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Performance Based Track Geometry and the Track Geometry Interaction Map

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Summary: The Track Geometry Interaction Map (TGIM) is proposed as an effective way to evaluate the impact of multiple track geometry parameters on rail safety. Multi-body dynamics software has been used to simulate vehicle performance over track containing a large number of randomly generated lateral and vertical track geometry combinations. A TGIM based safety threshold is generated that appears to offer both economic and safety advantages over the current FRA track safety standards.

Index Terms: Track safety rule, Vehicle performance, and dynamic simulation.

1 INTRODUCTION

Track geometry standards in North America [1] and elsewhere are based on physical measures of track surface, alignment, gauge and other geometry variations. The use of geometry based maintenance indicators and safety limits has served the rail industry adequately to this point but its limitations are becoming especially obvious as measuring systems improve and understanding increases. The inability of current track standards to account for the performance of different vehicle types, or to deal with combinations of track geometry perturbations in different directions (say vertical and lateral) are examples of the inadequacy of current standards.

A significant and relatively recent development is the use of sensing systems such as accelerometers on revenue rail cars (typically locomotives), in concert with GPS to identify track locations where particularly violent, and possibly unsafe, vehicle accelerations or forces are encountered. This is the basis for Performance Based Track Geometry (PBTG) [2, 3] which has in the last few years received increasing interest from operating railroads, the research community, and regulatory agencies within North America. The reasons for the interest are many, but a huge advantage is that PBTG measurements can conceivably be made on revenue vehicles, or at least revenue trains. For the railroad this could eliminate the need for costly track geometry measuring systems and disruption to revenue traffic. It also allows for regular trending of performance and better predictive maintenance opportunities. For regulatory agencies, much more frequent inspection, coupled with maintenance to a force (or acceleration) level can be expected to promote improved safety.

The development of hardware systems to service the PBTG opportunity is well under way but a significant "missing link" is an understanding of the relationship between vehicle response (acceleration or force) and track geometry characteristics. A high force or acceleration response may indicate that there is "something wrong with the track" but just what that is, it turns out, is not usually very obvious. A simple but reliable relationship between vehicle performance (accelerations or wheel-rail forces) and track geometry is the key to determining the track maintenance requirements required to eliminate the measured problems.

Previous work [4] has shown that the correlation between measured wheel-rail force and an individual track geometry parameter (e.g. lateral alignment) is very weak. In many cases, none of the standard track geometry parameters can account for the high forces measured with an instrumented wheelset. In this paper we suggest the weak correlation occurs because many of the unfavorable vehicle responses are the result of *combinations* of track geometry defects. A new geometry parameter is proposed that is based on vehicle response to combined track perturbations.

2 FIELD EXPERIENCE

In 1997 Transport Canada and BC Rail sponsored a test to compare track geometry measurements with forces measured by an instrumented wheelset [4]. An empty tank car was run over 430 km of track, from Prince George to Lillooet, British Columbia. About 80% of the test route was curved track, including several very sharp curves up to 16 degrees (109m radius).

Detailed data analysis was conducted to compare the wheelset forces with geometry for given track classes. The results were discouraging – there was very little correlation between individual geometry parameters and wheel/rail forces (e.g. Figure 1). The highest correlation coefficient was only 0.54. Most of the Chapter XI force exceedences (L/V>1.0 or wheel unloading > 90% of the static load) were not associated with FRA geometry defects. For example, of the 8 AAR Chapter XI force defects only one matched with an urgent geometry defect. Of 70 locations where forces exceeded 80% of the Chapter XI force defect levels, there were only 13 matches with priority geometry defects. Similar test results have been reported by others [5, 6]. Maintaining to the current track standards is thus not enough to prevent high wheel/rail forces – those sufficient to trigger a derailment - from occurring.

In the last few years there has been a dramatic increase in the availability of robust, lower power, autonomous electronic systems able to collect and transmit vast quantities of performance data to remote sites for subsequent analysis and display. Wayside systems (e.g. bearing acoustic, wheel impact load, truck hunting and angle-of-attack) able to measure the performance of passing fleets of vehicles are proliferating. Vehicle mounted systems are a more recent development (e.g. track geometry, vehicle and truck mounted accelerometer packages [7]) but their increasing affordability and effectiveness in trending track conditions and identifying "trouble spots" ensures that they will have a continuing role in supporting the maintenance process.

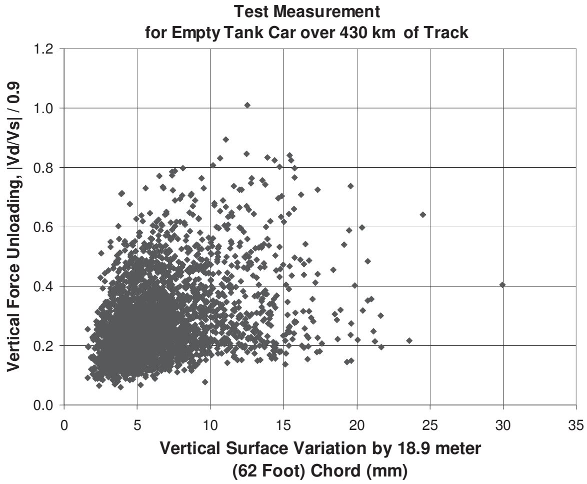

Figure 1: Vertical force unloading vs. track vertical surface variation.

Although the train mounted systems are effective in identifying problem track or locations of poor vehicle/track interaction, they are thus far proving very poor at determining the maintenance action required to address the problem locations. At the moment, railroads must send out a knowledgeable track inspector to physically review the identified area and diagnose the problem. Even with the implementation of neural networks and extensive field training, diagnostic systems appear aimed to provide no better than 80% accurate in identifying the required remedial measures.

The inability thus far to correlate measured force or acceleration defects with track geometry parameters is believed to be due to the reliance on existing, fixed wavelength (62 or 31 foot chord) measurements of track geometry and the application of only single geometry parameters. With support from the US Federal Railroad Administration, the NRC Centre for Surface Transportation Technology (NRC-CSTT) is using vehicle modeling and multiple regression techniques to develop robust methods of correlating combined track geometry perturbation characteristics with forces and accelerations measured with various systems on North American track.

3 TRACK GEOMETRY INTERACTION MAP AND PARAMETER (TGIMP)

If there is no dynamic interaction between vertical and lateral directions, the vertical (lateral) responses of a vehicle will be only related to the vertical (lateral) variations of track. But vertical and lateral interactions are coupled in some manner and the occurrence of vertical and lateral track perturbations together within some longitudinal distance of each other can, and will, result in a coupled interaction.

To examine the interaction effect, NRC-CSTT has developed the Track Geometry Interaction Map (TGIM). The approach is to map and then analyze the contours of vehicle response that arises due to combinations of perturbations in the track. A schematic of TGIM is shown in Figure 2. Each point in the plane corresponds to the peak response of the vehicle at that (alignment, surface) coordinate, and a contour connects all points that produce the same level of vehicle response. If there is no dynamic interaction between the two perturbations, the contours will be a series of horizontal or vertical lines. By examining the vehicle response to various combinations of perturbations (through measurement or modeling), it should be possible to map a contour or threshold within which the vehicle performance remains at acceptable levels and beyond which the performance (or risk, or costs) are unacceptable. The expectation is that through modeling or measurement, we can identify safety (or maintenance) thresholds for operations that are probably less conservative for single defects, but more conservative (and thus safer) for combined defects.

TGIM can be applied to different vehicle responses or performance indicators, like lateral (L) or vertical (V) wheel-rail force, combinations of forces (e.g. L/V), car body accelerations, hunting, rock-and-roll or any other vehicle response that can be measured and/or modeled. In the present study we consider combinations of lateral (alignment) and vertical (surface) errors and their effect on the L/V ratio (L/V>1 indicates a high risk of wheel climb derailment), and vertical wheel unloading ($V_{UL} = 1\text{-}V/V_{static} > 0.9$ indicates a high risk of wheel lift-off).

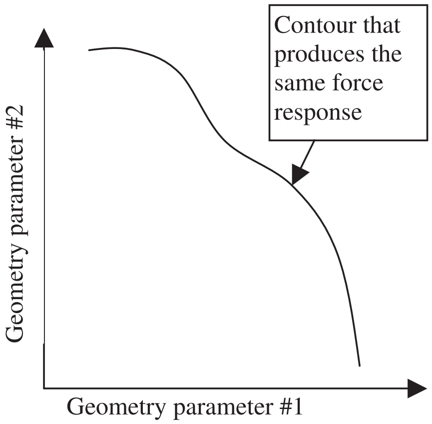

Figure 2: Track Geometry Interaction Map (TGIM) concept.

Multi-body dynamics software is proving increasingly capable of modeling vehicle/track performance even in highly dynamic environments. For this particular exercise CSTT used Vampire to model a typical North American covered hopper car equipped with a moderately worn three-piece truck:

Wheelbase=1.78 m (70 inches)
Truck center-to-center distance=12.3 m (40.5')
Wheel load = 16.3 tons (35.9 kips)
Wheel tread taper = 1:20
Secondary stiffness per spring group:
    lateral=2,070 N/mm (12 kips/in)
    vertical=4,390 N/mm (25 kips/in)

The friction coefficient was set to 0.5 and the vehicle speed to 80 kph (48 mph). The unworn wheel shape (AAR1B) was used on worn rail profiles measured on a typical (moderately worn) main line track in Canada.

A matrix of 16 alignment and 16 surface values (i.e. 256 total) was used in the present dynamic simulations. Both the surface and alignment variations were based on the AAR Chapter XI track shapes (Figure 3), with wavelengths equal to 12 meters (39 feet). The surface and alignment variations are set to be coincident (without offset), which based on previous experience will give the strongest dynamic vehicle response. An example of the simulation results for tangent track is shown in Figure 4. The contour lines represent combinations of lateral and vertical alignment that give equal levels of wheel unloading V_{UL}. Not surprisingly, the combination of defects results in higher level responses than occurs for the vertical and lateral defects alone. The corresponding plot for L/V is shown in Figure 5. In both cases, considerable dynamic interaction between the lateral and vertical geometry errors can be seen in the zone where the lateral alignment (peak-to-peak) is larger than about 25mm. In the zone where the lateral alignment is less than about 25mm, no obvious interaction can be observed, i.e. alignment has little effect on V_{UL} and surface has little effect on L/V.

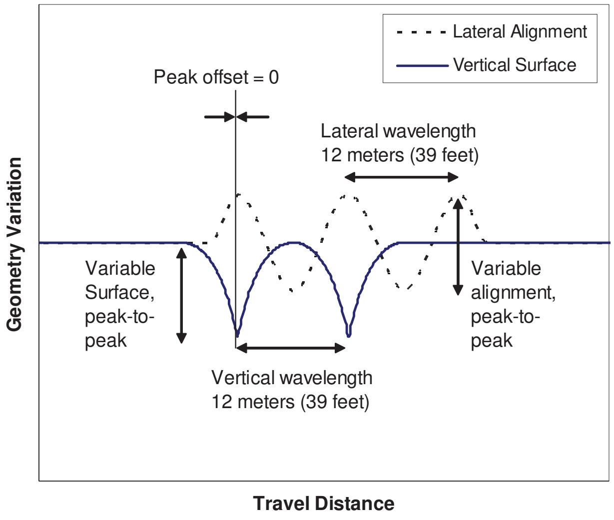

Figure 3: Track shapes for vertical and lateral alignment variations.

If we consider the unsafe conditions for operation on to be dictated by the AAR Chapter X1 levels (i.e. $V_{UL}/0.9 > 1.0$ and $L/V > 1.0$), the safe operation zone in terms of the force response can be written as

$$\mathrm{MAX}(\, L/V,\ V_{UL}/0.9\,) < 1.0 \qquad (1)$$

The same is shown graphically in Figure 6 by combining the $V_{UL}=0.9$ contour of Figure 4 with the L/V=1 contour of Figure 5. Combinations of vertical and lateral perturbations that fall beyond the boundary are "unsafe" for the particular vehicle and conditions simulated here. Note that the boundary is mainly governed by AAR's 90% wheel unloading limit.

Also shown in Figure 6 are the FRA safety limits for Class 4 track[1]. We see that the zone bounded by the FRA limits allows combinations of track geometry errors that could produce unsafe vehicle performance, but is overly conservative for the single geometry defects.

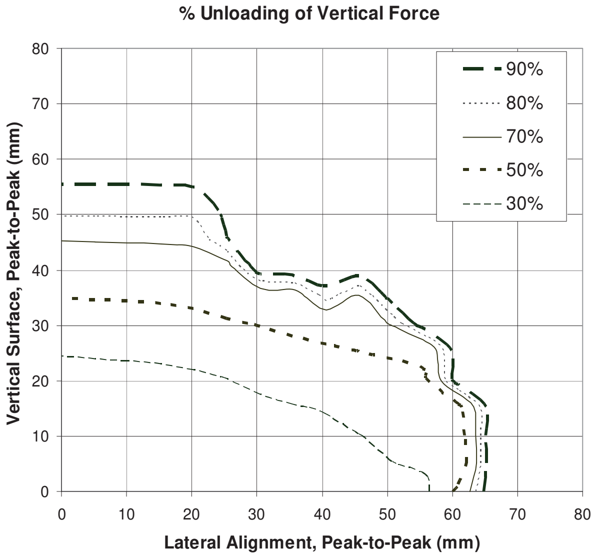

Figure 4: Iso-curves of vertical force response.

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[1] Both surface and alignment limits are defined by mid-offset of 62 foot chord in current track safety rule. However, the 62 foot chord filter has an abnormal feature that filters geometry variation to *zero* for irregularity having "blind point" wavelengths equal to 62/2 (31), 62/4 (15.5), 62/6 (10.3),… feet. To avoid the abnormal shrinking effect to geometry variations that have a wavelength closing to these "blind points", the 62 foot chord filter has *not* been applied to geometry variations in this paper.

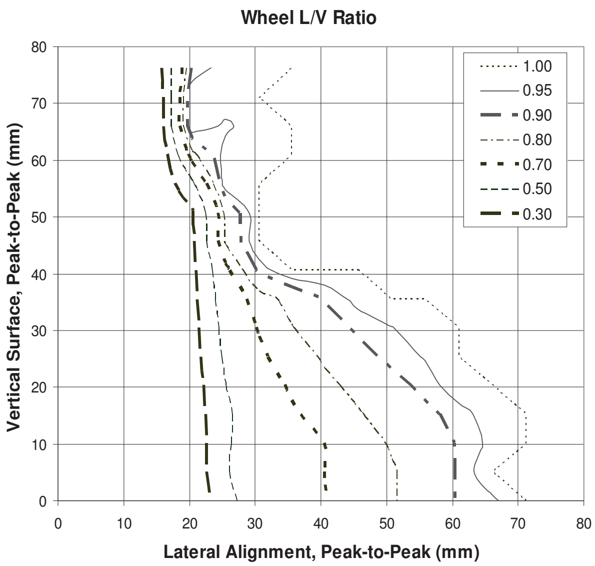

Figure 5: Iso-curves of the instantaneous lateral and vertical force response (L/V).

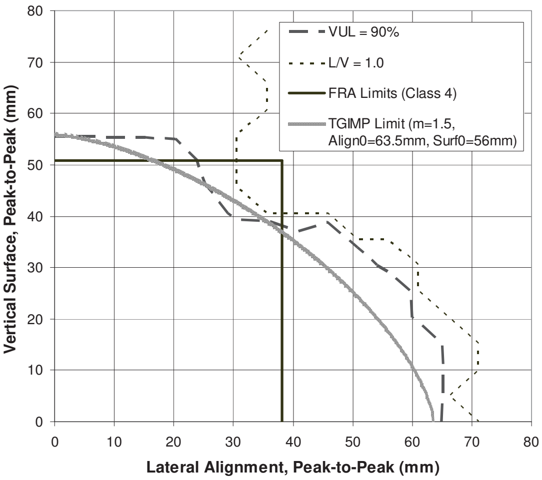

Figure 6: Safe operating boundaries for vertical and lateral geometry errors.

The safe limits identified by the TGIM contour of Figure 6 can be approximately described by a new track geometry parameter, which we call TGIMP:

$$TGIMP = \left[\left(\frac{Align}{Align_0} \right)^m + \left(\frac{Surf}{Surf_0} \right)^m \right]^{1/m} \qquad (2)$$

where $m>0$ is a constant, *Align* and *Surf* are alignment and surface variations, and $Align_0$ and $Surf_0$ are individual limits of alignment and surface variations. $TGIMP \leq 1.0$ represents safe operating conditions and the safe limit is bounded by *TGIMP* = 1, that is,

$$\left[\left(\frac{Align}{Align_0} \right)^m + \left(\frac{Surf}{Surf_0} \right)^m \right]^{1/m} = 1$$

(3)

In this formulation, the strength of lateral/vertical interaction can be adjusted by the constant *m*, *m*>>1 for weak interaction, *m*<<1 for strong interaction and 1<*m*<2 for moderate interaction (*m* = 2 giving a circular or elliptic contour).

In Figure 6, a TGIMP = 1 contour with *m*=1.5, $Align_0$=67.5mm (2.5 inch) and $Surf_0$=56mm (2.2 inch) describes the safe limit obtained from present simulations. This TGIMP limit takes into account the influence of combined vertical and lateral irregularities, it is less conservative for single defects, and more conservative (and thus safer) for combined defects.

4 APPLICATION TO RANDOM TRACK VARIATIONS

The analysis of Section 3 used the defect configuration of Figure 3 with a fixed wavelength of 12m (39 ft) and *zero* longitudinal offset between the lateral and vertical peaks. To determine the effect of other wavelengths and offsets on the TGIMP limit, a large number of track shapes were created using a random number generator to select an alignment between 0 and 100mm, surface amplitude between 0 and 75mm, wavelengths from 3 to 25m and offsets between fully in phase and fully out of phase. An in-house software tool called AutoRD was used to automatically generate the track features, setup the rail dynamics simulations and post-process the results files. AutoRD supports simulation engines such as NUCARS and Vampire and is able to systematically or randomly vary any vehicle, wheel-rail contact, friction, track geometry or stiffness parameter. The 4315 simulations of this effort were performed by Vampire.

Figure 7 plots only those combinations that produce unsafe wheel-rail force, i.e. MAX(L/V, $V_{UL}/0.9 \geq 1$). The FRA and TGIMP limits of Figure 6 are also plotted. It can be seen that the FRA limits are still conservative for single defects (surface or alignment), but allow several risky geometry combinations. The original TGIMP limit derived from the fixed wavelength and zero offset track irregularities also encompasses several risky conditions, especially with large alignment defects. The AutoRD approach has identified several combinations of wavelength and peak offset that are particularly problematic for this vehicle. The highest values are associated with a large lateral alignment. A revised TGIMP limit was worked out by using a set of new parameters: $m = 2$, $Align_0 = 50$mm and $Surf_0 = 50$mm. Compared with the FRA limits, the revised TGIMP limit excludes all the unsafe geometry combinations and extends the safe zone for the single lateral alignment error. The new TGIMP limit is now a circular contour.

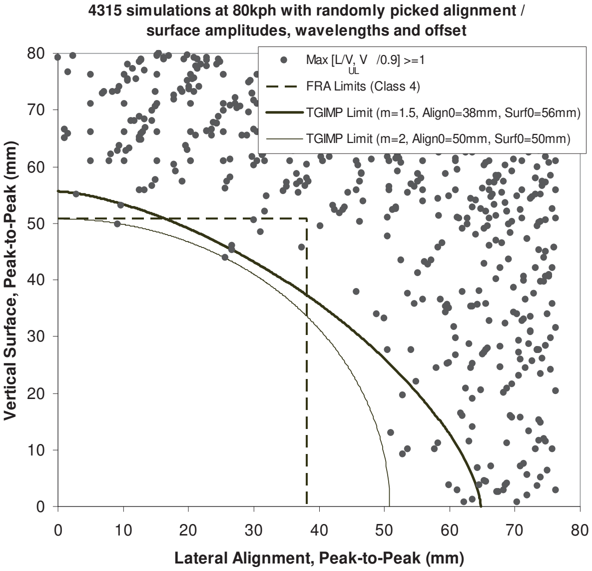

Figure 7: Safe operation boundaries based on simulations with 4315 different sets of track error characteristics.

The same poor correlation between individual track geometry and individual force response found in Figure 1 is seen in Figure 8 where we plot wheel unloading against the vertical defect size. Some small vertical errors are associated with quite large vertical force responses. If we instead plot the force against the TGIMP parameter (Equation 2), the influence of the lateral defect is considered. Figure 9 shows that the correlation improves significantly, though clearly the random values of wavelength and offset contribute considerably to the scatter.

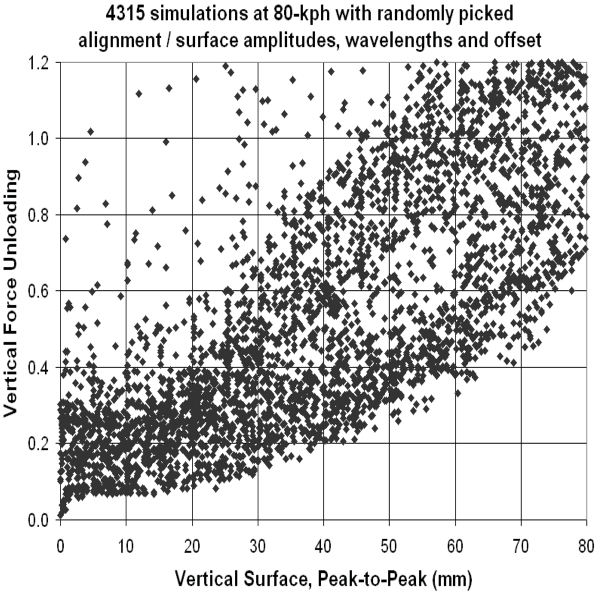

Figure 8: Poor correlation between the vertical force unloading and a vertical track defect if the lateral alignment error is not considered.

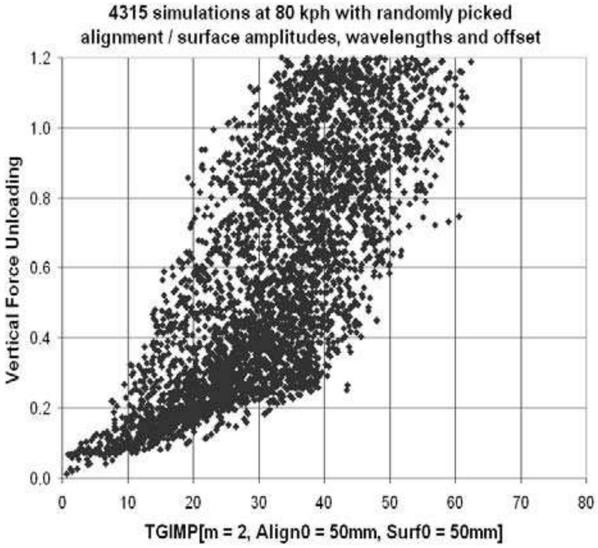

Figure 9: Plot of vertical force unloading against the TGIM parameter.

5 DISCUSSION, SUMMARY AND FUTURE WORK

It is reasonable to question whether modern rail track typically encounters combined lateral and vertical track geometry errors. Analysis of geometry for a 5-km segment of track that is compliant to class four standards found that there were several locations where the lateral and vertical alignment varied together, see Figure 10. Surf62_max and Align62_max are the maximum measured values of the surface (vertical) and alignment errors, based on a 19m (62 foot) chord, measured on that stretch of track. Examination of larger stretches of both tangent and curved track will further establish the relevance of this work.

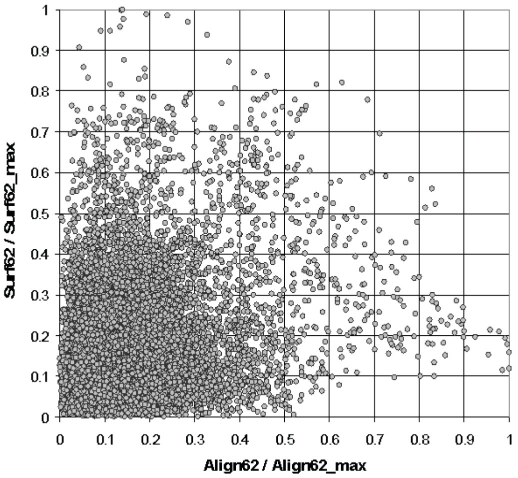

Figure 10: Measured combinations of vertical and lateral errors for a segment of tangent main line track in Canada.

Besides the randomly distributed track wavelengths and offsets examined here, there is no doubt that the TGIMP threshold will depend on other operating conditions. These include track curvature, gauge, vehicle type and load, travel speed, friction conditions, wheel and rail profiles etc. However, even considering the wide range of permutations that this proposes, it should be possible to identify a threshold that takes into account the interaction effects. This can be done either through modeling or careful field measurement. The TGIM approach suggested in this paper provides a promising way to begin understanding how vehicle and track conditions impact the measured forces and accelerations that are the basis of Performance Based Track geometry.

The present results show that the proposed geometry parameter - TGIMP - is a simple and effective combination parameter to relate lateral and vertical geometry errors to vehicle response. The safe operation limit based on TGIMP can effectively take into account the interaction effects of the combined track geometry errors. Compared with the existing FRA track safety limits, the TGIMP limit has been shown to have potential advantage that it can reduce operation risk in high interaction zones, and at the same time reduce maintenance required in relatively low interaction zones.

Further simulation work using the random parameter approach is planned to study the effects of other operational conditions including speed, curvature, car length, car suspension, wheel-rail contact conditions and friction.

The same TGIM approach can be applied to different vehicle response modes (e.g. rock and roll, hunting, bounce) and car types (e.g. locomotives and tank cars). Since accelerometers, by virtue of cost, are more likely to be employed than instrumented wheelsets for performance monitoring, the TGIM approach will be applied to both.

As Figure 4 and 5 show, the vehicle response varies non-linearly with the level of the defects. The TGIM approach can also be used to identify maintenance thresholds above which the wheel/rail forces begin to contribute to excessive rates of vehicle and track deterioration.

Finally, it is important to validate the TGIMP parameter and its threshold through correlation of simultaneously measured vehicle response and track geometry data. High quality data collected through careful field measurement is required for such work.

6 ACKNOWLEDGEMENTS

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