

Development and Validation of the SAE J3052 High Pressure Differential Flow Rate Recommended Practice

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ABSTRACT

This paper describes the development work that went into the creation of the SAE J3052 “Brake Hydraulic Component Flow Rate Measurement at High Delta Pressure”, and also shows some example applications. The SAE J3052 recommended practice is intended to measure flow characteristics through brake hydraulic components and subsystems driven by pressure differentials above 1 bar, and was anticipated by the task force to be invoked for components and subsystems for which pressure response characteristics are critical for the operation of the system (such as service brake pressure response and stopping distance, or pressure rise rate of a single hydraulic circuit in response to an Electronic Stability Control command). Data generated by this procedure may be used as a direct assessment of the flow performance of a brake hydraulic component, or they may be used to build subsystem or system-level models.

Two significant variants of test methodology were studied, including use of a servo-actuator against a hydraulic cylinder to push fluid through the test specimens at a high rate, and the use of a high pressure pump to create a target pressure differential across the test specimen.

In the course of test development, experiments were run with two different calibrated orifice sizes, with two different ESC modules (representing common test specimens), and two different calipers (relevant to the servo-actuator based method). Data derived from each method were fitted into brake system models for two different vehicle (a car and a light truck). Observing which method produced better correlation to physical vehicle test results was the final arbiter of the best methodology, and shaped the final form of the recommended practice.

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INTRODUCTION

In calendar year 2014, the SAE J3052 task force was formed to create a recommended practice for measuring flow rates in hydraulic brake components and subsystems driven by large pressure differentials. This task force was formed largely from the members of the SAE J2994 task force, that had SAE Just completed work on the recommended practice for measuring flow rates at low delta pressures (below 1 bar).

The newly formed task force acknowledge that several new mega-trends in the automotive industry would likely increase the need/ usefulness of industry standard methods for measuring hydraulic component flow rates. Globally increasing fuel economy and carbon emissions standards are pushing tighter and tighter balancing of stopping distance and tire rolling resistance, elevating the need for very accurate (usually model-based) pressure response time

estimation to determine the brake system's role in stopping distance. Proliferation of new apply system technologies is creating new, highly complicated system integration considerations, with less tune-ability for response time characteristics during development, which also drives the need for accurate response time modeling early in vehicle program architecting. Finally, enormous pressure to reduce development costs and speed up development times are simultaneously reducing the availability of test vehicles, and compressing development timelines, which creates greater incentive for up-front modeling work.

Since the core brake components that typically influence system pressure response characteristics are commonly shared across suppliers' customer base, it made logical sense to seek industry-standard methods for performing measurements and presenting test data.

This paper is organized into 7 key sections for readability:

1. Considerations for test development
2. Servo-Hydraulic Actuator based Test Development
3. High Pressure Pump based Test Development
4. Comparison of Data from both methods
5. Brake System Modeling Results
6. Summary and Conclusions
7. Future Work

1. CONSIDERATIONS FOR TEST DEVELOPMENT

Brake events that lead to the high pressure differentials that are the subject of SAE J3052 are by their very nature highly transient, and take place over a very short time period (it is the forcing of a relatively large slug of fluid through flow restrictions in a very short time, after all, that generates the high pressure differentials). Examples of events that fit this description include stopping distance tests / panic brake applications, Electronic Stability Control (ESC) events, Traction Control System events (TCS), and Active Safety/ Crash Mitigation (AS/CM) system events.

Typical events start with the brake system in an un-applied, un-pressurized “rest” state. Fluid from the master cylinder, or from an electric pump, is then forcibly pushed into the brake system. This causes a pressure wave, accelerating brake fluid in the system and causing it to flow. Fluid is displaced into one or more brake calipers (depending on the event), forcing the piston(s) out against the pads and in turn against the brake disc(s). As the caliper fills with fluid, it requires higher and higher pressure to force more fluid in - the flow rate slows and the pressure differential across the brake system reduces. An entire event - such as a reaching the front wheel slip threshold in a stopping distance test where the Antilock Brake System (ABS) starts to modulate pressure - can take as little as 200 milliseconds.

A significant consideration in the development of a procedure to simulate these conditions was whether it was important or not to reproduce this highly transient flow, with acceleration and deceleration of the fluid. This would certainly be the most realistic, however, it is considerably more difficult to measure accurately and repeatably. Steady-state flow measurements have proven very useful in characterizing hydraulic flow in other situations (such as the low pressure differential flow testing described in SAE J2994 [3]).

These competing effects - getting the most accurate reproduction of the flow during an event by including all of the transients, versus getting the most accurate measurement of the flow - were explored through testing. Two key testing concepts were explored - a test set-up using a servo-hydraulic actuator against a master cylinder, and

forcing fluid through the system into a caliper, much like in a real vehicle, and a different setup, that used a high powered pump to circulate fluid through the component(s) of interest at a high enough flow rate to reach the pressure differentials of interest.

Each of these test set-ups are described, along with some illustrative test results, in the ensuing sections.

2. SERVO-HYDRAULIC ACTUATOR BASED TEST DEVELOPMENT

Background and Test Set-Up

A Link™ Model 3900 dynamometer (typically used for NVH testing in the General Motors Milford Proving Grounds Brake Laboratory), equipped with a servo-hydraulic actuator acting against a master cylinder, was used for test development. As noted in the preceding section, this methodology allowed brake events to be reproduced in a realistic manner, with the master cylinder ramming a slug of fluid through the brake system (and therefore through the component being tested), and into a brake caliper.

The test set-up is shown in diagrammatic and photographic form in [figure 1](#). Three pressure transducers in total were used - two were built into the dynamometer (one at the output of the servo-hydraulic actuator, and the other SAE Just after the flow meter, close to the brake hardware on test). The third was installed directly into the brake caliper through the bleeder screw location and read into an auxiliary data acquisition port on the dynamometer. The dynamometer was equipped with a gear-type flow meter, which would be the primary measure of flow rate.

The authors will comment here briefly for the benefit of readers that may consider using similar equipment for highly transient measurements - it was found during testing that the signal conditioner used for the flow meter caused a small time delay in reporting the signal to the main data acquisition system. This caused enough of a delay such that the occurrence of peak pressure-driven flow rate lagged behind the occurrence of peak pressure differential (enough so that it could not be comfortably explained as a pressure wave in the system, which would theoretically propagate from the pressure transducer to the flow meter at the speed of sound, contributing to a lag of only a couple of milliseconds). To avoid confusion, it will also be foreshadowed here that testing by this method tended to produce two “peaks” in flow, one which likely was inertial and related to the initial pressure wave, and the other driven mainly by the pressure differential. To resolve the time lag in the instrumentation, both the raw and the conditioned signal from the flow meter were recorded into the dynamometer’s main data acquisition system. The raw signal was used to synchronize the time scale of the conditioned signal to the rest of the measured data.

A matrix of tests was completed, testing a range of target apply rates, target peak pressure levels, and Devices Under Test (car and truck ABS units with car and truck calipers). The test plan is summarized in [figure 1](#):

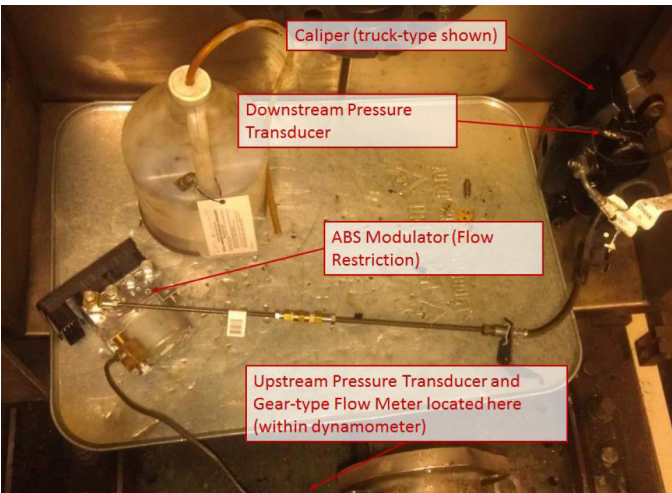
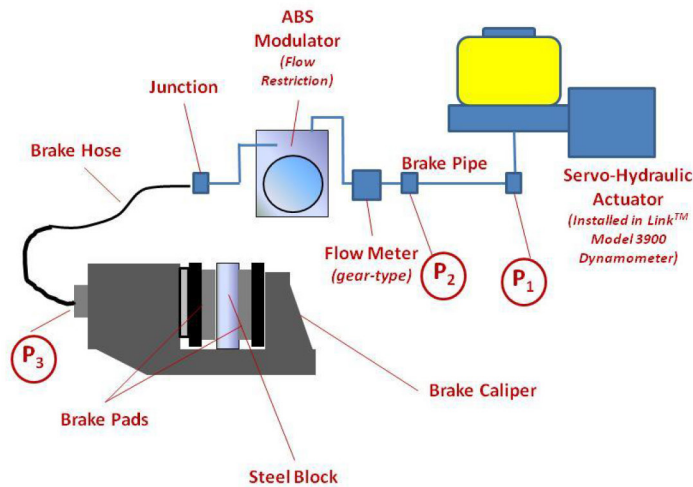


Figure Set 1. ABOVE - Block Diagram of Dynamometer (Servo-Hydraulic Actuator) Base Measurement; BELOW - photograph of set-up

From the data collected, the pressure difference across the test specimen (the antilock brake control unit) could be computed in real time, and the volumetric flow rate was recorded direction via the flow meter.

[Figure 3](#) shows a pair of typical data traces versus time from these measurements - one with the car caliper and matching ABS control unit paired, and the other with a swap to the truck ABS unit on otherwise the same test setup. Both example runs were at a target 50 MPa/sec apply rate and 20 MPa pressure target.

Run	Caliper	ABS	Target Apply Rate	Target Pressure
--	--	--	bar/sec	bar
1	car	car	200	100
2	car	car	200	200
3	car	car	500	100
4	car	car	500	200
5	car	car	1000	100
6	car	car	1000	200
7	car	truck	200	100
8	car	truck	200	200
9	car	truck	500	100
10	car	truck	500	200
11	car	truck	1000	100
12	car	truck	1000	200
13	truck	car	200	100
14	truck	car	200	100
15	truck	car	200	200
16	truck	car	500	100
17	truck	car	500	200
18	truck	car	1000	100
19	truck	car	1000	200
20	truck	truck	200	100
21	truck	truck	200	200
22	truck	truck	500	100
23	truck	truck	500	200
24	truck	truck	1000	100
25	truck	truck	1000	200

Figure 2. Servo-hydraulic actuator-based flow measurement test matrix

In both example runs, the flow rate quickly reaches a transient peak, and there is some initial fluctuation in the flow rate (either due to the dynamics of the flow meter, or possibly due to pressure wave propagation and reflection within the hydraulic system on test). The peak “steady” flow occurs at approximately the time the peak pressure differential occurs, and then both flow and pressure differential taper off as the caliper fills with fluid. By comparing the car and truck ABS control unit test results in [Figure 3](#), one can immediately see that there is a measureable difference in flow characteristics, with the flow rate of the hydraulic system with the car ABS control unit reaching over 32 cc/sec, but the same hydraulic system with the truck ABS control unit reaching only 21 cc/sec.

[Figure 4](#) shows the same data in a different format; in these plots, the flow rates are plotted versus the square root of the pressure differential. This gives a fairly linear relationship (which confirms the model used by Pang and Agnew in representing the flow through an orifice restriction [1]). The data points floating above the main curve are from the initial “bounce” in the flow rate before the flow takes on a steady relationship versus the pressure differential.

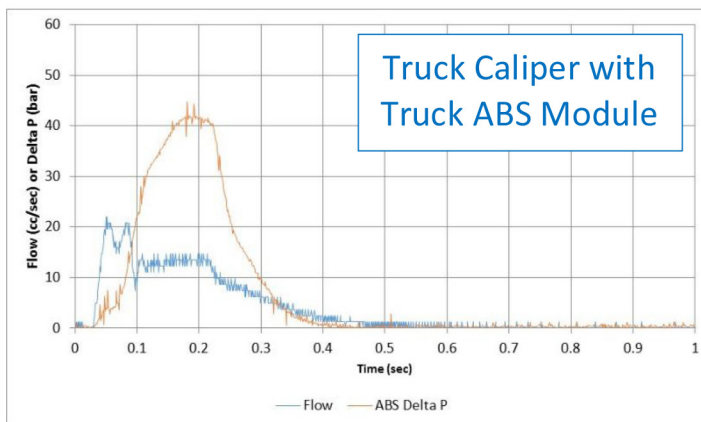
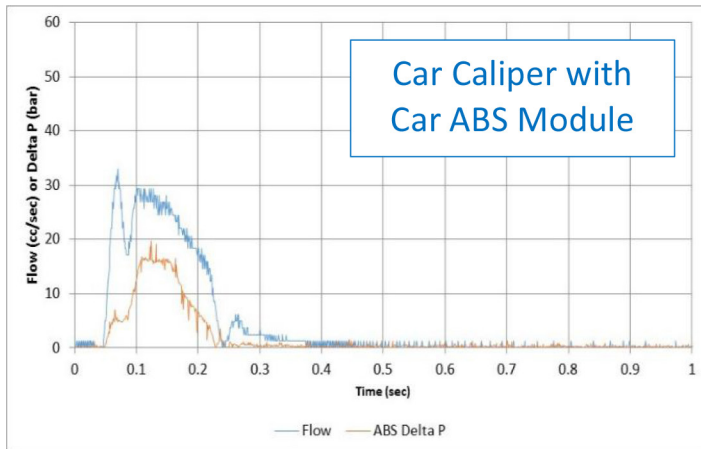


Figure Set 3. Measured Flow Rate and Pressure Drop across ABS Module -ABOVE Car Caliper with Car ABS Module; BELOW Car Caliper with Truck ABS Module.

The slope of the flow rate versus square root of the pressure differential becomes a “flow coefficient” that relates the flow rate to the square root of pressure. In the equation used by Pang and Agnew (below), this flow coefficient is the ratio of the geometric flow coefficient, C_i , to the square root of the fluid density, ρ :

$$Q_i = \frac{C_i}{\sqrt{\rho}} \sqrt{\Delta P}$$

In this manner it may be seen that these measurements suggest that the car ABS control unit flows more than 3 times more volume for a given pressure differential (note - this contrasts somewhat with the steady flow measurements, see [section 4](#)).

The results of the full test matrix represented in [figure 2](#) were summarized as flow coefficients (normalized by density - what is reported is the $C_i/\rho^{0.5}$ in [equation 1](#) above). Flow coefficients (the slope of the flow volume versus square root of the pressure differential) regression were fitted to the full pressure differential range, and then also piece-wise to 0.1 sec intervals through the first 0.5 seconds of the event. The full table of results may be seen in [Appendix A](#). [Figure set 5](#) summarizes the main effects of caliper type, ABS control module, and target apply rate:

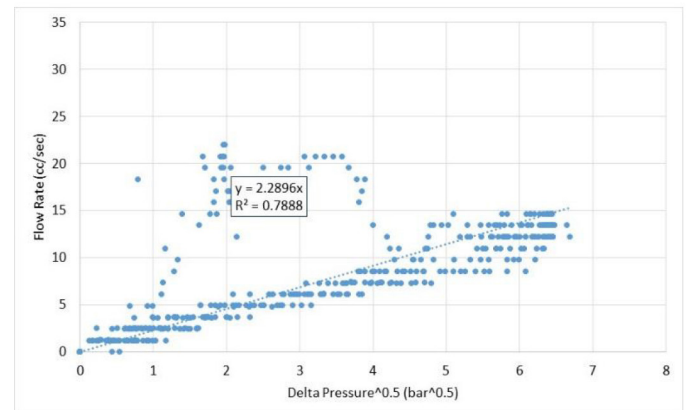
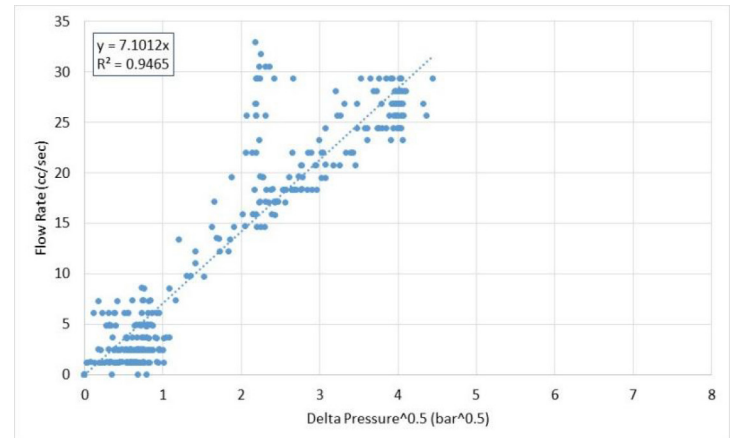


Figure Set 4. Flow Rate versus the Square Root of Pressure Differential across ABS Module - ABOVE Car Caliper with Car ABS Module; BELOW Car Caliper with Truck ABS Module.

After opening with a strong caution - this method tended to produce flow coefficients that are notably higher than the method that was ultimately selected - one may note that the test results tended to make intuitive sense. The caliper type had minimal effect, which was anticipated given that its role in the process was mainly to collect fluid, and should have no direct effect on the flow characteristics of the hydraulic system (it would have the peripheral effect of altering the time-dependent parameters, such as rate of pressure build in the caliper, and time spent within a given pressure differential range; this effect would be small). The ABS control unit, which was anticipated to be the main flow restriction of the system due to the internal valves, had a significant effect on the flow coefficient. The apply rate had a modest effect, with the flow coefficient increasing slightly with increasing apply rates.

In addition to the test matrix shown in [figure 2](#), two calibrated orifice restrictions were measured, one with a 0.7mm diameter cross section, and the other with a 1.0mm diameter cross section. The orifices were included since their flow geometry is much simpler than that of the ABS control units, and allows for a more straight-forward comparison of test methodologies. Summary results for the orifice tests are shown in [section 4](#), in comparison to results of testing the same orifice block samples with the SAE J3052 recommended steady flow method.