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ON SCALING OF BRAKE TEST SAE J2522

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ON SCALING OF BRAKE TEST SAE J2522

By

David S. McKavanagh

B.S., Southern Illinois University, 2017

A Thesis

Submitted in Partial Fulfillment of the Requirements for the

Master of Science Degree

Department of Mechanical Engineering and Energy Processes

in the Graduate School

Southern Illinois University Carbondale

May 2020

THESIS APPROVAL

ON SCALING OF BRAKE TEST SAE J2522

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David S. McKavanagh

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of
Master of Science
in the field of Mechanical Engineering

Approved by:
Dr. Peter Filip, Chair
Dr. Rasit Koc
Dr. Farhan Chowdhury

Graduate School
Southern Illinois University Carbondale
December 13, 2019

AN ABSTRACT OF THE THESIS OF

David S. McKavanagh, for the Master of Science degree in Mechanical Engineering and Energy Processes, presented on December 13, 2019, at Southern Illinois University Carbondale.

TITLE: On Scaling of Brake Test SAE J 2522

MAJOR PROFESSOR: Dr. Peter Filip

Friction brakes represent the most important safety feature literally in all vehicles and their rigorous “friction testing” is usually performed on several platforms/scales and completed with field tests. Since friction and wear are system properties, it is not trivial to design “small scale” tests and to correlate data generated at different levels of testing complexity. Nevertheless, the economy of the brake materials development process could be improved, when interpretation of friction and wear test data is based on a deeper/proper understanding of physics and chemistry of ongoing friction phenomena. This contribution follows the two series previously presented at SAE Brake Colloquia and compares the data generated in the full-scale brake dynamometer SAE J 2522 performance test (Link Engineering 2800M dynamometer) with data generated in bench-top (small scale) friction tester (Bruker UMT) equipped with environmental chamber controlling temperature. Scaling laws of physics were adopted for design of the small-scale testing procedure, however, a different scaling philosophy as well as different friction materials were used when compared to the previously reported findings. Identical commercial OEM brake pad samples containing biodegradable environmentally friendly fibers and commercial OEM cast iron rotors were used in both dynamometer and scaled-down bench-top friction tests. Friction and wear surfaces/mechanisms were studied by using scanning electron microscopy (Quanta

FEG 450 by FEI) equipped with the energy dispersive X-ray microanalysis (Inca System), and 3D optical microscope (NPFLEX by Bruker). Major conclusions proposed for this study can be summarized as follows: 1) Proper scaling by using physics principles allows for reasonable correlation of dynamometer and bench-top test data, although the results differentiate, particularly during fade and high temperature tests. These findings further support the previously published data and indicate that differences in scaling philosophy neither the types of tested materials have considerable impact on the generated data. 2) It is very important to properly select representative pad samples, as their size is considerably smaller compared to full pads. When the identical rotor materials are used, the repeatability of data is excellent and the sensitivity to typical differences of the bulk microstructure of cast iron is minimal. 3) When the testing results generated on dynamometer and bench tester matched well. the friction surfaces of full pads tested in dynamometer and the friction surfaces of small pad samples exhibited identical topography and chemistry.

AKNOWLEDGEMENTS

I would like to express my most sincere gratitude to my wife for supporting me through the process of researching, writing, editing and presenting my thesis. I would also like to thank Dr. Peter Filip for suggesting this topic for my thesis as it has been an amazing learning experience learning from one of the leading researchers in the field of friction science. I would like to thank him for his guidance, mentoring, patience and support during this research. I would like to thank Dr. Rasit Koc and Dr. Farhan Chowdhury for their time serving on my thesis committee, and for their advice and comments on my research. Tim Attig also deserves a monumental amount of thanks for all the time that he put in helping me when something went wrong, mostly because of user error. I would also like to thank Dr. Steven Shaffer and Dr. Khorameh Farokhadeh for their help trouble shooting any of the problems that I encountered during this research and also with helping me understand how the machine works and what was needed to be done to work with brake materials. I would also like to thank Rohit Jogineedi and Sai Kancharla for their help throughout the process of testing and writing and for helping me understand what was going on with the experimentation. Lastly, I would like to thank my sons Jayden and Nicholas, for their patience with their father throughout the process of my research.

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CHAPTER 1

INTRODUCTION

With those in the field of friction science understanding that friction is not a material property but rather it Is the system reacting to the forces that are acting upon the system. The idea that friction is not a material property seems to be a little counterproductive when it comes to the idea of friction materials being a thing. That there is an entire category of materials that focuses on the field of friction and how it manifests would make it seem as though it should be a property of a material. In fact, according to Bharat Bhushan, in his book Introduction to Tribology, friction is the resistance of at least one body to motion as the body slides or rolls tangentially over a second body with which it is in contact [1]. Though most brake friction material is not composed of a single substance, it is usually a formulation of binders, reinforcements, fillers and possibly friction modifiers [2-4]. These formulations being what is used for modern day automotive braking, this was not always the case of brake materials and friction. The early forerunners of brakes were used by Phoenicians for slowing their war chariots, later evolving to something that was slipped under the wheels of coaches to stop them, with the first automobiles having a manual brake consisting of cranks, levers, rods or cables, though these were ideas just carried over from horse-drawn carriages [5]. These first brakes were blocks covered with leather, and would usually have to be replaced often; one such example is of Bertha Benz’s 100-kilometer first ever long-distance drive in August 1888, where the saddlers of the towns and villages where need to replace the leather coverings of the brake blocks several times during her journey [5]. Today’s automobiles have brakes systems that can last nearly 500 times that distance before needing to replace the brake pads of the vehicle.

The study of brakes and friction science has come a long way from a block covered in leather, today there are so many differing formulations and compositions for brake pads that they have been broken down into certain groups, such as, Non-Asbestos Organic (NAO), Low-Metallic, Non-Metallic, Ceramic, and Semi-Metallic pads, these 5 different types of pads make up the type of pads that are on most passenger vehicles, they might also be on larger vehicles such as semi-trucks as well, but those are classified as being heavy-duty brakes and have a higher metal content [6]. With all these different types of brake pads there have been many different attempts to test all of them on different types of machines to determine the brake material's properties. The chosen brakes being those of a Toyota Camry as it could be considered a typical vehicle that could be owned by an average family in the United States, with the specific type of brake being tested as a high-end performance brake. Using a full-scale inertia dynamometer seems to have been the long-standing practice of testing for the materials coefficient of friction [7-17]. As time has passed researchers have been using either a scaled dynamometer or creating smaller rigs with which to test brake materials on [18-26]. These two areas seem to be where most researchers focus their test on, as these appear to be what most researchers have access to, or they feel like their created testers will provide the best results for their materials. More recently with the ability to create smaller testing machines and even smaller sensors, research has progressed into the use of bench-top tribology testers, such as the Bruker Universal Mechanical Tester (UMT), to test the properties of their friction materials [27-33]. Each of these groups are different as they are informative, they each research different aspects of friction materials or formulations but with those that actually used standards there seemed to be two that stood out, one was a Chinese standard and the other was one from the Society of Automotive Engineers (SAE)[9, 13-16, 33-36]. This standard was used because of its almost seeming universal acceptance and the amount of data points that it tries to achieve throughout the testing procedure. This standard is the SAE J 2522 test procedure, with many of the researchers calling it the A.K. Master test procedure, but as it is this is a mistake on their parts as these are two different but very similar tests, the A.K. Master is widely accepted within the European Union (E.U.) while the SAE J 2522 is seemingly accepted in more places than that [37]. The researchers using sub-scale and bench top testers seem to be using certain data points to test their materials, points such as: Temperature, Applied Pressure, Velocity, acceleration, and similar points that are contained within many standards. Using those points without using a standard to test the properties of the friction material. Would it be possible to scale down the J2522 for use in a bench top tester? Finding material on scaling led to many differing takes on scaling laws. Finding a scaling procedure that would fit was rather difficult but through the use of previous work a few laws of scaling were found and then applied for use [38, 39]. Since the completion of testing there has been a change in how and why the lab is conduction scaling of velocity. As stated in Appendix D, the change is due to there being a problem with doing a straight scaling of the RPM of the velocity, due to the velocity being that of linear velocity of the vehicle and not the velocity of sliding that is being done on the brake materials. This new scaling type is that of scaling the linear velocity as it effects the brake and scaling that speed then taking the radius of the UMT’s rotor into account.

CHAPTER 2

METHODS AND MATERIALS

2.1 OVERVIEW

In this study, we are planning to develop a scaling routine that will allow for a full-size dynamometer standard to be used on a bench-top tribometer. The first step in this process was to determine the type of vehicle we wanted to use as a model for the testing process, ultimately settling upon a Toyota Camry as the model vehicle that would be the basis for our testing. The reason for this choice is that it is a common family car that is reasonably priced. After choosing a vehicle to be the base for our testing, we had to then decide upon a brake to be used as the basis for our samples, with there being a plethora of pads to choose from, we decided to look at brakes that were environmentally friendly and of a higher quality than the standard brake pad, thus we decided to go with Akebono ACT-1222 ProACT Ultra-Premium Ceramic brake pads, as shown in fig. 1.

Figure 1: Akebono ACT-1222 ProACT Ultra-Premium Ceramic Brake Pads

With the three major items being chosen for the test, the vehicle, the brake pads, and the industry standard, we could begin the process of scaling the inertia dynamometer's tests down for use on our bench-top tester.

2.2 SCALING STANDARD

When trying to develop a strategy for scaling of the full-scale test down to the bench-top, there were a few different theories that could be used to scale the test down, but the theory that had been used within other research done previously, within our lab, was that of scaling the apparent contact areas of the brake pads to down to our required sample sizes. The reason for scaling the apparent contact areas is that if the use of just contact area is used the sample size would become too small to still be considered a homogeneous compound. The general rule of this theory is called the "Square Law" which takes the lengths into account are as follows:

$$(ratio\ of\ areas) = (ratio\ of\ lengths)^2 \qquad \text{Equation 1}$$

$$(\boldsymbol{ratio\ of\ volumes}) = (\boldsymbol{ratio\ of\ lengths})^{\mathbf{3}} \qquad \text{Equation 2}$$

It follows that these two equations can be expressed thusly:

$$(\boldsymbol{ratio\ of\ volumes})^{(\mathbf{1/3})} = (\boldsymbol{ratio\ of\ areas})^{(\mathbf{1/2})} = (\boldsymbol{ratio\ of\ lengths})^{\mathbf{1}} \qquad \text{Equation 3}$$

With these three equations figured into the scaling, a scaling standard can then be developed for different forces, such as:

Table 1: scaling factors of selected forces

Force	Scaling
Surface Tension	l^1
Fluid Force/ Electrostatic Force	l^2
Weight/ Inertia Force/ Electromagnetic	l^3
Electromagnetic Force (Constant Current Density)	l^4

Now that the scaling factors have been shown and how they can be found there are certain physical qualities that need to have a scaling factor found for. Once these have been found the data can be scaled from the large-scale tester (Dynamometer) to the small-scale tester (Universal Mechanical Tester). The following table is are the physical qualities and their corresponding scaling factors:

Table 2: Scaling Exponents

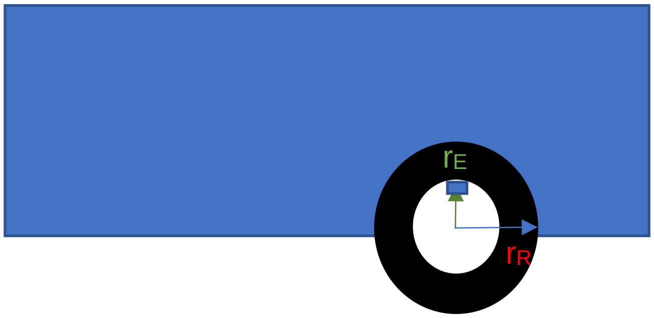
Physical Quality	Scaling Exponent
Bending Stiffness	1
Shear Stiffness	1
Surface Tension	1
Strength to Weight Ratio	1
Van der Waals Force	1
Strength	2
Elastic Potential Energy	2
Mass	3
Inertia Force	3,4
Kinetic Energy	4
Potential Energy	4
Second Moment of Inertia	4
Mass Moment of Inertia	5

Some of these qualities are not going to be used within the testing, and others will be used, so these other qualities will also need to have scaling exponents. Specifically, the following are some of the needed Scaling Exponents:

Table 3: Scaling Exponents for parameters used within SAE J2522 test

Parameter	Scaling Exponents
Angular Velocity (RPM)	-0.5
Velocity (m/s)	0.5
Area (m^2)	2
Force (N)	3
Time (s)	0.5

With these five parameters the scaling from the large-scale test to the small-scale test and start to develop the scaling strategy with which to scale down and conduct the test on the small scale. Calculating the linear velocity of the brake is an important part of the testing process, this is because the velocity that is given in the standard is the velocity of the tire and not that of the brake. The calculation to find the linear velocity acting on the brakes is as follows:



r_R-rolling radius

r_E-effective radius

Figure 2: depiction of rolling radius vs effective radius

vV-Velocity of vehicle

ω= angular velocity of wheel

$$v_V = r_R \omega$$

$$\omega = \frac{v_V}{r_R}$$

Friction or Sliding Velocity $$v_S = r_e \omega$$

$$\omega = \frac{v_S}{r_e}$$

Hence, $$\frac{v_S}{r_e} = \frac{v_V}{r_R}$$

$$\frac{v_S}{v_v} = \frac{r_e}{r_R}$$

$$v_S = v_V \frac{r_e}{r_R}$$

Equation 4: equation set for figuring out the sliding velocity of the brake pad

V_{SUMT} is the sliding speed of the UMT and it is to be the scaled down v_S. This is how the scaling for the linear velocity is supposed to be performed, this was not how it was performed with in the testing done in this thesis but is how it will be done moving forward with this experiment in the future.

CHAPTER 3

PROCESSES

3.1 SCALING

As can be seen above, once a scaling procedure has been selected, we can then proceed to scale the SAE J 2522 from the full-scale dynamometer, down to the UMT benchtop tester.

Table 4: SAE J2522 Velocity and Pressure Requirements

Step Number	Name	Engagements	Initial Velocity (km/h)	Final Velocity (km/h)	Pressure (bar)
1	Mu Green	30	80	30	30
2	Burnish	64	80	30	Variable
3	Characteristic Value	6	80	30	30
4.1	Pressure Sensitivity	8	40	5	10-80
4.2	Pressure Sensitivity	8	80	40	10-80
4.3	Pressure Sensitivity	8	120	80	10-80
4.4	Pressure Sensitivity	8	160	130	10-80
4.5	Pressure Sensitivity	8	200	170	10-80
5	Characteristic Value	6	80	30	30
6	Cold	1	40	5	30
7.1	Motorway	1	100	5	
7.2	Motorway	1	90% Max	50% Max	
8	Characteristic Value	18	80	30	30
9	Fade	15	100	5	160
10	Recovery	18	80	30	30
11	Pressure Sensitivity	8	80	30	10-80

12.1	Temp./Pressure Sens.	9	80	30	30
12.2	Temp./Pressure Sens.	8	80	30	10-80
13	Recovery	18	80	30	30
14	Fade	15	100	5	160
15	Recovery	18	80	30	30

Measuring the apparent contact area of the Akebono ACT-1222 ProACT Ultra-Premium Ceramic brake pads to be our Area 1, and the three square sample pads as being our Area 2, we can then take the square root of A1 over A2 to get our lambda value so that we have our scaling value, λ.

$$\lambda = \sqrt{\frac{A_1}{A_2}} \qquad \text{Equation 5}$$

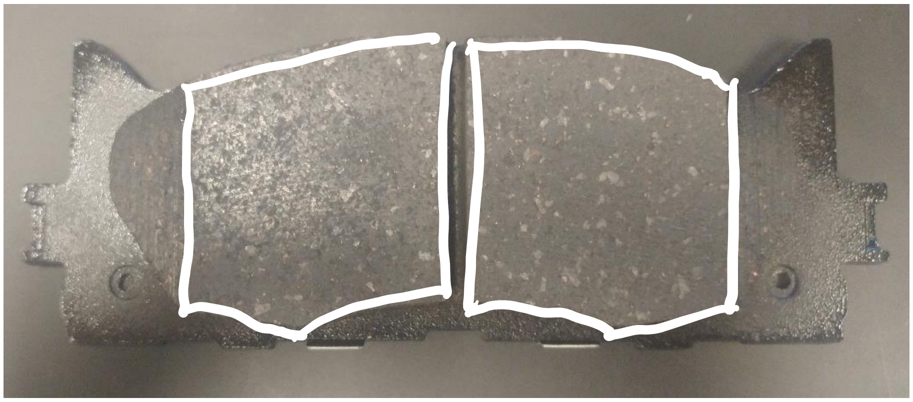


Figure 3: Apparent contact area of one Akebono brake pad (there are 2 used in the full scale dynamometer)

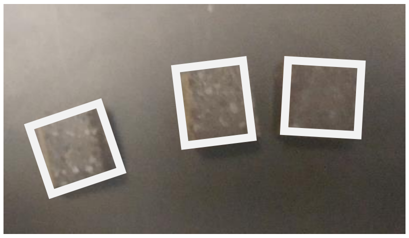


Figure 4: Contact area for the samples

Using these two sets of contact areas of 4050 mm^2 and 300 mm^2, respectively, to find the λ value for our scaling, we get a λ value of 5.20. With this value figured out we can then start to populate our scaling exponents so that we can calculate the scaled values of our parameters from the SAE J 2522 standard.

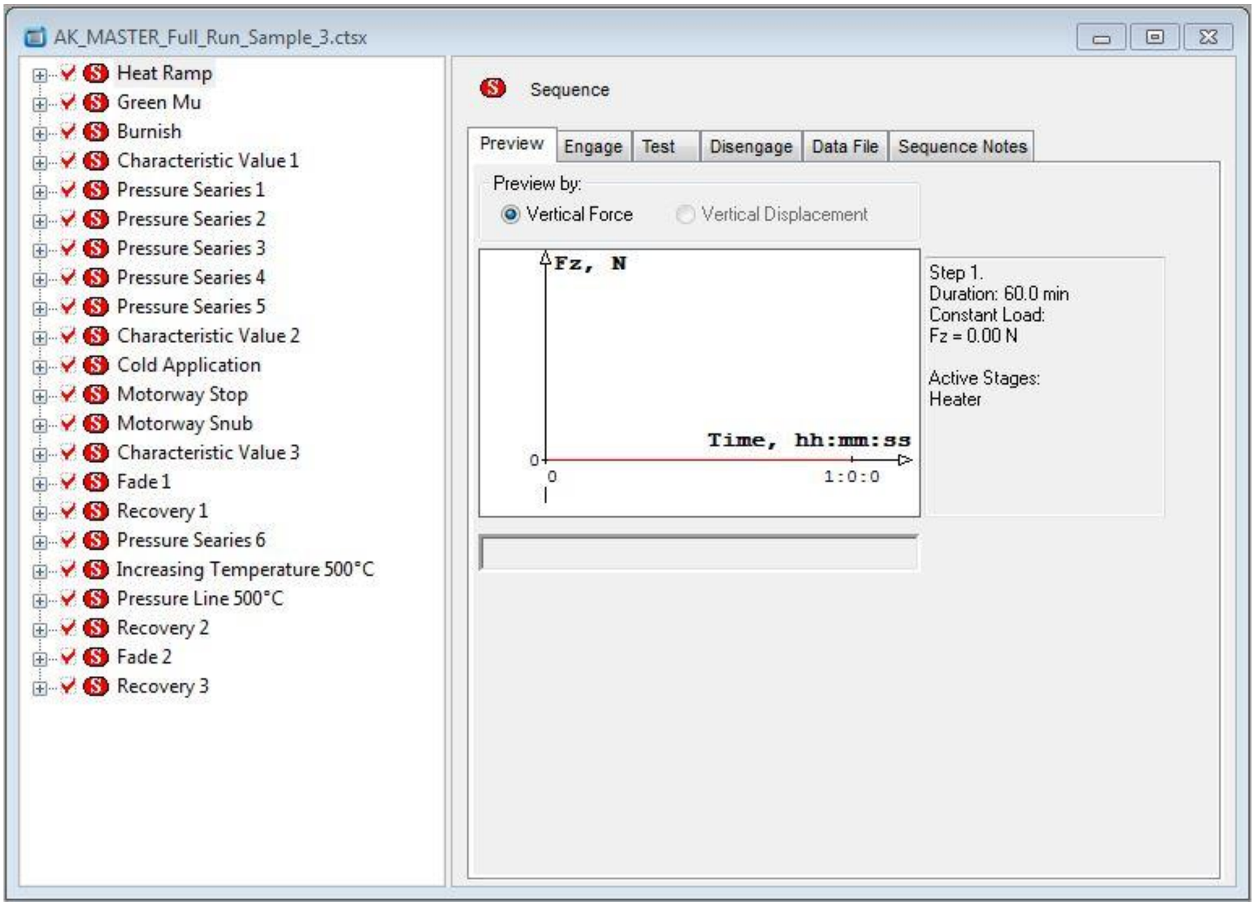
Table 5: Important parameters and accompanying scaling factors from Mu Green Section

Parameters	Dynamometer	Scaling Factor	UMT
Force (N)	129600	λ^3=140.3	923.76
Initial Velocity (m/s)	27.8	$\lambda^{0.5}$=2.28	12.2
Final Velocity (m/s)	1.39	$\lambda^{0.5}$=2.28	0.61
Initial Angular Velocity (RPM)	826.35	$\lambda^{-0.5}$=0.44	1883.67
Final Angular Velocity (RPM)	41.32	$\lambda^{-0.5}$=0.44	94.18
Time (sec)	6.73	$\lambda^{0.5}$=2.28	2.95

The full calculations for a perfect world can be seen in the appendix following the proposal. Once all of the parameters and their corresponding values have been found the scripts for running the test can begin. The parameters for all sections of the have been shown within the appendix A.

3.2 UMT SCRIPT

With a stated goal of creating a script that would allow for the complete SAE J2522 and having scaled the parameters down so that the full scale values will now correspond to the size difference between the machines, a script needs to be written that would allow for each section of the test to begin when the initiation criteria are met.



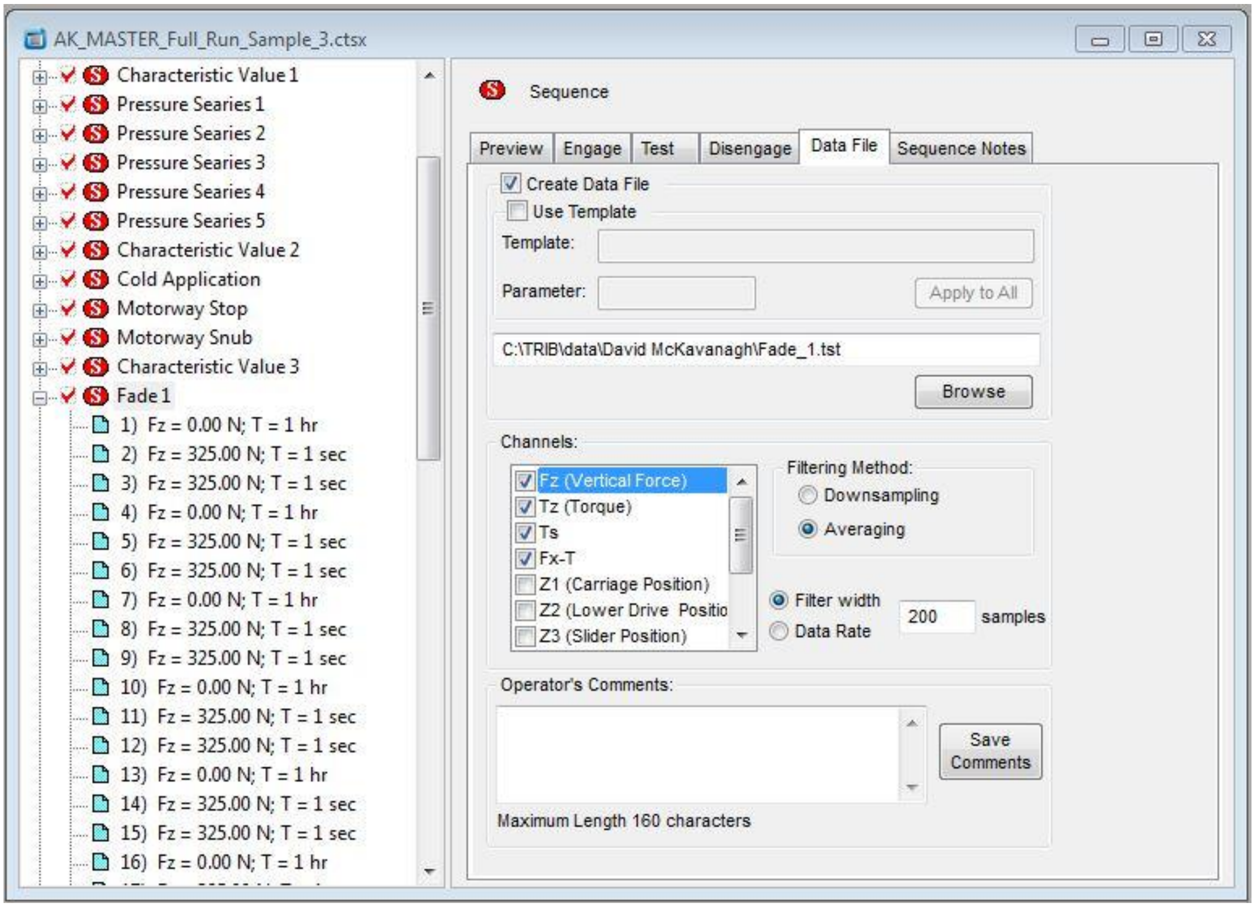
● Vertical Force ○ Vertical Displacement

Step 1.
Duration: 60.0 min
Constant Load:
Fz = 0.00 N

Active Stages:
Heater

Figure 5: Script interface after creating all of the sections of the SAE J2522.

Once the script has been created, a sequence will need to be created for each of the sections of the SAE J2522, as can be seen within Fig. 4, with the exception of the Heat Ramp section which is being used to heat the heating chamber to 99°C as the test on the UMT is to be done as close to the standard as possible. The next step is to input the parameters into the appropriate sections of the sequences.



Characteristic Value 1
Pressure Searies 1
Pressure Searies 2
Pressure Searies 3
Pressure Searies 4
Pressure Searies 5
Characteristic Value 2
Cold Application
Motorway Stop
Motorway Snub
Characteristic Value 3
Fade 1
1) Fz = 0.00 N; T = 1 hr
2) Fz = 325.00 N; T = 1 sec
3) Fz = 325.00 N; T = 1 sec
4) Fz = 0.00 N; T = 1 hr
5) Fz = 325.00 N; T = 1 sec
6) Fz = 325.00 N; T = 1 sec
7) Fz = 0.00 N; T = 1 hr
8) Fz = 325.00 N; T = 1 sec
9) Fz = 325.00 N; T = 1 sec
10) Fz = 0.00 N; T = 1 hr
11) Fz = 325.00 N; T = 1 sec
12) Fz = 325.00 N; T = 1 sec
13) Fz = 0.00 N; T = 1 hr
14) Fz = 325.00 N; T = 1 sec
15) Fz = 325.00 N; T = 1 sec
16) Fz = 0.00 N; T = 1 hr

☑ Create Data File
☐ Use Template
Template:
Parameter:
C:\TRIB\data\David McKavanagh\Fade_1.tst

Channels:
☑ Fz (Vertical Force)
☑ Tz (Torque)
☑ Ts
☑ Fx-T
☐ Z1 (Carriage Position)
☐ Z2 (Lower Drive Positio
☐ Z3 (Slider Position)

Filtering Method:
○ Downsampling
● Averaging

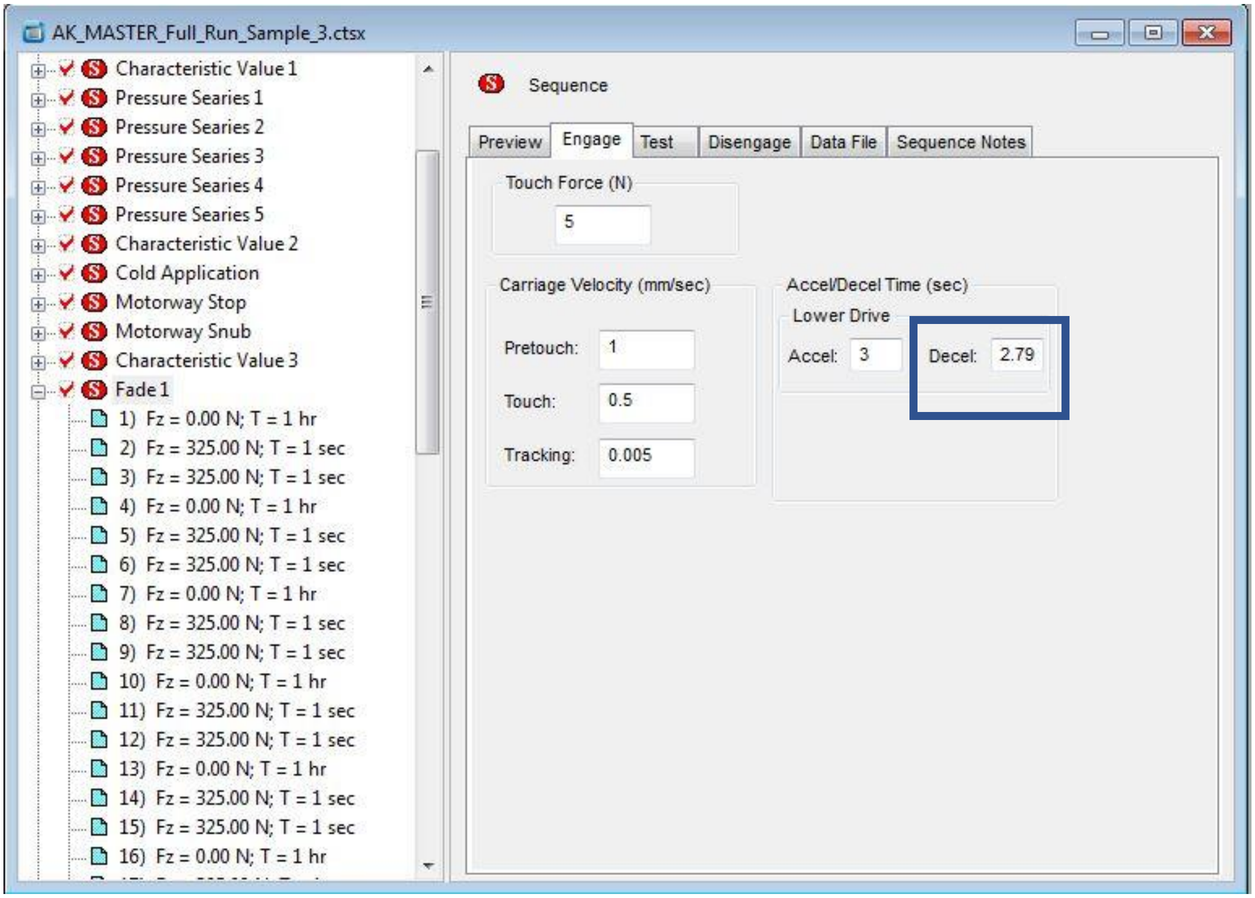
● Filter width
○ Data Rate
200 samples

Operator's Comments:

Maximum Length 160 characters

Figure 6: The First step is to ensure that the data is being saved.

Within the data file tab of the sequence, the “create data file” button needs to be checked and the location of the file needs to be placed within the box, as well as under “Channels” ensuring that each of the data sources is checked so that the data will be saved within the file. In this case the data from Fz, Tx, Ts, Fx-T, Lower Drive Speed, and TR have all been checked so this that the data from those channels will be saved. Those channels being the normal force, torque, Sample Temperature, Force in the X-axis, RPM of the lower drive, and the Temperature of the heating chamber, respectively.



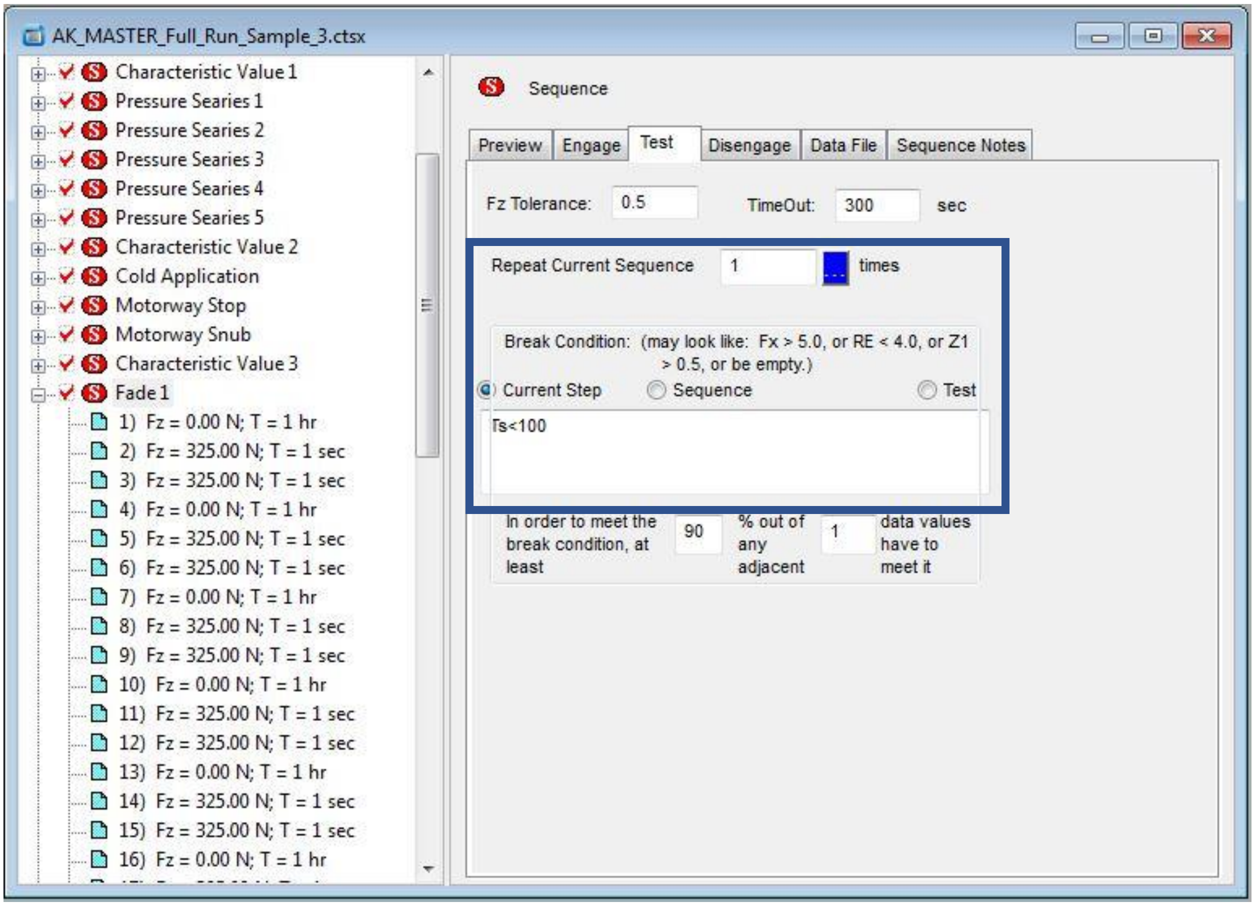
Touch Force (N): 5

Carriage Velocity (mm/sec)
Pretouch: 1
Touch: 0.5
Tracking: 0.005

Accel/Decel Time (sec)
Lower Drive
Accel: 3
Decel: 2.79

Figure 7: Setting the Engagement parameters.

Once the data file has been set up the next step is to set the engagement parameters for the sequence, these being the touch force(N) and the Deceleration time, which is different for each sequence of the script.



- Characteristic Value 1
- Pressure Searies 1
- Pressure Searies 2
- Pressure Searies 3
- Pressure Searies 4
- Pressure Searies 5
- Characteristic Value 2
- Cold Application
- Motorway Stop
- Motorway Snub
- Characteristic Value 3
- Fade 1
  - 1) Fz = 0.00 N; T = 1 hr
  - 2) Fz = 325.00 N; T = 1 sec
  - 3) Fz = 325.00 N; T = 1 sec
  - 4) Fz = 0.00 N; T = 1 hr
  - 5) Fz = 325.00 N; T = 1 sec
  - 6) Fz = 325.00 N; T = 1 sec
  - 7) Fz = 0.00 N; T = 1 hr
  - 8) Fz = 325.00 N; T = 1 sec
  - 9) Fz = 325.00 N; T = 1 sec
  - 10) Fz = 0.00 N; T = 1 hr
  - 11) Fz = 325.00 N; T = 1 sec
  - 12) Fz = 325.00 N; T = 1 sec
  - 13) Fz = 0.00 N; T = 1 hr
  - 14) Fz = 325.00 N; T = 1 sec
  - 15) Fz = 325.00 N; T = 1 sec
  - 16) Fz = 0.00 N; T = 1 hr

Fz Tolerance: 0.5 TimeOut: 300 sec

Repeat Current Sequence 1 times

Break Condition: (may look like: Fx > 5.0, or RE < 4.0, or Z1 > 0.5, or be empty.)

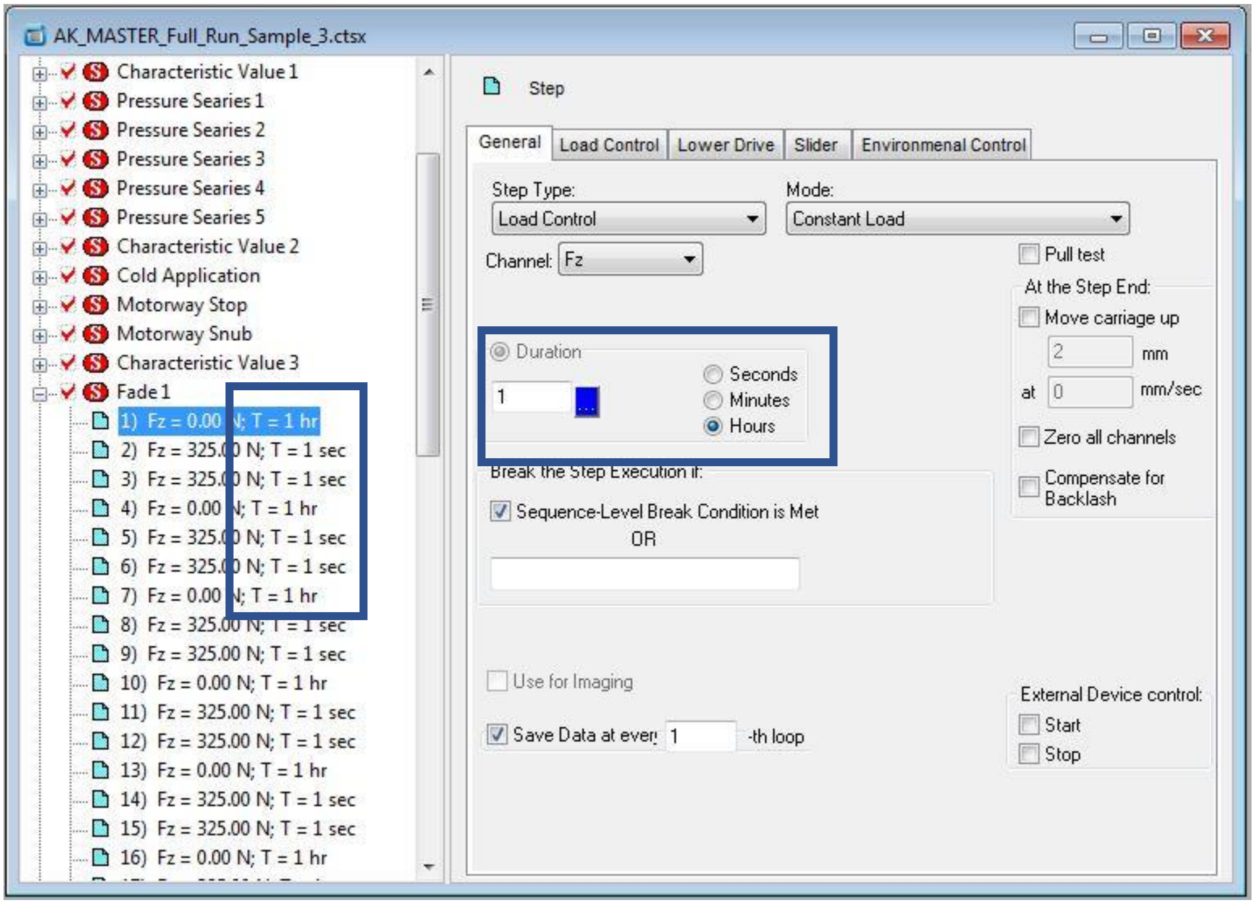
● Current Step ○ Sequence ○ Test

Ts<100

In order to meet the break condition, at least 90 % out of any adjacent 1 data values have to meet it

Figure 8: Fixing the Test Parameters.

The next tab, being the Test tab, is where the repeat current sequence and the break conditions need to be set, for the repeat current sequence this will come from the number of runs that need to be completed, be it once, six times, or eighteen times, depending upon which test section is being done. The break conditions are also different depending on the section, most of the conditions will be Ts<100, this being that the test will skip the current step once the sample is at less than 100°C, or other temperature as required by the SAE J2522.



AK_MASTER_Full_Run_Sample_3.ctsx

- Characteristic Value 1
- Pressure Searies 1
- Pressure Searies 2
- Pressure Searies 3
- Pressure Searies 4
- Pressure Searies 5
- Characteristic Value 2
- Cold Application
- Motorway Stop
- Motorway Snub
- Characteristic Value 3
- Fade 1
  - 1) Fz = 0.00 N; T = 1 hr
  - 2) Fz = 325.00 N; T = 1 sec
  - 3) Fz = 325.00 N; T = 1 sec
  - 4) Fz = 0.00 N; T = 1 hr
  - 5) Fz = 325.00 N; T = 1 sec
  - 6) Fz = 325.00 N; T = 1 sec
  - 7) Fz = 0.00 N; T = 1 hr
  - 8) Fz = 325.00 N; T = 1 sec
  - 9) Fz = 325.00 N; T = 1 sec
  - 10) Fz = 0.00 N; T = 1 hr
  - 11) Fz = 325.00 N; T = 1 sec
  - 12) Fz = 325.00 N; T = 1 sec
  - 13) Fz = 0.00 N; T = 1 hr
  - 14) Fz = 325.00 N; T = 1 sec
  - 15) Fz = 325.00 N; T = 1 sec
  - 16) Fz = 0.00 N; T = 1 hr

Step Type: Load Control

Mode: Constant Load

Channel: Fz

● Duration: 1

○ Seconds
○ Minutes
● Hours

Break the Step Execution if:

☑ Sequence-Level Break Condition is Met

OR

☐ Pull test

At the Step End:

☐ Move carriage up 2 mm at 0 mm/sec

☐ Zero all channels

☐ Compensate for Backlash

☐ Use for Imaging

☑ Save Data at every 1 -th loop

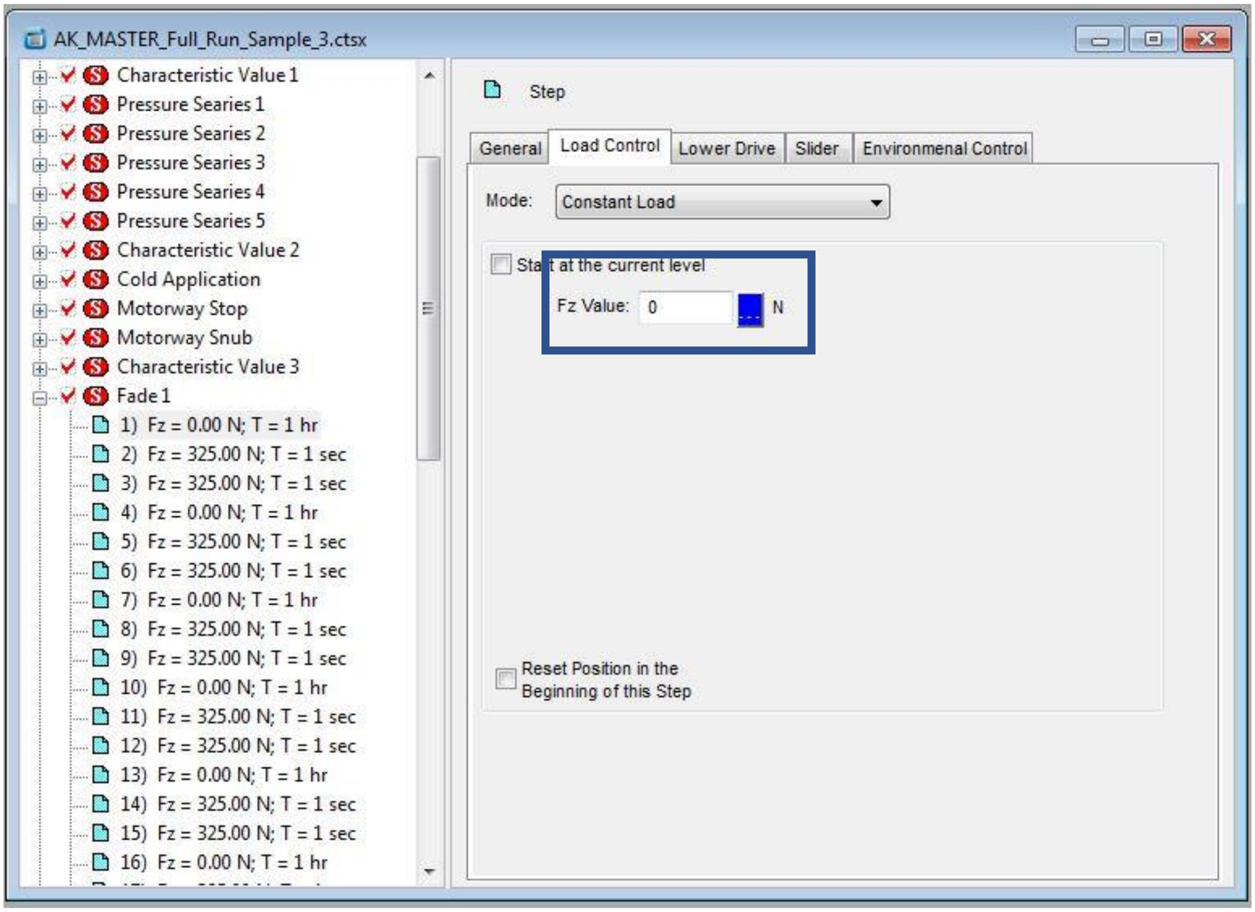
External Device control:

☐ Start

☐ Stop

Figure 9: Setting the time for individual steps

Now the problem with the setup of the individual steps is that the data that is needed is what is recorded from in between the actual steps. What this means is that between steps 2 and 3 is the data that is needed so the two steps do not have to be very long as the deceleration that is taking place once step 2 has finished is the point at which the calculated deceleration time kicks in and once it has decelerated to the second RPM of the 3rd step that steps time is then engaged. What this means is that the data needed is from between steps 2 and 3, 4 and 5, and so on until the sequence is complete.



AK_MASTER_Full_Run_Sample_3.ctsx

- Characteristic Value 1
- Pressure Searies 1
- Pressure Searies 2
- Pressure Searies 3
- Pressure Searies 4
- Pressure Searies 5
- Characteristic Value 2
- Cold Application
- Motorway Stop
- Motorway Snub
- Characteristic Value 3
- Fade 1
  - 1) Fz = 0.00 N; T = 1 hr
  - 2) Fz = 325.00 N; T = 1 sec
  - 3) Fz = 325.00 N; T = 1 sec
  - 4) Fz = 0.00 N; T = 1 hr
  - 5) Fz = 325.00 N; T = 1 sec
  - 6) Fz = 325.00 N; T = 1 sec
  - 7) Fz = 0.00 N; T = 1 hr
  - 8) Fz = 325.00 N; T = 1 sec
  - 9) Fz = 325.00 N; T = 1 sec
  - 10) Fz = 0.00 N; T = 1 hr
  - 11) Fz = 325.00 N; T = 1 sec
  - 12) Fz = 325.00 N; T = 1 sec
  - 13) Fz = 0.00 N; T = 1 hr
  - 14) Fz = 325.00 N; T = 1 sec
  - 15) Fz = 325.00 N; T = 1 sec
  - 16) Fz = 0.00 N; T = 1 hr

Step

Mode: Constant Load

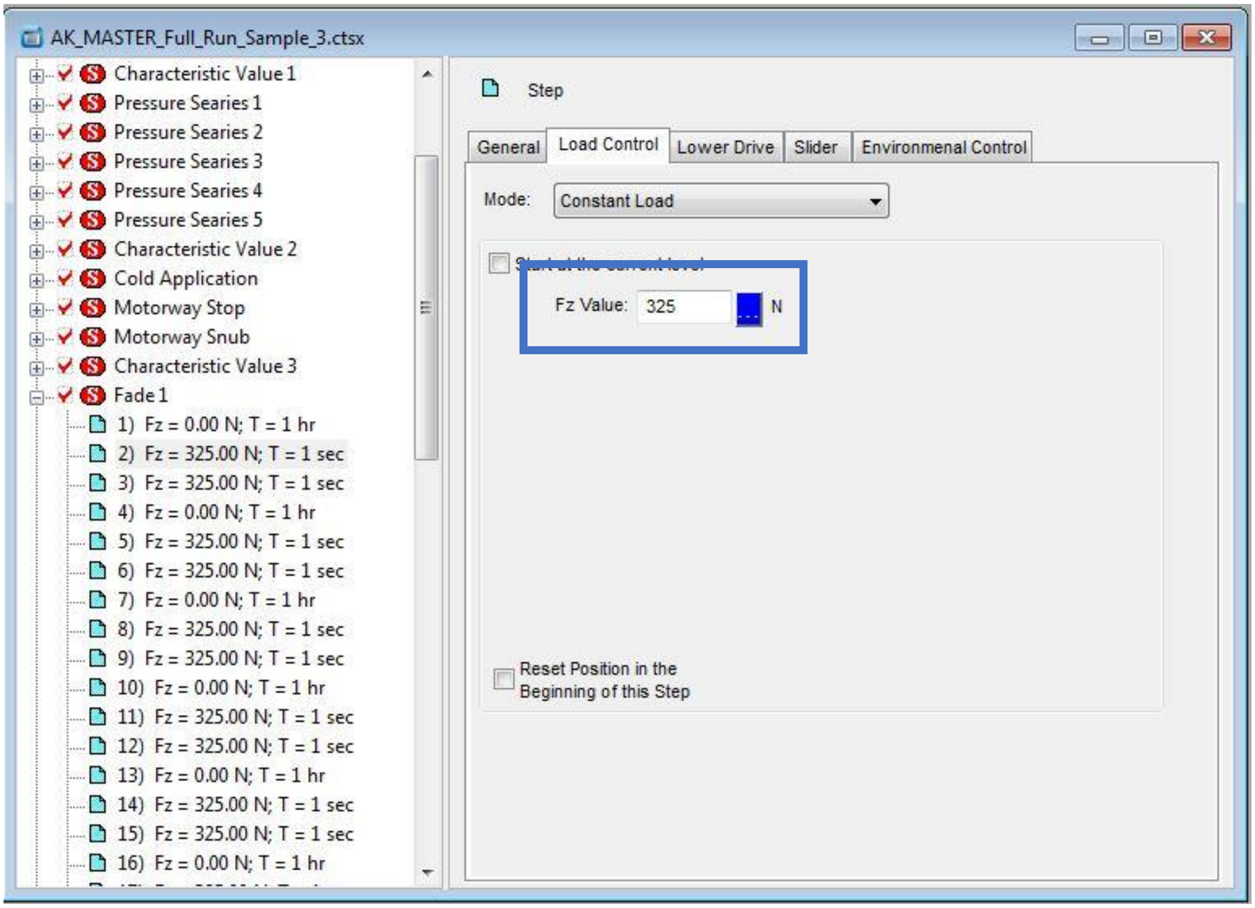
☐ Sta t at the current level

Fz Value: 0 N

☐ Reset Position in the Beginning of this Step

Figure 10: Normal Force acting on the rotating caliper.

During the first step of the sequences there is no normal force being exerted on the brake rotor as the first step is the heating phase of the sequence and thus no force needs to be used.



1) Fz = 0.00 N; T = 1 hr
2) Fz = 325.00 N; T = 1 sec
3) Fz = 325.00 N; T = 1 sec
4) Fz = 0.00 N; T = 1 hr
5) Fz = 325.00 N; T = 1 sec
6) Fz = 325.00 N; T = 1 sec
7) Fz = 0.00 N; T = 1 hr
8) Fz = 325.00 N; T = 1 sec
9) Fz = 325.00 N; T = 1 sec
10) Fz = 0.00 N; T = 1 hr
11) Fz = 325.00 N; T = 1 sec
12) Fz = 325.00 N; T = 1 sec
13) Fz = 0.00 N; T = 1 hr
14) Fz = 325.00 N; T = 1 sec
15) Fz = 325.00 N; T = 1 sec
16) Fz = 0.00 N; T = 1 hr

Mode: Constant Load

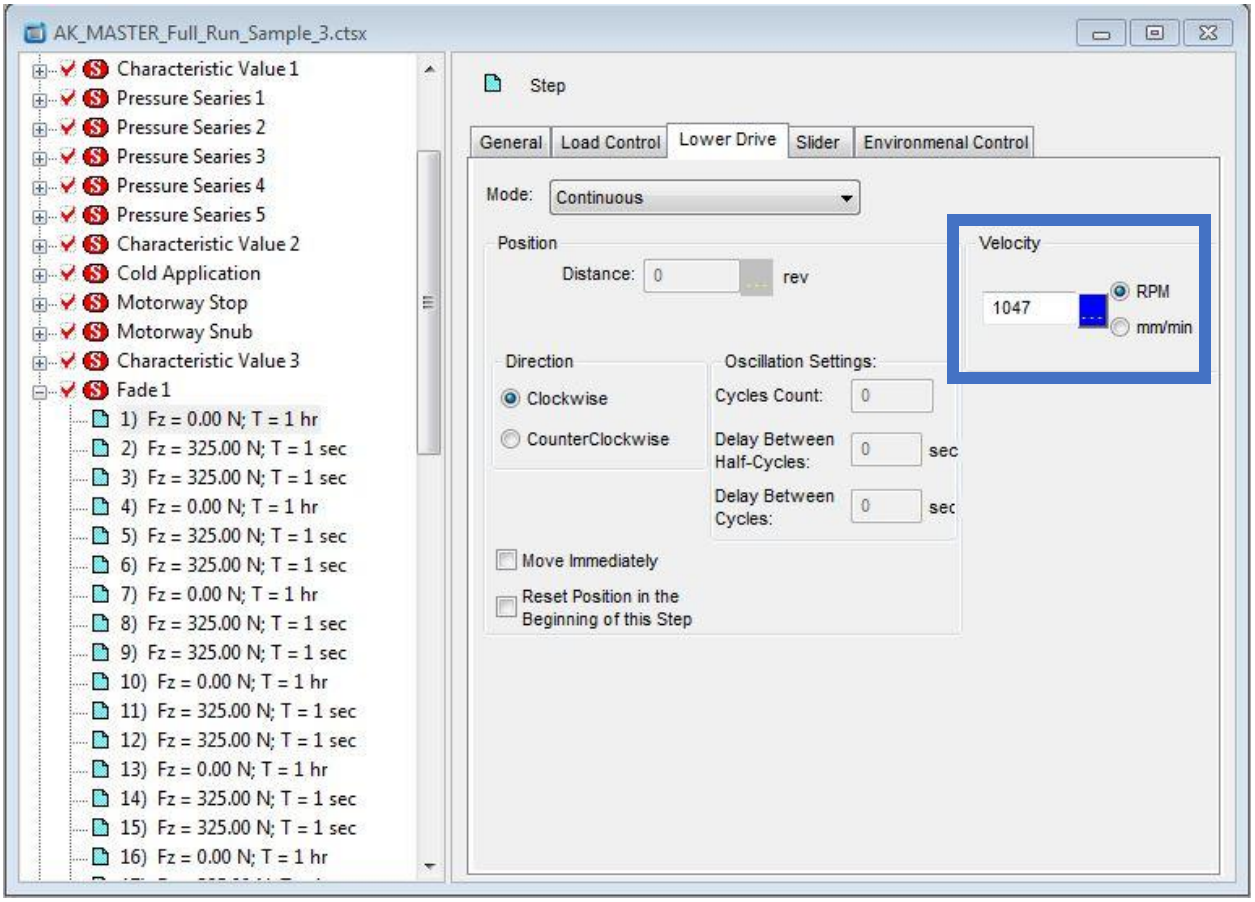
☐ Start at the current level

Fz Value: 325 N

☐ Reset Position in the Beginning of this Step

Figure 11: Changing the Normal Force.

Once the heating chamber and the sample have reached the target temperature, the UMT will then proceed to apply a normal force upon the rotating brake rotor, in this case a normal force of 325 Newtons. This force is found by taking the required pressure from the standard and using the contact area of the brake pad to turn it into the amount of force acting upon that pad then using the scaling factor to go from a full size brake pad down to the sample size used inside the UMT. In the case of the first Fade section it is a force of 650 Newtons. The reason that it is half of that is that the UMT is unable to apply 650 Newtons on the rotor as it is going at the required speed. So, a “safety factor” was used to reduce everything within the Fade sections by 1/2.



Characteristic Value 1
Pressure Searies 1
Pressure Searies 2
Pressure Searies 3
Pressure Searies 4
Pressure Searies 5
Characteristic Value 2
Cold Application
Motorway Stop
Motorway Snub
Characteristic Value 3
Fade 1
1) Fz = 0.00 N; T = 1 hr
2) Fz = 325.00 N; T = 1 sec
3) Fz = 325.00 N; T = 1 sec
4) Fz = 0.00 N; T = 1 hr
5) Fz = 325.00 N; T = 1 sec
6) Fz = 325.00 N; T = 1 sec
7) Fz = 0.00 N; T = 1 hr
8) Fz = 325.00 N; T = 1 sec
9) Fz = 325.00 N; T = 1 sec
10) Fz = 0.00 N; T = 1 hr
11) Fz = 325.00 N; T = 1 sec
12) Fz = 325.00 N; T = 1 sec
13) Fz = 0.00 N; T = 1 hr
14) Fz = 325.00 N; T = 1 sec
15) Fz = 325.00 N; T = 1 sec
16) Fz = 0.00 N; T = 1 hr

Mode: Continuous

Position
Distance: 0 rev

Velocity
1047 ● RPM ○ mm/min

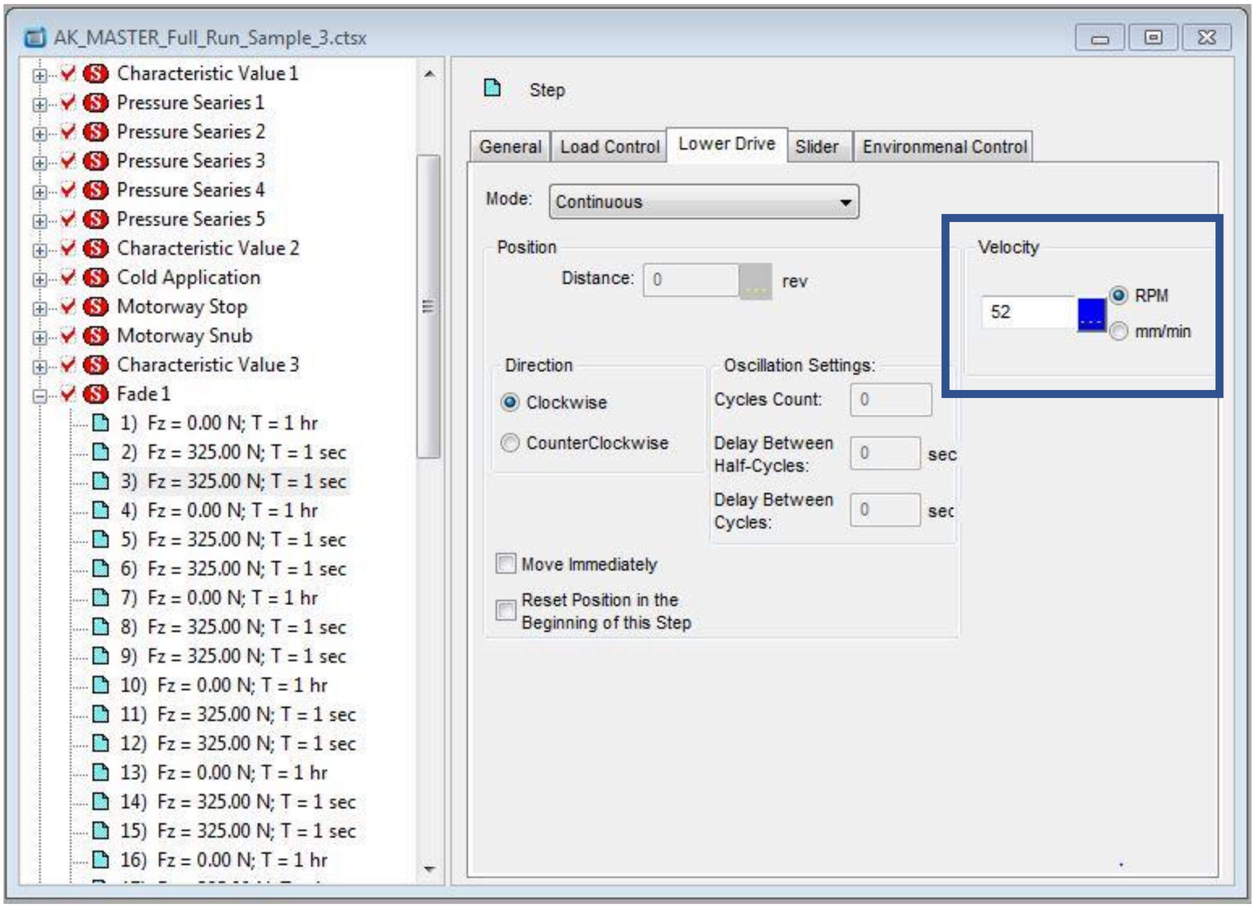
Direction
● Clockwise
○ CounterClockwise

Oscillation Settings:
Cycles Count: 0
Delay Between Half-Cycles: 0 sec
Delay Between Cycles: 0 sec

☐ Move Immediately
☐ Reset Position in the Beginning of this Step

Figure 12: The required Velocity of the rotor.

The initial velocity it set at the required rpm and is set to run for a second which is the shortest amount of time that the UMT will allow a step to take but will continue to record the data through to the next step. The important part of this is that having set the deceleration time previously that when the next step engages that it will decelerate for the set amount of time so that the data is done during the correct amount of time.



- Characteristic Value 1
- Pressure Searies 1
- Pressure Searies 2
- Pressure Searies 3
- Pressure Searies 4
- Pressure Searies 5
- Characteristic Value 2
- Cold Application
- Motorway Stop
- Motorway Snub
- Characteristic Value 3
- Fade 1
  - 1) Fz = 0.00 N; T = 1 hr
  - 2) Fz = 325.00 N; T = 1 sec
  - 3) Fz = 325.00 N; T = 1 sec
  - 4) Fz = 0.00 N; T = 1 hr
  - 5) Fz = 325.00 N; T = 1 sec
  - 6) Fz = 325.00 N; T = 1 sec
  - 7) Fz = 0.00 N; T = 1 hr
  - 8) Fz = 325.00 N; T = 1 sec
  - 9) Fz = 325.00 N; T = 1 sec
  - 10) Fz = 0.00 N; T = 1 hr
  - 11) Fz = 325.00 N; T = 1 sec
  - 12) Fz = 325.00 N; T = 1 sec
  - 13) Fz = 0.00 N; T = 1 hr
  - 14) Fz = 325.00 N; T = 1 sec
  - 15) Fz = 325.00 N; T = 1 sec
  - 16) Fz = 0.00 N; T = 1 hr

Mode: Continuous

Position
Distance: 0 rev

Velocity
52 ● RPM ○ mm/min

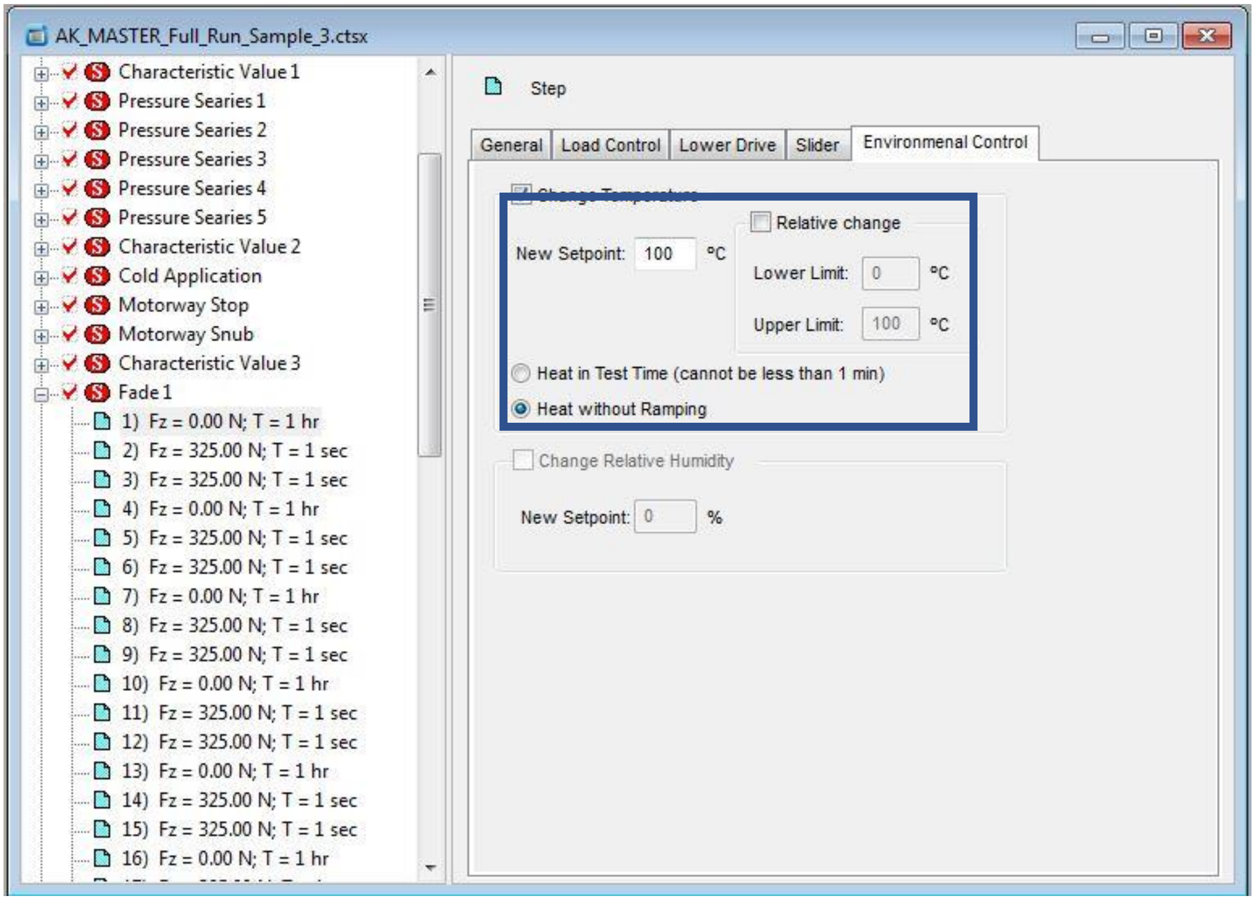
Direction
● Clockwise
○ CounterClockwise

Oscillation Settings:
Cycles Count: 0
Delay Between Half-Cycles: 0 sec
Delay Between Cycles: 0 sec

☐ Move Immediately
☐ Reset Position in the Beginning of this Step

Figure 13:Change in step and Velocity.

With the final velocity set to the required rpm and set to the shortest time so that there is a minimal amount of data collected, as stated above the actual step is not where the data needed comes from.



Characteristic Value 1
Pressure Searies 1
Pressure Searies 2
Pressure Searies 3
Pressure Searies 4
Pressure Searies 5
Characteristic Value 2
Cold Application
Motorway Stop
Motorway Snub
Characteristic Value 3
Fade 1
1) Fz = 0.00 N; T = 1 hr
2) Fz = 325.00 N; T = 1 sec
3) Fz = 325.00 N; T = 1 sec
4) Fz = 0.00 N; T = 1 hr
5) Fz = 325.00 N; T = 1 sec
6) Fz = 325.00 N; T = 1 sec
7) Fz = 0.00 N; T = 1 hr
8) Fz = 325.00 N; T = 1 sec
9) Fz = 325.00 N; T = 1 sec
10) Fz = 0.00 N; T = 1 hr
11) Fz = 325.00 N; T = 1 sec
12) Fz = 325.00 N; T = 1 sec
13) Fz = 0.00 N; T = 1 hr
14) Fz = 325.00 N; T = 1 sec
15) Fz = 325.00 N; T = 1 sec
16) Fz = 0.00 N; T = 1 hr

☑ Change Temperature
New Setpoint: 100 °C
☐ Relative change
Lower Limit: 0 °C
Upper Limit: 100 °C
○ Heat in Test Time (cannot be less than 1 min)
● Heat without Ramping

☐ Change Relative Humidity
New Setpoint: 0 %

Figure 14: Setting the Temperature.

While the temperatures needed in most of the sequences is 100°C there are a few different temperatures that are required, the highest being 500°C and the lowest being 40°C. While the heating chamber takes time to heat to the required temps, there are two choice to choose from, either heating in test time, meaning it will take all the set time to heat to the target time, this is a bad choice as one of the advantages of the UMT is shorter running times. The other option is to heat without ramping, which will make the heating chamber heat as quickly as possible, and with a break condition set to cause the step to end when the temperature is reach, the next step can begin.

CHAPTER 4

RESULTS

4.1 COEFFICIENT OF FRICTION

Table 6: Results from preliminary test runs

Characteristic Values	Section Number	Mu desc.	Dynamo	UMT	Difference
			AVG	AVG	
Characteristic Value	3	OP6	0.45	0.31	0.14
Speed/Pressure	4.3	v120	0.44	0.32	0.12
Speed/Pressure	4.5	vmax	0.3	0.31	-0.01
Characteristic Value	5	OP6	0.3	0.33	-0.03
Cold	6	T40	0.31	0.25	0.06
Motorway Appl 2	7	MW2	0.28	0.24	0.04
Characteristic Value	8	OP18	0.35	0.32	0.03
Fade 1	9	F1	0.26	0.34	-0.08
Recovery	10	OP18	0.36	0.39	-0.03
Temperature	12	T500	0.35	0.41	-0.06
Recovery	13	OP18	0.31	0.40	-0.09
Fade 2	14	F2	0.38	0.36	0.02
Recovery	15	OP18	0.36	0.37	-0.01

Table 6 shows the results from the first few applications of the scaled tests as compared to the results from the full-scale Inertia Dynamometer.

These results show promising results as the differences between the dynamometer and the UMT are not of by much of a significant value. With further testing and applications of these tests there might be a possibility of showing that a small-scale bench top tester can replicate the results of the full-scale Inertia Dynamometer.

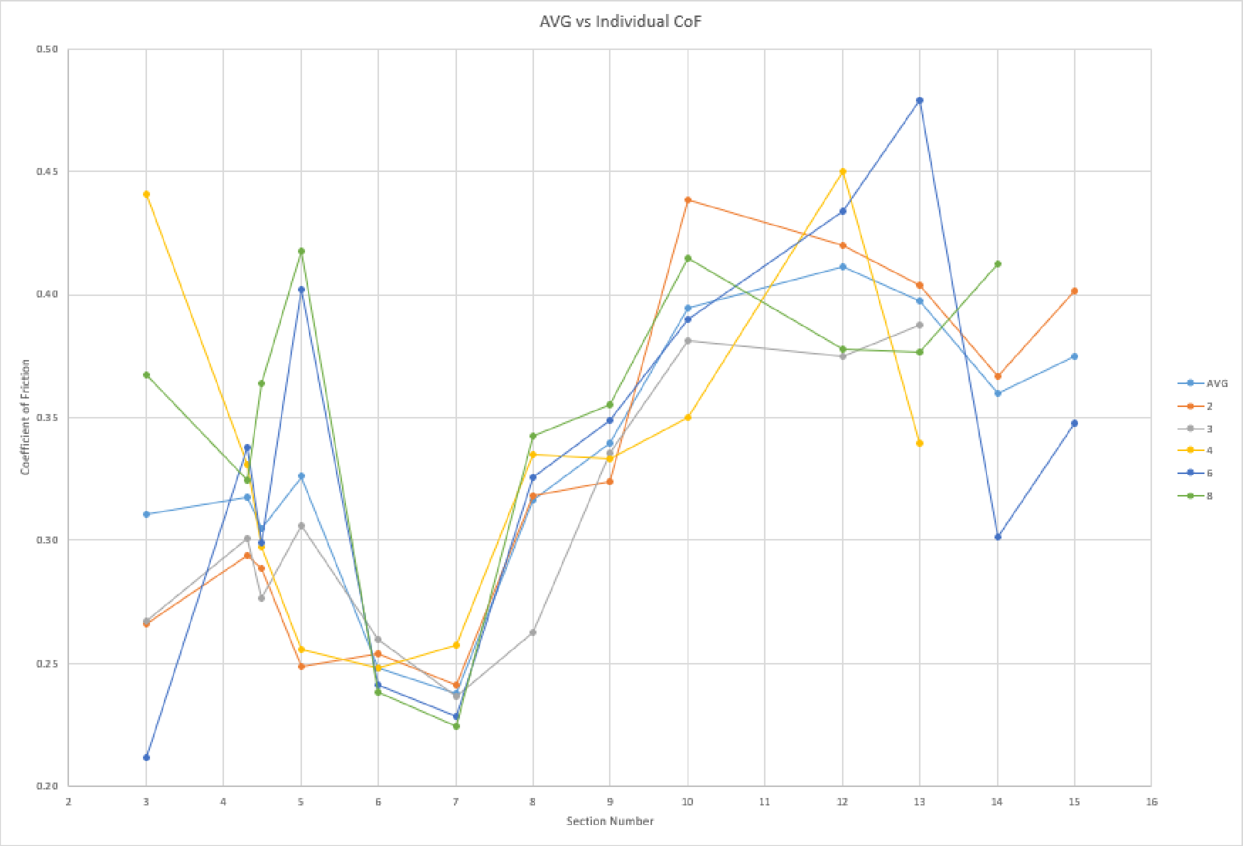


Figure 15: Comparison of the Average Coefficient of friction to the individual samples.

While all of the samples that were run used the full script that was developed for use with this research, not all samples completed the full test, some of the samples could not sustain cohesion and turned to dust, what caused this is unknown but their data still added to the overall experiment.

4.2 SCANNING ELECTRON MICROSCOPY

Through the use of a scanning Electron Microscope (SEM) the samples from the UMT and the Dynamometer can be compared to see if their wear patterns are similar, this can give better insight into what is happening to the materials in contact. If the track patterns are similar this means that what is happening on the full-scale dynamometer is also being replicated within the heating chamber of the UMT.

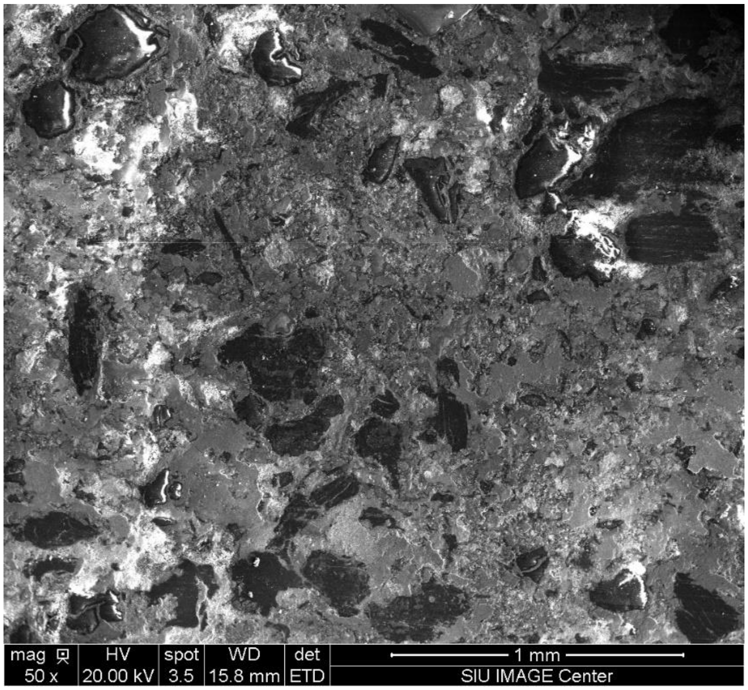


Figure 16: Sample from test done on full scale dynamometer.

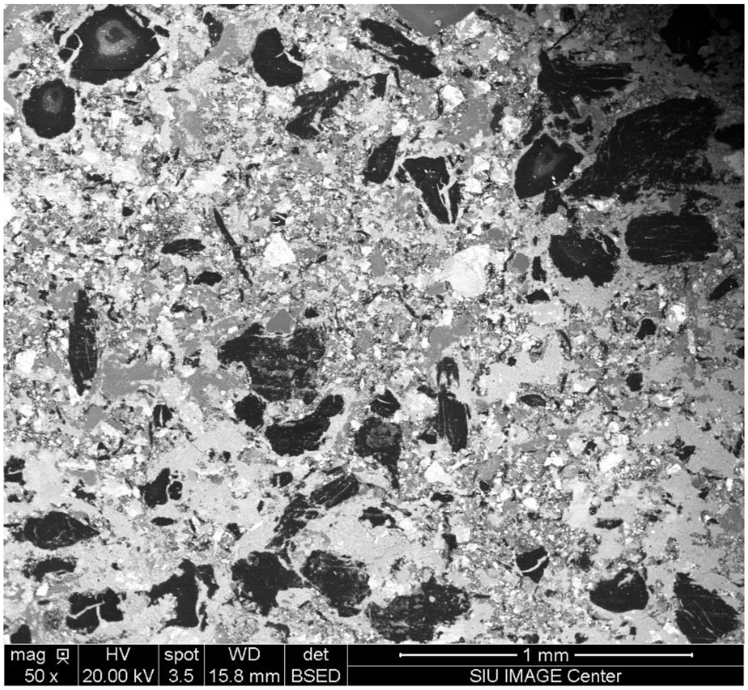


Figure 17: Backscattered SEM taken of the dynamometer sample.

These two images taken using the SEM allow for a visual comparison of the samples that were run on the full-scale brake dynamometer and the small-scale samples that were run on the UMT to see if there are similar phenomena going on in both sets of samples. This is needed since the data seems to suggest that the UMT can emulate the full-scale brake dynamometer, even with a second scaling done on the samples and in two tests a “safety factor” was used. Using the backscattered and topographical SEM images taken from the full-scale dynamometer and comparing them to backscattered and topographical SEM images from the UMT samples will give a better understanding of the results and the actual phenomena that are affecting the surface of the brake material that is being used.

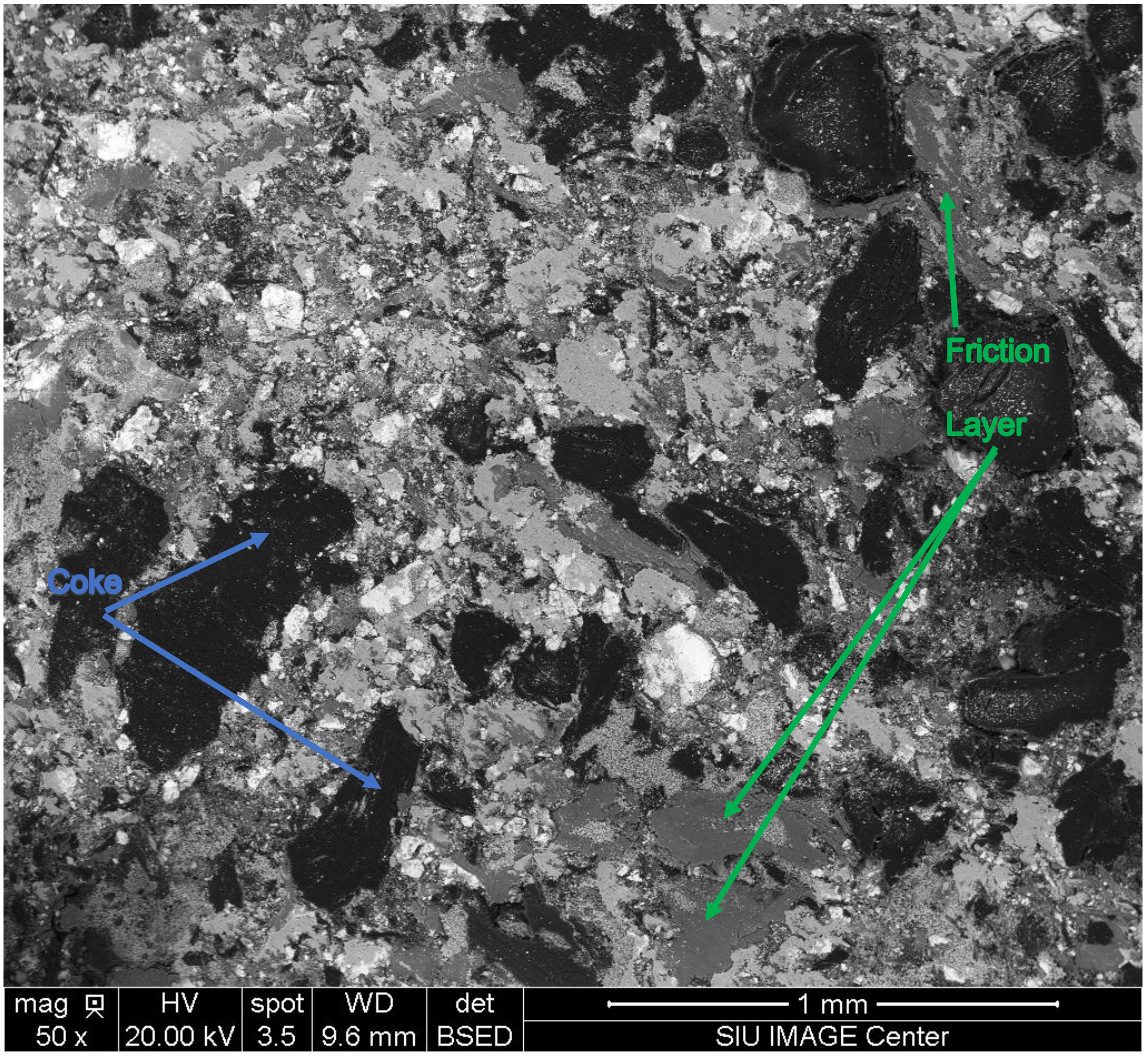


Figure 18: Backscattered SEM taken of a sample from the UMT.

The heavier elements within the brake pad appear as lighter colors on the image while the black/darker colored areas are the coke used in the creation of the brake pads. The friction layer above marked in green is one of the areas that when compared should show similar wear patterns if the data is correct and similar phenomena is taking place at the point of contact. As can be seen in Fig. 16 there seems to be a much more expansive area of the friction layer, this may be due to the fact that the brake pads have a larger area in contact with the brake rotor, but the fact that there are some large areas in both samples give a good indication that the entire surface is in contact with the rotor.

Along with the friction layer, both samples have areas of coke buildup as well as areas where the filler is being stripped from the surface to help create that friction layer.

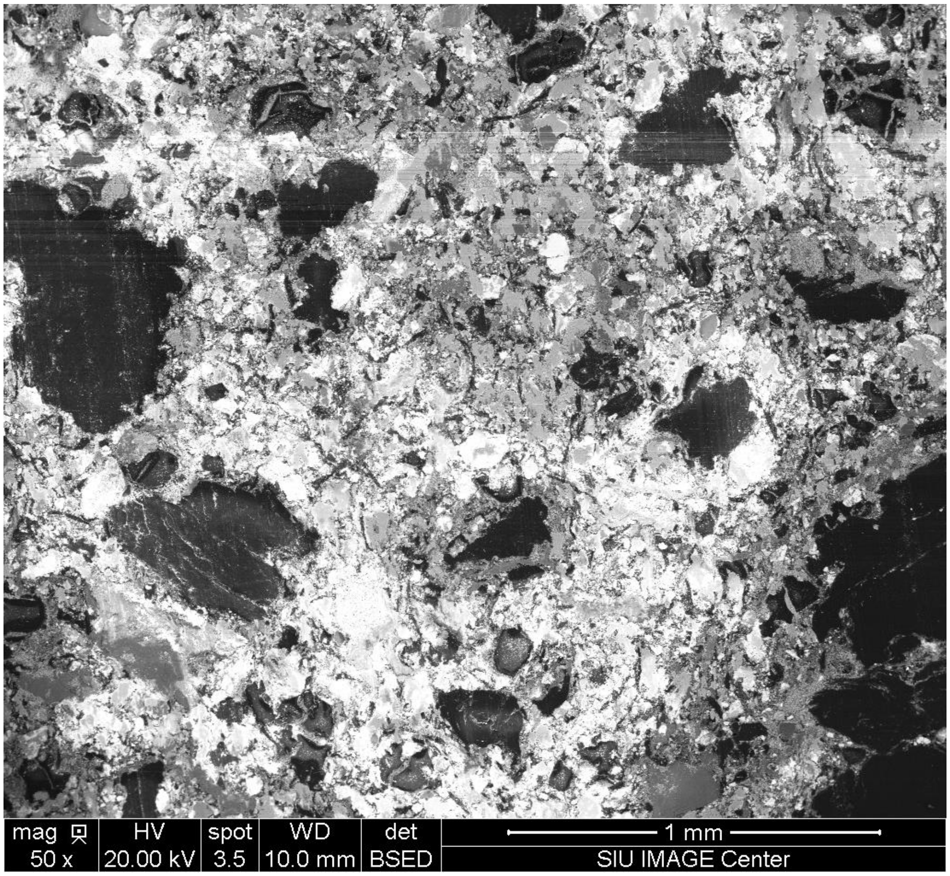


Figure 19: Backscattered SEM from a different sample.

Figure 18 shows a backscattered SEM from a different set of samples then those in Figure 17. This sample has few more heavy elements in its sample than the first one, while these are from the same type of brakes from the same set it was not taken from the same spot within the brakes. This speaks to the fact that the brakes are not homogeneous throughout their makeup and can have different ratios of elements throughout the pad.

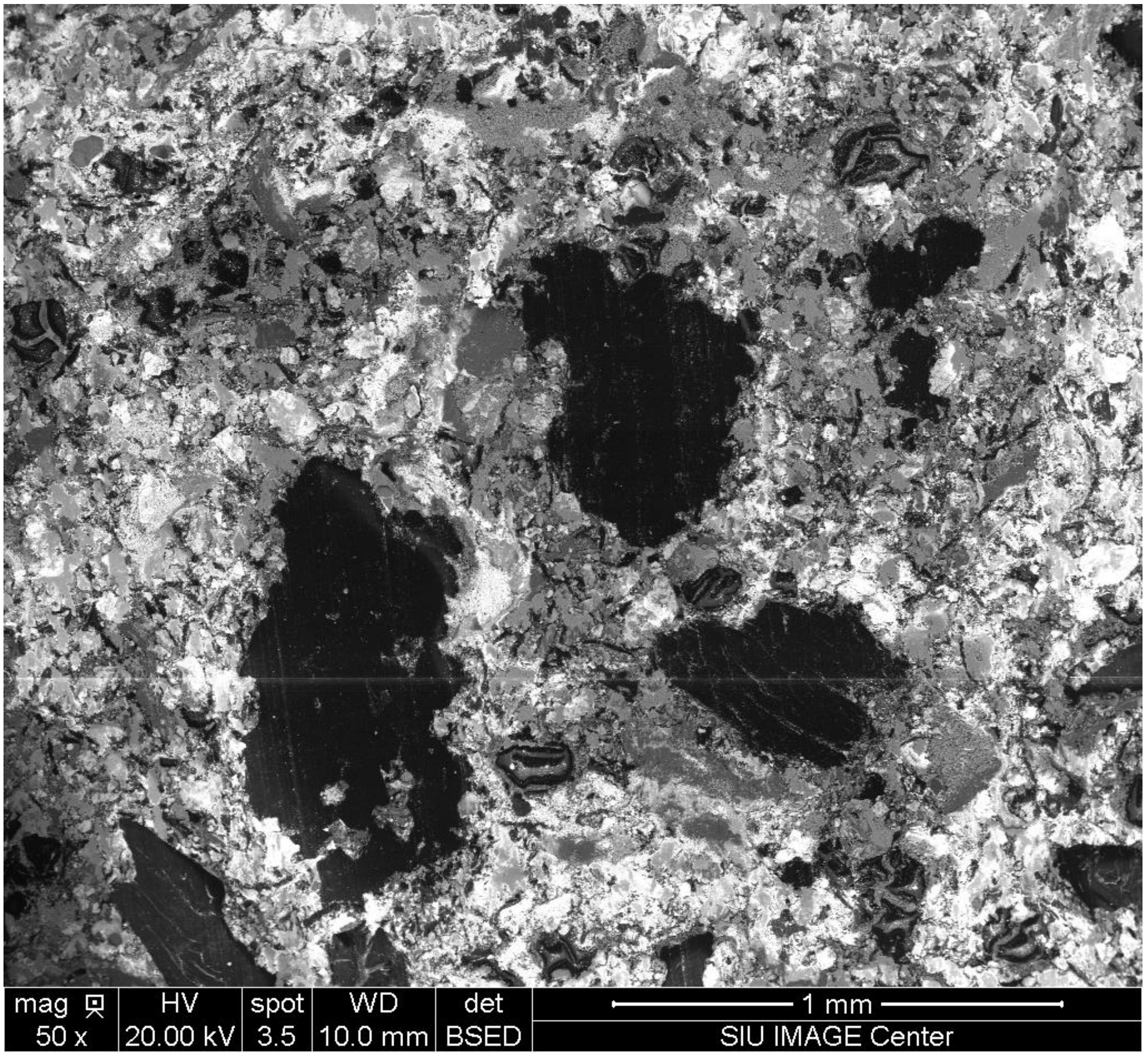


Figure 20: Same sample but at a different location.

Figure 19 shows the same sample as figure 18 but at a different location on the sample.

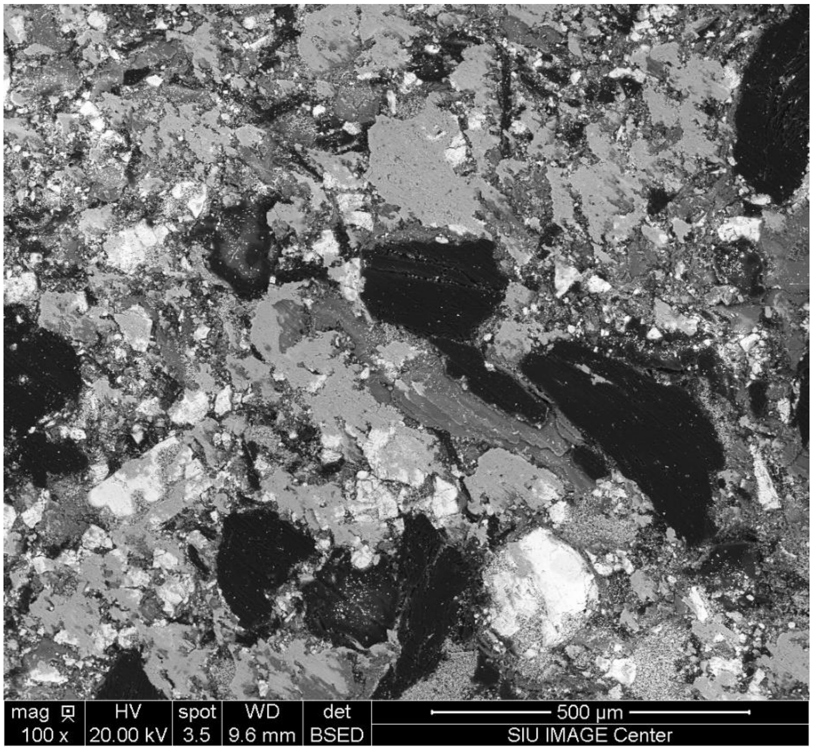


Figure 21: Backscattered SEM of the sample from Fig. 17.

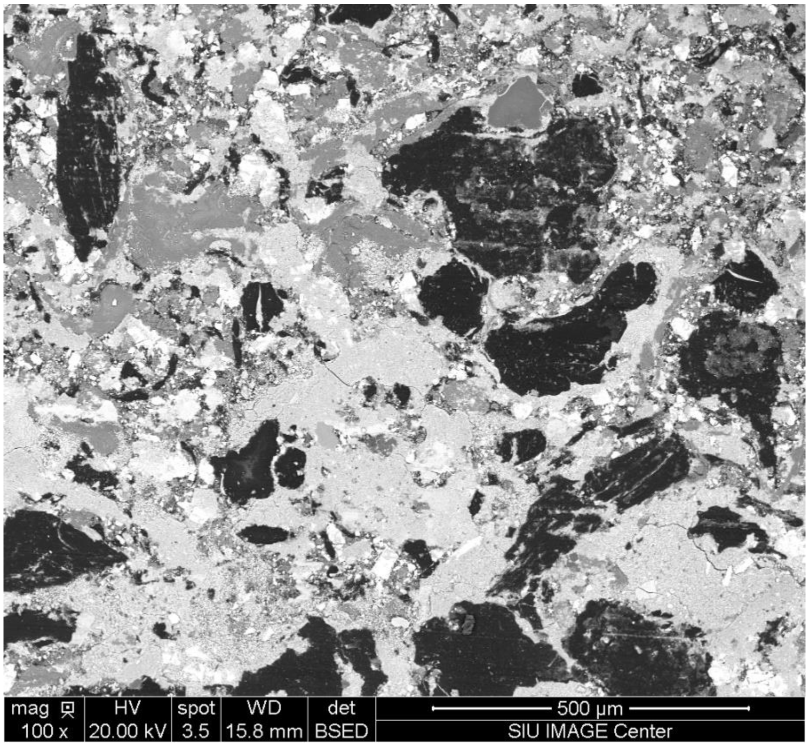


Figure 22: Backscattered SEM of the sample from the full-scale dynamometer.

Figures 20 & 21 are taken at a higher magnification to show a closer view of the surface of the brake samples from the UMT and the Dynamometer, respectively.

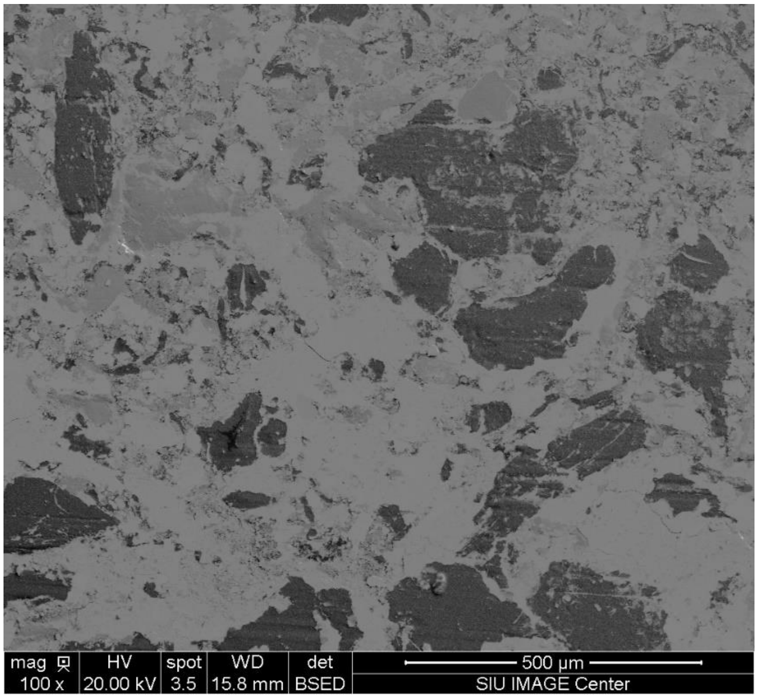


Figure 23: Topographical SEM of the samples from the dynamometer.

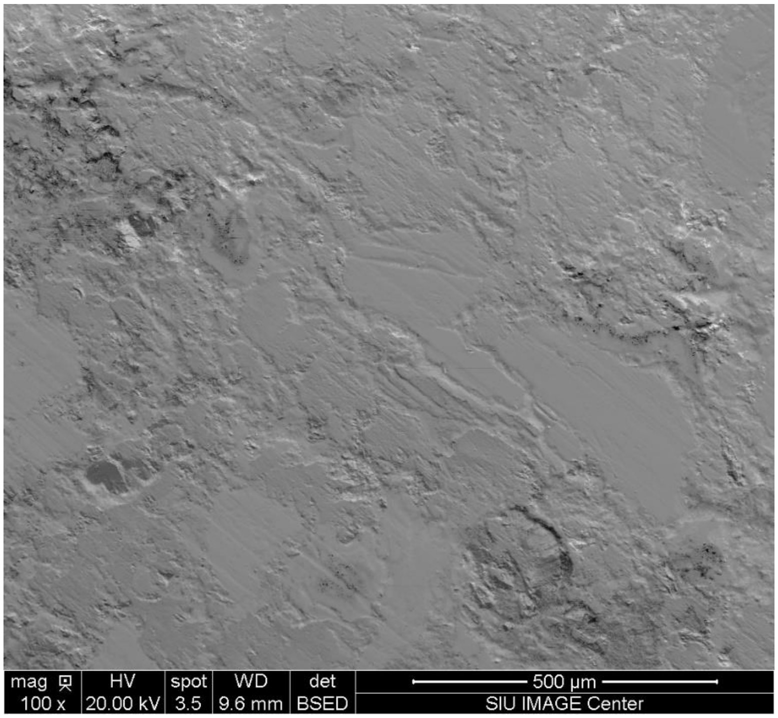


Figure 24: Topographical SEM of the sample from the UMT.

The differences between figure 22 and 23 are rather staggering in that, the dark areas that appear on the full-scale dynamometer are not present in the UMT samples, this may be due to the different conditions that the samples are being subjected to. While these differences were reduced since previous work done in the lab, some are still present [38,39]. While the data would suggest that the dynamometer and the UMT are similar in their results the images that were taken using the SEM show that this is not the case, that the two machines subject the material to two separate types of friction and wear.

4.3 FUTURE WORK

Future work with the UMT is strongly suggested with fresh brake pads, rotors, and different types of brake pads. If research could be done quickly on a single vehicle with multiple pads could be shown to be able to emulate the full test regime and give similar results to a full-scale dynamometers results this would show that if scaled properly that it can give an idea of the coefficient of friction that the brakes could give. While reducing the number of differences in the tests seems to have given better results to the tests, there are still some areas that are different between the two testing machines. One thing that could lead to a reduction in differences would be to take the reading of the rotor instead of the sample this would give a more accurate temperature reading that the test regime requires.

If the machine could work under the required forces of a single scaling, then this would give a more accurate idea of what the brakes are being subjected to. If there was a way to get the friction surfaces to become similar and the data to be similar, then this would be ideal. Since friction and wear are system properties this task is made more difficult for researchers to test on the small scale and have the same results be emulated at the full-scale.

CHAPTER 5

CONCLUSION

Throughout this research there were three main goals that were trying to be achieved, they were: can a benchtop tester emulate the results from a full-scale brake dynamometer, can a script be written to allow for a full run of the entire testing procedure, and to examine if there are similarities or differences in the friction and wear detected in both the dynamometer and the UMT. After using proper physics scaling the values that were achieved, which can be found in Appendix A, were too much for the UMT to be able to handle. To try and fix this problem, a second scaling was applied to the values where force was the value used in place of the apparent contact area finding the contact area. In the case of the Fade section of the test, these values still proved to be too much for the UMT to handle so a “safety factor” of 2 was applied to all of the parameters that had been scaled, to halve the forces acting on the system.

A full running script was able to be created for the UMT that would allow for a continuous run of the machine through a complete run of the SAE J2522 testing standard. Due to the forces acting on the machine though, it could not be run in one sitting without the machine seizing during use. As a requirement for a course the required torque that would be required to be provided by a motor in order to run the machine with only one scaling done was calculated, the torque required is at a minimum of 25 N*m, with 30 N*m being ideal for most applications.

The comparison of the two tests shows that even with a second scaling that the phenomena are having similar effects on the brake materials that comprise the brakes. This shows that even with the differences between the two testing machines in the conditions applied when the amount of differences is reduced that there are similarities in the wear patterns that appear on the brake materials. Within a brake dynamometer a set of brake pads are tested while in the UMT the test is done using smaller samples, for these reasons a dynamometer will show the friction behavior of the whole pad while the UMT can show the friction behavior of the composition used in the brake materials. This can allow for basic or fundamental research into different formulations of brake pads, thus allowing for many different new iterations of materials to be tested quickly and would be using the UMT to its strengths.

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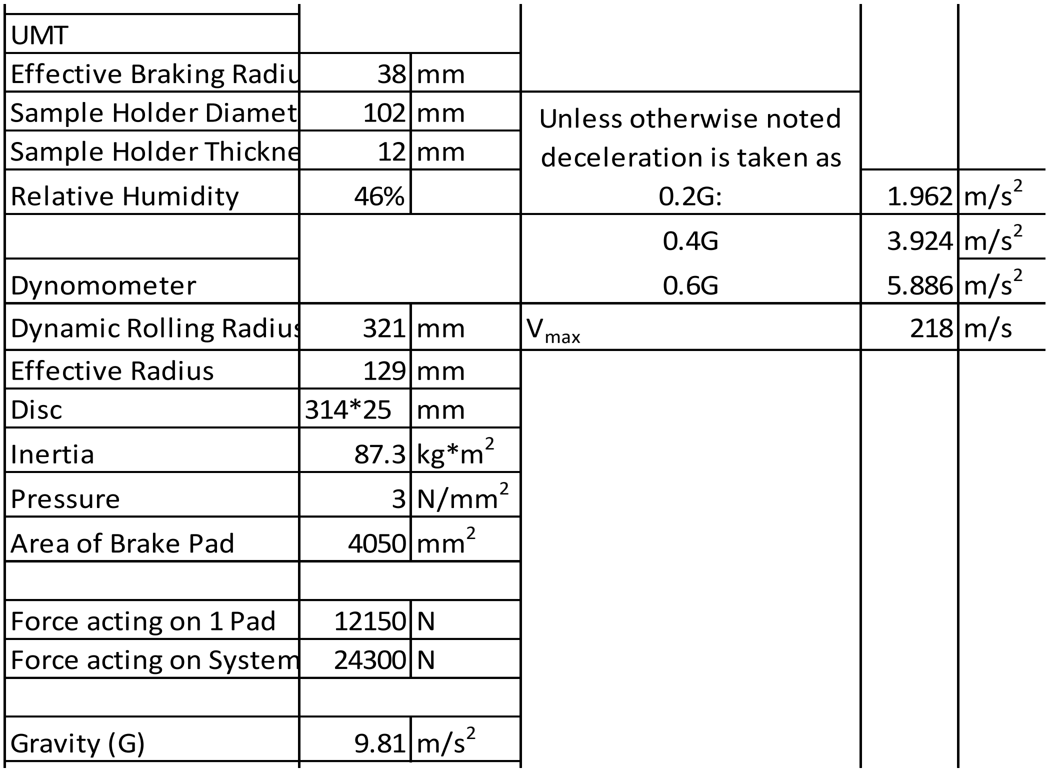
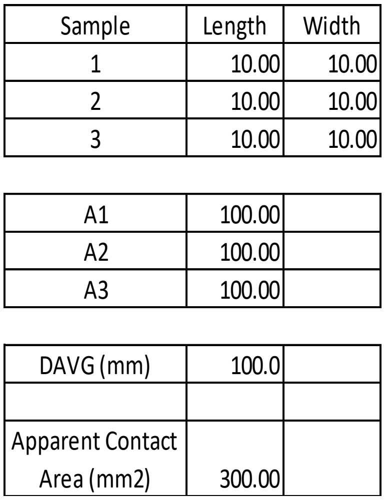
APPENDIX A:

SCALING CALCULATIONS



UMT					
Effective Braking Radiu	38	mm			
Sample Holder Diamet	102	mm	Unless otherwise noted deceleration is taken as		
Sample Holder Thickne	12	mm			
Relative Humidity	46%		0.2G:	1.962	m/s^2
			0.4G	3.924	m/s^2
Dynomometer			0.6G	5.886	m/s^2
Dynamic Rolling Radiu	321	mm	V_{max}	218	m/s
Effective Radius	129	mm			
Disc	314*25	mm			
Inertia	87.3	$kg*m^2$			
Pressure	3	N/mm^2			
Area of Brake Pad	4050	mm^2			
Force acting on 1 Pad	12150	N			
Force acting on System	24300	N			
Gravity (G)	9.81	m/s^2			

Figure 25: Given Data for use in the SAE J2522

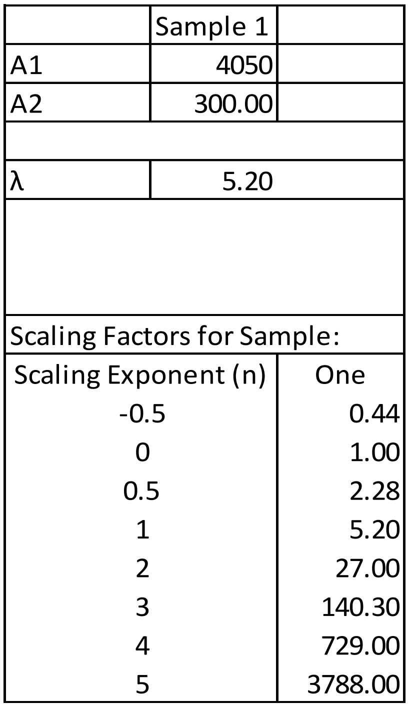


Sample	Length	Width
1	10.00	10.00
2	10.00	10.00
3	10.00	10.00

A1	100.00	
A2	100.00	
A3	100.00	

DAVG (mm)	100.0	
Apparent Contact Area (mm2)	300.00	

Figure 26: Area calculations of samples

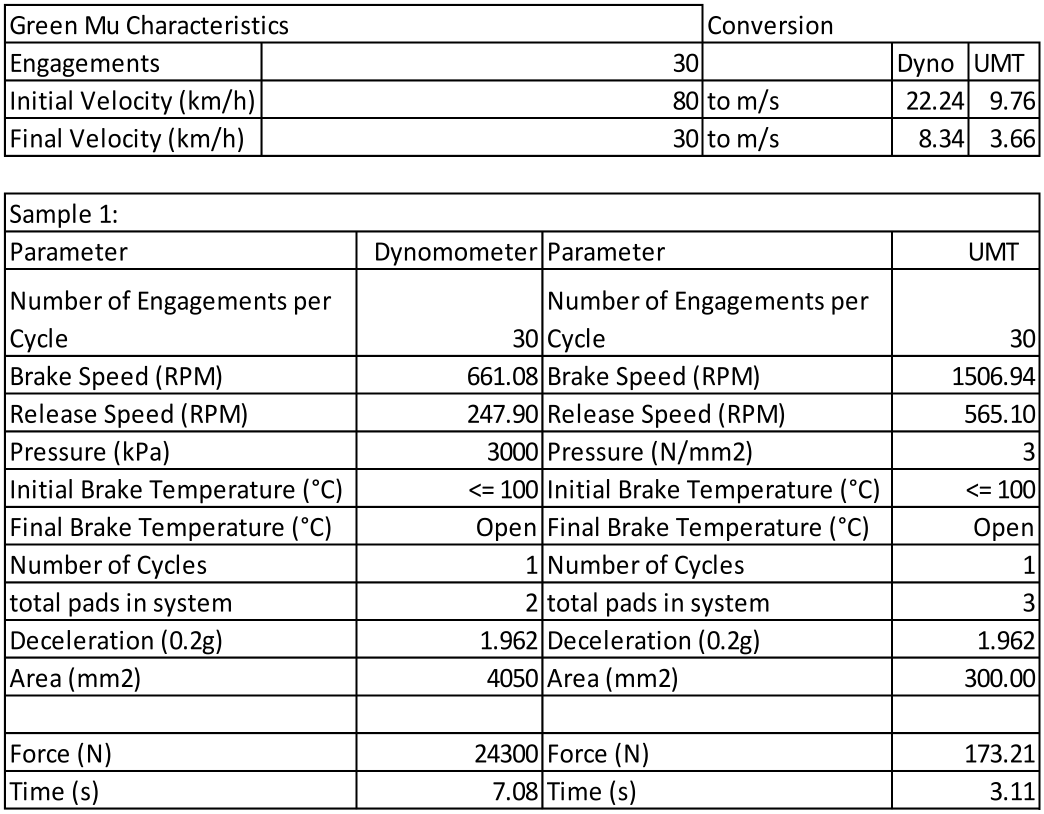


	Sample 1	
A1	4050	
A2	300.00	
λ	5.20	

Scaling Factors for Sample:

Scaling Exponent (n)	One
-0.5	0.44
0	1.00
0.5	2.28
1	5.20
2	27.00
3	140.30
4	729.00
5	3788.00

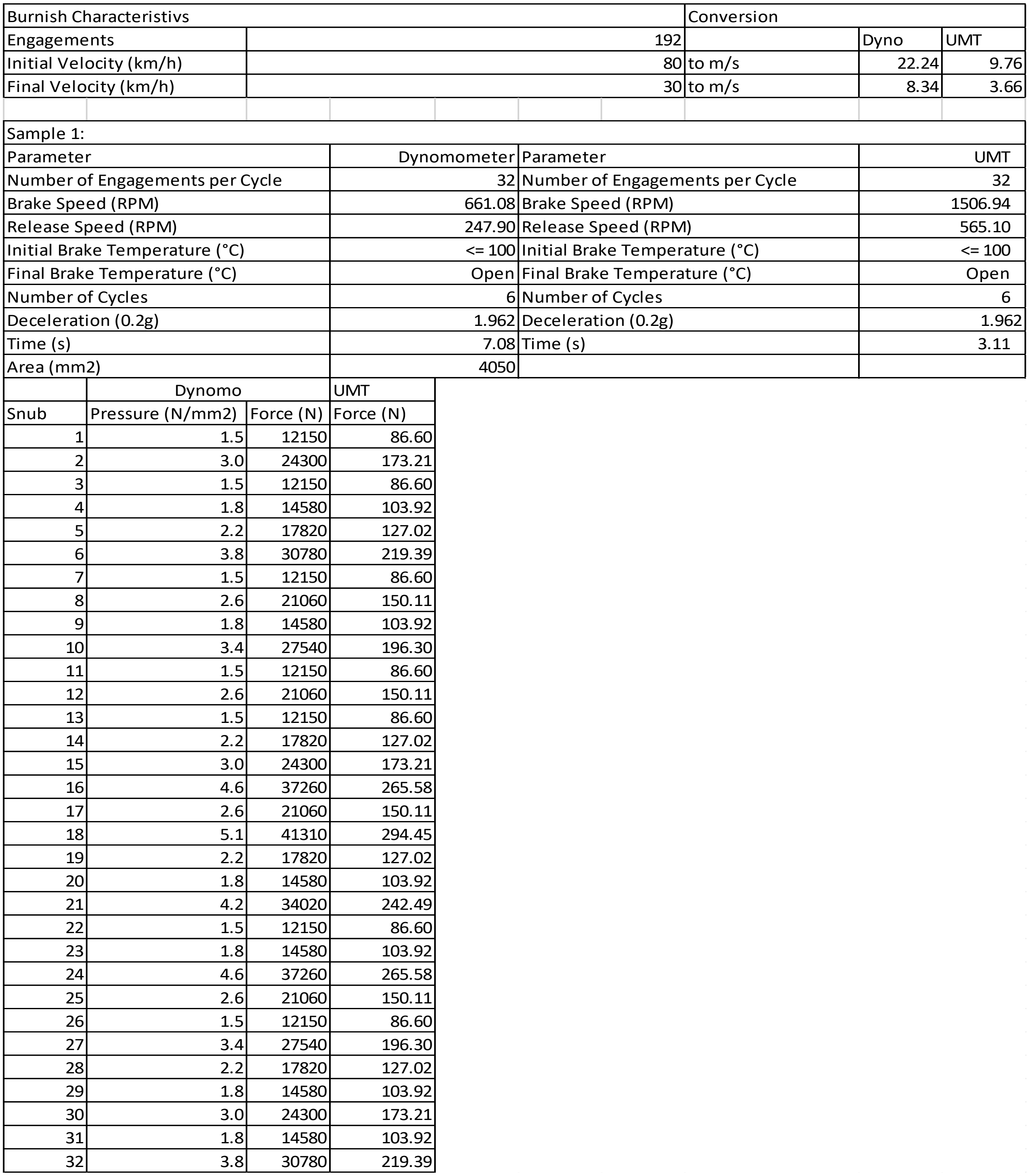
Figure 27: Scaling Factors for a perfect sample



Green Mu Characteristics		Conversion		
Engagements	30		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	30	Number of Engagements per Cycle	30
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Pressure (kPa)	3000	Pressure (N/mm2)	3
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
total pads in system	2	total pads in system	3
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Area (mm2)	4050	Area (mm2)	300.00
Force (N)	24300	Force (N)	173.21
Time (s)	7.08	Time (s)	3.11

Figure 28: Green Mu section of calculations between Dyno and UMT

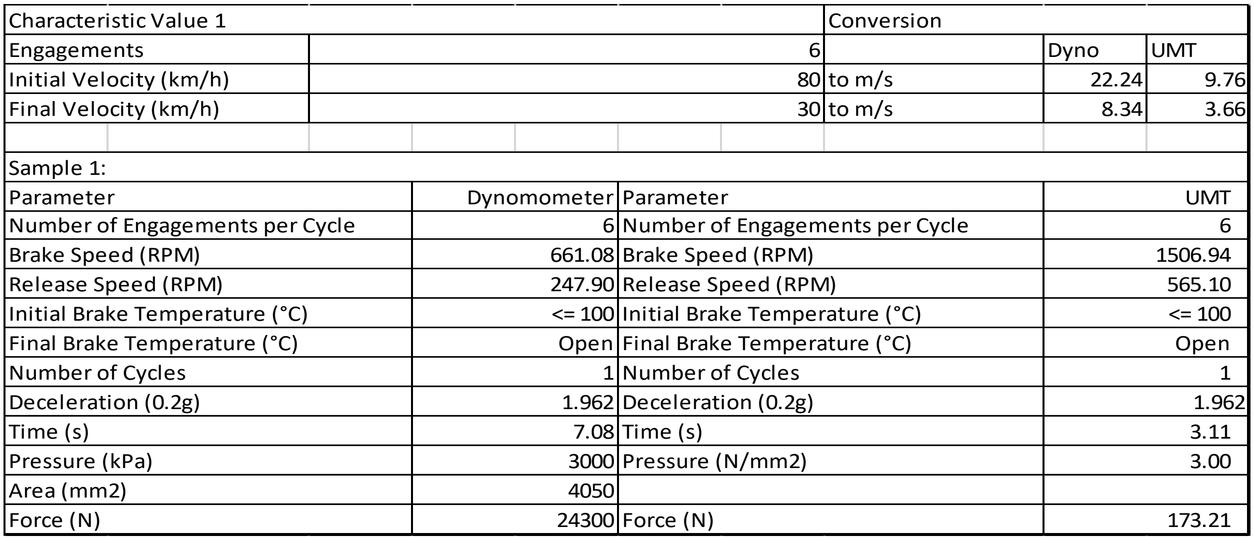


Burnish Characteristivs		Conversion		
Engagements	192		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	32	Number of Engagements per Cycle	32
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	6	Number of Cycles	6
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	7.08	Time (s)	3.11
Area (mm2)	4050		

	Dynomo		UMT
Snub	Pressure (N/mm2)	Force (N)	Force (N)
1	1.5	12150	86.60
2	3.0	24300	173.21
3	1.5	12150	86.60
4	1.8	14580	103.92
5	2.2	17820	127.02
6	3.8	30780	219.39
7	1.5	12150	86.60
8	2.6	21060	150.11
9	1.8	14580	103.92
10	3.4	27540	196.30
11	1.5	12150	86.60
12	2.6	21060	150.11
13	1.5	12150	86.60
14	2.2	17820	127.02
15	3.0	24300	173.21
16	4.6	37260	265.58
17	2.6	21060	150.11
18	5.1	41310	294.45
19	2.2	17820	127.02
20	1.8	14580	103.92
21	4.2	34020	242.49
22	1.5	12150	86.60
23	1.8	14580	103.92
24	4.6	37260	265.58
25	2.6	21060	150.11
26	1.5	12150	86.60
27	3.4	27540	196.30
28	2.2	17820	127.02
29	1.8	14580	103.92
30	3.0	24300	173.21
31	1.8	14580	103.92
32	3.8	30780	219.39

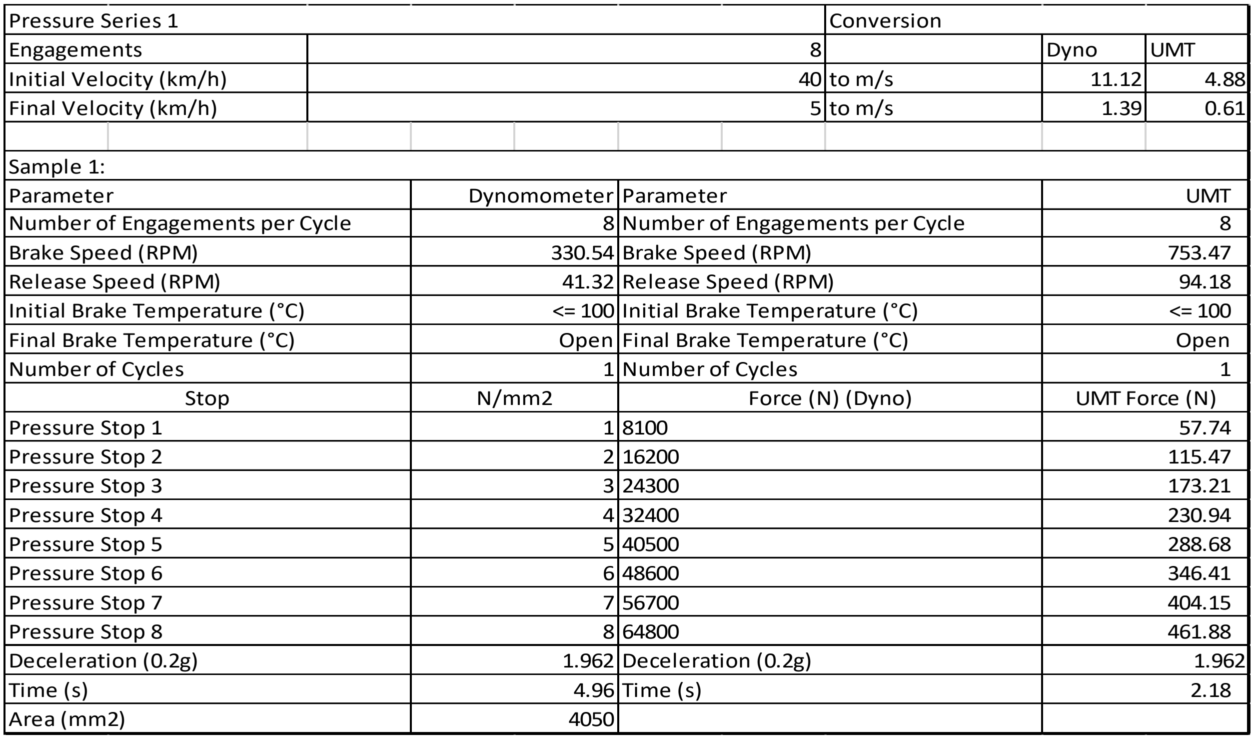
Figure 29: Burnish section of calculations between Dyno and UMT



Characteristic Value 1		Conversion		
Engagements	6		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66
Sample 1:				

Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	6	Number of Engagements per Cycle	6
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	7.08	Time (s)	3.11
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21

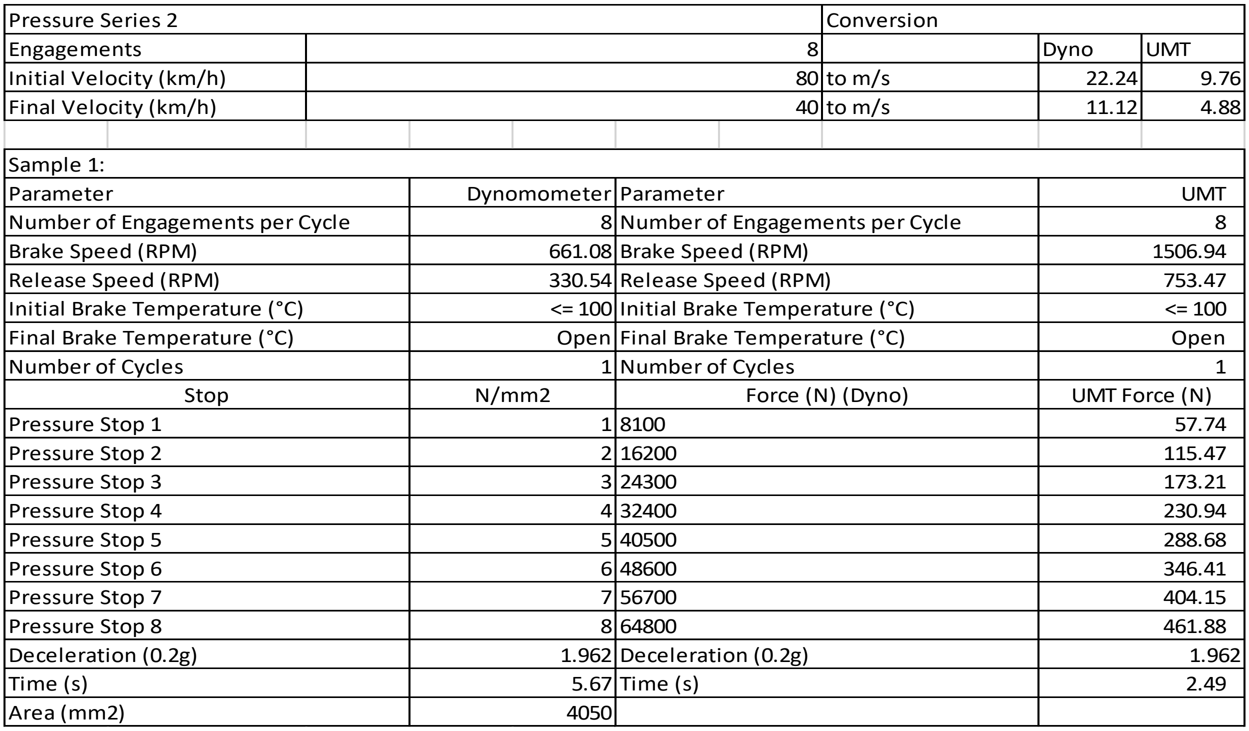
Figure 30: Characteristic Value section of calculations between Dyno and UMT



Pressure Series 1		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	40	to m/s	11.12	4.88
Final Velocity (km/h)	5	to m/s	1.39	0.61
Sample 1:				

Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	330.54	Brake Speed (RPM)	753.47
Release Speed (RPM)	41.32	Release Speed (RPM)	94.18
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	4.96	Time (s)	2.18
Area (mm2)	4050		

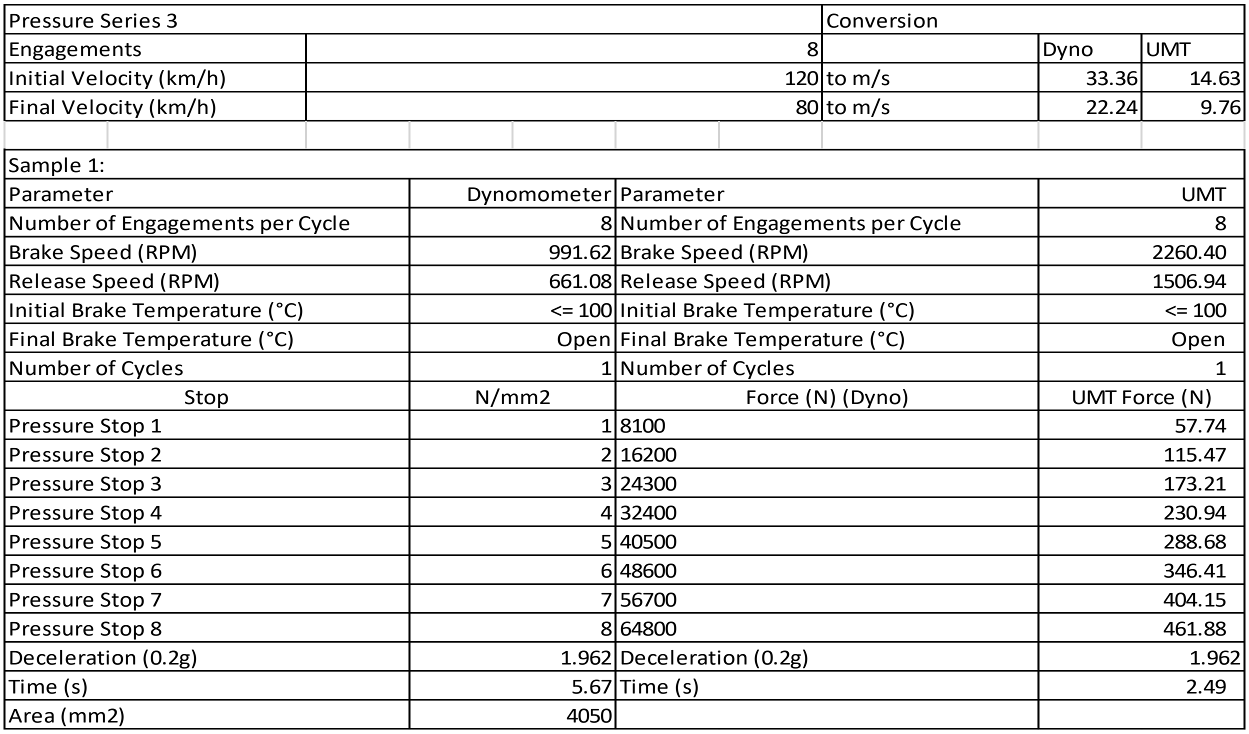
Figure 31: Pressure Series 1 section of calculations between Dyno and UMT



Pressure Series 2		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	40	to m/s	11.12	4.88

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	330.54	Release Speed (RPM)	753.47
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	5.67	Time (s)	2.49
Area (mm2)	4050		

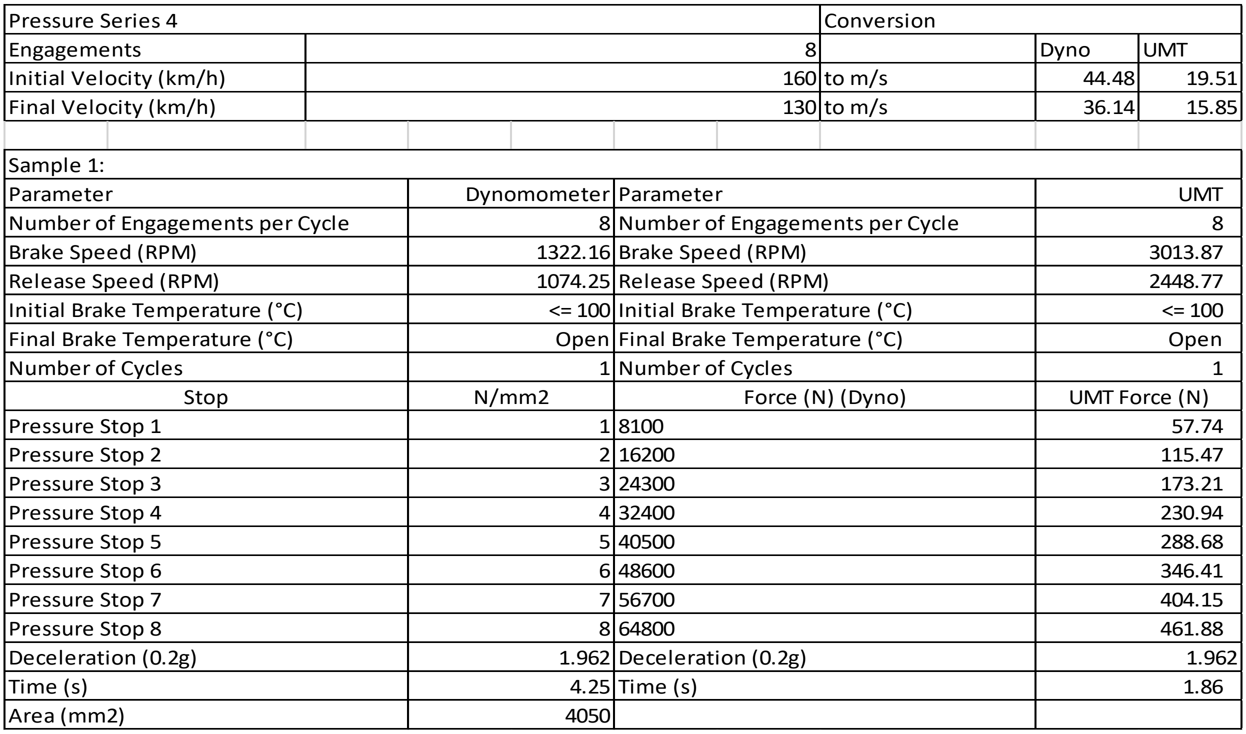
Figure 32: Pressure Series 2 section of calculations between Dyno and UMT



Pressure Series 3		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	120	to m/s	33.36	14.63
Final Velocity (km/h)	80	to m/s	22.24	9.76

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	991.62	Brake Speed (RPM)	2260.40
Release Speed (RPM)	661.08	Release Speed (RPM)	1506.94
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	5.67	Time (s)	2.49
Area (mm2)	4050		

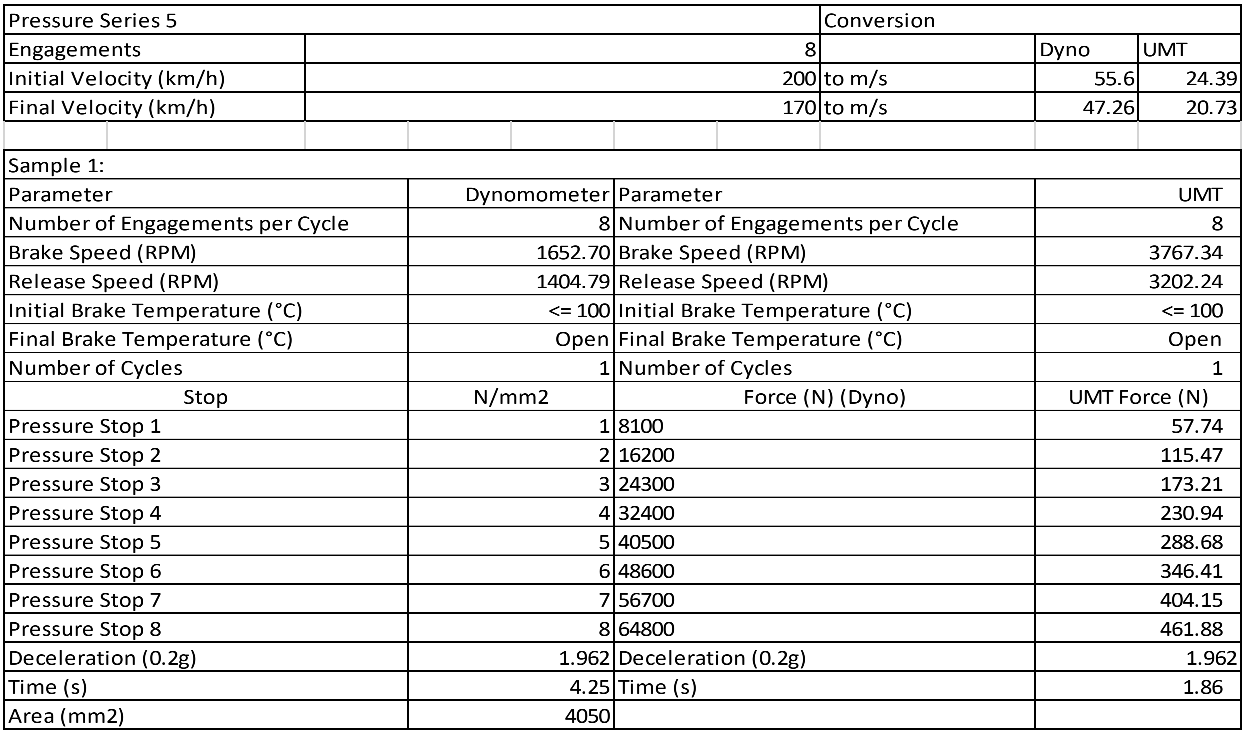
Figure 33: Pressure Series 3 section of calculations between Dyno and UMT



Pressure Series 4		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	160	to m/s	44.48	19.51
Final Velocity (km/h)	130	to m/s	36.14	15.85

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	1322.16	Brake Speed (RPM)	3013.87
Release Speed (RPM)	1074.25	Release Speed (RPM)	2448.77
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	4.25	Time (s)	1.86
Area (mm2)	4050		

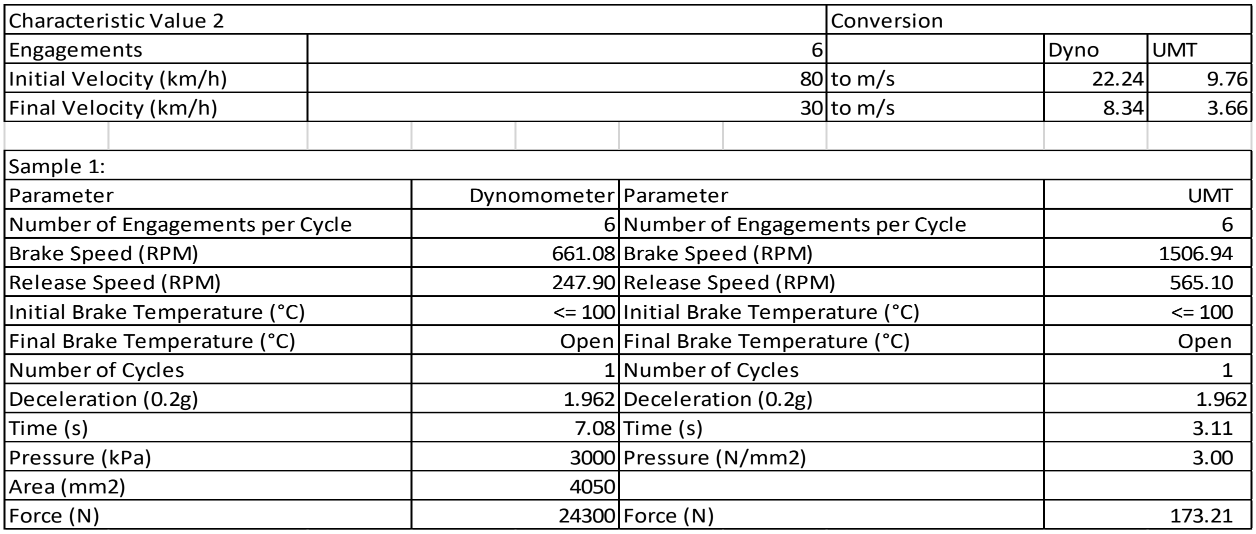
Figure 34: Pressure Series 4 section of calculations between Dyno and UMT



Pressure Series 5		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	200	to m/s	55.6	24.39
Final Velocity (km/h)	170	to m/s	47.26	20.73

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	1652.70	Brake Speed (RPM)	3767.34
Release Speed (RPM)	1404.79	Release Speed (RPM)	3202.24
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	4.25	Time (s)	1.86
Area (mm2)	4050		

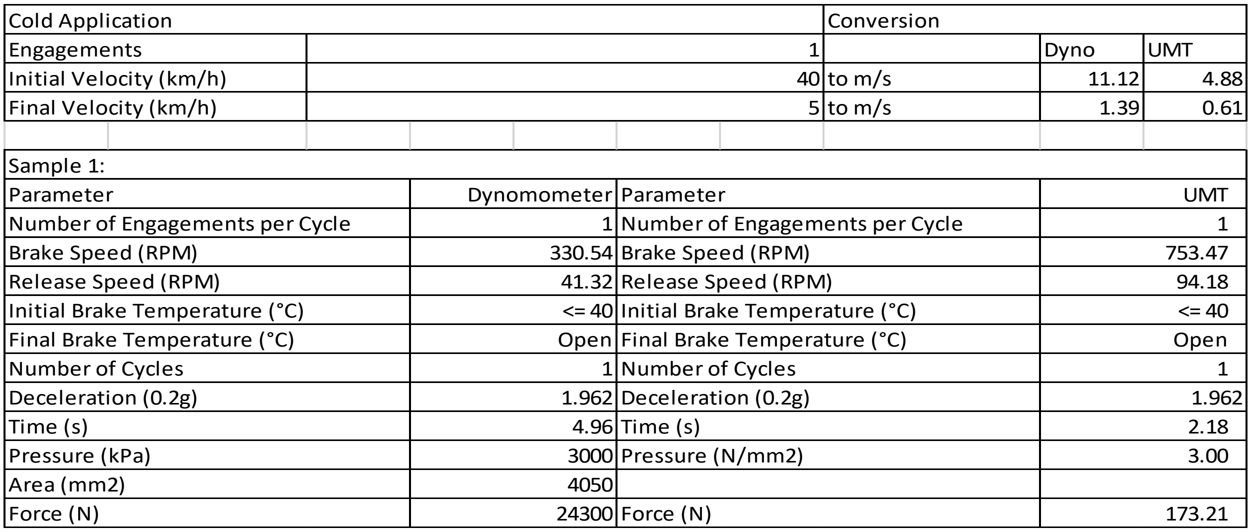
Figure 35: Pressure Series 5 section of calculations between Dyno and UMT



Characteristic Value 2		Conversion		
Engagements	6		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	6	Number of Engagements per Cycle	6
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	7.08	Time (s)	3.11
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21

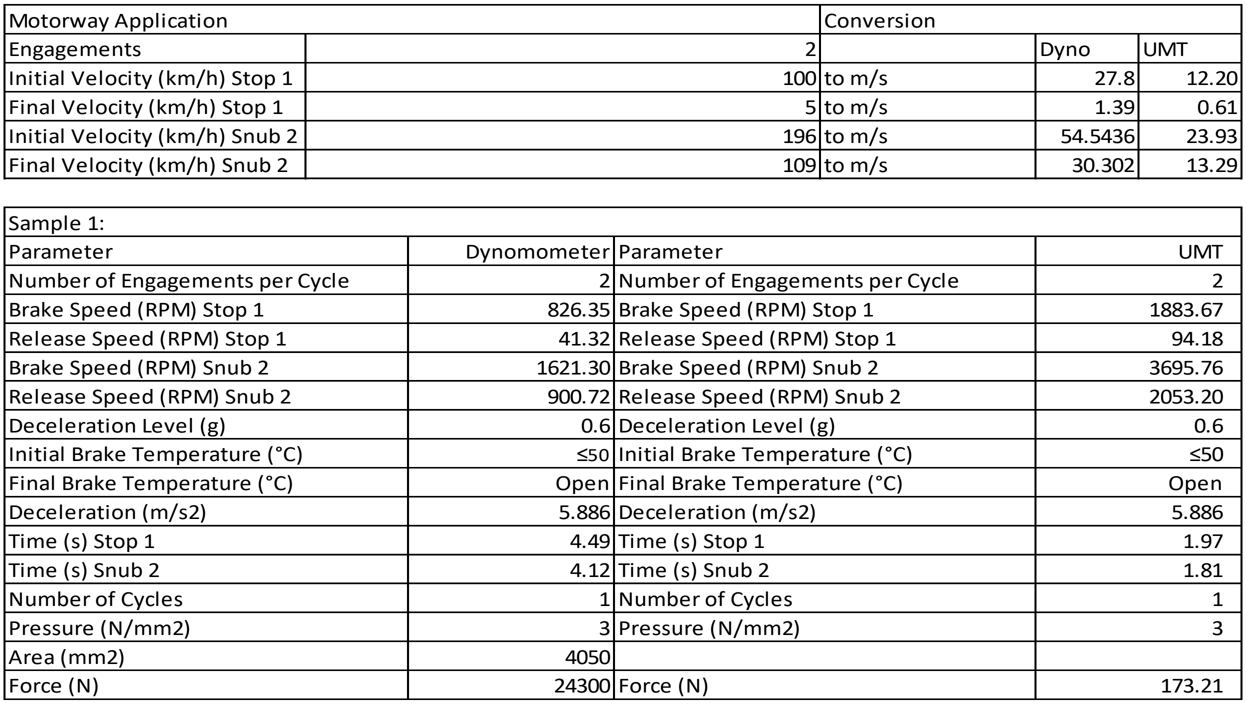
Figure 36: Characteristic Value 2 section of calculations between Dyno and UMT



Cold Application		Conversion		
Engagements	1		Dyno	UMT
Initial Velocity (km/h)	40	to m/s	11.12	4.88
Final Velocity (km/h)	5	to m/s	1.39	0.61

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	1	Number of Engagements per Cycle	1
Brake Speed (RPM)	330.54	Brake Speed (RPM)	753.47
Release Speed (RPM)	41.32	Release Speed (RPM)	94.18
Initial Brake Temperature (°C)	<= 40	Initial Brake Temperature (°C)	<= 40
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	4.96	Time (s)	2.18
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21

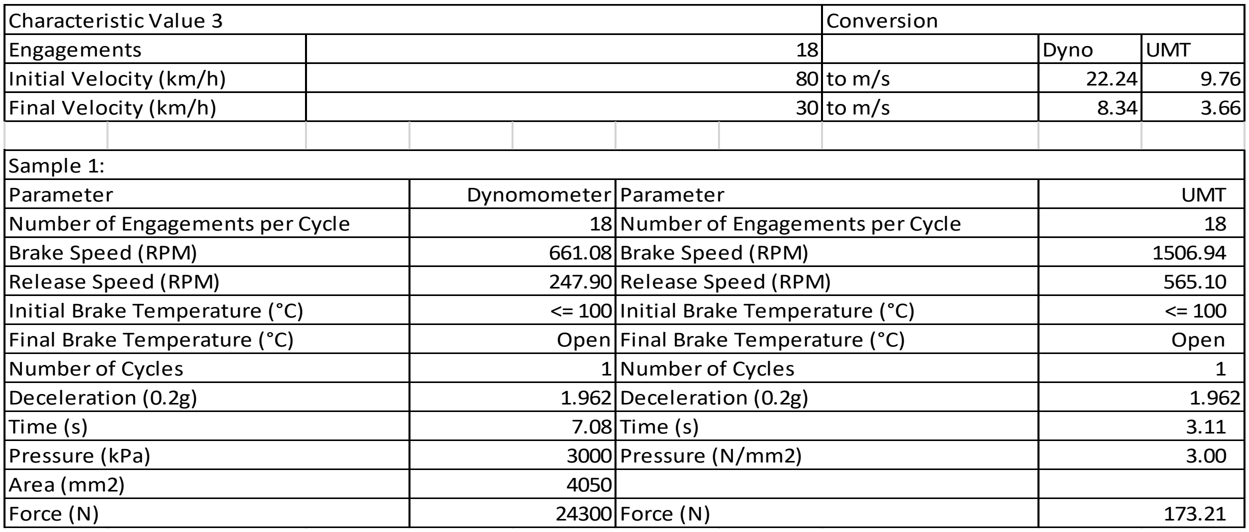
Figure 37: Cold Application section of calculations between Dyno and UMT



Motorway Application		Conversion		
Engagements	2		Dyno	UMT
Initial Velocity (km/h) Stop 1	100	to m/s	27.8	12.20
Final Velocity (km/h) Stop 1	5	to m/s	1.39	0.61
Initial Velocity (km/h) Snub 2	196	to m/s	54.5436	23.93
Final Velocity (km/h) Snub 2	109	to m/s	30.302	13.29

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	2	Number of Engagements per Cycle	2
Brake Speed (RPM) Stop 1	826.35	Brake Speed (RPM) Stop 1	1883.67
Release Speed (RPM) Stop 1	41.32	Release Speed (RPM) Stop 1	94.18
Brake Speed (RPM) Snub 2	1621.30	Brake Speed (RPM) Snub 2	3695.76
Release Speed (RPM) Snub 2	900.72	Release Speed (RPM) Snub 2	2053.20
Deceleration Level (g)	0.6	Deceleration Level (g)	0.6
Initial Brake Temperature (°C)	≤50	Initial Brake Temperature (°C)	≤50
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Deceleration (m/s2)	5.886	Deceleration (m/s2)	5.886
Time (s) Stop 1	4.49	Time (s) Stop 1	1.97
Time (s) Snub 2	4.12	Time (s) Snub 2	1.81
Number of Cycles	1	Number of Cycles	1
Pressure (N/mm2)	3	Pressure (N/mm2)	3
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21

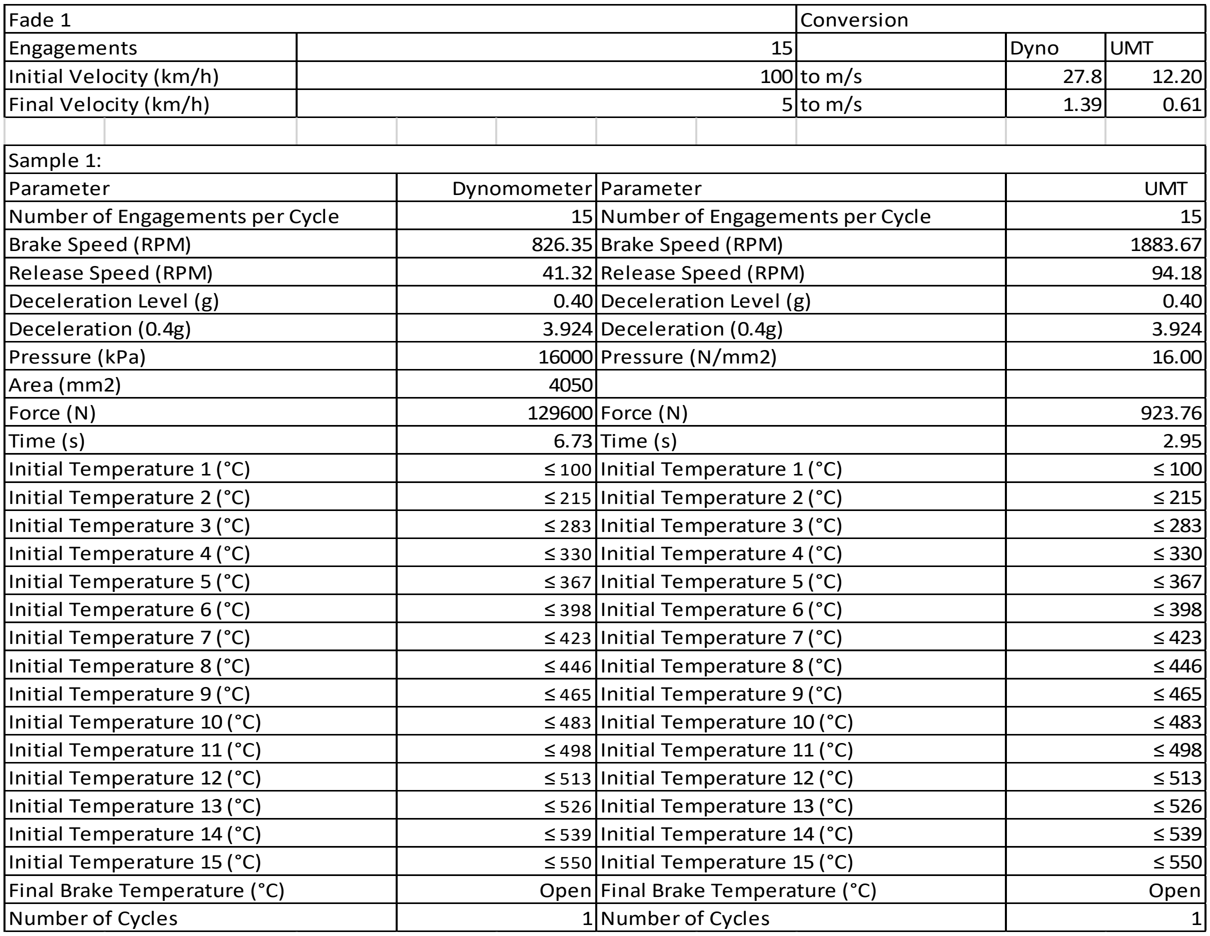
Figure 38: Motorway Snub and Stop section of calculations between Dyno and UMT



Characteristic Value 3		Conversion		
Engagements	18		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	18	Number of Engagements per Cycle	18
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	7.08	Time (s)	3.11
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21

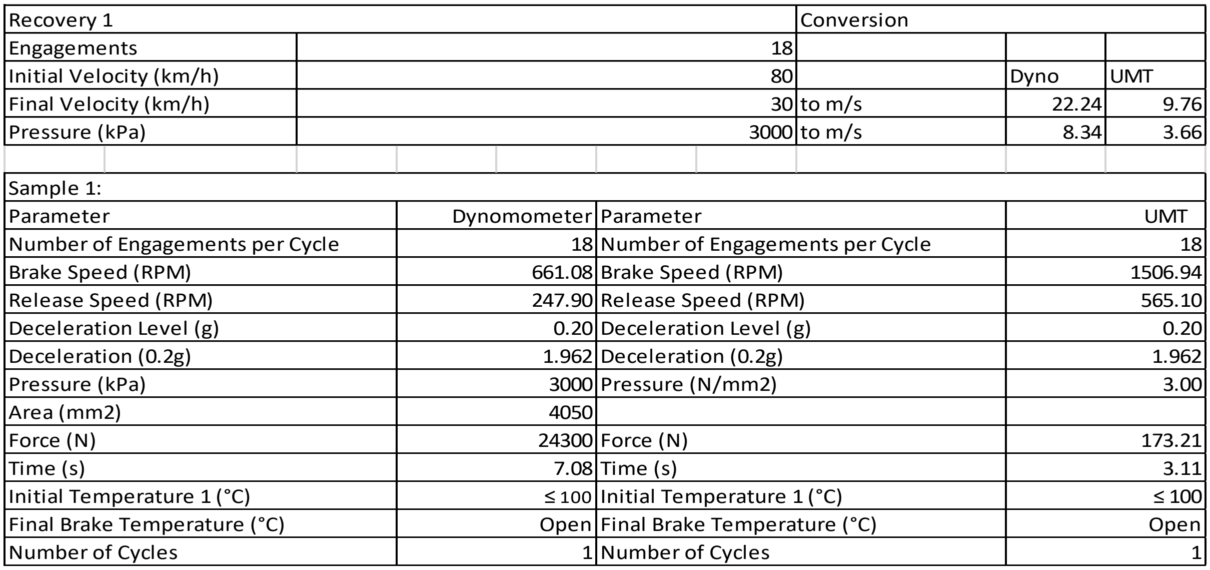
Figure 39: Characteristic Value 3 section of calculations between Dyno and UMT



Fade 1		Conversion		
Engagements	15		Dyno	UMT
Initial Velocity (km/h)	100	to m/s	27.8	12.20
Final Velocity (km/h)	5	to m/s	1.39	0.61

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	15	Number of Engagements per Cycle	15
Brake Speed (RPM)	826.35	Brake Speed (RPM)	1883.67
Release Speed (RPM)	41.32	Release Speed (RPM)	94.18
Deceleration Level (g)	0.40	Deceleration Level (g)	0.40
Deceleration (0.4g)	3.924	Deceleration (0.4g)	3.924
Pressure (kPa)	16000	Pressure (N/mm2)	16.00
Area (mm2)	4050		
Force (N)	129600	Force (N)	923.76
Time (s)	6.73	Time (s)	2.95
Initial Temperature 1 (°C)	≤ 100	Initial Temperature 1 (°C)	≤ 100
Initial Temperature 2 (°C)	≤ 215	Initial Temperature 2 (°C)	≤ 215
Initial Temperature 3 (°C)	≤ 283	Initial Temperature 3 (°C)	≤ 283
Initial Temperature 4 (°C)	≤ 330	Initial Temperature 4 (°C)	≤ 330
Initial Temperature 5 (°C)	≤ 367	Initial Temperature 5 (°C)	≤ 367
Initial Temperature 6 (°C)	≤ 398	Initial Temperature 6 (°C)	≤ 398
Initial Temperature 7 (°C)	≤ 423	Initial Temperature 7 (°C)	≤ 423
Initial Temperature 8 (°C)	≤ 446	Initial Temperature 8 (°C)	≤ 446
Initial Temperature 9 (°C)	≤ 465	Initial Temperature 9 (°C)	≤ 465
Initial Temperature 10 (°C)	≤ 483	Initial Temperature 10 (°C)	≤ 483
Initial Temperature 11 (°C)	≤ 498	Initial Temperature 11 (°C)	≤ 498
Initial Temperature 12 (°C)	≤ 513	Initial Temperature 12 (°C)	≤ 513
Initial Temperature 13 (°C)	≤ 526	Initial Temperature 13 (°C)	≤ 526
Initial Temperature 14 (°C)	≤ 539	Initial Temperature 14 (°C)	≤ 539
Initial Temperature 15 (°C)	≤ 550	Initial Temperature 15 (°C)	≤ 550
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1

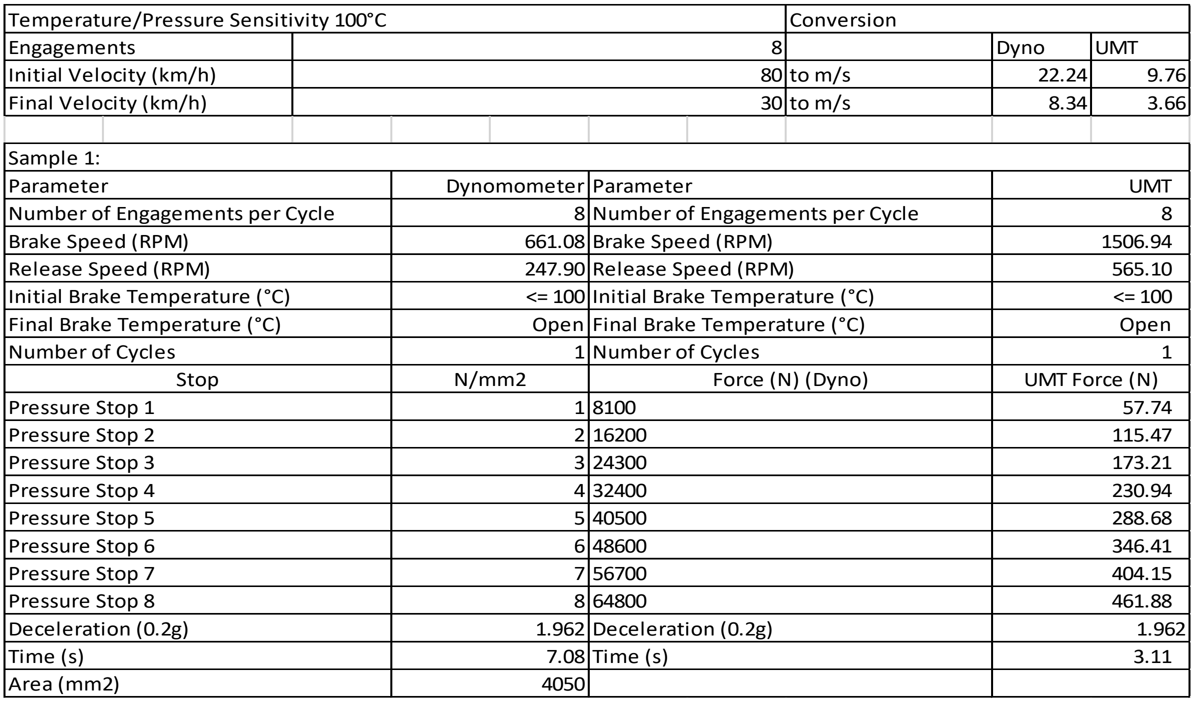
Figure 40: Fade 1 section of calculations between Dyno and UMT



Recovery 1		Conversion		
Engagements	18			
Initial Velocity (km/h)	80		Dyno	UMT
Final Velocity (km/h)	30	to m/s	22.24	9.76
Pressure (kPa)	3000	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	18	Number of Engagements per Cycle	18
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Deceleration Level (g)	0.20	Deceleration Level (g)	0.20
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21
Time (s)	7.08	Time (s)	3.11
Initial Temperature 1 (°C)	≤ 100	Initial Temperature 1 (°C)	≤ 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1

Figure 41: Recovery 1 section of calculations between Dyno and UMT

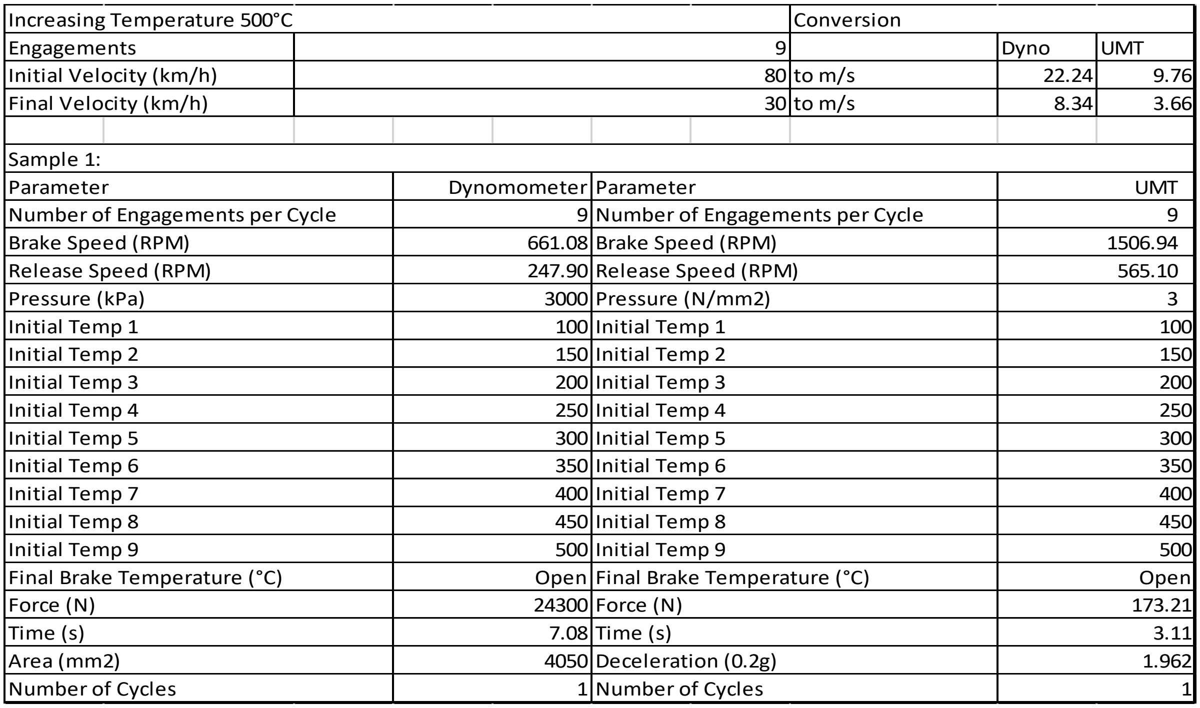


Temperature/Pressure Sensitivity 100°C		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:

Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Initial Brake Temperature (°C)	<= 100	Initial Brake Temperature (°C)	<= 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	7.08	Time (s)	3.11
Area (mm2)	4050		

Figure 42: Temperature/Pressure Sensitivity section of calculations between Dyno and UMT



Increasing Temperature 500°C		Conversion		
Engagements	9		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:

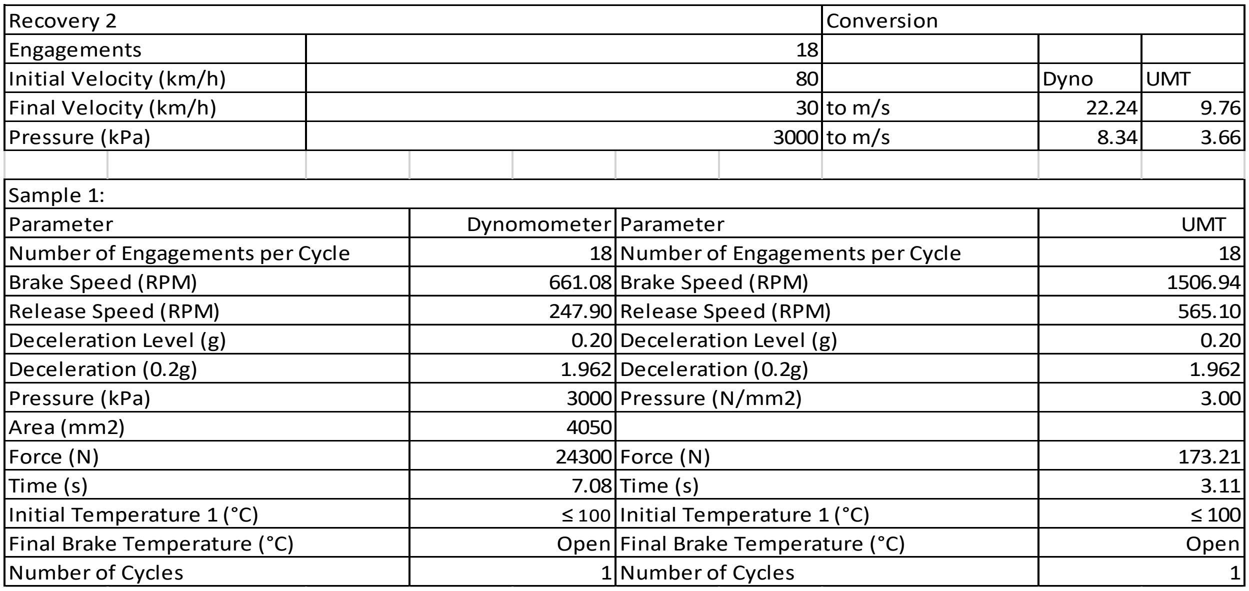
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	9	Number of Engagements per Cycle	9
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Pressure (kPa)	3000	Pressure (N/mm2)	3
Initial Temp 1	100	Initial Temp 1	100
Initial Temp 2	150	Initial Temp 2	150
Initial Temp 3	200	Initial Temp 3	200
Initial Temp 4	250	Initial Temp 4	250
Initial Temp 5	300	Initial Temp 5	300
Initial Temp 6	350	Initial Temp 6	350
Initial Temp 7	400	Initial Temp 7	400
Initial Temp 8	450	Initial Temp 8	450
Initial Temp 9	500	Initial Temp 9	500
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Force (N)	24300	Force (N)	173.21
Time (s)	7.08	Time (s)	3.11
Area (mm2)	4050	Deceleration (0.2g)	1.962
Number of Cycles	1	Number of Cycles	1

Figure 43: Increasing Temperature 500°C section of calculations between Dyno and UMT

Pressure Line 500°C		Conversion		
Engagements	8		Dyno	UMT
Initial Velocity (km/h)	80	to m/s	22.24	9.76
Final Velocity (km/h)	30	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	8	Number of Engagements per Cycle	8
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Initial Brake Temperature (°C)	<= 500	Initial Brake Temperature (°C)	<= 500
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1
Stop	N/mm2	Force (N) (Dyno)	UMT Force (N)
Pressure Stop 1	1	8100	57.74
Pressure Stop 2	2	16200	115.47
Pressure Stop 3	3	24300	173.21
Pressure Stop 4	4	32400	230.94
Pressure Stop 5	5	40500	288.68
Pressure Stop 6	6	48600	346.41
Pressure Stop 7	7	56700	404.15
Pressure Stop 8	8	64800	461.88
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Time (s)	7.08	Time (s)	3.11
Area (mm2)	4050		

Figure 44: Pressure Line at 500° section of calculations between Dyno and UMT



Recovery 2		Conversion		
Engagements	18			
Initial Velocity (km/h)	80		Dyno	UMT
Final Velocity (km/h)	30	to m/s	22.24	9.76
Pressure (kPa)	3000	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	18	Number of Engagements per Cycle	18
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Deceleration Level (g)	0.20	Deceleration Level (g)	0.20
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21
Time (s)	7.08	Time (s)	3.11
Initial Temperature 1 (°C)	≤ 100	Initial Temperature 1 (°C)	≤ 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1

Figure 45: Recovery 2 section of calculations between Dyno and UMT

Fade 2		Conversion		
Engagements	15		Dyno	UMT
Initial Velocity (km/h)	100	to m/s	27.8	12.20
Final Velocity (km/h)	5	to m/s	1.39	0.61

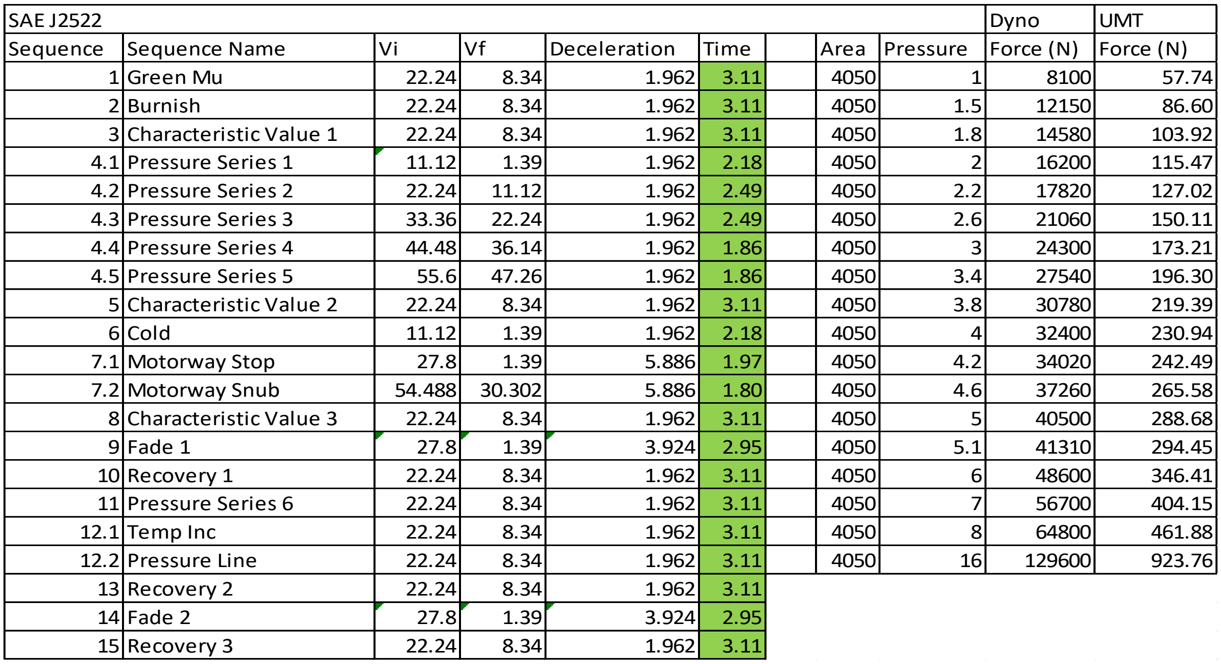
Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	15	Number of Engagements per Cycle	15
Brake Speed (RPM)	826.35	Brake Speed (RPM)	1883.67
Release Speed (RPM)	41.32	Release Speed (RPM)	94.18
Deceleration Level (g)	0.40	Deceleration Level (g)	0.40
Deceleration (0.4g)	3.924	Deceleration (0.4g)	3.924
Pressure (kPa)	16000	Pressure (N/mm2)	16.00
Area (mm2)	4050		
Force (N)	129600	Force (N)	923.76
Time (s)	6.73	Time (s)	2.95
Initial Temperature 1 (°C)	≤ 100	Initial Temperature 1 (°C)	≤ 100
Initial Temperature 2 (°C)	≤ 215	Initial Temperature 2 (°C)	≤ 215
Initial Temperature 3 (°C)	≤ 283	Initial Temperature 3 (°C)	≤ 283
Initial Temperature 4 (°C)	≤ 330	Initial Temperature 4 (°C)	≤ 330
Initial Temperature 5 (°C)	≤ 367	Initial Temperature 5 (°C)	≤ 367
Initial Temperature 6 (°C)	≤ 398	Initial Temperature 6 (°C)	≤ 398
Initial Temperature 7 (°C)	≤ 423	Initial Temperature 7 (°C)	≤ 423
Initial Temperature 8 (°C)	≤ 446	Initial Temperature 8 (°C)	≤ 446
Initial Temperature 9 (°C)	≤ 465	Initial Temperature 9 (°C)	≤ 465
Initial Temperature 10 (°C)	≤ 483	Initial Temperature 10 (°C)	≤ 483
Initial Temperature 11 (°C)	≤ 498	Initial Temperature 11 (°C)	≤ 498
Initial Temperature 12 (°C)	≤ 513	Initial Temperature 12 (°C)	≤ 513
Initial Temperature 13 (°C)	≤ 526	Initial Temperature 13 (°C)	≤ 526
Initial Temperature 14 (°C)	≤ 539	Initial Temperature 14 (°C)	≤ 539
Initial Temperature 15 (°C)	≤ 550	Initial Temperature 15 (°C)	≤ 550
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1

Figure 46: Fade 2 section of calculations between Dyno and UMT

Recovery 3		Conversion		
Engagements	18			
Initial Velocity (km/h)	80		Dyno	UMT
Final Velocity (km/h)	30	to m/s	22.24	9.76
Pressure (kPa)	3000	to m/s	8.34	3.66

Sample 1:			
Parameter	Dynomometer	Parameter	UMT
Number of Engagements per Cycle	18	Number of Engagements per Cycle	18
Brake Speed (RPM)	661.08	Brake Speed (RPM)	1506.94
Release Speed (RPM)	247.90	Release Speed (RPM)	565.10
Deceleration Level (g)	0.20	Deceleration Level (g)	0.20
Deceleration (0.2g)	1.962	Deceleration (0.2g)	1.962
Pressure (kPa)	3000	Pressure (N/mm2)	3.00
Area (mm2)	4050		
Force (N)	24300	Force (N)	173.21
Time (s)	7.08	Time (s)	3.11
Initial Temperature 1 (°C)	≤ 100	Initial Temperature 1 (°C)	≤ 100
Final Brake Temperature (°C)	Open	Final Brake Temperature (°C)	Open
Number of Cycles	1	Number of Cycles	1

Figure 47: Recovery 3 section of calculations between Dyno and UMT

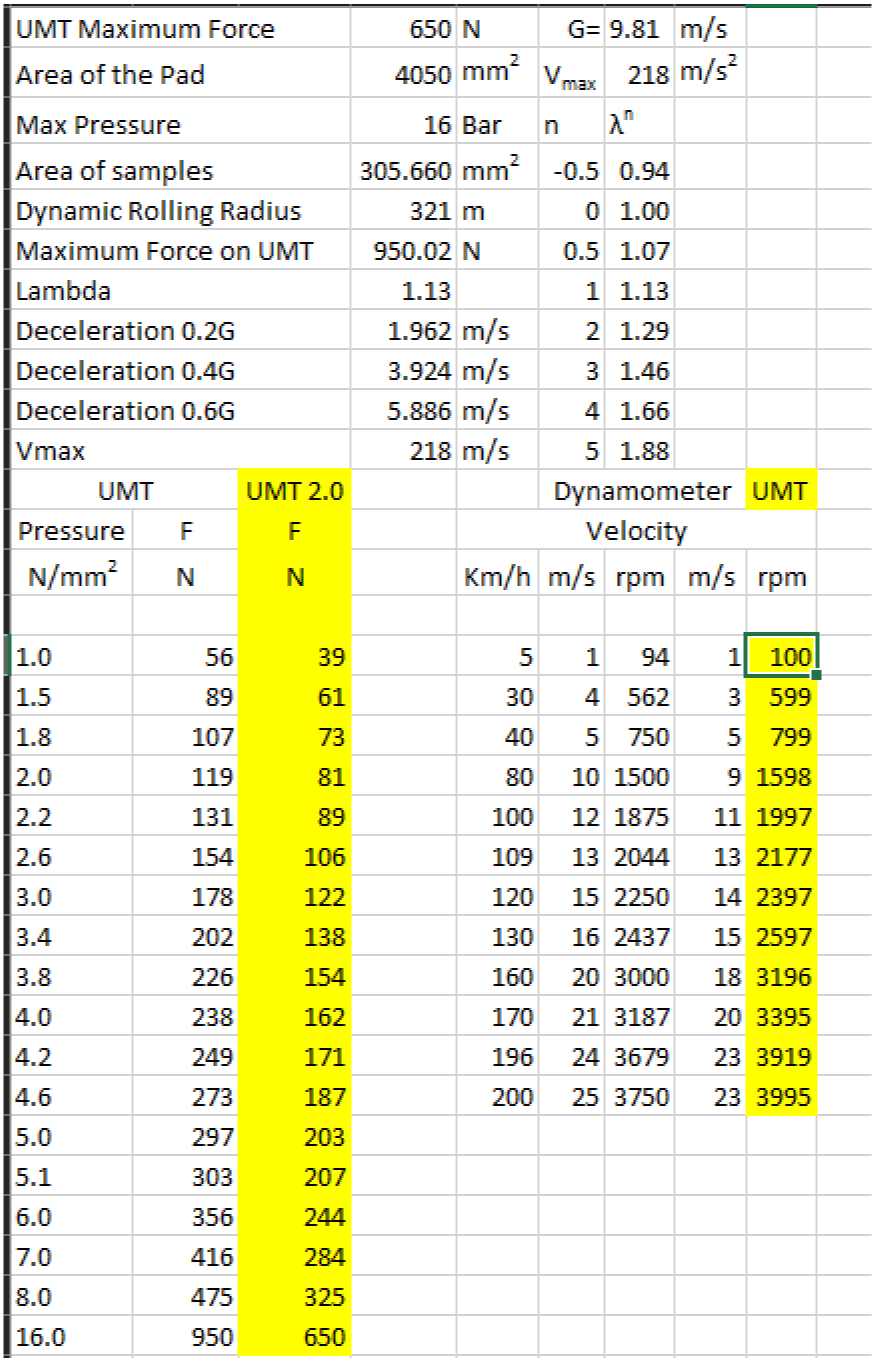


SAE J2522									Dyno	UMT
Sequence	Sequence Name	Vi	Vf	Deceleration	Time		Area	Pressure	Force (N)	Force (N)
1	Green Mu	22.24	8.34	1.962	3.11		4050	1	8100	57.74
2	Burnish	22.24	8.34	1.962	3.11		4050	1.5	12150	86.60
3	Characteristic Value 1	22.24	8.34	1.962	3.11		4050	1.8	14580	103.92
4.1	Pressure Series 1	11.12	1.39	1.962	2.18		4050	2	16200	115.47
4.2	Pressure Series 2	22.24	11.12	1.962	2.49		4050	2.2	17820	127.02
4.3	Pressure Series 3	33.36	22.24	1.962	2.49		4050	2.6	21060	150.11
4.4	Pressure Series 4	44.48	36.14	1.962	1.86		4050	3	24300	173.21
4.5	Pressure Series 5	55.6	47.26	1.962	1.86		4050	3.4	27540	196.30
5	Characteristic Value 2	22.24	8.34	1.962	3.11		4050	3.8	30780	219.39
6	Cold	11.12	1.39	1.962	2.18		4050	4	32400	230.94
7.1	Motorway Stop	27.8	1.39	5.886	1.97		4050	4.2	34020	242.49
7.2	Motorway Snub	54.488	30.302	5.886	1.80		4050	4.6	37260	265.58
8	Characteristic Value 3	22.24	8.34	1.962	3.11		4050	5	40500	288.68
9	Fade 1	27.8	1.39	3.924	2.95		4050	5.1	41310	294.45
10	Recovery 1	22.24	8.34	1.962	3.11		4050	6	48600	346.41
11	Pressure Series 6	22.24	8.34	1.962	3.11		4050	7	56700	404.15
12.1	Temp Inc	22.24	8.34	1.962	3.11		4050	8	64800	461.88
12.2	Pressure Line	22.24	8.34	1.962	3.11		4050	16	129600	923.76
13	Recovery 2	22.24	8.34	1.962	3.11					
14	Fade 2	27.8	1.39	3.924	2.95					
15	Recovery 3	22.24	8.34	1.962	3.11					

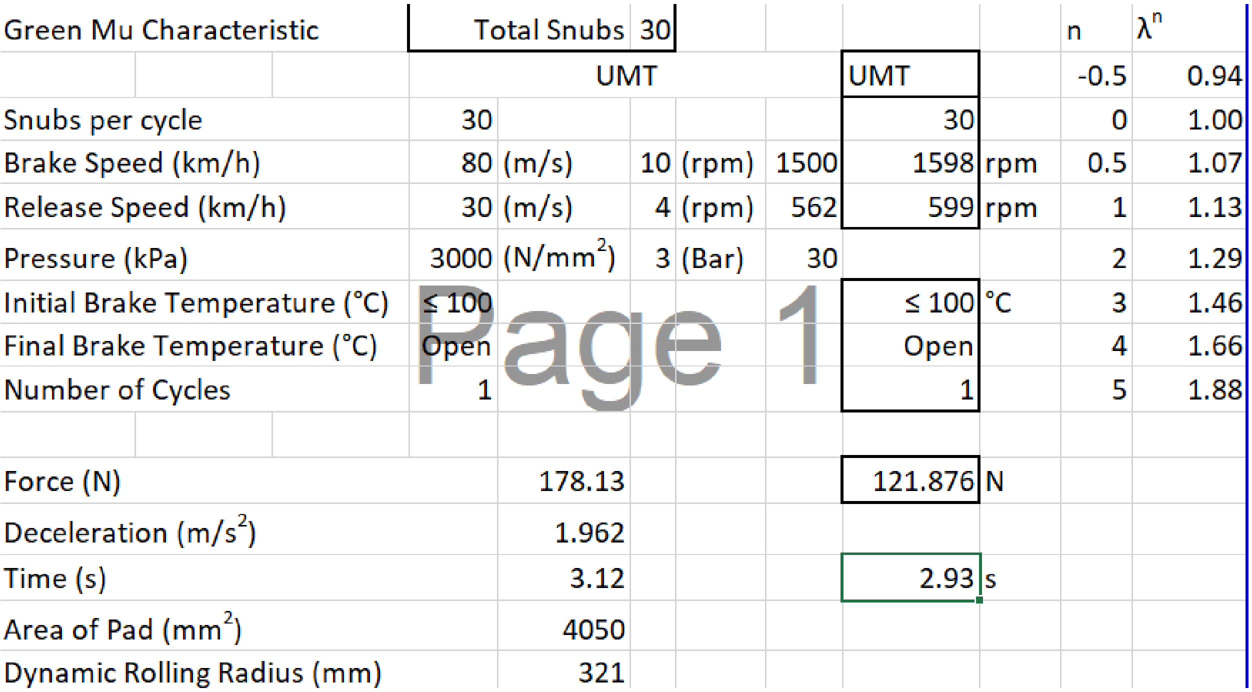
Figure 48: Time and Force Calculations for each section

APPENDIX B:

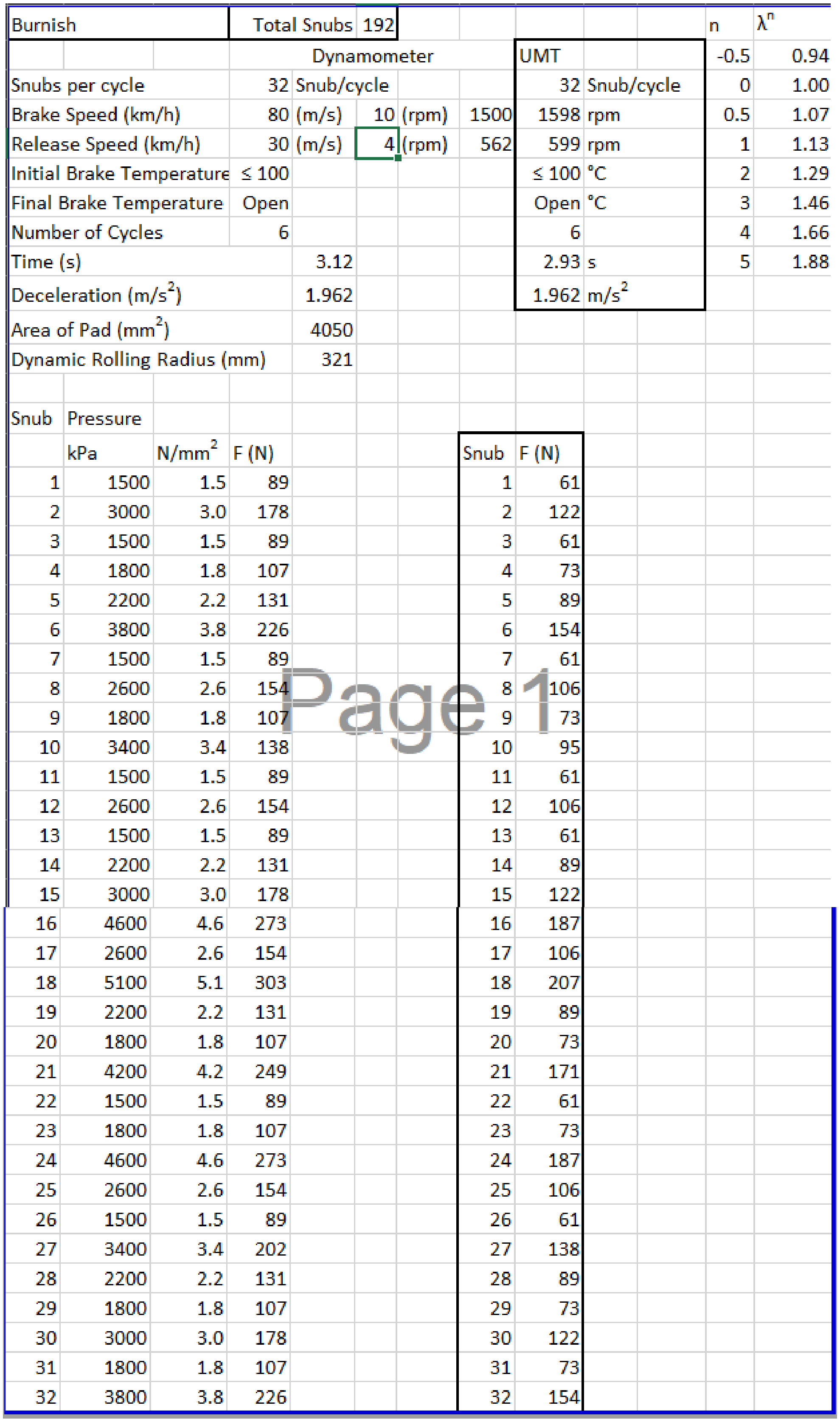
SECOND SCALING



UMT Maximum Force			650	N	G=	9.81	m/s	
Area of the Pad			4050	mm^2	V_{max}	218	m/s^2	
Max Pressure			16	Bar	n	λ^n		
Area of samples			305.660	mm^2	-0.5	0.94		
Dynamic Rolling Radius			321	m	0	1.00		
Maximum Force on UMT			950.02	N	0.5	1.07		
Lambda			1.13		1	1.13		
Deceleration 0.2G			1.962	m/s	2	1.29		
Deceleration 0.4G			3.924	m/s	3	1.46		
Deceleration 0.6G			5.886	m/s	4	1.66		
Vmax			218	m/s	5	1.88		
UMT		UMT 2.0			Dynamometer			UMT
Pressure	F	F			Velocity			
N/mm^2	N	N		Km/h	m/s	rpm	m/s	rpm
1.0	56	39		5	1	94	1	100
1.5	89	61		30	4	562	3	599
1.8	107	73		40	5	750	5	799
2.0	119	81		80	10	1500	9	1598
2.2	131	89		100	12	1875	11	1997
2.6	154	106		109	13	2044	13	2177
3.0	178	122		120	15	2250	14	2397
3.4	202	138		130	16	2437	15	2597
3.8	226	154		160	20	3000	18	3196
4.0	238	162		170	21	3187	20	3395
4.2	249	171		196	24	3679	23	3919
4.6	273	187		200	25	3750	23	3995
5.0	297	203						
5.1	303	207						
6.0	356	244						
7.0	416	284						
8.0	475	325						
16.0	950	650						

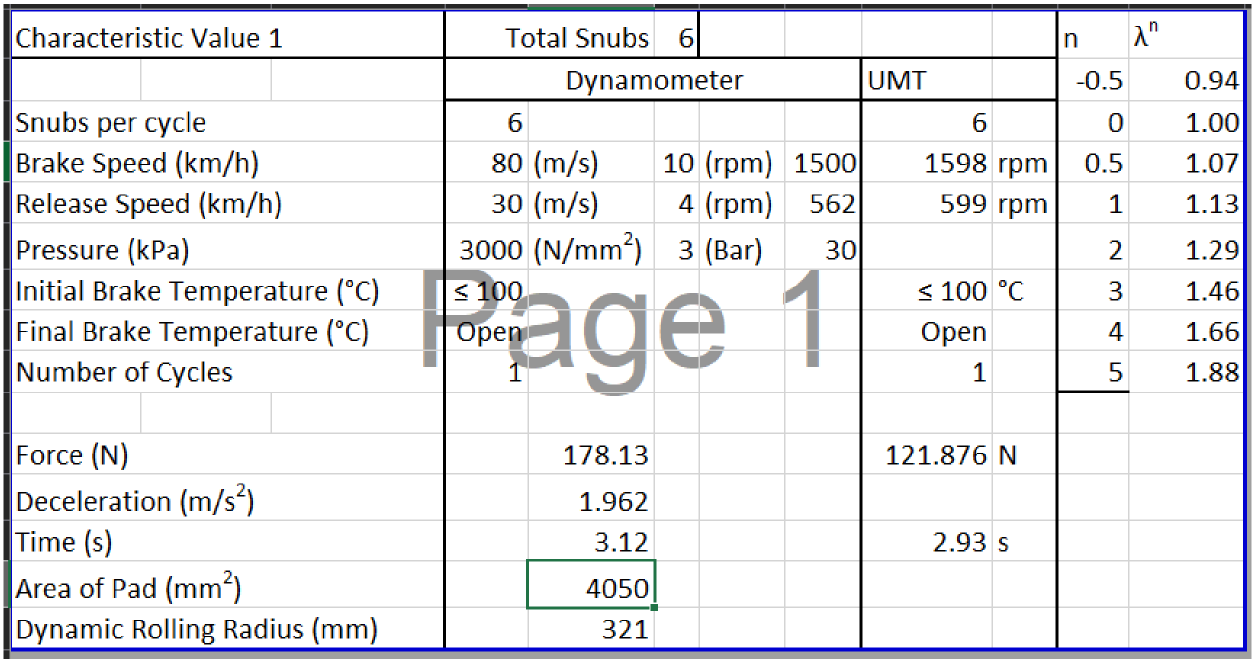


Green Mu Characteristic		Total Snubs	30					n	λ^n
	UMT					UMT		-0.5	0.94
Snubs per cycle	30					30		0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30			2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	°C	3	1.46
Final Brake Temperature (°C)	Open					Open		4	1.66
Number of Cycles	1					1		5	1.88
Force (N)		178.13				121.876	N		
Deceleration (m/s^2)		1.962							
Time (s)		3.12				2.93	s		
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

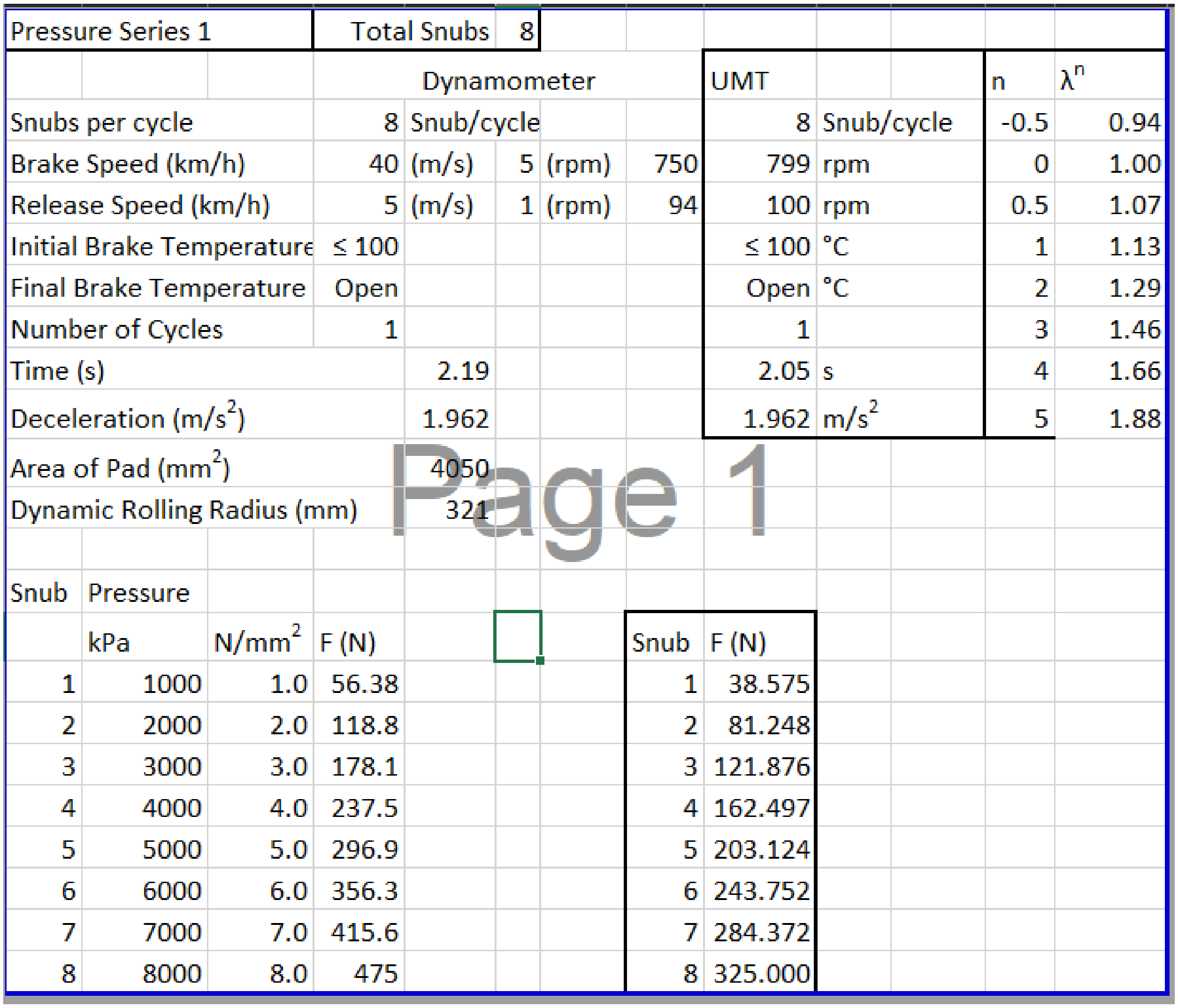


Burnish	Total Snubs	192						n	λ^n
	Dynamometer					UMT		-0.5	0.94
Snubs per cycle	32	Snub/cycle				32	Snub/cycle	0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	1	1.13
Initial Brake Temperature	≤ 100					≤ 100	°C	2	1.29
Final Brake Temperature	Open					Open	°C	3	1.46
Number of Cycles	6					6		4	1.66
Time (s)		3.12				2.93	s	5	1.88
Deceleration (m/s^2)		1.962				1.962	m/s^2		
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

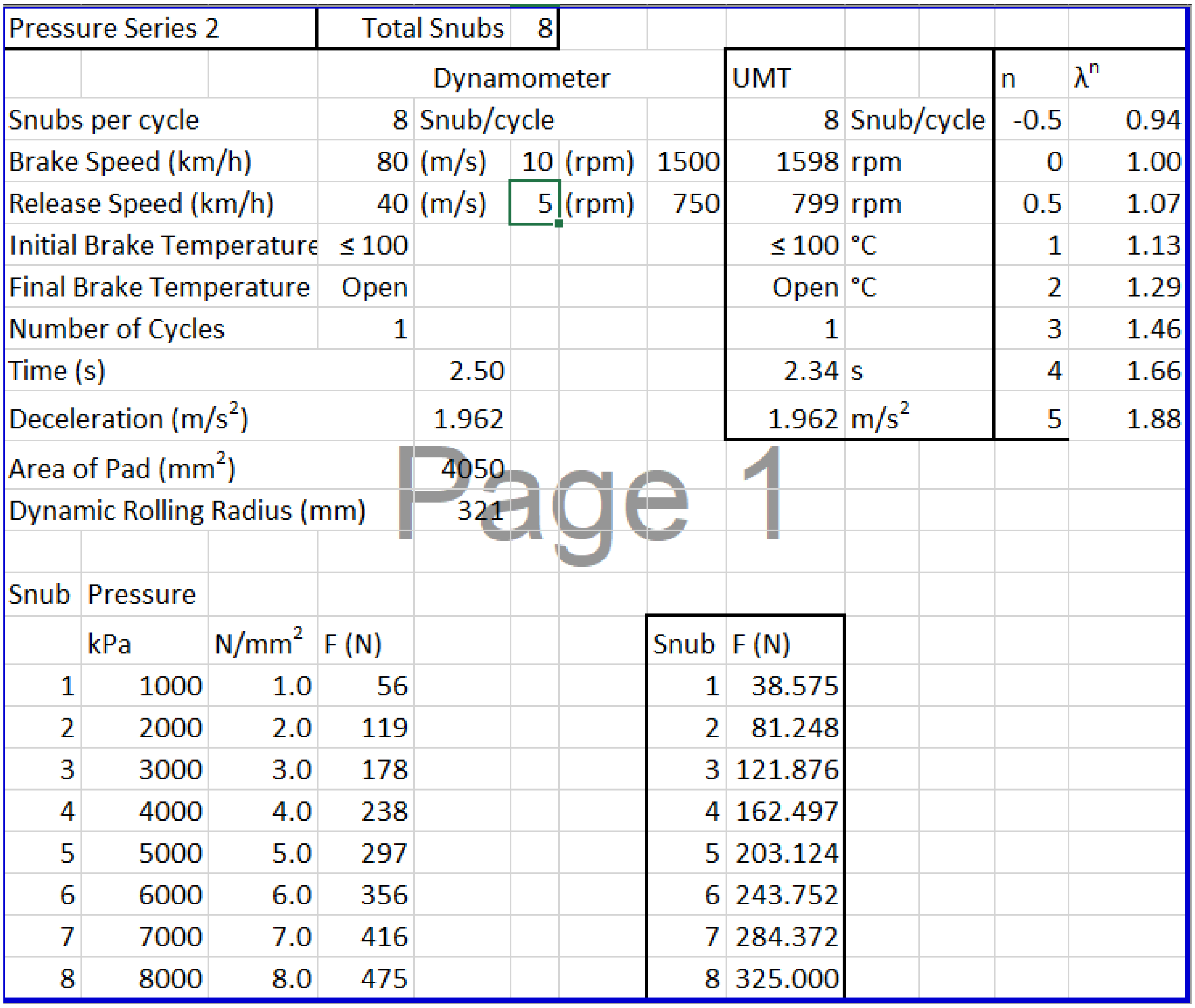
Snub	Pressure kPa	N/mm^2	F (N)	Snub	F (N)
1	1500	1.5	89	1	61
2	3000	3.0	178	2	122
3	1500	1.5	89	3	61
4	1800	1.8	107	4	73
5	2200	2.2	131	5	89
6	3800	3.8	226	6	154
7	1500	1.5	89	7	61
8	2600	2.6	154	8	106
9	1800	1.8	107	9	73
10	3400	3.4	138	10	95
11	1500	1.5	89	11	61
12	2600	2.6	154	12	106
13	1500	1.5	89	13	61
14	2200	2.2	131	14	89
15	3000	3.0	178	15	122
16	4600	4.6	273	16	187
17	2600	2.6	154	17	106
18	5100	5.1	303	18	207
19	2200	2.2	131	19	89
20	1800	1.8	107	20	73
21	4200	4.2	249	21	171
22	1500	1.5	89	22	61
23	1800	1.8	107	23	73
24	4600	4.6	273	24	187
25	2600	2.6	154	25	106
26	1500	1.5	89	26	61
27	3400	3.4	202	27	138
28	2200	2.2	131	28	89
29	1800	1.8	107	29	73
30	3000	3.0	178	30	122
31	1800	1.8	107	31	73
32	3800	3.8	226	32	154



Characteristic Value 1		Total Snubs	6					n	λ^n
	Dynamometer					UMT		-0.5	0.94
Snubs per cycle	6					6		0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30			2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	°C	3	1.46
Final Brake Temperature (°C)	Open					Open		4	1.66
Number of Cycles	1					1		5	1.88
Force (N)		178.13				121.876	N		
Deceleration (m/s^2)		1.962							
Time (s)		3.12				2.93	s		
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							



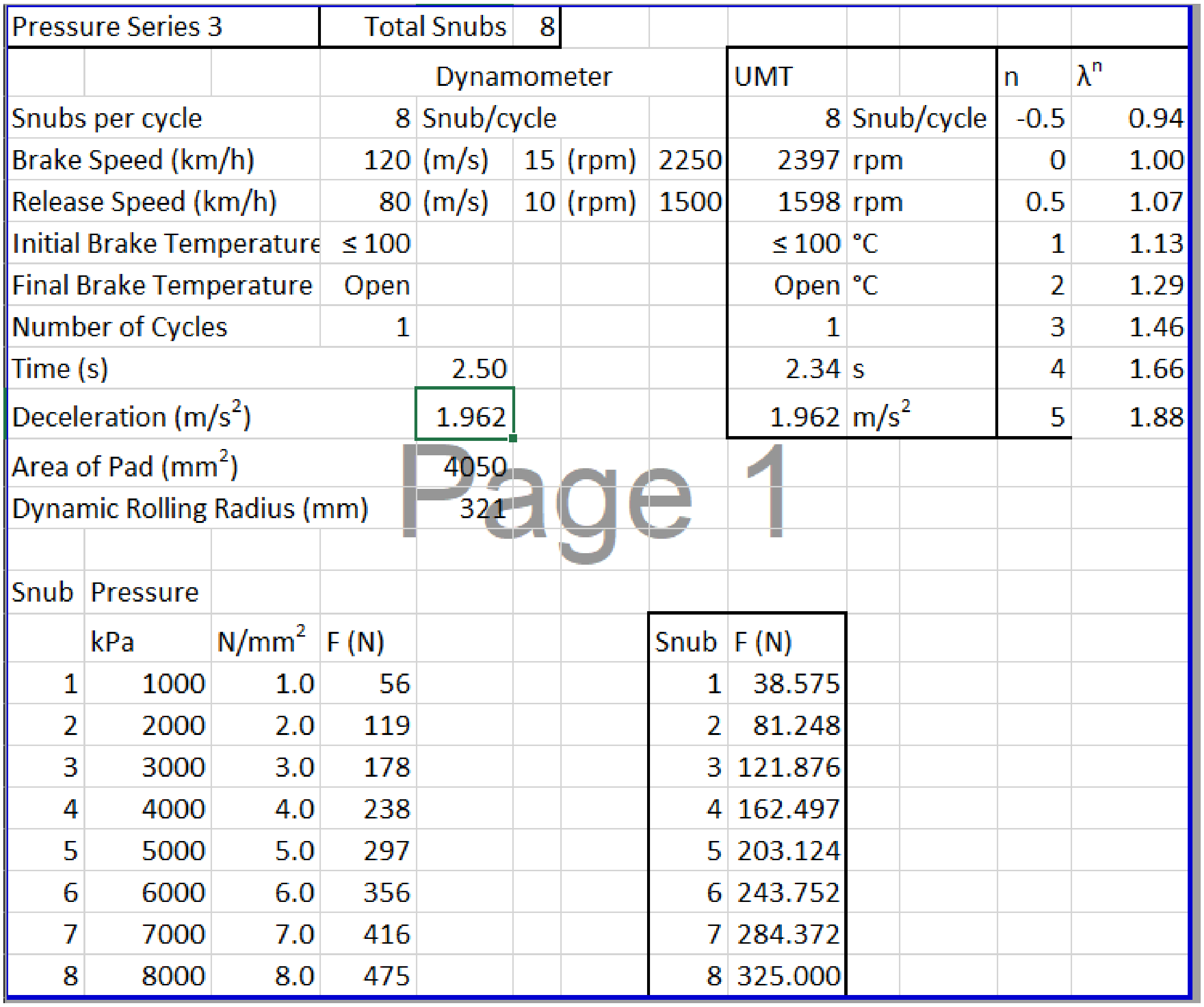
Pressure Series 1			Total Snubs		8						
			Dynamometer					UMT		n	λ^n
Snubs per cycle			8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)			40	(m/s)	5	(rpm)	750	799	rpm	0	1.00
Release Speed (km/h)			5	(m/s)	1	(rpm)	94	100	rpm	0.5	1.07
Initial Brake Temperature			≤ 100					≤ 100	°C	1	1.13
Final Brake Temperature			Open					Open	°C	2	1.29
Number of Cycles			1					1		3	1.46
Time (s)				2.19				2.05	s	4	1.66
Deceleration (m/s^2)				1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)				4050							
Dynamic Rolling Radius (mm)				321							
Snub	Pressure										
	kPa	N/mm^2	F (N)				Snub	F (N)			
1	1000	1.0	56.38				1	38.575			
2	2000	2.0	118.8				2	81.248			
3	3000	3.0	178.1				3	121.876			
4	4000	4.0	237.5				4	162.497			
5	5000	5.0	296.9				5	203.124			
6	6000	6.0	356.3				6	243.752			
7	7000	7.0	415.6				7	284.372			
8	8000	8.0	475				8	325.000			



Pressure Series 2	Total Snubs	8							
	Dynamometer					UMT		n	λ^n
Snubs per cycle	8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0	1.00
Release Speed (km/h)	40	(m/s)	5	(rpm)	750	799	rpm	0.5	1.07
Initial Brake Temperature	≤ 100					≤ 100	°C	1	1.13
Final Brake Temperature	Open					Open	°C	2	1.29
Number of Cycles	1					1		3	1.46
Time (s)		2.50				2.34	s	4	1.66
Deceleration (m/s^2)		1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

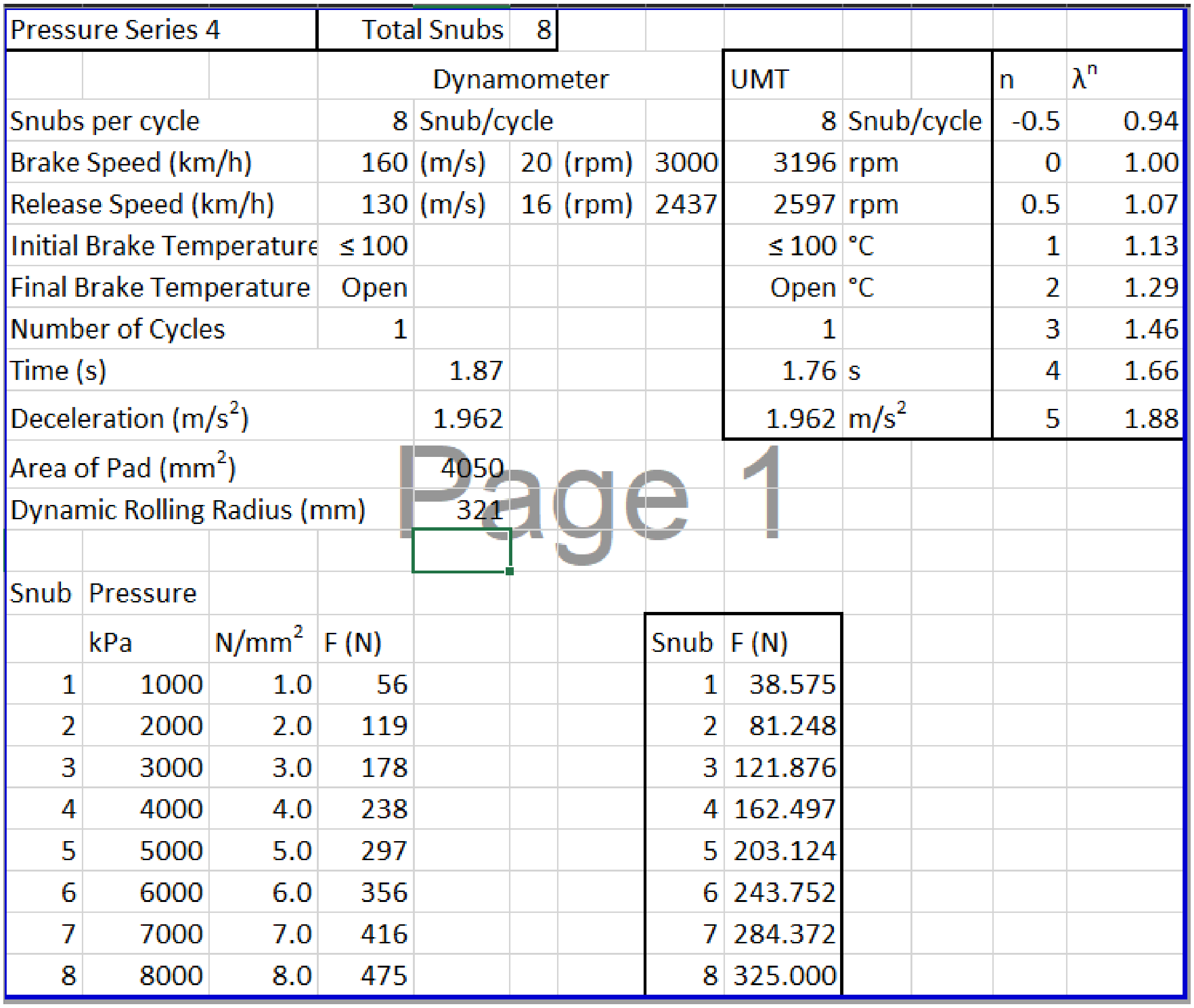
Snub	Pressure		
	kPa	N/mm^2	F (N)
1	1000	1.0	56
2	2000	2.0	119
3	3000	3.0	178
4	4000	4.0	238
5	5000	5.0	297
6	6000	6.0	356
7	7000	7.0	416
8	8000	8.0	475

Snub	F (N)
1	38.575
2	81.248
3	121.876
4	162.497
5	203.124
6	243.752
7	284.372
8	325.000



Pressure Series 3	Total Snubs	8							
	Dynamometer					UMT		n	λ^n
Snubs per cycle	8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)	120	(m/s)	15	(rpm)	2250	2397	rpm	0	1.00
Release Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0.5	1.07
Initial Brake Temperature	≤ 100					≤ 100	°C	1	1.13
Final Brake Temperature	Open					Open	°C	2	1.29
Number of Cycles	1					1		3	1.46
Time (s)		2.50				2.34	s	4	1.66
Deceleration (m/s^2)		1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

Snub	Pressure				Snub	F (N)
	kPa	N/mm^2	F (N)			
1	1000	1.0	56		1	38.575
2	2000	2.0	119		2	81.248
3	3000	3.0	178		3	121.876
4	4000	4.0	238		4	162.497
5	5000	5.0	297		5	203.124
6	6000	6.0	356		6	243.752
7	7000	7.0	416		7	284.372
8	8000	8.0	475		8	325.000

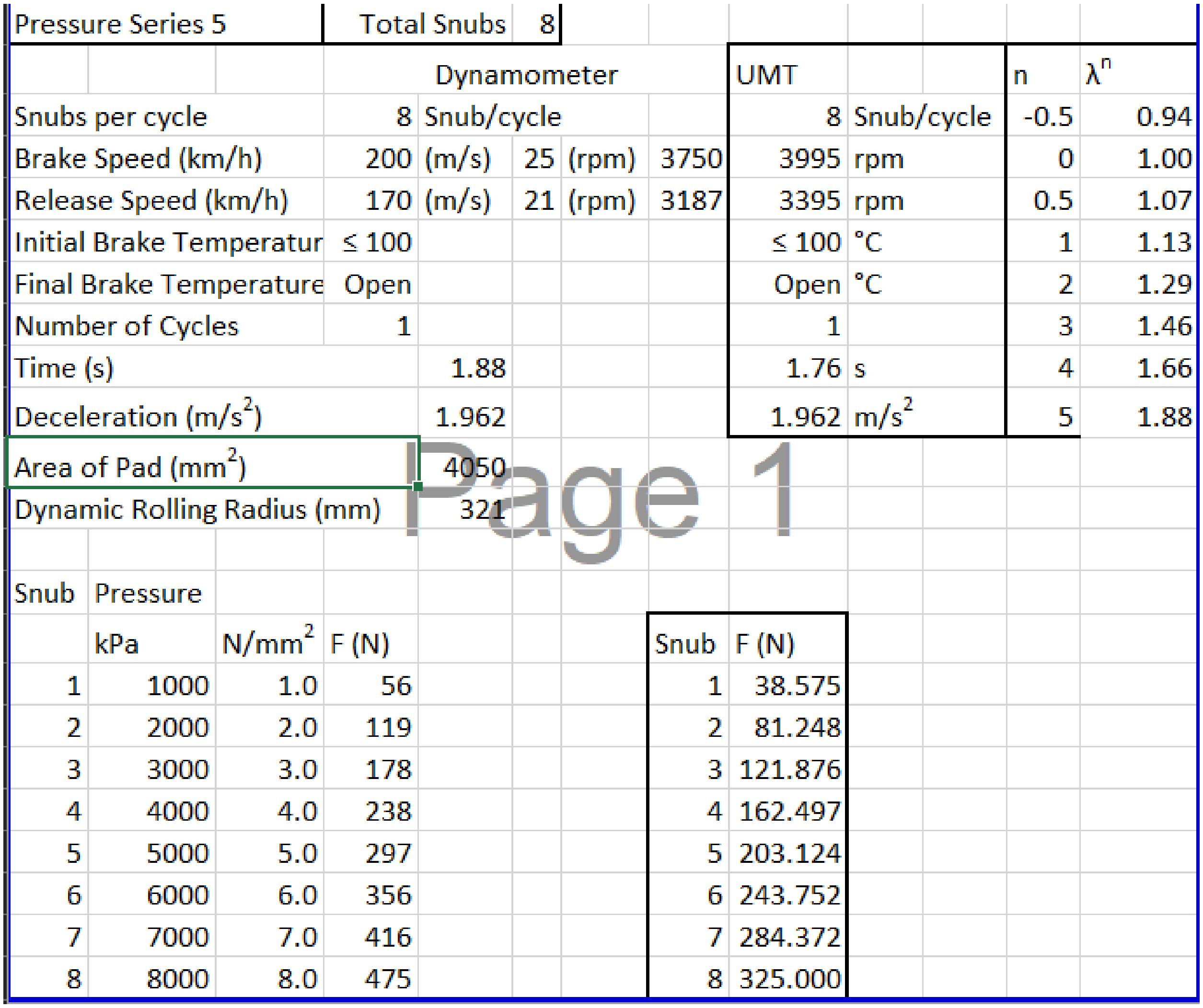


Pressure Series 4	Total Snubs	8

	Dynamometer					UMT		n	λ^n
Snubs per cycle	8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)	160	(m/s)	20	(rpm)	3000	3196	rpm	0	1.00
Release Speed (km/h)	130	(m/s)	16	(rpm)	2437	2597	rpm	0.5	1.07
Initial Brake Temperature	≤ 100					≤ 100	°C	1	1.13
Final Brake Temperature	Open					Open	°C	2	1.29
Number of Cycles	1					1		3	1.46
Time (s)		1.87				1.76	s	4	1.66
Deceleration (m/s^2)		1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

Snub	Pressure		
	kPa	N/mm^2	F (N)
1	1000	1.0	56
2	2000	2.0	119
3	3000	3.0	178
4	4000	4.0	238
5	5000	5.0	297
6	6000	6.0	356
7	7000	7.0	416
8	8000	8.0	475

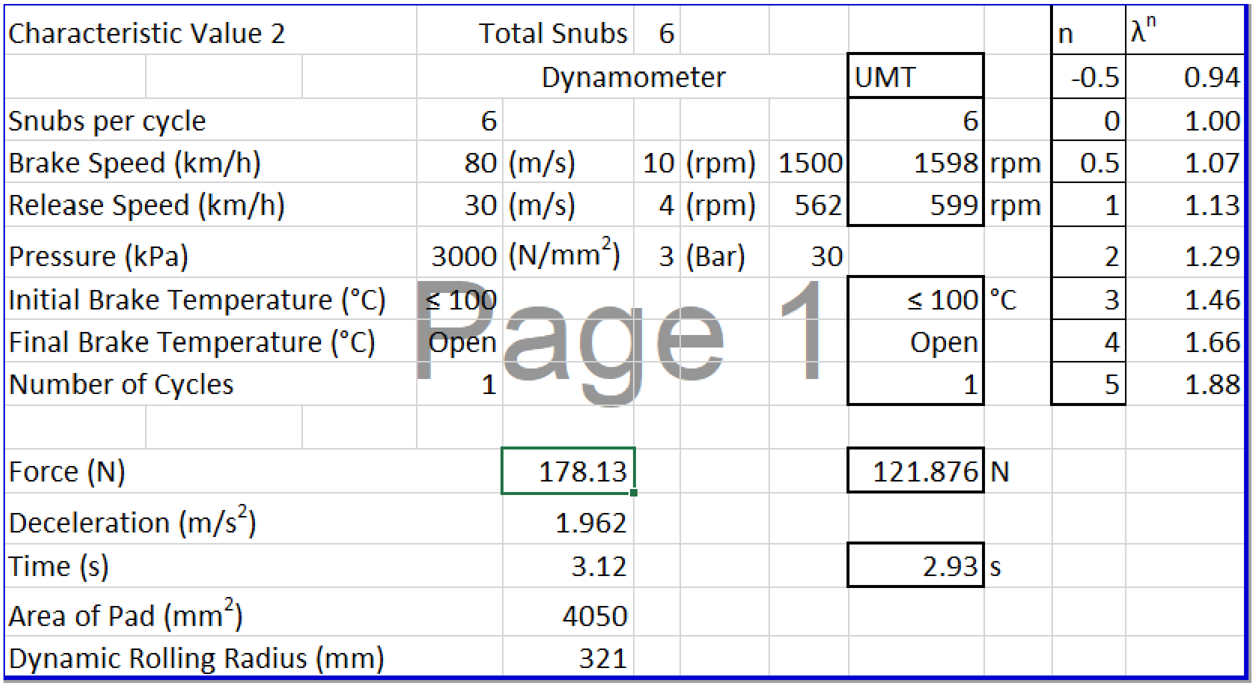
Snub	F (N)
1	38.575
2	81.248
3	121.876
4	162.497
5	203.124
6	243.752
7	284.372
8	325.000



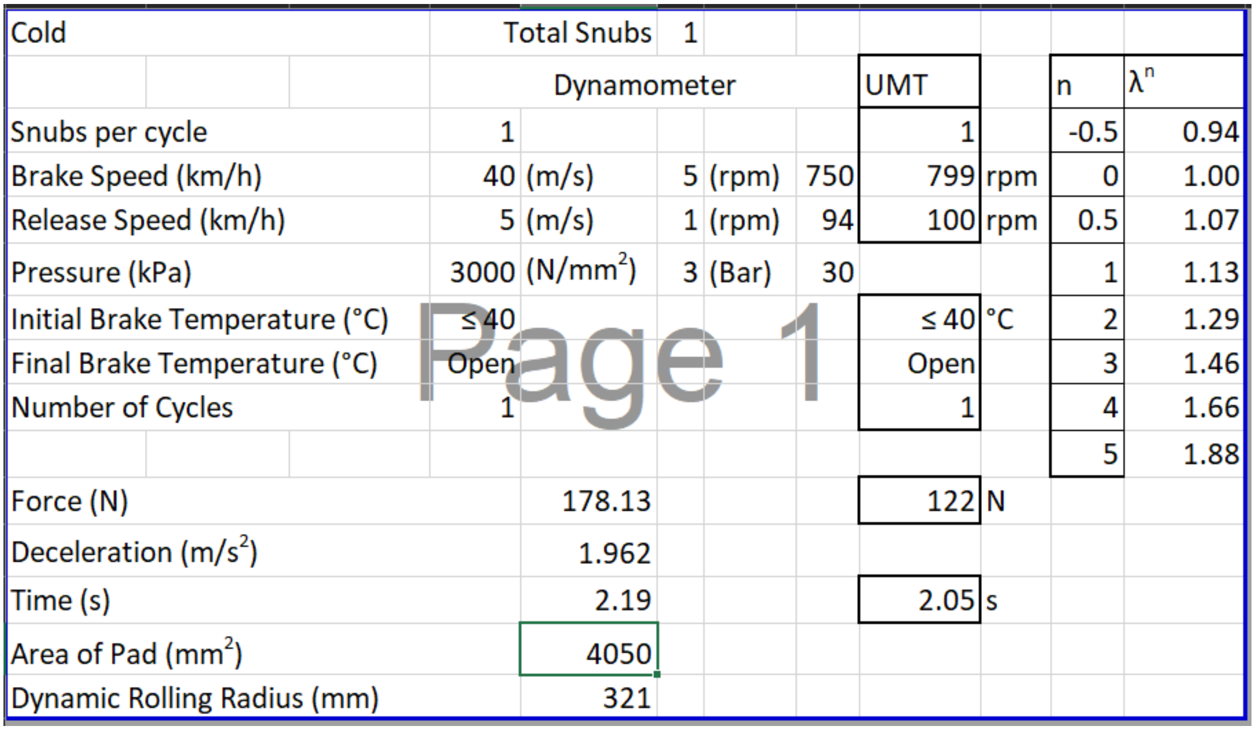
Pressure Series 5		Total Snubs	8						
		Dynamometer				UMT		n	λ^n
Snubs per cycle	8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)	200	(m/s)	25	(rpm)	3750	3995	rpm	0	1.00
Release Speed (km/h)	170	(m/s)	21	(rpm)	3187	3395	rpm	0.5	1.07
Initial Brake Temperatur	≤ 100					≤ 100	°C	1	1.13
Final Brake Temperature	Open					Open	°C	2	1.29
Number of Cycles	1					1		3	1.46
Time (s)		1.88				1.76	s	4	1.66
Deceleration (m/s^2)		1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

Snub	Pressure		
	kPa	N/mm^2	F (N)
1	1000	1.0	56
2	2000	2.0	119
3	3000	3.0	178
4	4000	4.0	238
5	5000	5.0	297
6	6000	6.0	356
7	7000	7.0	416
8	8000	8.0	475

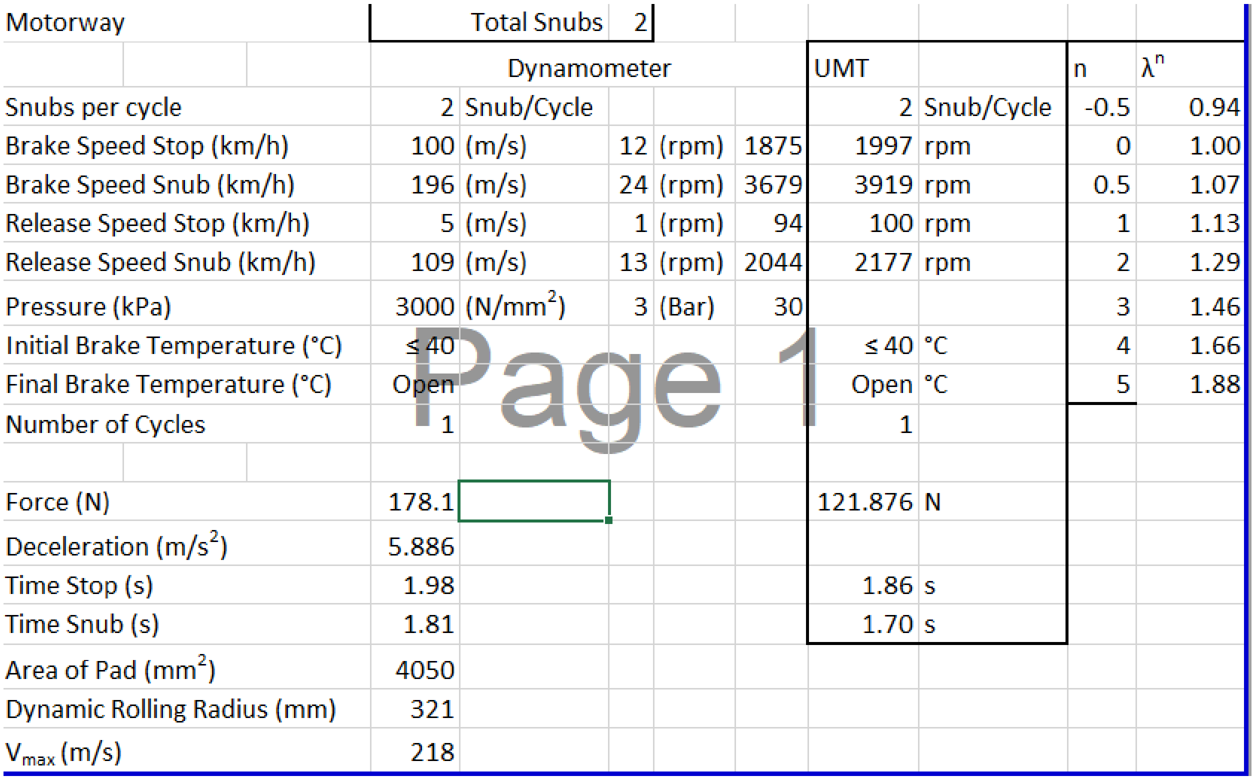
Snub	F (N)
1	38.575
2	81.248
3	121.876
4	162.497
5	203.124
6	243.752
7	284.372
8	325.000



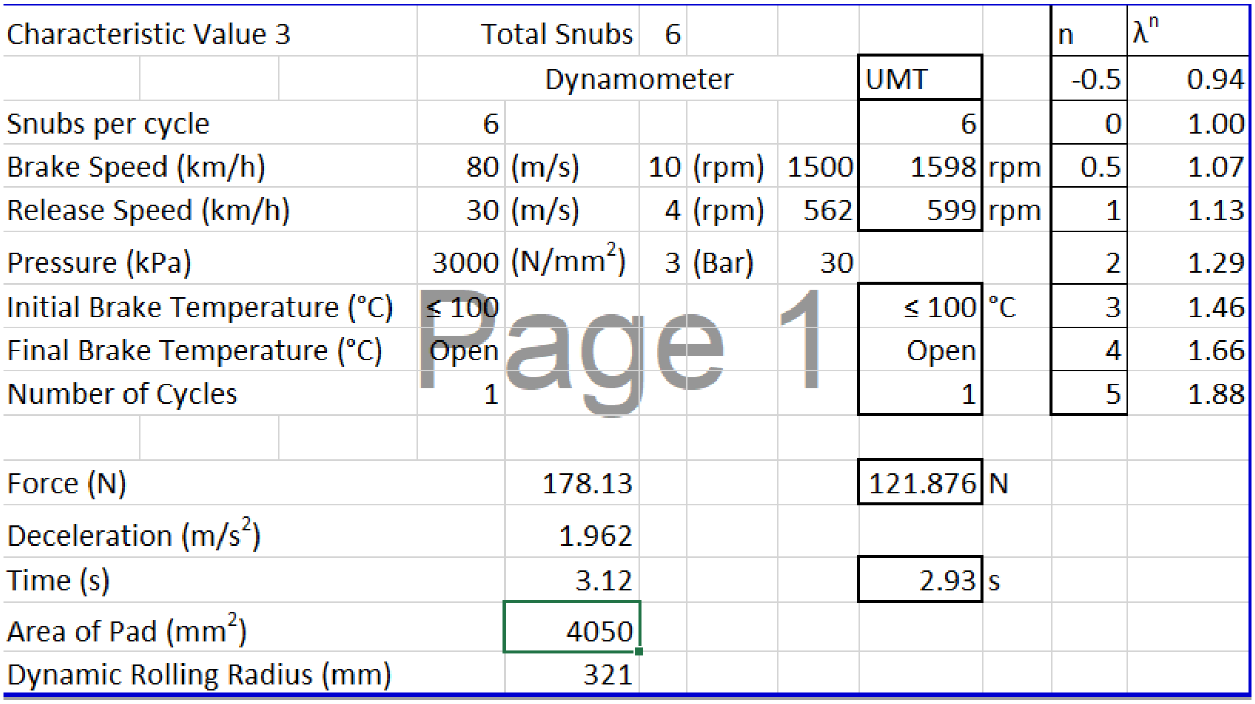
Characteristic Value 2	Total Snubs	6						n	λ^n
	Dynamometer					UMT		-0.5	0.94
Snubs per cycle	6					6		0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30			2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	°C	3	1.46
Final Brake Temperature (°C)	Open					Open		4	1.66
Number of Cycles	1					1		5	1.88
Force (N)		178.13				121.876	N		
Deceleration (m/s^2)		1.962							
Time (s)		3.12				2.93	s		
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							



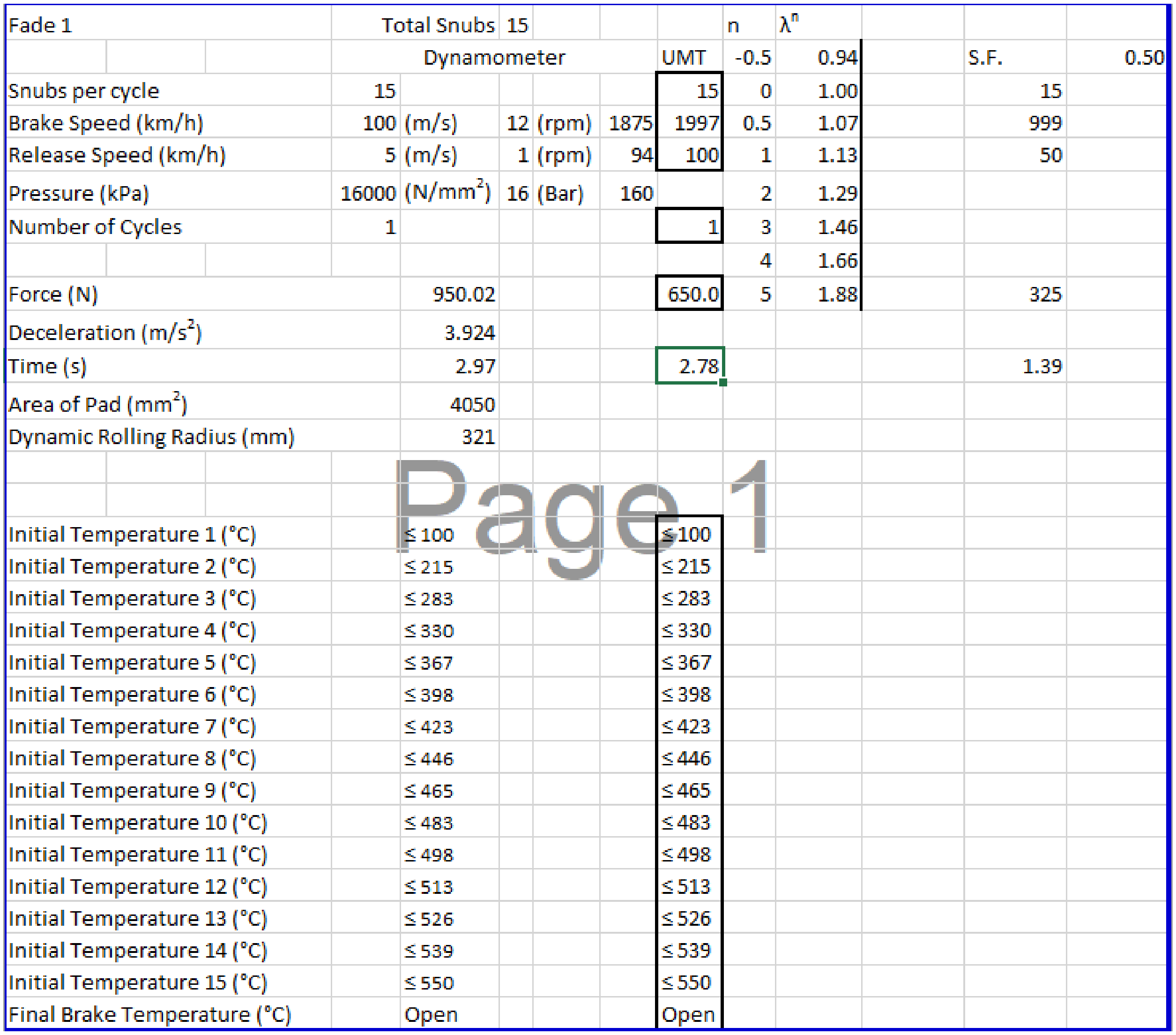
Cold	Total Snubs	1							
	Dynamometer					UMT		n	λ^n
Snubs per cycle	1					1		-0.5	0.94
Brake Speed (km/h)	40	(m/s)	5	(rpm)	750	799	rpm	0	1.00
Release Speed (km/h)	5	(m/s)	1	(rpm)	94	100	rpm	0.5	1.07
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30			1	1.13
Initial Brake Temperature (°C)	≤ 40					≤ 40	°C	2	1.29
Final Brake Temperature (°C)	Open					Open		3	1.46
Number of Cycles	1					1		4	1.66
								5	1.88
Force (N)		178.13				122	N		
Deceleration (m/s^2)		1.962							
Time (s)		2.19				2.05	s		
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							



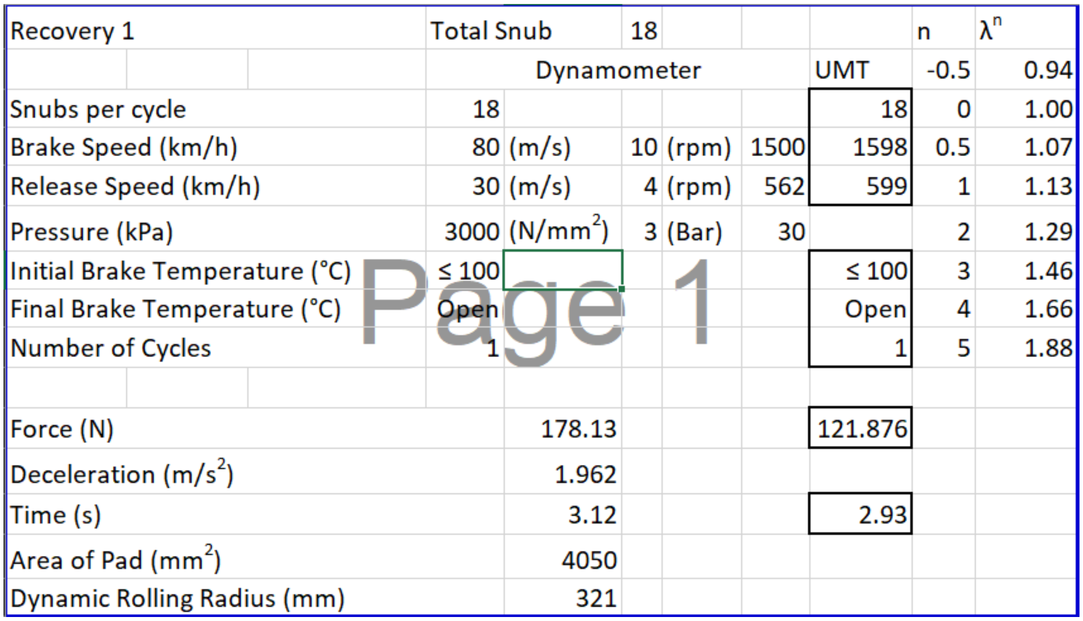
Motorway	Total Snubs	2							
	Dynamometer					UMT		n	λ^n
Snubs per cycle	2	Snub/Cycle				2	Snub/Cycle	-0.5	0.94
Brake Speed Stop (km/h)	100	(m/s)	12	(rpm)	1875	1997	rpm	0	1.00
Brake Speed Snub (km/h)	196	(m/s)	24	(rpm)	3679	3919	rpm	0.5	1.07
Release Speed Stop (km/h)	5	(m/s)	1	(rpm)	94	100	rpm	1	1.13
Release Speed Snub (km/h)	109	(m/s)	13	(rpm)	2044	2177	rpm	2	1.29
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30			3	1.46
Initial Brake Temperature (°C)	≤ 40					≤ 40	°C	4	1.66
Final Brake Temperature (°C)	Open					Open	°C	5	1.88
Number of Cycles	1					1			
Force (N)	178.1					121.876	N		
Deceleration (m/s^2)	5.886								
Time Stop (s)	1.98					1.86	s		
Time Snub (s)	1.81					1.70	s		
Area of Pad (mm^2)	4050								
Dynamic Rolling Radius (mm)	321								
V_{max} (m/s)	218								



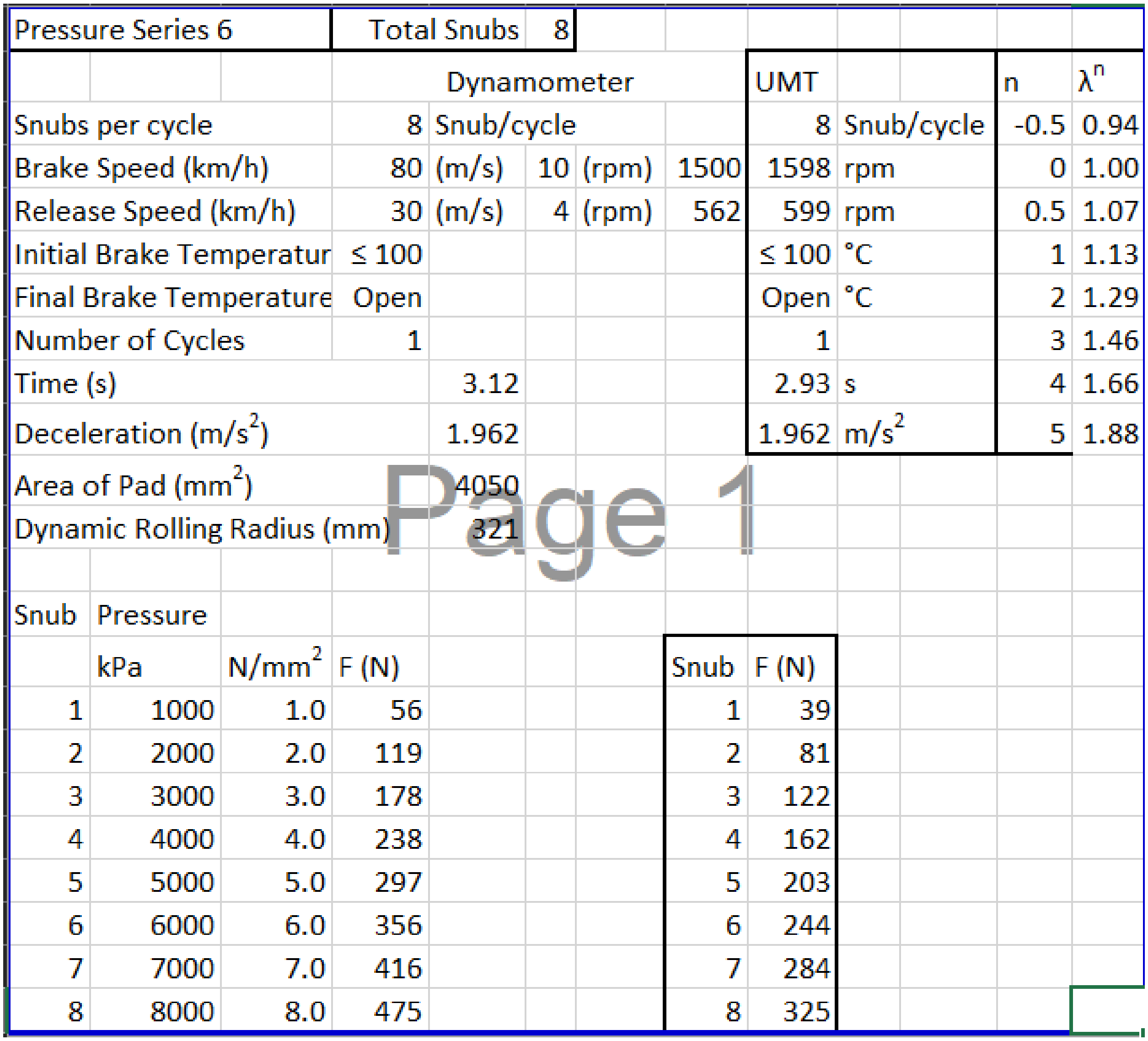
Characteristic Value 3	Total Snubs	6						n	λ^n
	Dynamometer					UMT		-0.5	0.94
Snubs per cycle	6					6		0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30			2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	°C	3	1.46
Final Brake Temperature (°C)	Open					Open		4	1.66
Number of Cycles	1					1		5	1.88
Force (N)		178.13				121.876	N		
Deceleration (m/s^2)		1.962							
Time (s)		3.12				2.93	s		
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							



Fade 1		Total Snubs	15				n	λ^n			
		Dynamometer				UMT	-0.5	0.94		S.F.	0.50
Snubs per cycle	15					15	0	1.00		15	
Brake Speed (km/h)	100	(m/s)	12	(rpm)	1875	1997	0.5	1.07		999	
Release Speed (km/h)	5	(m/s)	1	(rpm)	94	100	1	1.13		50	
Pressure (kPa)	16000	(N/mm^2)	16	(Bar)	160		2	1.29			
Number of Cycles	1					1	3	1.46			
							4	1.66			
Force (N)		950.02				650.0	5	1.88		325	
Deceleration (m/s^2)		3.924									
Time (s)		2.97				2.78				1.39	
Area of Pad (mm^2)		4050									
Dynamic Rolling Radius (mm)		321									
Initial Temperature 1 (°C)		≤ 100				≤ 100					
Initial Temperature 2 (°C)		≤ 215				≤ 215					
Initial Temperature 3 (°C)		≤ 283				≤ 283					
Initial Temperature 4 (°C)		≤ 330				≤ 330					
Initial Temperature 5 (°C)		≤ 367				≤ 367					
Initial Temperature 6 (°C)		≤ 398				≤ 398					
Initial Temperature 7 (°C)		≤ 423				≤ 423					
Initial Temperature 8 (°C)		≤ 446				≤ 446					
Initial Temperature 9 (°C)		≤ 465				≤ 465					
Initial Temperature 10 (°C)		≤ 483				≤ 483					
Initial Temperature 11 (°C)		≤ 498				≤ 498					
Initial Temperature 12 (°C)		≤ 513				≤ 513					
Initial Temperature 13 (°C)		≤ 526				≤ 526					
Initial Temperature 14 (°C)		≤ 539				≤ 539					
Initial Temperature 15 (°C)		≤ 550				≤ 550					
Final Brake Temperature (°C)		Open				Open					



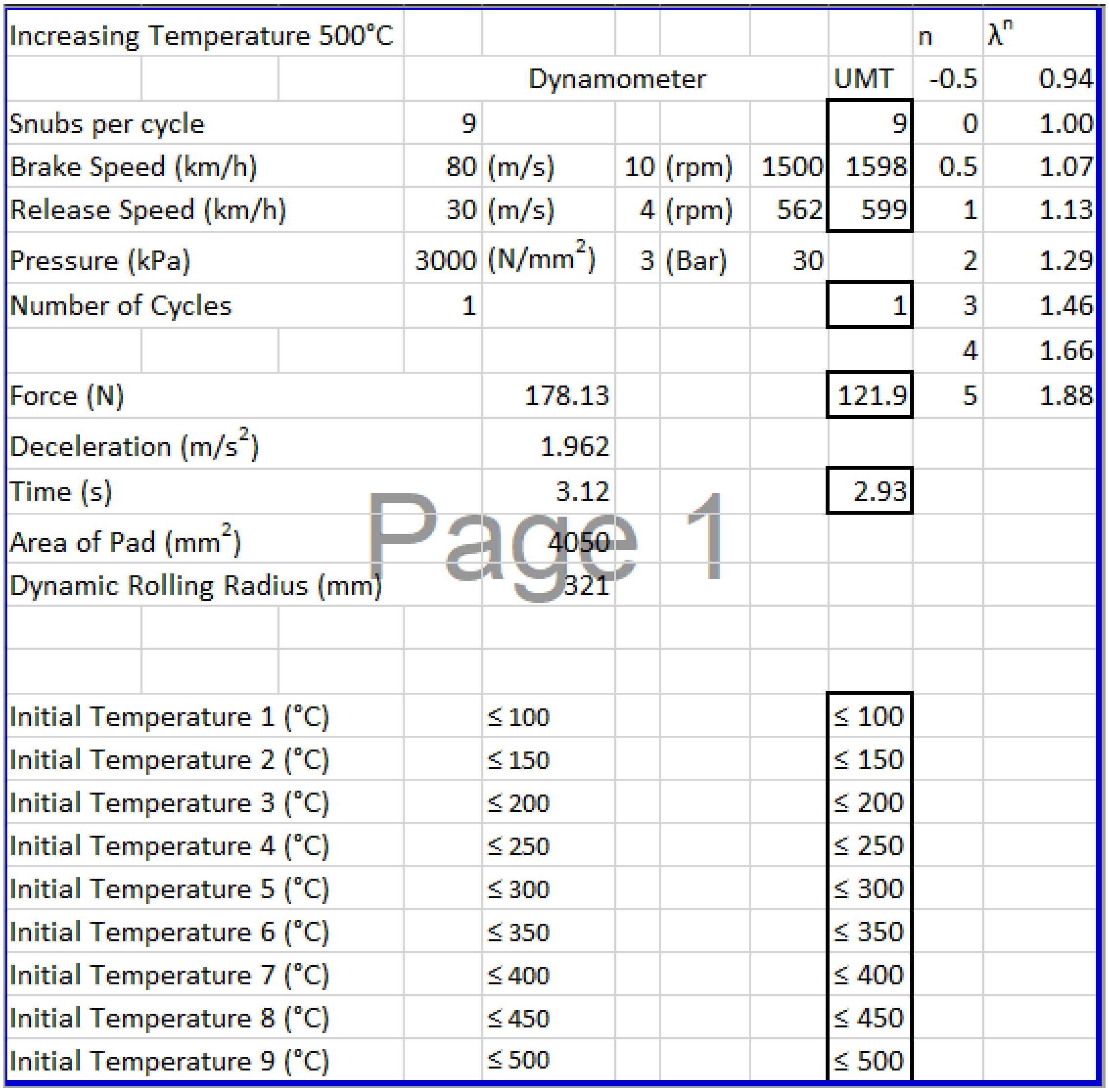
Recovery 1	Total Snub		18				n	λ^n
		Dynamometer				UMT	-0.5	0.94
Snubs per cycle	18					18	0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30		2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	3	1.46
Final Brake Temperature (°C)	Open					Open	4	1.66
Number of Cycles	1					1	5	1.88
Force (N)		178.13				121.876		
Deceleration (m/s^2)		1.962						
Time (s)		3.12				2.93		
Area of Pad (mm^2)		4050						
Dynamic Rolling Radius (mm)		321						



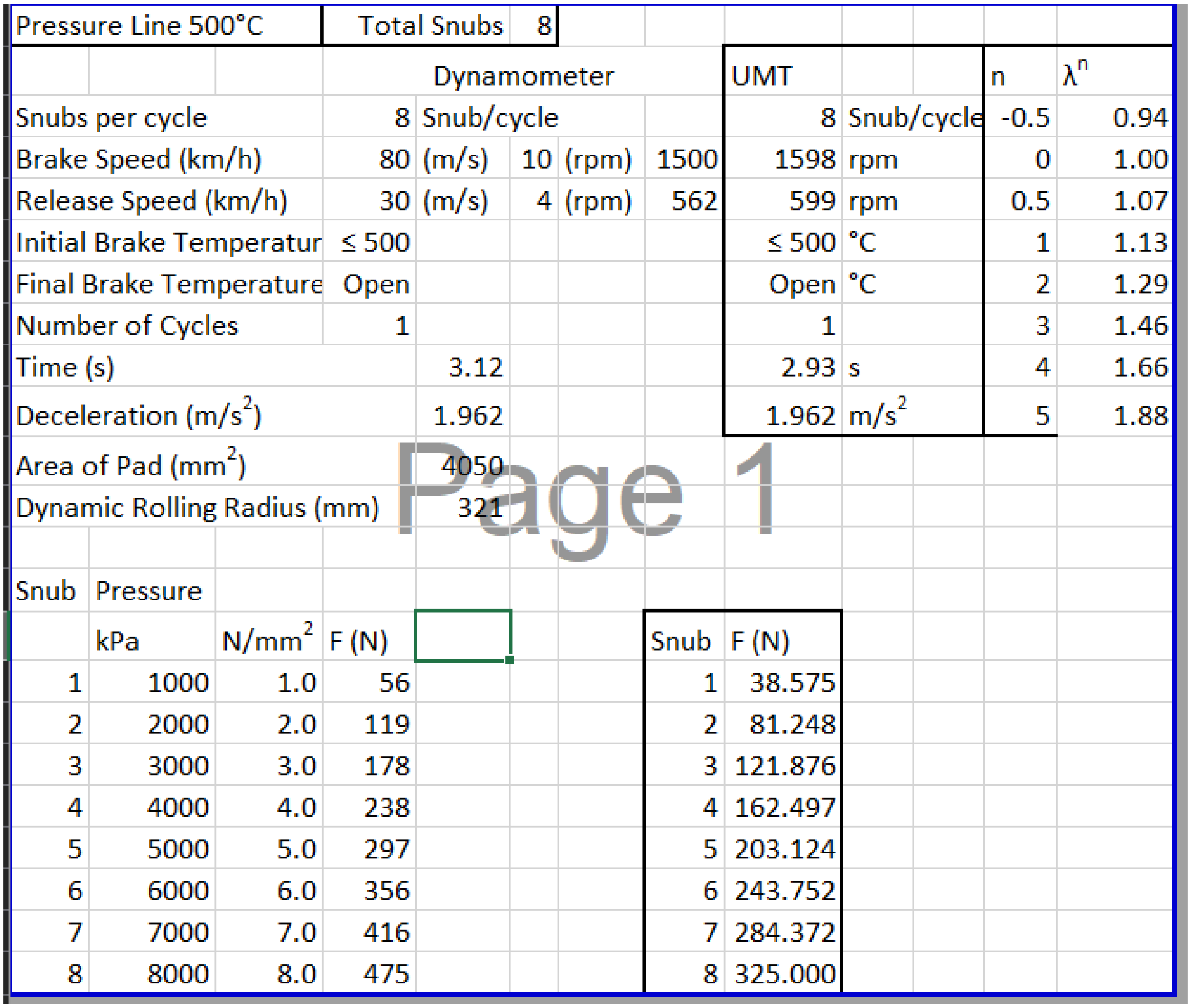
Pressure Series 6		Total Snubs	8						
		Dynamometer				UMT		n	λ^n
Snubs per cycle	8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0	1.00
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	0.5	1.07
Initial Brake Temperatur	≤ 100					≤ 100	°C	1	1.13
Final Brake Temperature	Open					Open	°C	2	1.29
Number of Cycles	1					1		3	1.46
Time (s)		3.12				2.93	s	4	1.66
Deceleration (m/s^2)		1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

Snub	Pressure		
	kPa	N/mm^2	F (N)
1	1000	1.0	56
2	2000	2.0	119
3	3000	3.0	178
4	4000	4.0	238
5	5000	5.0	297
6	6000	6.0	356
7	7000	7.0	416
8	8000	8.0	475

Snub	F (N)
1	39
2	81
3	122
4	162
5	203
6	244
7	284
8	325



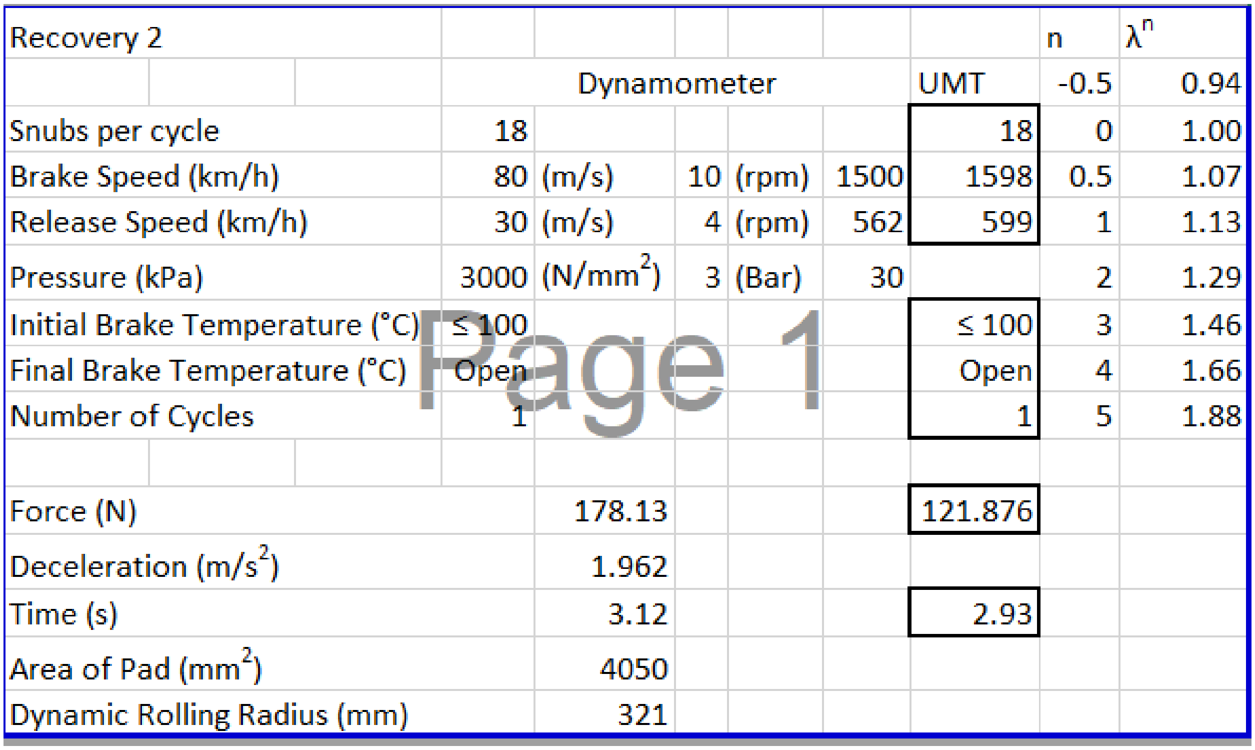
Increasing Temperature 500°C							n	λ^n
		Dynamometer				UMT	-0.5	0.94
Snubs per cycle	9					9	0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30		2	1.29
Number of Cycles	1					1	3	1.46
							4	1.66
Force (N)		178.13				121.9	5	1.88
Deceleration (m/s^2)		1.962						
Time (s)		3.12				2.93		
Area of Pad (mm^2)		4050						
Dynamic Rolling Radius (mm)		321						
Initial Temperature 1 (°C)		≤ 100				≤ 100		
Initial Temperature 2 (°C)		≤ 150				≤ 150		
Initial Temperature 3 (°C)		≤ 200				≤ 200		
Initial Temperature 4 (°C)		≤ 250				≤ 250		
Initial Temperature 5 (°C)		≤ 300				≤ 300		
Initial Temperature 6 (°C)		≤ 350				≤ 350		
Initial Temperature 7 (°C)		≤ 400				≤ 400		
Initial Temperature 8 (°C)		≤ 450				≤ 450		
Initial Temperature 9 (°C)		≤ 500				≤ 500		



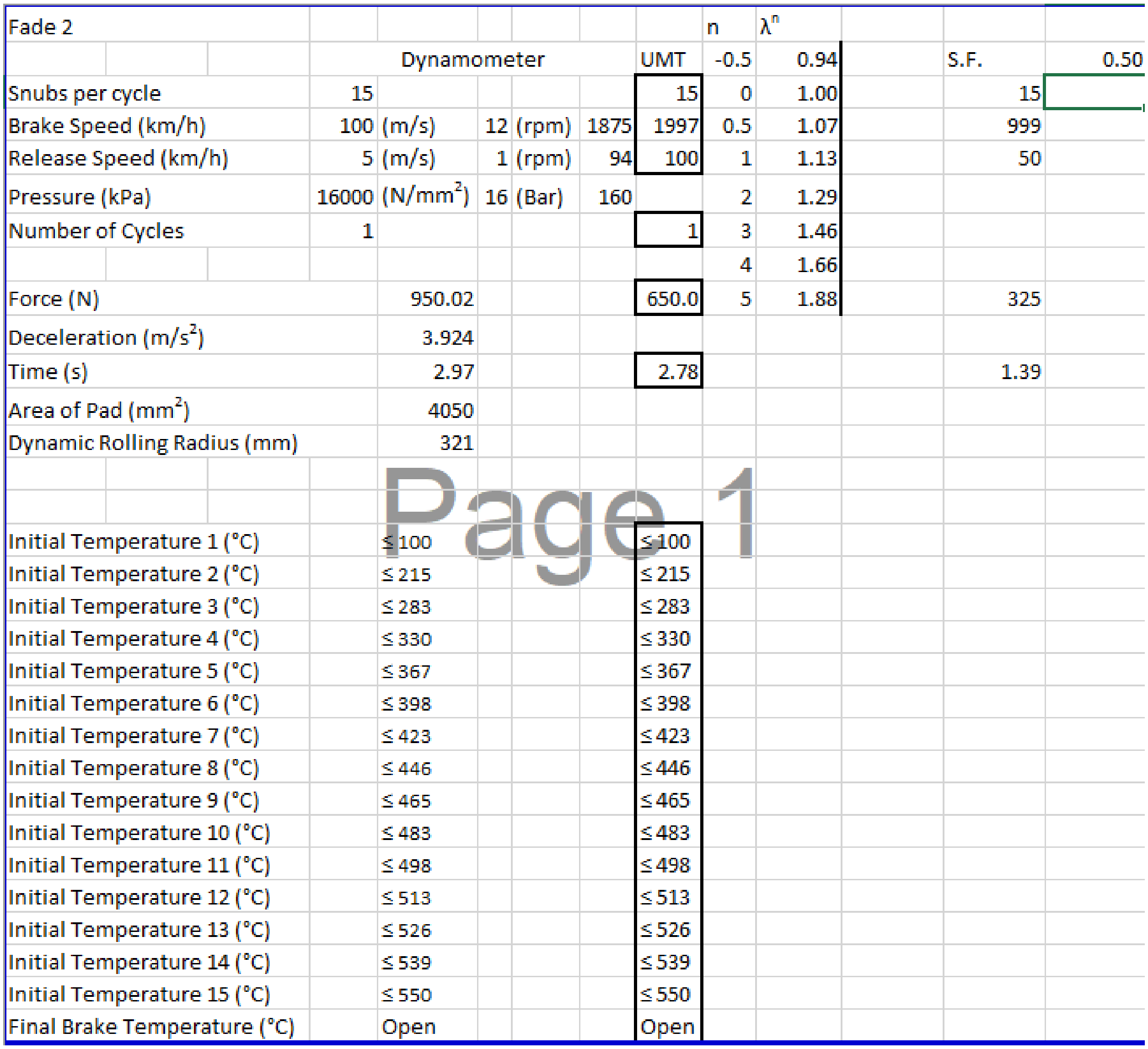
Pressure Line 500°C	Total Snubs	8

	Dynamometer					UMT		n	λ^n
Snubs per cycle	8	Snub/cycle				8	Snub/cycle	-0.5	0.94
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	rpm	0	1.00
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	rpm	0.5	1.07
Initial Brake Temperatur	≤ 500					≤ 500	°C	1	1.13
Final Brake Temperature	Open					Open	°C	2	1.29
Number of Cycles	1					1		3	1.46
Time (s)		3.12				2.93	s	4	1.66
Deceleration (m/s^2)		1.962				1.962	m/s^2	5	1.88
Area of Pad (mm^2)		4050							
Dynamic Rolling Radius (mm)		321							

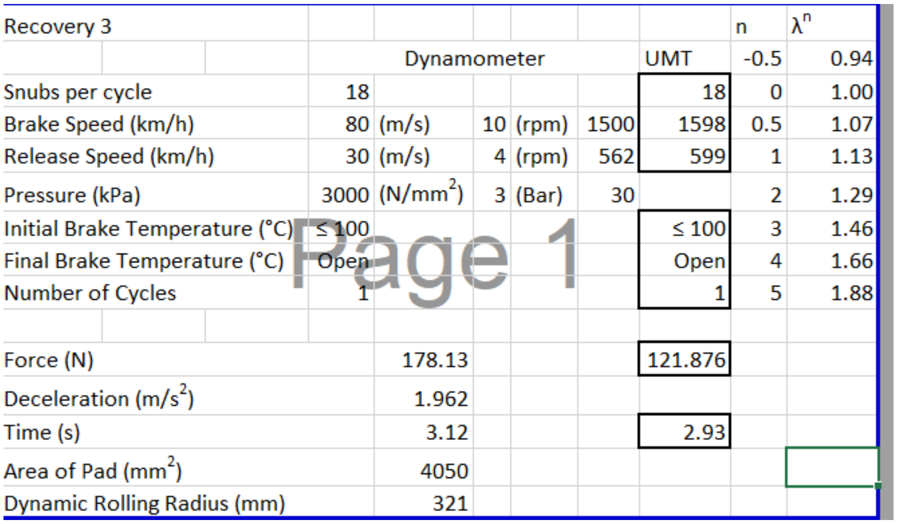
Snub	Pressure				
	kPa	N/mm^2	F (N)	Snub	F (N)
1	1000	1.0	56	1	38.575
2	2000	2.0	119	2	81.248
3	3000	3.0	178	3	121.876
4	4000	4.0	238	4	162.497
5	5000	5.0	297	5	203.124
6	6000	6.0	356	6	243.752
7	7000	7.0	416	7	284.372
8	8000	8.0	475	8	325.000



Recovery 2							n	λ^n
	Dynamometer					UMT	-0.5	0.94
Snubs per cycle	18					18	0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30		2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	3	1.46
Final Brake Temperature (°C)	Open					Open	4	1.66
Number of Cycles	1					1	5	1.88
Force (N)		178.13				121.876		
Deceleration (m/s^2)		1.962						
Time (s)		3.12				2.93		
Area of Pad (mm^2)		4050						
Dynamic Rolling Radius (mm)		321						



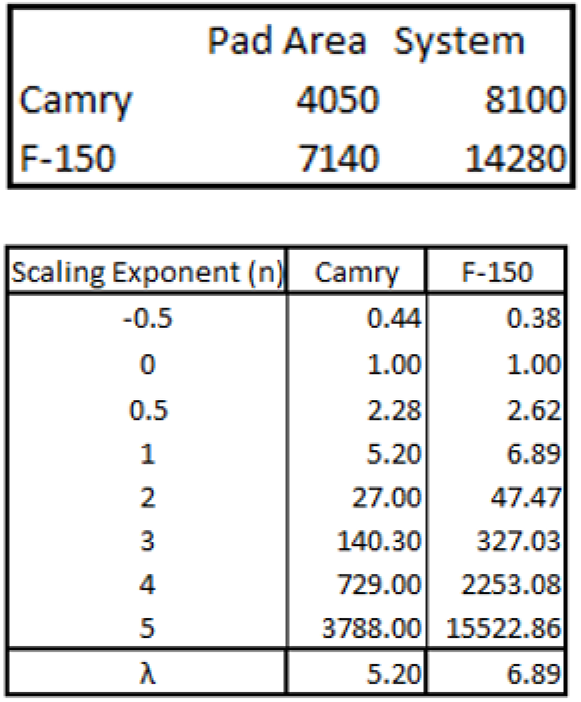
Fade 2							n	λ^n			
		Dynamometer				UMT	-0.5	0.94		S.F.	0.50
Snubs per cycle	15					15	0	1.00		15	
Brake Speed (km/h)	100	(m/s)	12	(rpm)	1875	1997	0.5	1.07		999	
Release Speed (km/h)	5	(m/s)	1	(rpm)	94	100	1	1.13		50	
Pressure (kPa)	16000	(N/mm^2)	16	(Bar)	160		2	1.29			
Number of Cycles	1					1	3	1.46			
							4	1.66			
Force (N)		950.02				650.0	5	1.88		325	
Deceleration (m/s^2)		3.924									
Time (s)		2.97				2.78				1.39	
Area of Pad (mm^2)		4050									
Dynamic Rolling Radius (mm)		321									
Initial Temperature 1 (°C)		≤ 100				≤ 100					
Initial Temperature 2 (°C)		≤ 215				≤ 215					
Initial Temperature 3 (°C)		≤ 283				≤ 283					
Initial Temperature 4 (°C)		≤ 330				≤ 330					
Initial Temperature 5 (°C)		≤ 367				≤ 367					
Initial Temperature 6 (°C)		≤ 398				≤ 398					
Initial Temperature 7 (°C)		≤ 423				≤ 423					
Initial Temperature 8 (°C)		≤ 446				≤ 446					
Initial Temperature 9 (°C)		≤ 465				≤ 465					
Initial Temperature 10 (°C)		≤ 483				≤ 483					
Initial Temperature 11 (°C)		≤ 498				≤ 498					
Initial Temperature 12 (°C)		≤ 513				≤ 513					
Initial Temperature 13 (°C)		≤ 526				≤ 526					
Initial Temperature 14 (°C)		≤ 539				≤ 539					
Initial Temperature 15 (°C)		≤ 550				≤ 550					
Final Brake Temperature (°C)		Open				Open					



Recovery 3							n	λ^n
		Dynamometer				UMT	-0.5	0.94
Snubs per cycle	18					18	0	1.00
Brake Speed (km/h)	80	(m/s)	10	(rpm)	1500	1598	0.5	1.07
Release Speed (km/h)	30	(m/s)	4	(rpm)	562	599	1	1.13
Pressure (kPa)	3000	(N/mm^2)	3	(Bar)	30		2	1.29
Initial Brake Temperature (°C)	≤ 100					≤ 100	3	1.46
Final Brake Temperature (°C)	Open					Open	4	1.66
Number of Cycles	1					1	5	1.88
Force (N)		178.13				121.876		
Deceleration (m/s^2)		1.962						
Time (s)		3.12				2.93		
Area of Pad (mm^2)		4050						
Dynamic Rolling Radius (mm)		321						

APPENDIX C:

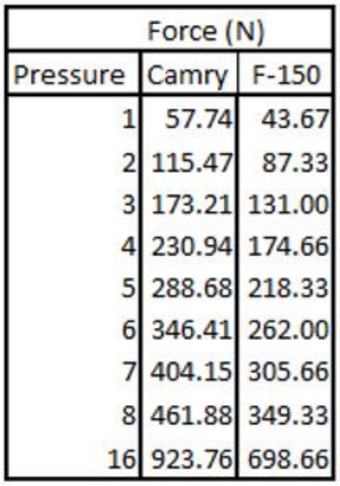
TORQUE CALCULATIONS



	Pad Area	System
Camry	4050	8100
F-150	7140	14280

Scaling Exponent (n)	Camry	F-150
-0.5	0.44	0.38
0	1.00	1.00
0.5	2.28	2.62
1	5.20	6.89
2	27.00	47.47
3	140.30	327.03
4	729.00	2253.08
5	3788.00	15522.86
λ	5.20	6.89

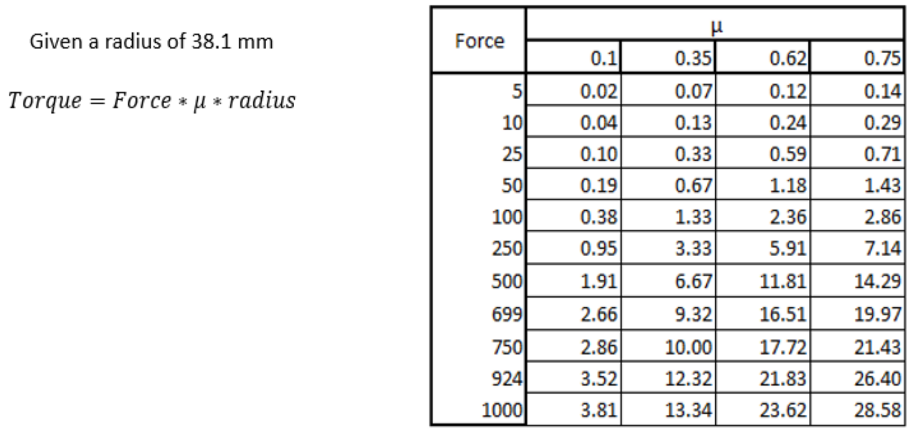
Figure 49: Pad area and Scaling exponents.



	Force (N)	
Pressure	Camry	F-150
1	57.74	43.67
2	115.47	87.33
3	173.21	131.00
4	230.94	174.66
5	288.68	218.33
6	346.41	262.00
7	404.15	305.66
8	461.88	349.33
16	923.76	698.66

Figure 50: Forces being applied to the contact area.

Torque Calculations



Given a radius of 38.1 mm

$$Torque = Force * \mu * radius$$

Force	μ			
	0.1	0.35	0.62	0.75
5	0.02	0.07	0.12	0.14
10	0.04	0.13	0.24	0.29
25	0.10	0.33	0.59	0.71
50	0.19	0.67	1.18	1.43
100	0.38	1.33	2.36	2.86
250	0.95	3.33	5.91	7.14
500	1.91	6.67	11.81	14.29
699	2.66	9.32	16.51	19.97
750	2.86	10.00	17.72	21.43
924	3.52	12.32	21.83	26.40
1000	3.81	13.34	23.62	28.58

Figure 51: Torque required for the different forces and μ.

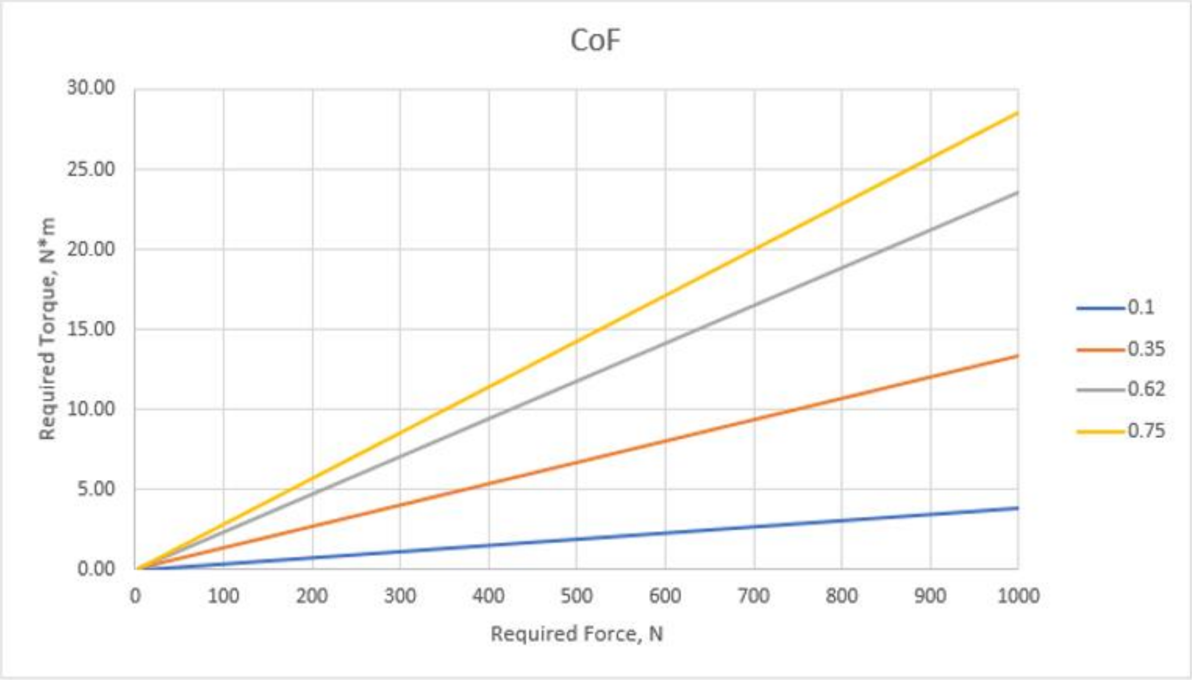


Figure 52: Graph of required torque.

APPENDIX D:

LINEAR VELOCITY VS. ANGULAR VELOCITY

After the completion of the research, it was brought to the attention of the research lab that there was an issue with directly scaling angular velocity (RPM) and that instead the Linear velocity should be scaled then used to determine the angular velocity. The lab has since started to scale using linear velocity for determining angular velocity instead of the previous method.

$$Linear\ Velocity = 2 * \pi * radius * \frac{RPM}{60}$$

Equation 6: New formula to be used to calculate the angular velocity.

So, to scale rpm, the radius needs to be scaled as well, but with a fixed radius of 38.1mm, this radius must be used for the calculations. So instead of making it worse, the lab is now scaling using linear velocity then calculating the RPM using the radius of 38.1 mm.

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Thesis Paper Title:

On Scaling of Brake Test SAE J2522

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