ABSTRACT
The benefits of effective Top of Rail (TOR) friction control in heavy haul freight operations (including fuel savings and asset life extension) have become clearly understood and verified over the past two decades. This is reflected by the increasing deployment of TOR friction control in concert with existing or improved Gauge Face (GF) lubrication in recent years. Optimizing the deployment of TOR friction control in a given territory requires reliable estimates of both the benefits and costs of deployment. As the benefits can take a substantial amount of tonnage (and time) to verify and quantify, the analysis when evaluating alternative TOR materials tends to focus on the cost side of the equation. Rather than comparing cost per unit volume between materials, a more effective approach involves comparing the Cost Per Treated Mile (CPTM), which is a function of material performance and corresponding factors such as carry distance and required application rates. Given the realistic difficulty in measuring TOR effectiveness through direct measurement of friction levels (due to the influence of factors such as wheel conditioning), measurement of lateral forces (and L/V ratios) using strain gauge based systems has emerged as the most reliable means of assessing TOR friction control effectiveness. While a comparison of lateral forces (e.g. between baseline and treated conditions) to determine TOR effectiveness is simple in concept, there are a number of critical operating factors that can have deleterious effects on the statistical validity of the results. This paper provides a review of several factors affecting lateral force measurement and analysis with respect to TOR material evaluation. A reliable set of methods for data filtering is presented to maximize comparability between conditions and ensure the statistical validity of results so that they can be reliably used in decision making.
INTRODUCTION
In recent years many heavy haul freight railroads have implemented Top of Rail (TOR) Friction Management in concert with the longer standing practice of Gauge Face Lubrication to reduce fuel consumption and/or extend track and vehicle component life. With an increasing number of different TOR material concepts entering the market the selection of the appropriate material becomes one of the key challenges. As impacts on fuel consumption or on track life can only be reasonably analyzed during an extended time period (up to multiple years) a short term criterion has to be selected that allows for technical and economic evaluation of different materials. The measurement and analysis of lateral forces can provide an efficient way of determining the effectiveness of TOR friction management within reasonable time periods.

MATERIALS FOR TOP OF RAIL
Materials for TOR application can be divided into two groups that have distinctive functional differentiation. Friction Modifiers (FM) aim at reducing high friction levels to an optimized intermediate coefficient of friction (COF) of 0.3 – 0.4. Besides the optimized friction conditions, an FM also provides positive friction characteristics between the wheel and the rail. An FM consists of a water-based suspension containing solid materials, and does not contain any liquid oil or grease (1) components. The water in these materials acts solely as a transport medium which rapidly evaporates under wheel-rail interface conditions. After the water has evaporated, the remaining dry thin film particles condition the rail and the wheel surfaces. This mechanism provides the above mentioned optimized friction conditions. There are minimal hazards associated with applying excess FM material. Unlike lubricants, friction modifiers maintain intermediate friction over a wide range of material thicknesses, while lubricants continually lower the coefficient of friction as more material is applied (2).

The second group of materials is called TOR lubricants. These materials also aim to optimize the COF between the wheel and the rail. The primarily functional difference is that the achievable COF is strongly dependent on the amount of material applied. This mechanism is referred to as mixed mode and/or boundary lubrication. This material type can also contain solid particles. Compared to an FM, these materials are non-drying or very slowly drying, leaving a liquid film between the wheel and the rail over an extended time period and carry distance. These materials can be sub classified into TOR Oils, TOR Greases and TOR Hybrids, the last of which contain a mixture of water and oil.

COST PER TREATED MILE MODEL
Historically railroads have sourced TOR-FM materials based on their cost per unit volume. However, differences in field performance caused by the different functional characteristics of these TOR materials require a new methodology for economic assessment. The material with the lowest cost per volume might not provide the maximum economic benefit. A “Cost Per Treated Mile” (CPTM) approach can help normalize the costs for different TOR materials over a given territory. This model can determine the cost for effectively (getting all of the expected benefits to the full extent) treating one mile of track with a TOR material. Equation 1 shows the components of the CPTM model.

\[ CPTM = \frac{(A \times B \times C \times D \times F) + (C \times E)}{G} \]  

(1)

The different parameters in the CPTM model are explained in TABLE 1.
TABLE 1: Parameters of the “Cost per Treated Mile” model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>TOR material price</td>
<td>$/gal</td>
</tr>
<tr>
<td>B</td>
<td>Application rate</td>
<td>gal/1000 axles</td>
</tr>
<tr>
<td>C</td>
<td>Number of wayside applicators in a track section (miles). This is based on the carry-down performance of the TOR material.</td>
<td># units</td>
</tr>
<tr>
<td>D</td>
<td>Average uptime of wayside units</td>
<td>%</td>
</tr>
<tr>
<td>E</td>
<td>Average annual maintenance cost of a wayside unit</td>
<td>$/unit</td>
</tr>
<tr>
<td>F</td>
<td>Annual number of axle passes on the track section</td>
<td>kaxles</td>
</tr>
<tr>
<td>G</td>
<td>Track section length (miles)</td>
<td>miles</td>
</tr>
</tbody>
</table>

The factors D, E, F and G do not directly depend on the actual TOR product performance and will not be further analyzed in this paper. It can be intuitively seen that carry distance and application rate will have a predominant effect in determining CPTM, and this can be quantified through rigorous sensitivity analysis (e.g. Monte Carlo Analysis) of the factors directly related to product performance (A, B, C).

A strategically planned field trial can be used to determine carry-down characteristics and application rates of different TOR materials based on measured lateral force reductions. The thorough planning of a field trial will significantly contribute to the success of a trial. This paper will primarily focus on the methodology necessary to objectively determine the important Cost Per Treated Mile model factors.

**FORCE MEASUREMENTS**

Measuring TOR effectiveness directly through measurement of friction levels will result in difficulties providing meaningful results. This is due to the influence of factors such as the degree of wheel conditioning or limitations of the measurement devices. However, the reduction of lateral forces at a given distance from an application site can be used to effectively determine the carry-down characteristics of a TOR material. For this purpose, L/V force stations are used to measure lateral (L) and vertical (V) forces in curves. These stations use strain gauges attached to the web and foot of the rail to calculate lateral and vertical forces by measuring the rail deflection caused by each passing wheel. For the calculation of absolute force values a periodic calibration of the force station is necessary. Each passing train produces a LOAD file that provides general information including date, time, direction, average speed, number of axles and number of cars and locomotives in the file header. The detailed axle by axle information includes axle number, car number, locomotive/car differentiation, speed and vertical as well as lateral forces. These LOAD files provide the raw data input for an L/V analysis.

**MATERIAL APPLICATION RATES**

The above mentioned sensitivity analysis indicates that the TOR material application rate has the second biggest impact on the CPTM model. Therefore, it is recommended that for a trial the application rates should be verified on site, especially with new TOR materials. Depending on the material type and the application equipment’s type and condition, the same application settings may result in different effective material output for different materials. Effective material output is typically measured in volume (ml, gal, fl oz) per 1000 axles.

**FACTORS INFLUENCING L/V**

The typical train mix (loaded and empty trains, fast and slow trains, short and long train, different train types etc.) in a given territory or sub-division will result in a very wide scatter of measured lateral forces that might blur any lateral force reductions provided by a TOR material. While in principal one could (for example) employ a multi-variant regression to compensate for a range of influencing factors, the factors affecting L/V measurements tend to be quite non-linear and non-monotonic in nature. In practical terms, overcoming this scatter and providing reliable and statistically significant data for the CPTM model requires thorough data filtering and analysis methodology.
The following factors will significantly impact lateral forces:

**Crib:** An L/V site typically consists of two (or more) measurement cribs for the purpose of redundancy. When analyzing lateral forces and L/V ratios, comparisons between test phases should only be made using data from the same crib. Curving dynamics will result in differences in lateral forces measured between cribs even if they are only spaced one or two crosstie distances apart. FIGURE 1 compares the lateral force distributions for the same train between the two cribs of an L/V site. It can be seen in this specific example that crib 2 records significantly lower lateral forces.

![FIGURE 1: Differences in lateral forces between two cribs of the same L/V site (distribution chart).](image)

**Locomotives:** Due to axle load and tractive effort locomotive axles can behave differently compared to un-driven car axles (FIGURE 2).

![FIGURE 2: Differences between locomotive axles (first four data points) and car axles (leading axles only) comparing vertical loads and resultant lateral loads on the low rail.](image)

**Leading and trailing axles:** The geometric alignment of a typical North American Three-Piece Truck in a sharp curve (above 5-6° curvature) will result in a relatively large angle of attack between the leading axle and the rail. This will in turn generally lead to flange contact between the high rail and the leading wheelset. The resulting levels of lateral creepage at the leading axle will produce correspondingly high lateral forces that will be transmitted between these axles and the track. Under these conditions trailing axles will normally stay (approximately) radially aligned with the curve and as such will tend to transmit relatively low lateral forces. FIGURE 3 demonstrates the difference in lateral forces between leading and trailing axles for a train (distribution chart).
FIGURE 3: Differences in lateral forces between leading and trailing axles (distribution chart).

Train speed: Changes in train speed will result in a change of the distribution of lateral forces at both the high and low rails. The impact of a change in speed is not straightforward, and depends largely on the relationship between the current speed and the balance speed in the curve. For example, operating speeds significantly below balance speed will tend to aggravate L/V ratios as the vertical load transfers to the low rail and angle of attack increases. An example of the influence of train speed (slow order) is shown in FIGURE 4. In this specific case there is a shift of lateral forces from the high rail to the low rail during the time of the slow order being in effect. There are statistical methods available to partially compensate for train speed changes if necessary.

FIGURE 4: Example of the influence of train speed on lateral forces. Due to a slow speed order lateral forces shift from the high rail (lateral force decrease) to the low rail (lateral force increase).

Vertical force / train load: Fully loaded trains will result in the highest vertical forces, in turn causing high lateral forces. This is a direct result of the relationship between creepage, friction levels and L/V ratios. Conversely, empty cars (lower vertical forces) will exhibit significantly lower lateral forces compared to loaded cars. FIGURE 5 shows an axle by axle graph for leading axles comparing vertical forces and resultant lateral forces for vehicles with different loading conditions within a train.
FIGURE 5: Impact of different loading conditions of cars (vertical forces) on the resultant lateral forces. Typically the higher the vertical force the higher the resultant lateral force.

Train length: Train length can have a significant impact on lateral forces and L/V ratios. However, this is also not straightforward as the effect is interrelated with the specific implementation of locomotive power (e.g. distributed power configurations) and resulting in-train forces.

Train type: Specific train types might result in different lateral forces dependent on the truck type. FIGURE 6 compares coal trains having frame braced trucks (improved steering) with grain trains that use conventional trucks. Train types might be filtered by using available AEI data or train lineup information provided by the operator.

FIGURE 6: Impact of different train types on lateral forces.

Other factors: Maintenance activities (grinding, tamping, surfacing, re-gauging) will impact the geometrical conditions of a curve and will thereby change the curving behavior of vehicles. This will cause a significant change in measured lateral forces during a trial and will require a re-calibration of the test site.
FIGURE 7: Influence of maintenance activities (here: rail grinding) on lateral forces. Uptrend of lateral forces after grinding visible.

The unknown: Besides all of the factors listed above, there is a chance that some unknown factors can impact the L/V results significantly. These factors are assumed to be related to weather conditions and/or operational conditions (e.g. track quality, TOR contamination ...). Due to the absence of 24/7 observation of the test site, these factors may be difficult to identify. However, if trial outcomes diverge from expected results (despite using a thorough analysis methodology) these “unknown” factors will need to be carefully considered.

APPLICATION OF METHODOLOGY

Based on these influencing factors, a thorough filter analysis needs to be applied to the raw data to obtain statistically meaningful results. Typical examples of filter settings for a TOR trial are listed in TABLE 2. This combination of filters was developed during a trial together with TTCI (3) and was further refined over time by L.B. Foster.

TABLE 2: Example filter settings for L/V analysis.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>Westbound, track 1</td>
</tr>
<tr>
<td>Axles:</td>
<td>Leading axles only</td>
</tr>
<tr>
<td>Vehicle:</td>
<td>Cars only</td>
</tr>
<tr>
<td>Loading conditions:</td>
<td>Axles with a vertical load above 25 kips</td>
</tr>
<tr>
<td>Speed range</td>
<td>Typical speed range for the test site. Example: 24-28 mph</td>
</tr>
<tr>
<td>Train length</td>
<td>Trains with more than 350 axles</td>
</tr>
</tbody>
</table>

The output of this analysis is a table that lists all of the trains that completely or partially meet the filter criteria. For each of these filtered trains the average vertical and lateral force values are calculated and listed (including data like date, time, speed, etc.). If only parts of the train meet the vertical filter criterion then only these axles are used to calculate the average force values for this train. This master data is then used to provide three different type of diagrams for visualization.

A “scatter plot” will provide the average lateral forces per filtered train over a given time. This chart will provide a general overview about the different phases of a trial and the general trends. A trial phase is
defined as a period of time where the application settings of a product have been kept constant. Significant observable changes due to other factors (e.g. rail grinds, slow orders) may interrupt a trial phase. The reference for each trial phase is a baseline dry (bl-dry) phase where no TOR material was applied. Due to the above mentioned factors, baseline dry conditions might change over the course of a trial. Therefore it is important to include repeating short bl-dry phases during the course of longer trials for verification purposes.

![TOR Material Performance on Rolling Grade, Class 1 railroad](image)

**FIGURE 8:** Scatter Plot of a typical TOR material trial. Each filtered train is represented by one marker (high and low rail). The different trial phases and transition periods are indicated.

The distribution of these average lateral forces per train for each trial phase is shown in a distribution chart. The chart also includes a cumulative plot for each phase (dotted lines). This allows a clear visualization of the impact of a trial phase on the change in lateral forces. **FIGURE 9** shows that the high lateral forces in the “bl dry” phase are cut off by the TOR material application and that the whole distribution has shifted to lower lateral forces (all high rail [HR] data). The figure also indicates the impact of different application rates of the TOR material.

![Distribution plot for different phases of a trial (HR only). Trial phase 2 has a higher TOR material application setting compared to trial phase 1.](image)
Finally an average lateral force reduction per test phase and the corresponding % reduction in lateral forces per phase as referenced to the corresponding bl-dry phase can be calculated (FIGURE 10). This diagram also includes information about the standard deviation of the different product phases as well as the number of trains that were included in each trial phase. A significance test for each trial phase is conducted to verify that the changes measured are related to the application of a TOR material and are not caused by random data variation.

![Average Lateral Forces Diagram](image)

**FIGURE 10:** Average Lateral forces (HR) per trial phase including % reduction, standard deviation information and train count per trial phase.

A number of errors can be made during an L/V analysis. These errors range from the hand picking of individual trains per trial phase to not applying all of the necessary filters. These errors will impact the calculated results of a trial and might lead to misleading conclusions about the performance of a tested product and/or application settings. FIGURE 11 gives an example of comparing two extreme cases of lateral force analysis.

![Distribution Chart](image)

**FIGURE 11:** Comparison of two extreme cases of lateral force analysis (distribution chart). 11a: the chart was created by using no filters at all. 11b: the chart was created by applying all recommended filters.

In FIGURE 11a, no filters were applied prior to generating the distribution chart. In FIGURE 11b, all of the recommended and necessary filters were applied. The chart without filters applied provides an ambiguous result compared to the filtered chart. Depending on the local conditions (traffic, curve condition, maintenance) different errors in the filter methodology may have different impacts on the outcome of the
analysis. Consequently it is recommended to apply all filter criteria at the appropriate settings and values in order to provide consistent and reliable results.

**SUMMARY**

With different material concepts for TOR products available, simply assessing the price per volume of the material will not provide a reliable criterion for choosing the most economic product. The proposed “Cost Per Treated Mile” (CPTM) model can help in determining the actual costs for effectively treating a mile of track including factors like application rate, carry-down and traffic conditions among others. As the CPTM model is highly sensitive to carry-down and application rate a thorough test methodology to determine these factors is recommended. Lateral forces and their reductions can be used as a reliable indicator for the carry-down characteristics of a material. The filter methodology proposed will provide reliable and statistically significant lateral force information for determining the carry-down distance of a TOR material.

The CPTM model will provide reliable economic product information based on short term trial information. However, long term factors like the impact of a TOR material on corrugation growth, wear, rolling contact fatigue development and grinding cycles should also be considered for selecting an appropriate product for TOR application. This holistic concept will provide an objective approach for selecting the appropriate and most economic TOR product for an infrastructure owner.

**LITERATURE:**


**TABLE CAPTIONS:**

TABLE 1: Parameters of the “Cost per Treated Mile” model.

TABLE 2: Example filter settings for L/V analysis.

**FIGURE CAPTIONS:**

FIGURE 1: Differences in lateral forces between two cribs of the same L/V site (distribution chart).

FIGURE 2: Differences between locomotive axles (first four data points) and car axles (leading axles only) comparing vertical loads and resultant lateral loads on the low rail.

FIGURE 3: Differences in lateral forces between leading and trailing axles (distribution chart).
FIGURE 4: Example of the influence of train speed on lateral forces. Due to a slow speed order lateral forces shift from the high rail (lateral force decrease) to the low rail (lateral force increase).

FIGURE 5: Impact of different loading conditions of cars (vertical forces) on the resultant lateral forces. Typically the higher the vertical force the higher the resultant lateral force.

FIGURE 6: Impact of different train types on lateral forces.

FIGURE 7: Influence of maintenance activities (here: rail grinding) on lateral forces. Uptrend of lateral forces after grinding visible.

FIGURE 8: Scatter Plot of a typical TOR material trial. Each filtered train is represented by one marker (high and low rail). The different trial phases and transition periods are indicated.

FIGURE 9: Distribution plot for different phases of a trial (HR only). Trial phase 2 has a higher TOR material application setting compared to trial phase 1.

FIGURE 10: Average Lateral forces (HR) per trial phase including % reduction, standard deviation information and train count per trial phase.

FIGURE 11: Comparison of two extreme cases of lateral force analysis (distribution chart). 11a: the chart was created by using no filters at all. 11b: the chart was created by applying all recommended filters.
Lateral forces as indicator for an efficient friction management.

Dr. Richard Stock

L.B. Foster
Outline

- Friction
- TOR Material concepts
- CPTM
- Lateral Forces and influencing factors
- Lateral Force Analysis
- Conclusions

Friction

- Coulomb’s law of friction

\[ F = N \times \mu \]

\[ N = m \times g \]

\[ \mu = \frac{F}{N} \]

Measure Friction!

Friction – Coefficient of Friction

- Friction is always a function of two surfaces not one
- Wheel – Rail Friction Levels
- Tribometer only tells you half the story (rail)

TOR Materials

<table>
<thead>
<tr>
<th>TOR Lubricant</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOR Oil</td>
</tr>
<tr>
<td>TOR Grease</td>
</tr>
<tr>
<td>TOR Hybrid</td>
</tr>
</tbody>
</table>

Friction Modifier characteristics, water based, no liquid oil or grease, drying material, solid particles

Lubricant characteristics, oil or grease based, non drying, water content and solid particles possible

Influencing Friction Levels

Dry contact: Mixture of different brittle, solid third body materials like wear debris, oxides, sand, brake shoe debris...

\[ \mu = 0.5-0.8 \]

FM treated contact: Pliable FM particles adjust shear properties of third body layer and thereby adjusting a desired W/R friction level.

\[ \mu = 0.3-0.4 \]

Mixed/boundary lubrication: Lubricant is present but there is still considerable contact between the different surfaces in the W/R interface.

\[ \mu = 0.2-0.6 \]

Film lubrication: A thick liquid lubricant film is separating the contacting surfaces and thereby reducing the W/R friction level to a minimum.

\[ \mu < 0.1 \]
Cost per Treated Mile Model

- Cost to effectively treat one mile of track
  - get all the expected benefits

Cost Per Treated Mile

- Most influential factors (based on sensitivity analysis):
  1. Applicator spacing / carry down
  2. Application rate
  3. Product price ($)

Lateral Forces

- Lateral forces as indicator for friction conditions
- L/V load station (lateral/vertical forces) in a sharp curve (saturated steering)
- Thorough planned field trial
  - Carry Down Information
  - Material application rates

Factors influencing L/V

- Train mix in each subdivision
  - Fast, slow, long, short, different train types, maintenance vehicles…
  - Scatter of Lateral and Vertical Forces
- Filter for relevant data

L/V load station

- Typically 2 cribs per L/V site (redundancy)
- Curving dynamics – differences between cribs

Locomotive vs. cars

- Locomotive
  - Driven axles, high axle load
- Example: 2 locos and the first 9 cars of a train
Truck Alignment

- Sharp curves: trailing axle is radially aligned while the leading axle has an angle of attack (AOA)

Leading vs. Trailing Axles

- Highest lateral forces for leading axles

Train Speed

- Change of lateral force distribution with train speed
  - Current speed vs. balanced speed of curve
  \[ v = \text{normal [mph]} \]
  \[ v = \text{slow [mph]} \]

Train Speed Influence

- Slow order

Vertical Force / Train Load

- The higher the vertical force the higher the lateral force (for constant friction)
- Loaded trains transmit higher lateral forces than empty trains.
Car Load Impact

- Intermodal train with mixed loading

Train length

- Impact interrelate with
  - Locomotive power
  - Train speed
- Resulting in different in-train forces
  - Buff and drag forces

Train Type

- Vehicle design and truck design will impact steering capabilities and lateral forces
  - Standard three piece truck vs. frame braced trucks

Train Type Comparison

- Coal trains with frame braced trucks

Train Type Comparison

- Coal trains with frame braced trucks

Reduced lateral forces due to improved steering
Track Maintenance
• Maintenance activities will change geometrical track conditions and vehicle steering
  – Grinding
  – Re-gaging
  – Tamping
  – Resurfacing

Impact of Grinding
• Change in lateral forces after grinding

The Unknown
• Unknown factors WILL impact L/V measurements

Methodology Application
• Statistical meaningful results / overcome scatter
• Example with applied filters
  – Direction: westbound, track 1
  – Axles: leading axles only
  – Vehicles: cars only / no locos
  – Loading conditions: axes with vertical load > 25kips
  – Speed range: 24mph – 28 mph (typical range)
  – Train length: >350 axles

Scatter Plot Results

Distribution and Average
**Possible Errors and Mistakes**

- Hand picked trains
- Semi–filtered results (partial filter application)
- Ambiguous and non-relevant results

![Graph showing hand picked trains vs. semi-filtered results](image)

**Conclusions**

- L/V variation, analysis errors
- Lateral Force Application methodology
- Applicator spacing - Material application rates
- CPTM – cost per treated mile model
- Cost to effectively treat one mile of track

Efficient Friction Management implementation

**Thank You For Your Attention**

![Image of train tracks](image)