

Automotive Brake Hose Fluid Consumption Characteristics and Its Effects on Brake System Pedal Feel

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04/12/2010David Antanaitis, Mark Riefe and Joel Sanford
General Motors Corporation

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ABSTRACT

During the automotive brake system design and development process, a large number of performance characteristics must be comprehended, assessed, and balanced against each other and, at times, competing performance objectives for the vehicle under development. One area in brake development that is critical to customer acceptance due to its impact on a vehicle's perceived quality is brake pedal feel. While a number of papers have focused on the specification, quantification and modeling of brake pedal feel and the various subsystem characteristics that affect it, few papers have focused specifically on brake corner hoses and their effect on pedal feel, in particular, during race-track conditions. Specifically, the effects of brake hose fluid consumption pedal travel and brake system response is not well comprehended during the brake development process. This paper introduces the basic construction of automotive brake hoses, the test methodologies and test results used to quantify brake hose fluid consumption under various operating conditions, and it illustrates the influence of hose performance at the vehicle-level using simple analyses on an example race track-capable sports car.

INTRODUCTION

Automotive brake system performance is multifaceted and includes pedal feel, stopping distance, vehicle stability, NVH, thermal and lining life considerations, and park brake performance. Two areas that are of particular interest to brake system design and development engineers are brake pedal feel and stopping distance. While a great deal of effort is expended on the research, quantification, and modeling of brake subsystems and components and their resultant effects on system-level pedal feel and stopping distance performance, corner brake hoses have not received as much

attention in terms of their performance effects. In particular, brake hoses can have a significant effect on corner-level and system-level fluid consumption as well as brake system response time, especially when viewed in terms of their overall contribution to a brake system's total weight.

Very little published work shows up in a literature search that directly relates to hose performance, with much of what literature are available focusing on hose durability and routing - subjects of perhaps the highest priority when it comes to brake hose design, and which do provide some important insight into general behavior of brake hoses, but are generally not focused on assessing the impact of the hose on brake system performance [1,2,3,4,5]. A review of research published on the properties of common brake hose construction materials suggests some expected behaviors, however. Work by Liang, Takahara, Saito, and Kajiyama [6] explored dynamic viscoelasticity and fatigue in polymeric fibers, including PVA (common in tire and brake hose construction). Earlier work by Willet [7] studied the viscoelastic properties of reinforcing fibers of tire cords, including rayon (a common hydraulic hose reinforcing material). Considering stainless braided hose - no literature searches were conducted on the properties of stainless steel, since the operating temperatures of hoses are expected to be well below the level at which the mechanical properties of steel change significantly, so efforts were focused on the PTFE inner tube. The work of Rae and Brown [8] revealed some of the mechanical properties of PTFE, including changes with temperature, and the work of Hernandez-Jimenez, Hernandez-Santiago, Macias-Garcia, and Sanchez-Gonzalez describes some of the viscoelastic behavior of PTFE [9]. The work of Evans and Wilcox [13], which focused on modeling steel fiber-reinforced thermoplastic high pressure hose, nonetheless offers some applicable theories on

some key behaviors that are indeed common with automotive polymer-reinforced hoses, including hysteresis.

This paper presents the results of a series of studies focused on quantifying the fluid consumption of brake hoses and the effect of this fluid consumption on system-level performance. The influences of hose length, rubber vs. steel braided construction, operating temperature, and pressure cycling during simulated race-track conditions were explored in the course of these studies. Analyses to relate hose performance to brake system-level performance such as pedal travel and hydraulic pressure response time were based on an example vehicle configuration. The example vehicle was a high-performance, race-track capable sports car with relatively small piston bores and low caliper fluid consumption.

This paper is presented in the following sections:

1. Brake Hose Construction Overview
2. Brake Hose Fluid Consumption Test Methodology
3. Phase 1: Ambient Temperature Fluid Consumption
4. Phase 2: Ambient Temperature Race-Track Pressure Profile Cycling
5. Phase 3: Fluid consumption vs. Temperature Testing
6. Phase 4: Elevated Temperature Race-Track Pressure Profile Cycling
7. Modeling of Effect of Brake Hose Fluid Consumption on Brake System Performance
8. Conclusions
9. Future Work

Throughout this paper, the term ‘fluid consumption’ is used to describe the volume of brake fluid that must be absorbed into the brake hose to support the hydraulic pressure that is supplied to it.

1. BRAKE HOSE CONSTRUCTION OVERVIEW

Automotive brake hydraulic hoses are of composite construction, typically with 5 layers. The innermost layer seals in the brake hydraulic fluid, and is typically constructed of EPDM (Ethylene Propylene Diene Monomer) or neoprene. This layer is typically wrapped in a reinforcing fiber weave layer, followed by an intermediate cushion layer of EPDM, neoprene or adhesive, a second reinforcing fiber weave layer, and finally, an outer covering of EPDM, neoprene, or Hypalon (this layer is typically minimized or even eliminated to minimize hose expansion). The reinforcing fiber weave layers are PVA (Polyvinyl Alcohol), rayon, or polyester. A steel or brass end fitting is installed on both ends. Fittings generally feature an internal pipe that seals against the

interior passage of the hose, and an external sleeve that is crimped over the outer covering of the hose to lock it into place. The crimp sleeve also provides support to guide the hose and prevent side loads from being absorbed by the internal sealing pipe.

Figures 1 and 2 show the cross-section of each end of one of the subject brake hoses of this paper. This particular hose featured brass end fittings; although zinc-plated steel is also a common end fitting material. The flexible portion of the hose features 5 layers, as described above (EPDM rubber and rayon fiber were used in this particular sample). Figure 3 shows a cut-away of one of the steel braided hoses that was tested (the inset of figure 3 shows the relatively simple tubular construction of the inner PTFE liner):

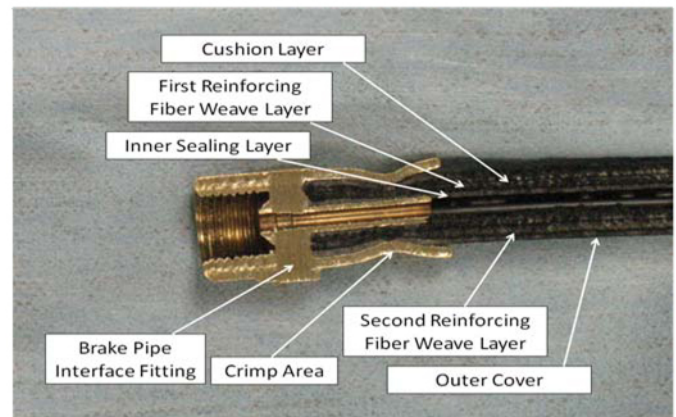


Figure 1. Cutaway of Hose Body-Side (Brake Pipe Interface) End

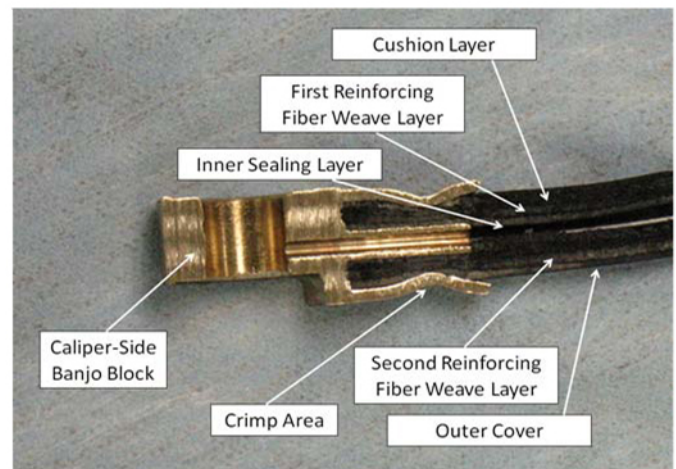


Figure 2. Cutaway of Hose Caliper-Side (Banjo Block) End

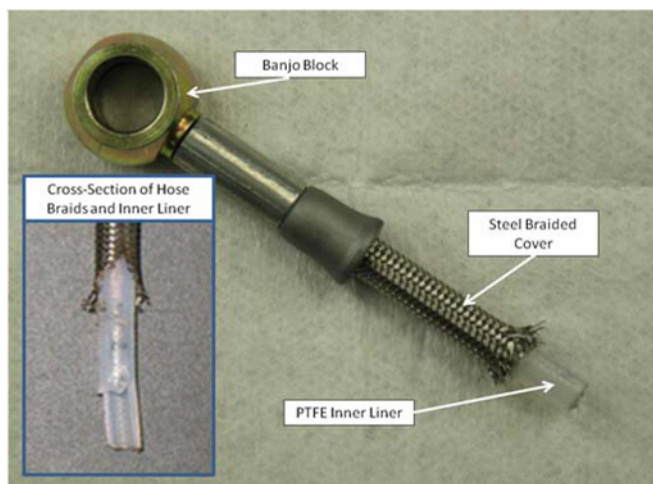


Figure 3. Cut-away of Steel Braided Hose

2. BRAKE HOSE FLUID CONSUMPTION TESTING

Brake hose fluid consumption testing was carried out on two brake dynamometers, each equipped with an apply system capable of both ramp (with a programmable apply rate) and step (20,000 kPa per second) applies. Since both dynamometers were viewed as equivalent for purposes of this study, the remainder of this paper will refer to only one dynamometer for simplicity. Four major phases of testing were completed:

- Phase 1: Ambient temperature fluid consumption testing of multiple hose designs, including one steel braided hose
- Phase 2: Ambient temperature race-track pressure profile testing.
- Phase 3: Fluid consumption vs. Temperature testing of one rubber and one steel braided hose
- Phase 4: Elevated temperature race-track pressure profile testing of rubber hose.

3. PHASE 1: AMBIENT TEMPERATURE FLUID CONSUMPTION TESTING

This first phase of testing was aimed at quantifying the fluid consumption characteristics of a wide range of different rubber hose designs and lengths. A total of 33 rubber hoses from 8 different manufacturers, with rubber section lengths ranging from 102 up to 670mm were included, along with a steel braided hose in two lengths but otherwise similar construction (245 and 400mm between end fittings).

One end of each brake hose sample was connected to the hard plumbing (steel brake line) of the dynamometer, and the other

end of the brake hose was connected to a bleeder block. The hose was bled, using a low pressure bleed, to remove any air trapped in the system. Once the bleed was complete, the hose was subjected to three pressure ramp applies (5000 kPa/sec, up to 13,000 kPa). Fluid displacement and pressure data were collected and analyzed. The test setup is shown schematically in [figure 4](#).

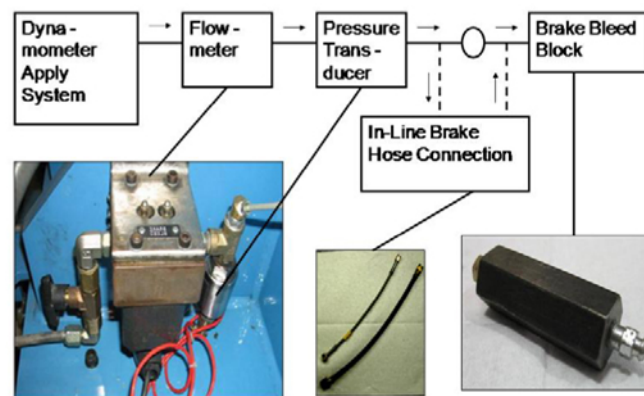


Figure 4. Schematic of Test Set-Up

In addition to understanding the fluid consumption (related to expansion) of a brake hose, the test equipment (a single-ended inertia dynamometer) needed to be measured for fluid consumption because the pressure transducer is mounted downstream of the brake fluid flow meter. To do this, the brake hose was removed and the brake pipe was capped. Once the brake pipe was capped and bled, ramp applies were performed to measure fluid consumption of the dynamometer and brake pipe.

The corrected fluid consumption results for a subset of the brake hoses tested are displayed in [Table 1](#) (the shortest, a median length, and the longest), as are the fluid consumption results for the two dynamometers used to support this study. For a full table of results please consult [Appendix A](#). The corrected results were calculated by subtracting the measured fluid consumption of the dynamometer from the measured fluid consumption of the brake hoses with the dynamometer (the first dynamometer was used for phases 1 and 2 of testing, and the second dynamometer for phases 3 and 4). To aid in comparison, results are normalized to the length of the hose. Results are also shown graphically in [figures 5](#) and [6](#). [Figure 5](#) shows the hose fluid consumption (normalized by hose length) plotted against hose length for all of the hose samples tested. [Figure 6](#) shows hose fluid consumption per unit length for hoses (selected to represent the span of hose lengths tested) plotted against hydraulic pressure. A comparison with SAE J1401 specifications is also shown in [figure 6](#):

Table 1. Summary of Brake Hose Fluid Consumption at Discrete Pressure Levels - Ordered from Shortest to Longest Length

Hose Type and Length	Normalized Fluid Consumption (cc/meter length)				
	500 kPa	1000 kPa	2500 kPa	5000 kPa	12,000 kPa
EPDM(102 mm) R	0.321	0.503	0.589	0.882	1.288
EPDM (330 mm) F	0.095	0.175	0.271	0.444	0.762
EPDM (670 mm) F	0.039	0.086	0.200	0.386	0.751
PTFE Stainless (245 mm)	0.039	0.064	0.108	0.291	0.560
PTFE Stainless (400 mm)	0.041	0.065	0.117	0.231	0.399
Dyno 1 Fluid Consumption*	0.006	0.010	0.030	0.050	0.129
Dyno 2 Fluid Consumption*	0.015	0.019	0.041	0.078	0.178

***Dyno Fluid Consumption Values are NOT Normalized**

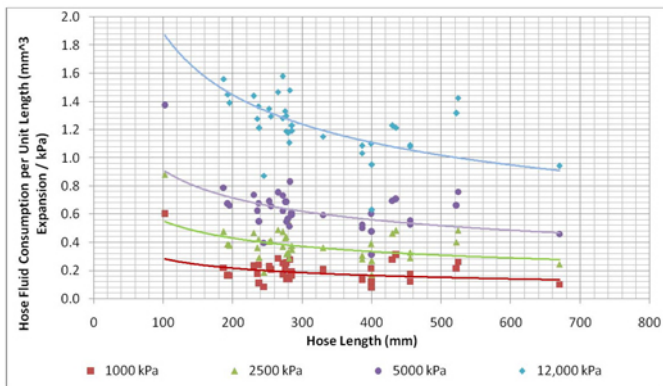


Figure 5. Summary of Brake Hose Fluid Consumption per Unit Length at Discrete Pressure Levels

The hose fluid consumption per unit length tended to decrease as the hose length increased. This phenomenon likely has two main causes: (a) as hose length increases, the added fluid consumption of any air trapped in the test setup (fittings, junctions, hose sample) becomes less and less significant, and (b) the hose material is highly anisotropic due to much of its strength being provided by directional fiber weave layers with significantly higher hoop stiffness than axial stiffness (due to the angles of the reinforcing fiber orientation). An unrestrained (as in this test) 3/16" cross section hose must support up to 214N of axial force at 12,000 kPa of hydraulic pressure, which can cause appreciable axial expansion in addition to the circumferential expansion. As hose length increases, the ratio of its surface area to its cross-sectional area increases, and the influence of its axial expansion under pressure relative to its circumferential (radial) expansion becomes less significant.

Almost all hoses tested meet the expansion requirements of SAEJ1401 for 'Low Expansion' hoses; and all met the requirements for 'Regular' hoses by a significant margin. This is expected, as this population of hoses were designed to lower hose expansion (fluid consumption) limits than the SAE J1401 'Regular' hose specifications allow.

All of the rubber hoses tested exhibited hysteresis in the fluid consumption versus hydraulic pressure relationships. To illustrate this, results from the shortest, the longest, and a medium-length hoses are shown in figure 7 below. Hysteresis is defined as the difference between hose fluid consumption at a given pressure while pressure is being released versus while pressure is being applied. It can be expressed as a percentage by taking the maximum hysteresis and dividing by the maximum fluid consumption during the apply-release cycle (percentage values are shown in the legend of figure 7). It is convenient to point out here that the apparent step-wise behavior of the fluid consumption data during the apply is showing the resolution of the fluid displacement transducer on the dynamometer (approximately 10 mm³):

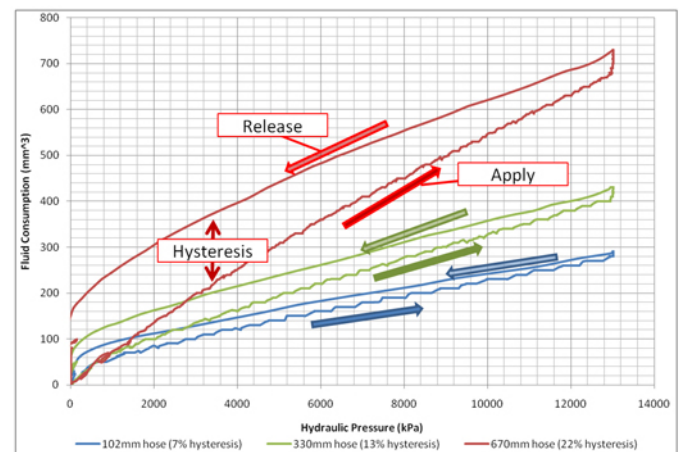


Figure 7. Fluid Consumption vs. Pressure Hysteresis - three representative hose lengths

The rubber brake hoses exhibited significant fluid consumption versus hydraulic pressure hysteresis. Hysteresis appeared to be more pronounced for longer hose lengths. The mechanisms behind the hysteresis were not investigated in detail in the course of this study, but two likely mechanisms are offered for consideration: (a) viscoelastic deformation of the hose inner liner and the fiber reinforcement makes the relaxation of the hose after experiencing pressure time-dependent, and likely following a much slower time scale

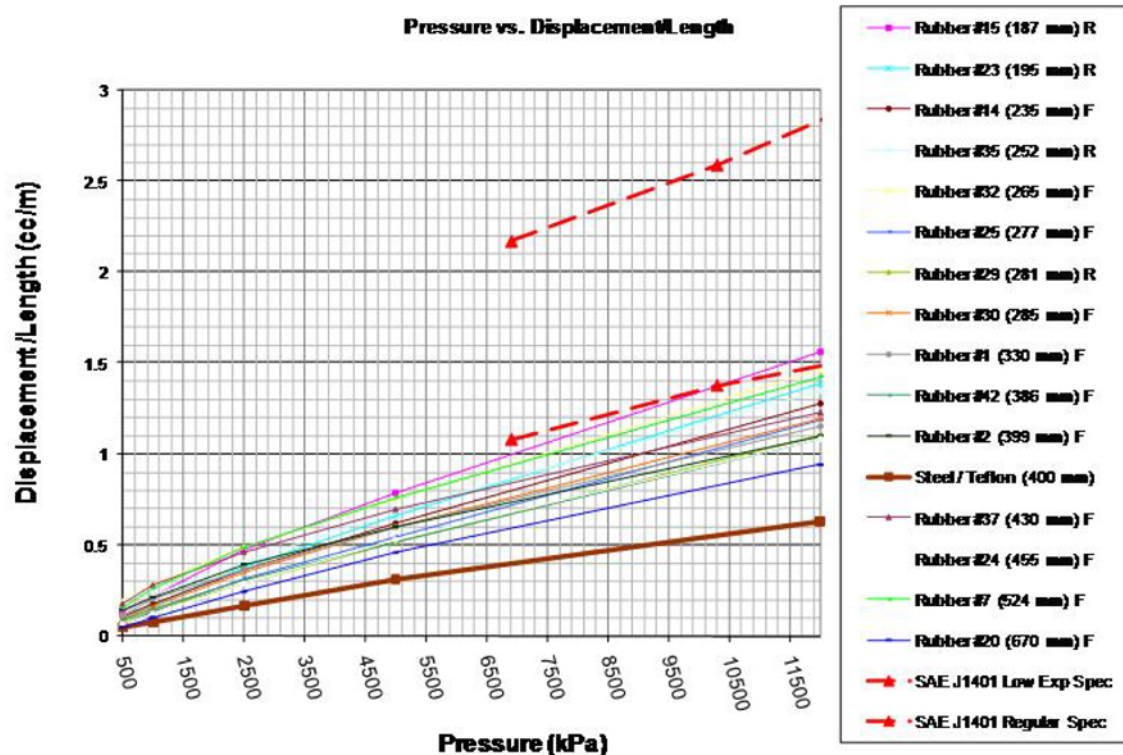


Figure 6. Summary of Brake Hose Fluid Consumption per Unit Length - select hoses

than the apply and release cycle. The hose holds some of the geometry it acquires during the high pressure apply due to the viscoelastic nature of the materials it is constructed from. (b) Movement of strands of fiber reinforcement relative to one another can cause the hose to tend to hold its shape and resist changes in its geometry. This effect requires force to both change the geometry of the hose as pressure is ramped up, and force to return the hose to its original, pre-apply shape as pressure is ramped down (this force is provided by the elastic energy stored in the hose material as its geometry was changed by the application of pressure).

In order to assess how much difference there was from manufacturer to manufacturer in hose fluid consumption characteristics, one hose from each of six manufacturers represented in this phase of the study was selected for comparison. The selected hoses were of as close to the same length as possible. This set of hoses had a median length of 269mm, a minimum length of 237mm, and a maximum length of 282mm. Normalized fluid consumption per unit length was computed at 12,000 kPa hydraulic pressure and plotted in figure 8 below:

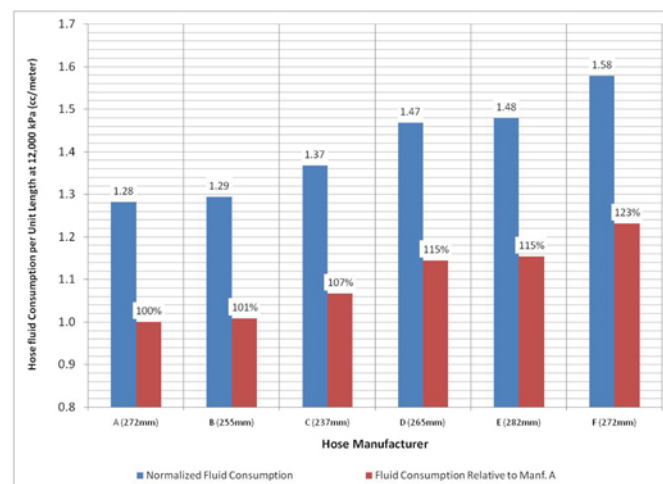


Figure 8. Normalized Fluid Consumption per Unit Length at 12,000 kPa - Various Manufacturers

There was approximately 23% range in normalized (to length) hose fluid consumption at 12,000 kPa across hose samples of similar length from six different hose manufacturers.

As shown in table 1, steel braid clad PTFE hoses in two lengths (245mm and 400mm) were included in this phase of the study. These data were compared to rubber hoses of similar lengths (237mm and 399mm, respectively). The

comparison is expressed in terms of normalized fluid consumption per unit hose length, and is shown in [figure 9](#) below:

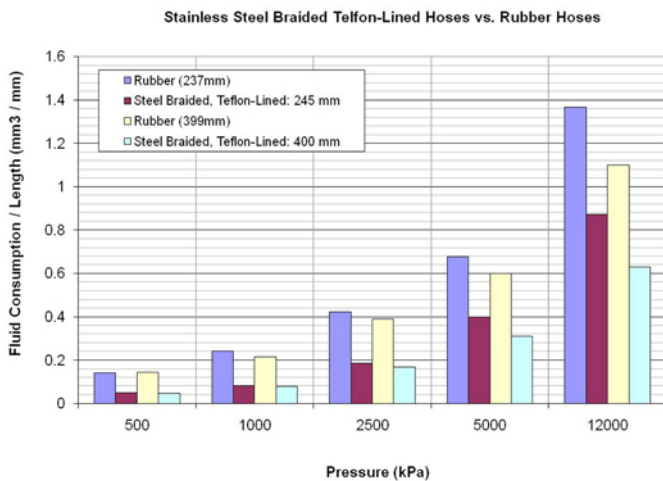


Figure 9. Rubber vs. PTFE/steel braided hose Ambient Temperature Fluid Consumption for Similar Hose Lengths

The PTFE / steel braided hoses offered up to a 52% reduction in hose fluid consumption across the pressure range versus a rubber hose of comparable length.

It is often of interest when performing development work at a brake corner subsystem level to comprehend what the contribution of components within the brake corner is to total fluid consumption. [Figure 10](#) shows the contribution of the brake hose, expressed in terms of the percentage of the total brake corner fluid consumption, for two different caliper sizes (1×38mm, typical used for smaller car rear brake applications, and 2×51mm, typically used in light truck front applications). Data from three hoses were selected to represent the range of hose lengths (102mm, 330mm, and 670mm lengths):

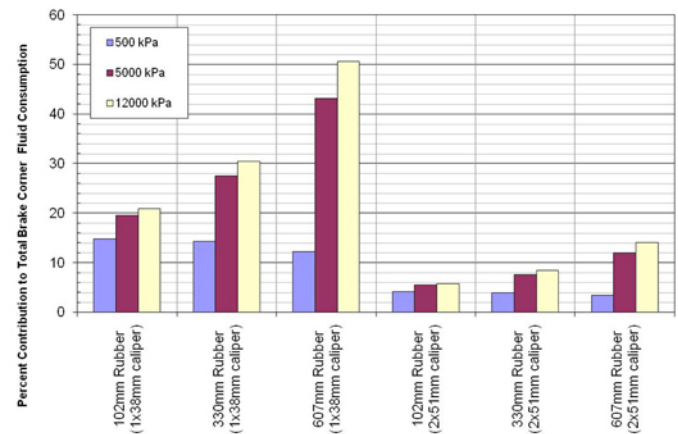


Figure 10. Contribution of Brake Hose to Total Brake Corner Fluid Consumption

The brake hose itself can contribute significantly (on a percentage basis) to the total brake fluid consumption of a smaller-bore (1×38mm) caliper in a brake corner (20 to 50% across the lengths of hoses in this study). It makes a smaller, but still notable, contribution to total brake corner fluid consumption when considering a larger-bore (2×51mm) caliper - 6 to 14% in the range of hose lengths included in this study. Given that the hose assembly generally weighs an order of magnitude less than a caliper; this contribution is significant on a weight-normalized basis.

4. PHASE 2: AMBIENT TEMPERATURE RACE TRACK PRESSURE PROFILE TESTING

This phase of the study was initiated to support diagnosis of a seemingly permanent increase in pedal travel (of approximately 4-5mm at moderate pressure) that occurred in the example vehicle. The increase in pedal travel remained after replacement of the friction material (pads and rotors) and after multiple attempts to bleed the brake system.

To support this activity, hydraulic pressure histories were measured in-vehicle and re-created on the brake dynamometer to study what effect pressure cycling of this type had on hose fluid consumption. For correlation, brake hoses removed from a vehicle that had seen approximately 36 tanks of fuel of race track usage were measured. A test script was developed to subject two new front rubber brake hoses to pressure cycling experienced on the example vehicle while running laps on the Milford Road Course (a closed loop, high speed road course [10]). The pressure cycle profiles (see [Appendix B](#)) were developed from vehicle data, and used for the pressure cycling test. The number of cycles was based upon vehicle testing as follows:

- 1 cycle = 9 pressure sequences (represents 9 braking events per race lap)