**FSAE Tire Test Consortium -- ROUND 8**

From: Edward M. Kasprzak, FSAE TTC Co-Director
To: FSAE TTC members
Date: 31 August 2018

This document describes the tests, data and files provided for Round 8 by the FSAE Tire Test Consortium. Please read this document carefully before using the FSAE TTC data.

Contents:



## 1. INTRODUCTION

Round 8 of FSAE TTC testing was conducted from July 30-August 1, 2018 at the Calspan Tire Research Facility. All data is available to FSAE TTC members via the private server at: http://www.fsaettc.org. The public, introductory FSAE TTC website can be found at www.millikenresearch.com/fsaettc.html.

TTC members are reminded of the terms of their membership. The participant agreement (data license) is included at the end of this document along with our privacy policy.

The TTC private forum, http://www.fsaettc.org, exists for students to openly discuss the data without violating the terms of TTC membership.

All TTC members are strongly encouraged to display the Calspan logo on their vehicle and website—several options are available in the "fromCalspan.zip" download. Calspan has given the TTC considerable price breaks through the years, and you should consider them one of your sponsors.

Note: While two of the three Directors are affiliated with Milliken Research Associates, Inc. and the public webpage is hosted at an MRA web address, the FSAE TTC is not part of Milliken Research Associates, Inc.

## 2. ACKNOWLEDGEMENTS

The FSAE Tire Test Consortium has been founded, organized and lead by three co-Directors since its inception in December 2004:

**Dr. Edward M. Kasprzak**, EMK Vehicle Dynamics, LLC and Milliken Research Associates, Inc.
**Mr. Doug Milliken**, Milliken Research Associates, Inc.
**Dr. Bob Woods**, University of Texas, Arlington

Since Round 3, **Brian Seater** (formerly of Washington State University) has contributed greatly to the FSAE TTC. He established and maintains the TTC private forum where students can download and openly discuss the tire data.

**Denny Trimble** (University of Washington) helped establish the FSAE TTC during his student days and moved-on prior to Round 4.

The FSAE TTC has received support from the following organizations:

**Hoosier Racing Tire, Continental AG, The Goodyear Tire and Rubber Company** donated tires and shipped them to Calspan at no cost to the FSAE TTC for the Round 8 tests. All have a long history as excellent supporters of the FSAE TTC.

In past rounds, **Michelin** and **Dunlop Motorsport** have donated tires and shipped them to Calspan at no cost to the FSAE TTC. **Cooper Tire & Rubber Company** has also donated **Avon** tires and shipped them to Calspan at no cost to the FSAE TTC, as well as financing the Round 7 tests.

**Keizer Aluminum Wheels**, http://keizerwheels.com, provided 10 inch wheels at a discounted price.
**Diamond Racing Wheels,** http://www.diamondracingwheels.com, produced the steel 13 inch wheels.

**Calspan Tire Research Facility (TIRF),** https://www.calspan.com/services/transportation-testing-research-equipment/tire-performance-testing/ . Thanks to Dave Gentz, Greg Campbell, and everyone at Calspan for making another round of tire tests possible. Calspan continues to support the FSAE TTC and are always interested to hear of schools applying the data to their FSAE entries. Everyone worked just as hard on this project as they do with their corporate and professional racing customers. The Calspan Tire Research Facility is a top-notch operation—display your Calspan decal with pride on your car and on your website. Be sure to reference Calspan and the FSAE TTC properly when using the data.

Calspan has also provided a presentation describing the Tire Research Facility. This is included in the distribution—see “fromCalspan.zip”.

## 3. OVERVIEW -- ROUND 8

The eighth round of FSAE TTC tests was conducted from July 30-August 1, 2018. The bulk of the test plan is similar to Rounds 6 and 7 with “traditional sweeps” for cornering tests (free-rolling, slip angle sweeps) and drive-brake-combined tests (slip ratio sweeps), along with the low speed transient tests and traditional sweeps at various roadway speeds introduced in Round 6. New in Round 8 are camber (inclination) sweeps at the end of the final free-rolling run on each tire.

The following constructions were tested, each on two different rim widths:

- Continental 43329, 205/470R-13
- Goodyear D2704, 20.0X7.0 13
- Hoosier 43070, 16.0 x 6.0 - 10, LCO
- Hoosier 43070, 16.0 x 6.0 - 10, R25B
- Hoosier 43075, 16.0 x 7.5 - 10, LCO
- Hoosier 43075, 16.0 x 7.5 - 10, R25B

All 10 inch tires were tested on aluminum wheels purchased from Keizer Aluminum Wheels, http://keizerwheels.com . All 13 inch tires were tested on steel wheels purchased from Diamond Racing Wheels, http://www.diamondracingwheels.com .

The wheels are the same as used in previous FSAE TTC rounds. Regardless of rim width or diameter, all wheels have the appropriate backspacing to align the wheel center with the center of the tire tread.

10 inch tires were tested using an offset adapter, so data is collected in free-rolling only. See Section 9 “Test Comments” for details.

Testing of the 10 inch tires in Round 8 went smoothly, while testing of the 13 inch tires did not. See Section 9 “Test Comments” for details.

## 4. RUN GUIDE & SUMMARY TABLES

The test plan and the resulting test data is presented as a series of runs on the test machine. Data for each tire is spread across multiple runs.

There are two documents which provide information on the contents of each run:

**RunGuide_Round8.pdf** provides a one-page summary of the tire/rim combination and test type for each test run. You are strongly encouraged to make good use of this document. Note that a single tire was used for each row in this table. Thus, the tire used for run 5 was also used for runs 6 and 7, as the runs were conducted back-to-back.

**1965 Summary Tables.xls** is provided by Calspan. It contains more detailed information on each run. While understanding this document is not essential, it contains some post-processed metrics which may be useful. This spreadsheet includes the following pages:

- Cornering Test Schedule – description of the free-rolling test runs
- Braking Test Schedule – description of the drive-brake-combined test runs
- Tire ID Schedule – list of tires, including compounds and other sidewall codes
- Spring Rate, CS – Calspan-calculated cornering stiffness, cornering stiffness coefficient, lateral force at zero slip angle and spring rates from the main data sweeps.
- Pre- Post- Spring Rates – spring rates from the numerous spring rate tests throughout the runs
- Tire and Wheel Weights
- Pyrometer Reading – list of carcass temperatures taken with needle probe immediately after the end of each run. Probe temperatures were taken across the tread in three locations—inner edge, centerline and outer edge. Locations roughly correspond to the IR sensor locations.

The summary tables are found in the “fromCalspan.zip” download.

## 5. DATA FILES AND CHANNELS

This is Calspan Tire Research Facility project number 1965. This number is used with the run number to identify each run. For example, a typical data file might be named "1965run7.dat", which is Run 7 in this project.

Data sets have been provided by Calspan in ASCII format. The TTC directors have produced Matlab versions of these files. Both ASCII and Matlab files are available in USCS and SI units. Data files are also divided into "raw" and "run" types. The primary difference is that the "raw" files include all of the data between the main test sweeps, while the "run" files remove most of the in-between points and special test sequences. For some applications, the "run" data will be sufficient.

To summarize, data is presented in the following formats. Each can be downloaded in their own .zip file:

ASCII, USCS units, "raw" data (data files begin with "A", end in ".dat")
ASCII, USCS units, "run" data (data files begin with "A", end in ".dat")
ASCII, SI units, "raw" data (data files begin with "B", end in ".dat")
ASCII, SI units, "run" data (data files begin with "B", end in ".dat")
Matlab, USCS units, "raw" data (data files begin with "A", end in ".mat")
Matlab, USCS units, "run" data (data files begin with "A", end in ".mat")
Matlab, SI units, "raw" data (data files begin with "B", end in ".mat")
Matlab, SI units, "run" data (data files begin with "B", end in ".mat")

Separate .zip files are provided for 10 inch and 13 inch tires.

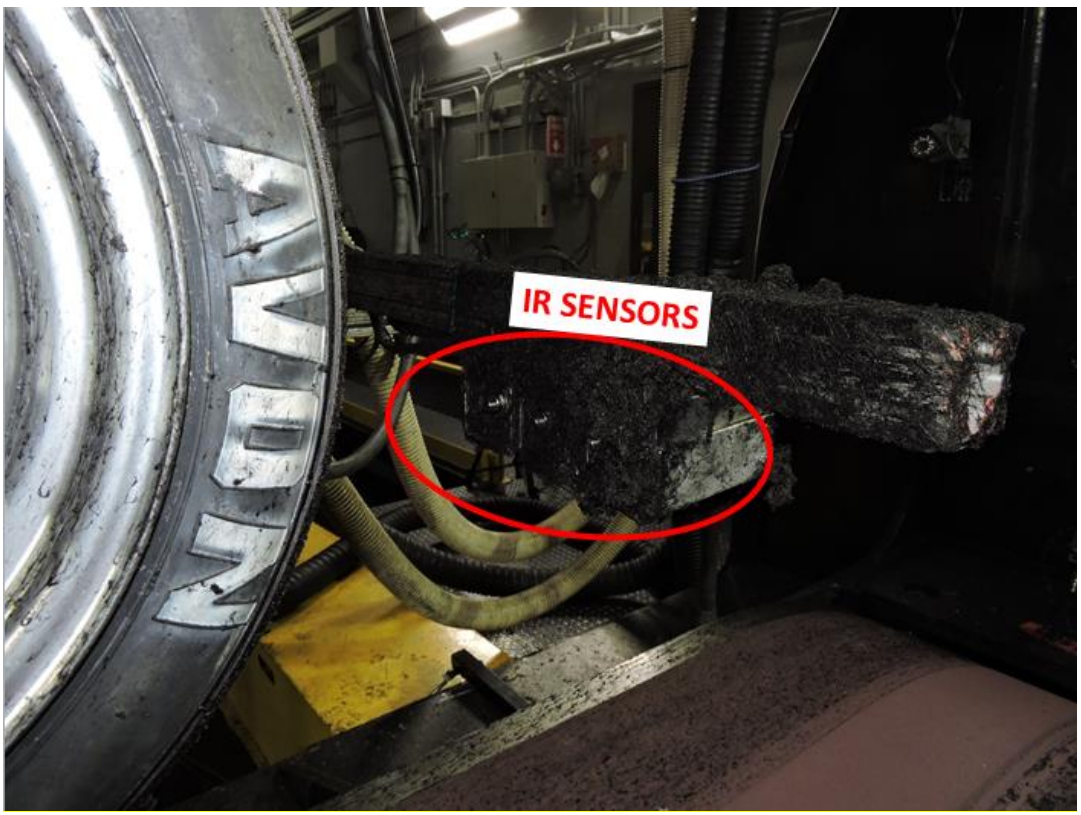
All data is reported in SAE sign convention (see SAE J670e, SAE 2047 or "Race Car Vehicle Dynamics" by Milliken/Milliken, page 39). Data collection occurs at 100 Hz. The data channels are:

| Channel | Units | Description |
|---|---|---|
| AMBTMP | degC or degF | Ambient room temperature |
| ET | sec | Elapsed time for the test |
| FX | N or lb | Longitudinal Force |
| FY | N or lb | Lateral Force |
| FZ | N or lb | Normal Load |
| IA | deg | Inclination Angle |
| MX | N-m or lb-ft | Overturning Moment |
| MZ | N-m or lb-ft | Aligning Torque |
| N | rpm | Wheel rotational speed |
| NFX | unitless | Normalized longitudinal force (FX/FZ) |
| NFY | unitless | Normalized lateral force (FY/FZ) |
| P | kPa or psi | Tire pressure |
| RE | cm or in | Effective Radius |
| RL | cm or in | Loaded Radius |
| RST | degC or degF | Road surface temperature |

| | | |
|---|---|---|
| SA | deg | Slip Angle |
| SL | unitless | Slip Ratio based on RE (such that SL=0 gives FX=0) |
| SR | unitless | Slip Ratio based on RL (used for Calspan machine control, SR=0 does not give FX=0) |
| TSTC | degC or degF | Tire Surface Temperature--Center |
| TSTI | degC or degF | Tire Surface Temperature--Inboard |
| TSTO | degC or degF | Tire Surface Temperature--Outboard |
| V | kph or mph | Road Speed |

For more on SL and SR definitions, see “Race Car Vehicle Dynamics” by Milliken/Milliken, page 62.

The infrared tire surface temperature sensors were mounted in front of the tire (nominally 270 deg from the footprint). The location was similar to Round 6, and a bit higher than Round 7 (Round 7 pictured below). The IR sensor windows were cleaned prior to each run. Stray rubber may have occasionally fouled the sensors during the runs—keep this in mind when interpreting IR sensor data.




Calspan has provided post-run photos of every tire tested.

## 6. TRANSIENT TEST PLAN

The transient test runs are identical to Round 6. They begin with initial spring rate tests. Then, several low-speed transient tests are performed, all at zero inclination angle. See Figure 1. Note that all subplots in Figure 1 have the same x-axis time scale.

Transient tests at each operating condition (load and inflation pressure) involve stopping the tire, steering to a new slip angle at zero speed and then rolling the tire forward slowly. Steer angles of −1, +1 and +6 deg are used, with a return to 0 deg for each step steer. As the tire rolls slowly forward, the force and moment channels respond as the tire seeks a new equilibrium condition, see Figure 2. This response distance, sometimes characterized by a "relaxation length" metric, is an indication of tire transient response.

Figures (from the identical Round 6 tests) appear on the next page.

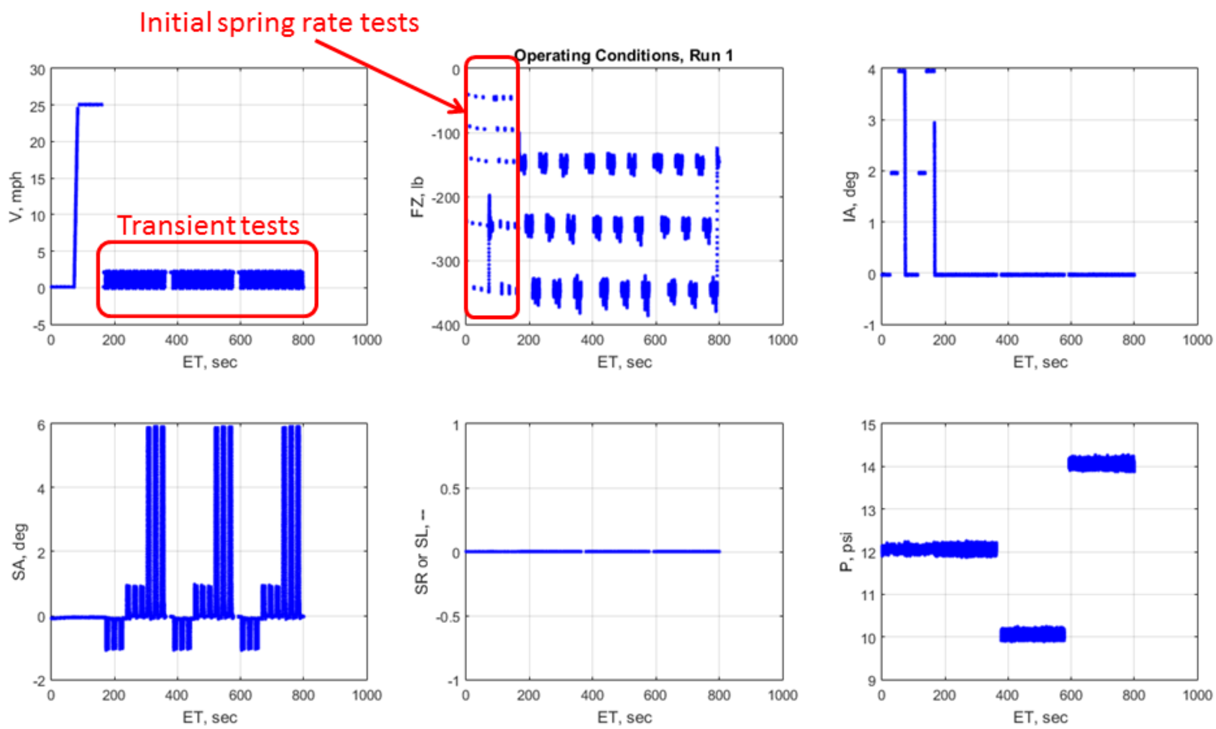



Figure 1.  Transient test plan.

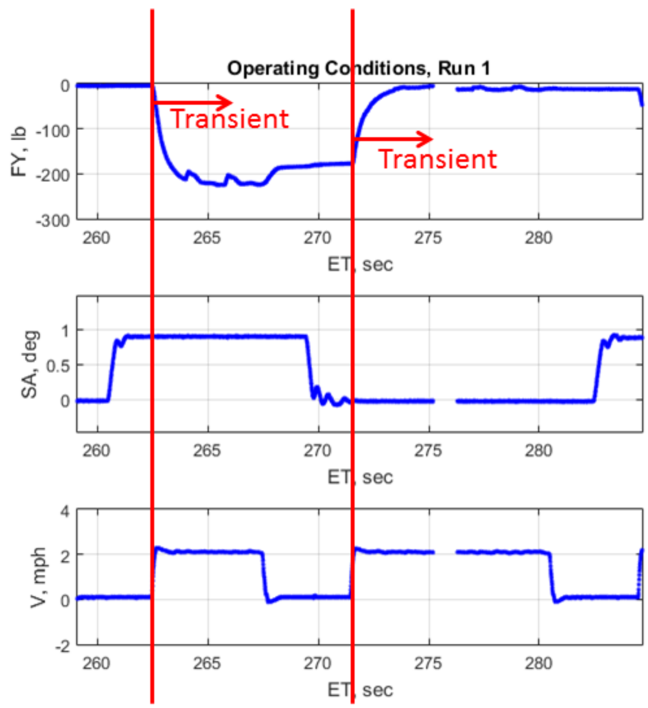



Figure 2.  Lateral force (FY) transient due to step steer in slip angle (SA), with velocity (V) shown. This is one steer out, steer back cycle at one operating condition.

## 7. CORNERING TEST PLAN

The Round 8 cornering test plan was very similar to the one used in Rounds 6 and 7. There are two differences. First, the steer commands have been updated to adjust to changes in Calspan's steering capability. This has been done in an attempt to reproduce the slip angle inputs from previous rounds. This is not an exact process, and the timing of various events in the cornering data will differ slightly from data collected in Rounds 6 & 7. Second, each cornering test now ends with a block of camber (inclination) sweeps. These are discussed toward the end of this section.

The cornering test was run immediately after the transient test using the same tire. Cornering tests are broken in to two runs due to the length of the test and the resulting size of the data files. Figure 3 presents the first half, while Figure 4 presents the second half.

Cornering tests begin with a "cold to hot" series of twelve slip angle sweeps at one load. This helps bring the tire up to temperature and gives an indication of how a new tire changes as it breaks-in and heats up.

There are multiple spring rate blocks in the cornering tests. The initial spring rate test occurs immediately following the cold-to-hot sweeps. The remainder occurs at the end of each pressure block.

There is a break-in block before the main slip angle sweeps start. This further exercises the tire before the main force and moment data is taken.

The main sweeps involve sweeping slip angle through ±12 deg at each operating condition (load, inclination and inflation pressure). The first slip angle sweep block is longer than the rest because it contains a few "conditioning sweeps". These are a last attempt to exercise the tire and stabilize its performance before taking the main block of force and moment data.

In all cornering tests the SAE slip ratio (SL) is zero. The tire is free-rolling.

The first three pressures are completed in the first half of the cornering test, see Figure 3. After a short pause for data collection the test resumes, see Figure 4. Before returning to the main sweeps, another cold-to-hot block is run in an attempt to restore the thermal state of the tire.

Figure 4 shows an 8 psi block. For 13 inch wheels the highest load was reduced at 8 psi from 350 lb to 300 lb to prevent debeading. Other modifications were made for the 13 inch tires in an attempt to discourage debeading—do not expect 13 inch cornering tests to follow the same test plans (each run may be a little different). This is discussed further in Section 9, "Test Comments". For 10 inch tires, the 350 lb load was replaced with a 200 lb load at all pressures.

Figure 4 also includes a 12 psi block. This block is identical to the first 12 psi block in Figure 3. This is an opportunity to compare the two blocks for any changes in performance due to wear or heating.

Next are slip angle sweeps at 15 and 45 mph. These are only run at zero inclination angle and 12 psi. Compare this data with the standard test data at 25 mph to see how velocity affects tire performance.

Finally, new in Round 8 are camber (inclination) sweeps at zero slip angle. These are run at all inflation pressures and three normal loads, sweeping the tire from −4 to +4 deg of inclination angle at zero slip angle.

Figures from Round 8 appear on the next page.

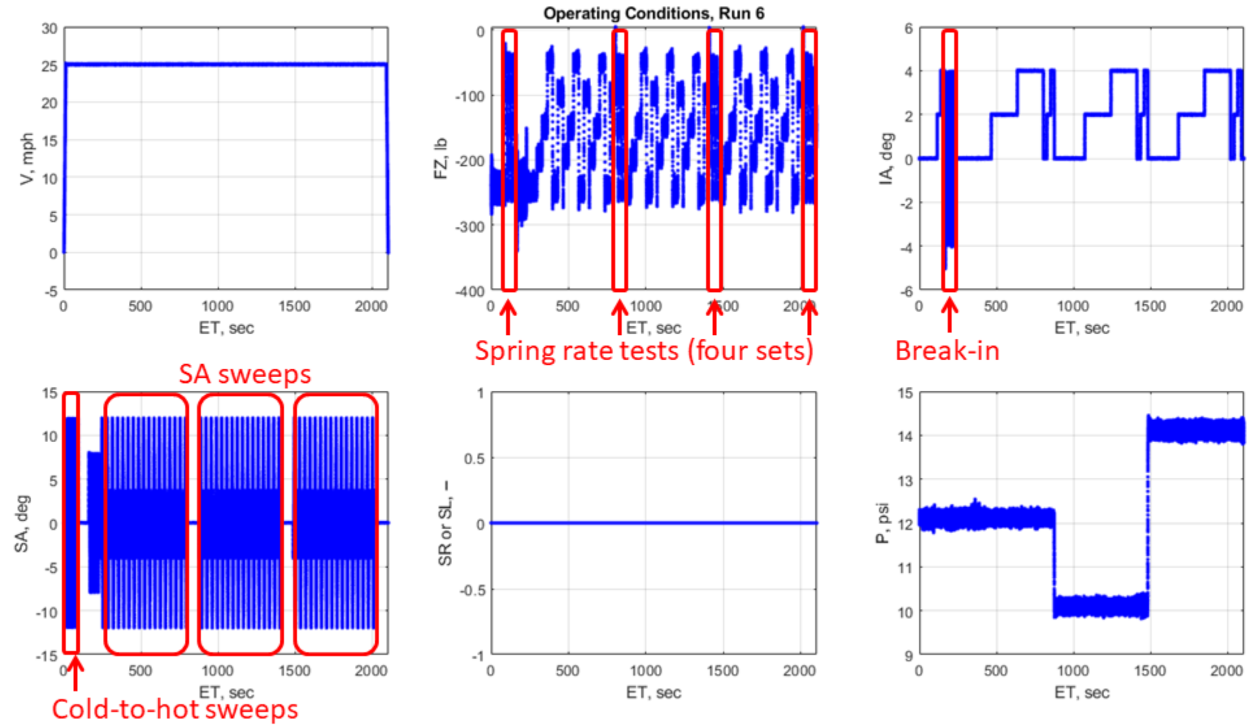



Figure 3. Cornering Test Plan, first half.

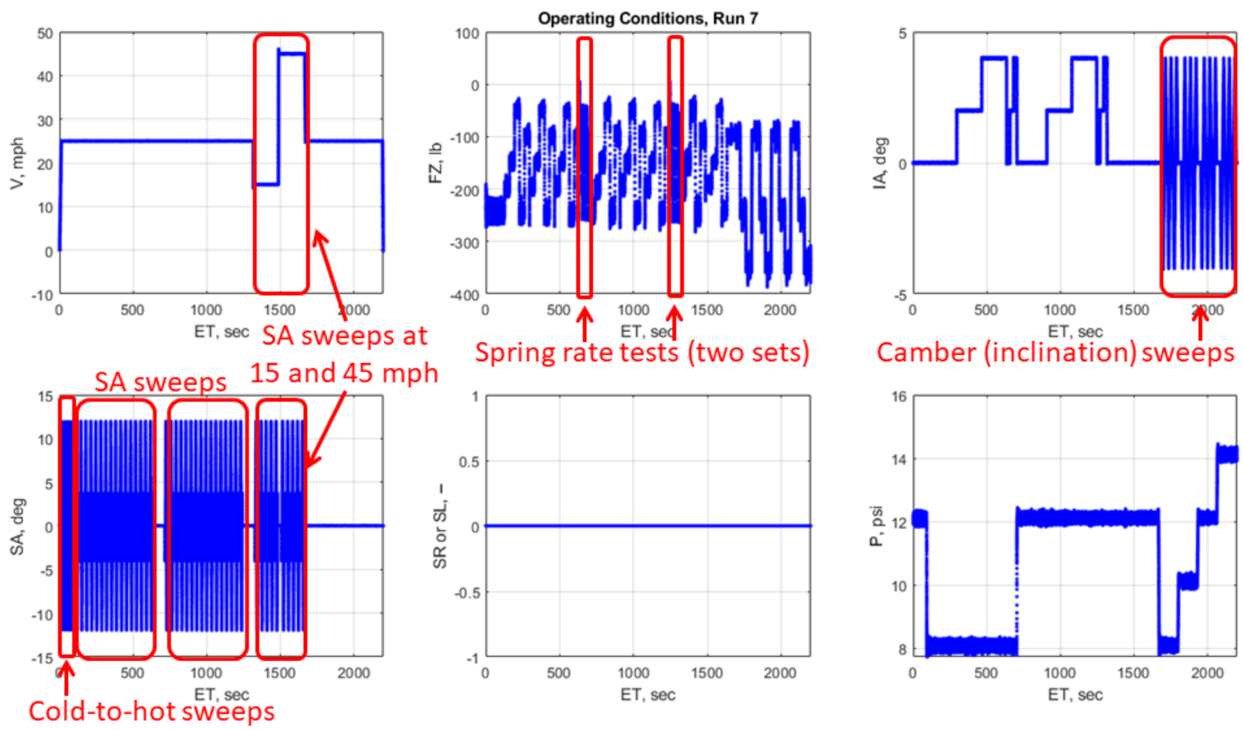



Figure 4. Cornering test plan, second half.

## 8. DRIVE/BRAKE TEST PLAN

The drive/brake test plan is identical to Rounds 6 & 7 except for small adjustments to the slip angle commands during the warmup run (cold-to-hot, break-in and conditioning sweeps). These changes are in response to updates at the Calspan Tire Research Facility and attempt to produce the same slip angle behavior as in previous rounds.

Unlike the cornering tests where slip angle was swept, the drive-brake-combined tests use slip ratio sweeps. Slip angle is held constant during the main portion of the test. The term “combined” is often used to describe simultaneous non-zero slip angle and slip ratio.

The only time slip angle is not held constant is during the warmup run. This warmup is similar to the warmup used in the cornering tests, and would be identical if the transient tests were removed. The warmup run plan can be seen in Figure 5.

Like the cornering tests, the main portion of the drive-brake-combined tests are split across two data files. The first half is seen in Figure 6. Here, the first three pressure blocks are conducted. There are no spring rate tests in this run—the entire run is composed of slip ratio sweeps at fixed slip angles. The data in Figure 6 appears to show a range of slip angles, but the only values used during slip ratio sweeps are 0, 2 and 4 deg. Transitions between these set points, occurring between sweeps, are captured in the data.

Figure 7 completes the drive/brake tests. It includes a 12 psi block. This block is identical to the first 12 psi block in Figure 6. This is an opportunity to compare the two blocks for any changes in performance due to wear or heating.

The test concludes with slip ratio sweeps at 15 and 45 mph, conducted at zero inclination and 12 psi. Compare this data with the standard test data at 25 mph to see how velocity affects tire performance.

Figures (from the identical Round 6 tests) appear on the next page.

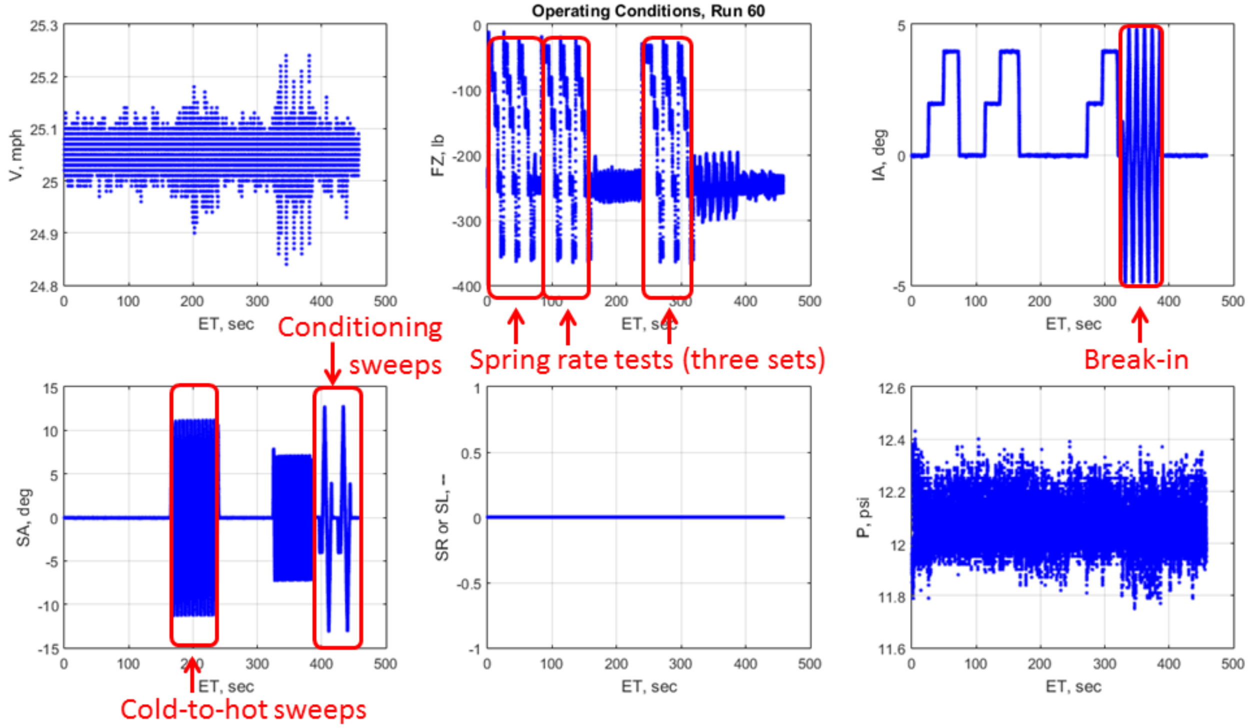



Figure 5. Drive/brake Warm-up Run Plan.

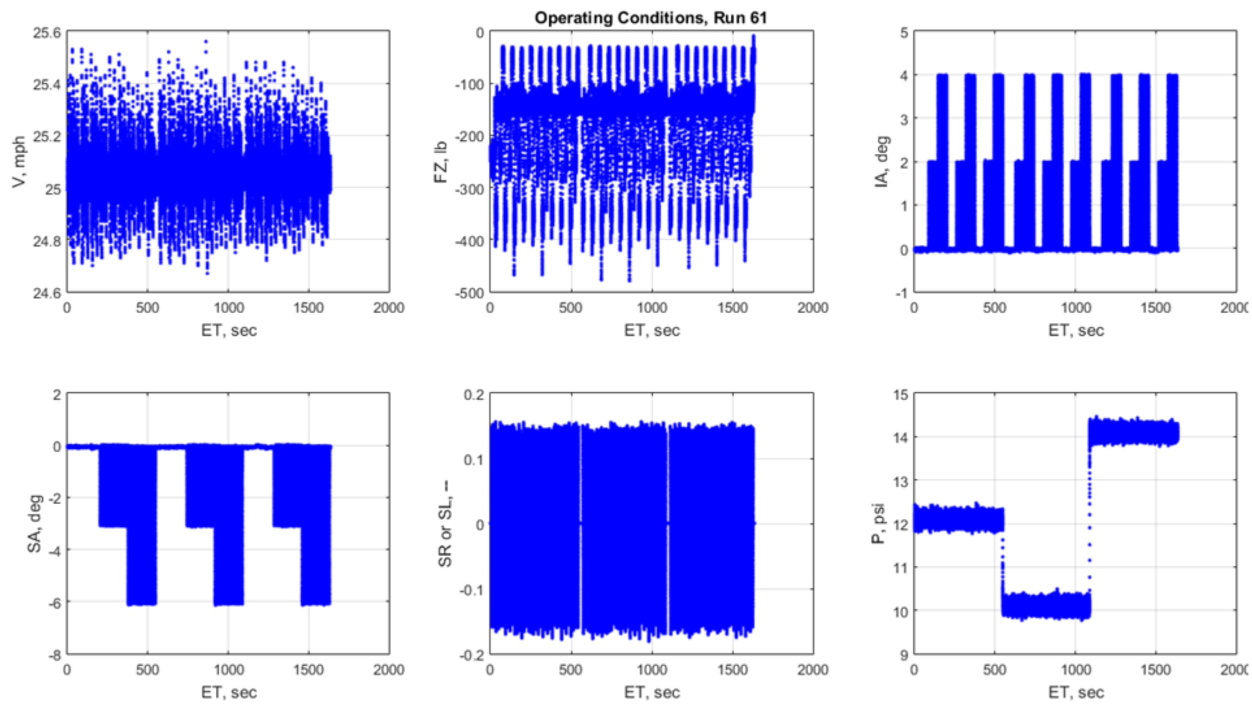



Figure 6. Drive/Brake/Combined, first half.

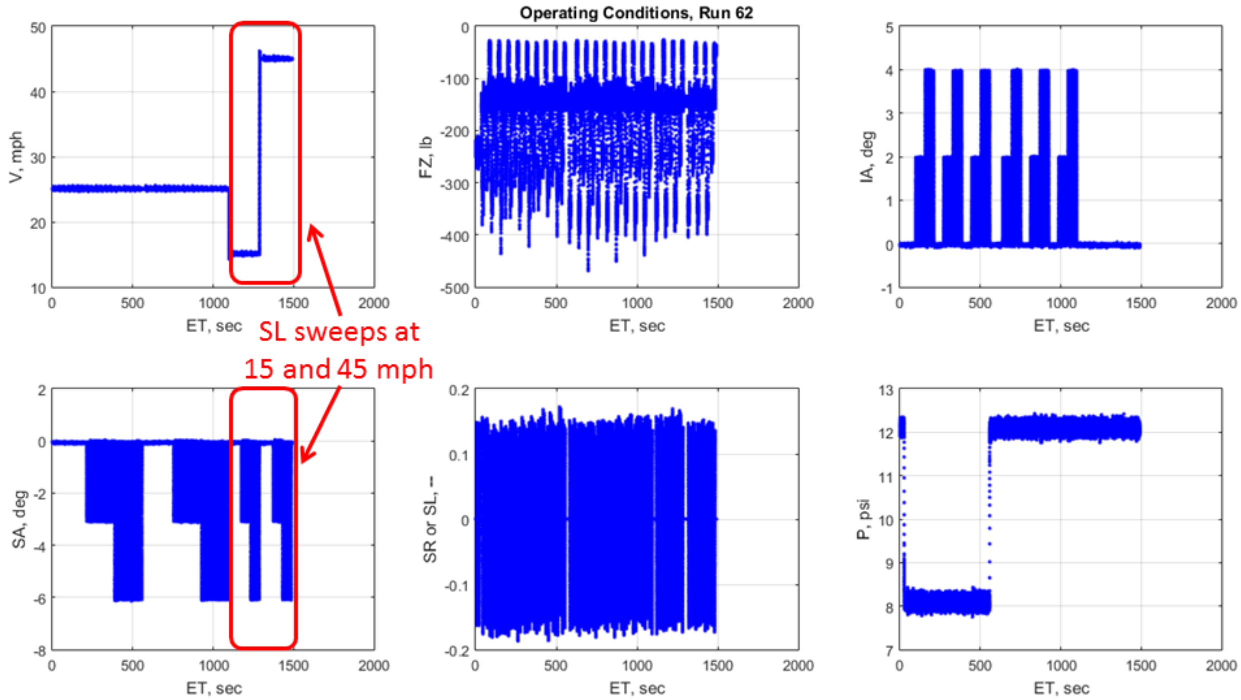



Figure 7. Drive/Brake/Combined, second half.

## 9. TEST COMMENTS

A few important comments on the Round 8 tests:

All 10 inch tire testing went very smoothly. This data was collected using an offset adapter. The spindle on the Calspan Tire Research Facility test machine cannot descend low enough for the 10 inch tires to touch the roadway without an adapter. Because the adapter cannot transmit drive/brake torques, all 10 inch tire data is free-rolling only.

The only aborted run in the 10 inch tire data occurred in Run 3 when the air line came disconnected, resulting in a loss of inflation pressure. The air line was reattached and the test was restarted (now called Run 4) using the same tire. Data from Run 3 is not presented. We do not see any issues in the Run 4 data because of the abort in Run 3.

There were multiple issues when testing the 13 inch tires, almost all related to debeading. Tires pulled themselves off the rim no less than eleven times during Round 8 tests. This was unexpected, and we still do not fully understand the root cause(s). The wheels used in this round have been used in previous rounds. The Goodyear tire (D2704) was tested several rounds ago with minimal debeading issues on the same rims. We have tested similar Continental tires in two previous rounds on the same rims, again with minimal debeading problems. Thus, this issue was not expected.

We will be conducting some tests on the wheels later this year in an attempt to learn more. The wheels themselves may be out of spec after several rounds of use.

While the test plan/matrices are nearly identical to previous rounds they were completely reprogrammed by Calspan for Round 8 to accommodate upgrades to their system. This introduces the possibility that the reprogramming and Calspan's increased capability has introduced some unexpected, extreme conditions which the tire did not see in previous rounds. That said, the cornering matrices used with the 10 inch tires are largely the same as used with the 13 inch tires (copy, paste and change a few loads...), so if the test program and machine response are an issue it only upset the 13s and not the 10s.

Another possible root cause is the way the tires were mounted and dismounted from the tires. We inquired about this while the Calspan tests were underway. Calspan reports that there were no apparent differences in how they mounted/dismounted the tires this time compared to previous rounds, although this does not completely remove the possibility of a process-related issue.

Repeated debeading of the 13 inch tires has two significant effects on the measured data: First, for the data that is presented, the cornering test plan was repeatedly revised in an attempt to avoid the more extreme conditions. This was a collaborative effort between the Calspan staff and the TTC directors. As a result, no two 13 inch cornering files may have the exact same test matrix—this may make analysis more difficult. Second, it was not possible to get a full set of data on all of the 13 inch tires. Each tire/rim combination is now discussed in detail:

- Continental 43329, 205/470R-13, 7 inch rim: Our first free-rolling attempts at this tire resulted in several debeadings. With a modified free-rolling test plan, however, we were able to get a full set of free-rolling data (runs 35-37). Drive/brake tests were successful and uneventful (runs 47-49).

- Continental 43329, 205/470R-13, 8 inch rim: No data presented for this tire. Even when using several different modified free-rolling test plans we could not keep the tire on the rim. If time allowed, we would have tried this tire on a 6 inch wide rim, just to get a second width. Between the problems with the Continental 13 and the Goodyear 13, though, we needed to move-on to drive/brake before this could be attempted. Three attempts were also made to get drive/brake data on an 8 inch rim, and all debeaded.

- Goodyear D2704, 20.0X7.0 13, 8 inch rim: This tire/rim combination suffered two debeadings in free-rolling, but we were able to make a full set of free-rolling data using a modified test plan (runs 41, 42 & 44). Drive/brake tests were successful and uneventful (runs 56-58).

- Goodyear D2704, 20.0X7.0 13, 7 inch rim: This tire/rim combination was involved in a different kind of issue. This was the last tire on the machine during the first day of testing and it was erroneously mounted and tested backwards (the Goodyear tires are directional). This was discovered early the next morning. The "backwards" free-rolling data is provided (runs 30-32) but should be used with caution. All inclination angles in this data are opposite what the tire prefers, and there may be other, unknown issues related to running the tire in the opposite orientation. Due to time considerations we ran this tire/rim combination with the correct tire orientation as a single "super run", which attempted to combine the most relevant parts of the usual 2$^{nd}$ and 3$^{rd}$ free-rolling runs. This was the very last free-rolling run we attempted and the data is presented in run 46. Drive/brake tests were successful and uneventful (runs 56-58). This tire/rim combination is the only one of the four 13 inch tire/rim combinations that never debeaded.

We note that the difficulties we had keeping the 13 inch tires on the rims are in no way a reflection on the Continental or Goodyear tires. There appear to be tire/rim compatibility (rim spec), operating condition (machine programming & response) and/or mounting process issues. We aim to provide an update to the FSAE TTC membership later this year after we dig deeper into these issues.

Tire wear was very good for all tires and tests. No tires were worn out during testing. When referring to RunGuide_Round8.pdf, note that each row of the table uses a single instance of that tire to collect all the data.

The roadway belt on the test machine at Calspan is typically very clean and very smooth, so the peak friction values in the test data can be higher than what is seen on a typical racing surface (or parking lot). In past Rounds the "real world" peak lateral and longitudinal forces reported by FSAE teams are roughly 2/3 of those seen at Calspan. Such disagreement is always an issue with laboratory tire testing—how well or poorly the magnitudes agree are a strong function of tire construction and compound. As with all laboratory test data, correlation with real world performance is very important.

The TTC directors do their best to select tires and define test matrices which will benefit as many TTC members as possible. We also know we cannot make everyone happy. Round 9 of testing is likely in a few years. We will seek student input on tires & test plan when the time comes. Thank you to everyone who provided input to Round 8.

## 10. TIRE MODELS

Various tire models or modeling tools may be posted on the FSAE TTC private forum. These are often donated by TTC sponsors. The FSAE TTC does not provide tire models.

## 11. SUGGESTIONS FOR ANALYSIS

A few items which you might find interesting when analyzing the data:

Crossplot the data several different ways. Start with the "traditional" plots: lateral force vs. slip angle and longitudinal force vs. slip ratio. Then plot vs. normal load, inclination, pressure or even tread surface temperature. There are many, many ways to visualize and analyze the tire data.

Compare the 12 psi runs taken at the start and end of each tire's test. What differences do you see between a new tire and a used tire operating at a nominal thermal equilibrium?

Plot the lateral force vs. slip angle data during the "cold to hot" sweeps. How does the tire change with temperature and break-in?

Look at the tire spring rate tests, and the variation of the rates with load, inflation pressure, inclination angle, rim width and speed.

Study the data at different rim widths to establish its effect on tire performance.

During the transient tests, look at the distance a tire needs to roll to reach a new steady-state after a step steer. Look at the response in all force and moment channels. After a step steer at zero speed the force and moment data does not stay constant until the tire starts rolling. Why?

Compare tire force and moment performance at different speeds.

Camber sweeps are a new addition in this round of testing. What can you learn about the effect of inclination angle at zero slip angle?

## 12. QUESTIONS/COMMENTS

Please direct your questions to Dr. Edward M. Kasprzak, kasprzak@fsaettc.org.

## 13. FORMULA SAE TIRE TEST CONSORTIUM — PARTICIPANT AGREEMENT

Thank you for your participation in the Formula SAE Tire Test Consortium (FSAE TTC). Membership in the TTC is granted to schools that have paid the one-time US$500 registration fee. Individuals (students, faculty, etc.) from member schools who make use of the TTC membership agree to the following terms:

1. Your school's membership entitles you to all data collected by the FSAE TTC (2005-present). Access to this data is through the FSAE TTC secure forum at www.fsaettc.org. Individual username requests require a valid, personal, university-domain e-mail address.

2. You may use this data within your school (Formula SAE, Senior Design Projects, research, etc.). You may also share this data with industry supporters who are helping your Formula SAE team make use of the data. Those in industry may not make any use of the data except to assist your Formula SAE team.

3. You may not use this data outside of your school (e.g., summer jobs, post-graduation positions). You are prohibited from donating or selling the data to any other individual, group, team or university, or posting it on the internet. Commercial use of this data is prohibited.

4. Presentation/publication of the data in de-identified graphical or tabular form is permitted, provided the author acknowledges the *"Formula SAE Tire Test Consortium (FSAE TTC)"* and the *"Calspan Tire Research Facility (TIRF)"*.

5. Your school's FSAE/FS car will display the Calspan decal in every year the data contributes to the design of the car.

If you do not agree to the terms of this agreement you should ask for your personal secure-forum username to be terminated and you should stop using the data. Your school's membership will remain in effect.

Direct any questions to FSAE TTC Co-Director Dr. Edward M. Kasprzak, kasprzak@fsaettc.org

FSAE Tire Test Consortium public website: www.millikenresearch.com/fsaettc.html

FSAE Tire Test Consortium secure forum: www.fsaettc.org

## 14. FORMULA SAE TIRE TEST CONSORTIUM — PRIVACY POLICY

The FSAE TTC collects contact information for each registered consortium member. This information will only be used for TTC-related purposes and will never be shared beyond the TTC Directors. Username requests on fsaettc.org require submission of a valid, personal, university-domain e-mail address (no team domains or company domains). The TTC Directors will occasionally e-mail you with TTC bulletins. Your e-mail address will never be shared beyond the TTC Directors. Your e-mail address must be able to receive TTC e-mails to keep your username active.

The phpBB software that runs the TTC secure website also includes a generic privacy policy which discusses the use of cookies and other details. This is located at:
http://www.fsaettc.org/ucp.php?mode=privacy&sid=a592a4808aad26407a70fc1708d91bcd