# COMPARISON OF TOR LUBRICATION SYSTEMS ON THE IRON ORE LINE


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## SUMMARY

The Iron Ore Line (IOL) is a 473 km long track section which is located in northern Sweden and northern Norway, and has been in operation since 1903. The northern part is located above the Arctic Circle. The IOL is mainly used to transport iron ore and pellets from the mines in Kiruna and Malmberget to Narvik Harbour (Norway) in the northwest and Luleå Harbour (Sweden) in the southeast. The track section on the Swedish side is owned by the Swedish Government and managed by Trafikverket (the Swedish Transport Administration), while the ore trains are owned and managed by the freight operator (LKAB).

The IOL has seen a considerable increase in the axle load and traffic volume recently. Due to the introduction of new vehicles with a 30-ton axle load, the rails were gradually replaced between 2006 and 2009 with heavier rails, generally with a steel grade of 350LHT. The rail and wheels suffer from rolling contact fatigue (RCF) due to high friction between the rail and wheel. To control the wheel-rail interface, wayside top-of-rail (TOR) lubrication has been tested.

The reliability of the TOR lubrication equipment and the lubricants in northern conditions has not been investigated, and the long-term maintenance support required for TOR lubrication is unknown to the infrastructure manager. Furthermore, can TOR lubrication reduce the rail and wheel maintenance costs? This project has been conducted through collaboration between the main operator (LKAB) and the infrastructure manager (Trafikverket); the costs have been shared and the results analysed in collaboration.

This paper describes the test period of two years, using two different TOR lubrication systems at two different places on the IOL, one situated in the northern loop and one in the southern loop, each with different operational conditions. The paper shows the actual operational conditions for the pilot test locations, the friction values close to the systems, the rail forces during the test period and some results for the noise measurements. Furthermore, the paper discusses whether improvements of the wheel-rail system resulted from the test operation, and what recommendations can be made for the continued use of TOR lubrication on the IOL.


## 1. INTRODUCTION

This investigation was carried out within the framework of a project conducted from 2013 to 2014 and studied two top-of-rail (TOR) lubrication systems on the Swedish Iron Ore Line (IOL) (Malmbanan). The project has been a collaboration between the infrastructure manager (IM) and the main rolling stock operator on the IOL. The track is owned by the Swedish Government, the IM of the track is Trafikverket, and the traffic on the track is dominated by the ore trains operated by the Swedish mining company LKAB.

The IOL has seen a considerable increase in the axle load and traffic volume recently. Due to the introduction of new, heavier and longer vehicles with a 30-ton axle load, the rails were at the same time gradually replaced with heavier rails; i.e. 50 kg/m rails were replaced with 60 kg/m rails, with a steel grade of 350 LHT. The IOL is the northernmost heavy haul line and part of the line has an arctic climate. Furthermore, the line is the northernmost electrified railway line in the world. The rail and wheels suffer from rolling contact fatigue (RCF) [1], probably due to high friction between the rail and wheel [2]. To control the friction of the wheel-rail interface, wayside gauge face (GF) lubrication and TOR lubrication can be used. There are already GF lubrication units installed on the IOL, and these have recently been complemented and updated.

There are risks involved in introducing lubricants, since they can contribute to speeding up the process of crack propagation through decreasing the friction in the crack face and/or increasing the hydraulic pressure in existing cracks [3], and these risks have to be taken into consideration.

A great deal of research has already been conducted on this topic, for instance laboratory tests of lubricants, field studies on different heavy haul lines, the development of methods for evaluating TOR systems, investigation of the influence of the bar length, etc. [4, 5, 6, 7]. There are results showing that the dynamic forces and the wear of wheels and rails will decrease through the use of TOR lubrication, and that the safety on the track will increase with TOR lubrication through a decrease in the L/V ratio (the lateral forces divided by the vertical forces) [8].

There is a lack of publications dealing with how TOR systems survive in real service in cold and harsh climates with large quantities of snow, as well as publications describing the problems in this connection and comparing different TOR systems.

The IOL consists of two loops, one in the northern area and one in the southern area; one of the test systems is placed in the northern loop, while the other is placed in the southern loop.

This paper compares two different TOR systems, in two different locations, from two different suppliers, and using two different lubricants. The measurements presented concern the track forces, friction coefficients and noise from the trains. Furthermore, the paper considers the maintainability and supportability of the systems and gives recommendations for a further lubrication strategy for the Swedish side of the IOL.

## 2. THE SWEDISH IRON ORE LINE (IOL) – MALMBANAN

The IOL has a gauge width of 1,435 mm and is a 473 km long section of electrified single track located in northern Sweden and northern Norway, mainly above the Arctic Circle, see Figure 1. The main part of the track runs on the Swedish side. The line consist of two loops: the northern loop, whose traffic consists mainly of the flow of iron and pellets from the mines in Kiruna to the harbour in Narvik, and the southern loop, whose traffic consists mainly of the flow of iron and pellets from the mines in Malmberget to the harbour in Luleå. The northern loop has been in operation since 1903 and the southern loop has been in operation since 1888. The whole line was constructed for an axle load of 14 metric tons, but the track has been updated for an axle load of 30 metric tons, and this has generated research [9]. The IOL is highly utilised now and will be utilised more in the future due to an expected increase in the volume of iron transported in the existing form and new forms [10]. To meet the increased demands on the IOL, research is at present being conducted to investigate different possibilities of increasing the capacity of the track [11].

The IOL is a well-maintained section of track; for instance, the rails are ground twice per year for every curve below 650 m in radius, once per year for larger curves, and once every three years for tangent track. The profiles have been developed to fit the heavy haul loads and four different profiles are utilised, as the number of anti-head check-profiles depends on the curve radius.

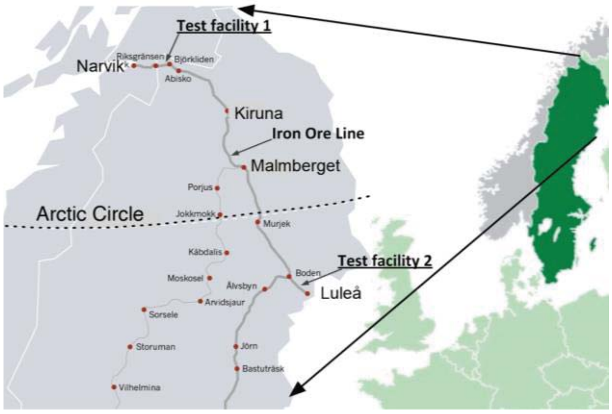


**Figure 1: The Iron Ore Line, located in northern Sweden and Norway, the main part of the line being located above the Arctic Circle. Two test facilities have been used, one in the northern loop and one in the southern loop.**

The climate in northern Sweden is harsh and is characterized by cold winters, large quantities of snow and snowstorms, but the summer can be fairly warm. The temperature can vary to a great extent for the same stretch of track; for example, for the stretch from Boden to Gällivare the temperature can vary by almost 70°C [12]. The snow depth can in some places along the IOL exceed 1 m.

## 3. THE TRAFFIC ON THE IOL

The traffic on the IOL is a mixture of passenger trains, cargo trains and iron ore trains. The axle loads and speeds range from those of light and fast passenger trains to those of heavy and slow iron ore trains. The maximum line speed for the IOL is 130 km/h. The iron ore trains run loaded at 60 km/h and unloaded at 70 km/h on the Swedish side, while on the Norwegian side the corresponding speeds are 50 km/h and 60 km/h. The iron ore trains are owned and managed by the freight operator and mining company LKAB. The trains are pulled by a module consisting of two electrified IORE locomotives, and the length of a train with 68 wagons is 750 m; see Figure 2a for the locomotive and Figure 2b for the wagon. The wheel configuration of the locomotives is three axles on each bogie, while the wagon has three-piece bogies with two axles on each bogie. The total gross weight of a loaded train is around 8,500 metric tons. The axle load for these trains is 30 metric tons and the number of axles is 284. The total number of locomotive modules is 17 and the total number of wagons is 1,130. The maintenance regime for locomotive wheels is explained in [1].

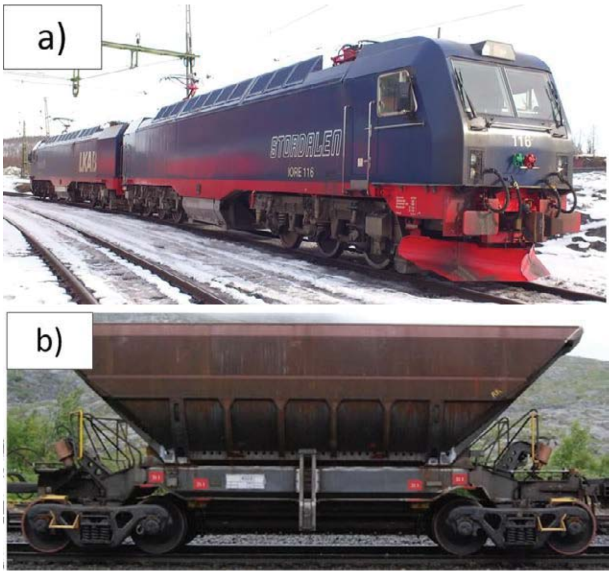


**Figure 2: a) The IORE locomotive.**
**b) The FAMMOORR$^{050}$ iron ore wagon** [13].

The traffic, in terms of the number of trains per day and the million gross tons (MGT) per year, is expected to increase from 2013 to 2018 due to greater ore production from existing and new mines, see Table 1.

| Iron ore trains | No/day 2013 | No/day 2018 | MGT 2013 | MGT 2018 |
|---|---|---|---|---|
| Northern loop | 8 | 12 | 32 | 48 |
| Southern loop | 3-4 | 4 | 14 | 18 |

**Table 1: Traffic volumes on the IOL in 2013 and 2018 for iron ore trains.**

## 4. TOP-OF-RAIL LUBRICATION

There are three different types of friction modifier (FM): 1) low-friction FM for friction coefficients under 0.2 for GF applications for decreasing the wear on the wheel and rail, 2) high-friction FM for friction coefficients between 0.2 and 0.4 for TOR applications resulting in the reduction of energy, noise and vibrations, 3) very high-friction FM for increasing the traction and braking, for instance by using sand [14]. This paper treats only high-friction FM applied on the top of the rail.

TOR lubrication systems lubricate the top of the rail for curves and tangent track, while GF lubrication systems lubricate only the high rail in curves and apply the lubricant around 10 mm below the top of the rail when using Clicomatic [15]. Figure 3a shows the position of the TOR and GF lubricants for the high rail in a curve and Figure 3b shows the position of TOR lubricants on the low rail in curves and both rails in tangent track. GF lubrication is already in use on the IOL and recently the equipment has been updated and complemented. The friction coefficient on the GF should be less than 0.2, while the desired friction with the friction modifier is u=0.3-0.35 [16].

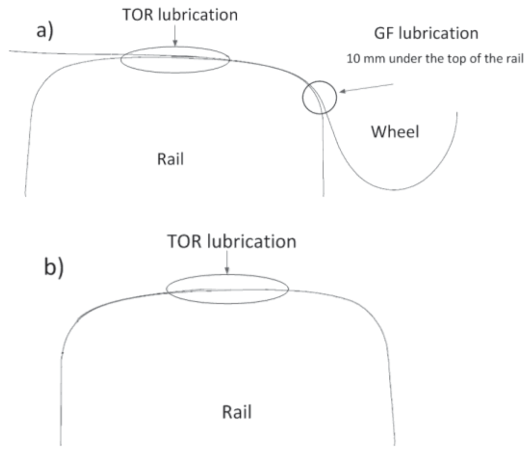


**Figure 3: a) Application of TOR and GF lubricant on the upper rail in curves.**
**b) Application of TOR lubricant on the low rail in curves and on tangent track on both rails.**

The FM has a positive friction, which means that a larger slip gives a larger friction coefficient. A test has been carried out which has shown that, in a traction force-creep diagram, FM gives the shape of a positive friction behaviour, GF lubrication gives a shape that is more like the shape of a friction behaviour between positive and negative friction, and dry contact between the wheel and rail gives the shape of a negative friction behaviour [17]. Figure 4 shows a sketch of a three-body-layer interface traction-creep curve, illustrating friction behaviour with a positive, a neutral and a negative curve. The figure also shows the contact area of the slip condition within the phase between free roll to full slip [18]. The full slip condition starts around 0.01-0.02 in creep [18]. Positive friction behaviour eliminates the slip-stick phenomena, which entail many disadvantages [19].

There are both on-board and wayside types of TOR equipment, but this paper deals only with wayside TOR equipment. On-board TOR equipment is placed on the trains and can lubricate a whole track section, while wayside TOR equipment can only lubricate part of a track section and is often located in critical track sections.

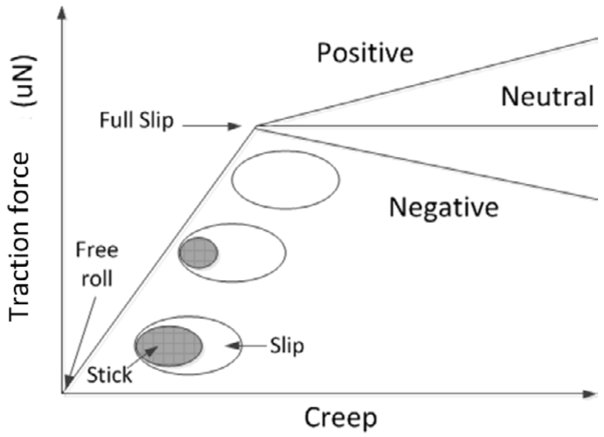


**Figure 4: Different types of friction behaviour, adapted from [19, 20].**

On the market there are many different suppliers of FM for railway applications, and some examples can be found in Table 2. For the tests performed in the present research study, two FMs were selected, the Whitmore TOR ARMOR™ friction modifier and the KELTRACK® top-of-rail friction modifier.

The reason for choosing these two lubricants and the QHi Rail and L.B. Foster systems was that in the one case the equipment and FM were already in use in Sweden, and in the other case the equipment and FM had already been extensively utilised in heavy haul applications in other countries.

The types of GF lubricants recommended for use on the Swedish railway can be found in [15].

| TOR Equipment | Friction Modifier (FM) |
|---|---|
| QHi Rail | TOR ARMOR, Whitmore |
| L.B. Foster | KELTRACK |
| Loram | TOR-FM™ FRICTION MODIFIER |
| ELPA, CL-E1 TOP | TORAX - Top Of Rail Anti X |
| HY-Power | TRAM-SILENCE, Fuchs |
| Lincoln | |

**Table 2: Some examples of TOR equipment and FM that can be found on the market.**

## 5. TEST FACILITIES

The tests for the present study were performed at two different facilities, one in the northern loop of the IOL and one in the southern loop of the IOL. Test facility 1 is situated above the Arctic Circle and close to the Norwegian border at Tornehamn, where there are arctic conditions with large quantities of snow and strong winds. Test facility 2 is located at Sävast, in the southern loop of the IOL, and the climate here is friendlier, with smaller amounts of snow. Figure 1 shows the locations of test facility 1 and 2, and the road distance between these facilities is around 480 km. The mean temperatures for facility 1 and 2 differ, and Table 3 shows the mean temperature for each month, as well as the mean temperature per year (for the one-year period from September 2013 to August 2014). For both facilities the coldest mean temperature appeared in January, while the warmest month was July. The coldest and hottest measured temperatures during this one-year period for facility 1 were -31.4°C and 28.4°C, while for facility 2 the corresponding values were -32.8°C and 30.9°C. The precipitation is shown in the table as a relative value, with the yearly precipitation for facility 2 being denoted by 1(normalized to 1), which means, for instance, that for facility 2 the mean precipitation for December represents 24% of all the precipitation for this one-year period. Furthermore, the total precipitation of the period for facility 1 was 171% of that for facility 2. The largest precipitation for facility 1 fell in November, while the largest precipitation for facility 2 fell in February.

| | Temperature | | Precipitation | |
|---|---|---|---|---|
| Year-Month | Fac.1 | Fac.2 | Fac.1 | Fac.2 |
| 2013-09 | 6.85 | 9.82 | 0.10 | 0.02 |
| 2013-10 | -0.06 | 2.27 | 0.16 | 0.03 |
| 2013-11 | -4.55 | -4.44 | 0.43 | 0.12 |
| 2013-12 | -5.54 | -5.33 | 0.35 | 0.24 |
| 2014-01 | -15.01 | -13.18 | 0.05 | 0.16 |
| 2014-02 | -5.31 | -2.55 | 0.05 | 0.26 |
| 2014-03 | -5.57 | -1.50 | 0.28 | 0.07 |
| 2014-04 | -1.57 | 1.31 | 0.21 | 0.01 |
| 2014-05 | 2.14 | 7.96 | 0.03 | 0.02 |
| 2014-06 | 8.19 | 12.12 | 0.02 | 0.01 |
| 2014-07 | 16.64 | 19.47 | 0.01 | 0.02 |
| 2014-08 | 10.51 | 15.20 | 0.01 | 0.04 |
| Mean/tot. per year | 0.56 | 3.43 | 1.71 | 1.00 |

**Table 3: The mean temperatures and the precipitation for facility 1 and facility 2 for the one-year period and for each month from September 2013 to August 2014.**

Figure 5 illustrates the influence of the precipitation during the winter season on the TOR equipment at facility 1, showing unit no. 2 in the open area. The snow influences the maintainability in that one needs to shovel snow away from the unit to be able to perform inspections and maintenance activities.

**Figure 5: TOR equipment at facility 1 in April 2014.**

### 5.1. Facility 1, Tornehamn

The track at Tornehamn dates from 2006 and its components are 60 kg/m rail with a steel grade of 350 LHT, concrete sleepers and elastic fastenings with an inclination of 1/30.

This facility was chosen due to the hard climate of its location and the large amount of traffic from iron ore trains. Moreover, the track sub-section here consists of small curves, a tunnel and a snow shield, and is a sub-section typical of the northern loop of the IOL, see Figure 6. At the bottom of the figure is the km-scale, and the TOR units are placed at 1,519 km and 1,520 km, the first in a tunnel and the second in an open area close to the GF lubrication unit, according to the recommendations of the supplier. The figure shows a section of 4 km which includes 12 curves. An advantage of this position is its accessibility from the road and, therefore, the fact that it is easier to maintain the TOR unit.

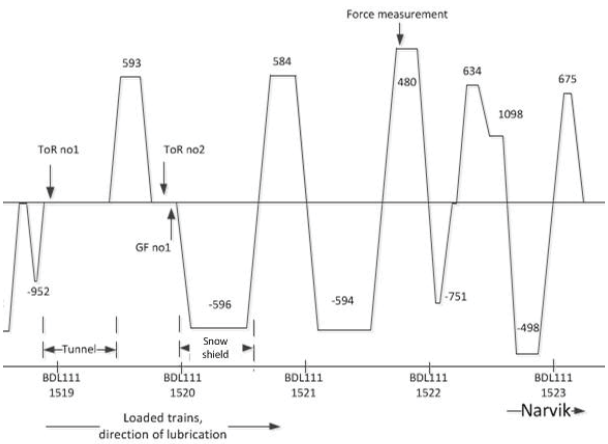


**Figure 6: The track geometry of test facility 1, loaded trains running in the direction towards Narvik.**

The existing GF lubrication system was replaced with one from the same supplier as that of the TOR unit. This equipment is powered by electricity. The TOR equipment is equipment A with lubricant A. The loaded trains roll towards Narvik, i.e. in same direction as the direction in which the TOR equipment works. The annual tonnage of the track section is over 30 MGT. The rail force measurements were recorded around 2.5 km from the TOR equipment by strain gauges placed on the rail. The number of curves in the northern loop larger than 500 m is ten and the number of curves smaller than 600 m is 78. In the northern part of the IOL, 79% of the track consists of curves [18].

### 5.2. Facility 2, Sävast

The track at Facility 2 dates from 1994; in the first curve after the TOR equipment, the low rail was replaced in 2013 and the high rail was replaced in 2011. The track components are 60 kg/m rail with a steel grade of 350 LHT, concrete sleepers and elastic fastenings with an inclination of 1/30.

This test section consists of larger and fewer curves than facility 1, and close to the TOR unit is the smallest curve in this area with a curve radius of -484 m, see Figure 7. At the bottom of the figure is the km-scale, and the TOR unit is placed at 1,153 km. The figure shows a section of 5 km which includes 5 curves. This area is representative of the southern loop of the IOL. Other reasons for choosing this area were its good accessibility and the fact that the curve has an installation for track force measurement and already existing equipment for GF lubrication from the same supplier. The TOR equipment is equipment B with lubricant B, and the equipment is powered by a battery that is charged by a solar panel and an electric generator driven with wind-energy. Loaded trains roll towards Luleå, i.e. in the same direction as the direction in which the TOR equipment works. The annual tonnage of the track section is around 20 MBT. The distance from the TOR unit to the track force measurement point is around 300 m. In the southern part of the IOL, 35% of the track consists of curves [18].

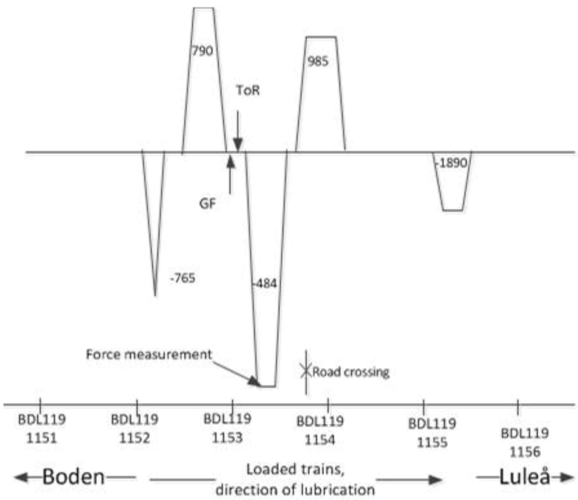


**Figure 7: The track geometry of facility 2, loaded trains running in the direction towards Luleå.**

## 6. MEASUREMENTS

Many different types of inspections and measurements are utilised to verify the impact of lubrication, and the present study utilised friction, track force and sound measurements.

### 6.1. Friction

The friction was measured frequently during the test period with a hand-pushed tribometer, see Figure 8 [21].

The hand-pushed tribometer shows good agreement with other laboratory equipment for friction measurement [21]. This tribometer is a conventionally used friction measurement instrument in this area and has been used in many research studies. The instrument is operated by one person, has a wheel that brakes and measures the friction between the wheel and the rail, and displays the friction value on a screen. The tribometer screen shows a new value every two seconds. The friction was measured before applying the FM and during the operational phase on the top of the rail, as well as on the GF. The extent to which this represents the real friction of a train in operation has not yet been investigated.

**Figure 8: The manually pushed tribometer used to determine the friction.**

Figure 9 shows the measurements of the friction coefficient made at Facility 1 on 7 October 2014, i.e. after 17 months of service. More information about the boxplot can be finding in the ref [22]. The left-hand-side (LHS) and right-hand-side (RHS) rail measurements (LHS(1) and RHS(1), respectively) were made along a stretch running from the TOR equipment and 600 m in the direction towards Narvik. Then a reference measurement of the friction coefficient (Ref(LHS)) in Figure 9 was made far away from the TOR equipment. There was a difference between the left and the right rail due to friction. The friction coefficient was higher on the left rail and the spread of the friction coefficient on that rail was smaller. The right rail had a larger spread of the friction coefficient and the mean value of its friction coefficient level was lower than that of the left rail. The reference measurement was only performed on the left rail and showed a smaller spread of the friction; the mean value concerns the right and left rails close to the TOR equipment.

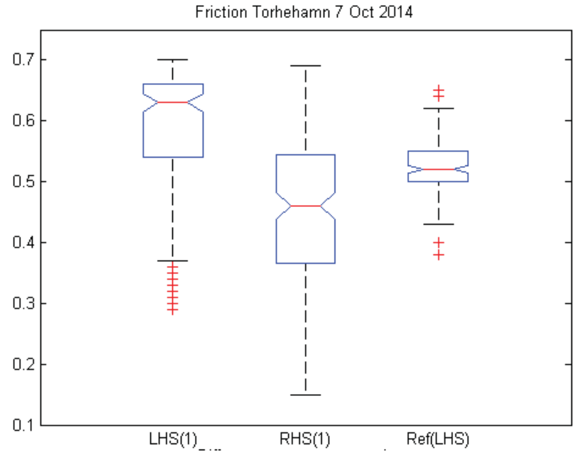


**Figure 9: Friction coefficient measured at facility 1 on 7 Oct. 2014.**

Figure 10 shows the measurements of the friction coefficient made at facility 2 on 9 October 2014, i.e. after the TOR equipment had been in service for 17 months.

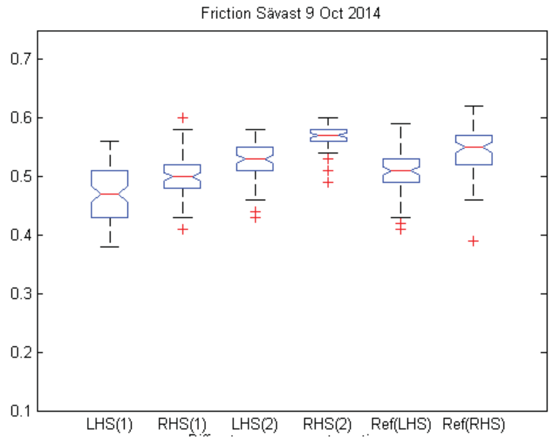


**Figure 10: Friction coefficient measured at facility 2 on 9 Oct 2014.**

The LHS and RHS rails were measured along a stretch running from the TOR equipment and 600 m along the track; there is also a reference section far away from the TOR equipment. All the measurements were performed in the direction towards Luleå; LHS(1) and RHS(1) were made 0-300 m from the TOR equipment, while LHS(2) and RHS(2) were made 300-600 m from the TOR equipment. The reference measurements, Ref(LHS) and Ref(RHS), were performed around 8 km from the TOR equipment. The LHS rail had a lower friction in general, close to the equipment, 300 m from the equipment, and even 8 km from the equipment. Close to the equipment the friction was lowest, while 300 m from the equipment the friction was higher or at least the same as that on the reference section. The outliers (marked with "+" in the figure) indicate points with low friction which may have been due to the train's on-board system for gauge corner lubrication. The friction coefficient spread a great deal close to the TOR unit and less 300m from the unit. The RHS rail had a higher friction coefficient in general, and here too the reference measurements showed a lower friction coefficient than the measurements made in the section between 300 m and 600 m from the TOR equipment.

### 6.2. Rail Forces

At each test site the high rail and low rail forces were measured by strain sensors; for more information on this, see [23]. The forces for all the leading wagon axles of all the iron ore trains were measured. The left-hand curves generated negative lateral forces and the right-hand curves generated positive lateral forces, in accordance with the established behaviour of right-hand and left-hand curves.

At facility 1 the rail forces were measured around 2,500 m from the TOR equipment in the middle of a 480 m curve; Figure 6 shows where the measurement position was situated. Figure 11 shows the L/V for two different dates, the first of which was before the TOR lubrication started, while the second was after the TOR lubrication system had been in service for one year. The dashed line shows the zero value, the closer to the zero the better. For the low rail the mean value is the same for these two measurements, while for the high rail the mean value of the L/V ratio changes, and the value after one year of service is smaller than that before the start of TOR lubrication; in other words the value of L/V decreases after one year of service for facility 1.

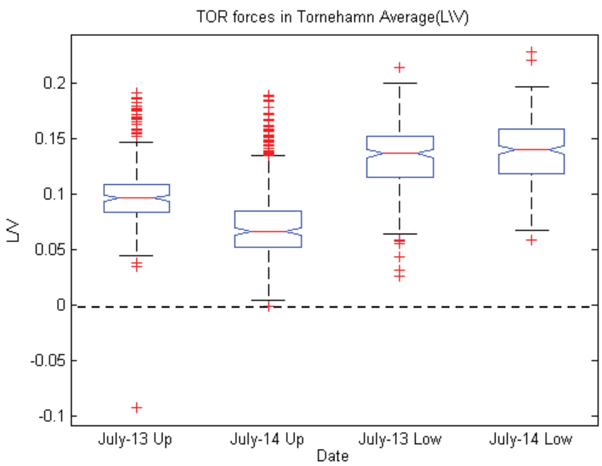


**Figure 11: The average L/V for facility 1, before the start of TOR lubrication and after one year of service.**

At facility 2 the rail forces were measured around 300 m from the TOR equipment in the middle of the 484 m curve; Figure 7 shows where the measurements were performed. Figure 12 shows the L/V for the high and low rail for three different dates, the first of which was before the TOR lubrication started, the second of which was after the TOR lubrication system had been in service for one year, and the third of which was after the TOR lubrication system had been in service for one year and three months. For the low rail the mean value is approximately the same for all three measurements, while for the high rail the mean value of the L/V ratio changes more. Before the start the value is closest to zero, after one year of service the value is further away from zero, and after one year and three months the value lies between the value at the start and the value after one year of service.

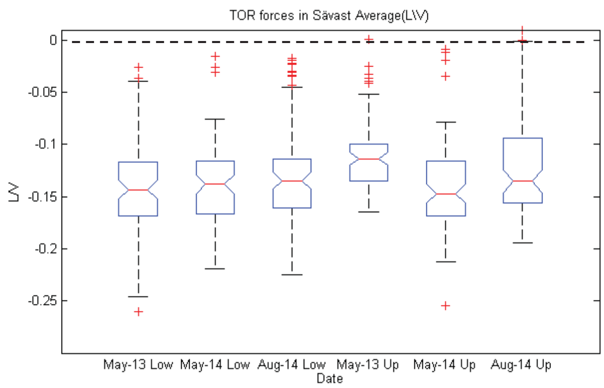


**Figure 12: The average L/V for facility 2, before the start of the TOR lubrication, after one year, and after one year and three months.**

### 6.3. Sound Measurements

Sound measurements were carried out at Facility 2 in May 2013 to verify the impact of FM lubricant on the noise from trains. Previous research has shown that FM lubricant can reduce the noise from the wheel-rail interface [24].

This noise is generated in different parts of the interface and can be divided into the following categories: rolling noise, flat spot noise, ground-borne vibrations, structure-borne noise, TOR squeal and flange noise. The noise acts at different frequencies, and Table 4 shows the frequencies for each noise category.

| |
|---|
| Rolling noise 30-5000 |
| Flat spot noise 50-250 |
| Ground-borne vibrations 4-80 |
| Structure-borne noise 30-200 |
| TOR squeal 1000-5000 |
| Flanging noise 5000-10000 |

**Table 4: Noise types and frequencies (Hz) [24].**

The test curve has a radius of -484 m, and the sound was recorded one day before the application of the lubricant and after the application of the lubricant. The lubricant was applied with rollers on the rail head. The total number of trains subjected to sound measurements was 31, 14 before applying the lubricant and 16 after applying the lubricant. This test was carried out according to the standard EN ISO 3095:2005. Two types of sound measurements were performed. One microphone setup was used to measure the whole train sound according to the standard, in such a way that two microphones, one on each side of the track, were positioned 7.5 m from the track centre and 1.2 m above the top of the rail head. The other microphone setup involved the placement of two microphones, one on each side of the track, 0.5 m from the rail to catch the wheel-rail noise, see Figure 13. Measurements of the vibration from the wheel-rail interface were also performed by an accelerometer installed on each rail web.

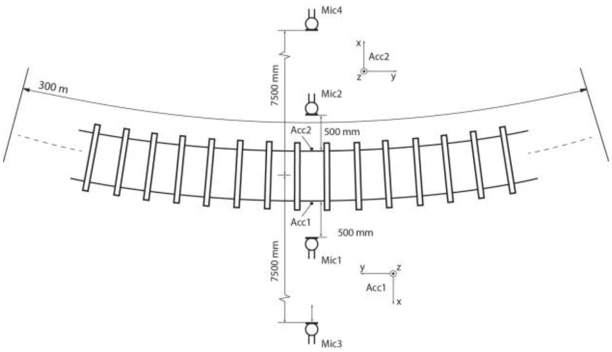


**Figure 13: The measurement setups illustrating the mounting for Mic. 1-4 and Acc. 1 & 2 [25].**

### 6.4. High-speed Filming

To verify if the lubricants would stick on the wheel, high-speed filming of wheels was carried out when they passed the lubrication bars. This was performed for the equipment at facility 2 in November 2013 using a high-speed camera and additional lights. The camera was a regular high-speed camera and the additional lights were three Bosch Big Knick car lights mounted on a camera stand and powered by a car battery. The film shows that the wheel is in connection with the lubricant and picks it up from all four nozzles, see Figure 14.

**Figure 14: High-speed filming of train wheel passing over the TOR unit at facility 2.**

## 7. SUMMARY

This section summarises the activities treated in this paper, namely friction measurements, rail force measurements, sound measurements, maintenance of the equipment, and improvement of the wheel-rail system using TOR lubrication.

### 7.1. Friction

The friction was measured with a tribometer which has high precision, but its accuracy compared to the real friction between the wheel and rail is unknown. It cannot be excluded that the level of friction coefficient measured by the tribometer is not in agreement with the real level of friction coefficient encountered by the train. Furthermore, we cannot assume that at places where we have measured a high level of friction, there is not any FM lubrication on the track. The friction varies a great deal close to the TOR unit and even on the reference sections. It is not possible to conclude that high friction means the absence of FM lubricant on the rail, and here we need more research. More information on the friction measurements performed in this project can be found in [2].

### 7.2. Rail Forces

The TOR lubrication performed at facility 1 gave good results for L/V. For the low rail, there is not any difference in the L/V, but for the high rail the results are positive in that the L/V ratio decreases with TOR lubrication. Facility 1 shows improvements of the L/V, in contrast to facility 2, and one reason for this may be that there are two TOR units mounted at facility 1 and only one at facility 2. The setup at facility 1 may improve the carrying distance of the lubricant. The rail forces at facility 2 are not changed by the TOR lubricants in a positive manner. The low rail almost has the same L/V and TOR lubrication of the high rail seems to have a more negative influence on the L/V, with the absolute value increasing.

### 7.3. Sound

The sound was only measured at facility 2. The curve where the measurement was carried out has a radius of -484 m and does not suffer from high noise levels. The sound from some frequencies for some trains decreased through the use of the TOR lubrication. The effect was largest for frequencies above 3 kHz and the passenger trains, which operate at higher velocities than the iron ore trains [25]. More research is needed to investigate the effect of TOR lubrication on noise generation in smaller curves.

### 7.4. Maintenance of the Equipment

The TOR equipment needs supporting maintenance for it to work properly, and there were many times when the equipment at facility 2 went dry. The existing maintenance organisation seems to have problems handling this new equipment, due to a lack of routines and experience of TOR systems. Here there is a need for more information and preparation of the maintenance organisation to get the maintenance to work at the level required. The maintenance activities consisted of refilling the lubrication tank, adjusting the lubrication bars, and replacing the strip on the lubrication bars. In the winter season the maintainability of the equipment placed at facility 1 in the open area was hampered due to large amounts of snow. One needs to take this difficulty into account when placing the equipment, in order to avoid maintainability problems.

### 7.5. Improving the Wheel-rail System

As yet, no significant improvement of the wheel-rail system through the use of TOR lubrication has been detected at these two test facilities. Further investigations need to be performed on the system level in such a way that all the relevant activities are included, such as the operation and maintenance of the wheel, the rail and the TOR equipment.

## 8. CONCLUDING REMARKS

All these results need to be put in the context of the environment, the track and the traffic on the IOL. It is not possible to state that more research and deeper analysis of the data will give another picture of the results. Based on this investigation, the conclusion to be communicated to the IM is that we have not, as yet, been able to find a reason for implementing TOR FM lubrication on the IOL. More research needs to be carried out to determine when TOR FM lubrication will give advantages and reduce the LCC for the wheel-rail system.

One reason why there is no big difference between the situation before and the situation after the application of TOR FM on the IOL may be the good wheel and rail maintenance which is already being practised. The rails are well maintained through re-profiling twice every year in curves below 600 m, while the wheel profiles receive good maintenance through the re-profiling of wheels based on information from manual inspections and automatic scanning by a wheel profile measurement system [26]. This good maintenance of the wheel-rail system gives good steering and ride comfort on the track, and results in only a small dynamic component being transferred from the train to the track.

### 8.1. Further Work

A future project will start through cooperation between the Swedish IM, the Norwegian IM and Luleå University of Technology, with the aim of delving deeper into this research area, ascertaining when TOR lubrication is financially feasible, and determining the requirements for the implementation of TOR lubrication and the criteria for successful implementation.

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