Swedish Tests of Block Brake Performance in Winter Conditions

Test period: 2018-03-14 – 2018-04-14

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0. Revision History

Rev	Date	Editor/Author	Notes
0.1	181010	DL	Initial document
0.2	181001	DL	Document formatted, spell check done
0.3	181210	DL	More detailed info on measurement setup Reviewer´s text added
0.4	181210	DL	Text update regarding test tours
0.5	190128	DL	Text update regarding test tours
1.0	200824	DL	New analysis including all brake events

1. Introduction

On the request of Swedish Transport Authority, Damill AB has helped in doing field tests of different block brake shoes when operating in winter conditions. The reason is that new type of materials has entered the EU market: sintered and composite materials. They are supposed to be more gently to the wheel running surface and to be more silent compared to classic models made of cast iron. Their advantages has now been added with some possible disadvantages. In the Scandinavian countries there has been reported serious indications of bad braking performance in winter condition. Separate tests on this matter have been conducted in Finland and Sweden during winter and spring 2018. This report presents the Swedish tests.

2. Measurement setup

The measurement setup has been arranged with an aim to measure the wheel tangential forces under each shoe when brakes are applied. That gives an immediate reading that is directly proportional to the friction coefficient between wheel and brake shoe. The force was achieved by measuring the counteracting force of the vertical hanger that keeps the shoe holder in position, see figure 1. Two adjacent axles in a train with a total of eight shoe holder hangers where instrumented with strain gauges, see figure 2. The strain gauges were arranged in a Wheatstone bridge with 2 active elements while the other two elements where active as temperature compensation. The sensors where connect to a rugged logger unit placed on board of one of the wagons which communicated with a computer inside the locomotive cabin. During the test runs of up to 12 hours, each sensor was continuously scanned with a specially adapted software using 2000 Hz as sampling rate. The incoming signals was low pass-filtered to 10Hz where after every 100th sample was stored in data file. The resulting actual sampling rate in data files are then 20Hz making it possible to study exact force behaviour when braking. The computer inside the loco was also equipped with a remote access communication module so technicians could support the measurement team on board.

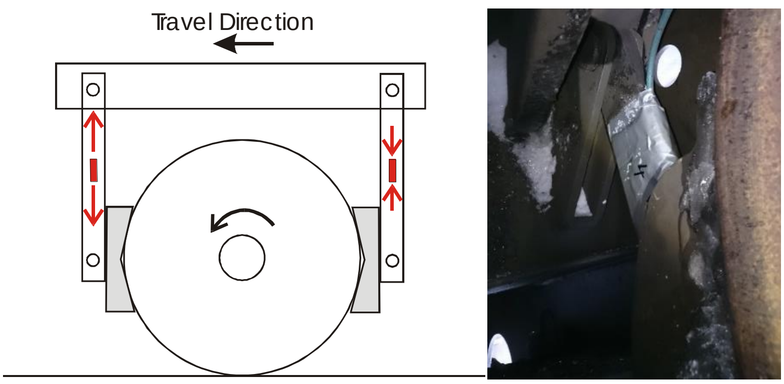


Figure 1: The principle of the measurement is to measure friction under brake shoes by measuring the longitudinal forces in hangers keeping the brake shoe holders in position. To the right is a photo of the actual installation on one of the hangers.

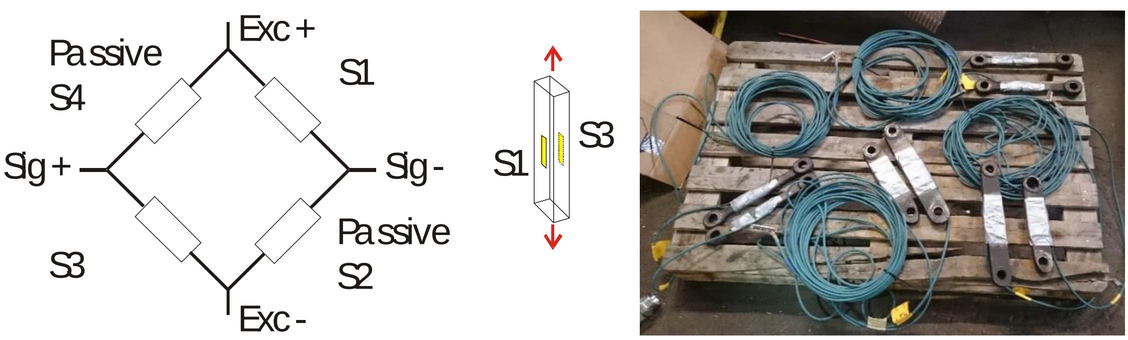


Figure 2: Preparation of the brake shoe holder hangers. Two resistive strain gauges HBM LY41/6 were bonded onto each side of the hangers and then connected to a Whetstone measurement bridge. This setup suppress bending stress but clarify pure longitudinal stress in the material.

For this test has the Swedish Transport Authority chartered a train consisting of a diesel locomotive and six open freight wagons of type Sps. The wagons have been empty all through the tests. Their tare weight is 22000 kg giving an axle load of 5500 kg and wheel load of 2750 kg. As the train needed to swap travel direction, the instrumented shoes where placed in the middle of the train to get a symmetric setup where train length ahead of test axles are unchanged, see figure 3, 4 and 5.

When it comes to absolute forces, the diagrams in this report show values that, when summed up for each wheel, reaches normally up to 4000-6000N and with an absolute maximum of 7000N observed 180315 just before trained stopped completely. That maximum value corresponds to a traction coefficient between wheel and rail of 7000N/(2750kg*9,82)=0,26. It seems high but possible as it happened when the brake shoes went from dynamic to static friction. When studying time to stop, an important factor here is that the locomotive brakes where disengaged during the tests so the locomotive dynamic weight has to be distributed on six wagons (=24 axles). The locomotive was of type “T44” with a dynamic weight of approximately 80 tons. That means each wagon wheel must take care of braking (80+6*22,5)/(24*2)= 4,48 tons.

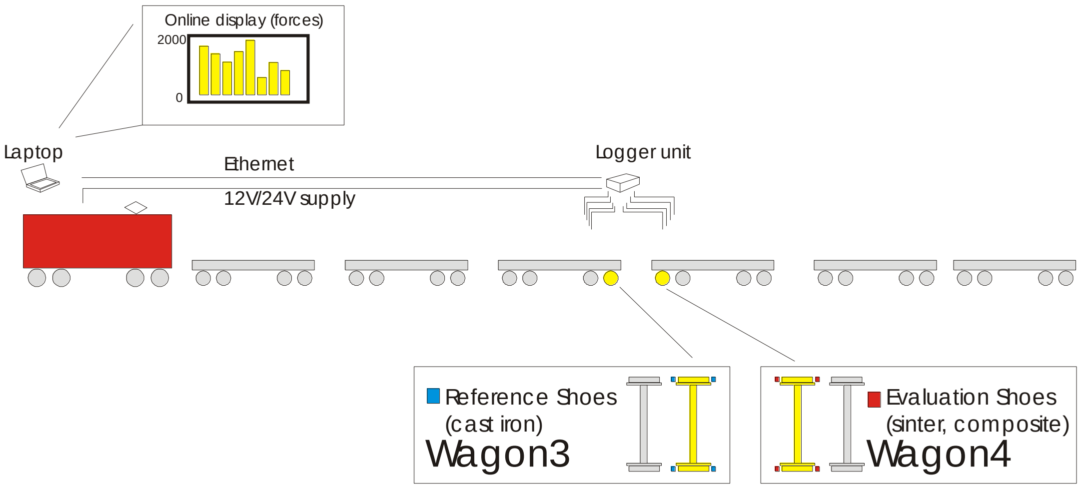


Figure 3: Illustration of the full measurement setup.

Figure 4: Logger unit on board of one of the wagons.

Figure 5: Identity of the instrumented wagons in these test

The eight instrumented hangers where arranged in the channel order presented in table 1. The front/back reference refer to a locomotive position as in figure 3 and front meaning closest to locomotive.

Table 1: Channel order and positions of the instrumented hangers. Analysis presented in this report is mainly made on the green coloured channel as some cable problems occurred on left side sensors during test period.

Channel	Position/Name
1	Wagon 3, 4th axle, left front
2	Wagon 3, 4th axle, left back
3	Wagon 3, 4th axle, right front
4	Wagon 3, 4th axle, right back
5	Wagon 4, 1st axle, left front
6	Wagon 4, 1st axle, left back
7	Wagon 4, 1st axle, right front
8	Wagon 4, 1st axle, right back

3. Test tours

Test tours have been conducted in the middle and northern part of Sweden during a period in spring of 2018. After initial instrumentation in beginning of March, there was some need to tune the measurement system and the first relevant tour was performed on March 14th. During the period March 14th -March 28th, daily tours where conducted where wagon 4 had different composite brake shoes while wagon 3 had the standard cast iron brake shoes all the time. The tests included the following setups:

March14th-March 17th: Wagon 4 was tested with Knorr-Bremse IB116 organic composite brake shoes.

March 25th – March 28th: Wagon 4 was tested with Cofren C952-1 sintered composite brake shoes.

April 13th – April 14th: The difference from first setup was that all axles in train had new Knorr-Bremse IB116 organic composite brake shoes and the test tours were performed in weather without snow dust and ice build-up.

After each replacement of brake shoes, the train was run about 500km before measurement was started. This was made for brake shoe run-in.

4. Sanity check of data

After acquisition of data and before doing any detailed analysis, it is relevant to check if the data is correctly scaled and that it interacts well with the manual observations presented in Appendix A. The method of measuring brake forces by getting hanger tension is easy to validate. Common laws of physics (Newtons F=m*a) imply that the theoretic mean brake force ($F_{theoretic}$) can be calculated based on train dynamic mass (m_{dyn}), the observed velocity change ($v_{end-}v_{start}$) given in notes and the duration of the brake event (T_{break}) given by measured data. If that calculation is done for a single wheel, the result should be very close to the measured mean force (F_{actual}) given as the sum of hanger forces for that wheel during a brake event. After skipping the sign for negative acceleration and compressive forces, we get:

$$F_{theoretic} = m_{dyn} * |a_{mean}| = m_{dyn} * |(v_{end-}v_{start})|/T_{break}$$

and

$$F_{actual} = |F_{mean\_hanger1}| + |F_{mean\_hanger2}|$$

Doing the math for some selected brake events on each test tour gives data in Table 2. The table shows only brake events where the pressure is noted to be 1,0 bar which makes it possible to relate the forces also to the applied pressure. We can see that for most brake events, the theoretic brake force fall in range between measured mean values for cast iron and composite shoes. But there is one clear exception. The last tours on dates 2018-04-13 and 2018-04-14 seem to differ. The measured forces are much lower than both required theoretic values and earlier measurement at same brake pressure. Something has happened to the measurement setup. After some consideration, we decide to skip these tours from further analysis. Our measured data for these dates cannot be fully comparable with data from earlier tours.

Please observe that the now presented method of comparing actual and theoretic brake forces does not assume a perfect match between theoretic and actual values. We get measured actual data from only 2 out of 48 wheels while the calculated $F_{theoretic}$ is a mean value of all these 48 wheels where 46 of them have cast iron brake shoes (dates 2018-04-13 and 2018-04-14 excluded). A statistic spread must be accepted, especially due to variations in friction between brake shoes and wheels. Several sources on Internet gives data for both static and kinetic (slipping) friction between cast iron (=brake shoe) and steel (=wheel). Static friction can vary between 0,21 on a wet surface and 0,4 on a dry surface. The kinetic friction is lower and the number 0,23 is often presented for a dry contact. A wet surface goes even lower than that but it is not so easy to find documented values o Internet. If we assume that our studied brake shoes can work in any of the three conditions **ice coated/wet/dry**, we can assume the friction coefficient of cast iron shoes to vary between 0-0,23 while in motion and up to 0,4 when the wheel is coming to a complete stop. If we exclude the ice coated operation and only expect more or less snow (water) lubrication, a friction range of 0,1 in wet sliding conditions and 0,4 in dry static seems relevant. That should generate a possible spread of forces where values can drop to ratio 1/4 when going from fully dry stopped to fully wet sliding operation. Going back to Table 2 and the column for maximum forces for cast iron shoes, we can see one value reaching 6733N which was a situation where the train went to a complete stop according to the log in Appendix A. In the other end, the lowest maximum was found to be 1850N which can very well be a wet brake event. That gives the range ratio 1850/6733 N or ratio 1/3,6. This is fairly close to what can be expected.

The logical discussion presented here is not intended to be an evaluation of the brake shoe performance but to act as help in judging data sanity. From that perspective, data is still considered to be relevant if we skip the last two days where locomotive brakes have been engaged.

Table 2: A selected list of brake events where brake pressure, according to notes, has been 1,0 bar. Last tours had few or no brake events with 1,0 bar so we have presented also some 0,9 bar values. Calculated theoretic mean brake forces for 1 wheel can be compared to actual measured values for cast iron and composite brake shoes. Last dates 2018-04-13 and 2018-04-14 indicate a lower level in measured amplitudes.

Date	Start time [s]	Duration [s]	Direction	Tst type	Brake Pressure [bar]	Mean Cast Iron Frc. [N]	Mean Comp Frc. [N]	Max Cast Iron Frc. [N]	Max Comp Frc. [N]	Spd drop [km/h]	Theoretic Mean Frc. [N]
2018-03-15	12:48:26	29	FW	IB116	1	3147	1265	4563	1769	35	1502
2018-03-15	13:04:48	34	FW	IB116	1	3324	1343	4367	1840	55	2013
2018-03-15	14:39:01	31	FW	IB116	1	3847	1065	5244	1423	50	2007
2018-03-15	17:14:00	25	BW	IB116	1	2617	1785	4060	2245	50	2489
2018-03-15	17:24:51	34	BW	IB116	1	2601	3139	5153	4640	75	2745
2018-03-15	19:40:16	30	BW	IB116	1	2687	1802	4301	3627	75	3111
2018-03-15	19:58:37	33	BW	IB116	1	1915	2083	2965	2817	45	1697
2018-03-15	20:09:28	32	BW	IB116	1	1791	1984	2720	2630	55	2139
2018-03-16	08:56:37	34	BW	IB116	1	2109	2307	2925	3172	70	2562
2018-03-16	10:40:31	30	BW	IB116	1	2107	1342	4329	3783	40	1659
2018-03-16	11:00:48	55	BW	IB116	1	1590	2169	2382	3073	80	1810
2018-03-16	18:51:06	40	FW	IB116	1	3716	1684	5537	2215	55	1711
2018-03-16	19:03:18	27	FW	IB116	1	3548	1147	5313	1690	30	1383
2018-03-16	19:48:50	39	FW	IB116	1	2794	1252	3825	1749	35	1117
2018-03-16	20:07:11	36	FW	IB116	1	3130	1784	4749	2716	50	1728
2018-03-17	08:50:32	40	FW	IB116	1	3237	2195	4935	2908	60	1867
2018-03-17	09:04:25	42	FW	IB116	1	2968	2343	4410	3158	80	2370
2018-03-17	10:59:33	35	FW	IB116	1	2785	1633	3879	2318	50	1778
2018-03-17	14:14:03	39	BW	IB116	1	2719	2007	4606	3338	70	2234
2018-03-25	17:42:35	24	FW	C952-1	1	2014	2223	5639	3286	40	2074
2018-03-25	19:16:59	23	FW	C952-1	1	3083	1477	4814	2208	25	1353
2018-03-25	19:43:50	37	FW	C952-1	1	3610	1720	4995	2234	55	1850
2018-03-25	20:03:08	22	FW	C952-1	1	4676	2626	6733	3495	75	4242
2018-03-26	09:30:37	38	FW	C952-1	1	2451	2101	3722	2637	50	1637
2018-03-26	13:21:34	32	BW	C952-1	1	1888	1745	3034	2579	60	2333
2018-03-26	14:05:17	29	BW	C952-1	1	1167	1461	1850	1788	40	1716
2018-03-26	16:00:11	39	BW	C952-1	1	1825	1746	3290	2119	65	2074
2018-03-26	16:03:27	24	BW	C952-1	1	1764	1220	3127	1867	55	2852
2018-03-26	16:35:18	26	BW	C952-1	1	2014	1906	3361	2613	50	2393
2018-04-13	13:30:53	24	BW	IB116	1	1035	985	1527	1413	50	2593
2018-04-13	13:56:33	13	BW	IB116	1	840	702	1164	1184	30	2872
2018-04-13	14:08:48	14	BW	IB116	0,9	691	803	1053	1194	30	2667
2018-04-13	15:01:36	21	BW	IB116	0,9	1061	1025	1399	1411	35	2074
2018-04-14	09:05:18	23	BW	IB116	0,9	912	955	1327	1422	40	2164

5. Analysis of brake force amplitudes

There has been many aspects to consider when doing the analysis. At first we had problem in understanding the behaviour with unsymmetrical load on front and rear hanger of each wheel. The front shoe (in travel direction) always takes more load compared to the rear one. This asymmetry is found with all of the three brake shoe types, see figure 6 and 7 for examples. More examples are found in Appendix B.

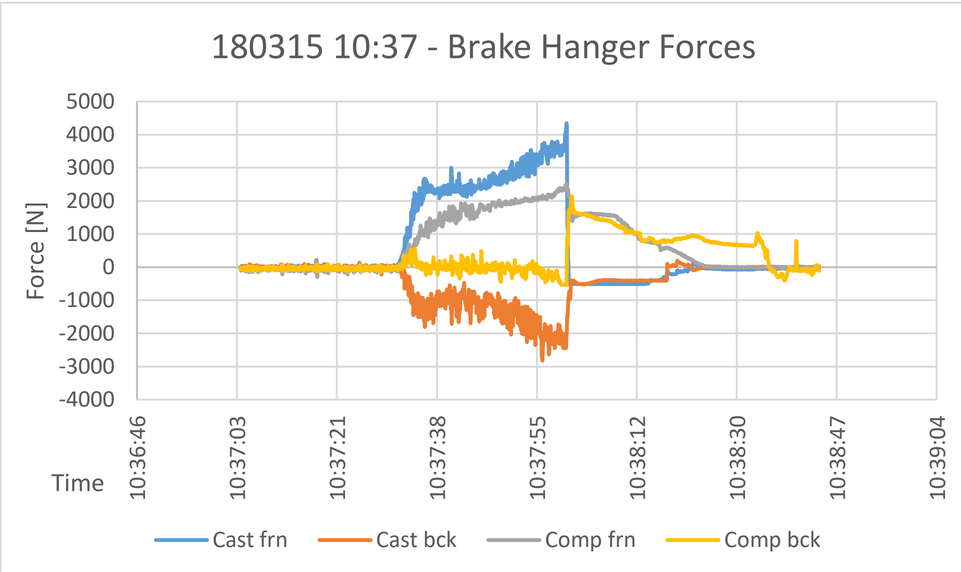


Figure 6: Example of forces in hangers when braking from 70 km/h to 0 km/h using 1,0 bar brake pressure reduction. Train travels forward with wagon3 ahead of wagon4. Negative forces mean compression. The composite brake shoe in front of wheel gives about 70% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 20% of the force given by the cast iron brake shoe. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

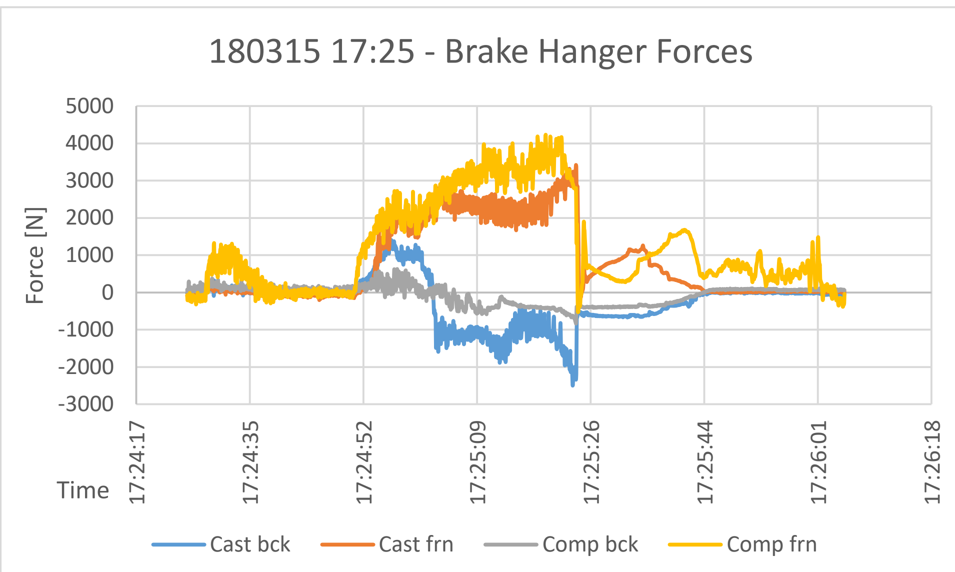


Figure 7: Example of forces in hangers when braking from 75 km/h to 0 km/h using 1,0 bar brake pressure reduction. Train travels backward with wagon4 ahead of wagon3. Negative forces mean compression. The composite brake shoe in front of wheel gives about 70% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 30-50% of the force given by the cast iron brake shoe. It takes about 10s of braking before rear shoes are clean enough to add braking

torque. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

After evaluation of a lot of possible theories, we can still not fully explain the unbalance. Ideas have included effects from hanger angles relative to the wheel and effects from snow lubricating the rear shoe, but they have not been confirmed. As it happens in any weather condition, we cannot find any relation to ice or snow build-up. We therefor skip it from further consideration and summarize both hanger forces (including sign) to give a total wheel brake force.

Next question came when we realized that also the total forces for same type of shoe differ depending on travel direction, se figure 8.

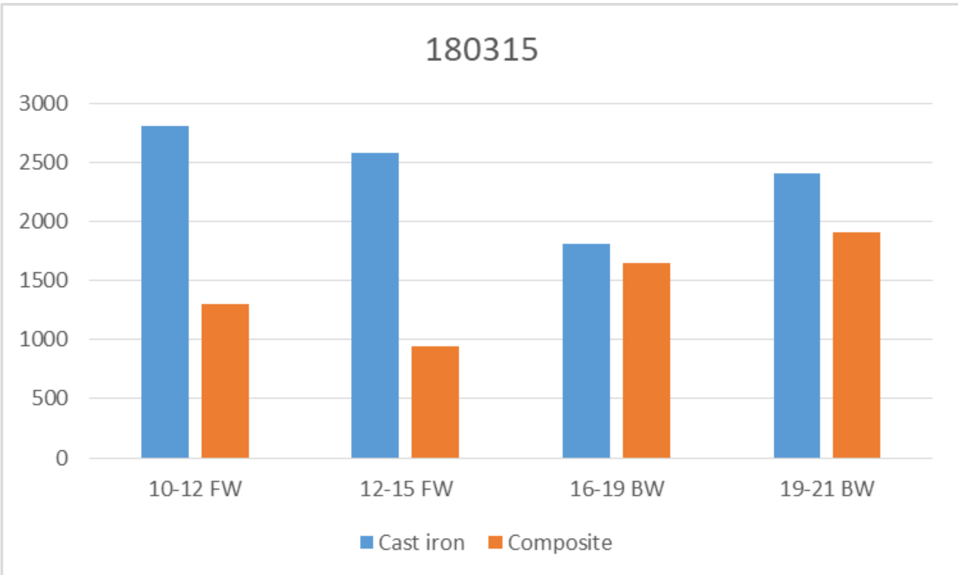


Figure 8: This is a bar diagram showing the mean values of brake forces during test day 180315. Mean values are based on only first 10 seconds of each brake event. X-axis indicates time of day for each tour and travel direction forward (FW) or backward (BW). Y-axis shows forces in [N]. When the cast iron shoes are placed in trailing position (travel direction BW), the actual brake forces goes down while composite shoes are now in front and increase their force.

The data in Figure 8 shows only one day of tests and only the first seconds of each brake events but the information seems important. Therefore we extended the calculation to all test days. After excluding the dates 180413-180414 as described earlier and also exclude brake events where trains comes to a complete stop, the result is as presented in Table 3. Data titled "Mean of mean forces" describes mean values for every brake event (full cycle) that are the mean values calculated across all brake events. The other block titled "Mean of max forces" presents maximum readings from each event that are mean value calculated across all brake events. The last data block titled "Max of max forces" is simply the max values found among all brake events. Please observe that we have excluded some brake events leading to complete stop as the cast iron brake shoes then generate a short peak value at end of event due to static friction and that value is not relevant to add as maximum for the braking event.

Table 3: Data from all brake events except those who ends in a total stop which add unwanted static friction readings for cast iron shoes. Data is splitted based on travel direction. Values presented in unit [N].

Forces measured at all brake pressures, splitted on travel direction

Tour	Direction	Mean of Mean Forces		Mean of Max Forces [N		Max of Max Forces		# of
		Cast iron	Comp.	Cast iron	Comp.	Cast iron	Comp.	events
All	FW	2310	1219	3642	1737	7513	5207	96
All	BW	1524	1492	2290	1978	4701	4329	96

Table 4: Same data as table 3 but now also splitted on different tours with different shoe types. Values presented in unit [N].

Forces measured at all brake pressures, splitted on shoe type and travel direction

Tour	Direction	Mean of Mean Forces		Mean of Max Forces [N		Max of Max Forces		# of
		Cast iron	Comp.	Cast iron	Comp.	Cast iron	Comp.	events
IB116	FW	2307	1226	3795	1779	7513	5207	70
IB116	BW	1656	1629	2531	2180	4701	4329	60
C952-1	FW	2318	1202	3230	1625	4995	2712	26
C952-1	BW	1250	1288	1816	1668	3361	3173	32

Table 5: Data from brake events where brake pressure was noted to be 1,0 bar. Some events have been excluded where train comes to full stop. Values presented in unit [N].

Forces measured at brake pressure=1,0 bar

Tour	Direction	Mean of Mean Forces		Mean of Max Forces [N		Max of Max Forces		# of
		Cast iron	Comp.	Cast iron	Comp.	Cast iron	Comp.	events
IB116	FW	3188	1658	4627	2309	5569	3254	19
IB116	BW	1849	2175	2945	2927	4060	3648	14
C952-1	FW	3048	1766	4510	2360	4995	2637	3
C952-1	BW	1732	1616	2932	2193	3361	2613	5

It is obvious that the cast iron shoes perform better when train is running forward and the shoe is in front of the coupling compared to be mounted in trailing position when train is running backwards. The latter case gives a drop to 55% of values for training running forward. For the composite shoes we have much less data with only 5 brake events in each direction with brake pressure 1,0 bar. The differences are within +/-26% where IB 116 gives higher values in leading position and C952 gives higher values in trailing position. The standard deviation is between 270-530N for these small data sets so the spread is not statistically reliable to be a proof of direction dependence but we can see that composite shoes are less sensitive to travel direction but also give lower forces than cast iron shoes when operated at same pressure.

After thorough investigations, it is obvious that braking shoes made of cast iron are less effective when running on the trailing axle, i.e. after wagon coupler between wagon 3 and wagon 4. Such a conclusion is supported by observations from the test days, telling us that the snow dust become more intense after each gap between wagons, see figure 9. These open flatbed wagons without loaded cargo runs quite smoothly and do not cause so much air turbulence when in motion but at the front and end of each wagon, the end wall, see figure 4, causes turbulent airflow and a lot of snow dust lifted from ground level. That will affect the trailing axle by exposing it to more snow dust and thereby a higher possibility to get water lubrication and/or ice buildup. Realizing such a phenomena made the analysis more complex.

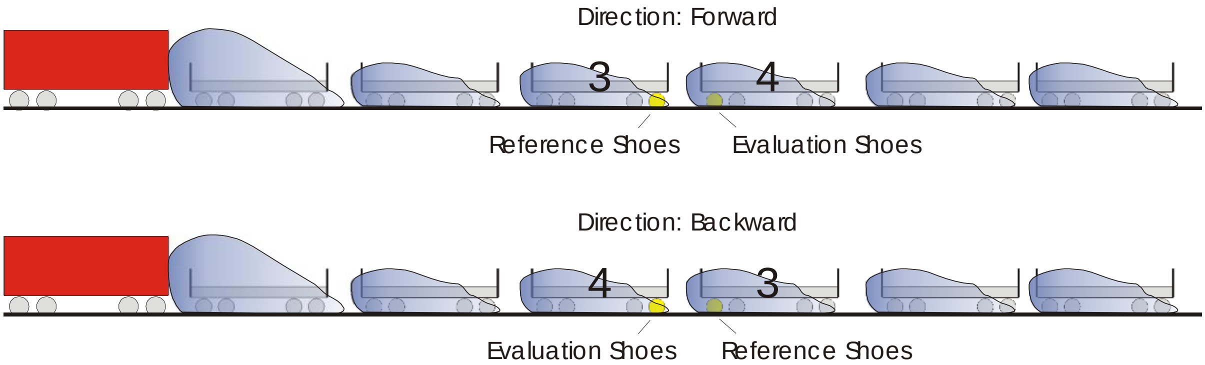


Figure 9: Snow dust fed by turbulent air flow between wagons.

6. Analysis of brake force response time

The effect of position dependency moved our focus from comparing maximum brake force on wagon 3 and wagon 4 in each journey to instead compare same position between different journeys. In appendix D are all tours and all brake events presented with calculated time since last preceding brake event, duration for each individual brake event, delay of brake response if any. The threshold that triggers start of a brake event is when any of the instrumented wheel (with either cast iron or composite shoes) reaches and pass 500N in total brake force and timer stops when both wheel drops below the same threshold. In Figure 10-11 we can see delay times in each travel direction. Both types of brake shoes showed delays of 5-6 seconds when running in trailing position but the composite brake shoes had a few extreme delays over 5 seconds and up to over 30 seconds. These events are listed in Table 6 and also plotted in Figures 12-17. It is obvious that both type of brake shoes have problems to generate brake force at some of the events but it is more often for the composite type. If we look in Table 3 and the "Mean of Max Forces" we can see that when train is running forward, we can expect a ratio around 1:2 between composite and cast iron shoe forces (cast iron running dry) and when running backward (cast iron running wet), a ratio of 1:1,2. Large deviations from these ratios indicate problems.

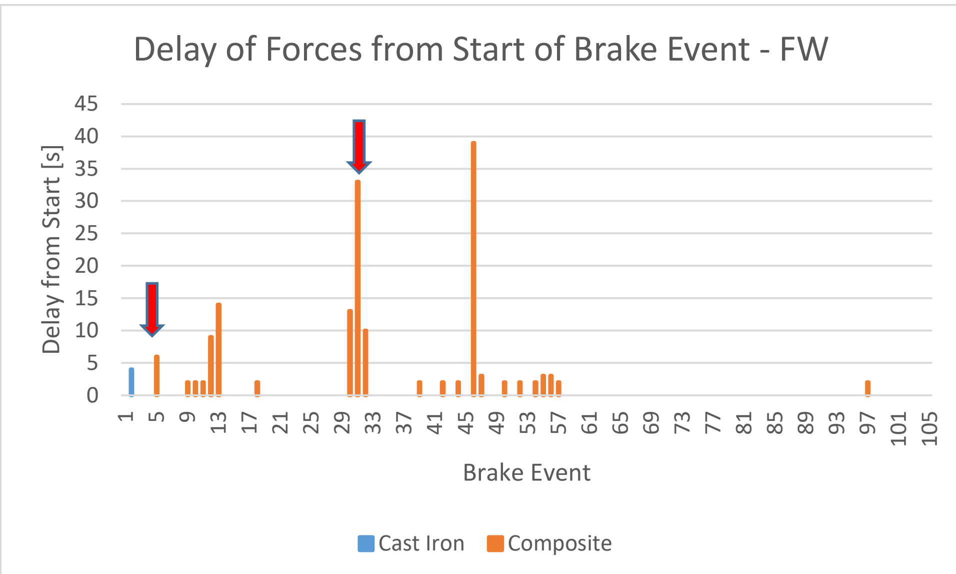


Figure 10: Delay of forces relative to the start of the brake event when going in forward direction. The arrows indicate events which ended without the brake shoes managed to reach the threshold 500N.

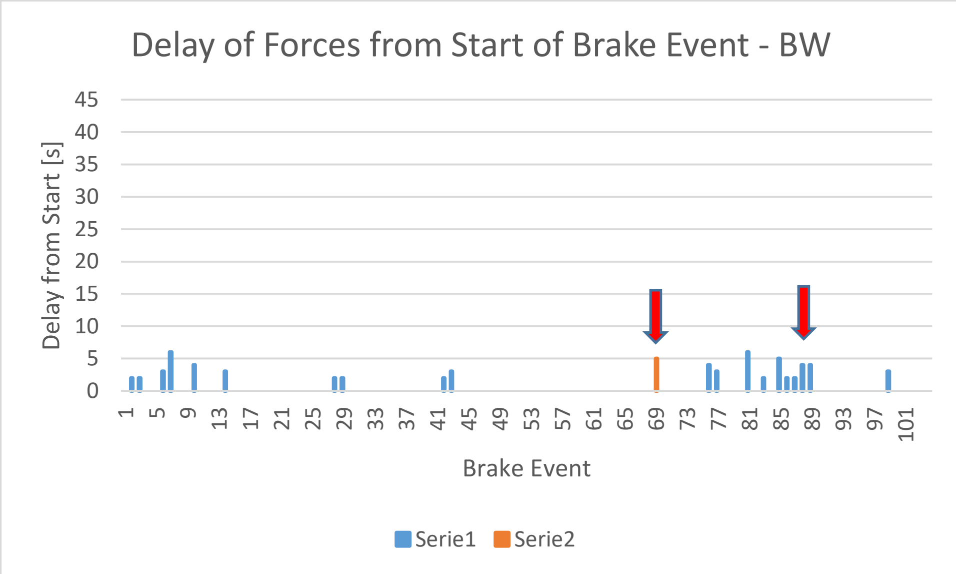


Figure 11: Delay of forces relative to the start of the brake event when going in backward direction. The arrows indicate events which ended without the brake shoes managed to reach the threshold 500N.

Table 6: Parameters for composite as plotted in figure 10.

Index	Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
5	18-03-15	10:12:44	707	6	FW	IB116	0,5	0	6	147	456	1585	477
12	18-03-15	11:36:46	94	37	FW	IB116	1,0	0	9	1070	499	2404	607
13	18-03-15	11:38:16	53	35	FW	IB116	0,5	0	14	801	492	1773	770
30	18-03-15	15:04:27	836	39	FW	IB116	0,8	0	13	2648	494	4264	902
31	18-03-15	15:05:50	43	33	FW	IB116	0,8	0	33	2120	346	2585	443
32	18-03-15	15:06:37	14	25	FW	IB116	0,5	0	10	1465	500	3060	879
46	18-03-16	16:33:14	709	56	FW	IB116	0,8	0	39	1691	462	4583	1270

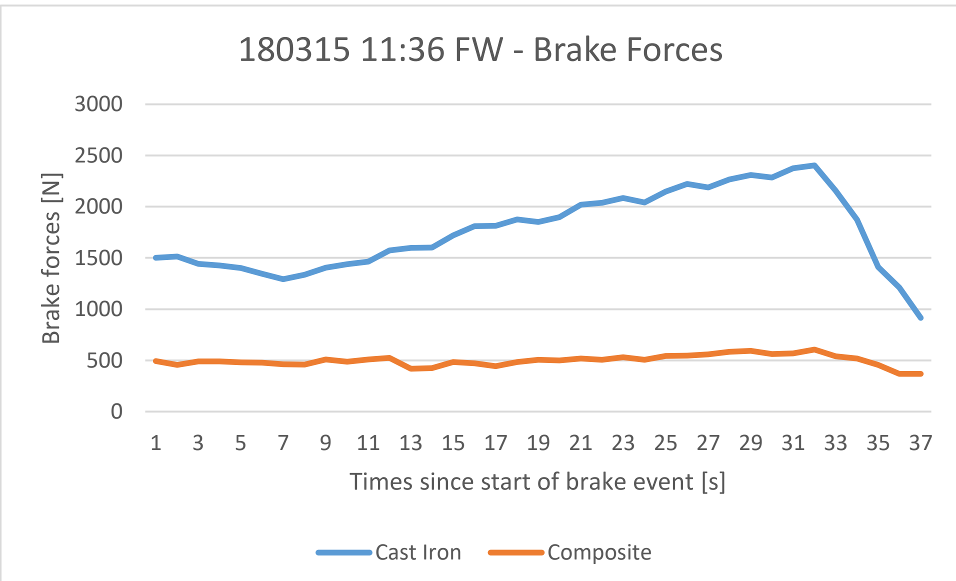


Figure 12: Braking at 1,0 bar pressure. It seems as the cast iron brake force is slowly increasing while the composite brake force is constantly low. At the end, ratio is 1:5 between composite and cast iron. Probable ice build-up on both types of shoes.

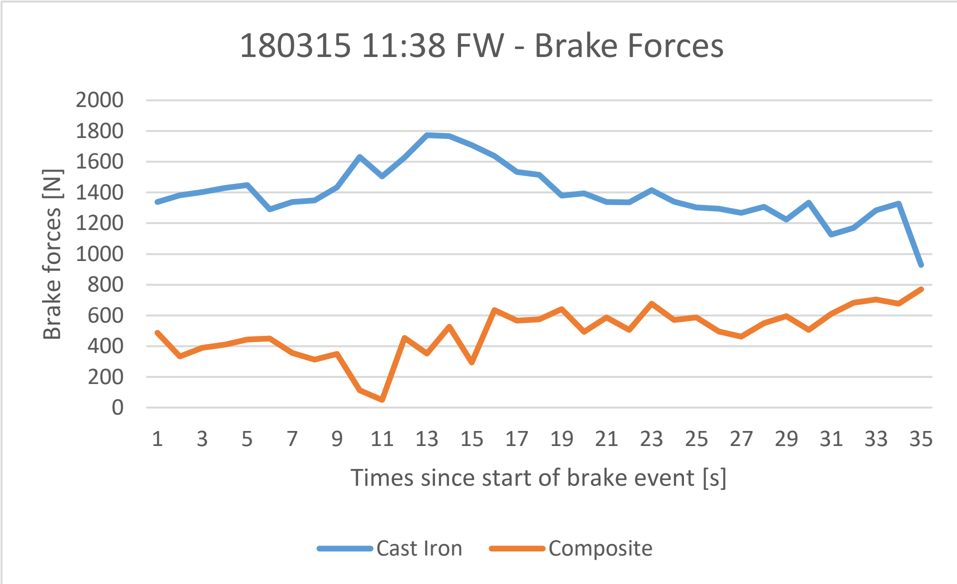


Figure 13: Braking at 0,5 bar pressure. After about 14s the composite block forces starts to slowly increase while cast iron forces decrease. At the end, ratio is 1:1,1 between composite and cast iron. Probable ice build-up on both type of shoes.

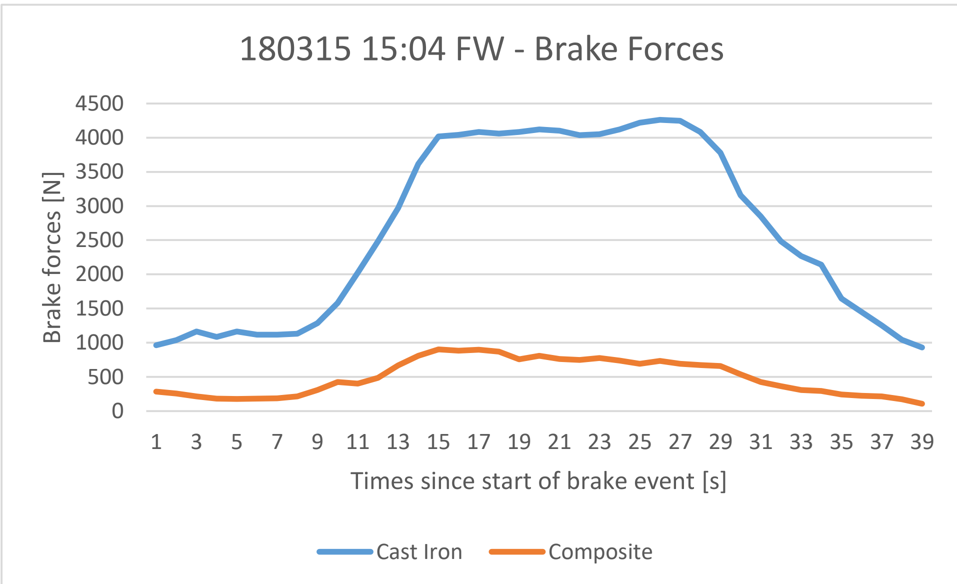


Figure 14: Braking at 0,8 bar pressure. Very low response from composite shoes but better from the cast iron shoes. At the best, ratio is 1:4 between composite and cast iron but about 1:5 at the end. Probable ice build-up on composite shoes.

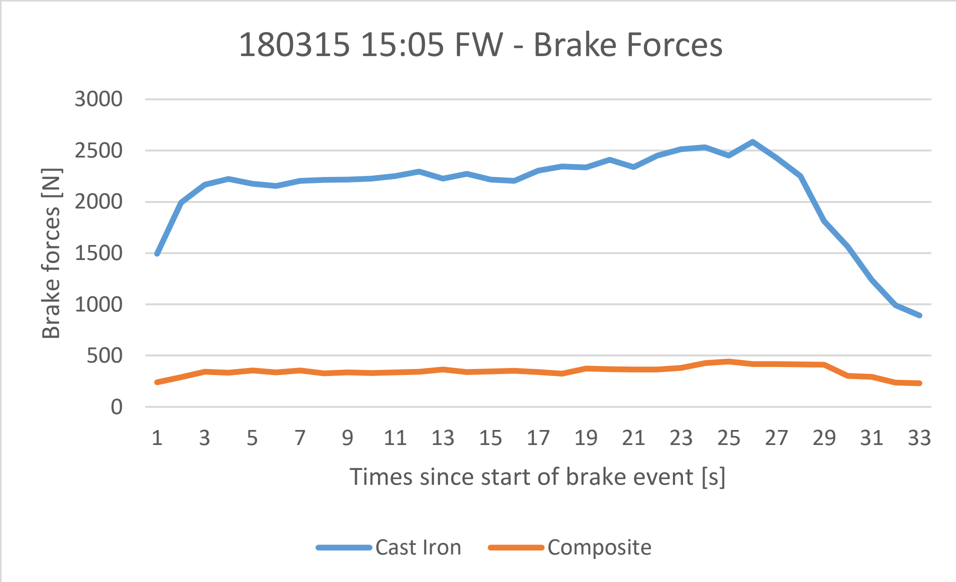


Figure 15: Braking at 0,8 bar pressure. Very low response from composite shoes and not full from cast iron either. At the end, ratio is 1:3 between composite and cast iron. Probable ice build-up on both type of shoes.

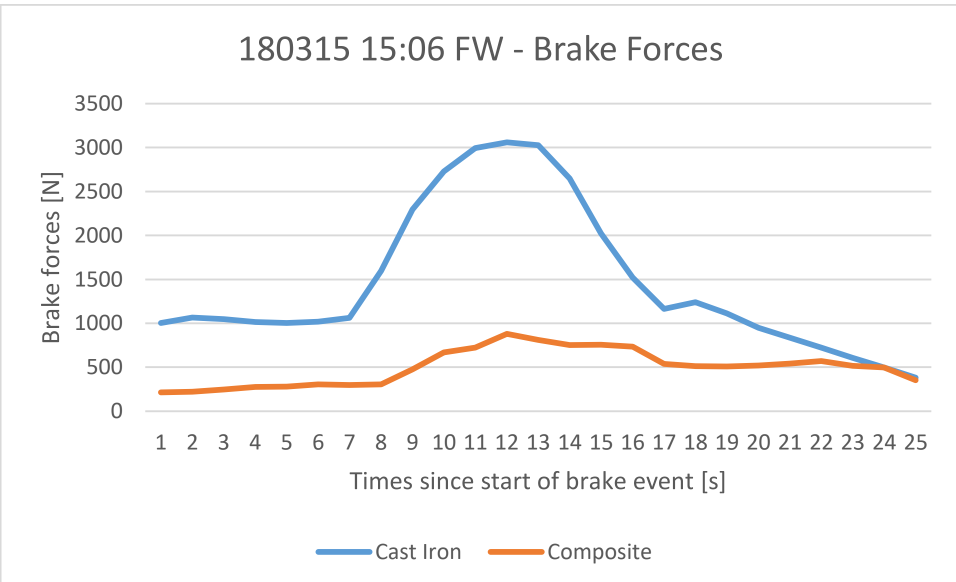


Figure 16: Braking at 0,5 bar pressure. At maximum brake pressure, the ratio is 1:3 between composite and cast iron but about 1:1 at the end. Probable ice build-up on composite shoes.

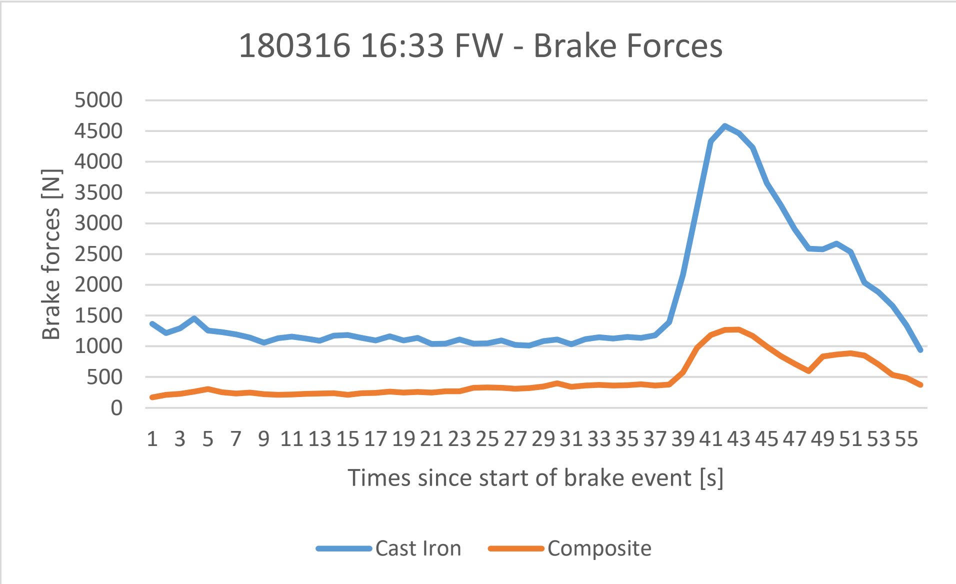


Figure 17: Braking at 0,8 bar pressure. Very low response from both type of shoes composite shoes during first 39s but slowly increasing forces from composite shoes. It is not clear if the brake pressure really was fully applied at the start. At maximum braking force, the ratio is 1:3,5 between composite and cast iron and about 1:2 at the end. Probable ice build-up on composite shoes.

7. Results and comments

7.1 Results

It is commonly known that cast iron brake shoes increase their friction when train speed is decreased while composite brake shoes have the opposite behaviour. In this report we have investigated the performance of different brake shoes in winter conditions (below 0°C and snow) and at different speeds by testing a lot of brake events (192 events) with both cast iron and composite brake shoes. The tests were conducted during a 2 month period 2018. They give good input for an evaluation. Figure 18 shows one of the test wheels after ice build-up.

The test runs have included two types of composite brake blocks. It is the organic type IB116 and the sintered type C952-1 and they have been compared to traditional cast iron shoes on a separate wheel, not changed during the tests. The test train consisted of 6 unloaded freight wagons and was run in speed range 0-100 km/h. The tests included several changes of travel direction which gave an obvious change in brake shoe behaviour. The reason to this variation is assumed to be caused by altered aerodynamics around each wheel and thereby changes in how the wheels are exposures to snow dust, see section 5.

When discussing performance of the two types of brake shoes, we can start with Table4 in this report and compare brake forces. In this context, brake forces are the total circumferential forces on each wheel generated by the pair of brake shoes and the forces must, according to equilibrium equations and when skipping momentum of inertia on wheels, equal applied circumferential force from the rail to the wheel. From Table4 we can see that:

1. Cast iron shoes can vary about a factor of 2,0 in friction factor (μ). We assume this is due to variations going from dry to wet conditions when lubricated by water or melted snow.
2. Both type of composite brake shoes seems to be quite unaffected by the amount of water lubrication. They generate about the same forces in both travel directions and the forces are close to those found from cast iron shoes when running in wet environment.
3. Both cast iron and composite shoes can have a delay in force generation when running in assumed icy weather. They slowly increase their output. By calculating with a threshold level of 500N in sum of forces from the brake shoes on each wheel, the delay could reach 5-6 seconds for cast iron shoes. For composite shoes we encountered 7 events showing delays from 6-39 seconds, see Table 6. This is a potential risk if it happens to the major part of the brake shoes in a train at the same time, but we have not investigated if it can be compensated by heavier brake pressure drop. A short travel time since last brake event should also be a possible factor that reduces or eliminates the problem but it cannot be verified in our tests. If there is a relation, it is probable that it is governed by accumulated brake energy generation over time (controlling brake shoe and wheel temperature) rather than time between brake events. The problem with delays in brake force generation could in our test occur after less than one minute travel since last brake event.

Our hypothesis from the tests is that the lower thermal conductivity of the composite brake shoes makes them go much colder than the corresponding cast iron type of shoe. That will lead to a lack of de-icing capability and an unwanted ice build-up on and around the shoe. The problem is not present in all winter conditions as many factors are involved. One example of a specific situation is when the wheel, due to braking, has a temperature above freezing point while air, and brake shoes have a temperature below freezing point. That fact combined with heavy snow dust from the ground will rapidly cover the brake shoes with a layer of ice. In figure 25 is a photo showing how the situation can look like.

Figure 18: Photo of ice build-up on trailing brake shoe. The vehicle has been running in right direction before photo is taken.

Based on the complexity of the problem, it is very difficult to give any general number on how much the braking power will be reduced. In this report we present the most severe case happened at date 18-03-15 and at hour 15:05, see Table 6. The mean brake force from the cast iron braked wheel was 2120N while the composite braked wheel showed 346N, or just 16% of the cast iron braked wheel. As we have described, the normal friction ratio between (dry) cast iron brake shoes ahead of coupling and trailing wheels with composite brake shoes has been 1:2 (= 50%) during the tests. That means we had an actual drop in performance of 16%/50%= 33% for that specific case, lasting 33 seconds.

The result of this test project is, without doubt, a clear indication of possible loss in brake efficiency when using composite brake shoes instead of cast iron shoes in winter conditions.

7.2 Comments on the test setup

The method of applying strain gauge sensors to brake shoe hangers is powerful for this kind of tests if the implementation is thoroughly done, included good sealing and cable clamping, to avoid sensor losses. The advantages are e.g.:

1. Easy validation of measured values if sensors are applied to brake shoes that are commonly used in the train and the retardation and total train weight is known.
2. Individual brake shoes can be evaluated and actual friction factors for them can be calculated on axle level.
3. Variations of brake performance between axles in same vehicle can be studied

As information for future projects regarding railway brakes with friction material, the tests can be much more detailed if one add some more measured parameters to the test setup. Such parameters are:

1. Brake pressure and train speed should be measured online by the monitoring system.
2. Temperature of ambient air, the brake shoes and the wheel surfaces should be valuable to measure as well.
3. One or more cameras should be mounted close to each test wheel for ocular and real time recording of the brake shoe operation and related ice build-up.
4. A small non-contact displacement sensors between brake shoes and wheel should be valuable when examining thickness of possible ice layers on brake shoes and how they are removed by the applied brake.
5. Tests should include both loaded and unloaded wagons and also different wagon designs. That if the aerodynamics around a wagon end affects the amount of snow dust
6. Tests should include measurement on different axle positions in a vehicle as that also affects the snow dust density and the potential risk of ice build-up.

By adding any or all of these extra parameters it would be possible to make a more detailed analysis of the brake shoe performance related to winter conditions

Appendix A – Notes from each test tour

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
2018-03-14	1	14:30	Östersund- Hoting- Forsmo	-13	0	70	1.0		
	2	15:44:30			0	70	1.0	20	
	3	15:47:40			10	80	1.3	0	
	4	15:50:40			10	80	1.0	40	
	5	15:53:40			0	70	0.8	40	
	6	16:09:40			10	80	0.9	30	
	7	16:24:40			0	70 40	0.8 0.6	40 0	
	8	16:50:00			10	65	1.0	5	
	9	?	?	?	?	?	?	?	
	10	18:22:23			10	75	1.0	40	
	11	18:31:23			9	70	1.0	70	
	12	18:40:23				75	1.2	40	
	13								
	14	?			10	75	0.7	50	
	15	19:40			5	70	0.8	20	
2018-03-14	1	19:49	Forsmo- Långsele	-9	0	70	0.5	50	
	2	19:52				40	0.6	0	
	3	20:12				35	0.1	0	
2018-03-15	1	09:44:48	Långsele- Forsmo- Hoting	-14	0	70	1.0	40	
	2	09:49:58			0	75	0.7	50	
	3	09:53:18			10	75	1.0	40	
	4	09:59:58			10	75	0.7	50	
	5	10:11:58			7	75	0.5	65	
	6	10:21:58			7	75	0.5	65	
	7	10:27:58		-13	0	75	1.2	0	Snow dust- Medium
	8	10:33:58				50	0.5	30	
	9	10:40				70	1.0	0	
	10	10:49			10	80	1.0	0	
	11	10:59			7	80	1.5	40	
	12	11:19			0	75	1.2	0	
	13	11:35			0	70	1.0	5	
	14	11:37			0	40	0.5	20 --> 0	

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
2018-03-15	1	12:49	Hoting- Östersund	-8	8	75	1.0	40	Snow dust- Little
	2	13:05			0	75	1.0	20	
	3	13:09			9	75	0.9	30	
	4	13:14			9	75	0.6	50	
	5	13:18			0	55	1.0	40	
	6	13:25			7	75	0.1	40	
	7	13:41			0	77	0.8	40	Snow dust- Little
	8	13:48			0	75	0.6	50	
	9	14:12			6	70	0.6	40	
	10	14:17			7	75	1.1	30	
	11	14:18			7	75	1.5	10	
	12	14:25			8	75	0.7	50	
	13	14:31			8	75	1.2	0	Snow dust- Little
	14	14:36			8	80	0.6	60	
	15	14:39			7	70	1.0	20	
	16	14:42			10	80	0.6	55	
	17	14:50			0	80	0.9	40	
	18	15:05			7	70	0.8	30	
	19	15:06			0	30	0.5	0	Snow dust- Little
	1	16:34	Östersund- Hoting- Forsmo	-6	7	80	0.6	50	Snow dust- Little
	2	16:43			0	65	0.8	30	
	3	16:50			0	80	1.1	0	
	4	17:01			0	70	0.8	20	
	5	17:14			0	60	1.0	10	
	6	17:25			10	75	1.0	0	
	7	17:29			8	85	1.4	0	
	8	17:32			10	80	0.8	20	
	9	17:55			0	80	1.0	20	
	10	18:06			0	40	0.6	0	
	11	18:27			0	80	1.0	30	
	12	18:38			0	80	0.7	50	
	13	18:43	Hoting	-14	7	75	1.5	20	Snow dust - Little
	1	19:41	Hoting- Forsmo		0	70	1.0	0	
	2	19:59			10	75	1.0	30	
	3	20:10			0	75	1.0	20	
	4	20:38			5	75	1.0	0	
	5	20:51			10	75	1.0	30	
	6	21:06			10	75	0.8	40	
	7	21:20	Forsmo- Långsele	-14	7	70	0.6	40	
	8	21:26			5	90	0.7	70	
	9	21:32			0	100	1.1	0	

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
2018-03-16	1	08:57	Långsele- Bräcke	-18	7	100	1.0	30	Snow dust- Little
	2	09:05			0	100	1.1	0	
	3	09:14			0	90	0.7	40	
	4	09:16			0	30	0.5	0	
	5	09:45	?	?	?	?	?	?	Blocks stuck by ice
	6	09:59			10	100	0.8	40	
	7	10:09			7 Uppför	65	0.9	20	
	8	10:12			0	40	0.5	0	
	9	10:29			0	95	0.9	30	
	10	10:38			0	85	0.9	20	
	11	10:40			0	40	1.0	0	
	12	11:01			10	100	1.0	20	
	13	11:08		-13	7	100	1.0	70	
	14	11:20			0	90	0.6	40	
	15	11:22			0	40	0.5	0	
	1	12:53	Bräcke- Östersund	-9	0	100	1.0	20	Snow dust- Medium
	2	13:00			0	100	0.8	70	
	3	13:06			0	95	0.6	75	
	4	13:09			9	100	1.0	60	
	5	13:33			8	85	0.8	40	
	6	13:35			0	40	1.1	0	Temp: Cast -0.4frn -3,2bck/Comp -6frn -9,4bck
	1	15:06	Östersund- Hoting	-8	10	80	1.0	40	Snow dust- Little
	2	15:14			7	70	0.8	40	
	3	15:39			8	75	1.5	30	Elk run over
	4	15:59			0	85	1.0	40	
	5	16:01			7	80	0.6	60	
	6	16:17			7	75	1.0	0	
	7	16:22			9	75	1.0	40	
	8	16:34			7	70	0.8	20	
	9	16:54			7	80	1.0	20	
	10	17:19			8	70	1.5	0	
	11	17:29			0	45	0.8	0	
	1	18:36	Hoting- Forsmo	-12	10	75	0.6	50	
	2	18:51			10	75	1.0	20	
	3	19:04			0	70	1.0	40	
	4	19:10			7	70	0.8	20	
	5	19:16			0	45	0.6	20	
	6	19:49			10	75	1.0	40	
	7	20:01			7	80	0.6	50	
	8	20:07			0	80	1.0	30	
	9	20:17			8	80	1.5	20	
	10	20:19			8	30	0.5	0	

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
	1	20:23	Forsmo- Långsele	-14	0	40	0.7	0	
	2	20:58			0	75	0.6	40 kmr	
	3	21:02			0	30	0.8	0	
	4	10:25			0	100	1.0	60	
	5	10:27			0	90	0.6	80	
2018-03-17	1	08:44	Långsele- Bräcke	-18	8	100	0.8	80	Snow dust- Little
	2	08:51			0	100	1.0	40	
	3	08:53			0	40	0.8	0	
	4	09:05			0	100	1.0	20	
	5	09:12			10	100	1.0	20	
	6	09:15			0	40	0.5	0	
	7	11:00			6	100	1.0	50	
	8	11:08			10	100	0.9	60	
	9	11:14			0	100	1.0	40	
	10	11:17			0	40	0.7	0	
	11	11:28			0	100	1.0	0	
	12	11:29			0	40	0.6	0	
	13	11:40			0	40	0.9	0	
	1	12:49	Bräcke- Östersund	-11	0	100	1.0	70	Snow dust- Little/Medium
	2	12:52			0	100	1.0	40	
	3	12:55			0	40	0.7	0	
	4	13:10			0	100	0.9	70	
	5	13:13			0	100	0.9	70	
	6	13:20			0	95	0.8	80	
	7	13:22			9	95	0.8	80	
	8	13:34			0	100	1.0	60	
	9	13:44			0	100	1.0	40	
	10	13:46			0	60	0.6	40	

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
	1	14:06	Östersund- Hoting		0	80	0.6	60	Snow dust- Little
	2	14:08			0	70	0.8	40	
	3	14:15			6	70	1.0	0	
	4	14:18			0	70	0.8	40	
	5	14:23			0	75	1.0	20	
	6	14:37			0	80	0.8	60	
	7	14:47			0	75	0.6	40	Snow dust- Little
	8	14:52			0	80	0.9	40	
	9	15:01			7	80	0.8	40	
	10	15:04			0	80	0.6	40	
	11	15:13			0	80	0.6	50	
	12	15:20			10	80	0.6	60	
	13	15:21			7	60	0.5	40	
	14	15:24			7	80	0.6	60	
	15	15:26			0	75	0.8	50	
	16	15:31			10	75	0.8	40	
	17	15:36			0	70	0.6	30	
	18	15:37			0	30	0.8	0	
	19	15:48			10	80	0.7	50	
	20	15:57			0	80	0.8	50	
	21	15:59			0	70	0.5	35	
	22	16:06			9	80	0.6	50	
	23	16:28			0	60	0.6	40	
	24	16:31			0	40	0.6	0	
	1	17:54	Hoting- Forsmo	-2	10	80	0.7	50	Loco failure at Betåsen
2018-03-25	1	15:05	Östersund- Hoting	-2	0	75	1.0	20	Snow dust-Heavy// Sinter blocks
	2	15:09			0	80	0.6	50	
	3	15:13			10	80	1.0	20	
	4	15:17			0	65	0.8	30	
	5	15:23			7	70	0.6	50	
	6	15:40			0	75	0.8	0	
	7	15:56			3	70	0.9	40	
	8	16:01			0	80	0.9	0	
	9	16:09			7	85	0.5	60	
	10	16:13			0	80	0.7	40	
	11	16:30			7	80	0.6	60	
	12	16:45			0	75	0.7	30	
	13	16:46			0	15	1.5	0	
	14	17:14			0	75	0.9	20	
	15	17:15			0	20	0.8	0	
	16	17:42			0	40	1.0	0	

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
	1	18:48	Hoting- Långsele	-7	7	70	0.7	40	Snow dust-Medium/Heavy
	2	18:59			7	75	0.7	0	
	3	19:07			10	70	0.6	40	
	4	19:17			7	75	1.0	50	
	5	19:44			7	75	1.0	20	
	6	19:57			10	75	0.6	40	
	7	20:03			10	75	1.0	0	Elk in track
	8	20:09			10	75	0.5	60	
	9	20:25			10	75	0.8	30	
	10	20:32			0	85	0.5	60	Snow dust- Little
	11	20:39			0	65	0.8	40	Snow dust- None
	12	20:43			0	30	0.8	0	
2018-03-26	1	09:11	Långsele- Bräcke	-11	8	100	0.9	60	
	2	09:19			7	100	0.7	70	
	3	09:25			0	100	0.9	70	
	4	09:31			10	100	1.0	50	
	5	09:51			0	100	1.1	50	Snow dust- Medium
	6	09:59			7	100	0.6	70	Snow dust- Medium
	7	10:04			0	90	0.7	60	
	8	10:05			0	60	0.6	40	
	9	10:06			0	30	0.5	0	Snow dust- None
	1	12:39	Bräcke- Östersund	-6	0	100	0.8	70	Snow dust- Medium
	2	12:44			0	80	0.8	0	
	3	13:09			0	100	0.8	80	
	4	13:16			10	100	0.5	80	
	5	13:22			0	80	1.0	20	
	6	14:05			0	100	1.0	60	Snow dust- None
	7	14:18			7	70	0.5	40	
	1	14:53	Östersund- Hoting	-4	0	80	0.8	50	Snow dust- Medium
	2	15:00			10	75	0.6	60	
	3	15:03			7	70	0.6	40	
	4	15:11			7	60	0.7	30	
	5	15:21			10	80	0.7	60	
	6	15:49			0	65	0.5	50	
	7	15:57			10	75	0.6	50	
	8	16:00			0	80	1.0	25	
	9	16:04			0	80	1.0	60	
	10	16:22			7	70	0.5	60	
	11	16:35			7	80	1.0	30	
	12	16:54			7	70	0.4	65	
	13	17:00			10	75	0.5	60	
	14	17:22			7	65	0.5	55	
	15	17:35			0	40	0.7	0	

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
	1	18:45	Hoting- Långsele	-4	8	75	0.5	60	
	2	18:48			7	70	0.5	50	
	3	19:16			10	75	0.7	60	
	4	19:27			10	75	0.5	65	Snow dust- None
	5	19:33			10	75	0.7	55	Snow dust- None
	6	19:44			7	75	0.5	60	Snow dust- None
	7	19:52			7	75	0.8	30	Snow dust- None
	8	19:57			10	75	0.7	50	
	9	20:05			8	75	0.7	45	
	10	20:13			9	75	0.7	60	Snow dust- None
	11	20:16			9	75	0.5	65	Snow dust- None
	12	20:18			9	75	0.5	50	
	13	20:34		-8	0	70	0.8	25	Forsmo
	14	20:35			0	35	0.5	10	Forsmo
	15	20:36			0	10	0.6	0	Forsmo
	16	20:53			0	50	0.5	20	Forsmo
	17	20:54			0	25	0.5	0	Forsmo
2018-03-27	1	09:45	Forsmo- Hoting	-12	10	75	0.6	60	
	2	09:49			10	75	0.4	65	
	3	09:55			10	75	0.6	55	
	4	10:27			0	75	0.6	40	
	5	10:45			10	75	0.5	60	
	6	11:28			0	50	0.5	40	
	7	11:30			0	40	1.0	0	
	1	13:25	Hoting- Östersund	-2	7	60	0.6	45	
	2	13:34			8	65	0.5	50	
	3	13:41			0	50	0.5	30	
2018-03-28	1	12:08	Östersund- Duved	-7	0	100	1.0	40	
	2	12:26			0	100	1.0	60	
	3	12:35			0	100	?	50	
	4	13:05			0	95	0.8	10	
	5	13:43			0	70	1.0	0	
	1	14:50	Duved- Östersund	-2	0	70	1.0	50	Snow dust- Little

Date	Test #	Time	Position/line	Temp [°]	Incl. [‰]	Init speed [km/h]	Brake pressure [bar]	Post speed [km/h]	Comment
2018-04-13	1	13:04	Kopparåsen- Kiruna	?	?	70	0.1	40	
	2	?			0	70	0.6	40	
	3	?			0	40	0.6	0	
	4	13:31			0	70	1.0	20	
	5	13:35			0	75	1.1	20	
	6	13:38			0	75	0.9	50	
	7	13:39			0	50	0.6	20	Snow dust- Little
	8	13:42			0	20	0.6	5	
	9	13:47			0	65	0.7	35	
	10	13:57			0	45	1.0	15	
	11	14:00			0	60	0.7	35	Snow dust- None
	12	14:09			7	90	0.9	60	
	13	14:34			0	90	0.9	70	
	14	14:43			0	75	1.0	40	
	15	15:00			10	80	0.6	55	
	16	15:01			0	55	0.9	20	
2018-04-14	1	09:03	Kiruna- Boden		0	80	1.2	45	Snow dust- None
	2	09:05			0	80	0.9	40	
	3	09:07			0	40	0.6	10	
	4	09:08			0	10	0.6	0	
	5	09:23			0	70	0.6	40	
	6	09:25			0	40	0.8	0	
	7	10:21			10	95	0.5	90	

Appendix B – Examples of brake events

In this Appendix we present examples of brake events that are randomly selected from the data files. The diagrams show forces from both hangers on each wheel. One wheel has the reference brake shoes made of cast iron and the other wheel has either organic or sinter composite 20shoes.

B1 Data from tours with IB116 organic composite brake shoes

In this section are diagrams of hanger forces when using organic composite brake shoes. Hangers in front of each wheel (ahead of wheel seen in travel direction) will always sense a traction load while hangers behind the wheel will sense a compression load. Six brake events is presented in figure 6-11. Depending on the snow and ice build-up, the forces will vary a lot. In the diagrams, the abbreviations "Cast frn" means Cast iron – front position and "Cast bck" means Cast iron – back position. In same manner, "Comp frn", "Comp bck" means composite in each position. Front and back always refer to the travel direction, not the wagon number nor wagon A/B end.

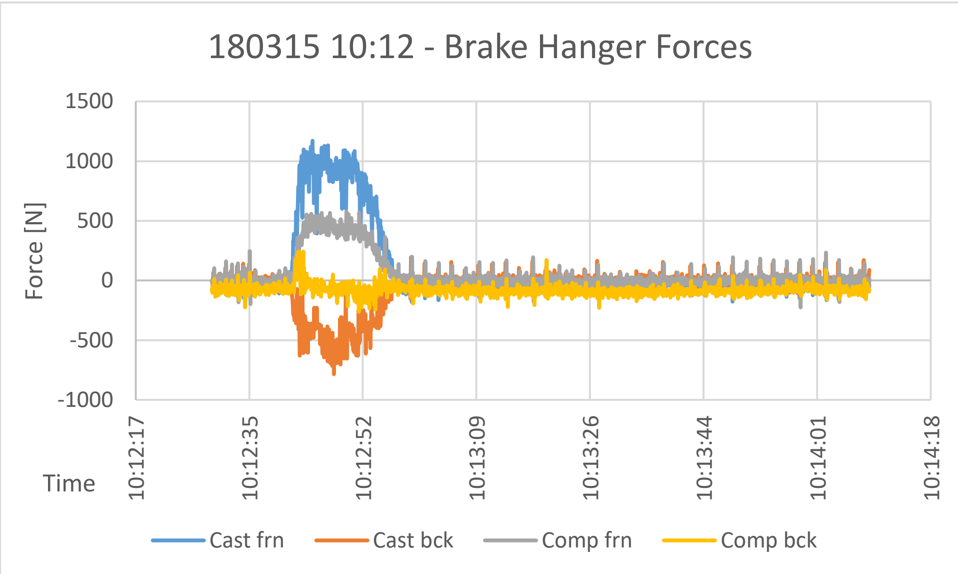


Figure B1 Forces in hangers when braking from 75 km/h to 65 km/h using 0,5 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 50% of the braking forces given by the cast iron type. The brake shoe behind wheel give nearly no contribution to braking. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

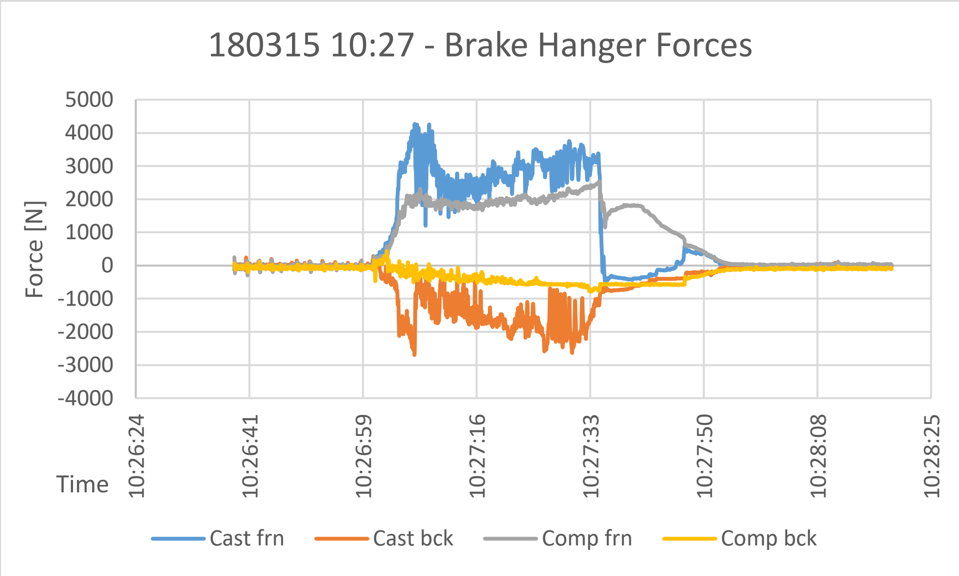


Figure B2: Forces in hangers when braking from 75 km/h to 0 km/h using 1,2 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 70% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 30% of the force given by the cast iron brake shoe. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

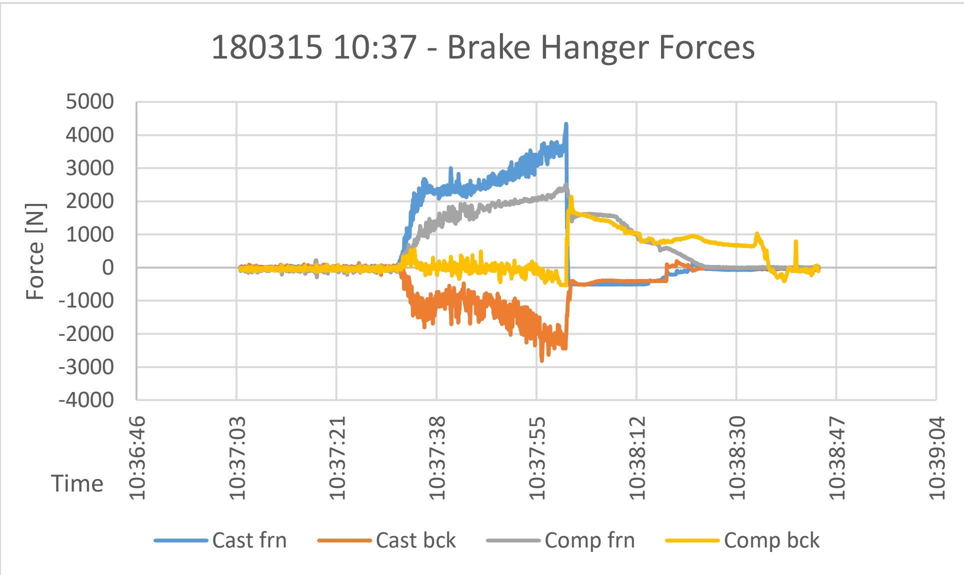


Figure B3: Forces in hangers when braking from 70 km/h to 0 km/h using 1,0 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 70% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 20% of the force given by the cast iron brake shoe. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

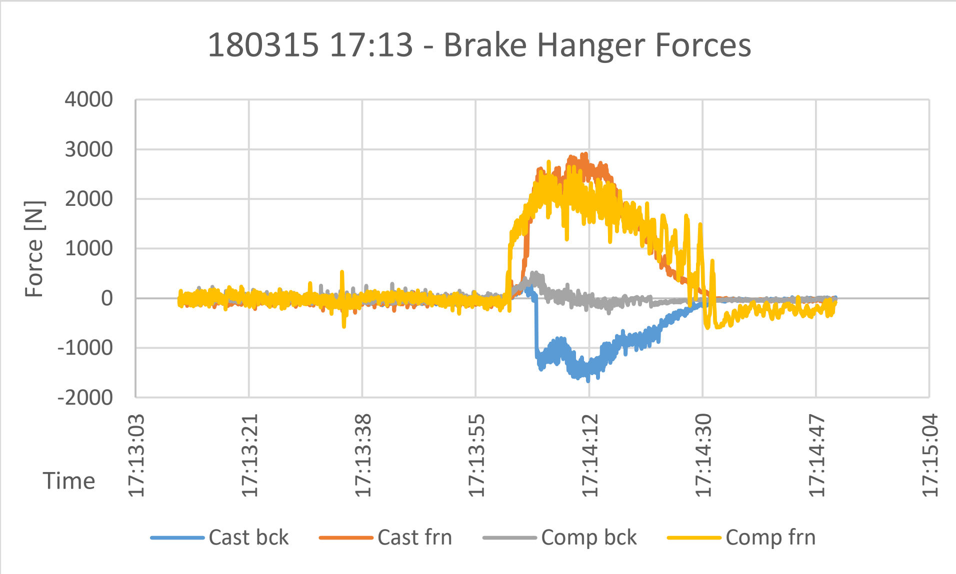


Figure B4: Forces in hangers when braking from 60 km/h to 10 km/h using 1,0 bar brake pressure reduction. The composite brake shoe in front of wheel now gives about same braking forces as the cast iron type. On the contrary, the composite brake shoe behind wheel give nearly no contribution to the braking process. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

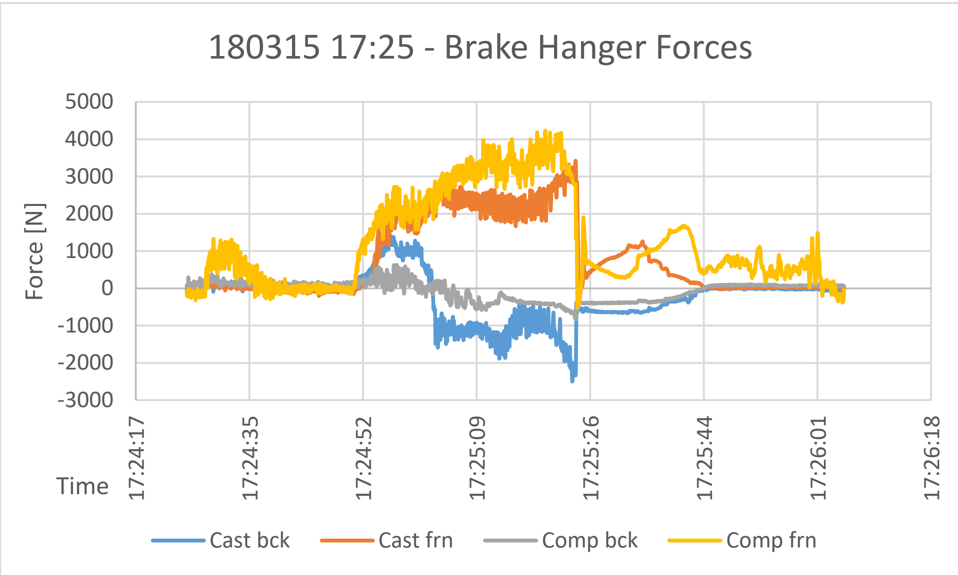


Figure B5 Forces in hangers when braking from 75 km/h to 0 km/h using 1,0 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 70% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 30-50% of the force given by the cast iron brake shoe. It takes about 10s of braking before rear shoes are clean enough to add braking torque. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

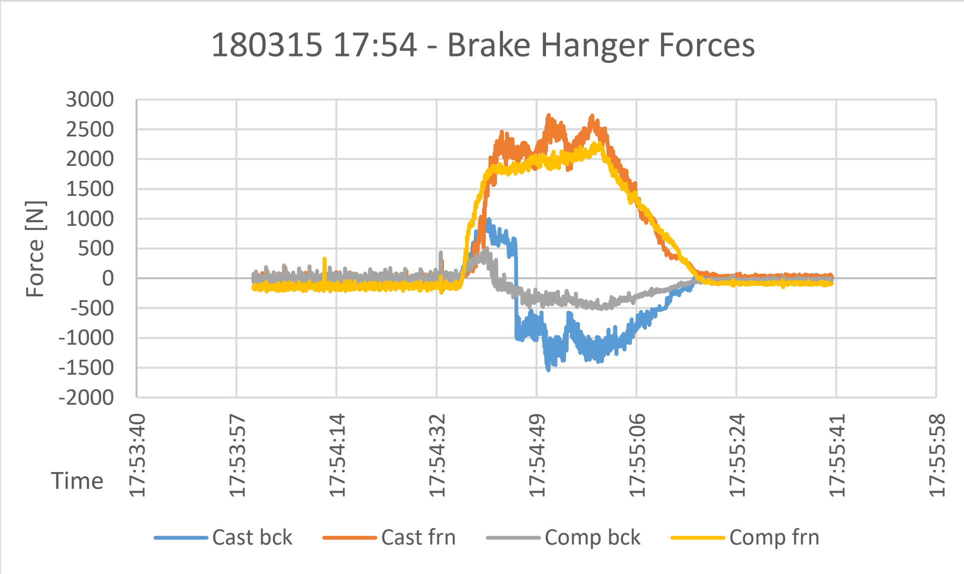


Figure B6: Forces in hangers when braking from 80 km/h to 20 km/h using 1,0 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 80% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 50% of the force given by the cast iron brake shoe. It takes about 5s of braking before rear shoes are clean enough to add braking torque. There is an obvious difference between front and rear brake shoe performance where the front brake shoe always give higher readings. This apply also for cast iron type shoes.

B2. Data from tours with C952-1 sintered composite brake shoes

In this section are diagrams of hanger forces when using sintered composite brake shoes. Hangers in front of each wheel (ahead of wheel seen in travel direction) will always sense a traction load while hangers behind the wheel will sense a compression load. Nine brake events is presented in figure 12-20. Depending on the snow and ice build-up, the forces will vary a lot. In the diagrams, the abbreviations “Cast frn” means Cast iron – front position and “Cast bck” means Cast iron – back position. In same manner, “Sint frn”, “Sint bck” means sintered brake blocks in each position. Front and back always refer to the travel direction, not the wagon number nor wagon A/B end.

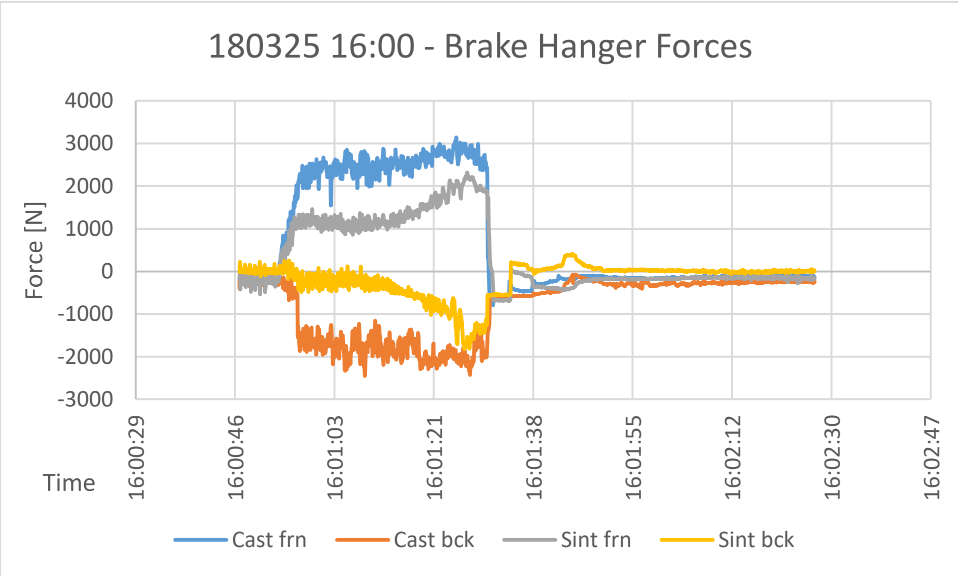


Figure B7: Forces in hangers when braking from 80 km/h to 0 km/h using 0,9 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 80% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give about 30-50% of the force given by the cast iron brake shoe. The forces generated by the cast iron brake shoes are now quite symmetric for the composite brake shoes, there is an obvious difference between front and rear brake shoe performance where the front brake shoes give higher readings.

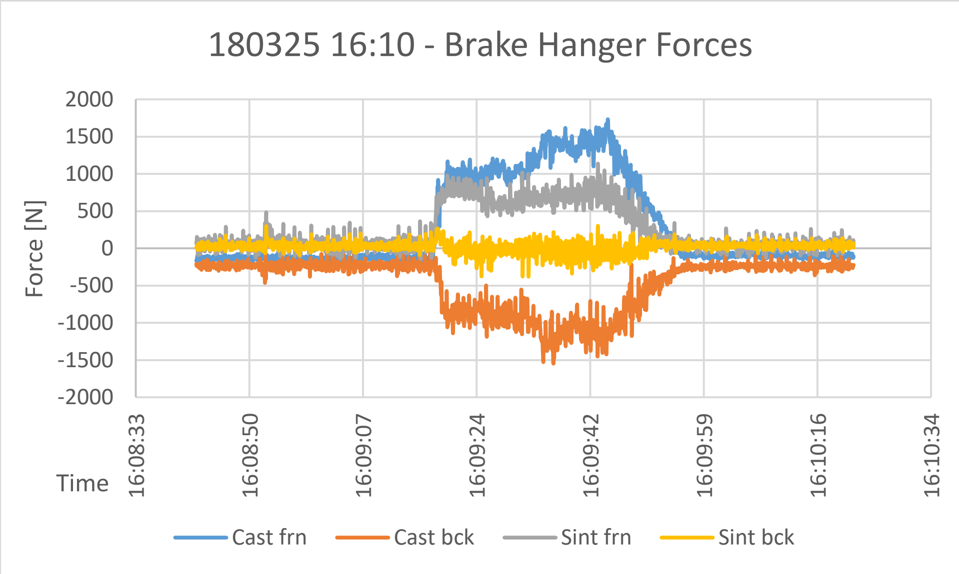


Figure B8: Forces in hangers when braking from 85 km/h to 60 km/h using 0,5 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 50-60% of the braking forces given by the cast iron type. The composite brake shoe behind wheel give nearly no contribution to the braking torque. The cast iron brake shoe behind the wheel contribute with about 80% of the force given by the front mounted cast iron brake shoe.

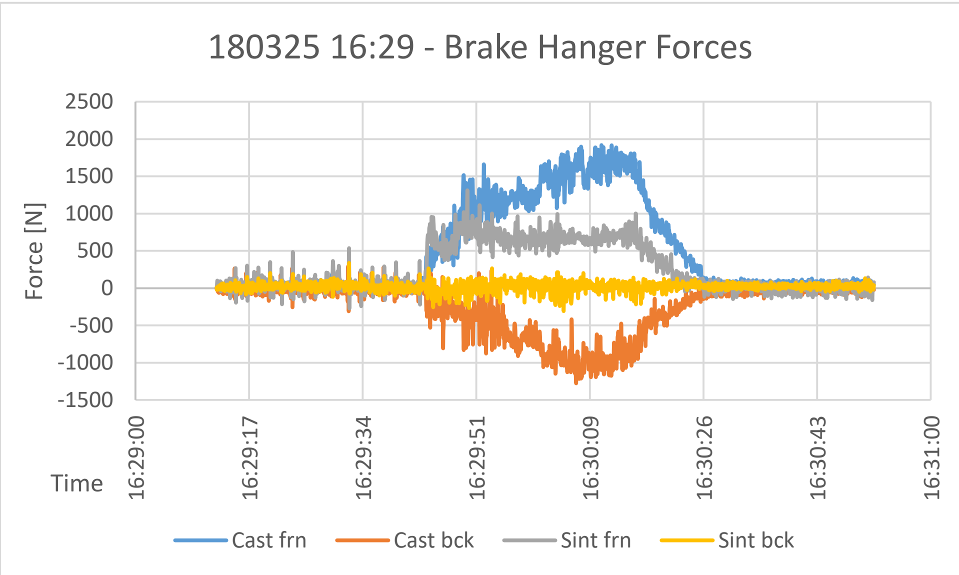


Figure B9: Forces in hangers when braking from 80 km/h to 60 km/h using 0,6 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 40% of the braking forces given by the cast iron type. The composite brake shoe behind wheel gives no contribution to the braking torque while the force given by the rear cast iron brake shoe is around 70% of the front mounted shoe.

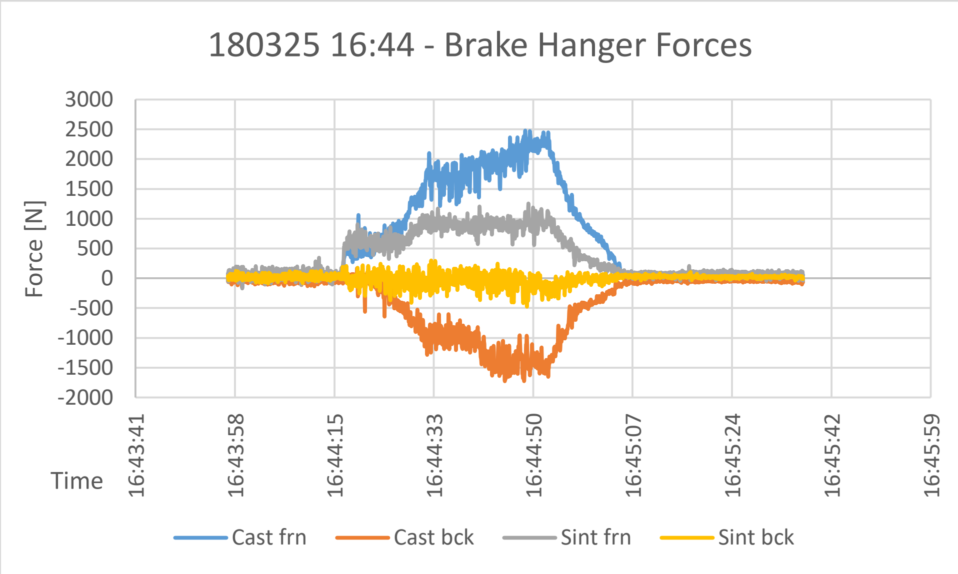


Figure B10: Forces in hangers when braking from 75 km/h to 30 km/h using 0,7 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 50% of the braking forces given by the cast iron type. The composite brake shoe behind wheel gives nearly no contribution to the braking torque while the force given by the rear cast iron brake shoe is around 70% of the front mounted shoe.

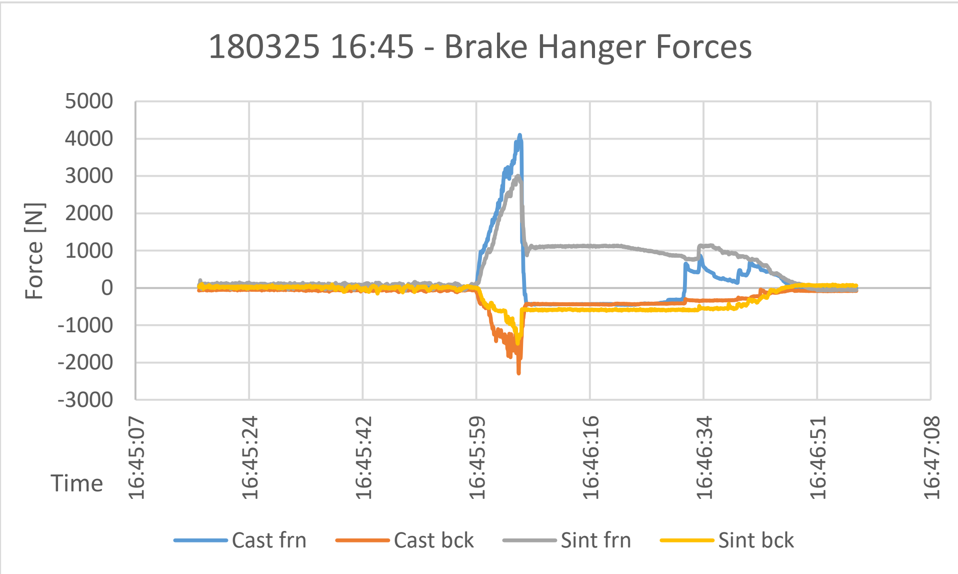


Figure B11: Forces in hangers when braking from 75 km/h to 30 km/h using 0,7 bar brake pressure reduction immediately followed by pressure decrease to 1,5 bar for speed down to 0 km/h. The composite brake shoe in front of wheel gives about 75% of the braking forces given by the cast iron type. The composite brake shoe behind wheel gives about 50% of the force from the rear cast iron brake shoe. The force given by the rear cast iron brake shoe is around 50% of the front mounted shoe.

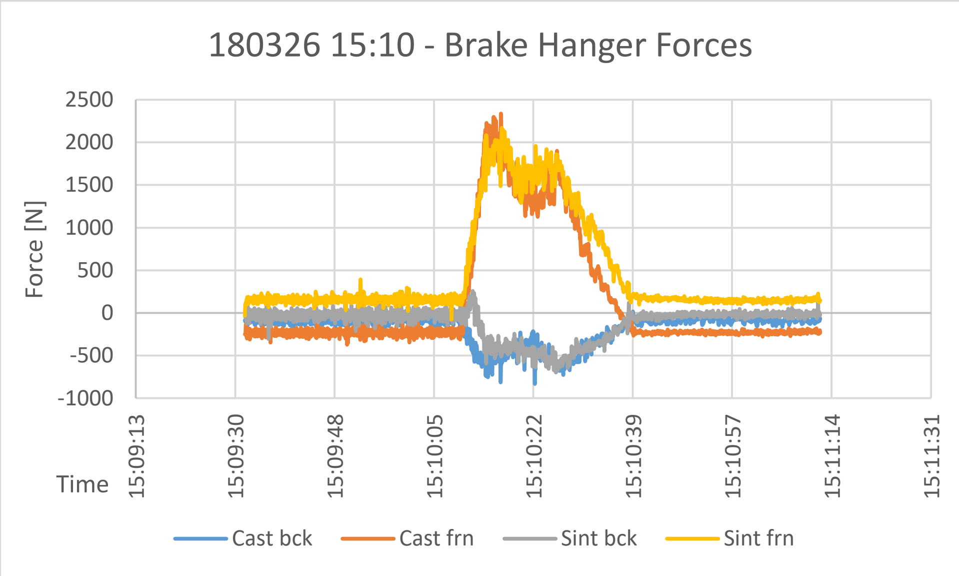


Figure B12: Forces in hangers when braking from 60 km/h to 30 km/h using 0,7 bar brake pressure reduction. The composite brake shoe in front of wheel gives the same or even higher force than the braking forces given by the cast iron type. The composite brake shoe behind wheel also gives the same force as the rear cast iron brake shoe. The forces given by the rear brake shoes are around 30% of the forces from the front mounted shoes.

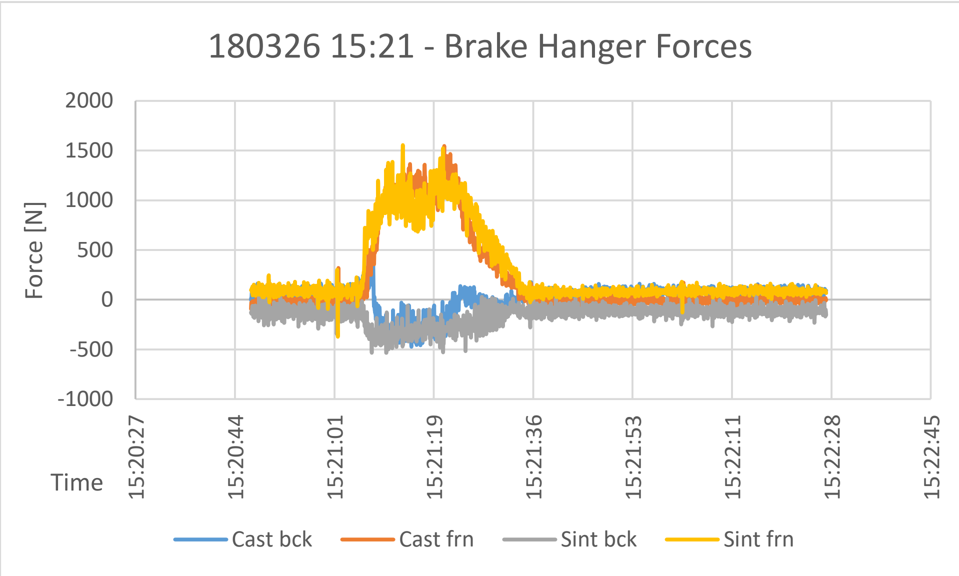


Figure B13: Forces in hangers when braking from 80 km/h to 60 km/h using 0,7 bar brake pressure reduction. The composite brake shoe in front of wheel gives about the same braking forces as the cast iron type. The composite brake shoe behind wheel also gives the same braking forces as the rear cast iron brake shoe. The force given by the rear cast iron brake shoe is around 30-40% of the front mounted shoe.

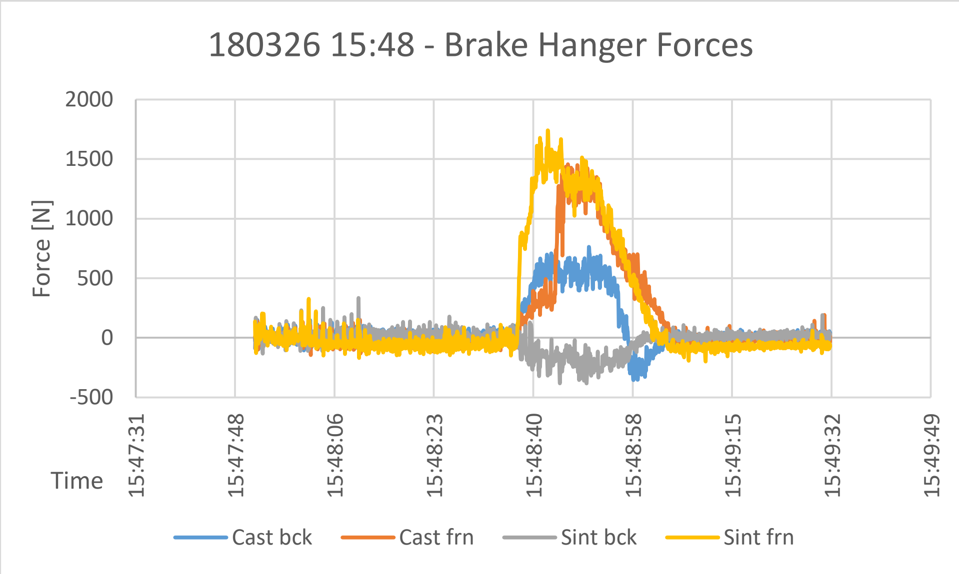


Figure B14: Forces in hangers when braking from 65 km/h to 50 km/h using 0,5 bar brake pressure reduction. The composite brake shoe in front of wheel gives faster response than the cast iron type and reaches 20% higher forces. The rear composite brake shoe reacts with a small contribution to braking with around 20% of the front mounted composite brake shoe. The rear cast iron brake shoe is totally off going to tension for most part of the braking sequence. This assumes to be a result of icy surface on the shoe making it act like squeezing a slippery bath soap in your hand. The wheel suspension will stretch both brake shoes downwards until friction is large enough to lift the rear brake shoe.

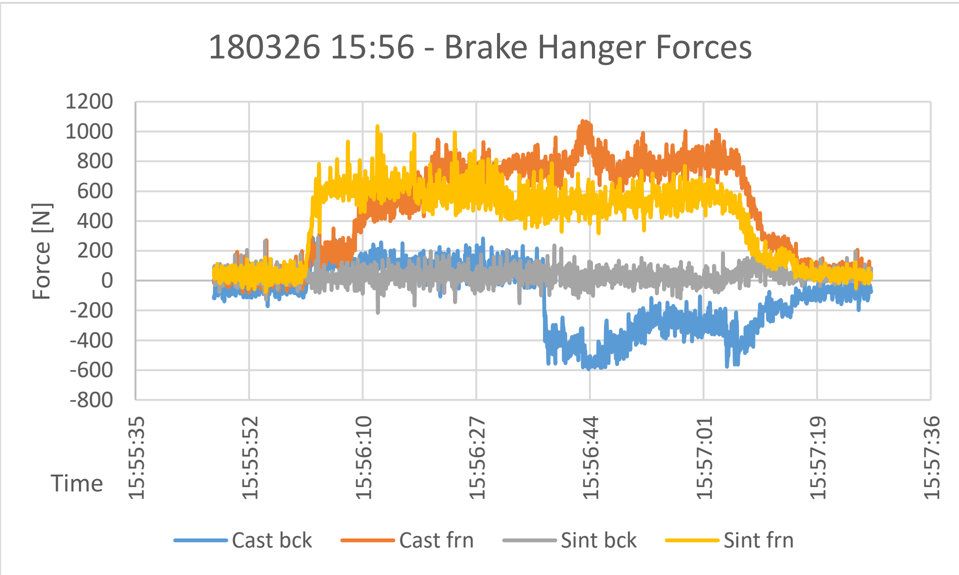


Figure B15: Forces in hangers when braking from 75 km/h to 50 km/h using 0,6 bar brake pressure reduction. The composite brake shoe in front of wheel gives about 75% of the force given by the cast iron type. The composite brake shoe behind wheel does not react at all. The rear cast iron brake shoe comes alive after about 30s going to about 50% of the force from front mounted cast iron shoe. As in figure 19, we assume the ice build-up is the reason to this behaviour.

B3. Data from tours with IB116 organic composite brake shoes and without snow dust

At the end of the test period there was some test tours in good weather without any snow dust. The test train was now equipped with composite brake blocks on all axles except on the reference axle in wagon 3 (still cast iron type). Here it is very obvious that the composite blocks behave very similar to the cast iron type when ice is gone. But we have an obvious problem as measured values are much lower than expected at 1,0 bar braking pressure. There is a possible problem that water/humidity in sensor cable connectors might have caused a reduced amplification. The monitoring system had been unpowered/unheated for more than two weeks since last measurement activity and when train is parked outdoor, humidity enters the electronics.

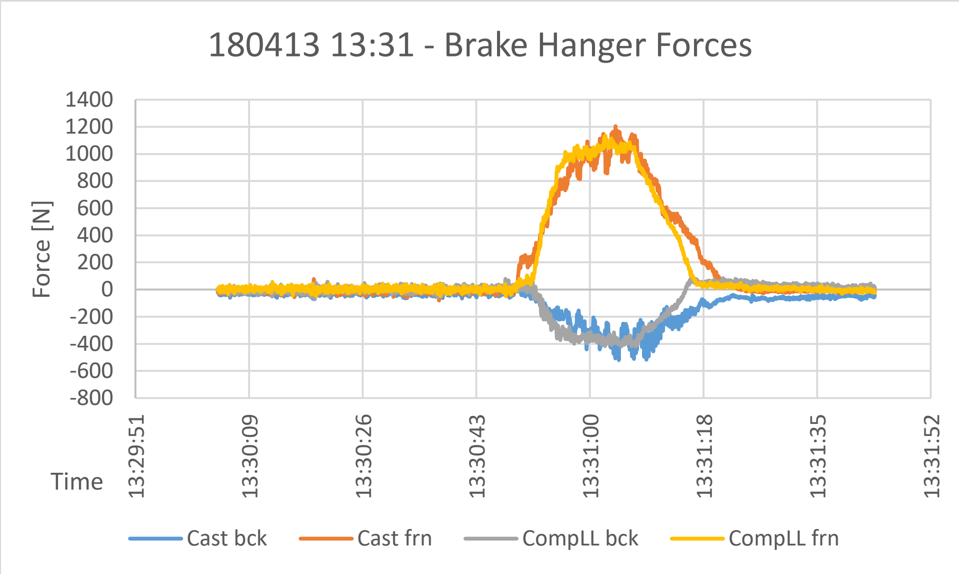


Figure B16: Forces in hangers when braking from 70 km/h to 20 km/h using 1,0 bar brake pressure reduction. The composite brake shoe in front of wheel gives the same force as the cast iron type. The composite brake shoe behind wheel also gives the same force as the rear cast iron brake shoe. The forces given by the rear brake shoes are around 40% of the forces from the front mounted shoes.

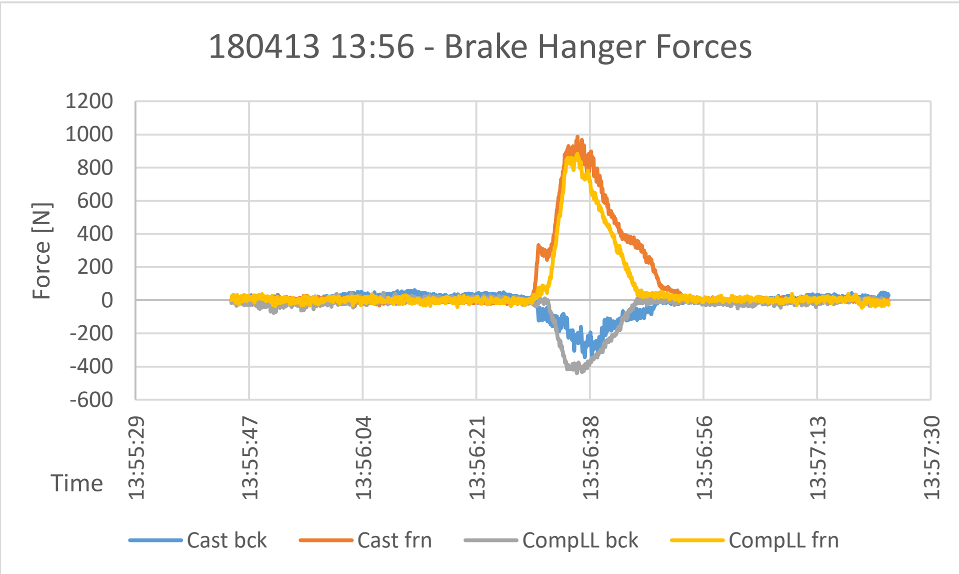


Figure B17: Forces in hangers when braking from 45 km/h to 15 km/h using 1,0 bar brake pressure reduction. The composite brake shoe in front of wheel gives the same force as the cast iron type. The composite brake shoe behind wheel also gives the same or even partly higher force than the rear cast iron

brake shoe. The forces given by the rear brake shoes are around 40% of the forces from the front mounted shoes.

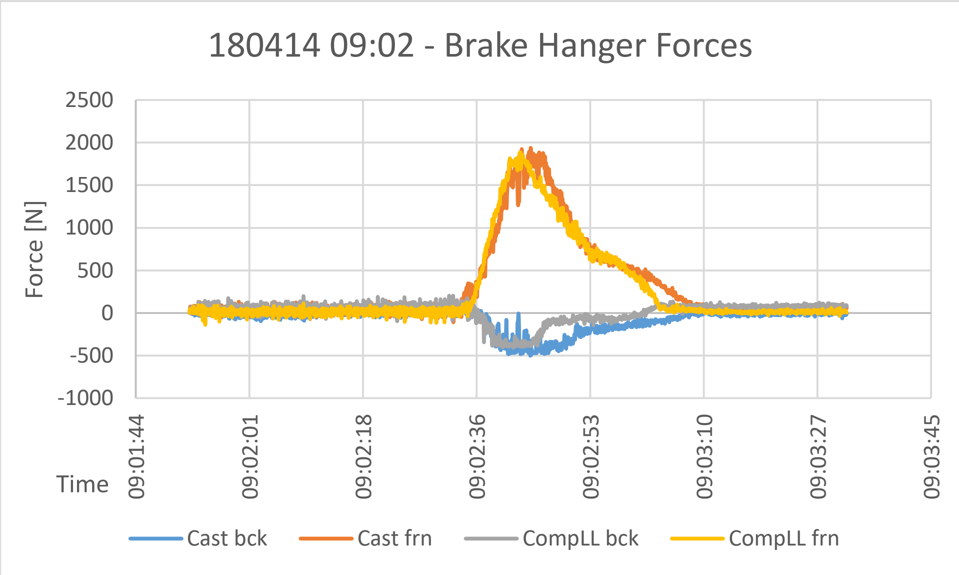


Figure B18: Forces in hangers when braking from 80 km/h to 45 km/h using 1,2 bar brake pressure reduction. The composite brake shoe in front of wheel gives the same force as the cast iron type. The composite brake shoe behind wheel also gives the same force as the rear cast iron brake shoe. The forces given by the rear brake shoes are around 20% of the forces from the front mounted shoes.

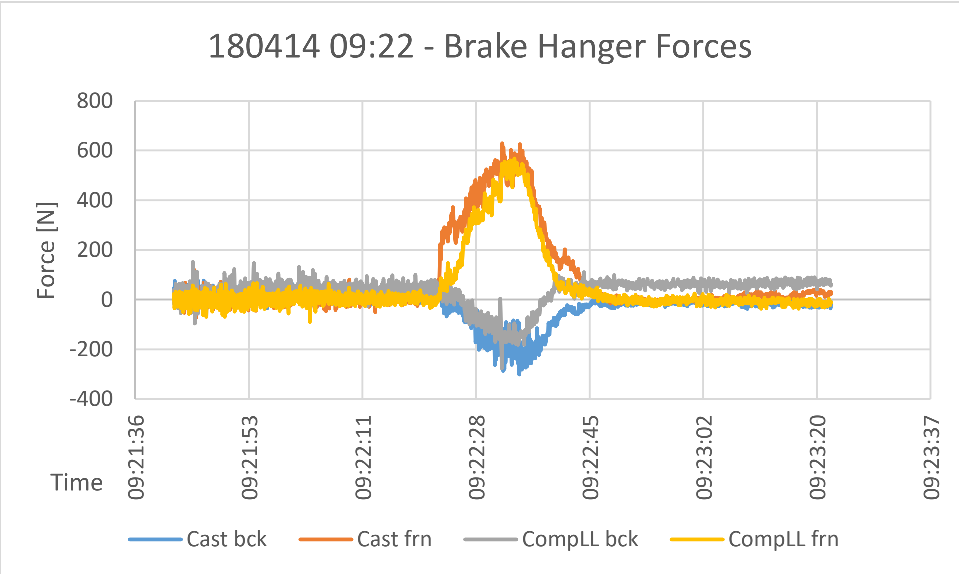


Figure 19: Forces in hangers when braking from 70 km/h to 40 km/h using 0,6 bar brake pressure reduction. The composite brake shoe in front of wheel gives the same force as the cast iron type. The composite brake shoe behind wheel also gives around 80% of the force given by the rear cast iron brake shoe. The forces given by the rear cast iron brake shoes are around 40% of the forces from the front mounted shoes.

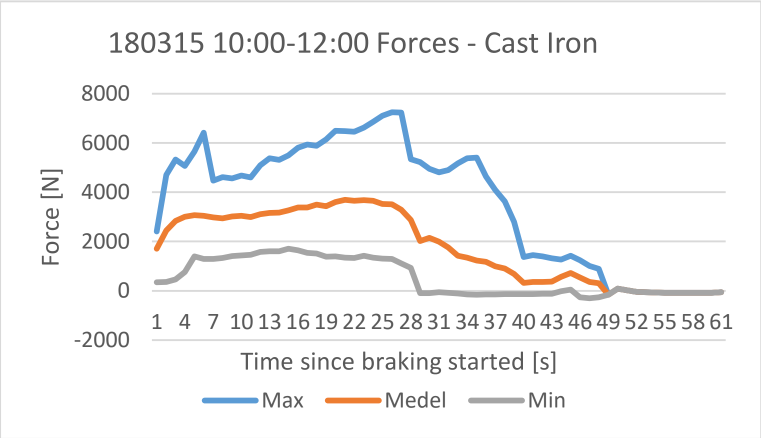
Appendix C – Statistical analysis of each test tour

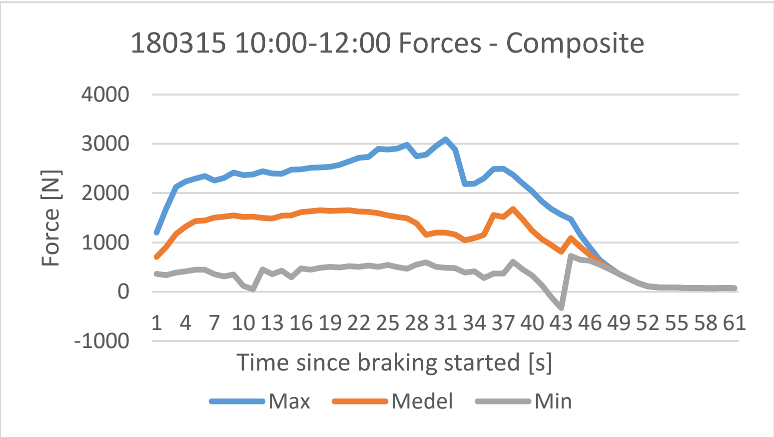
In this Appendix we have gathered the output from a time based analysis of all the journeys and all brake events. A special analysis software has been developed that scans data files and trigger a new event as soon as any of the hangers shows a force above 500N (either compression or tension). After that, the sum of forces from front and rear hanger on a wheel has been added to a total wheel brake force on each instrumented wheel. The following diagrams show the analysis results of each journey consisting of several brake events. Each journey is represented by three diagrams and each diagram consists of three curves. The first diagram in each set always shows brake forces from the reference wheel with cast Iron brake shoes while the second diagram show forces from the wheel with tested composite or sinter brake shoes. The third diagram shoes the ratio “test shoe” divided by “reference shoe”. A number lower than 100% means the test shoes produce less braking force than the reference shoes.

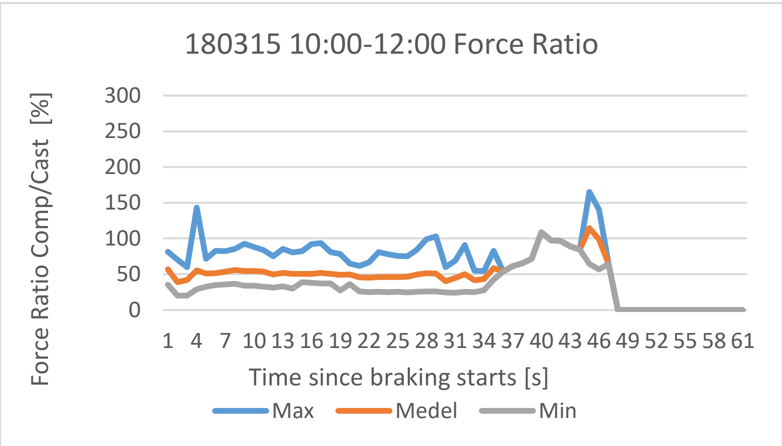
In each diagram, the three curves represent minimum, mean and maximum forces and ratios observed on that journey based on several brake events. The horizontal-axis shows time in seconds from start of every brake event. It must be noticed that the fluctuations in presented values are not only caused by brake shoe performance but also by the brake pressure applied. Such a factor is important when looking at absolute level of forces but somewhat less important when looking at the ratio, calculated momentarily for each brake event.

The title of each journey includes the word “forward” or “backward”. This has turned out to be a major parameter in the analysis and it tells us about the train travel direction. When going forward, the train moves with wagon 3 ahead of wagon 4. Going backward then means going in opposite direction with wagon4 ahead of wagon3.

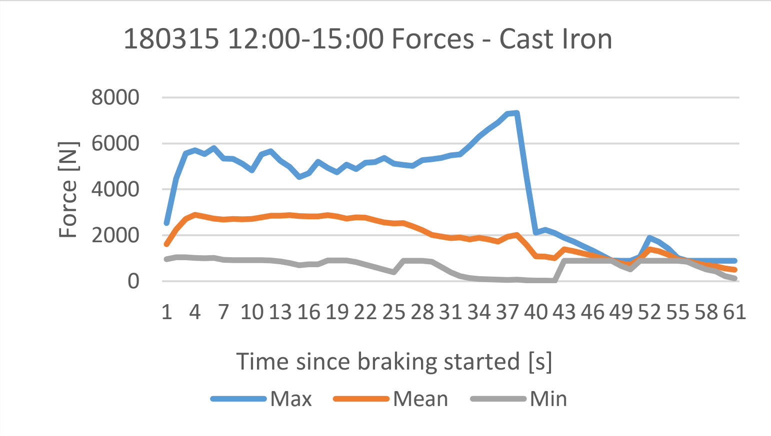
Forward - IB116 organic composite brake shoes

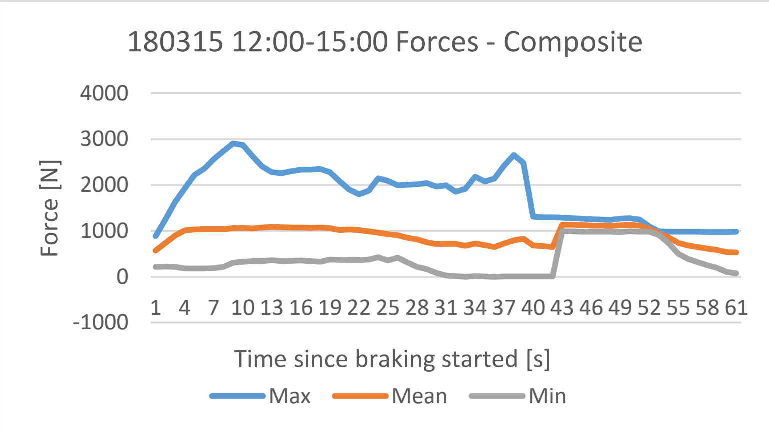


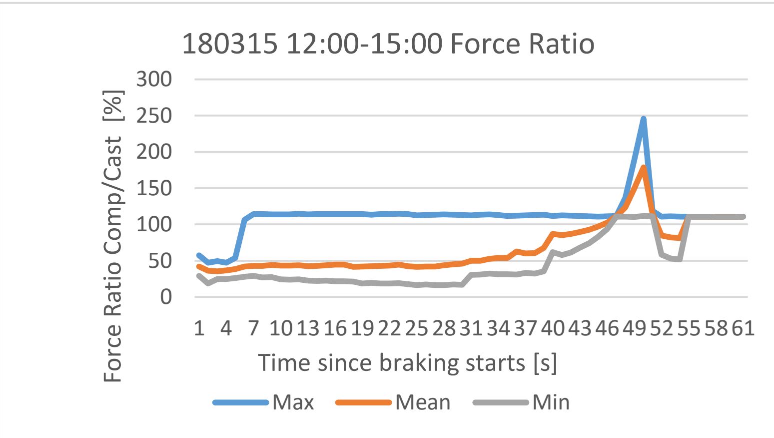




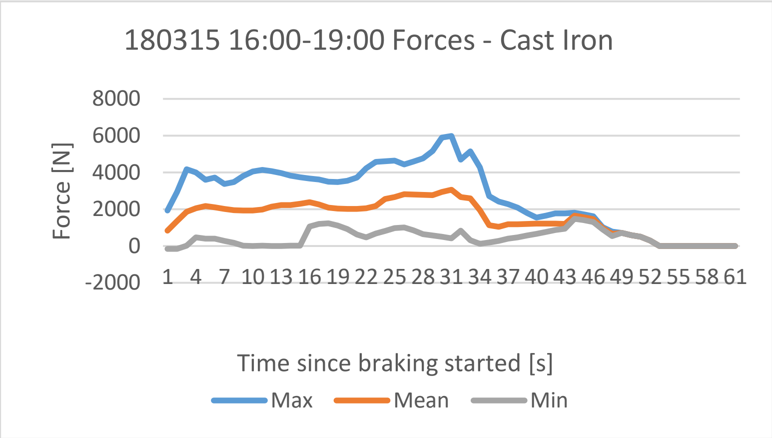
Forward - IB116 organic composite brake shoes

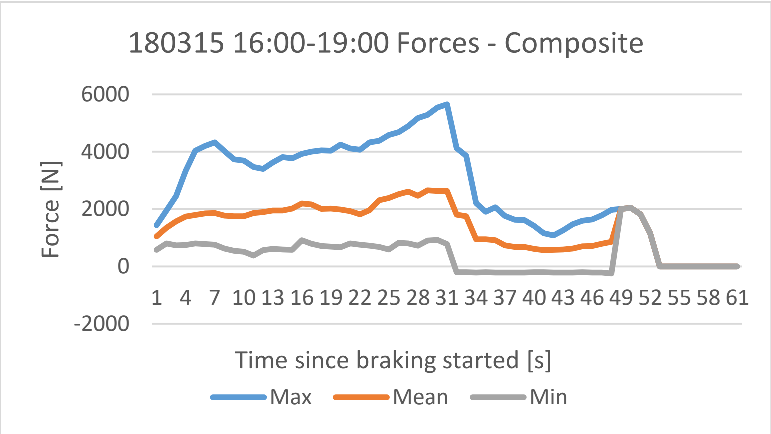


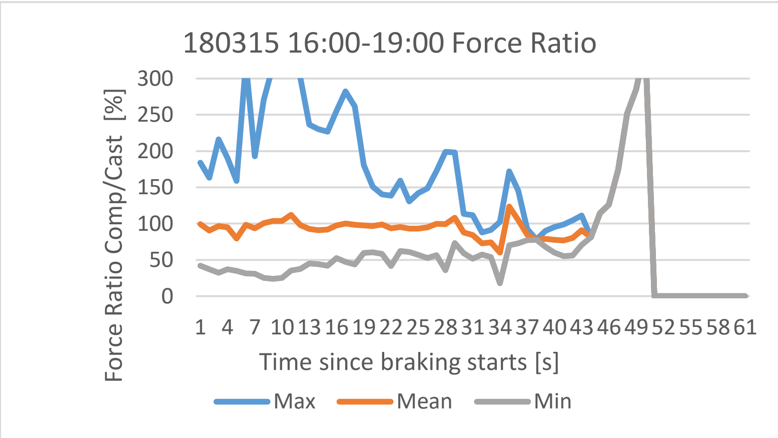




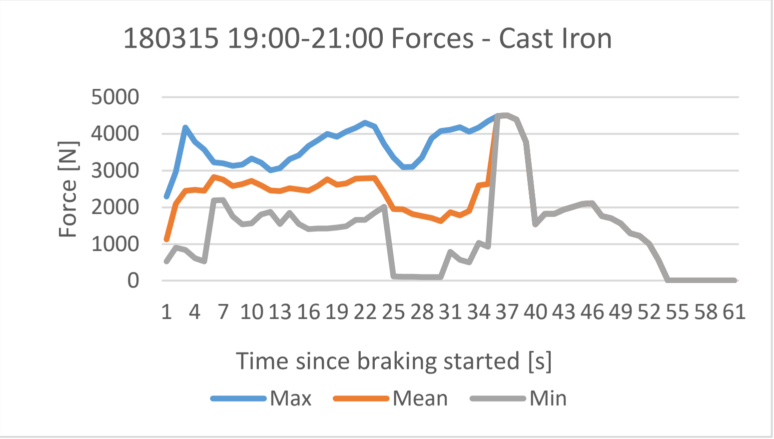
Backward - IB116 organic composite brake shoes

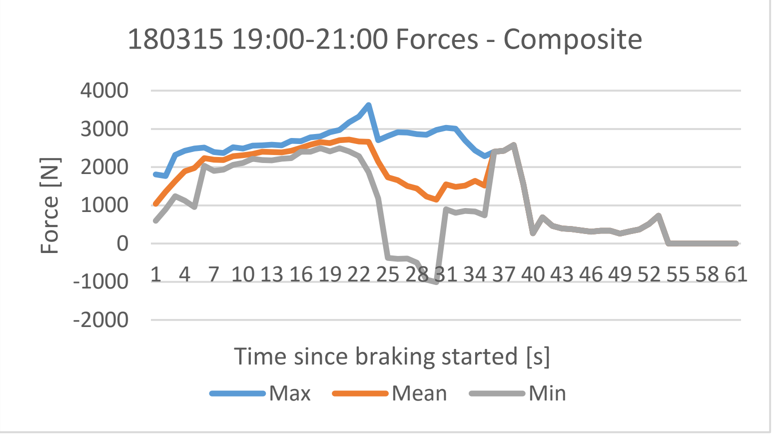


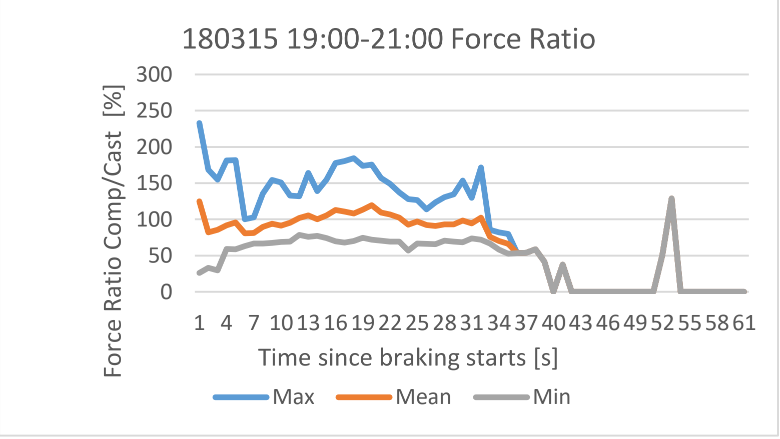




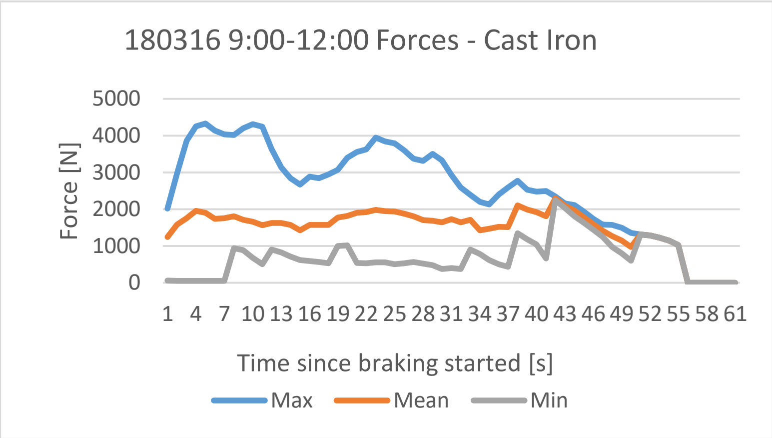
Backward - IB116 organic composite brake shoes

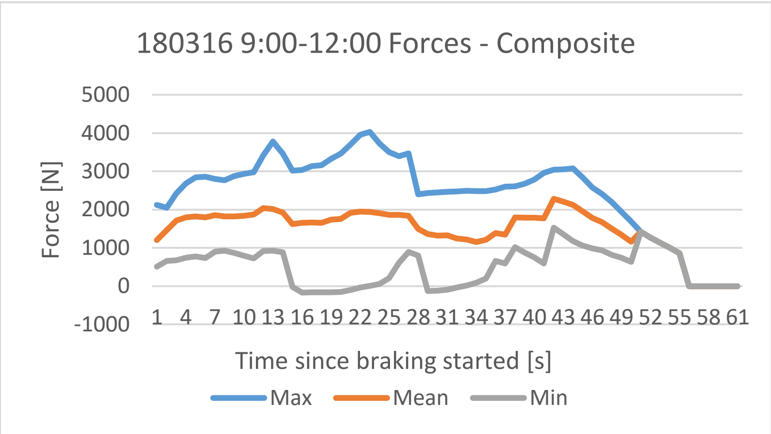


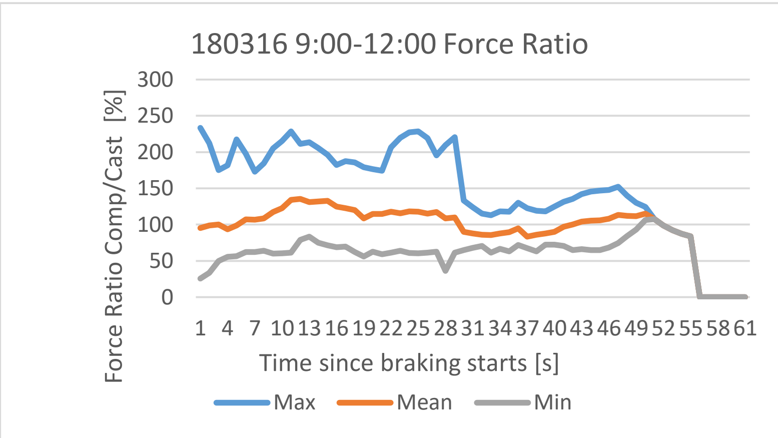




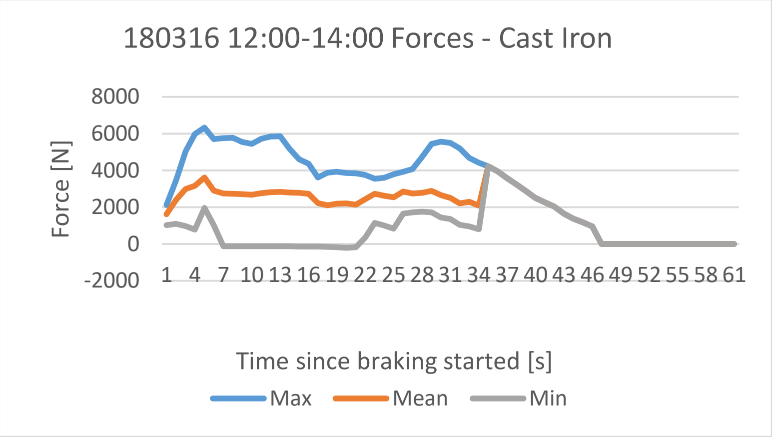
Backward - IB116 organic composite brake shoes

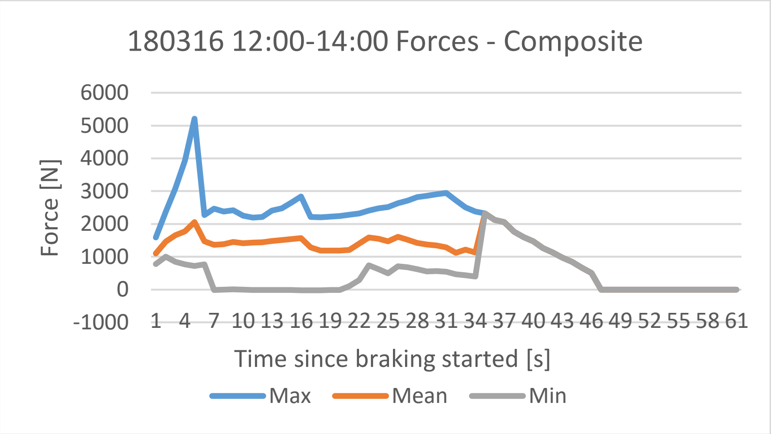


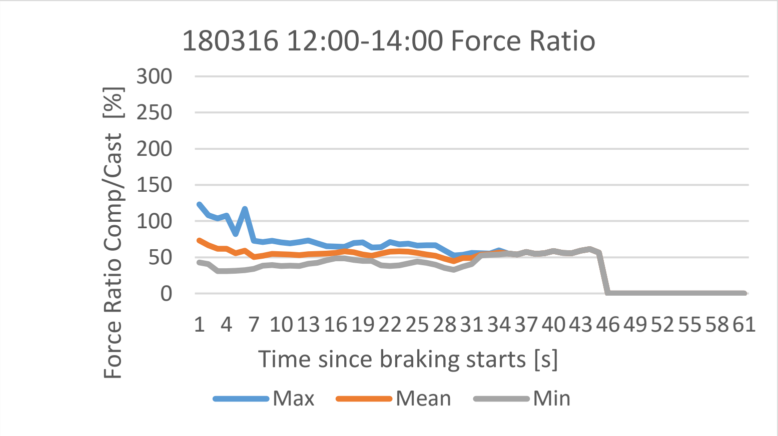




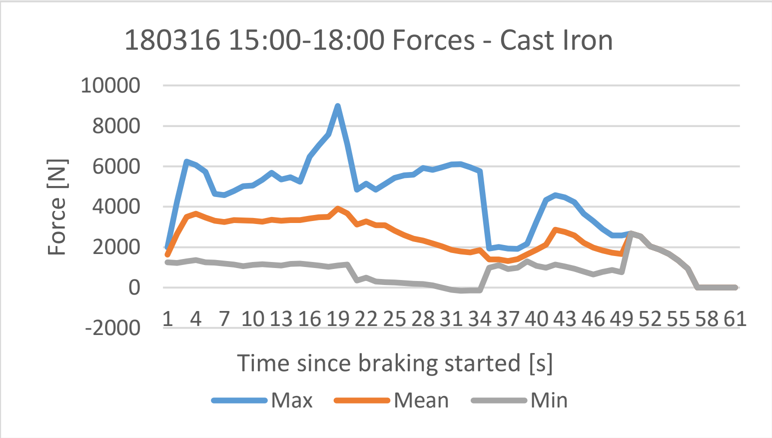
Forward - IB116 organic composite brake shoes

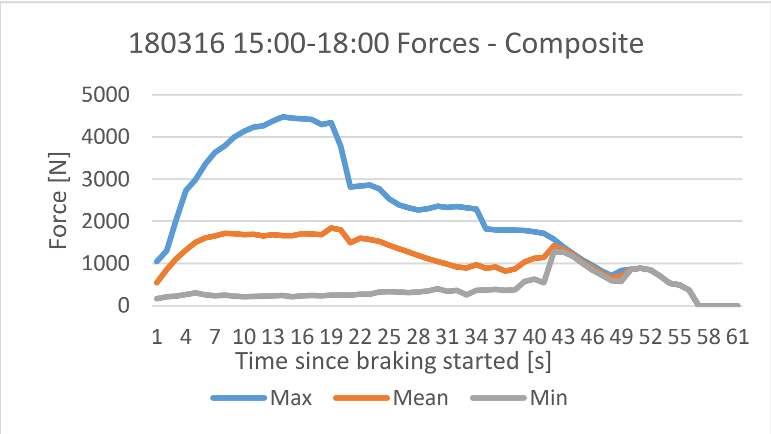


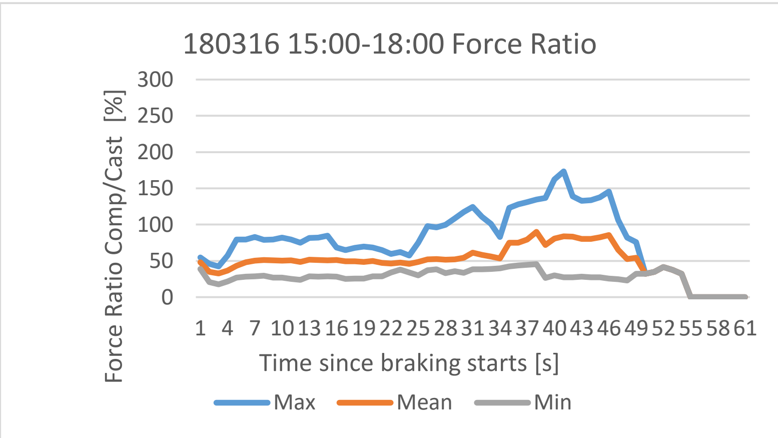




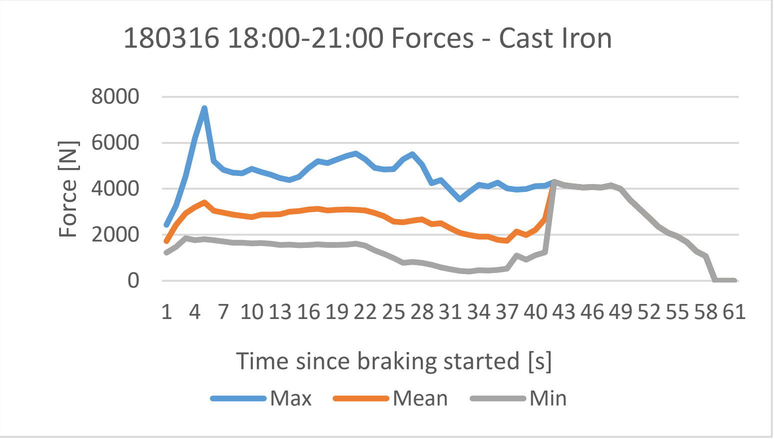
Forward - IB116 organic composite brake shoes

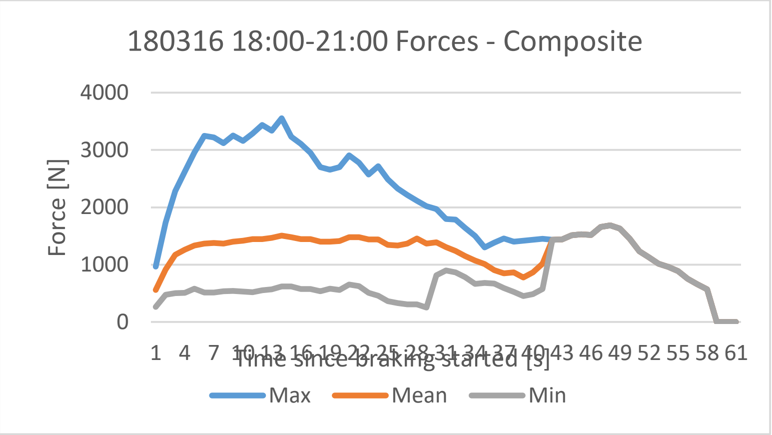


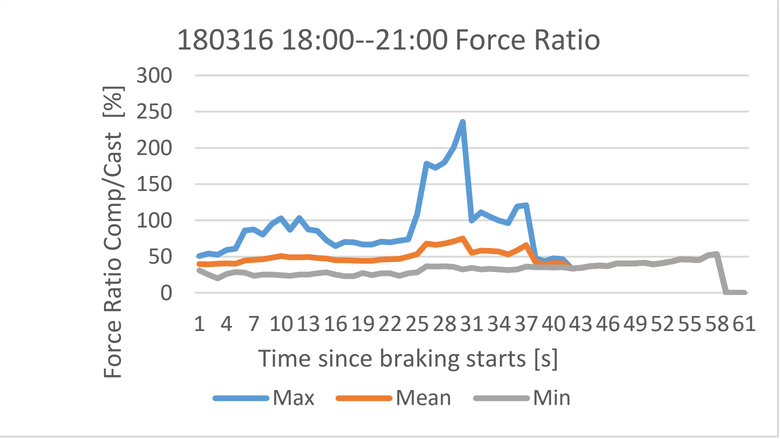




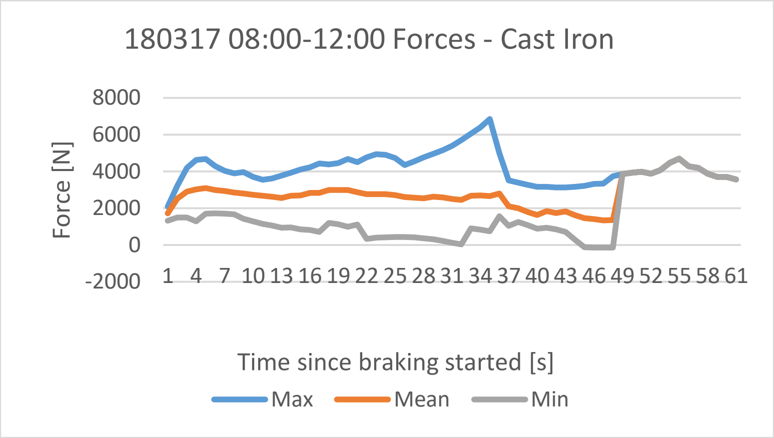
Forward - IB116 organic composite brake shoes

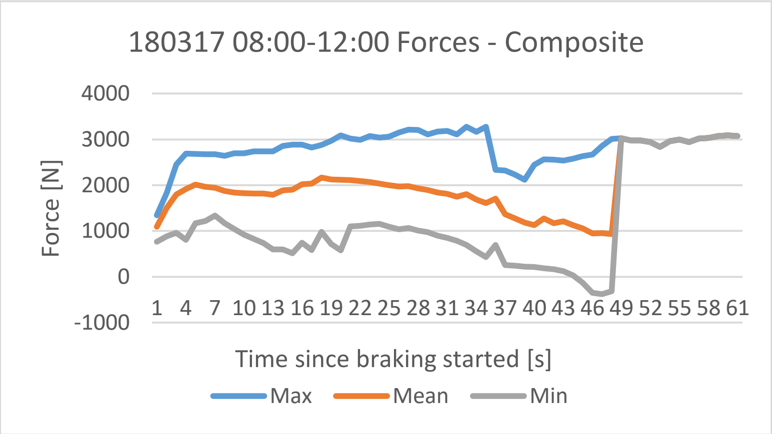


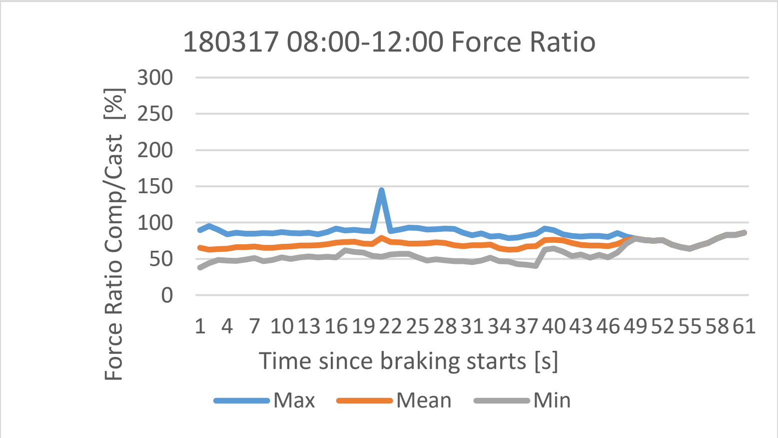




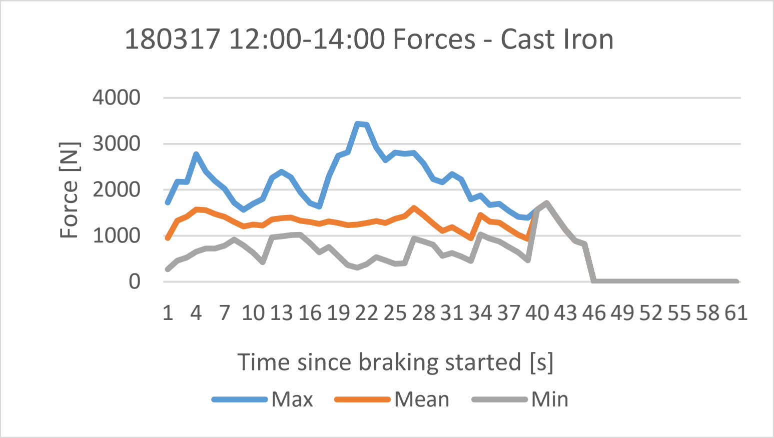
Forward - IB116 organic composite brake shoes

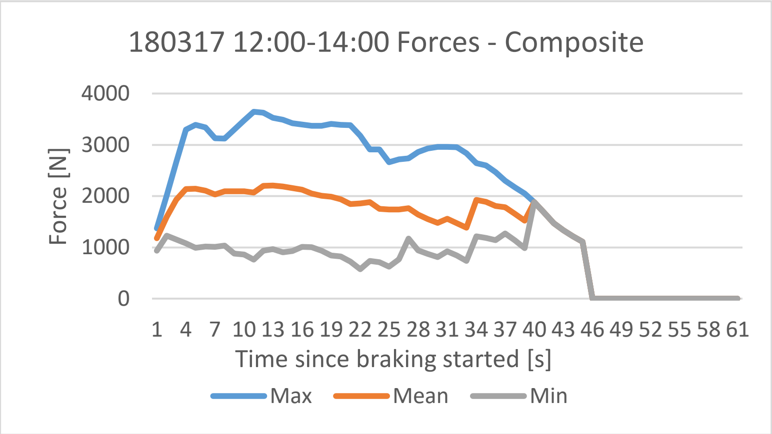


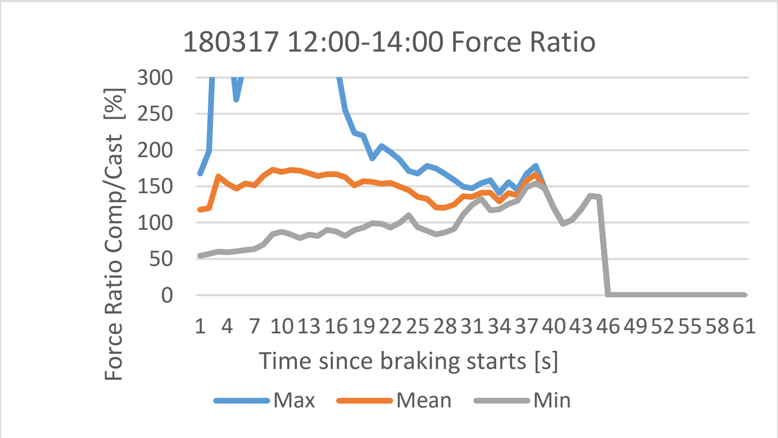




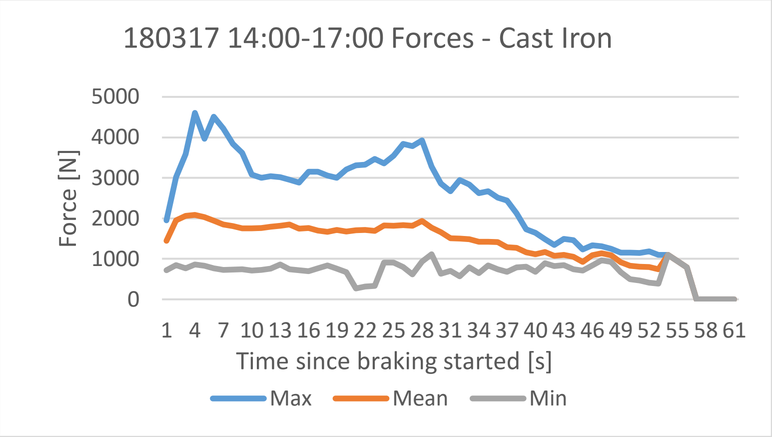
Backward - IB116 organic composite brake shoes

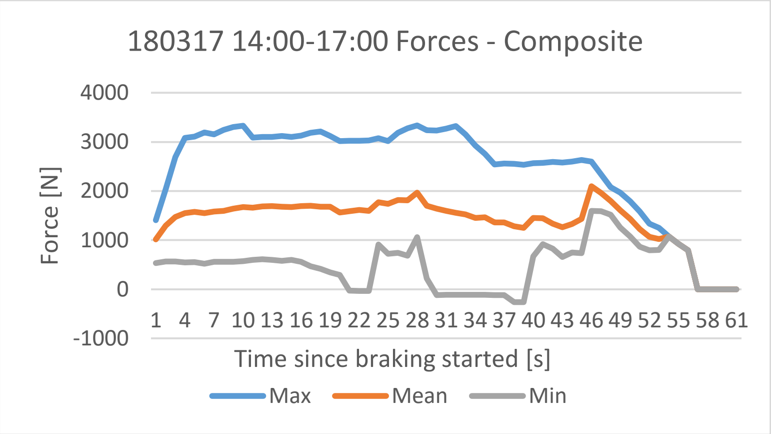


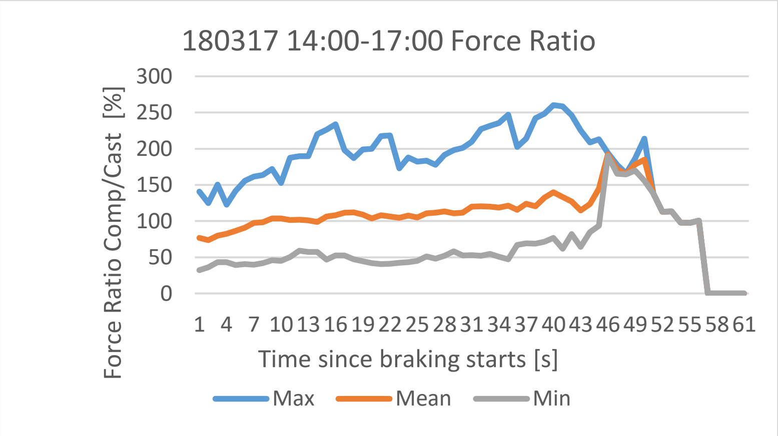




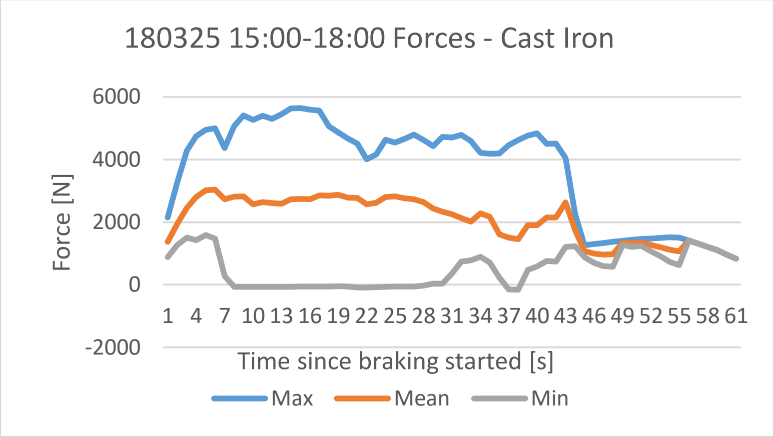
Backward - IB116 organic composite brake shoes

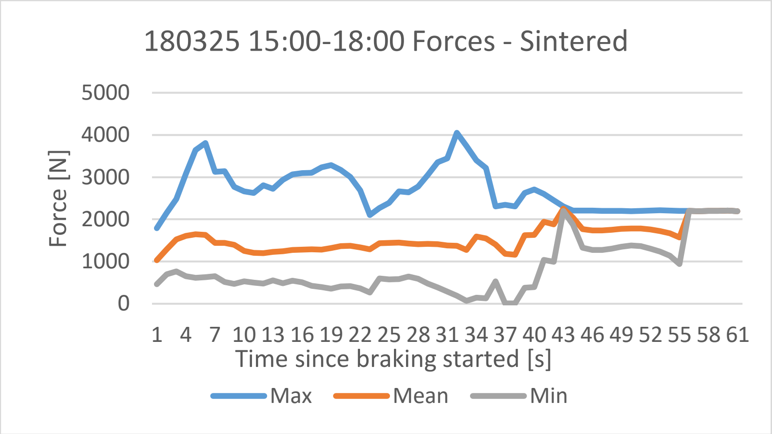


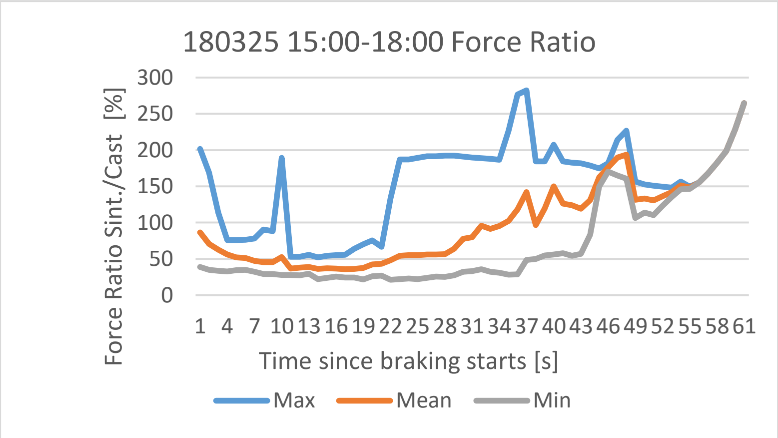




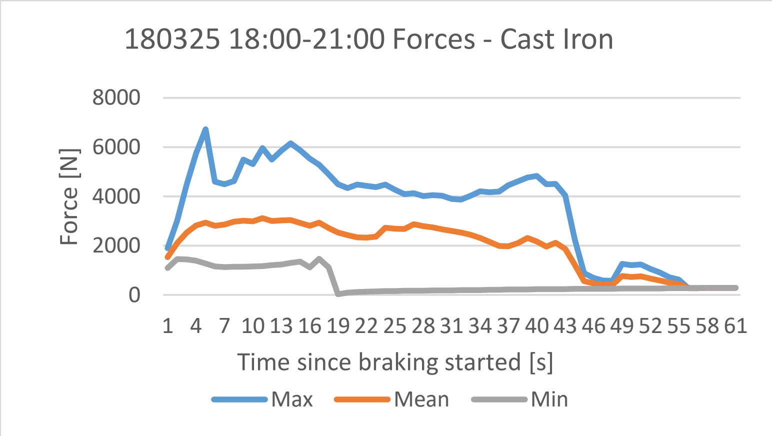
Forward - C952-1 sintered composite brake shoes

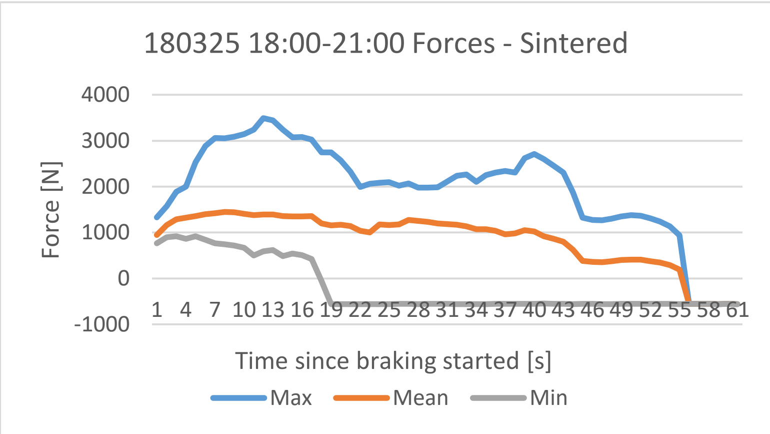


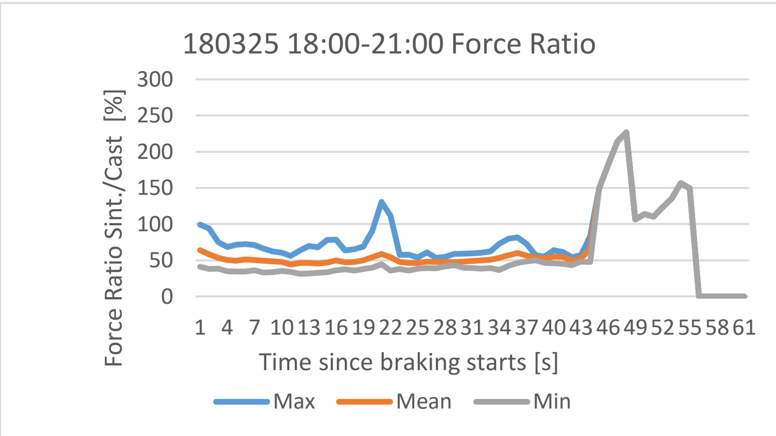




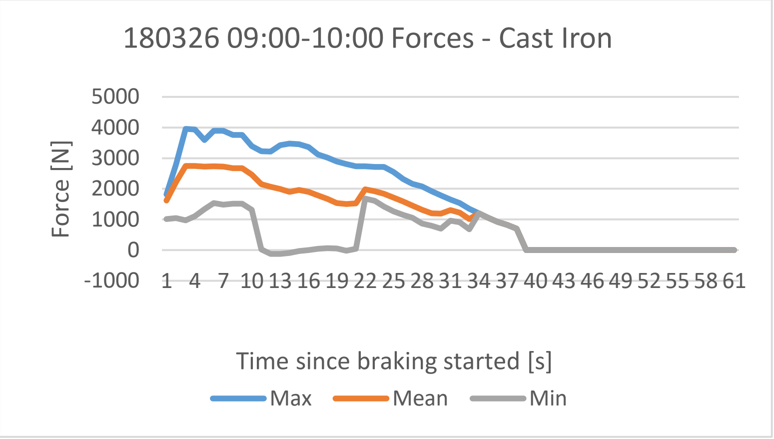
Forward - C952-1 sintered composite brake shoes

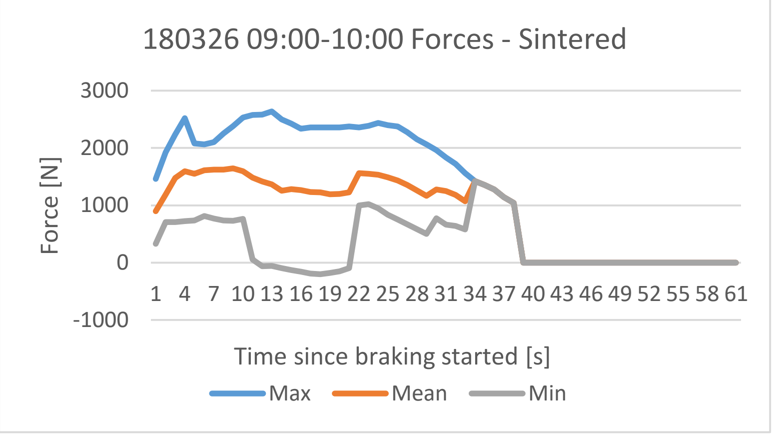


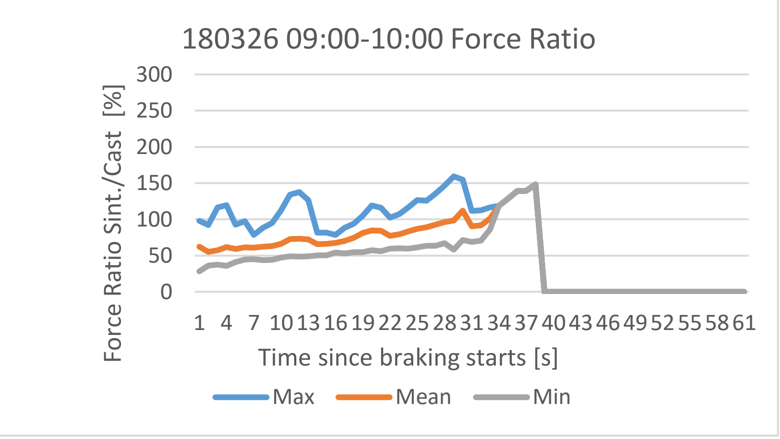




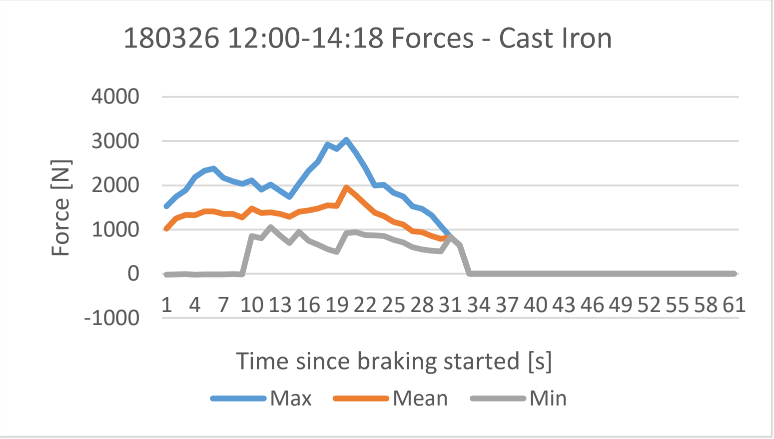
Forward - C952-1 sintered composite brake shoes

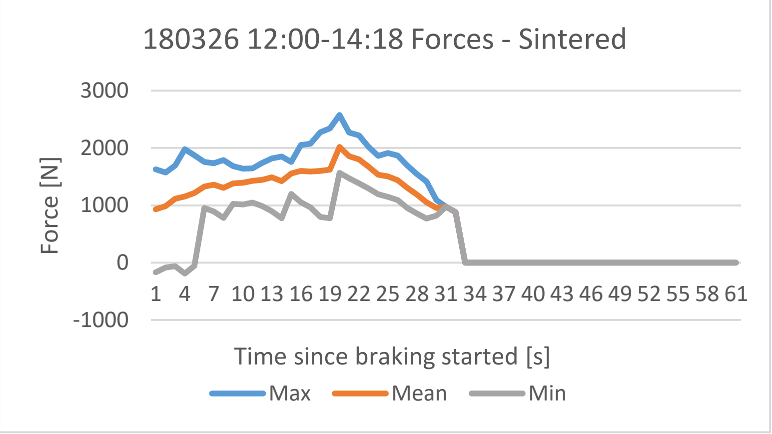


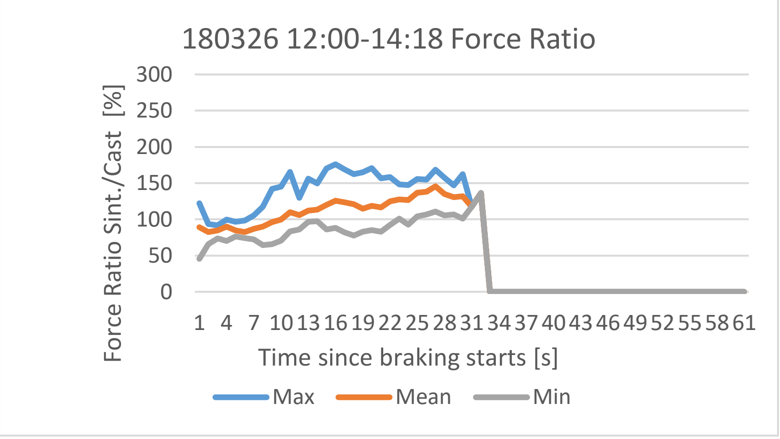




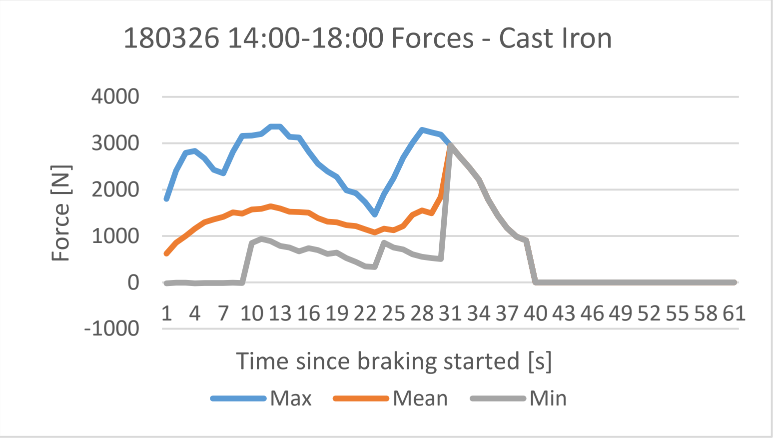
Backward - C952-1 sintered composite brake shoes

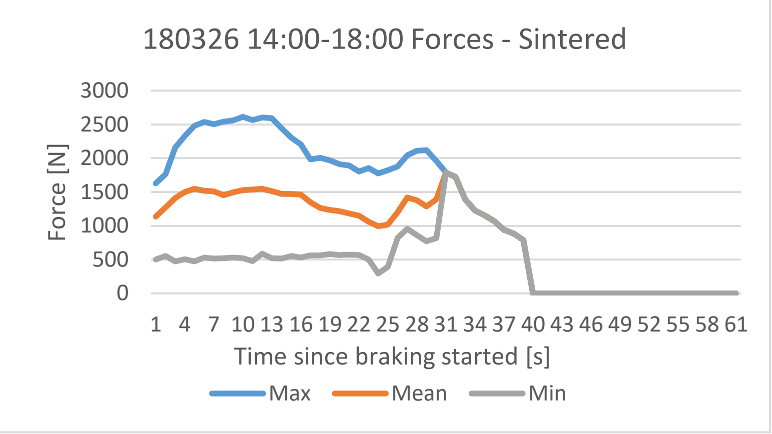


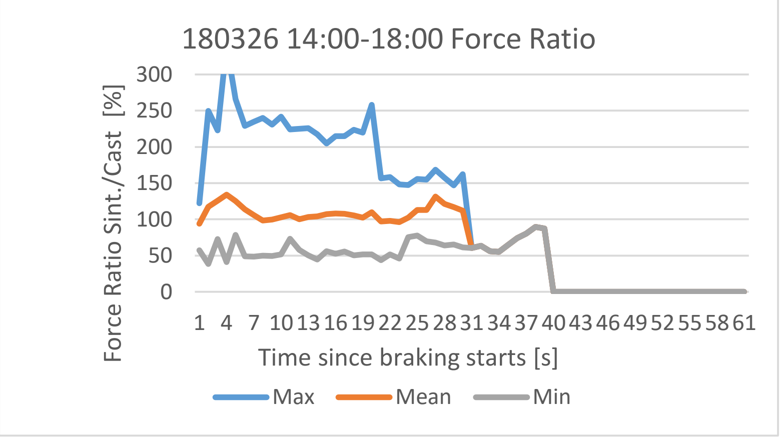




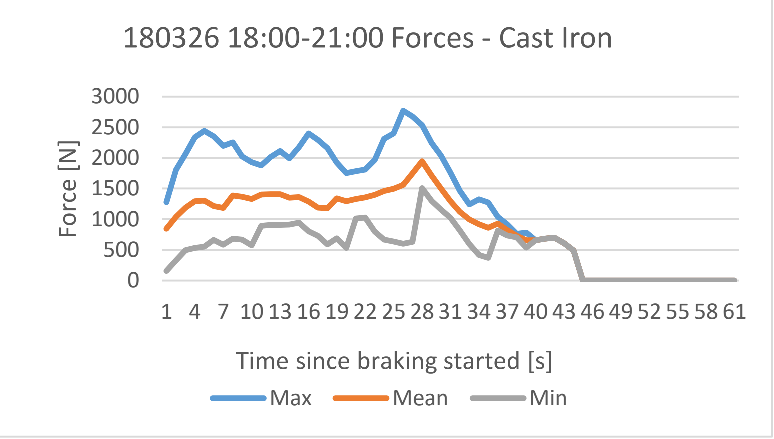
Backward - C952-1 sintered composite brake shoes

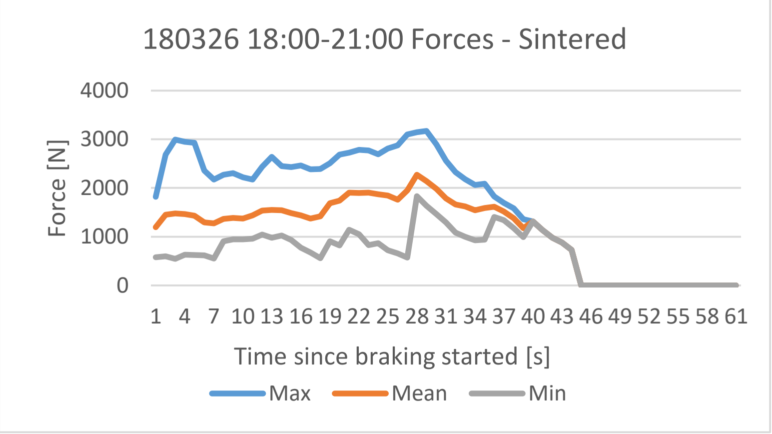


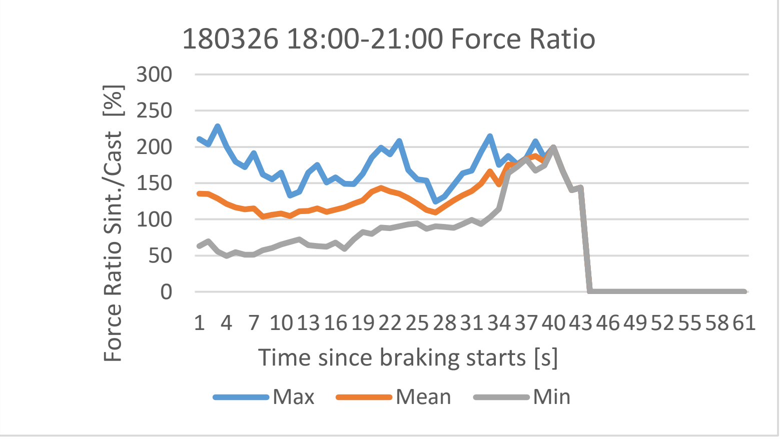




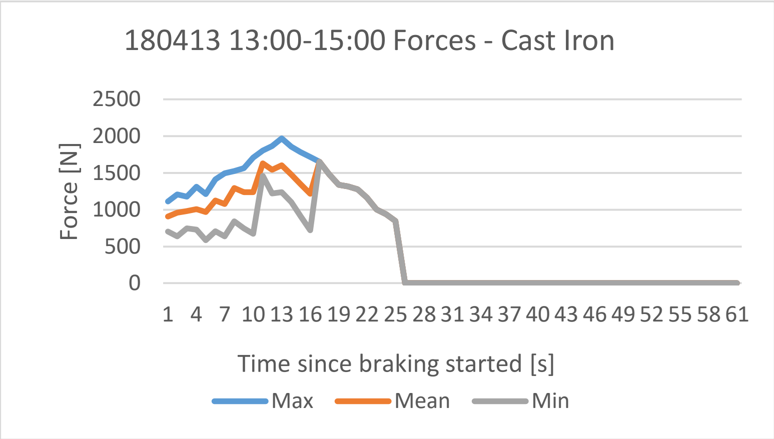
Backward - C952-1 sintered composite brake shoes

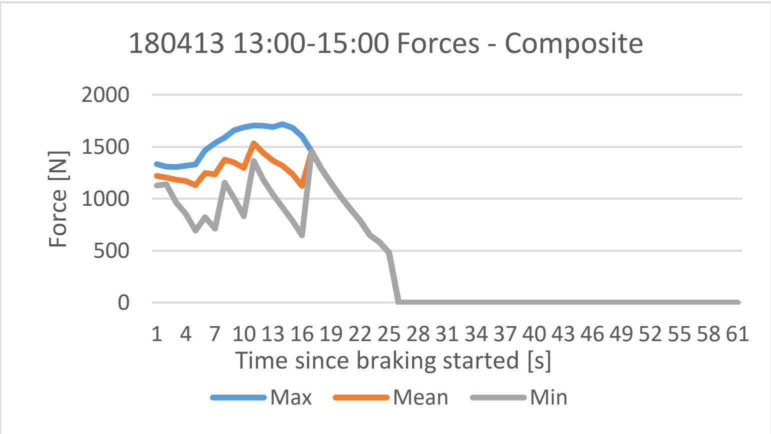


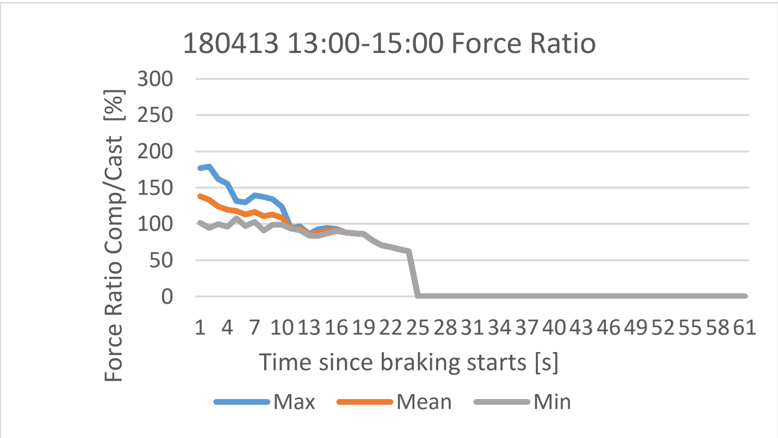




Backward - IB116 organic composite brake shoes







Appendix D – Time analysis of individual brake event

In this appendix we focus on the start of every brake event, presented in Table D1. Based on the two instrumented wheels, one with reference brakes shoes made of cast iron and another wheel with test brake shoes made of either organic composite or sintered composite material.

Table D1: All braking events that are analysed in this report are here listed in consecutive order. Column "Travel time" shows travelled time since last brake event. Column "Dur" shows how long the braking event lasted. Column "Dir" shows travel direction forward or backward. Columns "Dly Cast" and "Dly Comp" show delay until respective shoes reach 500N threshold. Columns "Mean Cast" and "Mean Comp" show mean braking forces during the full event. Columns "Max Cast'2 and "Max Comp" show maximum braking forces achieved.

Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
18-03-15	09:44:03	0	29	FW	IB116	1,0	0	0	1236	1820	4665	2413
18-03-15	09:49:37	304	29	FW	IB116	0,7	4	0	846	1214	3564	1793
18-03-15	09:52:50	164	35	FW	IB116	1,0	0	0	1663	1536	4173	2077
18-03-15	10:00:24	419	33	FW	IB116	0,7	0	0	1189	987	2866	1279
18-03-15	10:12:44	707	6	FW	IB116	0,5	0	6	147	456	1585	477
18-03-15	10:27:03	852	46	FW	IB116	1,2	0	0	2359	2212	5341	3090
18-03-15	10:37:32	583	61	FW	IB116	1,0	0	0	1786	1560	5788	2457
18-03-15	10:49:18	644	48	FW	IB116	1,0	0	0	2636	1570	5409	2493
18-03-15	10:59:06	540	34	FW	IB116	1,5	0	2	2094	1658	6419	2418
18-03-15	11:18:48	1148	43	FW	IB116	1,2	0	2	2398	1733	7247	2983
18-03-15	11:34:37	905	35	FW	IB116	1,0	0	2	1961	1147	4941	1808
18-03-15	11:36:46	94	37	FW	IB116	1,0	0	9	1070	499	2404	607
18-03-15	11:38:16	53	35	FW	IB116	0,5	0	14	801	492	1773	770
18-03-15	12:48:26	0	29	FW	IB116	1	0	0	3147	1265	4563	1769
18-03-15	13:04:48	953	34	FW	IB116	1	0	0	3324	1343	4367	1840
18-03-15	13:08:50	207	30	FW	IB116	0,9	0	0	3225	1692	4533	2352
18-03-15	13:14:01	281	38	FW	IB116	0,6	0	0	1652	721	2129	883
18-03-15	13:17:22	162	20	FW	IB116	1	0	2	3002	912	4864	1252
18-03-15	13:17:59	16	11	FW	IB116	0	0	0	1791	647	2075	737
18-03-15	13:18:48	38	17	FW	IB116	0	0	0	1850	872	3901	1328
18-03-15	13:25:19	374	36	FW	IB116	0,1	0	0	2238	1202	2957	1538
18-03-15	13:40:59	904	42	FW	IB116	0,8	0	0	2542	992	3305	1210
18-03-15	13:47:45	363	30	FW	IB116	0,6	0	0	1980	755	2508	890
18-03-15	14:11:15	1379	30	FW	IB116	0,6	0	0	2001	595	2690	786
18-03-15	14:16:10	264	36	FW	IB116	1,1	0	0	3614	1263	5155	1836
18-03-15	14:17:47	60	42	FW	IB116	1,5	0	0	2682	1033	5797	2907
18-03-15	14:25:00	391	24	FW	IB116	0,7	0	0	2469	866	3283	1033
18-03-15	14:30:21	297	63	FW	IB116	1,3	0	0	2929	1163	7329	2653
18-03-15	14:35:42	258	37	FW	IB116	0,6	0	0	1529	558	2025	848
18-03-15	14:39:01	161	31	FW	IB116	1	0	0	3847	1065	5244	1423
18-03-15	14:41:33	121	31	FW	IB116	0,6	0	0	2181	684	2762	841
18-03-15	14:49:57	472	33	FW	IB116	0,9	0	0	2735	1034	3882	1437
18-03-15	15:04:27	836	39	FW	IB116	0,8	0	13	2648	494	4264	902
18-03-15	15:05:50	43	33	FW	IB116	0,8	0	33	2120	346	2585	443
18-03-15	15:06:37	14	25	FW	IB116	0,5	0	10	1465	500	3060	879
18-03-15	15:10:59	236	103	FW	IB116	0	0	3	966	979	3064	1142
18-03-15	16:29:12	0	11	BW	IB116	0	0	0	1895	810	3209	1089
18-03-15	16:34:02	279	43	BW	IB116	0,6	0	0	1112	715	1365	988
18-03-15	16:42:38	474	23	BW	IB116	0,8	2	0	2000	999	3068	1420

Table D1 continued…

Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
18-03-15	16:49:31	389	34	BW	IB116	1,1	2	0	2878	1784	4701	2743
18-03-15	16:50:06	1	14	BW	IB116	1,1	0	0	1874	776	2491	1287
18-03-15	17:00:38	618	23	BW	IB116	0,8	0	0	2531	2553	4131	4058
18-03-15	17:14:00	779	25	BW	IB116	1	3	0	2617	1785	4060	2245
18-03-15	17:24:51	625	34	BW	IB116	1	6	0	2601	3139	5153	4640
18-03-15	17:28:10	147	48	BW	IB116	1,4	0	0	2097	2384	5976	5661
18-03-15	17:31:32	154	43	BW	IB116	0,8	0	0	2560	2221	3636	2818
18-03-15	17:54:37	1341	36	BW	IB116	1	4	0	2310	2068	3803	2858
18-03-15	18:05:35	622	10	BW	IB116	0,6	0	0	1983	1098	2710	1471
18-03-15	18:05:50	4	23	BW	IB116	0,6	0	0	1674	1175	2694	1722
18-03-15	18:06:26	14	15	BW	IB116	0	0	0	240	826	620	989
18-03-15	18:26:28	1186	31	BW	IB116	1	0	0	1430	2070	2282	2934
18-03-15	18:37:12	613	24	BW	IB116	0,7	3	0	1467	1135	2244	1461
18-03-15	18:42:17	280	22	BW	IB116	1,5	0	0	2222	2426	4176	4329
18-03-15	19:40:16	1982	30	BW	IB116	1	0	0	2687	1802	4301	3627
18-03-15	19:40:47	0	5	BW	IB116	0	0	0	733	1341	900	1809
18-03-15	19:58:37	1064	33	BW	IB116	1	0	0	1915	2083	2965	2817
18-03-15	20:09:28	618	32	BW	IB116	1	0	0	1791	1984	2720	2630
18-03-15	20:37:29	1648	53	BW	IB116	1	0	0	2563	1862	4502	3032
18-03-15	20:50:52	749	35	BW	IB116	1	0	0	2753	1976	3867	2684
18-03-16	08:56:37	0	34	BW	IB116	1	0	0	2109	2307	2925	3172
18-03-16	09:05:06	474	35	BW	IB116	1,1	0	0	2534	2320	3947	4033
18-03-16	09:13:35	474	37	BW	IB116	0,7	0	0	1194	1035	1727	1238
18-03-16	09:16:20	127	11	BW	IB116	0,5	0	0	1273	922	1449	1483
18-03-16	09:44:50	0	7	FW	IB116	0	7	0	53	1965	59	2123
18-03-16	09:53:08	491	50	BW	IB116	0	0	0	1573	1419	2775	1825
18-03-16	10:09:09	910	20	BW	IB116	0,9	0	0	1457	1586	2300	2212
18-03-16	10:10:43	74	11	BW	IB116	0,9	0	0	1532	1127	2272	1420
18-03-16	10:11:10	16	6	BW	IB116	0,5	0	0	1086	958	1591	1128
18-03-16	10:28:27	1031	37	BW	IB116	0,9	2	0	2409	1719	3561	2325
18-03-16	10:37:24	500	41	BW	IB116	0,9	2	0	2076	1784	3506	2163
18-03-16	10:40:31	146	30	BW	IB116	1	0	0	2107	1342	4329	3783
18-03-16	11:00:48	1187	55	BW	IB116	1	0	0	1590	2169	2382	3073
18-03-16	11:08:11	387	32	BW	IB116	1	0	0	1068	1934	1878	2542
18-03-16	11:19:18	635	18	BW	IB116	0,6	0	0	825	1403	993	1664
18-03-16	11:21:28	111	15	BW	IB116	0,5	0	0	1278	1090	2052	1495
18-03-16	12:37:45	0	21	FW	IB116	0	0	0	1000	825	6324	5207
18-03-16	12:52:31	864	46	FW	IB116	1	0	0	3285	2019	5569	2945
18-03-16	12:59:43	385	32	FW	IB116	0,8	0	0	2188	1102	2875	1512
18-03-16	13:06:00	344	25	FW	IB116	0,6	0	0	1801	899	2346	1126

Table D1 continued…

Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
18-03-16	13:08:34	129	34	FW	IB116	1	0	0	2682	1629	3396	1978
18-03-16	13:32:27	1398	34	FW	IB116	0,8	0	0	2934	1347	3928	1918
18-03-16	13:34:46	105	22	FW	IB116	1,1	0	0	3879	1717	5878	2835
18-03-16	13:35:11	3	4	FW	IB116	0	0	0	964	1070	1086	1255
18-03-16	15:05:49	0	33	FW	IB116	1	0	2	3437	1865	4598	2608
18-03-16	15:13:41	438	32	FW	IB116	0,8	0	0	3058	1044	4108	1335
18-03-16	15:39:17	1503	21	FW	IB116	1,5	0	0	3009	1417	6068	2306
18-03-16	15:43:53	255	18	FW	IB116	0	0	2	2186	567	3187	947
18-03-16	15:56:44	753	35	FW	IB116	1	0	2	3045	1658	4455	2372
18-03-16	15:59:55	156	41	FW	IB116	0,6	0	0	1574	702	2009	879
18-03-16	16:16:20	944	49	FW	IB116	1	0	2	3601	1831	6111	2357
18-03-16	16:20:52	222	33	FW	IB116	1	0	0	3287	1540	4568	2167
18-03-16	16:33:14	709	56	FW	IB116	0,8	0	39	1691	462	4583	1270
18-03-16	16:53:40	1169	38	FW	IB116	1	0	3	3611	1879	5139	2870
18-03-16	17:18:07	1429	34	FW	IB116	1,5	0	0	3233	2485	8988	4475
18-03-16	17:28:44	602	37	FW	IB116	0,8	0	0	2793	1110	4232	1874
18-03-16	18:35:03	3942	26	FW	IB116	0,6	0	2	2103	820	2961	1153
18-03-16	18:51:06	936	40	FW	IB116	1	0	0	3716	1684	5537	2215
18-03-16	19:03:18	691	27	FW	IB116	1	0	2	3548	1147	5313	1690
18-03-16	19:09:09	324	58	FW	IB116	0,8	0	0	3073	1241	4300	1683
18-03-16	19:15:07	300	29	FW	IB116	0,6	0	2	1996	558	2453	887
18-03-16	19:48:50	1993	39	FW	IB116	1	0	3	2794	1252	3825	1749
18-03-16	20:00:38	669	41	FW	IB116	0,6	0	3	2000	691	2686	962
18-03-16	20:07:11	352	36	FW	IB116	1	0	2	3130	1784	4749	2716
18-03-16	20:17:01	554	34	FW	IB116	1,5	0	0	3720	2376	7513	3553
18-03-16	20:18:30	54	37	FW	IB116	0,5	0	0	2471	1578	3363	2042
18-03-16	20:22:09	182	37	FW	IB116	0,7	0	0	2167	1468	3339	2432
18-03-16	20:58:05	2118	25	FW	IB116	0,6	0	0	1606	676	2064	802
18-03-17	08:44:06	0	15	FW	IB116	0,8	0	0	2023	1157	3257	1702
18-03-17	08:50:32	371	40	FW	IB116	1	0	0	3237	2195	4935	2908
18-03-17	08:52:33	80	32	FW	IB116	0,8	0	0	2303	1893	4388	3085
18-03-17	09:04:25	679	42	FW	IB116	1	0	0	2968	2343	4410	3158
18-03-17	09:10:36	329	92	FW	IB116	1	0	0	3208	2385	4690	3254
18-03-17	09:13:51	103	13	FW	IB116	0,5	0	0	1694	1317	2343	1921
18-03-17	09:14:56	51	4	FW	IB116	0	0	0	1427	998	1499	1099
18-03-17	10:24:41	4181	35	FW	IB116	0	0	0	2564	1865	4525	2740
18-03-17	10:26:48	92	40	FW	IB116	0	0	0	1870	1097	2244	1613
18-03-17	10:59:33	1924	35	FW	IB116	1	0	0	2785	1633	3879	2318
18-03-17	11:07:39	451	48	FW	IB116	0,9	0	0	2161	1532	3229	1836
18-03-17	11:13:40	312	48	FW	IB116	1	0	0	2518	1909	3813	2635

Table D1 continued…

Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
18-03-17	11:16:41	132	20	FW	IB116	0,7	0	0	2285	1276	3155	1644
18-03-17	11:27:04	603	48	FW	IB116	1	0	0	3354	2097	6845	3278
18-03-17	11:29:00	68	17	FW	IB116	0,6	0	0	1698	940	2608	1335
18-03-17	12:39:37	0	7	BW	IB116	0	0	0	1784	1163	1989	1261
18-03-17	12:49:07	563	33	BW	IB116	1	0	0	1348	1942	1855	2560
18-03-17	12:51:40	120	39	BW	IB116	1	0	0	1490	2485	3437	3648
18-03-17	12:54:50	150	21	BW	IB116	0,7	0	0	1321	1050	2187	1436
18-03-17	13:09:40	869	33	BW	IB116	0,9	0	0	1119	1863	1709	2338
18-03-17	13:12:51	158	26	BW	IB116	0,9	0	0	1141	2074	1653	3143
18-03-17	13:19:05	348	22	BW	IB116	0,8	0	0	1042	1321	1614	1799
18-03-17	13:21:18	111	25	BW	IB116	0,8	0	0	1057	1571	1534	2057
18-03-17	13:34:02	739	30	BW	IB116	1	2	0	1391	2435	2776	3390
18-03-17	13:43:45	552	45	BW	IB116	1	3	0	1668	2553	2811	3107
18-03-17	13:45:43	73	24	BW	IB116	0,6	0	0	1045	1126	1506	1352
18-03-17	13:47:19	72	11	BW	IB116	0	0	0	1249	1332	1885	1859
18-03-17	14:05:37	0	27	BW	IB116	0,6	0	0	1699	1329	2225	1680
18-03-17	14:07:53	108	23	BW	IB116	0,8	0	0	2120	1621	2956	2058
18-03-17	14:14:03	346	39	BW	IB116	1	0	0	2719	2007	4606	3338
18-03-17	14:17:29	167	25	BW	IB116	0,8	0	0	2478	1515	3074	2129
18-03-17	14:22:16	261	44	BW	IB116	1	0	0	2402	2665	3470	3321
18-03-17	14:27:26	265	15	BW	IB116	0	0	0	1345	1270	1705	1561
18-03-17	14:37:12	570	20	BW	IB116	0,8	0	0	1936	1344	3154	1748
18-03-17	14:46:21	529	36	BW	IB116	0,6	0	0	2429	1172	3264	1412
18-03-17	14:51:47	290	34	BW	IB116	0,9	0	0	1802	1654	3326	2160
18-03-17	15:00:06	464	56	BW	IB116	0,8	0	0	1467	2010	2686	2633
18-03-17	15:03:08	125	40	BW	IB116	0,6	0	0	915	1223	1205	1574
18-03-17	15:12:26	518	43	BW	IB116	0,6	0	0	1878	1375	2744	1695
18-03-17	15:19:36	387	27	BW	IB116	0,6	0	0	1581	1110	2083	1453
18-03-17	15:20:58	55	18	BW	IB116	0,5	0	0	1700	1263	2684	2038
18-03-17	15:23:20	124	53	BW	IB116	0,6	0	0	916	1045	1490	1597
18-03-17	15:25:03	49	38	BW	IB116	0,8	0	0	1685	1879	2710	2204
18-03-17	15:30:22	280	39	BW	IB116	0,8	0	0	1628	2356	2313	2843
18-03-17	15:35:17	255	23	BW	IB116	0,6	0	0	1419	1563	2153	2532
18-03-17	15:36:53	72	23	BW	IB116	0,8	0	0	1381	1301	3154	2438
18-03-17	15:47:16	600	45	BW	IB116	0,7	0	0	1406	1552	2269	1720
18-03-17	15:56:30	509	45	BW	IB116	0,8	0	0	1596	2124	2649	2528
18-03-17	15:58:14	58	37	BW	IB116	0,5	0	0	1558	1417	2089	1717
18-03-17	16:05:50	419	20	BW	IB116	0,6	0	0	1653	1396	2361	1794
18-03-17	16:27:45	1294	21	BW	IB116	0,6	0	0	1476	532	1743	650
18-03-17	16:30:41	155	32	BW	IB116	0,6	0	0	1611	1050	2099	1541

Table D1 continued…

Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
18-03-25	16:00:55	0	38	FW	C952-1	0,9	0	0	3762	1979	4795	4051
18-03-25	16:09:18	465	33	FW	C952-1	0,6	0	0	1951	602	2618	771
18-03-25	16:12:56	184	40	FW	C952-1	0,7	0	0	2756	845	3844	1242
18-03-25	16:29:47	971	33	FW	C952-1	0,6	0	0	1972	546	2621	774
18-03-25	16:44:27	846	35	FW	C952-1	0,7	0	0	2609	759	3719	1082
18-03-25	16:46:00	57	6	FW	C952-1	1,5	0	0	3720	2653	5003	3813
18-03-25	17:13:38	1616	33	FW	C952-1	0,9	0	0	3187	1837	4861	2371
18-03-25	17:14:46	34	22	FW	C952-1	0,8	0	0	1814	1642	4952	3138
18-03-25	17:42:35	1646	24	FW	C952-1	1	0	0	4017	2660	5639	3286
18-03-25	18:30:31	2802	23	FW	C952-1	0	0	0	1471	655	1760	1099
18-03-25	18:47:37	1002	38	FW	C952-1	0,7	0	0	2706	1173	3635	1518
18-03-25	18:58:59	644	55	FW	C952-1	0,7	0	0	3244	1718	4835	2712
18-03-25	18:30:31	-1764	23	FW	C952-1	0	0	0	1471	655	1760	1099
18-03-25	18:47:37	1002	38	FW	C952-1	0,7	0	0	2706	1173	3635	1518
18-03-25	18:58:59	644	55	FW	C952-1	0,7	0	0	3244	1718	4835	2712
18-03-25	19:06:39	404	41	FW	C952-1	0,6	0	0	2316	1015	2990	1464
18-03-25	19:16:59	578	23	FW	C952-1	1	0	0	3083	1477	4814	2208
18-03-25	19:43:50	1588	37	FW	C952-1	1	0	0	3610	1720	4995	2234
18-03-25	19:56:17	710	44	FW	C952-1	0,6	0	0	2234	989	3098	1353
18-03-25	20:03:08	366	22	FW	C952-1	1	0	0	4676	2626	6733	3495
18-03-25	20:09:02	333	26	FW	C952-1	0,5	0	0	2158	1112	2833	1340
18-03-25	20:25:13	945	36	FW	C952-1	0,8	0	0	3204	1590	3881	2069
18-03-25	20:32:15	385	21	FW	C952-1	0,5	0	0	1280	845	1531	1042
18-03-25	20:39:21	404	16	FW	C952-1	0,8	0	0	2063	1194	2411	1477
18-03-25	20:43:02	205	91	FW	C952-1	0,8	0	0	2556	1217	3090	1484
18-03-26	09:10:35	0	30	FW	C952-1	0,9	0	2	2480	1760	3956	2522
18-03-26	09:19:21	496	21	FW	C952-1	0,7	0	0	2021	1556	2845	1920
18-03-26	09:25:31	349	20	FW	C952-1	0,9	0	0	2352	1628	3811	2056
18-03-26	09:30:37	285	38	FW	C952-1	1	0	0	2451	2101	3722	2637
18-03-26	09:51:24	1208	29	FW	C952-1	1,1	0	0	2465	1315	3760	1875
18-03-26	09:59:07	434	33	FW	C952-1	0,6	0	0	1504	835	1752	1074
18-03-26	10:04:00	259	19	FW	C952-1	0,7	0	0	1732	880	2246	1112
18-03-26	10:05:20	60	14	FW	C952-1	0,6	0	0	1239	1263	2057	1669
18-03-26	10:06:49	74	21	FW	C952-1	0,5	0	0	1448	612	3897	1784
18-03-26	12:39:48	9158	5	BW	C952-1	0,8	0	5	1110	-112	1199	-58
18-03-26	12:43:42	228	14	BW	C952-1	0,8	0	0	1167	936	1312	1051
18-03-26	13:09:02	1506	19	BW	C952-1	0,8	0	0	1089	1150	1627	1404
18-03-26	13:21:34	733	32	BW	C952-1	1	0	0	1888	1745	3034	2579
18-03-26	14:05:17	2590	29	BW	C952-1	1	0	0	1167	1461	1850	1788
18-03-26	14:14:13	278	9	0	C952-1	0	9	0	-15	1045	-10	1628

Table D1 continued…

Date	Start time [s]	Travel time [s]	Dur. [s]	Dir.	Tst type	Press [bar]	Dly Cast	Dly Comp	Mean Cast [N]	Mean Comp [N]	Max Cast [N]	Max Comp [N]
18-03-26	14:17:29	186	30	BW	C952-1	0,5	0	0	1540	1527	2113	1910
18-03-26	14:52:58	2099	21	BW	C952-1	0,8	4	0	1538	1698	2635	2240
18-03-26	14:59:28	368	20	BW	C952-1	0,6	3	0	1191	1187	1638	1443
18-03-26	15:03:10	202	26	BW	C952-1	0,6	0	0	1112	811	1459	1180
18-03-26	15:10:11	394	23	BW	C952-1	0,7	0	0	1953	1748	2834	2177
18-03-26	15:21:09	634	19	BW	C952-1	0,7	0	0	1303	1073	1655	1314
18-03-26	15:48:39	1631	18	BW	C952-1	0,5	6	0	863	1472	1311	1817
18-03-26	15:56:42	465	25	BW	C952-1	0,6	0	0	1069	523	1434	584
18-03-26	16:00:11	183	39	BW	C952-1	1	2	0	1825	1746	3290	2119
18-03-26	16:03:27	157	24	BW	C952-1	1	0	0	1764	1220	3127	1867
18-03-26	16:22:05	1094	15	BW	C952-1	0,5	5	0	801	1379	1203	1801
18-03-26	16:35:18	777	26	BW	C952-1	1	2	0	2014	1906	3361	2613
18-03-26	16:59:40	1436	25	BW	C952-1	0,5	2	0	1051	1072	1347	1298
18-03-26	17:22:43	1358	4	BW	C952-1	0,5	4	0	378	861	422	915
18-03-26	17:35:13	746	23	BW	C952-1	0,7	4	0	712	1762	1127	2306
18-03-26	18:45:24	4188	7	BW	C952-1	0,5	0	0	891	592	1025	629
18-03-26	19:16:21	1850	27	BW	C952-1	0,7	0	0	1115	1019	1564	1248
18-03-26	19:33:12	360	18	BW	C952-1	0,7	0	0	1078	916	1620	1043
18-03-26	19:51:35	1084	34	BW	C952-1	0,8	0	0	1597	1644	2293	2611
18-03-26	19:56:58	289	26	BW	C952-1	0,7	0	0	931	1033	1196	1264
18-03-26	20:03:55	390	44	BW	C952-1	0,7	0	0	1107	1542	1647	2086
18-03-26	20:12:43	484	18	BW	C952-1	0,7	0	0	1345	1418	1930	2028
18-03-26	20:15:53	172	20	BW	C952-1	0,5	0	0	821	1138	956	1273
18-03-26	20:18:40	146	17	BW	C952-1	0,5	0	0	1180	1269	1494	1575
18-03-26	20:33:45	888	39	BW	C952-1	0,8	3	0	1677	2243	2768	3173
18-03-26	20:34:54	29	35	BW	C952-1	0,5	0	0	1435	1814	1993	2473
18-03-26	20:36:10	41	5	BW	C952-1	0,6	0	0	1717	2675	1951	2994
18-03-26	20:52:39	984	10	BW	C952-1	0,5	0	0	719	1314	791	1610
18-03-26	20:52:58	9	7	BW	C952-1	0,5	0	0	900	1277	1188	1447
18-03-26	20:54:18	72	16	BW	C952-1	0,5	0	0	1739	2196	2176	2640