Science-Based Approaches to Extending System Wheel/Rail Asset Life

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1.0 Overview

To optimize the benefit and return on investment of new technologies that extend asset life, a combination of field inspection and assessment must precede implementation of new maintenance programs, materials, and methodologies. Doing so will aid in optimizing overall wear, fatigue, and load environment of a railroad system. While a number of procedures and equipment are available for reducing railroad system wear and stress, this paper will emphasize the use of alternative friction-control methodologies and wheel/rail contact geometries. As friction at the wheel/rail interface interacts with the contact geometries, simply maximizing benefits to any single parameter, such as wear, fatigue, or load environment, the system performance may not be optimized. Thus examination and understanding of the system interaction is needed to ensure the best return on investment.

2.0 Two methodologies for improving rail/wheel system performance

Two complementary approaches have been developed and deployed by Transportation Technology Center, Inc. (TTCI) to extend wheel/rail life assets by reducing system wear and forces. These include:

- Assessing and improving rail lubrication/friction control
- Optimizing wheel/rail profiles

TTCI has developed methodologies for optimizing wheel/rail profiles that improve bogie steering performance to extend rail and wheel life while concurrently limiting rolling contact fatigue issues. The use of friction control will enhance these performance attributes and offers localized benefits to mitigate situations when optimized profiles cannot be maintained. While the total system approach incorporates both solutions, to clarify attributes and implementation issues of each, they will be described individually.

3.0 Lubrication and Friction Control

Lubrication of the gage face (GF) surface has been utilized by railroads for over one hundred years. In the heavy freight railroad environment, lubrication has, until recently, been implemented primarily as means of controlling friction at the GF with the intent to extend rail life. In the last 20 years, the industry has developed a better understanding of the relationship between friction control and subsequent system behavior. An extensive investigation using a matrix of wheel/rail friction variations under a wide range of curvatures and bogie conditions was conducted using NUCARS® to predict curving performance [Ref. 1]. This information was utilized to produce friction guidelines for new friction control methodologies that not only reduce system wear but, when properly implemented, can also reduce curving forces, improve running surface fatigue performance, and control noise.

The approach to improved friction control includes the following major steps:

- Field inspection and assessment of current conditions
- Review of railroad policies and site specific issues for improving friction control
- If needed, demonstrations of applicator and material performance to determine if railroad specific situations require alternative deployment
- Coordination of friction changes with the wheel/rail profile maintenance program

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2 NUCARS® is a registered trademark of the Transportation Technology Center, Inc.
• Implementation of improved friction control
• Management oversight and long term monitoring

3.1 Field inspection

The initial effort in improving rail friction conditions is to assess existing conditions and determine if they comply with target friction levels. Using recommendations from NUCARS predictions, results from field demonstrations, and current AREMA recommendations, the following friction guidelines are suggested:

• GF friction < 0.25 µ
• Top of rail (TOR) friction 0.35µ +/-0.05 µ
• Left to right rail differential < 0.1 µ

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While measuring rail friction is straightforward, this technique only determines part of the wheel/rail interface condition. Wheels are also subjected to, and become conditioned with, lubricants and friction modifiers. Measuring rail friction alone provides a spot indication of rail friction conditions and does not always fully correlate with total system performance. Revenue service is subjected to a wide range of trains, bogies, weight, and wheel/rail profiles. If additional information on system performance is needed, other indices can also be monitored. Some of these inspection techniques require a long time and/or the passage of one or more trains to collect the necessary data and may include:

• **Curving Forces:** Strain gages installed on the rail are used to determine lateral curving performance. Curving performance has been shown to change with friction patterns developed by GF and TOR friction control systems.

• **Energy:** Reductions in train energy consumption are train and site specific. Measuring train energy is expensive and has seen limited use in recent evaluations.

• **Wear (rail or wheel):** Long-term implementation of any friction control system is also reflected by reduced system wear. Most demonstrations conducted over a short time do not have a sufficient number of systems implemented to provide adequate coverage to properly affect system wear.

• **Rail Head Deflection:** Some success has been experienced measuring dynamic rail-head deflection under passing trains [Ref. 2]. Changes in curving forces with friction patterns are reflected by reduced gage widening.
deflections. This method is being considered for use as a portable means for determining TOR effectiveness at site-specific locations.

An example of how friction control policies can alter some of these performance indices is shown in Figure 2. This data was obtained on the Facility for Accelerated Service Testing (FAST)/Heavy Axle Load (HAL) loop during a period when the train was operating at the normally prescribed 40 mph (64 kph) speed. During a 45 lap period, the lubrication was purposely altered from the “normal” condition, which consists of moderate GF lubrication applied to the outside rail curves and a small amount of lubricant applied to the top of the inside rail.

![Figure 2: Example of curving forces and rail head deflections under a range of friction control conditions.](image)

In this example, higher lateral curving forces occurred when the high rail of the curve remained fully lubricated from a nearby wayside lubricator; however, the low rail application was turned off (laps 12 through 18). Such a condition can be found when a wayside lubricator over applies grease on one rail only with the low rail disabled. This generates very low friction values on the top and side GF of the high rail ($\mu < 0.20$), while at the same time maintaining a dry ($0.50 \mu$) friction on the top of the low rail. This condition violates two of the three recommended friction levels as stated in Section 3.1.

By conducting one or more monitoring methods at various locations, the inspection will allow documentation of where friction values need to be changed in order to improve system benefit.
3.2 Achieving friction control goals

After assessing existing friction values and current methods of application, improvements, if any, can be specified. If inspection of existing lubricators suggests a large number are not working or are improperly adjusted, then the first step will be to establish a program with the railroad to correct these deficiencies. In many cases the original installations of such systems were based on protecting key curves and locations, however over time some systems may have failed or components become worn or damaged. In some situations, due to localized budget restrictions or inappropriate maintenance policies, crews have not kept applicators filled, repaired, or maintained.

Such deficiencies must be rectified, followed by re-inspection of the site, to determine if proper application of lubricant or friction control materials is now being conducted. Coordination with vendors and suppliers is suggested to ensure the latest techniques and upgraded parts are in use. Often such feedback, followed by adjustment and repair efforts will show many of the areas initially indicating inadequate friction control are now properly, or nearly properly covered.

Based on the change needed to meet desired friction values, a number of technologies are available. These fall into two major categories:

- GF lubrication
- TOR friction control

The most significant difference between TOR friction control and conventional GF lubrication is the use of a friction modifier (FM) instead of a lubricant (grease or oil). TOR friction control achieves benefits when the top of both rails are at the target levels of 0.3µ to 0.4µ. While theoretically a lubricant could be used for this application, it is difficult to control such products to produce the desired friction value on a consistent basis. Figure 2 shows the conceptual relationship between a lubricant and friction modifier relative to product thickness on the running surface.

![Figure 2. Conceptual performance of a FM and lubricant (grease or oil).](image)

As product thickness of a lubricant or FM is increased, the resulting rail friction is reduced from a dry value of 0.5 µ. A typical lubricant produces a steady state friction of 0.35 µ over a very narrow band of film thickness, while a FM produces the desired 0.35 µ over a wider range of thickness. This feature of a FM allows TOR application systems to produce desirable friction levels over a wider range of product thickness than a lubricant.

3.3 Application systems

The two most commonly utilized application methods for either GF lubrication or TOR friction control are variations of:

- Fixed (wayside) applicators
- Mobile (usually locomotive mounted) applicators
Fixed – Wayside-Based Application Systems

Wayside-based application systems are presently the most widely used applicator format in North America. Typical wayside lubrication or TOR systems are similar in appearance to conventional GF applications, with the most notable difference in applicator bar configuration. These are mounted on the field side of the rail for TOR systems (Figure 3) and on the gage side of the rail for more traditional GF lubrication systems.

![Typical wayside-based TOR application system.](image)

Curving force data collected in territories equipped with multiple wayside-based TOR applicators suggests that more effective friction conditions are established with multiple applicators over a set distance than with a single unit [Ref. 3, 4, and 5]. This is likely due to wheels of a train becoming conditioned with grease or FM material after passing multiple applicators sites.

Mobile – Locomotive (or On-Car)-Based Application System

Locomotive-based GF and TOR friction control concepts are similar except for the point of application. GF lubrication systems spray lubricant directly onto the flanges of most if not all locomotive wheels. For TOR applications, dispensing nozzles are configured to apply FM product directly onto the top of the rail behind the last driven axle of a locomotive consist. For this reason, control systems require data input to determine last locomotive in consist and trailing end to activate only one pair (one nozzle for each rail) of applicators. A typical locomotive-based applicator configured for a TOR system is shown in Figure 4.

![Typical locomotive-based TOR application system nozzle mounted on sand bracket.](image)

Figure 4. Typical locomotive-based TOR application system nozzle mounted on sand bracket.
The deployment method (fixed or mobile) selected depends on a number of issues. While report space limitations prevent detailed discussions, generally when curves are uniformly spaced and less concentrated into localized bunches, the use of mobile-based systems becomes more attractive. When curves are concentrated in specific locations as well as being severe, the use of wayside-based applicators becomes more attractive. Other issues to investigate include access for wayside applicators, temperature variance, solar power capacity, operating environment, interchange of locomotives, labor policies, and past experience.

3.4 Demonstrations of applicator and material performance

In some instances, railroad specific requirements prevent standard deployment of friction control systems. For example, spacing of wayside applicators may need to be extended to fit site access and curve limits. In such cases a short demonstration of that particular deployment scenario would be conducted utilizing one or more of the measurement techniques outlined in Section 3.1. This should allow the railroad to quantify the benefit (where needed) and evaluate increased application rates or alternative lubricants or FM products before implementing that scenario on a wider basis.

In most cases, however, deployment would follow vendor or best practice recommendations (such as those found in Chapter 4 of the AREMA Manual). Minor adjustment or verification of improvements could still be conducted using the same measurement tools. An important aspect of implementation, however, is to ensure that the friction levels produced are indeed optimized so that interaction with profile grinding and other maintenance methodologies proceeds as intended.

3.5 Management oversight and long-term monitoring

While vendors continue to improve products, the day to day operations over a territory can become routine and employees will often follow a “whatever works” approach. In the case of friction control, periodic inspection and feedback to the staff maintaining these systems is essential in ensuring a viable return on investment. Also, as some systems age and wear, application patterns may vary and eventually create undesirable friction patterns, such as that shown by the eventual performance of the FM and Lubricant displayed in Figure 2.

On site inspection, not only of the applicators (be they wayside or on board based) but of the rail in curves, is essential. Feedback from such inspections to the applicator maintenance crew is needed to ensure proper operation when adjustment is needed. In the case of wayside applicators, inspection and adjustment is often conducted by the same person. This is an advantage as direct feedback of rail conditions created by each wayside applicator eliminates communication issues. Where on-board applicators are utilized, the feedback requires communication between ground inspectors and mechanical departments. As such communication paths generally do not exist in most railroad environments, implementation requires management support and enforcement.

Long-term monitoring of rail wear and surface conditions will also provide valuable information to management on the reliability and effectiveness of friction control systems. Such information is becoming easier to collect and summarize, with modern inspection cars often being equipped with automated rail profile monitoring equipment.

4.0 Wheel/Rail Profiles

Wheel/rail profiles have considerable effects on vehicle dynamic performance, wheel/rail wear, and the formation of rolling contact fatigue on wheel/rail rolling surfaces. To improve wheel/rail interaction and extend wheel/rail life, significant research has been conducted on more accurately assessing wheel/rail contact conditions.

Not very long ago, due to the limitation of profile measurement techniques and computer speed, only very limited numbers of wheel/rail profiles could be measured and analyzed in a system. Therefore, it was very difficult to have an overall view of wheel/rail profile shapes and contact conditions in a system. Benefiting from the measurement techniques developed and the significant improvement in computer speed and storage size in recent years, conducting a large number of profile measurements and performing comprehensive analysis on the measured profiles are now possible.
4.1 System level assessment of wheel/rail contact

TTCl has developed a computer software program, named WRTOL™ to assess wheel/rail contact conditions and to predict vehicle performance or the damage to surfaces caused by unfavorable wheel/rail profile combinations. A distinct feature of this program is capability to analyze contact situations of many wheelsets against a measured pair of rails (Rail Function in WRTOL), or many rails against a measured pair of wheels (Wheel Function in WRTOL). This method provides a comprehensive view of wheel/rail contact at the system level. The Rail Function of this software has also been further developed to work with an automated rail measurement system to perform onboard real time contact analysis [Ref. 6].

Figures 5 and 6 show examples of how the software can be used to quantify the wheel/rail contact conditions. Figure 5 displays the effective conicity comparison of two pairs of measured rail profiles from two sections of tangent track. The effective conicity is defined by Equation 1,

\[ \text{Effective conicity} = \frac{\Delta RRD}{2y} \]  

where \( \Delta RRD \) is the rolling radius difference of two wheels on the same solid axle in a wheelset with a lateral shift range of \( y \).

The rail profiles were analyzed against a group of representative wheel profiles that have different levels of flange and tread wear. About 80 percent of those wheels produce an effective conicity less than 0.35 when contacting with the rail profiles used for the top graph of Figure 5 compared to about 50 percent for the rail profiles used for the bottom graph of Figure 5. Therefore, the rail profiles used in the bottom graph of Figure 5 would have higher risk of inducing vehicle hunting. In contact patterns, the rails for the top graph of Figure 5 shows generally no flange root contact, while the rails for the bottom graph of Figure 5 shows about 50 percent of the wheels would have contact the rails at the flange root. Under this condition, the recommended grinding pattern would be to lower the rail gage shoulder to avoid wheel flange root contact for reducing the conicity.

Figure 6 displays the contact conformity comparison of two pairs of measured rail profiles from two curves. The conformity of wheels contacting the high rail is measured by the gap between the wheel flange throat and the rail gage corner during wheel flanging, as shown in Figure 7. The gap measurement is used as an indicator of wheelset steering performance in curves. A large gap can lead to severe two-point contact on the flanging wheel resulting in poor wheelset steering in curves. A large gap also requires a longer time to wear into a conformal contact situation than a smaller gap. In the top diagram of Figure 6, nearly 100 percent of wheels in the selected group produce a gap below 0.5 mm compared to about 90 percent of the wheels which produce a gap larger that 0.5 mm with about 75 percent of the wheels above 1.5 mm. Therefore, the lower rail profile pair is likely to induce higher lateral force and higher wear. Under this condition, grinding templates and the grinding procedures need to be checked to see if the rail gage corner has been over cut.

\[ \text{Conicity } (\%) \]

3 WRTOL™ is a trade mark of TTCl.
As discussed in Reference 6, when the assessment of individual rail profile (Figures 6 and 7) can be continually performed along the railway, the overall wheel/rail contact conditions in a system can be monitored.

### 4.2 Prediction of wheel/rail interaction using both measured profiles and pre-computed dynamic simulation results

To more accurately predict the situation at the wheel/rail interface, the wheel/rail contact conditions should also be analyzed with the consideration of vehicle/track conditions. Since performing vehicle simulations for every pair of rail profiles measured against a large group of wheel profiles is not practical, pre-computed dynamic data provided with the software can be used for predicting the likely wheel/rail interaction for the measured wheel/rail profiles.

TTCI has performed an extensive parametric study of vehicle performance using the NUCARS vehicle dynamic simulation package [Ref. 7]. The parameters, with each varying in a range that is commonly experienced in the actual vehicle/track conditions, investigated in the study include:

- Track curvature
- Two types of truck (standard three-piece truck and improved suspension truck)
- Lubrication at wheel/rail interface
- Rolling radius difference
- Operating speed (over or under balance)
- Contact conformity
The outputs related to wheel/rail interface from the simulations that are being documented include:

- Lateral force
- Longitudinal force
- Steering moment
- Wear index at each contact position
- Total rolling resistance of a vehicle

Based on the simulation results, a “Map” of vehicle performance has been produced using the specified wheel/rail profile contact features and vehicle/track conditions.

Note that each measured pair of rail profiles has contact features that are related to the profile shapes and the gage measured as it contacts with a pair of wheel profiles. The contact features are mainly indicated by the following parameters:

- Rolling radius difference/or Effective conicity (directly affect dynamic performance)
- Contact conformity (indicates how soon profiles can wear into conformal contact)
- Contact positions (affects wear pattern and the risk of rail roll)
- Contact stress under the given load (affects wear and the formation of RCF)

Therefore, with the specified contact parameters, the likely wheel/rail interaction can be predicted when combined with the correlated dynamic performance obtained from the simulations. Note that this prediction does not include the influence from track geometry irregularities and unusual truck defects. The prediction only intends to show the performance trend of typical cars with specified wheel/rail profiles. For example, a pair of rail profiles was measured on a curve of 291 meters in radius. When it contacts with a pair of selected wheel profiles, it shows the following contact features:

- $RRD2-RRD1 = 12$ mm
- $RRD3-RRD1 = -1.0$ mm
- Contact conformity = 1.0 mm

$RRD1$, 2, and 3 are defined as shown in Figure 8.

![Figure 8. Definition of $RRD1$, 2, and 3](image)

By looking up the “Map” of dynamic simulation results, Figures 9 and 10 show the lateral force, steering moment, and total rolling resistance related to these contact features at different values of $RRD3 - RRD1$ and three types of lubrication condition. The symbol of $\mu=0.5/0.15$ indicates the friction coefficient is 0.5 at the rail top and 0.15 at the rail gage. The dashed line in Figures 9 and 10 indicates the values for $RRD3 - RRD1 = -1$ mm. Note that the axle steering moment reduces or becomes negative as $RRD3$ larger than $RRD1$. More detailed results related to each contact point for different track conditions can be further explored in the “Map”.

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4.3. Applications of the assessment tools

By applying the predictive modeling tools introduced above and conducting field inspections, wheel/rail contact conditions can be assessed or predicted quantitatively at the system level. The assessment results that consider both profile contact features and their performance under different vehicle/track conditions may reveal problems that may not have been realized by only looking at a few wheel/rail profile combinations. Assessment results can also provide directions for improvement or suggest maintenance actions to be taken to extend wheel/rail life.

Note that in general, a pair of measured rail profiles may have several contact features as they contact with a group of representative wheel profiles collected from the system. For example, in the lower diagram of Figure 2, different percentages of wheels (in the wheel database used in this analysis) fall in several gap value bands of less than 0.5, 0.5 to 1.0, 1.0 to 2.0, and larger than 2.0 mm. Therefore, based on the contact features they represent, the effects on the dynamic wheel/rail interface can be searched in the different areas of the “Map”. The overall performance would be evaluated by considering all of these results. The wear patterns and the formation of RCF would also take into consideration the different contact positions with different traction forces.

If the wear rate can be estimated based on the current contact patterns, the next stage of contact features (with their specified contact parameters) may be predicted. Therefore, again, by looking up the performance “Map”, the general performance that system may progress into can also be predicted.

The concept of optimizing wheel/rail contact can be and has been applied to rail grinding trials and to the recommendations for wheel profiles. Figure 11 shows an example just after rail grinding on a curve. The resulting contact features included:
$RRD2 - RRD1 = 12 \text{ mm}$

$RRD3b - RRD1 = 0.8 \text{ mm}$

Contact conformity $= 1 \text{ mm}$

Because of a slightly higher gage shoulder on the low rail, the $RRD3b$ is 0.8 mm larger than $RRD1$ compared to the ideal position at $RRD3a$, which produced a rolling radius 0.8 mm smaller than $RRD1$. By looking up the “Map”, simulation results in Figures 9 and 10 at $RRD3 - RRD1 = 0.8 \text{ mm}$ indicate higher lateral forces and higher rolling resistances for both leading and trailing axles as the wheel contacts at the position of $RRD3b$ are compared with contact at $RRD3a$. This contact pattern is especially likely for the trailing wheels if the low rail shoulder is high. Figure 12 displays the surface RCF that was observed on the low rail with the high gage shoulder. Therefore, a modification to the low rail grinding template was made to move the contact region to the center of crown area on the low rail. This was also emphasized in the following rail grinding on the entire line.

![Figure 11. An example of wheel/rail contact pattern after grinding.](image1)

![Figure 12. Surface damage.](image2)

In summary, with an improved understanding of wheel/rail interaction and the newly developed analytical tools, improving wheel/rail asset life can be achieved using a science based approach. These methods will also help with economic evaluations of any benefits that may be received. Since this analysis would use wheel/rail interaction parameters such as forces, wear indices, and rolling resistance at different stages of improvement. These can be searched on the “Map” based on recommended or proposed contact features.
5.0 Results and Conclusions

Field inspection and measurement procedures have been developed to determine contact geometry and rail/wheel friction conditions. Through use of models that predict contact stresses and curving performance, improved profiles have been developed. An understanding of materials and application methods for lubrication and friction control along with their field behavior allows an improved friction environment to be implemented. Case studies of improved grinding and/or lubrication controls on Companhia Vale de Rio Dose (CVRD)-Brazil, Norfolk Southern [Ref. 8], Union Pacific Railroad [Ref. 9], and CN [Ref. 4] have been implemented to reduce rolling contact fatigue, extend rail life, and control curving forces. Field data has shown a reduction in curving forces by over 30 percent along with extending rail life by 50 percent through the proper use of friction control and wheel/rail profile maintenance.

References


