Brake Evaluation

Introduction
This report will evaluate the brake performance and consistency, based on measured data. The data presented in this report is from the hot laps and the braking tests at the Cabalen Road Course. However, a brief summary of the test vehicle and the sensors that were used will first be described.

Vehicle and Sensor Description
The primary sensors used for this report, the Kistler Roadyn S625 Wheel Force Transducers, are described in detail here. Descriptions of the other sensors used in the test can be found in the introduction.

Description
The wheel force sensor is mounted on a vehicle as a complete wheel and measures multiaxial loads imposed on the vehicle by the pavement. It enables precise measurement of forces and moments, each of which are represented as three vectors in an orthogonal reference system.

Math Channels and Constants
The data channels from the sensors were logged at the following frequencies:

Wheel force transducer *500 Hz*
GPS *20 Hz*
Brake pressure: *50 Hz*
Brake temperature: *10 Hz*

The slip ratio was calculated from wheel force transducer wheel speed, and the GPS speed:

*Tire Speed FL = WFT_FL_AngSpeed * TireRollOut_F*

Slip Ratio FL = (Tire Speed FL - GPS Speed) / GPS Speed

Figure 1: Kistler RoaDyn S625

Evaluation
Brake friction will be evaluated by comparing the brake pressure and the longitudinal wheel force. The friction dependency on brake temperature and vehicle speed will be analyzed. The analysis will focus on qualitative and not quantitative deductions, because of the lack of enough measurement data for creating a quantitative model.

Note, that the brake pressure and longitudinal wheel force is a function of not only the brakes, but also the tires. The longitudinal tire force vs. slip ratio function is close to linear in the small slip ratio range. But after this function is saturated, the longitudinal tire force starts to fall off with increasing slip ratio. Therefore increasing brake pressure once the tire has reached its limit will result in lower longitudinal wheel force. Figure 2 shows the measured longitudinal wheel force as a function of slip ratio during braking. The function has high deviation probably due to sensor inaccuracy, but the tire saturation can be observed.

Kistler RoaDyn S625 Performance Specifications

Measuring range	F_x	kN	±20
(with 4 load cells)	F_y	kN	±15
	F_z	kN	±20
	M_x	kN·m	±4
	M_y	kN·m	±4
	M_z	kN·m	±4
Rotation angle accuracy		°	≈0,1
Max. weight* of measuring wheel	m	kg	≈10
Maximum Loads			
Fatigue strength (SAE J328)		kN	2,6
Degree of Protection			IP64
Operating temperature range			
Aluminium components		°C	<120
CFR components		°C	<110

Maximum speed (≈280 km/h)		min^{-1}	2 300
Max. shock acceleration	x	g	≤40
	y	g	≤20
	z	g	≤40
Accuracy			
Crosstalk	$F_y \rightarrow F_x, F_z$	%	≤1
	$F_x \leftrightarrow F_z$	%	≤1
	$F_x, F_z \rightarrow F_y$	%	≤2
Linearity		% FSO	≤0,5
Hysteresis		% FSO	≤0,5

*including 14" rim, hub adapter and stator, but excluding tire

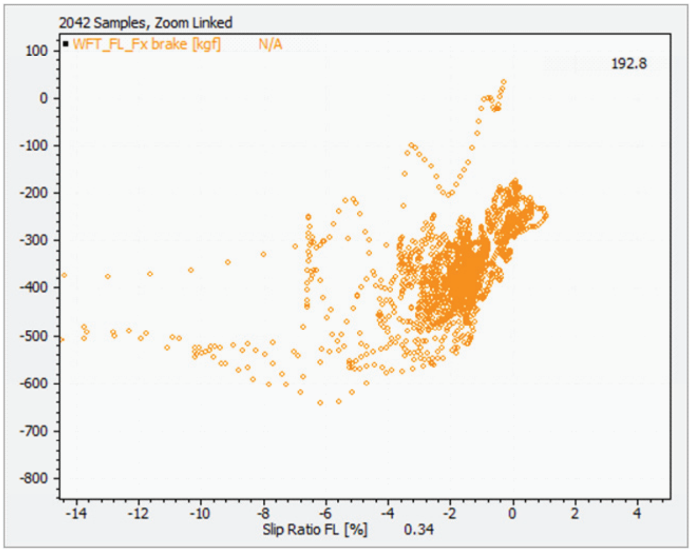

Figure 2: Longitudinal wheel force vs. slip ratio

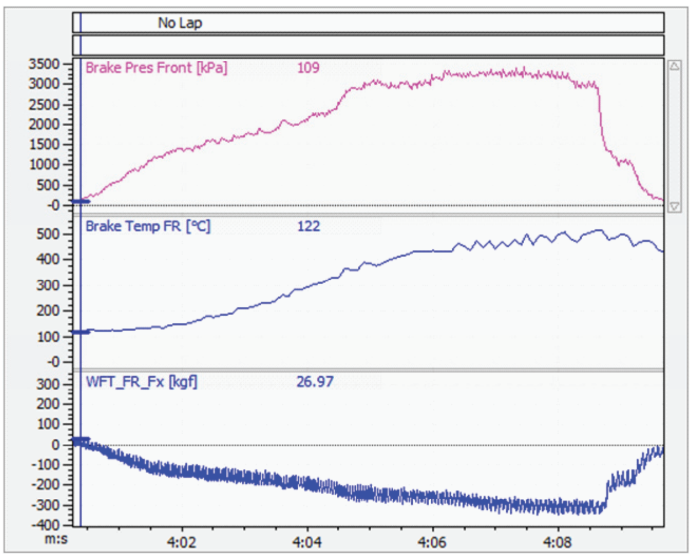

Figure 3: Brake test time graphs
(cold brakes, without downshifting)

Figure 3 shows time graphs from the brake test. The vehicle was braked from 180 to 0 km/h with cold brakes. It can be seen that the brake pressure was increased slowly until about 3000 kpa. After that it was constant until the brake was released. The temperature increased from 120 to 400 °C during the brake pressure increase to 3000 kpa, and from 400 to 500 °C during the constant brake pressure application. The longitudinal wheel force increased, when the brake pressure was constant. This suggests that the brake friction increased with the increasing brake temperature.

Figure 4 shows the wheel force as a function of the brake pressure with cold brakes. The plot is colored by brake temperature. It can be seen that at 3000 kpa the brake pressure of the wheel force is about 20% higher with the brake temperature above 450 °C. This suggests that the optimal brake temperature is above 450 °C.

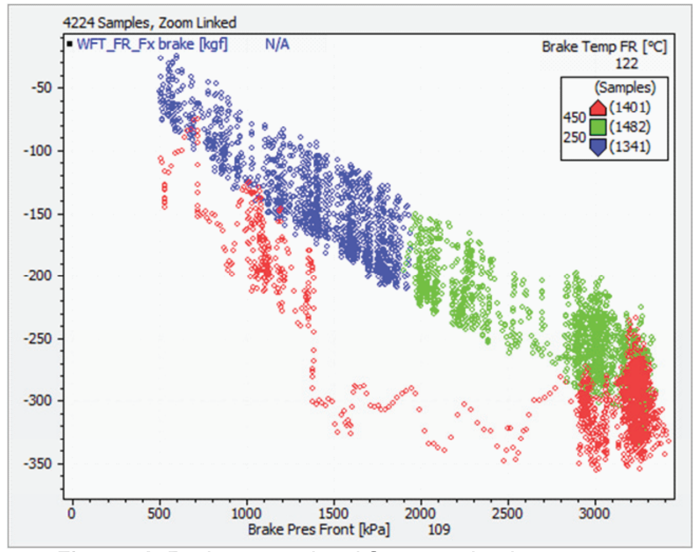

Figure 4: Brake test wheel force vs. brake pressure function (cold brakes, without downshifting)

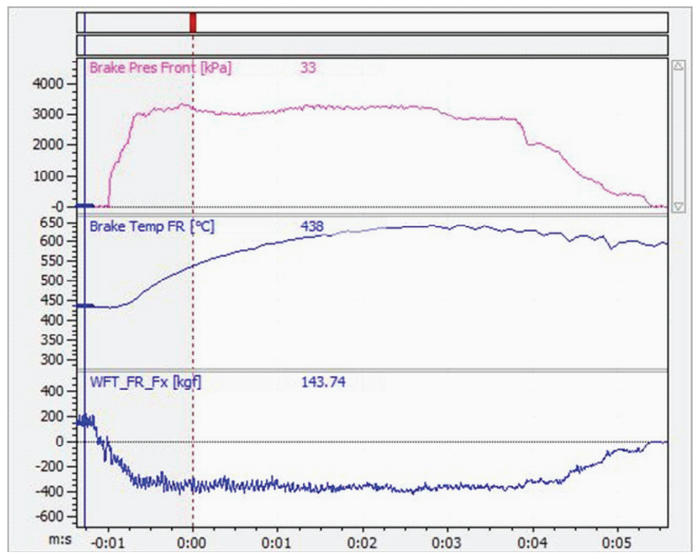

Figure 5: Brake test time graphs
(hot brakes, without downshifting)

Figure 5 shows time graphs of the brake test from 180 to 0 km/h with hot brakes. It can be seen that the brake pressure was increased aggressively until about 3000 kpa. After that it was constant until the brake was released. The brake temperature increased from 440 to 640 °C. The wheel force was relatively constant during the constant brake pressure application. This suggests that the brake friction does not change significantly between 440 and 640 °C.

Figure 6 shows the wheel force as a function of the brake pressure with hot brakes. The plot is colored by brake temperature. It can be seen that at 3000 kpa of brake pressure the wheel force is about the same across the temperature range. There is a difference between the wheel force below 3000 kpa of brake pressure, but the cause of this difference is probably hysteresis in the brake system and the characteristics of the tire force generation, and not the brake temperature dependency.

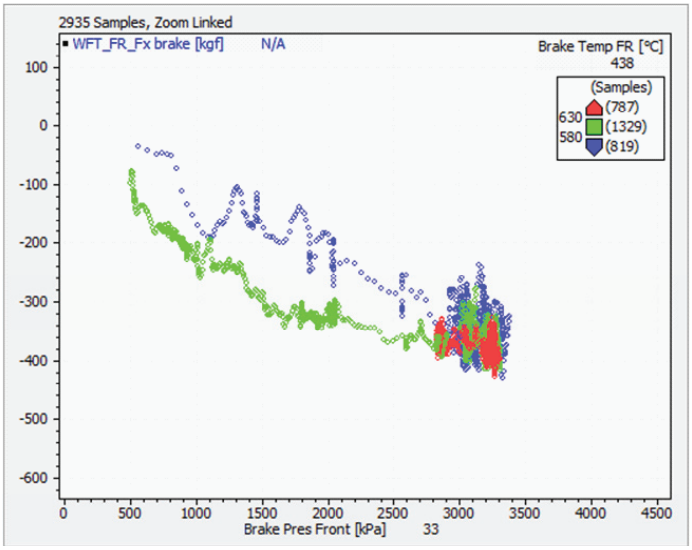

Figure 6: Brake test wheel force vs. brake pressure function (hot brakes). Colored by brake temperature.

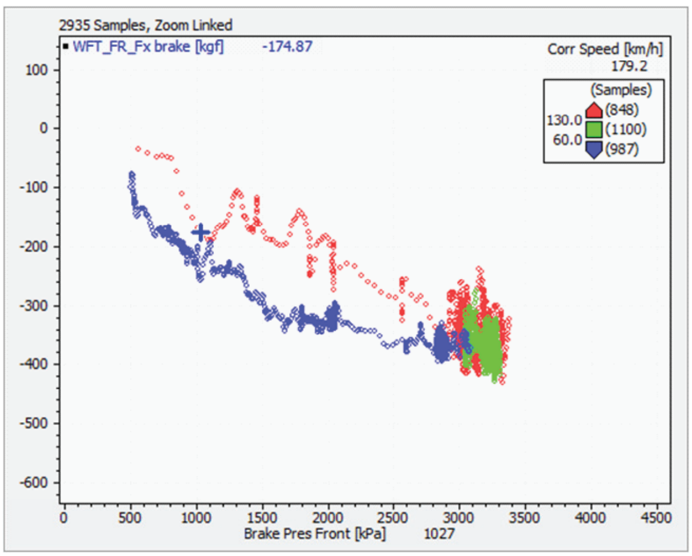

Figure 7: Brake test wheel force vs. brake pressure function (hot brakes). Colored by vehicle speed.

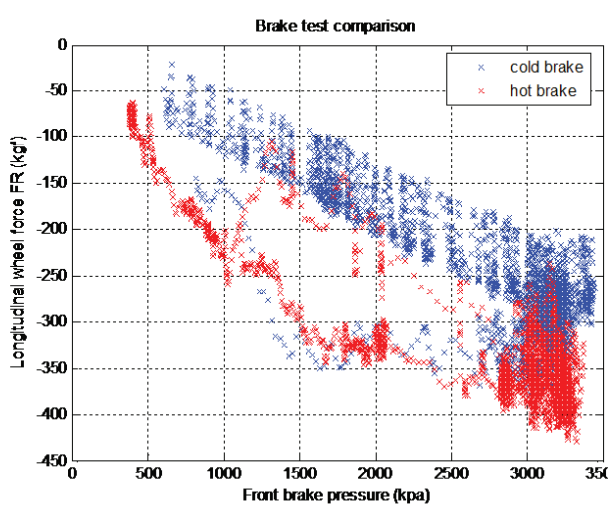

Figure 8: Brake test comparison (without downshifting)

Figure 7 shows the wheel force as a function of the brake pressure with hot brakes. The plot is colored by vehicle speed. It can be seen that at 3000 kpa of brake pressure the wheel force is about the same with all the examined vehicle speeds. This suggests that the vehicle speed dependency of the brake friction is negligible. The difference between the wheel forces below 3000 kpa of brake pressure is probably a result of hysteresis in the brake system and tire force generation, as mentioned above.

Figure 8 shows the wheel force as a function of the brake pressure. This data was from the brake test were the driver did not downshift while he was braking. The hot brake (440-640 °C) test shows about 20% higher brake friction than the cold brake (120-500 °C) test. The hysteresis seen with the cold brakes is also higher.

All of the data above was collected during straight line braking tests. Now, the braking efficiency during hot laps at the Cabalen Road Course hot laps will be analyzed. Data with cold and hot brakes will be examined. This data was collected from the same section of the track. The vehicle was braked from approximately 195 to 70 km/h. The hot data was collected two laps after the cold data. The average brake temperature increased about 100 °C over these laps. The FR brake temperature was compared to the FL wheel force, because the lack of the FL brake temperature and the FR wheel force measurement data.

Figure 9 shows the braking data with cold brakes. The brake is applied aggressively. The pressure reaches about 3500 kpa and is held there until the brake is released. The brake temperature increases from 300 to 500 °C.

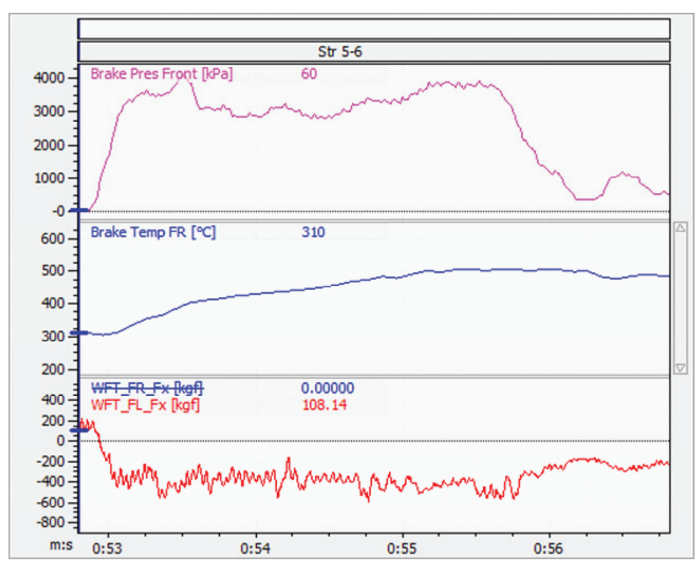

Figure 9: Hot lap braking time graphs (cold brakes, with downshifting)

Figure 10 shows the braking data with hot brakes. The brake is applied aggressively. The pressure reaches about a constant of about 3500 kpa until the brake is released. The brake temperature increases from 420 to 620 °C.

Figure 11 shows the wheel force as a function of the brake pressure during the hot laps. The data collected with cold brakes is shown in blue while the data with the hot brakes is in red. No significant difference in the performance of the cold and hot brakes can be seen.

The differences between the straight line braking test and the hot lap braking will be evaluated (with and without downshifting). Figure 12 shows time graphs comparing the brake pressure, wheel force, and longitudinal acceleration. It can be seen that the wheel force and acceleration is proportional to the brake pressure. Figure 13 shows the wheel force as a function of the brake pressure. The average wheel forces seem to be higher with the driver downshifting at the same brake pressure, but the differences are not so high.

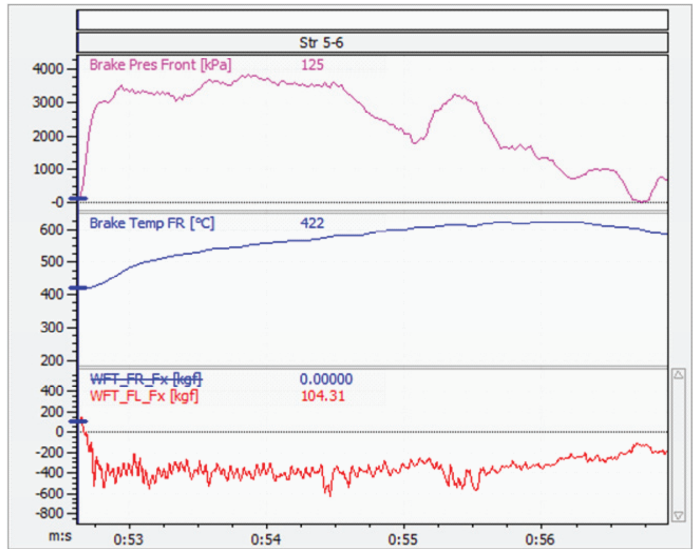

Figure 10: Hot lap braking time graphs (hot brakes, with downshifting)

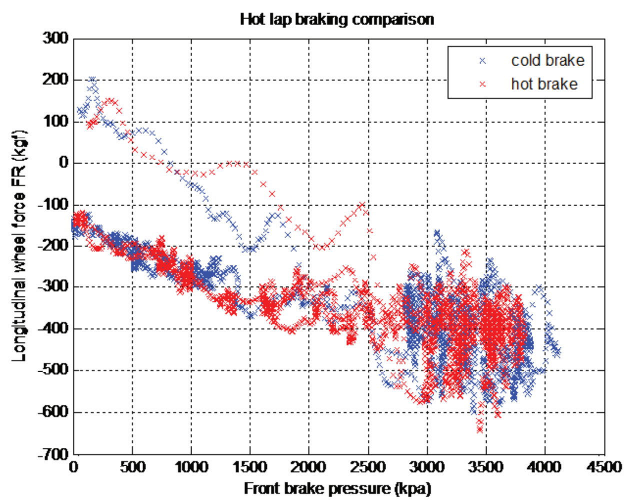

Figure 11: Hot lap braking comparison (with downshifting)

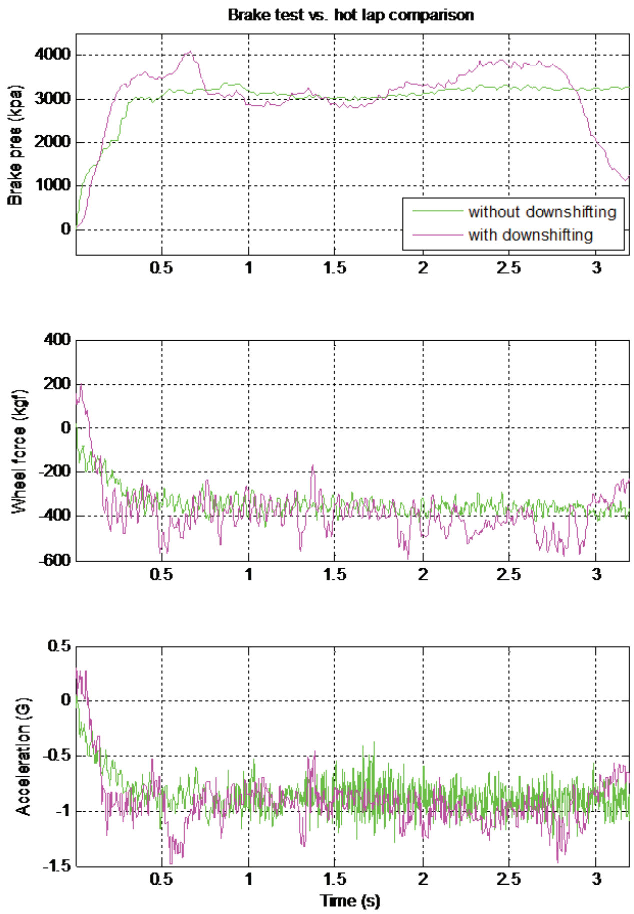

Figure 12: Brake test vs. hot lap comparison time graphs (with and without downshifting)

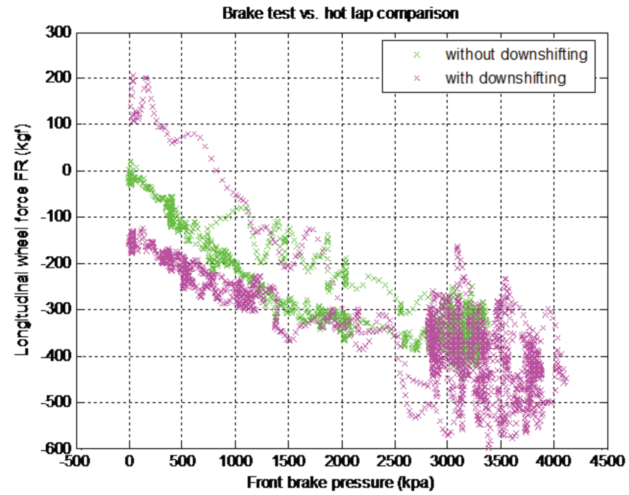

Figure 13: Brake test vs. hot lap comparison scatter plot (with and without downshifting)

Conclusion

Brake friction was evaluated comparing the brake pressure and longitudinal wheel force. The friction dependency on the brake temperature and vehicle speed was analyzed by comparing the straight line brake tests (without downshifting) to hot lap braking (with downshifting). There was 20% higher brake friction above 450 °C brake temperature, than between 250-400°C. The hot lap results showed no significant difference in brake friction with cold (300-500°C) and hot (420-620°C) brakes. This can be explained with the fact that the 450 °C brake temperature was reached relatively fast even with the cold brake, and there is no significant difference in friction above this temperature until approximately 620°C (according to the brake test results).