Estimation of Bogie Performance Criteria Through On-Board Condition Monitoring

Parham Shahidi[1], Dan Maraini[1], Brad Hopkins[1], and Andrew Seidel[1]

[1]*Amsted Rail Company, Inc. Chicago, IL, 60606, USA*

pshahidi@amstedrail.com
dmaraini@amstedrail.com
bhopkins@amstedrail.com
aseidel@amstedrail.com

ABSTRACT

In this paper, bogie performance criteria are reviewed and it is shown that a real-time, on-board condition monitoring system can efficiently monitor these criteria to improve failure mode detection in freight rail operations. Although the dynamics of rail car bogie performance are well understood in the industry, this topic has recently received renewed attention through impending regulatory changes. These changes seek to extend empty rail car performance criteria to include loaded rail cars as well. Currently, the monitoring of bogie performance is primarily accomplished by wayside detection systems in North America. These systems are only sparsely deployed in the track network and do not offer the ability to monitor bogies continuously. The lack of these elements leads to unexpected downtimes resulting in costly reactive maintenance and lengthy periods of time before an adequate performance history can be established. This paper reviews performance criteria which critically influence bogie performance and proposes a vibration based condition monitoring strategy to estimate system component deterioration and their contribution to the development of bogie hunting. The strategy addresses both sensing techniques and monitoring algorithms to maximize the efficiency of the monitoring solution. In particular it is proposed that understanding the relation of different hunting modes to car body oscillations can be used for a deeper understanding of the rail car condition which current technologies are not able to provide.

1. INTRODUCTION

A freight rail bogie is the main vehicle connecting the freight rail car body to the rail. Typical freight rail cars utilize two bogies underneath the car body to carry the lading. Railroad terminology refers to the most widely distributed bogie type in North America as the three-piece bogie. Figure 1 gives a general overview of the components of the three-piece bogie. The three main components of this system are the two side frames and connecting bolster.

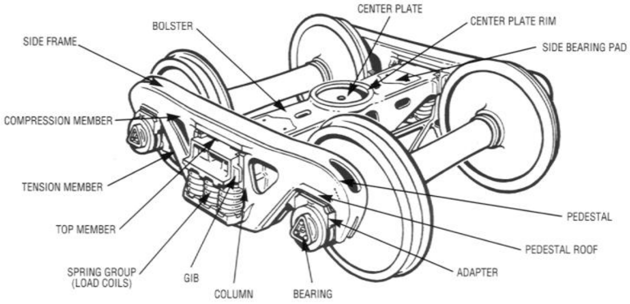

Figure 1. Standard North American three-piece bogie

This bogie type is also commonly used in Russia, China, Australia and most African countries. The bolster is connected to the side frames through a spring nest in each side frame which is referred to as the secondary or also central suspension. The two wheelsets are connected to the side frames by tapered roller bearings which are designed to maintain extremely high vertical and lateral loads. Many different sizes exist in North America carrying loads ranging from 177,000 to 315,000 lbs gross rail load (GRL). The bogie connects to the car body through the center plate.

The Association of American Railroads (AAR) is the standard setting organization for North America's railroads, focused on improving the safety and productivity of rail transportation. The AAR devises new rules for all aspects of rail transport, including freight car and bogie designs. Two major specifications exist, according to which all bogie systems intended for North American interchange service have to be designed. The first one is M-965, which was

---

adopted in 1968 and allowed for gross rail loads of up to 263,000 lbs. This rule was expanded in 2003 with the release of rule M-976 which was intended to regulate gross rail loads higher than 268,000 and up to 286,000 lbs. M-976 was directly related to AAR rule S-286 which sets the framework for the entire 286,000 GRL freight car. An extensive suite of tests exists which both M-965 and M-976 bogies have to pass in order to be approved for North American interchange service. This set of tests is formalized in the Manual of Standards and Recommended Practices (MSRP) C-II Chapter 11 (AAR, 2007) which contains the trackworthiness criteria limits that new freight car designs have to meet. These include performance limits for lateral stability on tangent track (hunting), operation in constant curves, spiral negotiation, cross level variation (twist and roll), surface variation (pitch and bounce), alignment variation on tangent track (yaw and sway) and alignment, gauge, and cross level variation in curves (dynamic curving). These tests use the ratio of lateral to vertical (L/V) forces exerted by the wheelset onto the rail, accelerations, degrees of roll and loading percentages to evaluate bogie performance. Among these criteria, the L/V criterion constitutes the most widely used performance metric in bogie testing. This makes intuitive sense since the wheelset is the component which connects the bogie to the track structure. The forces can be used in different combinations, as an individual wheel (L/V), axle sum Eq. (1) or truck side Eq. (2) ratio

$$Axle\ Sum\ \frac{L}{V} = \left[\frac{L}{V}\ (left\ ) + \frac{L}{V}\ (right\ )\right] \tag{1}$$

$$Truck\ Side\ \frac{L}{V} = \left[\frac{\sum L\ (truck\ side)}{\sum V\ (truck\ side)}\right] \tag{2}$$

Standard features of the modern rail car wheel, such as a flange and taper, have not always been part of the wheel. Figure 2 shows the two mentioned features on a wheelset.

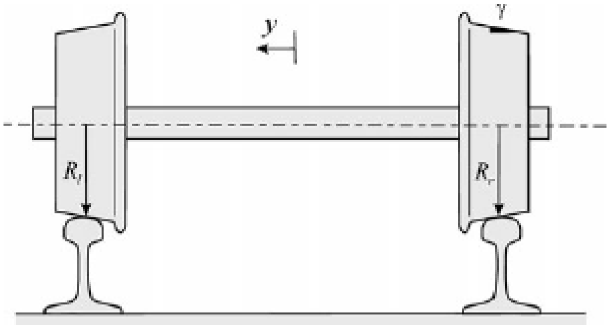

Figure 2. Wheelset in equilibrium position

Their invention, especially taper, can be credited to the need for improved guidance and proper curve negotiation. When the wheelset negotiates a curve, the outer rail follows a larger radius of curvature than the inner rail. This requires the outer wheel to travel a longer distance than the inner wheel. As the wheelset rotates with a constant angular velocity, one of the wheels or both wheels will slip. The slip can be reduced if the rolling radii of the two wheels are allowed to vary during the wheel motion. This change in the rolling radius is accomplished by using the tapered wheel profile. As the wheelset negotiates a curve, the wheelset will move laterally in the direction of the outer rail. Consequently, the outer wheel will have a larger rolling radius and higher velocity in the longitudinal direction as compared to the inner wheel. This reduces the slip and wear, and leads to better curving behavior (Shabana, Zaazaa, & Sugiyama, 2010). However, an inevitable side effect of the taper is the wheelset's inherent tendency to oscillate laterally. In 1883 Klingel (Klingel, 1883) derived the formula for this kinematic oscillation by relating wheel taper γ, wheel radius R_0, and distance between the wheel contact points G. Under perfect conditions on tangent track, the wheelset is centered with $y = 0$ and $R_l = R_r = R_0$. When the wheelset is laterally perturbed in the y-direction, the wheel taper will cause a decrease in radius for one wheel while the other wheel's radius increases. The combined difference ΔR in radii

$$\Delta R = y\gamma \tag{3}$$

results in a difference in wheel velocities on the same axle and is reacted by a yawing motion of the wheelset as shown in figure 3.

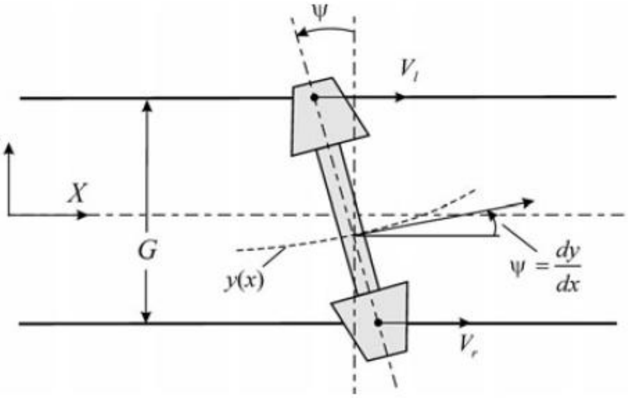

Figure 3. Hunting oscillation

In severe cases the wheelset will make flange contact with the rail in each oscillation as it "hunts" for its equilibrium position. For the same reason, this motion is commonly referred to as "hunting". The yaw motion is characterized by the yaw angle Ψ of the wheelset. In (Klingel, 1883) the underlying oscillatory motion of the wheelset was shown to be

$$\ddot{y} = \frac{-2R_0\omega^2 y\gamma}{G} \tag{4}$$

The solution of Eq. (4) is of the form

$$y = A\, sin(\omega_n t + C) \tag{5}$$

where A and C can be determined through initial conditions and ω_n is the natural frequency of the mechanical system.

$$\omega_n = V\sqrt{\frac{2\gamma}{R_0 G}} \tag{6}$$

Equations (5) and (6) are generally known as Klingel's Formulas (Klingel, 1883; Wickens, 1998) and describe the lateral oscillation of the wheelset due to the taper. The situation in which the taper of the wheels allows a bogie to negotiate a curve is the ideal for a perfectly aligned system. However, gradual wear from revenue service reduces this ability over time and affects bogie performance as a whole (Sawley, Urban, & Walker, 2005; Sawley & Wu, 2005). In addition to wheel wear, many other factors influence bogie performance. These include reduced warp restraint caused by worn suspension components, reduced rotational resistance caused by worn side bearings and manufacturing/reconditioning flaws such as mismatched side frames. Figure 4 shows four common misalignment faults of the bogie. In the case of rotational resistance it is worthwhile to note that a reduction decreases lateral stability but an increase worsens curving performance.

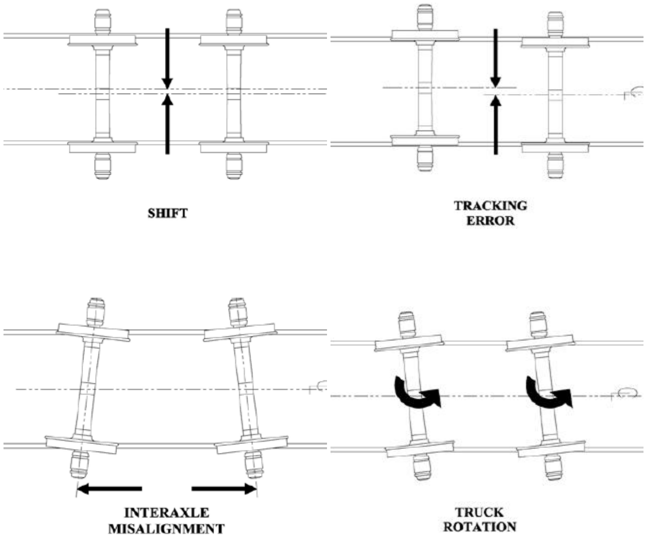

Figure 4. Bogie System Failure Modes

It is easy to see how each of the above mentioned fault conditions affects the wheelset alignment and triggers changes in the lateral and vertical forces of the wheels on the rail.

Failure modes of the rail car bogie system are generally defined as a decrease in performance and not a complete breakdown, as may be the case for other machinery. The industry relies heavily on wayside equipment for the detection of these deteriorated bogie components (Zakharov & Zharov, 2005). Different types of wayside equipment exist for detecting deteriorated parts on freight rail bogies. The two most relevant types for rail car bogie performance are Truck Performance Detectors (TPD) and Truck Hunting Detectors (THD). Both of these detectors consist of instrumentation which is added to the track to measure the lateral and vertical forces that rail car wheels exert on the track. TPDs achieve this through instrumentation of two reverse curves with strain gauges to measure the wheel lateral and vertical forces and wheelset angle of attack during curving. THDs are placed on tangent track and instrumented with strain gauges to measure wheelset hunting. Currently, approximately 15 TPDs and 172 THDs are in service across the North American rail network. The difference in their numbers stems from two reasons. First, TPDs are more expensive and more difficult to set up due to their two reverse curve requirement. Second, THDs are usually setup in conjunction with Wheel Impact Load Detectors (WILDs) as an additional functionality, adding less to the overall cost than a standalone TPD system. However, it is commonly accepted in the industry that TPD alerts are more worthy of repairs than THD alerts as they generally relate to a broader spectrum of root causes.

2. BOGIE PERFORMANCE CRITERIA

As mentioned previously, the Association of American Railroads Transportation Technology Center, Inc. (AAR/ TTCi) has established a set of design validation criteria for the quantification of bogie system performance through track testing. Although the tests consist of both static and dynamic requirements, this study will focus on dynamic requirements only. The dynamic requirements are divided into tests for smooth, unperturbed track and geometrically varying, perturbed track. The perturbed track tests are designed to excite vehicle dynamic modes historically associated with poor performance. The majority of the tests are evaluated by comparing wheel L/V force results against threshold limits per AAR MSRP C-II Chapter 11. Table 1 lists the criteria for these test regimes. As mentioned before, the most frequently used criterion of bogie performance (wheel L/V forces) comprises 9 out of the 21 requirements. This is followed by the percent load requirements (6) and acceleration based requirements (4). This shows that the industry has a historical affinity towards evaluating bogie performance by means of wheel L/V forces.

Table 1. AAR MSRP C-II Chapter XI Dynamic Performance Requirements

Test Regime	Criterion	Limit	
Hunting (empty)	Max. lat. Acc	1.5	[G]
	σ lat. Acc.	0.13	[G]
Constant Curving	95th perc max wheel	0.8	L/V
	95th perc max axle sum	1.5	L/V
Spiral Negotiation	Min. vert. load	10	[%]
	Max wheel	1.0	L/V
	Max axle sum	1.5	L/V
Twist/Roll	Max. roll	6	[°]
	Max axle sum	1.5	L/V
	Min. vert. load	10	[%]
	Dyn. augment acc.	1.0	[G]
	Loaded spring cap max.	95	[%]
Pitch/Bounce	Min. vert. load	10	[%]
	Dyn. augment acc.	1.0	[G]
	Loaded spring cap. max.	95	[%]
Yaw/Sway	Max. truck side	0.6	L/V
	Max axle sum	1.5	L/V
Dynamic Curving	Max wheel	1.0	L/V
	Max axle sum	1.5	L/V
	Max roll	6	[°]
	Min. vert. load	10	[%]

The unperturbed track tests include:

- *Lateral Stability on Tangent Track (Hunting):* hunting is the transfer of energy from forward motion into sustained lateral oscillations of the axle between the wheel flanges.

- *Operation in Constant Curves:* This tests the satisfactory negotiation of track curves. The resulting forces between wheel and rail have to be safe from any tendency to derail.

- *Spiral Negotiaion:* This tests satisfactory negotiation of spirals leading into and out of curves. The tests are required to show an adequate safety margin from any tendency to derail, especially under reduced wheel loading.

The perturbed track tests include:

- *Varying Cross-Level:* This tests the satisfactory negotiation of oscillatory cross-level excitations which may lead to large car roll and twist amplitudes. The tests have to show an adequate margin from any tendency to derail.

- *Surface Variation*: This tests the satisfactory negotiation of the car over track that provides an oscillatory excitation in pitch and bounce. A safety margin from any tendency to derail has to be shown.

- *Alignment Variation*: This tests the satisfactory negotiation of the car over track with misalignments that provide excitation in yaw and sway. A safety margin from any tendency to derail has to be shown.

- *Alignment, Gauge, Cross-Level Variation in Curves:* This tests the satisfactory negotiation of a combination of misalignments at low speeds. A safety margin from any tendency to derail has to be shown.

3. MODEL-BASED SIMULATIONS VS DATA DRIVEN DIAGNOSTICS

In recent years, the topic of advanced modeling techniques to supplement experiments such as the tests outlined above has received increased attention. In (Li & Goodall, 2004) a model-based approach is presented which derives theoretical knowledge from a mathematical model. Contrary to this method, data-driven approaches are used where mathematical models are unavailable and heuristic strategies have made solutions available. The authors argue in favor of a model-based approached, but steer their study away from complex non-linear simulation models. In the case of (Li & Goodall, 2004) this is permissible since it is assumed that the bogies in the study are passenger rail bogies with less non-linear effects, such as dry friction damping, stick-slip effects and clearances, than freight rail bogies (Iwnicki, 2006). The authors also mention the difficulties in generating fault accentuated signals (residuals) for fault detection and isolation purposes. Generally, a trade-off between accuracy and (computational) expense has to be considered when a realistic model is the goal. The alternative is to simulate hard faults, as the authors did in (Li & Goodall, 2004), even though this approach neglects gradual deterioration. Typical data-driven approaches usually focus more on gradual deterioration effects to establish cause and effect relationships. In both (Li & Goodall, 2004) and (Tsunashima & Mori, 2010) the proposed methods are tested only in simulation which is yet another drawback. Contrary to the opinion in (Li & Goodall, 2004) the best approach to be considered should be a combination of analytic simulation and experimental work. This is demonstrated in (Pogorelov, Simonov, Kovalev, Yazykov, & Lysikov, 2009) where the authors achieve this by using a multibody dynamics simulation package first to model the suspension and then validate their findings in a series of full scale experimental tests.

On the opposite end of the spectrum, purely empirical studies have been completed to determine root causes of suspension faults. In this type of study data is systematically collected to reflect failures as they appear in the field under revenue service conditions. In (H. M. Tournay & Lang, 2007; H. M. Tournay, Lang, & Wolgram, 2006) data from TPDs was analyzed and bogie systems which generated alerts were identified. Since the correlation between age and performance is well understood, old bogies with lowered warp restraint or mismatched side frames (due to reconditioning) were expected and not subject of the studies. The bogie systems with no obvious faults, which were expected to perform well, yet triggered an alert, were the main subjects of both studies. The studies took a multitude of factors into consideration, including car maintenance history, TPD metrics (truck gauge spreading force, truck warp factor etc), truck parts/condition into account and identified potential root causes for poor performance. (H. M. Tournay, Lang, & Wolgram, 2006) concluded that side bearing malfunction and car body twist had caused line contact in the center bowl, and (H. M. Tournay & Lang, 2007) concluded that high bogie to carbody rotational resistance due to out of tolerance side bearings and high friction in the center bowl had triggered the truck performance detector alarms. Evidently, a purely data-driven analysis of wayside detector data intended to provide actionable results is very different from a model based technique to predict suspension failure based on simulated acceleration data. Empirical data is reflective of faults encountered in the field but may be difficult to interpret initially until repeated patterns can be systematically observed and attributed to their root causes. In contrast to this, model based approaches provide simulated data in which a single variable can be changed while others are held steady to isolate the root cause of a failure. The complexity and accuracy of a simulation strongly influences the applicability of results found in this manner.

In between a theoretical model based and data-driven approach fall data-driven techniques with advanced sensors but without mathematical models (Sunder, Kolbasseff, Kieninger, Rohm, & Walter, 2001). These methods present an interesting alternative as they are more practical than the model based approaches, and hence more applicable. However, the lack of a mathematical model underutilizes available simulation methods to improve accuracy either for sensor placement or algorithm and sensor threshold design.

The differences in the three presented approaches highlight the issues any condition based monitoring or predictive maintenance based approach faces.

3.1. Data-Driven Interpretation of Model-Based Simulation Data

The above presented model-based approaches do not outline how their goal of condition based maintenance should be achieved in practice. Implementation issues such as power on freight rail cars, reliability in harsh environments, feasibility and wireless communication remain entirely untouched. If these deficiencies were added to a model based approach, it could be a more viable solution in terms of an industrial application. An understanding of the faults, the maintenance practices, and operating environment can significantly strengthen conclusions obtained from the analysis of a theoretical bogie model and lead to results more reflective of industry practices. This paper is proposing the fusion of these two approaches to implement a system for data-driven based interpretation of model based data of railway bogie performance.

The key for this proposal is to devise a representative model of a freight rail bogie that is adequately detailed and not too complex to be computationally solvable. (Fujie & True, 2003) and (Pogorelov et al., 2009) used simulations with 19 rigid bodies and triple digit degrees of freedom models. These are significant numbers as they show the complexity of modeling the conventional North American three piece bogie. An investigation of which aspect of the bogie model would be most beneficial to model in higher detail to achieve the goal of fault simulation is recommended. Typically, the suspension system of the bogie is of the highest relevance amongst all bogie components. The suspension system of a freight rail bogie is made up of two subsystems. These are the primary suspension which consists of the adapter and adapter pad at the pedestal seat in the side frame and the secondary suspension which consists of the spring nest and friction wedges inside the side frame. One possible focus for the modeling efforts could be the secondary suspension of the bogie, as this is the main component which reacts the dynamic forces from the wheels on the rest of the bogie. Warp of the bogie system, resulting from worn secondary suspension components such as friction wedges could be considered a target fault. As mentioned in the introduction, bogie warp is a condition under which the friction wedges fail to resist the longitudinal shift of the side frames which results in misalignment. The misalignment rotates the wheelsets such that they exert a larger than normal track gauge spreading force onto the track in curves. Figure 5 shows the alignment of the wheelsets under conditions of a warped bogie.

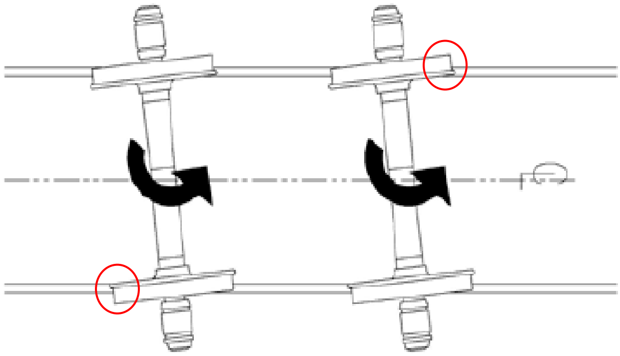

Figure 5. Wheelset alignment under warped bogie conditions

The red circles in figure 5 show where the increased forces would react with and potentially damage the track. Under lateral instability conditions (for loaded cars) on tangent track this fault would contribute to the development of hunting oscillations. It can be expected that symptoms of this fault will be discernible in the longitudinal acceleration signal from the side frames. An adequate method to iterate measurement responses towards deterioration should be implemented in the model. Measuring the response of bogie components in terms of displacements and accelerations, would allow the creation of meaningful thresholds and the selection of the most beneficial location on the bogie for sensor placement.

Another interesting fault for the proposed method is hunting. Hunting was explained in the introduction as the lateral oscillatory motion of the bogie system, which is initiated by the wheel taper. It worsens over time as the wheel profile wears hollow and as a result the lateral oscillations increase in magnitude when the rail vehicle enters instability on tangent track. It can be expected that symptoms of this fault will be discernible in the lateral acceleration signal from the side frames, bearing adapters and rail car body. MSRP C-II Chapter 11 specifically mandates the use of worn wheel profiles for the hunting tests described above. The mandated (KR) profile is formalized as an approximation for a wheel profile after 100,000 miles of revenue service. Figure 6 shows the change in the profile from a new to a KR worn wheel.

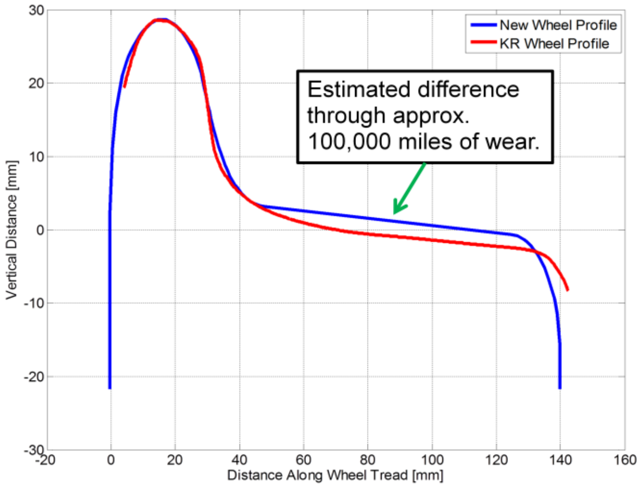

Figure 6. New wheel profile vs worn KR wheel profile

This fault mode is particularly interesting because MSRP C-II chapter 11 specifies acceleration levels as thresholds and not L/V ratios as it does for most of the other bogie performance tests. This makes the translation of regulatory requirements into actionable thresholds directly possible. Simulation results from the model will add the relationship of the oscillation severity to the wear of the wheel profile and potentially other root causes. These two examples show how the proposed method can be expanded and applied to additional bogie faults.

4. FIELD TEST

A first set of tests was conducted at Transportation Technologies Center, Inc. (TTCI) in Pueblo, CO. TTCI, a subsidiary of the Association of American Railroads, is a transportation research and testing organization. TTCI offers a wide range of tests for rail applications on their seven test tracks.

4.1. Field Test Setup

One of these tracks, the Railroad Test Track (RTT), is a 13.5-mile loop with four 50-minute curves and a single 1-degree, 15-minute reverse curve. Maximum speed is 165 mph and all curves have 6-inches of superelevation (difference in rail height on the same section of track - especially relevant in curves to maintain stability). The primary purpose of this track is high speed stability testing which is well suited for exciting lateral vehicle dynamic modes. The selection of lateral instability testing was based on two reasons: the first being that it is one of only two tests in MSRP C-II Chapter 11 which evaluate performance criteria as a quantity of acceleration in *G* and secondly, the industry's interest in modifying this specific requirement from currently empty cars to loaded cars. The increased interest in this particular instability mode is related to the introduction of higher load bogies as shown earlier in this paper. The higher car loads have resulted in wagon bodies with higher yaw/roll moments of inertia that react with relatively low warp restraint leading to coupled oscillatory resonance at speeds as low as 47 mph (H. Tournay, Wu, & Wilson, 2009). The extension of lateral instability tests is likely to affect product development and Mean-Time-To-Failure (MTTF) requirements, and as such poses a particularly well-suited example for an application of condition monitoring strategies.

For this study, one of the 50-minute (0.8 degree) curves with 6-inches superelevation was used to accelerate the train to target speeds, ranging from 40 mph to 80 mph. Figure 7 shows the profile of the segment of the RTT track that was used.

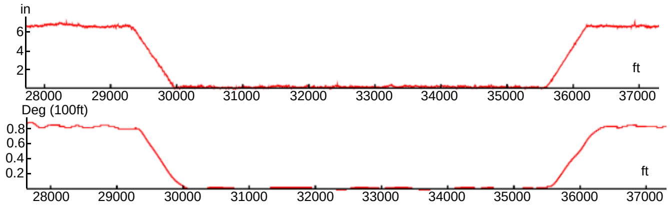

Figure 7. Test segment of RTT track

The upper graph shows the superelevation and the bottom graph shows the curvature. Once the target speed was reached, data acquisition systems began to measure the lateral and vertical accelerations at two sensor locations on the rail car body. Figure 8 shows the sensor locations at the A- and B-end on the loaded hopper car. The triangles indicate where the accelerometers were installed on the test car. Red indicates the accelerometers that were mounted near the roof of the car and green shows accelerometers on the deck above the bogie center location. The instrumentation of the test car was in accordance with MSRP C-II Chapter 11 rules for trackworthiness testing of new freight car designs. As previously mentioned, per AAR rules, hunting is quantified as the peak to peak magnitude and standard deviation of the lateral acceleration on the deck above the center of the bogie. The two additional accelerometers (red in figure 8) were added to the test setup to measure lateral acceleration at the top of the rail car body.

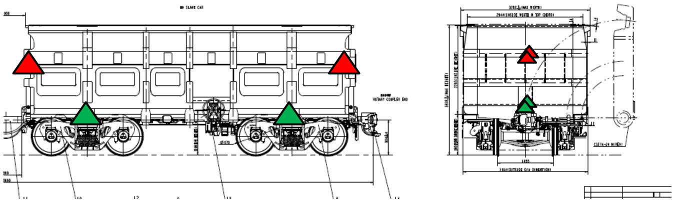

Figure 8. Instrumentation overview for loaded hopper car

Since the rail car body can be assumed to be rigid the extended moment arm between the center of rotation and measurement location at the top provides more pronounced acceleration which can be analyzed in correlation to the lower deck location. Additional signal processing requirements per the AAR rules were followed.

4.2. Field Test results

The field tests led to a number of significant results. Figure 9 shows the power spectral densities of each run's time series data from the rail car's top A-end location. It can be observed that a distinct resonant frequency becomes detectable above 55 mph and that the resonance is located between 2.0 and 3.0 Hz, depending on the speed of the test run. This is not a coincidence as it is well known in the industry that hunting occurs in this frequency range.

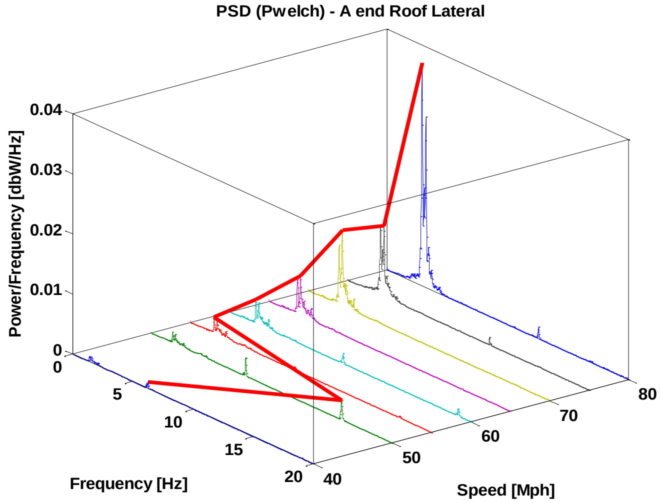

Figure 9. Frequency domain data between 40 and 80 mph

Furthermore, this frequency range also correlates to that of the kinematic analysis in the introduction and can be regarded as the propagated vibration of the wheelset's side to side oscillation in which the wheel flange contacts the rail. The finding of this result is significant because it shows that when factors such as wheel taper and lading are controlled so that they favor excitation of a dynamic failure mode, accelerations indicative of this failure can be measured. Moreover, the progressively increased test speeds show the gradual increase of the oscillatory power in frequency domain. The increased oscillatory power at the roof of the car body versus the sill location can be observed in figure 10. There, the 80 mph test run data is shown in four different locations and it can be observed that the roof and sill follow similar trends with different magnitudes.

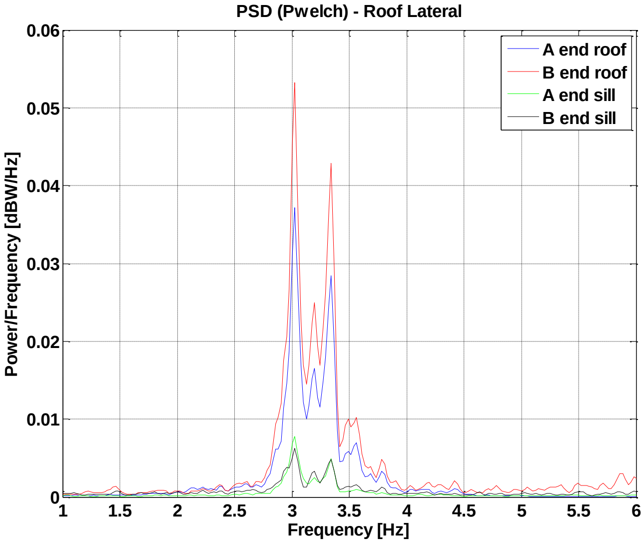

Figure 10. Comparison of roof vs sill location at 80 mph

5. DISCUSSION

It was shown in the field test section that actionable information could be obtained from accelerometers in the sill or roof locations of the rail car. This first test can be assumed as a proof of concept for expansion of the outlined monitoring strategy to the following additional bogie faults, historically associated with certain component failures:

- Bogie Misalignment: figure 4 in the introduction showed four different misalignment faults for bogies. Having various root causes (H. M. Tournay, Lang, Wolgram, & Chapman, 2006) these misalignments lead to forces resulting from the complex, dynamic interactions of the bogie parts and track. Identification of interactions such as warp restraint and angle of attack and the effect an increase or reduction would have on the dynamic behavior of the bogie system is proposed.
- Spring Nest: faulty operation of this suspension component is coupled to the vertical motion of the bolster and anomalies could be detectable if there is a

significant change in the displacement when this component wears.

- Side Bearings: are intended to support the even distribution of the lading and prevent hunting. If contact forces are too high, the rotation of the car body against the bogie can be inhibited leading to high curving forces. If they are too low, lateral oscillations will not be adequately resisted.
- Wheels: this fault can be quantified by wheelset lateral oscillations as they occur when wheels are worn hollow and begin to lose their self-centering abilities as outlined in the kinematic analysis.

For the first three of the above described faults a triaxial accelerometer would be a suitable sensor package to identify the faults. The longitudinal axis would sense side frame displacements due to bolster rotation, the vertical axis would sense bolster vertical displacements and the lateral axis would sense lateral oscillations such as bogie hunting. For the last fault, wheelset displacements, the best acceleration axis would be the lateral axis.

To detect these faults the selected sensor package would be placed on the bogie. Multiple locations meet the requirements outlined above and could work but should be investigated in simulations and field testing to confirm applicability. Three particular locations are of high interest: 1. Either end of the side frame, 2. Either end of the bolster and 3. Bearing adapter locations. Additional knowledge can be gained by placing accelerometers on the car body, especially if yaw/roll coupled instability modes of the car body are of interest. Simulating the dynamic modes with a model and supplementing the findings with a field test would provide a better understanding of which location is preferable and provides higher accuracy in detecting these faults.

To create actionable thresholds it would be furthermore of interest to relate currently existing TPD alarm levels to acceleration limits. TPDs classify bogies as bad actors based on force and angle of attack based TPD data. The criteria for this are either two events exceeding the forces shown in figure 11 within 12 months or two Lead Axle High Rail L/V values of 1.05 also within 12 months. Both of these requirements were established in parallel to MSRP C-II Chapter 11 and are outlined in detail in (H. M. Tournay, Lang, Wolgram, et al., 2006). Multibody simulation packages are able to estimate these wheel lateral and vertical forces as part of a simulation. One issue the authors mention is the intermittent behavior of TPDs during successive passes of the same car. It has proven to be a major obstacle to the interpretation of TPD data. This is yet another aspect in favor of the proposed monitoring approach.

For THDs the condemning criteria are either two events with a Salient Hunting Index above or equal to 0.35 or a single Salient Hunting Index above 0.5. Hunting is investigated in (H. M. Tournay, Wu, & Wilson, 2008) with respect to its occurrence under loaded car conditions. This is relevant as it directly pertains to the pending rule change to extend empty car criteria to loaded car criteria. Investigation of factors such as adapter pad (primary suspension) and wheel profile combinations resulted in concluding that loaded car hunting is a resonant coupling between the yaw oscillation of the wheelset and natural frequency of rail car body in a yaw mode that includes in-phase body roll motion.

Table 2. TPD Truck gauge spread force (TGSF) limits

TGSF (kips)	Site Curvature (degrees)
28	≤ 4.0
33	≥ 4.0 < 5.0
38	≥ 5.0 < 6.0
43	≥ 6.0 < 7.0
48	≥ 7.0 < 8.0
53	≥ 8.0 < 9.0
58	≥ 9.0

From a component perspective it primarily depends on frictional warp properties, adapter pad stiffness and taper wear of the wheelsets. A meaningful combination of these fault modes and hierarchical structure for which to monitor first shall be derived from these initial findings.

6. CONCLUSION

Problems in monitoring the condition of the standard North American three piece bogie were outlined in this study and a strategy to attack these from a combined data-driven and analytic simulation approach was presented. An overview of bogie performance standards from a regulatory perspective and existing technologies that are currently in use in railroad revenue service was provided. Challenges that these technologies pose in terms of implementation effort, preventive action effectiveness, and faulty component identification were presented.

A field study presented initial results of an investigation of lateral instability and how these results can be used to detect gradual wear in components that are tied to a particular fault mode. The addition of a model to simulate these failures prior to field testing was proposed and would enable researchers to make decisions about locations for sensor placement and thresholds. Finally, currently used performance parameters for the two dominant monitoring technologies were presented and it was outlined how these performance parameters could be 1) linked to components associated with the performance parameters, 2) adopted in a condition monitoring strategy to reflect the existing performance standards. As an extension of this strategy the failure mode of loaded car hunting was presented as an example in which application of the proposed strategy is particularly sensible, as the determining performance factor can be directly linked to the regulatory standard and sensor measurements.

REFERENCES

AAR. (2007). Design, Fabrication, and Construction of Freight Cars *Manual of Standards and Recommended Practices C-II* (Vol. [M-1001]).

Fujie, X., & True, H. (2003, 22-24 April 2003). *On the dynamics of the three-piece-freight truck.* Paper presented at the Rail Conference, 2003. Proceedings of the 2003 IEEE/ASME Joint.

Iwnicki, S. (2006). *Handbook of railway vehicle dynamics*: CRC Press.

Klingel, W. (1883). Über den Lauf der Eisenbahnwagen auf gerader Bahn. *Organ für die Fortschritte des Eisenbahnwesens, 20*, 113-123.

Li, P., & Goodall, R. (2004). *Model-based condition monitoring for railway vehicle systems.* Paper presented at the Proceedings of the UKACC international conference on control, Bath, UK.

Pogorelov, D., Simonov, V., Kovalev, R., Yazykov, V., & Lysikov, N. (2009). *Simulation of Freight Car Dynamics: Mathematical Models, Safety, Wear*. Paper presented at the International Conference on Recent Advances in Railway Engineering (ICRARE), Tehran, Iran.

Sawley, K., Urban, C., & Walker, R. (2005). The effect of hollow-worn wheels on vehicle stability in straight track. *Wear, 258*(7–8), 1100-1108. doi: http://dx.doi.org/10.1016/j.wear.2004.03.058

Sawley, K., & Wu, H. (2005). The formation of hollow-worn wheels and their effect on wheel/rail interaction. *Wear, 258*(7–8), 1179-1186. doi: http://dx.doi.org/10.1016/j.wear.2004.03.029

Shabana, A. A., Zaazaa, K. E., & Sugiyama, H. (2010). *Railroad vehicle dynamics: A computational approach*: CRC Press.

Sunder, R., Kolbasseff, A., Kieninger, A., Rohm, A., & Walter, J. (2001). *Operational experiences with onboard diagnosis system for high speed trains.* Paper presented at the Proceedings of the World Congress on Rail Research.

Tournay, H., Wu, H., & Wilson, N. (2009). A Review of the Root Causes for Loaded Car Hunting, Technology Digest TD-09-014: AAR, TTCI, Pueblo, CO.

Tournay, H. M., & Lang, R. (2007). History and Teardown Results of Five Loaded Coal Cars Identified as Poor Performers while Passing accorss a Truck Performance Detector *R-985*. Washington, DC: Association of American Railroads/ Transportation Technologies Center, Inc.

Tournay, H. M., Lang, R., & Wolgram, T. (2006). History and Teardown Results of a Coal Car Identified as a Poor Performer while Passing Loaded Across a Truck Performance Detector *R-976*. Association of American Railroads50 F Street, NW Washington, DC 2001.

Tournay, H. M., Lang, R., Wolgram, T., & Chapman, S. (2006). Interpreting Truck Performance Detector Data To Establish Car And Truck Condition *R-977* (Vol. R-977). Association of American Railroads50 F Street, NW Washington, DC 2001.

Tournay, H. M., Wu, H., & Wilson, N. (2008). Investigation into the Root Causes for Loaded Car Hunting *R-995*. Association of American Railroads 50 F Street, NW Washington, DC 2001.

Tsunashima, H., & Mori, H. (2010, 27-30 Oct. 2010). *Condition monitoring of railway vehicle suspension using adaptive multiple model approach.* Paper presented at the Control Automation and Systems (ICCAS), 2010 International Conference on.

Wickens, A. H. (1998). The dynamics of railway vehicles—from Stephenson to Carter. doi: 10.1243/0954409981530805

Zakharov, S. M., & Zharov, I. A. (2005). Criteria of bogie performance and wheel/rail wear prediction based on wayside measurements. *Wear, 258*(7–8), 1135-1141. doi: http://dx.doi.org/10.1016/j.wear.2004.03.025

BIOGRAPHIES

Parham Shahidi is a Project Engineer in the Bogie Systems Engineering group at Amsted Rail Company, Inc. He holds a BS degree in Mechanical & Process Engineering from TU Darmstadt in Germany and a PhD in Mechanical Engineering from Virginia Tech. Parham has been working in the area of railroad engineering since 2007 starting with the development of a fatigue estimation system for conductors in graduate school. In 2011 he joined Amsted Rail where he has been working on rail vehicle dynamics and bearing condition monitoring projects. He has published more than 10 technical articles related to his research and is a board member of the German Engineers Association (VDI) in North America.

Dan Maraini is the Manager of Bogie Systems Engineering for Amsted Rail Company, Inc. He leads a team of Project Engineers focusing on condition monitoring solutions for freight railcars. Dan has been a part of Amsted Rail since 2008. In various positions, he has worked on wireless sensing, remote asset monitoring, and condition monitoring for freight rail applications. Dan is currently a PhD student in the department of Mechanical Engineering at Villanova University. His research focus lies on machinery diagnostics. He holds a MS in Mechanical Engineering from Villanova University and a BS in Physics from West Chester University of PA.

Brad Hopkins is a Project Engineer in the Bogie Systems Condition Monitoring group at Amsted Rail. He holds a BS, MS, and PhD in Mechanical Engineering from Virginia Tech. He has been working on track and railcar condition monitoring since 2010, with a focus on accelerometer-based monitoring and algorithm development. His current work includes broken rail detection, wheel defect monitoring, and end-of-car system monitoring. His additional research interests are vehicle dynamics, modeling, and simulation, controls, and vibration analysis.

Andrew Seidel is a Project Engineer in the Bogie Systems Engineering group at Amsted Rail Company, Inc. He holds a BS degree in Mechanical Engineering from Pennsylvania State University in State College, Pennsylvania. Andrew has been working in the area of railroad engineering since 2012 when he began working with end of car impact detection systems and railcar condition monitoring projects. He is a member of the American Society of Mechanical Engineers (ASME) and sits on the Mechanical Engineering Technical Advisory Board for Penn State University (Harrisburg campus).