Top of Rail Friction Control: Reductions in Fuel and Greenhouse Gas Emissions

John Cotter, Don Eadie and David Elvidge, Kelsan Technologies Corp. 1140 West 15th St., North Vancouver, B.C. Canada V7P 1M9, email jcotter@kelsan.com, Tel 604-984-6100

Norm Hooper, Jay Roberts and Tony Makowsky, BC Rail, P.O. Box 8770, Vancouver, BC Canada V6B 4X6

Yan Liu, Centre for Surface Transportation Technology, National Research Council of Canada, Uplands, Bldg. U-89, Ottawa, ON, Canada K1A 0R6

Summary

In 2003, BC Rail and Kelsan Technologies carried out a project to quantify the effect of Top of Rail (TOR) Friction Control on fuel consumption and Greenhouse Gas (GHG) emissions by reducing the curving resistance of a standard 3 piece North American truck. Measurable savings were based on monitoring changes in diesel fuel consumption, as well as mechanical drawbar forces. Results indicated a strong correlation between curve density and fuel savings when the test consist was under tractive effort. Calculated fuel savings ranged from 155 Liters/Million Ton-miles to a 744 Liters/Millions Ton-miles (2 to 12 %) on track ranging in curve density from 25 to 51 percent. Corresponding GHG Emission reductions (CO_2) ranged from 0.3 metric tonnes per million ton-miles to 2 metric tonnes per million ton-miles. No fuel savings/ GHG emission reductions were achieved when the consist was under dynamic braking.

Index Terms: Top of Rail Friction Control, Fuel Savings

1.0 INTRODUCTION

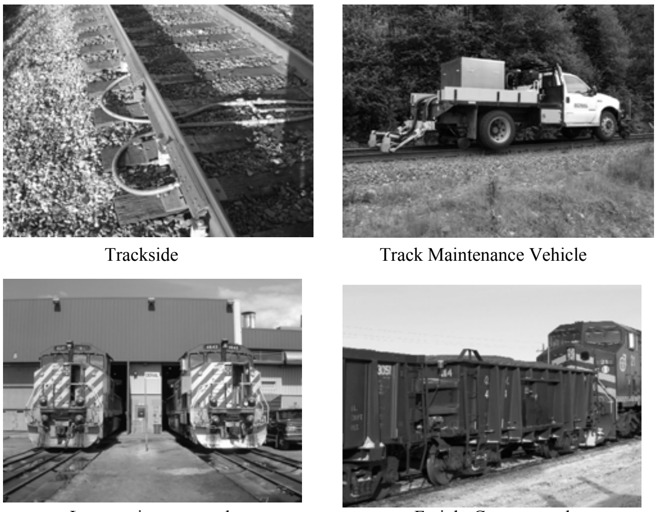
The Canadian Rail network operates on 72,500 km of track across 5 times zones through some of the most challenging topography and climate in the world. Freight railways consume over 2 billion litres of diesel per year. Over the past decade, Railways have reduced total fuel consumption by 5% while increasing revenue tonne-kilometers per litre by 28%. They have demonstrated innovation in their commitment to fuel savings and the reduction of atmospheric emissions through the use of locomotive auto start/stop, higher capacity cars, purchase of new high capacity locomotives and new routings. Expansion of multi-modal transportation, diverting road to rail, holds significant promise for over-all emission reductions.

The Canadian Federal Government is seeking performance agreements from the Transportation Industries for further GHG reductions. They are providing financial incentives for the development of innovative technologies, equipment and practices. The work presented in this paper would not have occurred without their support. Canadian Railways are private networks and the key to success will be whether the enhancing technologies are safe, efficient and cost-effective.

This paper outlines an investigation into the ability of TOR friction modifiers to reduce fuel consumption/GHG emissions by improving the steerability (reducing curving resistance) of the standard 3 piece North American truck.

Unlike lubricants, friction modifiers (KELTRACK®) are able to reduce the COF of dry rail and maintain the desired intermediate level of friction over a given number of trains or wheel passes. Friction modifiers formulated for freight applications contain no oils, greases or other liquid lubricant components. They are composed of engineered composite solids, polymers and other compounds that are mixed with water and deposited on top of the rail in liquid form. When the water evaporates, the remaining dry thin film (similar to "a coat of paint") maintains an optimal intermediate coefficient of friction.

True friction modifiers, such as KELTRACK®, can be dispensed onto the railhead in a number of different ways (figure 1). The ability to control friction at an intermediate level means that the product can be dispensed either *before* or *after* the driving wheels of locomotive. Commercially available TOR dispensing technology includes the wayside [1] and the track maintenance vehicle ("Hi-rail"). Significant strides have also been made in developing train mounted systems for both onboard locomotives as well as freight wagons [2, 3, 4, 5]. *In each case, the documented benefits derived from applying a TOR friction modifier are the same* [6, 7, 8, 9].



Trackside — Track Maintenance Vehicle — Locomotive mounted — Freight Car mounted

Figure 1: Methods of dispensing TOR friction modifiers

This testing was performed under the auspices of Transport Canada's Freight Sustainability Demonstration Program. This program was put in place to assess the impact of new, emerging technologies on reducing GHG emissions in the freight transportation sector. The project commenced in April 2003 and was completed approximately one year later with the issuing of the final report.

The TOR dispensing equipment, designed by Lubriquip, was installed on a Dash 9- 44CW locomotive. The system comprised of a control system, product metering pumps, dispensing nozzles, a storage reservoir, and heat tracing to allow the system to nominally operate in temperatures of -30 °C (or -22°F).

The test train consisted of 45 loaded sulphur wagons with an approximate trailing tonnage of 5450 metric tonnes (6000 tons). Motive power consisted of two 4400 HP CW-44 locomotives, including the TOR equipped locomotive. A total of twenty test trains were run (ten baseline & ten top of rail) between June and November 2003.

Testing was conducted on BC Rail's Chetwynd subdivision between Chetwynd and Prince George, British Columbia. The terrain was primarily rolling hills with several sections of ascending & descending grades

2.0 TEST METHODOLOGY

Measurable savings were based on monitoring changes in diesel fuel consumption, as well as mechanical drawbar forces using an instrumented shear pin. Specialized data acquisition equipment on board the main test locomotive monitored i) pertinent locomotive operating parameters, ii) consist location via an onboard GPS unit and iii) critical TOR application parameters. Calculations were performed by the National Research Council's Centre of Surface Transportation Technology (NRC-CSTT).

Rather than attempt to define fuel savings for the entire test trip, the analysis focused on defining the potential savings for nine predefined track segments. This would allow further detailed comparative analysis based on the differing characteristics of each segment (grade, curve density etc). The data could also be potentially used to develop a predictive fuel savings model to be applied outside of the test zone area. Determination of potential savings for the entire trip would have made the data unique to this particular section of BC Rail's Chetwynd subdivision. Key characteristics of these nine segment have been tabulated in table 1. .

Seg	Distance	Elevation	Curves	Grade %	Comments
1	19 km	Elevation climb from 695 ft to 758 ft	< 5°: 17 < 5°< 8°: 7 > 8°: 6	+0.30	Continual uphill climb
2	13 km	Elevation climb from 758 ft to 876 ft	< 5°: 20 < 5°< 8°: 11 > 8°: 2	+0.93	Steep Uphill
3	8 km	Elevation change from 876 ft to 879 ft	< 5°: 8 < 5°< 8°: 5 > 8°: 0	+0.00	Flat
4	16 km	Elevation change from 879 ft to 734 ft	< 5°: 22 < 5°< 8°: 13 > 8°: 10	-0.88	Downhill
5	40 km	Elevation change from 734 ft to 733 ft	< 5°: 46 < 5°< 8°: 13 > 8°: 4	+0.00	Rolling Terrain
6	62 km	Elevation change from 733 ft to 715 ft	< 5°: 61 < 5°< 8°: 13 > 8°: 1	-0.03	Rolling Terrain
7	35 km	Elevation change from 715 ft to 722 ft	< 5°: 14 < 5°< 8°: 6 > 8°: 0	+0.02	Rolling Terrain
8	26 km	Elevation change from 715 ft to 589 ft	< 5°: 8 < 5°< 8°: 1 > 8°: 0	-0.53	Downhill
9	18 km	Elevation change from 589 ft to 574 ft	< 5°: 14 < 5°< 8°: 4 > 8°: 1	-0.05	Flat

Table 1: Predefined Track Segments

Furthermore, it should be noted that the analysis focused on the potential savings where the test consist was under *tractive effort*. Effects of speed variation and braking were also filtered out in the analysis for each segment. Areas of dynamic braking were not included in the study as any changes in train momentum (potential work) attributed to the application of the friction modifier would be dissipated as heat. Under tractive effort, any changes in potential work will manifest itself as a *(measurable)* higher speed or a reduction in fuel consumption.

2.1 Accounting for Changes in Velocity Profiles

To account for differences in the velocity profile (ΔV), the mechanical work associated with the acceleration/ deceleration behaviour of the test consist was determined. The associated mechanical work is given as

$$\Delta W = ½ * c * M * [(V_2^2 - V_1^2]$$

Where M is the train mass and c = 1.05 is used to consider the effects of rotation motion of cars [10].

Calculations have demonstrated that the mechanical work associated with speed changes was usually quite low when compared with the total mechanical work measured. Only on "flat" track, which required very low mechanical work, did the component of the mechanical work associated with train acceleration/deceleration become considerable.

Unlike mechanical work, there is no direct way to calculate the associated fuel consumption due to a change in velocity profile. As a result, a method to correlate mechanical work and fuel consumption was developed. It was determined that, when under tractive effort, a strong relationship was observed between calculated mechanical work and fuel consumption. Figure 2 exhibits a typical example of such linear correlation. A "conversion factor" from fuel to mechanical work could then be obtained by performing a linear regression on the test data. It was found that the conversion values for the different segments and different tests agreed, with only some small variation.

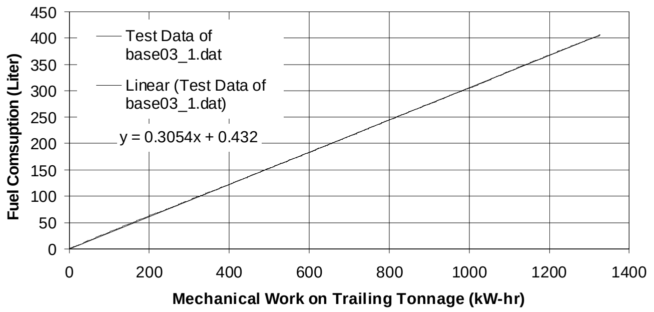


Figure 2: A typical example of relation between fuel consumption and mechanical work

2.2 Accounting for Air & Dynamic Braking

QTRON event recorder data was used to filter out sections where dynamic braking occurred. This filter process was conducted for each segment. As a result, non-DB sections common for all tests were obtained for each segment in each test. Segments #4 & #8 were excluded from further calculations as the significant downhill grade assured that the test consist was in dynamic braking virtually 100 % of the time. In most cases, the use of air braking coincided with the use of dynamic braking. No incidents of "power braking" were observed.

2.3 Calculation of Mechanical Work

With the measured coupler force F and distance increment ΔD of train motion, the mechanical work W was calculated as follows:

$$W = F_1 * \Delta D_1 + F_2 * \Delta D_2 + .. + F_n * \Delta D_n$$

Where F_1, F_2 … Fn are coupler force values measured at 1^{st}, 2^{nd} … and n-th second for a given piece of test data, and n is the total time in seconds for the test data. Accordingly, ΔD_1, ΔD_2, … ΔD_n are distance increment values measured at 1^{st}, 2^{nd} … and n-th second. By using this equation and the previous equation for work required to change speed profile, the mechanical work was calculated for a given segment in a given test.

2.4 Calculation of Fuel Consumption

Fuel consumption for each trip was determined from the recorded throttle settings (QTRON event recorder) on the test locomotive. Each throttle setting was converted to a fuel consumption rate based on the GE Dash 9 44CW "fleet engine" specification as shown in table 2.

Throttle Setting	RPM	Fuel L/Hr
8	1050	792.0
7	995	642.8
6	995	530.5
5	995	415.1
4	888	298.2
3	888	207.3
2	581	101.8
1	440	43.6
Idle	440	14.5
Low Idle	340	10.5
DB1	440	14.5
DB2	581	21.8
DB3	719	34.6
DB4	888	50.5

Table 2: GE Fuel Consumption Specification for a 4400 engine

These consumptions rates were further corrected for combustion efficiency and ancillary parasitic loads.

As the locomotive fuel combustion efficiency is affected by changes in air temperature and barometric pressure conditions, the following correction factors (CF), obtained from GE, were applied to determine the corrected fuel consumption rate.

<u>*Temperature correction*</u>
CF = 0.000379 x temp ℉ + 0.97727

<u>*Barometric pressure correction*</u>
$CF = (BP/28.86)^A$
Where BP = barometric pressure (inches of mercury)
A = use value of 0.093 for throttle notches 5,6,7,8
A = use value of 0.32 for lower throttle notches

Fuel consumption was also corrected for parasitic loads associated with the auxiliary generator.

This methodology assumes that the locomotive engines are equal in terms of fuel consumption and power output. In reality though, there will always be some variability from one engine to the next. The variability becomes much larger in older locomotives as it is dependent on the state of maintenance of the engine and the number of hours of operation since the last overhaul.

This potential variability in this demonstration project was minimized by:

- Maintaining the same motive power over the course of the test.

- Both test locomotives were overhauled prior to commencing the test.
- Focusing study was on determining the relative difference in fuel consumption.

The accuracy of this method is also dependent on notch setting dwell time. Short dwell times and frequent changes in the notch settings can introduce some error in the fuel consumption calculation. The specific concern is that changes in fuel consumption are not *instantaneous when changing to a different notch setting*; rather there is some delay in achieving the new fuel rate.

As a result, two slightly different methodologies were employed to determine (corrected) fuel consumption. The first method determined the (corrected) fuel consumption based on the assumption that ***discrete*** changes in notch setting resulted in *instantaneous* changes to the fuel rate. The second method derived the (corrected) fuel consumption from the calculated mechanical work based on the established linear correlation. The basis of this alternative approach is that the calculated fuel consumption represents a *composite* of notch settings.

2.5 GHG Emission Reduction Calculations

Determination of GHG emission reductions was based on calculating the tonnes CO_2 equivalent emissions for each liter of locomotive diesel fuel saved.

Carbon dioxide at 2738 g emission per litre plus methane at 0.15 g emission per litre weighted at 21 units of CO2 plus Nitrous oxide at 1.1 g emission per litre weighted at 310 units of CO2

3.0 RESULTS & DISCUSSION

3.1 Mechanical Work Savings

Table 3 highlights the calculated mechanical work savings based on the methodology described in the previous section. Please note that "curve density" refers to the total length of curved (mild, intermediate, & sharp) track in the entire segment

Seg	Length (km)	Grade	% Curve Density	Mechanical Work Savings (kwh/MTM)	% Savings
1	19	+0.30	34	387	1.93%
2	13	+0.93	42	824	2.06%
3	8	+0.0	51	2,857	12.40%
4	16	-0.88	47	NA	**NA**
5	40	+0.00	36	1,059	4.68%
6	62	-0.03	34	689	3.68%
7	35	+0.02	25	626	3.56%
8	26	-0.53	15	NA	**NA**
9	18	-0.05	35	1107	4.27 %

Table 3: Mechanical Work Savings *Note 1 : MTM- Million Ton-Miles*

Analysis of the mechanical work data indicates a strong relationship between increasing savings and increasingly curved track. As curving resistance is a function of the degree of curvature and the resistance coefficient (Davis et al), it is expected that a reduction in the resistance coefficient will have a more dramatic impact in areas of track with a higher degree of "curve density".

Segments 4 & 8 were observed to be in dynamic braking for 100 % of the time due to the descending grade. Measured mechanical work was "negative" indicating compression on the instrumented shear pin.

3.2 Fuel Savings

Fuel savings calculated by both methods are presented in table 4a & 4b.

	Discrete		Composite		Average	
Seg	Fuel Savings	% Savings	Fuel Savings	% Savings	**Fuel Savings**	**% Savings**
1	128	2.17	149	2.36	**139**	**2.3**
2	287	2.30	367	2.74	**327**	**2.5**
3	608	8.92	880	12.06	**744**	**10.5**
4						
5	115	1.77	312	4.35	**214**	**3.1**
6	155	2.81	195	3.29	**175**	**3.1**
7	129	2.48	181	3.25	**155**	**2.9**
8						
9	310	4.00	318	3.88	**314**	**3.9**

Table 4: Calculated Fuel Savings

In reviewing the data, there appears to be a strong relationship between fuel savings and "curve density" for both models as observed with the mechanical work savings. Figure 3 shows the relationship when the results from the two methods are averaged.

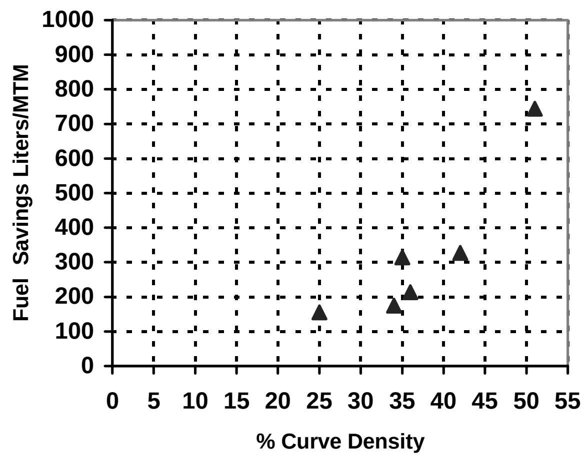


Figure 3: Averaged Savings combining both methodologies

In 2003, BNSF [11] investigated the effect of a TOR product, in this case a lubricant, on reducing truck hunting and rolling resistance on a section of tangent track. A different methodology was employed in which the test train was allowed to "coast down" a section of tangent track at various speeds. Based on BNSF's analysis, savings of approximately 2.1 % are possible due to reduction in rolling resistance (1.75 %) and truck hunting (0.21 %). On a system wide basis this translates to approximate savings of 106 L/MTM. For comparative purposes this data point has been added to the fuel savings data generated from this demonstration project (figure 4).

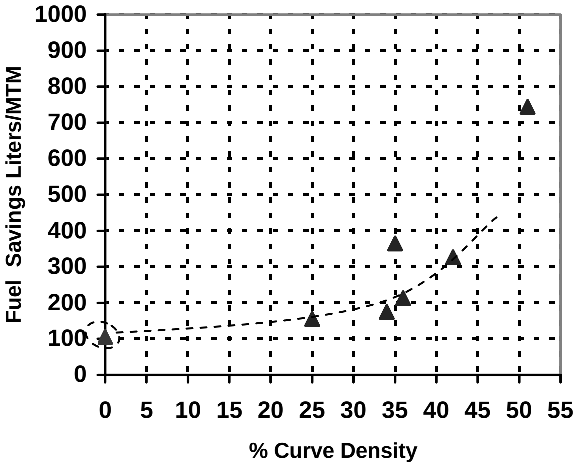


Figure 4: Fuel Savings including tangent data

In reviewing the data in figure 4, one will observe that the BNSF data does appear to follow the general trend of the data. Lower fuel savings are to be expected on tangent track in comparison to sections of track with significant curve density. However, the savings, on tangent track, are potentially significant due to the impact of truck hunting & rolling resistance at the elevated train speeds that are common on flat tangent track.

3.3 Fuel Savings & Dynamic Braking

On descending grades and under dynamic braking, fuel savings will be essentially zero. The reasons are as follows:

- Fuel consumption in regenerative braking is small in comparison to high notch settings.

- Intuitively, a higher curving resistance will assist in *retarding* the train resulting thereby complementing dynamic braking. Application of the friction modifier to reduce curving resistance will result in *increased* dynamic braking requirements to maintain track speed (thereby converting potential work to heat). Empirical analysis of QTRON data also indicated the addition of air braking during TOR conditioned test trains to assist train braking on descending grades.

Although no fuel savings are likely to be achieved when a consist is under sustained dynamic braking, other benefits can be derived through the application of a TOR friction modifier. These benefits would include:

- Reduction of lateral forces in curves for loaded freight trains
- Reduction in rail wear.

On sections of track with "rolling hills", both tractive effort and dynamic braking was observed to occur. The primary reason for the regenerative braking was to maintain track speed. For TOR conditioned train sets, an increase in both distance and time spent in dynamic braking was observed. This data has been summarized in figures 5 & 6:

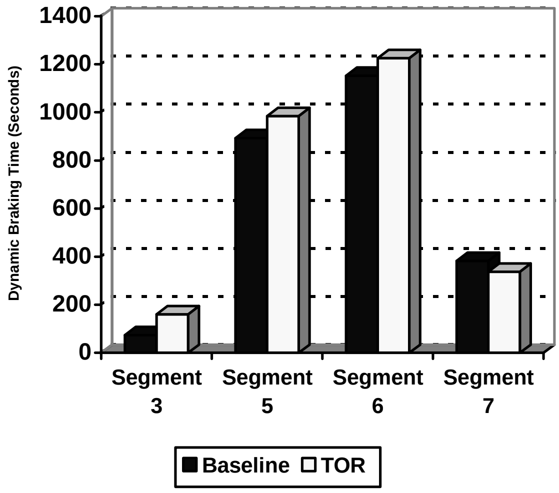


Figure 5: Segment Dynamic Braking Time (Seconds)

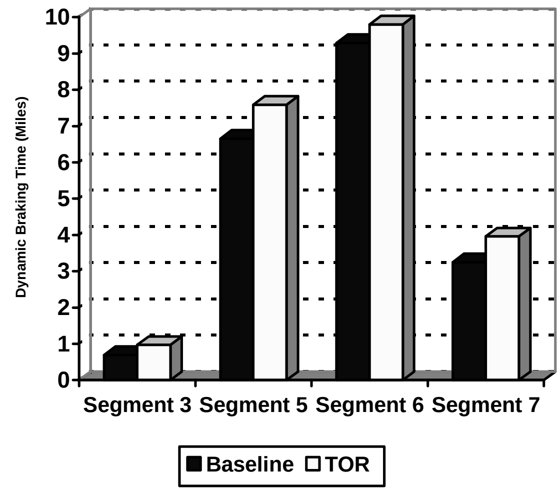


Figure 6: Segment Dynamic Braking Distance (Miles)

As mentioned previously, the application of a TOR friction modifier reduces curving resistance which can, under tractive effort, positively manifest itself as a reduction in notch setting(s) and/or increased train speed. In either case, the gain in potential work can be used effectively. Application of dynamic braking converts the gain in potential work into heat which cannot be utilized and could thus possibly limit the potential savings.

In assessing how DB influences the calculated savings for the data collected in flat segments where DB was present, the time & distance as well as trailing tonnage was used to calculated a dynamic braking fuel consumption value (L/MTM). This amount was then added to the calculated fuel consumption when the test consist was under tractive effort. The calculation was simplified by assuming that the average fuel consumption for each locomotive while under dynamic braking was 24.4 L/hr. The modified fuel savings are shown in table 5.

		Discrete		Composite	
Seg	% Curve Density	Fuel Savings (L/MTM)	Fuel Savings inc DB (L/MTM)	Fuel Savings (L/MTM)	Fuel Savings inc DB (L/MTM)
1*	34 %	128	128	149	149
2*	42 %	287	287	367	367
3	51 %	608	517	880	789
4	47 %	Descending Grade			
5	36 %	115	124	312	322
6	34 %	155	143	195	185
7	25 %	129	133	181	185
8	15 %	Descending Grade			

Table 5: Estimated Fuel Consumption per MTM for Dynamic Braking
** Note data remains unchanged as there was no reported Dynamic Braking*

For most of the segments there was either a slight increase or decrease in fuel savings. In segment 3 a significant reduction in fuel savings was observed due to increased dynamic braking.

3.4 GHG Emission Reduction

Figure 7 exhibits the corollary CO_2 emission reductions based on the calculated fuel savings, under tractive effort, plotted in figure 4.

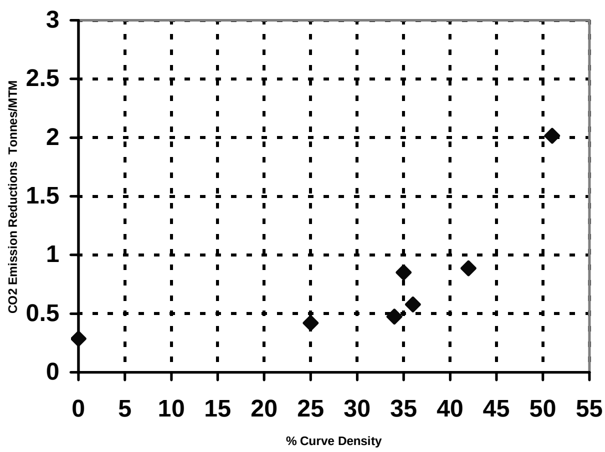


Figure 7: GHG Emission Reduction per Million Ton Mile

Based on 2002 Canadian freight traffic data, the potential reduction in GHG emissions ranges from 114.6 kilotonnes to 167.5 kilotonnes annually, or 2.1 % to 3.0 % of total freight railroad emissions. This is based on the premise that curve density for the entire Canadian freight track system lies somewhere in between 0 and 25 %. In mountainous terrain only, where there is significant curving resistance, the percentage savings is expected to increase. .

4.0 CONCLUSION

To summarize, the application of TOR friction modifiers was demonstrated to generate fuel savings ranging from 155 Liters/Million Ton-miles to a 744 Liters/Millions Ton-miles on track ranging in curve density from 25 to 51 percent. No fuel savings/ GHG emission reductions were achieved when the consist was under dynamic braking. Corresponding GHG Emission reductions (CO2) ranged from 0.3 metric tonnes per million ton-miles to 2 metric tonnes per million ton-miles.

It is recommended that the data generated in this demonstration project be used to develop a predictive fuel savings model to be applied outside of the test zone area

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4. Canadian Pacific Railway, for participating as a steering committee member

5. Lubriquip Inc, for providing technical support in installing & maintaining their TOR dispensing equipment

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