th>1150 (621)</th>
<th>1200 (649)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Wiper Fluid</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: Coolant/Water</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Coolant</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D: CV Grease</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E: Trans. Oil</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F: Engine Oil</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G: PS Fluid</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H: Brake Fluid</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I: Diesel</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>J: Gas - 87</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>K: Gas - 89</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>L: Gas - 91</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>


Y = Ignition
N = No Ignition
### Automotive Fluid Flamability Test Matrix

#### Ignition Source: Steel Friction Sparks

<table>
<thead>
<tr>
<th>Fluid / Temp °F (°C)</th>
<th>400 (204)</th>
<th>450 (232)</th>
<th>500 (260)</th>
<th>550 (288)</th>
<th>600 (316)</th>
<th>650 (343)</th>
<th>700 (371)</th>
<th>750 (399)</th>
<th>800 (427)</th>
<th>850 (454)</th>
<th>900 (482)</th>
<th>950 (510)</th>
<th>1000 (538)</th>
<th>1050 (566)</th>
<th>1100 (593)</th>
<th>1150 (621)</th>
<th>1200 (649)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Wiper Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: Coolant/Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Coolant</td>
<td>N</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D: CV Grease</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E: Trans. Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F: Engine Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G: PS Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H: Brake Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I: Diesel</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J: Gas - 87</td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K: Gas - 89</td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L: Gas - 91</td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Y = Ignition  N = No Ignition

---

### Automotive Fluid Flamability Test Matrix

#### Ignition Source: Igniter

<table>
<thead>
<tr>
<th>Fluid / Temp °F (°C)</th>
<th>400 (204)</th>
<th>450 (232)</th>
<th>500 (260)</th>
<th>550 (288)</th>
<th>600 (316)</th>
<th>650 (343)</th>
<th>700 (371)</th>
<th>750 (399)</th>
<th>800 (427)</th>
<th>850 (454)</th>
<th>900 (482)</th>
<th>950 (510)</th>
<th>1000 (538)</th>
<th>1050 (566)</th>
<th>1100 (593)</th>
<th>1150 (621)</th>
<th>1200 (649)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Wiper Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: Coolant/Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Coolant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D: CV Grease</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E: Trans. Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F: Engine Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G: PS Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H: Brake Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I: Diesel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J: Gas - 87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K: Gas - 89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L: Gas - 91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Y = Ignition  N = No Ignition
### Automotive Fluid Flammability Test Matrix

**Horizontal Steel Plate with Igniter**

<table>
<thead>
<tr>
<th>Fluid / Temp °F (°C)</th>
<th>100 (38)</th>
<th>125 (52)</th>
<th>150 (66)</th>
<th>175 (79)</th>
<th>200 (93)</th>
<th>225 (107)</th>
<th>250 (121)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Wiper Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: Coolant/Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Coolant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D: CV Grease</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E: Trans. Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F: Engine Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G: PS Fluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H: Brake Fluid</td>
<td>N¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I: Diesel</td>
<td></td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J: Gas - 87</td>
<td>Y¹/N²</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K: Gas - 89</td>
<td>Y³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L: Gas - 91</td>
<td>Y³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fluid Temp: Ambient  Spray Time: ~1 sec  Spray Pattern: Stream  Can Pressure: 80 psi  Spray Dist.: 5 ft

Y = Ignition

N = No Ignition

(1) Result with friction sparks
(2) Same results with igniter and 10 amp fuse
(3) Same results with igniter and friction sparks