

Gasoline Fuel Injector Spray Measurement and Characterization – A New SAE J2715 Recommended Practice

David L.S. Hung

Visteon Corporation

David L. Harrington

General Motors Corporation (Retired)

Anand H. Gandhi

Ford Motor Company

Lee E. Markle

Delphi Corporation

Scott E. Parrish

General Motors Corporation

Joseph S. Shakal

TSI Incorporated

Hamid Sayar

Siemens Corporation

Steven D. Cummings

Chrysler LLC

Jason L. Kramer

Robert Bosch LLC

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ABSTRACT

With increasingly stringent emissions regulations and concurrent requirements for enhanced engine thermal efficiency, a comprehensive characterization of the automotive gasoline fuel spray has become essential. The acquisition of accurate and repeatable spray data is even more critical when a combustion strategy such as gasoline direct injection is to be utilized. Without industry-wide standardization of testing procedures, large variabilities have been experienced in attempts to verify the claimed spray performance values for the Sauter mean diameter, D_{v90} , tip penetration and cone angle of many types of fuel sprays. A new SAE Recommended Practice document, J2715, has been developed by the SAE Gasoline Fuel Injection Standards Committee (GFISC) and is now available for the measurement and characterization of the fuel sprays from both gasoline direct injection and port fuel injection injectors. A primary motivation for the development of the standardized

procedures for test configuration, data acquisition, data reduction and reporting was to achieve significant reductions in the test-to-test and laboratory-to-laboratory variabilities of such reported spray data. All of the major areas of fuel injector spray testing and characterization are addressed in detail in the document, including spray imaging, high-resolution patternation and drop sizing by both phase-Doppler interferometry and laser diffraction.

Valuable lessons regarding the definitions and interpretations of commonly-used spray parameters were learned during the development of the J2715 document, and these are presented and discussed. Based upon the five years of committee discussions and consensus decisions, five key recommendations on fuel spray measurement and characterization are made to the worldwide automotive industry. The first, and most important, recommendation is that the Recommended Practices in SAE J2715 be utilized by the spray laboratories of all automotive companies and injector

manufacturers in place of the myriad of in-house test protocols that are currently being used.

To evaluate and quantify the efficacy of the new Recommended Practices in J2715, a comprehensive program of round-robin spray characterization tests was designed, and is currently being conducted in the spray testing laboratories of six injector manufacturers and end-users worldwide. This two-year testing protocol will be completed in mid-2008 and will compare the results of in-house testing procedures to those obtained using the J2715 procedures. This round-robin test program is described in detail, and an informative example of the initial test results for the direct-injection spray angle and spray-tip penetration is provided and discussed.

INTRODUCTION

The new SAE J2715 document [1] has been developed by the SAE Gasoline Fuel Injection Standards Committee (GFISC), and addresses the subject of characterizing automotive gasoline fuel sprays. The document introduces new recommended practices and definitions to achieve this. The objective of the development of J2715 is to promote uniformity in this field throughout the worldwide automotive industry. In this SAE Recommended Practice document a large number of detailed test protocols for fuel spray characterization are developed and promulgated. To accompany these testing procedures, a specific set of standardized test conditions are established and uniform data reduction and reporting procedures are derived.

The SAE GFISC Committee is comprised of representatives from fuel injector suppliers, vehicle manufacturers, automotive end users and spray testing laboratories, many of whom are fuel system specialists who are concerned with fuel spray measurement and characterization. With an accurate fuel spray characterization becoming increasingly important for combustion system development for both gasoline direct-injection and port fuel injection applications, the development of the SAE J2715 standards document was considered a critical priority for the automotive community.

SCOPE OF SAE J2715

These new recommended practices apply to the sprays from automotive fuel injectors that are used in both port fuel injection (PFI) and gasoline-direct injection (G-DI) engine applications. The SAE J2715 recommended practice document contains the detailed background, test procedures and data reduction protocols for nearly all fuel spray characterization metrics that are applicable to automotive applications. It is intended to be utilized in conjunction with other SAE J documents that address other (non-spray) injector performance metrics such as flow curve measurement and leakage testing. These are

SAE J1832 [2] for Port Fuel Injectors and the forthcoming SAE J2713 for Gasoline Direct Injectors.

PURPOSE OF SAE J2715

The development and publication of the new SAE J2715 Recommended Practice document has six main purposes. These are, in the chronological order of development:

1. To standardize the use of nomenclature and definitions specifically related to automotive gasoline fuel injector spray measurements.
2. To identify and define the key metrics which constitute the characterization of automotive gasoline fuel sprays.
3. To establish detailed test procedures and recommend test equipment and methods to measure and quantify these key metrics.
4. To establish recommended procedures for the data reduction and computation of spray characterization parameters for automotive gasoline fuel sprays.
5. To establish the detailed protocol and format for spray data reporting in order to facilitate both the interpretation and the third-party verification of the test results.
6. To facilitate the adoption and usage of the gasoline fuel spray definitions, standard conditions, testing protocols, data reduction procedures and data reporting practices in the new SAE J2715 document by the worldwide automotive industry.

FUEL SPRAY VARIABLES UTILIZED FOR SPRAY CHARACTERIZATION

The quantification of the characteristics of sprays from automotive gasoline fuel injectors is a very important, but specialized, area of measurement. The injection of fuel in an engine is a very rapid, transient event of a few milliseconds duration, and the resultant spray of atomized liquid fuel is not easily characterized. Parameters such as the mean drop diameter, the spray-tip penetration, the fuel mass distribution and the cone angle (or spray angle for G-DI) are critical to the selection of an injector for a given application. Ideally, the values would be determined with minimal measurement error by standardized procedures if the performance metrics of one injector are to be meaningfully compared to the performance of another. Standardized testing protocols are also necessary if the spray performance parameters being claimed by an injector manufacturer are to be independently verified by an end user or third-party test laboratory. Some measurements, such as those of spray-tip penetration, involve macroscopic spray parameters, while others, such as the mean drop size, involve the determination of microscopic characteristics.

The older and more common type of fuel spray in the automotive industry is that obtained from the port fuel injector. This type of injector is discussed in detail in

Reference [2]. This relatively low-pressure unit produces a fairly coarse spray over a 2 to 15 millisecond time of injection, and exhibits a mean drop diameter of 50 to 150 microns. In contrast, the spray from the newer gasoline direct injector produces a much finer spray over a 0.5 to 5.0 ms time of injection, providing a mean drop diameter of 10 to 25 microns. The fuel pressure utilized in G-DI injectors normally exceeds 8 MPa, and, for the latest designs, may exceed 20 MPa. Several important regions of a developing G-DI fuel spray are schematically illustrated for a swirl-type injector in Figure 1. There may or may not be after-injections, ligaments, spray fingers, or even a prominent sac spray, depending on the basic design of the injector. These are not the characterization metrics themselves, but are general descriptors of areas that may affect the values of the measured spray parameters.

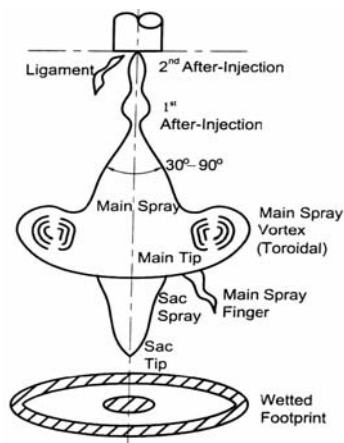


Figure 1 – Description of Observed Regions of a Transient G-DI Fuel Spray [3]

Figure 2 depicts a representative set of the G-DI injector sub-classifications by nozzle design. In addition, there are newer piezoelectric-actuated G-DI injectors for gasoline applications. There are corresponding sub-classifications for PFI injectors that include the common single spray, dual spray, hollow-cone and vacuum air-assist types. The details of G-DI injector and spray sub-classifications are provided in reference [3], which also documents numerous G-DI spray measurement techniques and variations in the measured values of spray characterization parameters for both ambient and on-engine conditions. In this reference the effects of wide ranges in the values of non-standard test conditions on the resultant G-DI fuel spray are illustrated and discussed, including the effect of variations in fuel temperature, fuel pressure and downstream ambient pressure. Reference [4] provides a general overview of the spray characteristics of atomizing nozzles, not necessarily just those of automotive injectors. The emphasis in this reference is upon the physics of how sprays are formed, and on the parameters that influence atomization, rather than upon the details of spray measurement procedures.

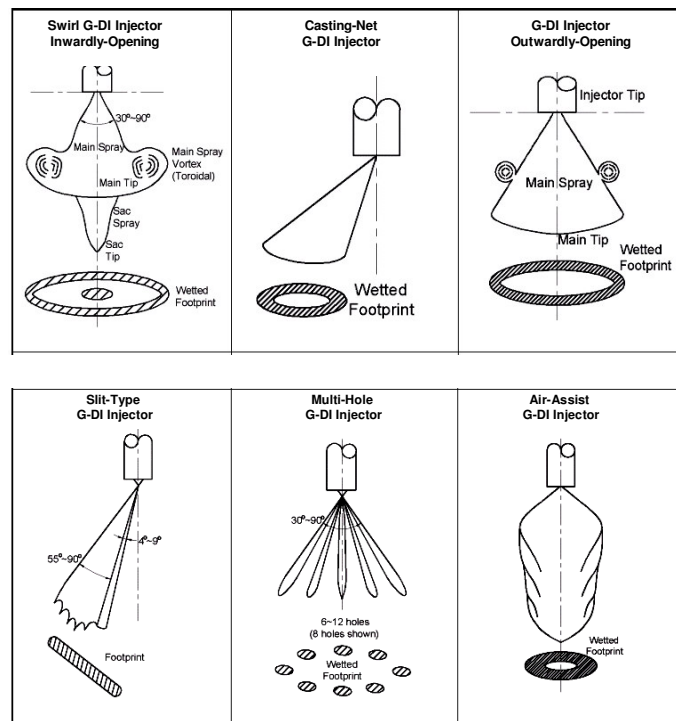


Figure 2 – G-DI Injector Sub-Classification by Nozzle Design [3]

The key metrics of an automotive gasoline fuel spray have been well established in the automotive industry by means of both engine testing and computational fluid dynamics modeling. This is due to the influences of these parameters on engine operation, combustion and emissions that have been verified over many years in a multitude of engine configurations. These key metrics and the associated parameters for an automotive gasoline fuel spray are identified and defined in detail in SAE J2715, and may be summarized as follows:

1. The angular extent of the spray envelope. This is the Cone Angle for a PFI injector spray, and is the Spray Angle for a G-DI injector spray.
2. The fuel mass distribution within the fuel spray for a PFI injector, including the location of the centroid of that fuel mass relative to the injector axis.
3. The spray-tip penetration characteristics and a key penetration point for the fuel spray from either a G-DI injector or a PFI injector.
4. The drop-size distribution, the Sauter mean diameter (SMD) and the D_{v90} , or 90% cumulative volume diameter. The latter two are generally accepted for automotive fuel spray applications as the most meaningful statistical parameters derived from the drop-size distribution. The meanings of the terms are as follows: the SMD represents the diameter of a drop having the same ratio of volume to surface area as the collection of all drops in the measured drop-size distribution curve; the D_{v90} represents the diameter of a drop for which the volume of all smaller drops in the measured drop-size distribution curve is 90% of the total volume of all drops in the curve. It is

a shorthand indicator of the largest drops in a spray from either a PFI injector or a G-DI injector.

5. Additional parameters that numerically characterize the resultant spray geometry from injectors having special features or options, such as a bent-spray injector (G-DI or PFI) or a PFI dual spray injector. These parameters are the Cone Bend Angle for a bent-spray (offset) PFI injector, and the Spray Bend Angle for a bent-spray G-DI injector. For a PFI dual spray injector the additional geometric parameters are the individual Cone Angles of the two plumes and the Separation Angle between them.

KEY CONSIDERATIONS IN G-DI AND PFI SPRAY MEASUREMENTS

Automotive gasoline fuel sprays can be characterized by defining the important spray metrics and then specifying a series of proven measurement techniques to numerically quantify those metrics. It is important to note, however, that certain measurement techniques are much more suitable for PFI sprays than for G-DI sprays, and vice versa, due to the nature of the sprays. This is the result of significant differences between PFI sprays and G-DI sprays regarding the mean drop size, light scattering, vaporization rate and penetration distance. For example, the angular extent of the direct injection spray (the spray angle) can be best quantified via imaging, whereas the angular extent of the PFI spray is best quantified by high-resolution (H-R) mechanical patternation. Although a single large drop scatters more light than a single small drop, it may easily be observed experimentally using a simple strobe light that the collection of relatively large drops in a PFI spray scatters significantly less light than the collection of smaller, but much more numerous, drops in a G-DI spray. As a result, the imaging of a PFI spray generally yields a poorly defined spray boundary. This leads to possible errors in the quantification of PFI spray geometry by imaging. Hence, with the exception of PFI spray-tip penetration, imaging of PFI sprays is not recommended for the determination of spray characterization parameters. The patternation restrictions regarding G-DI fuel sprays are discussed in the sub-section on Patternation Considerations.

The importance of quantifying the spray delivered by an automotive gasoline fuel injector has resulted in a significant number of research projects and technical developments over the past decade, and a number of excellent representative papers are listed as references [5, 6, 7, 8, 9]. In almost all cases the work is an application of a new measurement tool or technique to quantify one or more fuel spray metrics that are defined. This includes the measurement techniques that are recommended in J2715, as well as planar optical imaging and the application of optical patternation using laser fluorescence. Taken as a whole, these research projects on spray characterization do indeed provide insight into the problem, and all such work is invaluable to a committee that is attempting to introduce standardization into that field. Each measurement tool

and procedure that was reported in the technical literature was evaluated as to whether it was feasible for definitive measurement, and as to whether it should be considered as an accessible and reliable technique. A number of emerging optical techniques, including optical patternation, were considered to be still under rapid development, and were deemed to be not yet suitable for use in an industry-wide standard.

PULSE WIDTHS AND TIMING CONSIDERATIONS IN IMAGING

It was apparent in the development of SAE J2715 that there was little uniformity throughout the automotive industry in the use of the term “pulse width”, or in the definition of “time” in presenting spray data such as tip penetration or spray images. It was ascertained that this is a contributor to the scatter in the reported spray data from imaging. This lack of uniformity becomes quite important for G-DI injection systems, due to the fact that the pulse-control strategies can be significantly more complex than those of PFI systems. Many, but not all, G-DI drivers incorporate a designed driver charge delay (DCD) time between the initiation of the logic pulse from the engine control unit (ECU) and the command pulse of the driver to open the injector. This is normally done to ensure a maximum voltage level of the driver capacitor just prior to actuation. The interrelationships of four key timing traces are illustrated schematically in Figure 3. In the progression from the ECU logic pulse to the fuel delivery event there are alterations due to a possible DCD, as well as the effects of the individual times of mechanical opening and mechanical closing. The actual fuel delivery time between the first appearance of fuel at the injector tip (the SOF; start of fuel) and the end of fuel (EOF) is not generally equal to either the logic pulse width or the injection pulse width.

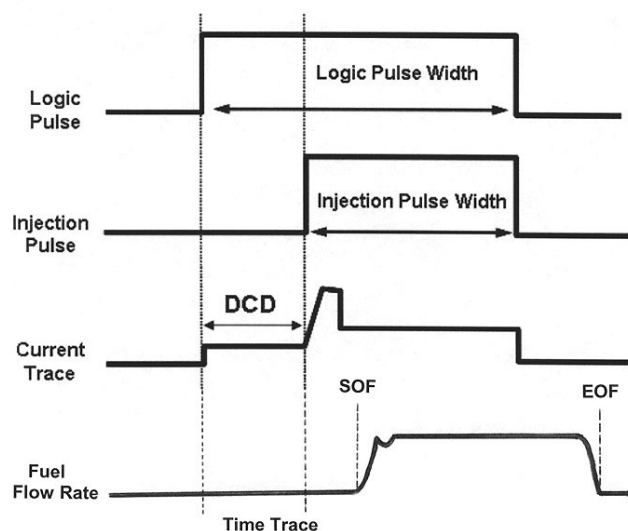


Figure 3 – Key Definitions in the Correct Usage of Pulse Width Terminology

70 There are further important considerations in selecting a representative time for spray imaging. The primary electronic logic pulse from the engine controller may be delayed by the DCD time, following which the actual injector opening time for the lifting of the injector pintle from the seat will be delayed by the mechanical opening time of the injector. The appearance of the first fuel at the injector tip, which is the initiation of the spray event, will not occur until these two time periods have elapsed. The values obtained from spray imaging are significantly affected by the image time selected, due to the fact that the spray is rapidly developing (and penetrating) with time. Hence, the flash time relative to other time markers in the system electronics must be chosen carefully, and should be clearly indicated when the acquired data is reported. As the SAE J2715 document was being developed it became evident that there were numerous in-house procedures for selecting the time to use in imaging the spray (the flash time), which included many combinations of whether or not to account for the DCD and/or the injector opening time. Therefore, it has been quite commonplace to not know the precise time basis that was used in procuring the data when spray imaging data are being presented. Without such information the data cannot be verified by retesting.

Thus, there are two basic questions that must be addressed prior to the imaging of sprays for the determination of the spray angle, the spray-tip penetration and the spray bend angle of a G-DI fuel spray; what precise imaging time is to be used, and when does that time start? As is evident in the timing diagrams in Figure 3, the DCD time (if it is present) should be ascertained and taken into account in establishing and reporting the time to be employed for spray imaging, particularly if the initiation of the electronic trigger phasing is the start of the logic pulse from the ECU. In the SAE J2715 document these considerations are fully discussed, and standardized procedures are recommended. For example, the fundamental imaging time for a G-DI spray is established as 1.50 ms after the time of the first appearance of fuel at the injector tip (SOF), which is independent of the duration of the mechanical opening time and the presence or absence of a DCD. This does, however, require a determination of the time of first fuel relative to the start of the ECU logic pulse. For PFI injectors the fundamental imaging time (used if required for penetration only) is specified as 5.0 ms after SOF.

PATTERNATION CONSIDERATIONS

The application of mechanical patternation (mass collection) to direct injection fuel sprays is not recommended due to the significant percentage loss of fuel that is associated with the reduced penetration and rapid evaporation of the very small drops. This results in a significant percentage of the fuel in each spray event that is never collected and measured in the patternator collection cells. Thus, it is specified in SAE J2715 that mechanical patternation should not be applied to G-DI sprays. Mechanical patternation measures the 2-D fuel mass distribution, and the cone angle is derived from the

radius corresponding to 90% cumulative mass as measured from the centroid of that distribution. The lack of a measured mass distribution for a G-DI fuel spray means that the usual cone angle calculation based upon such a distribution cannot be conducted, thus, strictly speaking, there is no known "cone angle" for the spray from a G-DI injector. The confusion regarding the angular extent of a G-DI fuel spray is traceable to the common practice within the industry to use the term "cone angle" for both PFI and G-DI sprays. For G-DI sprays, a common industry practice is to obtain a photo of the spray, measure the angle of the spray boundary at some distance down from the tip, and then denote this as the cone angle. It is here emphasized that the value acquired in this manner does not at all correspond to the mass-based PFI cone angle, and is not a measurement of the same physical characteristics. The solution to this practice that is recommended in SAE J2715 is to create a new term for the imaged angular extent of the G-DI spray, as imaged and analyzed according to a strictly defined protocol. This new recommended term is the G-DI "Spray Angle", which is addressed in detail in the section on G-DI Spray Angle Measurement.

EXPERIMENTAL TEST PROTOCOLS IN SAE J2715

Detailed test protocols for nearly every fuel spray characterization variable have been developed, and are sequentially listed in SAE J2715 according to the class of injector that is being tested. The test configurations and procedures for the measurement, data reduction and reporting of fuel spray characteristics are only briefly outlined here. The specific details on the test procedure and data reduction may be found in the SAE J2715 document.

In general, undertaking the task of measuring the key fuel spray variables such as the mean drop size or the cone angle is not to be taken lightly. Highly specialized laboratory facilities, safety equipment and test instrumentation are required, and, even with such facilities, significant time may be required to configure and align the test optics, and to acquire the many data points. Nearly all fuel spray characterization data is obtained in dedicated spray laboratories that are also laser optical laboratories. This implies that the technical staff conducting the tests must also be highly skilled in operating the instruments. The level of sophistication for the required instrumentation is higher for the measurement of the spray microscopic properties such as drop sizing than for the overall macroscopic properties such as spray-tip penetration. For these reasons, it is recommended in SAE J2715 that spray testing be done in an order starting with the geometric, macroscopic characteristics, which are obtained by imaging or patternation. Once those spray parameters are determined, the measurements can progress towards the detailed microscopic measurements, such as drop sizing. The macroscopic measurements are generally less difficult to perform and, in addition, can provide information that significantly facilitates the