Recent advances in top of rail onboard locomotive application

J. Cotter, J. VanderMarel, X. Lu & P. Fan
LB Foster Rail Technologies, Vancouver, Canada

X. Meng & J. Jia
Shuohuang Railway Development Co. Ltd, Suning, China

Managing the Top Of Rail (TOR) wheel/rail coefficient of friction, using friction modifiers (FM), has consistently demonstrated significant benefits to the heavy haul industry including fuel/energy savings, wheel & rail wear reduction, and reduced state of stress of the track infrastructure. Traditionally, the preferred method of FM application has been trackside systems. However, in some situations, it is desirable that friction modifiers are applied from on-board a train set due to several different factors. Recently, Shuohaung Railroad have installed three (3) prototype on-board TOR dispensing systems on their SS4B locomotives and have been successfully operating them for the last three years. Field testing, conducted by the Chinese Academy of Rail Sciences, have demonstrated energy savings of approximately 5 %, lateral force reductions of 10-20 %, and following train benefits for non TOR equipped train sets. Simple cost benefit analysis modelling is shown to favour on-board FM application over trackside FM application.

1 INTRODUCTION

1.1 *Total Friction Management*

Total Friction Management (TFM) is the process of controlling frictional properties at the wheel-rail interface (both top of rail and gauge face) within the prescribed Coefficient of Friction (CoF) target limits. The comprehensive benefits of Top of Rail (TOR) friction control, in combination with optimized gauge face (GF) lubrication, have been extensively tested, validated, and implemented in the heavy haul environment. [1,2,3,4,5,6,7,8,9,10].

TFM can be achieved by using either track mounted or train mounted systems (or a combination of both). Trackside equipment, employed in the heavy haul environment, typically range from simple mechanical units to more sophisticated electric units as shown in figure 1. Strategic placement of GF and TOR trackside application systems can provide an effective TFM program if well maintained. Typically, trackside units are spaced at distances from 2 – 7 km apart for both TOR & GF applications.

However, in some regions, such existing trackside infrastructure does not exist due to:

i) No previous history of trackside lubricator usage (traditionally GF lubrication).
ii) Terrain and lack of (easy) access to potential trackside lubricator sites
iii) Concern over theft and vandalism of fixed trackside assets
iv) High traffic volume in which any normal filling or maintenance operations, associated with trackside lubricators, can be perceived to have a significant impact on train operations.

Figure 1: Electric Trackside Applicator

Train mounted application systems provide an alternative method for applying TOR friction modifiers (as well as GF lubrication) to address the issues identified above. As the equipment is installed on a train set, as example, filling and maintenance operations can be done in a yard and any such normal routine activity does not have to impede train operations.

Figure 2: Coal Wagon mounted TOR Application System

An example of a train mounted TOR application system (AutoPilot™) is shown in figure 2. The AutoPilot™ is a mobile spray application system that can be mounted on a wagon and dispenses an atomized stream of the water-based KELTRACK® friction modifier on the top of rail running surface. The AutoPilot™ can independently determine speed, air brake usage, tangent or curve location. This allows the system to regulate friction modifier application by such parameters and maintain desired application targets under varying conditions. It is also fully autonomous.

More recently though, there has been a desire to migrate FM TOR application technology from a wagon to a locomotive platform for the following reasons:

i) Improved asset utilization. Wagon mounted systems are tied to unit trains (i.e. coal, iron ore etc.). Locomotives equipped with TOR application systems can be applied more broadly.
ii) Minimizes yard logistics for positioning the TOR equipped wagon behind the last locomotive in consist (required for power and compressed air)

1.2 *Shuohuang Railway*

Shuohuang Railway (SHR), owned and operated by the Shenhua Group Corporation Ltd. in China, is a Class 1 heavy haul freight railway used solely for coal transportation between Shenchi County in Shanxi Province and Huanghua Port in Hebei Province. Together with the Baoshen and Shenshuo Railways, two other rail networks within the Shenhua group of companies, the Shuohuang Railway provides one of two main west-to-east freight railway routes in China transporting coal to Bohai ports for off-shore shipment (Figure 3).

Shuohuang Railway has 594 km of dual track network contained within two operating subdivisions: Yuanping Subdivision (Shenchi South to Xibaipo = 256 km) and Suning Subdivision (Sanji to Huanghua Port= 333 km). Typical daily traffic volume is 96 loaded trains (coal) eastward (north track) and 96 empty trains westward (south track) to and from Huanghua Port, equating to a current annual operating tonnage of > 200 MGT (Million Gross Metric Tonnes).

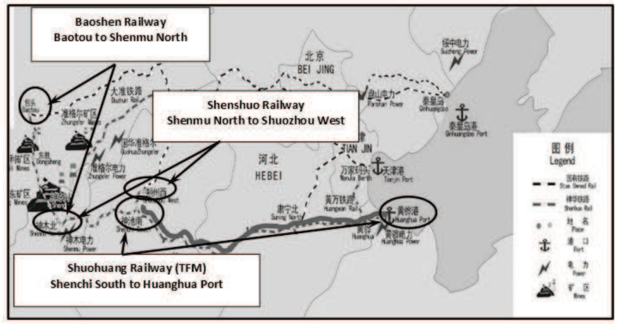


Figure 3: Shuohuang, Baoshen & Shenshuo Routes

Currently SHR operates both short trains and long trains. The short trains use single locomotive to pull 66 C64/C70 open-top gondola cars with a max. gross mass 5,000 tonnes and the long trains use two locomotives to pull 108 C70/C80 gondola cars with a max gross mass 10,000 tonnes. Locomotives used at SHR include 8-axle heavy load freight DC electric locomotive SS4B/SS4G. and 8-axle heavy load freight AC electric locomotive Shenhua HXD1 and HXD2.

Figure 4: SS4B 8-axle locomotive

Since February 2006, SHR has experienced accelerated rail wear and rolling contact fatigue (RCF) growth within many of the sharper / lower radius curves on its two subdivisions, following a significant increase in area operating tonnage. Extensive spalling has developed along the low rail tread surface and high rail gauge corner, combined with a notable increase in gauge face/corner wear along curve high rails. These conditions are typically more prevalent in curves with radius < 800m R.

SHR requested a locomotive mounted TOR application system to demonstrate top of rail friction control benefits and validate the TOR application technology on its trains traveling between Shenchi South and Huanga for a total round trip travel distance of 1179 km.

2 LOCOMOTIVE MOUNTED TOR SYSTEM

2.1 *Overview & Desired Functionality*

The primary objective was to develop a TOR application system which could provide the same functionality as the wagon mounted TOR system but could be fitted onto the SS4B dual locomotive pair (Zhuzhou Electric Locomotive Company).

Key desired functionality/characteristics of the TOR application system on a locomotive platform included the following:

- Small footprint
- Minimal installation time
- Autonomous operation (no input from train crew)
- Dual direction operation
- No impact on locomotive adhesion or train braking
- -30 °C to 40 °C Operating temperature range

2.2 *Prototype Design*

As shown in figure 5, the basic control and mechanical principles would remain unchanged (as compared to the wagon mounted system). The system would be designed to pump and (atomized) spray a water-based friction modifier onto the running rail. A key difference in this design was that the system would directly interface with the SS4B locomotive to obtain all required information (speed, location etc.).

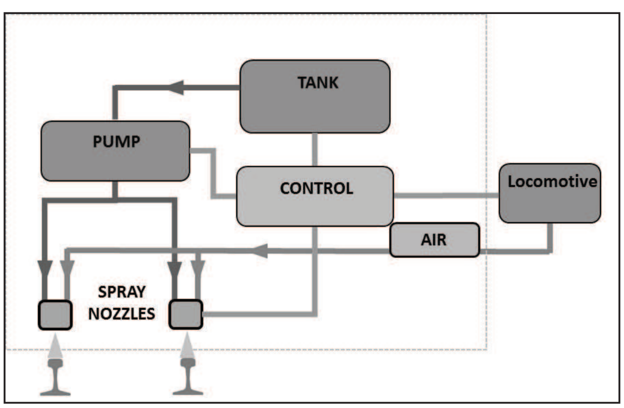


Figure 5: Locomotive based TOR Schematic

Several major design challenges included the creation of a small "footprint" for the dispensing system as well as identify a location for the spray nozzles. For the dispensing cabinet, a small reservoir/dispensing cabinet was designed to fit onto the back wall inside the locomotive cab (figure 6)

To support the additional mass of the nozzle and nozzle bracket, the original sander box and bogie were reinforced. The reinforcement design and work was completed by ZELC while LB Foster completed the FEA study on the reinforced bogie design. The nozzle bracket and nozzle were installed on the reinforced sander box mounting plate such that the nozzle tip was positioned centred over the rail and 70 mm above the top of rail surface (figure 6). Location of the spray nozzles was important to ensure that the they would "track" the running rail both on tangent as well as curved track.

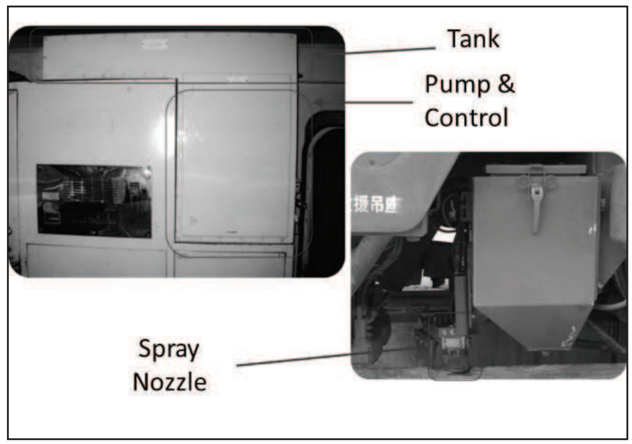


Figure 6: Location of Cabinet & Nozzles

As locomotive adhesion requires high friction, the prototype system was designed to spray only from the trailing locomotive and not directly in front of the locomotive wheels. This was achieved by having two separate systems, one in each locomotive cab (figure 7). A "master" control unit would activate only the TOR dispensing system located in the trailing locomotive. The TOR dispensing system in the lead locomotive would be shut off.

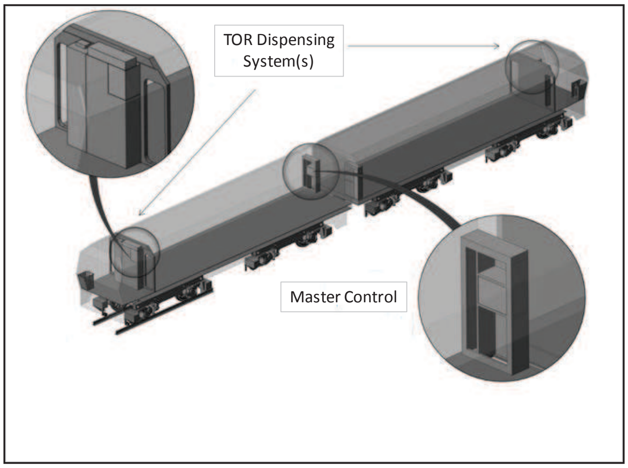


Figure 7: Location of primary components

2.3 *Type Testing*

The prototype TOR system was successfully subjected to a series of type tests in accordance with the Chinese national railway standards as shown in table 1.

GB/T 25119:2010	Electronic equipment used on rail vehicles (Equivalent to IEC 60571:2006)
GB/T 24338.4:2009	Railway application: Electromagnetic compatibility- Part 3-2: Rolling Stock – Apparatus
GB/T 21563:2008	Railway applications – Rolling stock equipment – Shock and vibration tests (Equivalent to IEC 61373:1999)

Table 1: Type Tests

2.4 *Installation*

The TOR application system was installed onto 3 SS4B locomotive pairs. It is estimated that the total installation time to equip each locomotive pair would be two days.

2.5 *Operation*

For testing purposes, the TOR prototype system operation consisted of spraying the KELTRACK® friction modifier at a rate of 30 ml/km/rail, on both tangent and curve track for both loaded and empty trains. Testing was undertaken between Shenchi South and Huanghua port for a total round trip application distance of 1179 km. Other application constraints included:

i) Friction modifier was applied only from the trailing end of the locomotive pair regardless of locomotive A-B orientation.
ii) Friction modifier application was disabled during full service air braking.
iii) Friction modifier application was not disabled during dynamic train braking.
iv) Friction modifier application was disabled in track regions surrounding rail car loading and unloading facilities

2.6 *Train Braking Test*

The Chinese Academy of Railway Science (CARS) conducted a series of braking tests on both loaded trains and empty trains, equipped with the TOR application system, on SHR main service line. One section at K172 with a high descending gradient and one flat straight section at K386 were selected for load train tests. The empty trains used one flat straight section at K241 for their braking tests. With dry rail surface, the comparison of braking performance of trains with and without the application of friction management technology and products demonstrates that the braking performance of both loaded trains and empty trains remain unchanged. The average deviation of braking distance of loaded trains was less than 3.4% and less than 3.6% for empty trains.

3 FIELD MEASURED BENEFITS

The Chinese Academy of Railway Sciences (CARS) conducted a series of field tests monitoring energy consumption, track dynamic response, as well as energy consumption for TOR applying trains.

3.1 *Energy Consumption Reduction*

Energy consumption of locomotives was monitored on operation trains which were under normal revenue train operation conditions during the 1,176km round trip railway line between Shenchi South and Huanghua Port of Shuohuang Railway. One monitoring cycle covered the loaded train in upstream direction and the empty train in down-stream direction.

The data was reviewed to remove any statistical outliers which may have been due to environmental or driver behaviour (Table 2)

	TOR FM System Activated		Baseline (TOR System Off)	
	With outliers	Without outliers	With outliers	Without outliers
Average Consumption	260	264	285	279
Standard Deviation	42.6	24.5	33.3	23.2
Max. Value	322	301	374	312
Min. Value	146	227	236	236
Range	176	74	138	76
Energy Savings	**8.9%**	**5.3%**		

Table 2: Energy Consumption Analysis

Note: measurements of energy consumption are in 100 kWh.

With the application of TOR friction management technology, the average saving of energy consumption of the locomotives was determined to be 5.3% (figure 8).

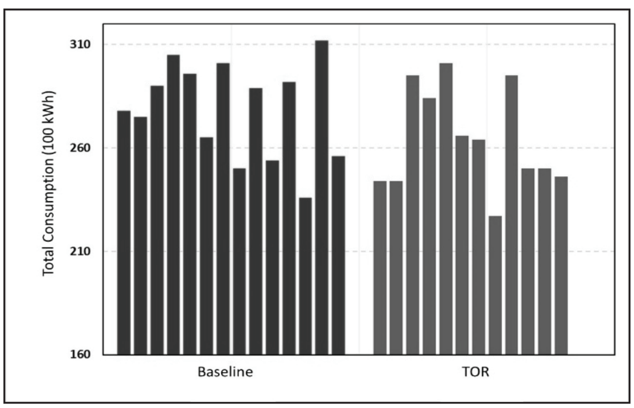


Figure 8: Energy Consumption Data

3.2 *Lateral Force Reduction*

CARS also studied the impact of the locomotive applied TOR friction modifier on lateral force reduction. Three test curves were selected (as shown in Table 3)

	"K18"	"K55"	"K64"
Radius (m)	400	500	500
Length (m)	342	1973	287
Super Elevation (mm)	85	90	90
Gradient (%)	10.0	9.4	8.3
Note	S-curve	S-curve	High wear

Table 3: Lateral Force Test Curves

Figures 9 and 10 exhibit the maximum and average lateral forces comparing baseline trains with those equipped with a TOR application system. It should be noted that the reported lateral forces in figures 9 & 10 represent the average of low and high rail lateral forces. In general, the lateral force values, on both high and low rails, decreased for all three curves by approximately 10% - 20% when TOR trains travelled through in comparison to baseline non TOR FM equipped trains.

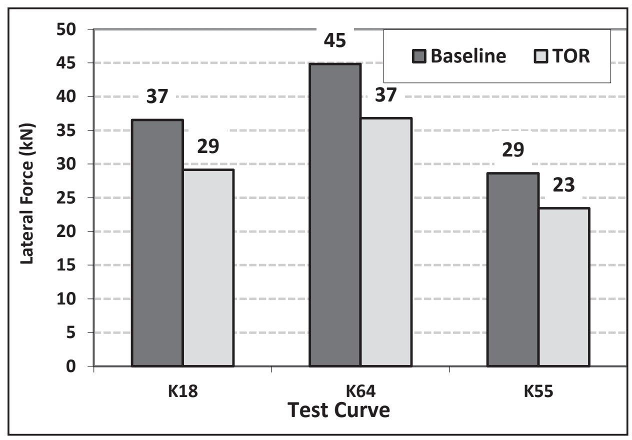


Figure 9: Measured Lateral Forces (Maximum)

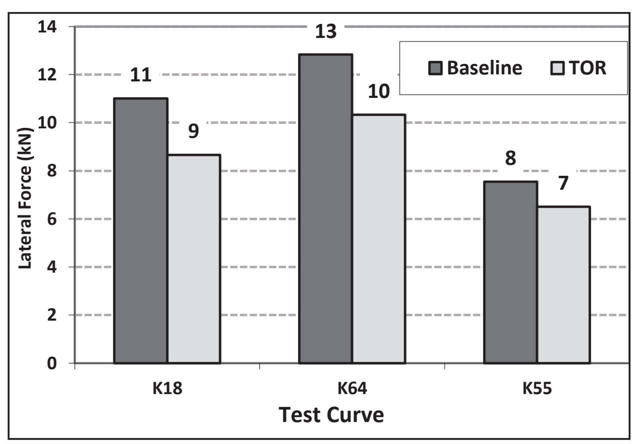


Figure 10: Measured Lateral Forces (Avg.)

3.3 *Retentivity*

During the trial, the lateral and vertical forces were continuously monitored for the TOR-applying train as well as the following six (non TOR applying) trains at the K18 test curve. The data was used to calculate the train operation safety parameter – derailment coefficient (L/V). In Figure 11, the HR/LR lateral forces for the TOR-applying train as well as for the 1st, 3rd, 4th and 6th following trains (non-TOR applying trains) are plotted for both the C64 and C80 type wagons. Also included in the plot is the average L/V value for (dry) baseline conditions.

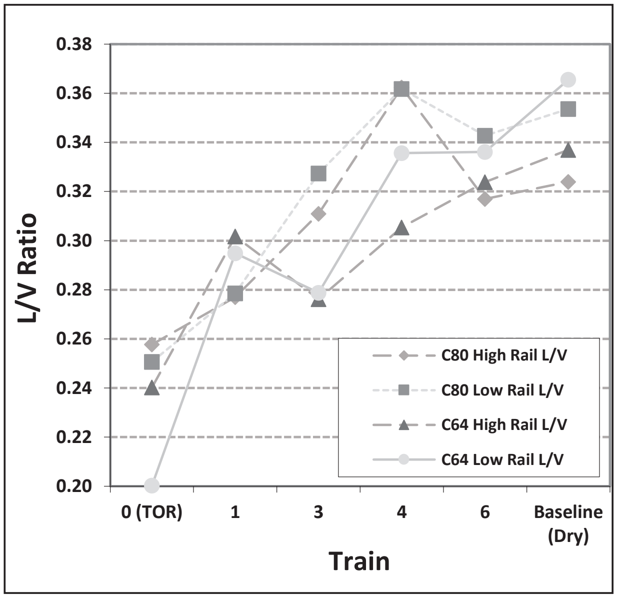


Figure 11: TOR FM Retentivity Data

In reference to Figure 11, one can see that the following 3 non-applying train sets do derive benefit, as witnessed by the reduced L/V ratios. This indicates the benefits of lateral force reduction due to residual TOR FM material on the railhead after the TOR-applying train.

It is important to note that the presence of residual TOR material after the applying train is significantly important for the following reasons:

i) One does not have to equip all train sets with TOR application equipment to maximize benefits

ii) As a corollary to the above, non TOR equipped train sets can also derive benefits (force reduction, fuel/energy savings, wheel wear savings)

Similar TOR FM residual behaviour was also observed in previous TOR on-board studies [11,12]

It should be stated though the residual TOR material should be a true friction modifier (such as KELTRACK®) rather than a lubricant to negate any potential impact on adhesion levels for following locomotives.

4 ECONOMIC ANALYSIS

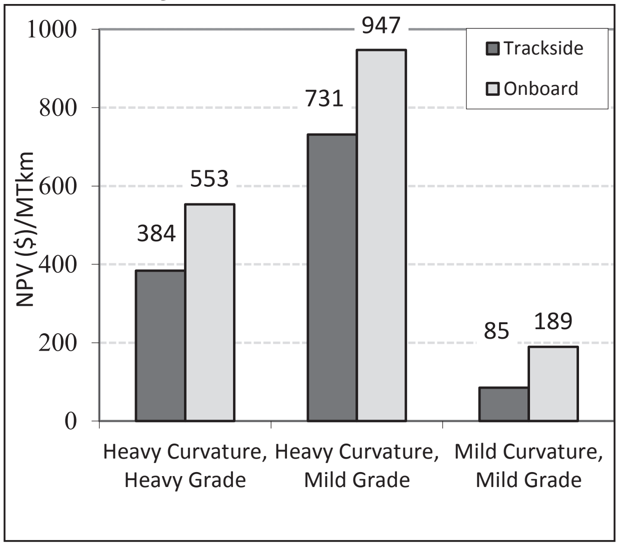
As mentioned in the beginning of the paper, a train mounted application system can offer potential advantages over a trackside application in those situations where track accessibility, asset security (theft & vandalism), or high traffic makes a trackside strategy unfeasible. But what about the economic case for on-board application, is there a significant cost difference?

To answer this question, a simple model was developed [13] which would compare the relative cost benefit ratio and payback period of implementing either approach. The model considers the following three track "segments": i) heavy curvature, & significant grade, ii) heavy curvature and mild grade and iii) mild curvature and mild grade.

The model calculates (conservatively) rail wear savings based on extrapolated results from documented TOR field tests. Fuel savings were also determined by extrapolation from controlled field tests [14]. TOR trackside applicator spacing and application rates were based on current best industry practices. Rail replacement, fuel & FM consumable costs were considered constant in the model. The model predominately focuses on relative capital costs, capital utilization, and relative application rates (re annualized costs).

Figure 12 highlights that the on-board approach would, in general, generate higher normalized benefits (NPV/MTkm) for all three segments. In reviewing the model, the primary driver for the improvement for the on-board case is the more efficient application method (0.060L/km for both rails) Trackside systems traditionally employ higher application rates (0.35 – 050 L/1000 axles) and rely on the wheel/rail interaction to transfer the FM product along the rail. As such it is prone to waste or splash as the transfer is limited to the contact band at the wheel/rail interface.

Figure 12: NPV/MTkm Assessment



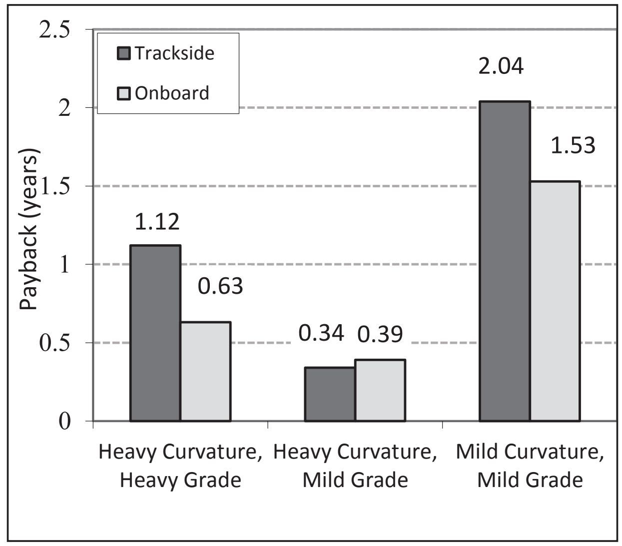


Figure 13: Payback Assessment

A few brief notes regarding the differing rail/fuel benefits results generated in the different segments:

i) The lower normalized benefit observed in the heavy curve/heavy grade segment (compared to the heavy curve/mild grade segment) was due to reduced fuel savings. In previous studies [14], it has been determined that fuel savings, attributed to TOR FM application, can only be generated when the locomotive is under tractive effort. In segments where there is heavy grade, locomotives would spend a significant amount of time under dynamic braking (downhill) in which fuel savings are not achievable.

ii) The lower NPV/MTkm benefits observed in the mild curve, mild grade segment (compared to heavy curve, mild grade segment) is due to lower rail wear savings and fuel savings (lower curving resistance). The flexibility of the locomotive system is that the application rate can be automatically reduced in those segments where benefits will be minimal.

Figure 13 highlights capital cost consideration by assessing payback. In general, the payback period is seen to be generally lower for the on-board case. Although it is likely that unit costs for on-board systems would be higher (due to customization) than trackside systems, faster payback can be achieved due to i) requirement for lower number of on-board units and higher asset utilization and ii) higher net benefits as discussed previously. The differences in payback period across the segments again reflect the differences in potential rail & fuel savings across the different segments.

5 CONCLUSION

In conclusion, this paper has reviewed the latest advancements of TOR FM application technology with specific focus on recent developments for an onboard locomotive system. The prototype onboard system, designed for the SS4B locomotive, was shown to generate energy savings as well as reductions in lateral forces. Testing also confirmed the presence of residual TOR material on the railhead which can provide additional benefits to non TOR applying train-sets; this has also been observed in previous field testing.

An onboard approach can be used in those regions where a traditional trackside solution is not feasible. Economic analysis also highlighted the comparatively favourable benefits and payback period of the onboard approach.

6 REFERENCES

[1] Davis K, Stickland W, Sherrock E. 1999. Evaluation of a Top of Rail Lubrication System *DOT/FRA/ORD-99-13*

[2] Sroba, P., Roney, M., Dashko, R. and Magel, E., 2001. Canadian Pacific Railway's 100%Effective Lubrication Initiative, Presentation for*AREMA 2001 Conference & Exhibition, Chicago, Illinois*

[3] Eadie, D., Oldknow, K., Maglalang, L., Makowsky, T., Reiff, R., Sroba, P. and Powell, W. 2006. Implementation of Wayside Top of Rail Friction

Control on North American Heavy Haul Freight Railways, *Proceedings of the World Congress on Railway Research, Montreal, Quebec*,

[4] Sroba, P., Oldknow, K., Dashko, R. and Roney, M. 2005. Canadian Pacific Railway 100% Effective Friction Management Strategy, *Proceedings of the IHHA Conference, Rio deJaneiro, Brazil*

[5] Roney, M., Eadie, D., Oldknow, K., Sroba, P., Caldwell, R. and Santoro, M. .2009. Total Friction Management on Canadian Pacific, *Proceedings of the IHHA Conference, Shanghai, China*

[6] Eadie, D., Elvidge, D., Oldknow, K., Stock, R., Pointner, P., Kalousek, J. and Klauser, P. 2006. The Effects of Top of Rail Friction Modifier on Wear and Rolling Contact Fatigue: Full Scale Rail-Wheel Test Rig Evaluation, Analysis and Modelling, *7th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, *Brisbane, Australia*,

[7] Reiff, R. 2007. Top of Rail Friction Control on Rail Surface Performance and Grinding, TTCI *Technology Digest TD-07-039*

[9] Eadie, D. 2013. A Review of Locomotive Fuel Savings with TOR-FM: Connecting theory and field results" *ARM Wheel/Rail Seminar*

[10] Peters, J. & Elvidge D. 2016 The Effect of Train Mounted TOR-FM on Wheel Life and Defects," *Proceedings of WRI Heavy Haul, Atlanta, Georgia*,

[11] Cotter, J. et al, 2005. Freight Car- based Top of Rail Friction Modifier Application System. *Proceedings of the IHHA Conference, Rio de Janeiro, Brazil*

[12] Cotter, J et al, 2007 Incorporation of Remote Monitoring Technology on a Train Mounted Top of Rail Friction Control Dispensing System. *Proceedings of the IHHA Conference, Kiruna, Sweden.*

[13] Oldknow, K, 2013 Internal LB Foster Report

[14] Cotter, J., Eadie, D., Elvidge, D., Hooper, N., Roberts, J., Makowsky, T. and Liu, Y. 2005. Top of Rail Friction Control: Reductions in Fuel and Greenhouse Gas Emissions, *Proceedings of the IHHA Conference, Rio de Janeiro, Brazil,*