

## AN EXPERIMENTAL STUDY OF THE INFLUENCE OF THE AMOUNT OF TOP-OF-RAIL FRICTION MODIFIERS ON TRACTION

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### ABSTRACT

*This study presents an experimental study of the effect of Top-of-Rail Friction Modifiers (TORFM) in quantities ranging from a small to a large amount on the progression of wheel-rail wear, using the Virginia Tech-FRA (VT-FRA) roller rig. TORFM behaves as a third body layer in between the wheel and rail and is applied to reduce wheel and rail wear while preserving a stable traction condition. An added benefit of TORFM is that it is estimated that it can reduce fuel consumption by controlling friction, although we are not aware of any proven data in support of this. Although widely used by the U.S. Class I railroads, there exists no proven method for determining, qualitatively or quantitatively, how the amount of TORFM and rail/wheel wear are related. Simply put, would increasing TORFM amount by a factor of two reduce wheel/rail wear and damage by one-half? How would such doubling effect traction or the longevity of TORFM on the wheel/rail surface? In this study, the VT-FRA roller rig is used to perform a series of tests under highly controlled conditions to shed more light on answering these questions. A series of controlled experiments are designed and performed in order to investigate the potential factors that may influence the traction performance. The wheel surface profile is measured by a high-precision, 3D, laser profiler to measure the progression of wheel wear for the duration of the experiments. The results indicate that it takes as much longer time for the traction force (traction coefficient) to reach a condition that is the same as the unlubricated rail, when compared between lightly-, moderately-, and heavily-lubricated conditions. The results further indicate that wear generation is delayed significantly among all lubrication conditions—even,*

*the lightly-lubricated—when compared with the unlubricated conditions. A further evaluation of the results and additional tests are needed to provide further insight into some of the preliminary results that we have observed thus far.*

Keywords: VT-FRA Roller Rig, Top-of-Rail Friction Modifier (TORFM); Wheel and Rail Wear; Traction and Adhesion; Third Body Layer

### 1. INTRODUCTION

Traction is one of the most critical parameters in wheel-rail contact since it determines the ability to provide the draw forces that are needed to operate a train on a steel rail. Good adhesion provides the ability to not only propel the train but also bring it to stop. Poor traction can lead to wheel sliding on the rail surface during the traction/braking, causing surface damages.

The wheel-rail traction is affected by many factors, including vehicle speed, axle load, temperature, surface roughness, and the presence of a third body layer. The third body layer such as water, oil, sand, and top-of-rail friction modifier (TORFM), exists between wheel and rail and it has a significant influence on the wheel-rail traction performance and wear progression [1].

Researchers have been investigating the adhesion condition with third body layers for a long time. Wang et al. [2] investigated the adhesion behavior of wheel/rail under dry and water conditions through a wheel-rail simulating facility and found that the water lubricant condition gave the lower values of the adhesion coefficient while the dry condition gave the higher values. Zhu et al. [3] investigated the influence of surface

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roughness on the adhesion coefficient with water and oil as lubricants, and results showed for rougher contact surfaces, the water-lubricated tests showed a higher adhesion coefficient than oil-lubricated ones do. Chang et al. [4] performed an experiment to study the adhesion characteristics at high speed under the water lubrication and showed that the water spray amount, the roughness of the wheel-rail contact surface and running speed have more significant influence than the water spray temperature and axle load. Liu et al. [5] measured the lateral adhesion ratio under dry and wet conditions using a two-disk test rig, and the results showed that after the application of water, the lateral adhesion ratio decreases. Arias-Cuevas et al. [6] investigated the influence of the number of sanding axles, the particle size of sand, and wheel slip on the adhesion recovery in leaf-contaminated wheel-rail contacts. The results showed that the application of sand contributes to removing the leaf layers from the disc surfaces, which leads to a higher adhesion coefficient in comparison with the untreated situation. Furthermore, a large particle size of the sand yields a higher adhesion coefficient, but it may bring more wear depending on the slip [7]. Huang et al. [8] studied the influence of sanding on adhesion and rolling contact fatigue of wheel/rail under wet conditions. The results demonstrated that with the particle diameter and feed rate of sand increasing, the adhesion coefficient increases, and the hardness of the wheel and roller after testing shows a relatively downward tendency.

Friction modifier, a human-added third body layer, is an engineered lubricant specially designed for providing specific and stable friction characteristics for traction and braking. It is a water-based particle suspension that evaporates in the contact leaving the solid particles behind to mix with the third-body layer presented on the railhead [9]. Researchers have been actively investigating this artificial third body layer from various perspectives for more than a couple of decades. Tomeoka et al. [10] developed an on-board lubrication system, which can spray friction modifier from a bogie to the top of rail accurately, and during the track test, one friction modifier was identified to reduce the wheel/rail force effectively. Matsumoto et al. [11] systematically tested the bogie curving performance with friction modifiers and results indicated that friction modifiers can reduce the lateral force of front-outside wheel and longitudinal forces of rear wheels. Arias-Cuevas et al. [12] experimented with friction modifiers in dry and wet conditions with a 1:1 twin-disk rig. The results showed that the adhesion coefficient with friction modifier is high in dry conditions compared with that in wet conditions. Although the friction modifier is already widely used on the railroads worldwide, there exists no proven method for measuring, qualitatively or quantitatively, how the amount of TORFM and rail/wheel wear are related, beyond the anecdotal information.

In this paper, an experimental study of the effect of Top-of-Rail Friction Modifiers (TORFM) in quantities ranging from a small to a large amount on the traction and the progression of wheel-rail wear has been performed using the Virginia Tech-FRA (VT-FRA) roller rig. A series of highly controlled experiments are performed in order to investigate the potential factors related

to the quantities of friction modifiers on the traction performance. Besides, the wheel surface profile is measured by the high-precision 3D-laser profiler to measure the progression of wheel wear for the duration of the experiments. The results indicate that it takes a much longer time for the traction forces (coefficients) to reach a condition that is the same as the unlubricated rail, when compared between lightly-, moderately-, and heavily-lubricated conditions. The results further indicate that wear generation is delayed significantly among all lubrication conditions—even, the lightly-lubricated—when compared with the unlubricated condition.

The rest of the paper is organized as follows. Section 2 presents the experimental setup and procedures. Section 3 presents the experimental results and analysis. Section 4 summarizes the conclusion.

## 2. Experimental Setup and Procedures

The experiments performed in this study were conducted using the state-of-the-art VT-FRA roller rig, a high precision equipment to emulate the actual wheel-rail interaction, as shown in Figure 1. The wheel is 1:4 scaled in diameter of the actual wheel, and the roller is five times larger than the wheel, which minimizes the contact patch distortion leading to an accurate imitation of the wheel-rail interface [13]. The relative velocity of the wheel and roller can be controlled precisely by the two AC motors. A 3D laser scanner is integrated into the roller rig, as shown in Figures 1b and 1c, to enable continuously measuring the wheel surface conditions during each experiment.

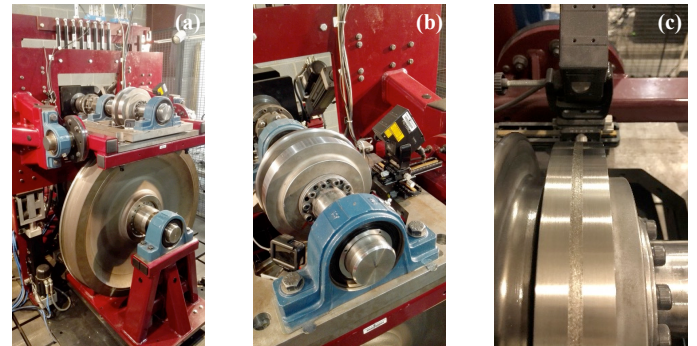


Figure 1: (a) VT-FRA roller rig [14]; (b) 3D laser scanner: side view; (c) 3D laser scanner: top view

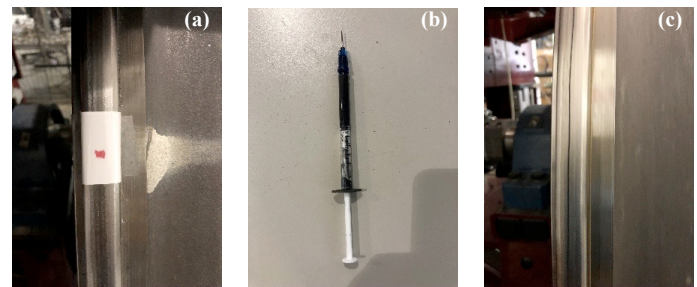


Figure 2: (a) pressure-sensitive film shows the contact band on roller; (b) selected syringe with 1.0 cc capacity; (c) a certain amount of friction modifier was applied evenly on the rotating roller surface

Table 1 summarizes the test procedure for a single experiment with 2% creepage at a speed of 3 km/h. The first step is to use sandpaper to redress the wheel surface so that each experiment begins with a smooth and clean surface condition. Different grades of sandpapers, from lower (coarse) grades to higher (fine) grades, are used to remove any uneven grooves left from previous experiments. Secondly, for each experiment, since the wheel diameter might have a tiny change after surface redressing, the roller rotational speed needs to be re-calibrated. This could be achieved by observing the longitudinal force until the force reaches nearly zero by adjusting the roller rotational speed. The purpose of zeroing the creepage at this step is to accurately formulate the later 2% creepage testing in step 5. In the third step, a pressure-sensitive film, shown in Figure 2a, is attached and taped on the roller surface. By bringing the roller and wheel surface into contact, we can clearly see the contact location and therefore, apply the friction modifier on the contact band of the roller surface. In step 4, a small syringe with 1.00 cc capacity and 0.02 cc resolution is selected as the tool to apply the friction modifiers on the surface of the freely rotating roller. A blunt needle is used together with the syringe so that the application of the friction modifier can be controlled better. Different quantities of the friction modifiers are applied on the roller surface in every individual experiment. In step 5, the roller and the wheel are brought into contact. By adjusting the wheel rotational speed, a 2% creepage can be precisely controlled, and the traction data can be recorded by the built-in DAQ system. It is worth mentioning that due to the limitation of the memory capacity of a single measurement, the data file needs to be saved every 250 seconds; therefore, in order to reach the desired 60-min testing, 15 consecutive short tests need to be performed for a single experiment. In step 6, isopropyl alcohol, hydrogen peroxide, and deionized water are used to fully clean the

generated third body layers attached on the wheel and roller surface after the experiment. The last step is to perform the analysis for the traction data. There are three surface images taken during a single experiment: after step 1, step 2, and step 6. Figure 3 shows a sample of three measurements captured by the laser scanner. It should be noted that a darker color represents a deeper surface profile. As indicated in Figure 3c, a clear wear band can be generated after the 60-mins experiment.

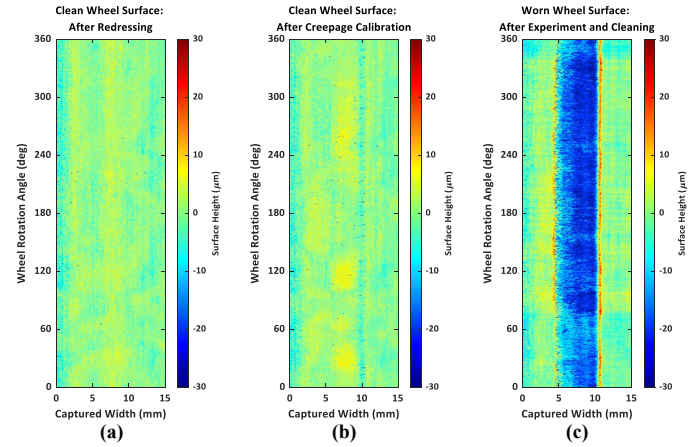


Figure 3. Surface images captured by the built-in laser scanner: (a) surface image after the surface redressing; (b) surface image after the zero creepage calibration; (c) surface image after the experiment and cleaning

Table 1. Experimental procedures for a single experiment

#	Step Name	Tool	Description	Laser Measurement
1	Surface Redress	Sandpapers	Use sandpapers (grade 40 -220) to remove the groove and smooth the surface	✓
2	Calibrate 0% Creepage	MotionScope	Zero longitudinal force by adjusting roller velocity counts to get accurate 2% later	✓
3	Find Contact Location	Sensitive Film	Attach the film on the roller and bring in contact to get the location of the band	
4	Apply TORFM	Syringe	Apply a certain amount of TORFM on the freely rotating roller (out of contact)	
5	Traction Test	Roller Rig	2% creepage, record data every 250s until reaching 60 mins	
6	Clean TORFM	91% isopropyl alcohol; 3% hydrogen peroxide; deionized water	Three-step cleaning to remove the TORFM completely	✓
7	Analyze Data	Matlab	Analyze the longitudinal force and coefficient and wear	

### 3. Experimental Results and Analysis

A series of controlled experiments were performed to investigate the traction condition under different TORFM lubricated conditions at the simulated speed of 3 km/h. The experiments were conducted using a cylinder wheel with zero angle-of-attack (AOA) and cant angle under approximately 10 kN wheel load at 2% creepage. A heavy amount of TORFM (0.5 cc), a moderate amount of TORFM (0.1 cc) and a light amount of TORFM (0.02 cc) were applied to the contact band of the roller surface in the lab testing. The unlubricated experiment with dry and clean wheel surface condition was also conducted for comparison. Three experiments were performed for every different lubricated condition and each experiment follows the procedures described in Section 2.

#### 3.1 Surface Condition After Experiment

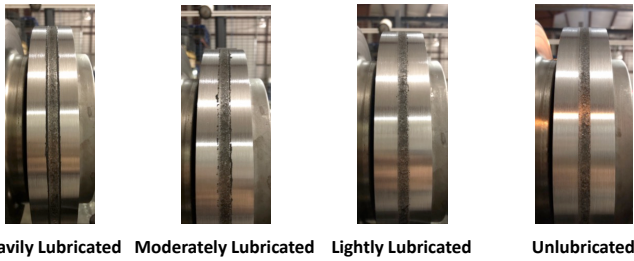


Figure 4. Surface images after performing the experiment without cleaning

Figure 4 shows the examples of surface image after the experiment with different lubricated conditions but before the surface cleaning. It can be noticed that, for the heavily-lubricated case, there was an excessive amount of friction modifier accumulated at the two edges of the contact band, which means some portion of the friction modifier applied on the contract band was migrated out of the band. As the amount of applied TORFM decreased, the friction modifier accumulated at the contact band edges decreased, showing that more proportion of the applied TORFM remained on the contact band. As shown in Figure 4c, for the lightly-lubricated case, there was only a tiny amount of friction modifier observed on the edges of the contact band,

indicating that most of the applied friction modifiers remained in the running band and got involved in the wheel-rail interactions during the one-hour experiment. Figure 4(d) displayed a clear wear band on the wheel surface in the unlubricated condition.

#### 3.2 Traction Coefficient

Figure 5a demonstrates the obtained traction coefficients under different (unlubricated, lightly-, moderately-, and heavily lubricated) conditions with friction modifiers. The longitudinal traction coefficient is defined as the ratio of the longitudinal force and the wheel load. Three experiments were performed for every case, and the traction curves shown are the averaged results. As we can see, the traction coefficient of the unlubricated case rises quickly to a peak value of around 0.5 at the beginning and then descends for a short period of time, ending up rising again to reach a plateau that continues for the duration of the test. The rise time at the beginning is about 7 mins. With friction modifiers, however, the traction coefficient curves behave distinctively different from the unlubricated case. The rising time in the lubricated condition is much longer and it needs significantly more time to reach the plateau, even under lightly-lubricated condition. As indicated in Figure 5a, the rising time for the lightly-, moderately- and heavily-lubricated cases are 31 mins, 39 mins and 52 mins, respectively, which are 4.4, 5.6 and 7.4 times than that of the unlubricated case. Since the quantity of the friction modifier was the only controlled variable in the experiment, therefore, this implies that the friction modifier has a strong effect on extending the rising time, the time to reach the traction coefficient plateau from the beginning. It is noticed that the traction coefficients in the lubricated conditions eventually stays between 0.5 and 0.55, very close to the plateau of the unlubricated condition, which potentially suggests that after a long time running for the wheel and roller, the lubricated conditions return to the unlubricated condition. Figure 5b shows the time to reach the plateau and the corresponding FM volume applied. It should be noted that the duration only increases by 26% with 5 times more of FM from lightly- to moderately-lubricated case, and it increases by only 68% with 25 times more of friction modifier from lightly to the heavily lubricated case.

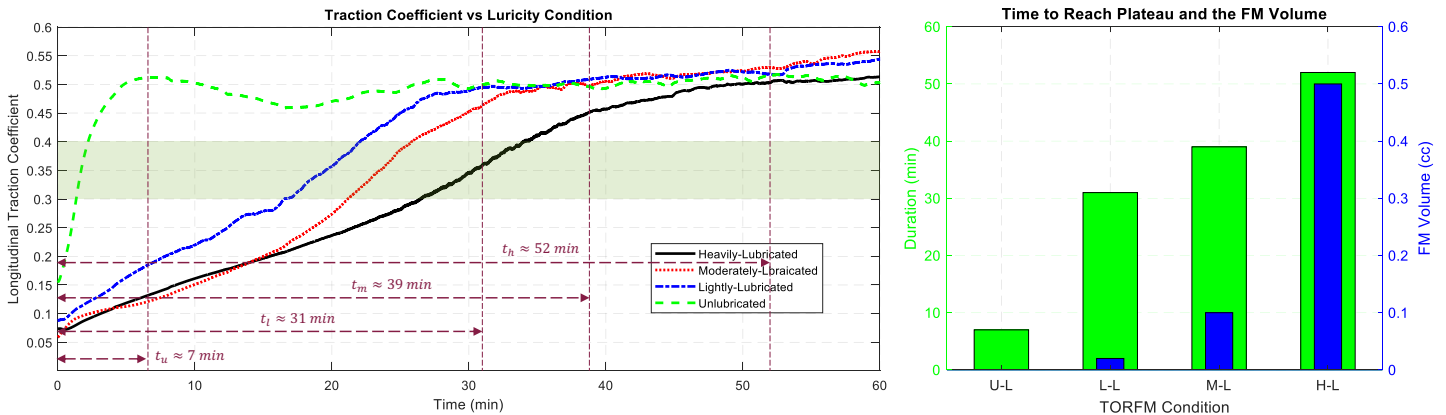


Figure 5: (a) Longitudinal traction coefficient with different amount of friction modifiers; (b) Duration for traction coefficient to reach plateau



Furthermore, the friction modifier is designed to create the targeted friction coefficient,  $\mu = 0.30 \sim 0.40$  [15, 16], at the wheel-rail contact; therefore, it would be helpful to discuss the traction results in this range for a better understanding of the friction modifier's effect. The shaded area in Figure 5a represents an example of the mentioned range. Additionally, the bar chart in Figure 6 shows the duration for  $\mu = 0.30 \sim 0.40$  in various lubricity conditions. There is a vast difference between the lubricated and unlubricated conditions. Even with a small amount of lubrication the duration that  $\mu = 0.30 \sim 0.40$  significantly increases from 0.86 min. for unlubricated condition to 5.6 min. for the lightly-lubricated condition, an increase of nearly 7 folds. With additional lubrication, the duration increases further to 7.6 min. for the heavily-lubricated conditions. The percent increase from lightly-lubricated and moderately- to heavily-lubricated conditions are not nearly as large as from unlubricated to lightly-lubricated condition. This indicates that the TORFM improves wheel traction condition even in light amounts but does not necessarily provide substantially more benefits when more added to the rail.

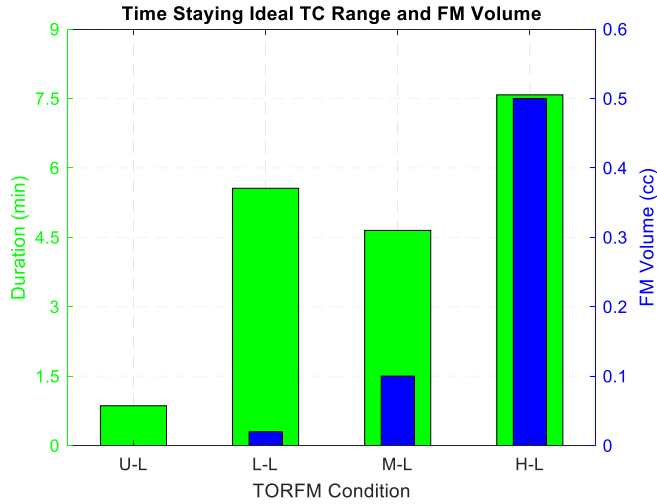


Figure 6 Duration for traction coefficient staying in  $[0.30, 0.40]$

### 3.3 Three-Phase Phenomenon with Friction Modifier

An interesting phenomenon observed often in raw traction force results is the presence of large oscillations prior to reaching the traction plateau, marked as “high-dynamic transient” phase. The oscillations are audible during the tests as what appears to be a stick-slip phenomenon at the wheel-rail contact. Interestingly, the oscillations and associated noise seldomly occur during the unlubricated tests or when the lubrication appears to be depleted (at the plateau). In order to illustrate this new phenomenon, the longitudinal force data of the lightly-lubricated condition are plotted in Figure 7 as an example.

Figure 7 displays the longitudinal force with 0.02 cc TORFM (lightly-lubricated condition) applied to the roller contact band. The thin line with cyan color represents the recorded raw data, and the dash-dot blue line is the filtered data

processed with 1.15 Hz low-pass filter and 15-second moving-average. The traction coefficient curve can be divided into three phases:

- Smooth-Transient Phase
- High-Dynamic-Transient Phase
- Steady-State Phase

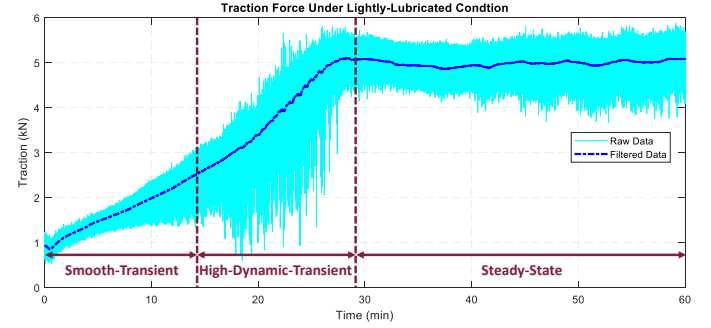


Figure 7. Longitudinal force of one experiment with 0.02 cc TORFM applied on the roller contact band

In the smooth-transient phase, the traction force starts from around 1000 N and gradually and smoothly increases to the next phase, the high-dynamic-transient phase. In the second phase, the longitudinal force experiences a certain degree of oscillation, as observed in both raw and filtered data. Not only that the oscillation is noticed from the curve, during the experiment, a squealing sound was also heard frequently. This leads us to believe that this is the period in which most of the wheel wear occurs.

### 3.4 Wheel Wear

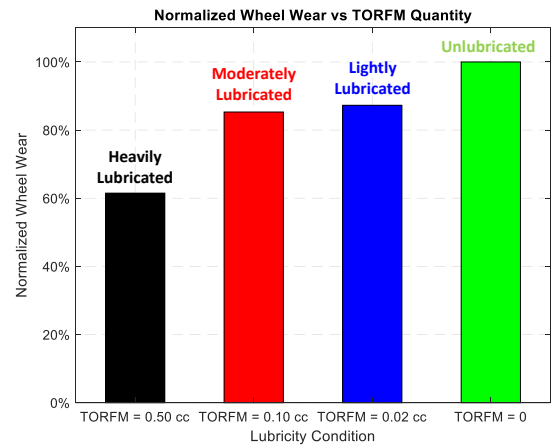


Figure 8. Normalized wheel wear relative to unlubricated condition

Figure 8 demonstrates the normalized wheel wear after the 60-min experiment for unlubricated and lubricated cases. The surface was cleaned after the experiment and the wheel profiles were measured before and after the experiment using the built-in laser scanner, as described in Section 2. The wheel wear is

defined as the material loss from the beginning to the end of the experiment, which could be calculated from the captured surface profiles. Three experiments were performed for each case, and the averaged results were obtained and thus normalized to the unlubricated averaged loss. The wheel wear measured in the lightly-, moderately- and heavily-lubricated condition can be reduced by 12%, 16% and 39%, compared with the unlubricated condition. It should be noted that there is a relatively large difference in wheel wear between the unlubricated condition and heavily-lubricated conditions, but the difference between lightly- and moderately-lubricated conditions is not that as large. Therefore, adding a small amount of friction modifier might be good enough to reduce the wear to a certain degree while preserving a desirable amount of traction and a reasonable investment.

#### 4. CONCLUSIONS

An experimental study and analysis of wheel-rail traction characteristics and wear progression with friction modifiers were performed, using the VT-FRA Roller Rig. A series of highly controlled experiments were conducted with various amounts of TORFM, ranging from light- to heavily-lubricated, along with an unlubricated condition. The results indicate that it takes a much longer time for traction forces (coefficients) to reach a condition that is the same as the unlubricated rail, when compared between lightly-, moderately-, and heavily-lubricated conditions. With friction modifiers, traction results clearly showed that adding even a small amount of friction modifiers would prolong the duration of time that the traction remains in a targeted range of  $\mu = 0.30 \sim 0.40$ . It is estimated that this would reduce wear while maintaining sufficient traction for achieving the required motive power.

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#### REFERENCES

- [1] Meierhofer, A., Hardwick, C., Lewis, R., Six, K., and Dietmaier, P., 2014, "Third body layer—experimental results and a model describing its influence on the traction coefficient," *Wear*, 314(1), pp. 148-154.
- [2] Wang, W. J., Shen, P., Song, J. H., Guo, J., Liu, Q. Y., and Jin, X. S., 2011, "Experimental study on adhesion behavior of wheel/rail under dry and water conditions," *Wear*, 271(9), pp. 2699-2705.
- [3] Zhu, Y., Olofsson, U., and Persson, K., 2012, "Investigation of factors influencing wheel–rail adhesion using a mini-traction machine," *Wear*, 292-293, pp. 218-231.
- [4] Chang, C., Chen, B., Cai, Y., and Wang, J., 2019, "An experimental study of high speed wheel-rail adhesion characteristics in wet condition on full scale roller rig," *Wear*, 440-441, p. 203092.
- [5] Liu, X., Xiao, C., and Meehan, P. A., 2019, "The effect of rolling speed on lateral adhesion at wheel/rail interface under dry and wet condition," *Wear*, 438-439, p. 203073.
- [6] Arias-Cuevas, O., Li, Z., Lewis, R., and Gallardo-Hernández, E. A., 2010, "Laboratory investigation of some sanding parameters to improve the adhesion in leaf-contaminated wheel—rail contacts," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(3), pp. 139-157.
- [7] Arias-Cuevas, O., Li, Z., and Lewis, R., 2011, "A laboratory investigation on the influence of the particle size and slip during sanding on the adhesion and wear in the wheel–rail contact," *Wear*, 271(1), pp. 14-24.
- [8] Huang, W., Cao, X., Wen, Z., Wang, W., Liu, Q., Zhu, M., and Jin, X., 2016, "A Subscale Experimental Investigation on the Influence of Sanding on Adhesion and Rolling Contact Fatigue of Wheel/Rail Under Water Condition," *Journal of Tribology*, 139(1).
- [9] Harmon, M., Santa, J. F., Jaramillo, J. A., Toro, A., Beagles, A., and Lewis, R., 2020, "Evaluation of the coefficient of friction of rail in the field and laboratory using several devices," *Tribology - Materials, Surfaces & Interfaces*, 14(2), pp. 119-129.
- [10] Tomeoka, M., Kabe, N., Tanimoto, M., Miyauchi, E., and Nakata, M., 2002, "Friction control between wheel and rail by means of on-board lubrication," *Wear*, 253(1), pp. 124-129.
- [11] Matsumoto, A., Sato, Y., Ohno, H., Tomeoka, M., Matsumoto, K., Ogino, T., Tanimoto, M., Oka, Y., and Okano, M., 2005, "Improvement of bogie curving performance by using friction modifier to rail/wheel interface: Verification by full-scale rolling stand test," *Wear*, 258(7), pp. 1201-1208.
- [12] Arias-Cuevas, O., Li, Z., Lewis, R., and Gallardo-Hernández, E. A., 2010, "Rolling–sliding laboratory tests of friction modifiers in dry and wet wheel–rail contacts," *Wear*, 268(3), pp. 543-551.
- [13] Radmehr, A., Hosseini Ahangarnejad, A., Tajaddini, A., and Ahmadian, M., "Surface Profile and Third-Body Layer Accumulation Measurement Using a 3D Laser Profiler," *Proc. 2020 Joint Rail ConferenceV001T13A004*.
- [14] Radmehr, A., Hosseini Ahangarnejad, A., Pan, Y., Hosseini, S., Tajaddini, A., and Ahmadian, M., "Wheel-Rail Contact Patch Geometry Measurement and Shape Analysis Under Various Loading Conditions," *Proc. 2020 Joint Rail ConferenceV001T13A005*.
- [15] Eadie, D. T., Santoro, M., and Kalousek, J., 2005, "Railway noise and the effect of top of rail liquid friction modifiers: changes in sound and vibration spectral distributions in curves," *Wear*, 258(7), pp. 1148-1155.
- [16] Khan, S. A., Lundberg, J., and Stenström, C., 2018, "Carry distance of top-of-rail friction modifiers," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232(10), pp. 2418-2430.