# PREDICTIVE CONDITION MONITORING OF RAILWAY ROLLING STOCK

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## SUMMARY

Stresses continue to increase on the rail infrastructure as axle loads and speeds increase and rolling stock maintenance costs conflict with time and economic constraints. Railroads are under increasing pressure to maintain their infrastructures while competing with other markets. Until recently, typical detector technologies have been developed from the track and structures perspective (and needs) and they reported forces acting on track structures. Rolling stock detectors have in general been exception- or alarm-based, reporting only after critical thresholds are exceeded. These detectors are not optimal for long-term observations, making them inappropriate for modern fleet and risk management.

The Wayside Monitoring Alliance members share a common and alternative philosophy and their detectors are developed from the rolling stock perspective, measuring on tangent track at line speeds. These detectors (wheel profile (ImageMap), truck geometry (WID), wheel condition (Teknis) and bearing condition (Vipac)) are highly specific and sensitive and they provide two critical advantages - they offer long-term trending of vehicle parameters; and they report root data instead of effects or symptomatic results. This is possible through software designed to follow each parameter from the time it first varies from nominal and a low-level alarm is raised. The result is an ability to predict component failure and to proactively schedule checks and repairs to vehicles before they suffer extra damage and stress track and structures.

Over several years the Alliance has developed an improved understanding of the inter-relatedness or coherence of the data from these detectors – and this is challenging some long held beliefs about managing rolling stock to cope with vehicle and track damage, risk and cost. Models are being created which predict the consequences of not acting promptly once rolling stock measurements vary from nominal values.

## INTRODUCTION

The rail industry, in North America especially, has been working under the Interchange Rules for some time. Thresholds were historically set based on levels determined to be harmful to track and structures. The underlying assumption has been that defects in wheels, bearings and suspension that are below industry accepted alarm thresholds are mostly harmless. Experiences shared by the authors suggest that this assumption is erroneous, particularly from the rolling stock perspective.

Current wayside monitoring practice for many railroads is typically to use “conventional” low-resolution means to assess equipment function. At speed it is possible to measure some large wheel impacts and gross truck geometry defects via strain gauge-based methods. Imminent bearing failures sometimes have an infrared signature that can be found by hot-box detectors. Wheel profiles and back-to-back gauge have not typically been measured at speed. These reactive practices are limited, appear to have a high rate of false alarms and are inadequate and inappropriate for today’s industry. In addition, due to the low-resolution of these methods, they do not allow for reliable trending and are intended primarily, or solely, as exception-based means for finding vehicles beyond alarm thresholds; that is, they are relied upon to flag equipment failing on track. Trains often must be stopped in the network and vehicles pulled and inspected for defects, leading to expensive delays and increased repair costs. In addition, as discussed below, leaving defective components in service until they reach high alarm thresholds causes further cumulative and expensive damage to other components.

Ideally, wayside detectors for rolling stock have the following basic characteristics:

- minimum missed “bad actors”
- minimum “false alarms”
- minimum required observations (passes or sites)

Predictive wayside detectors have a more stringent set of additional operating requirements:

- uniform system-wide performance standards
- repeatability at a wayside site and reproducibility throughout the rail network
- sensitivity to allow trends to be analysed and defects to be found earlier in their life cycle.

Ideally, predictive wayside detectors would also have the following characteristics:

- compatible data feed formats from complementary detectors to enable correlation of data (e.g. wheel and bearing monitors) to evaluate interrelated faults, root cause, and progression.
- “transfer function” - e.g. for data gathered on tangent track, reliable prediction of behaviours in curves

Independently the members of the Wayside Monitoring Alliance have researched and developed modern technologies to provide highly sensitive and specific methods for predictive monitoring of rolling stock. Evaluation of performance parameters has led to proprietary criteria that reflect the “health state” of rolling stock. These criteria relate to specific and persistent “signatures” of intact and damaged vehicle components. The methods chosen are sensitive and detect minor defects reproducibly long before alarms are normally raised. Benefits of utilizing sensors with greater resolution and dynamic range, combined with enhanced reproducibility, are that long-term trending of equipment is possible. Problem vehicles (“bad actors”) can reliably be followed over time. Users gain confidence in the value of the data.

Alliance detectors’ outputs can be fused into a common data management system so that where wayside monitors have been co-located it has been possible to observe inter-relatedness of defects as they develop. An ongoing goal is to co-locate a suite of all four Alliance detectors into a “Supersite”. The rich spectrum of integrated data provided for individual vehicles will hasten our understanding of rolling stock damage and will permit critical evaluation of hypotheses.

An important goal of predictive monitoring is to allow early, reliable, cost-effective detection of faults in rolling stock. Combining multiple detectors at discrete locations will allow vehicle owners to receive as much useful reliable life from their wheels, bearings and bogies as possible without compromising long-term health of other components of the vehicle or the integrity of track and infrastructure.

## 1. INTEGRATED WAYSIDE MONITORING

### 1.1 Principles of Operation

A unique aspect of the Alliance approach is that all of the systems can be mounted together or separately on tangent track and measure vehicles at normal line speeds. Data feeds are compatible and a common database compliments the individual data management schemes of each detector.

**1.2 Wheel Condition Monitor and Vehicle Dynamics** Teknis Electronics developed a Wheel Condition Monitor (WCM) that employs multiple sensor types in a hybrid sensor array. The Teknis array uses accelerometers, proprietary load cells and optional strain gauges to measure impacts, mass and strain respectively. This differs from traditional methods that use one sensor technology to measure peak impact forces, quasi-static mass and rail strain.

Teknis’ array was developed to meet the more stringent requirements of Predictive Monitoring and this requires that measurements be immune to common variables such as sprung mass and to environmental influences such as the rail current present in electrified tracks.

Teknis has learned from experience that 100% wheel coverage, the ability to sense multiple defects on a wheel and sensitivity to detect anomalies as small as 3mm is critical for predictive monitoring.

Strain gauges, when used to measure wheel surface condition must isolate impact data from the mass and vehicle dynamics in non-contiguous samples (Figure 1). The small impact values are embedded within large and variable mass and dynamic peaks. In addition, when used in certain electrified railways strain gauges can become problematic due to rail current-induced noise.

An alternative technology was chosen to quantify wheel condition. Teknis discovered that properly configured accelerometers have superior sensitivity and impact data reported is independent of sprung mass, electro-magnetic influence or where the wheel defect occurs in the array. (Fig. 2).

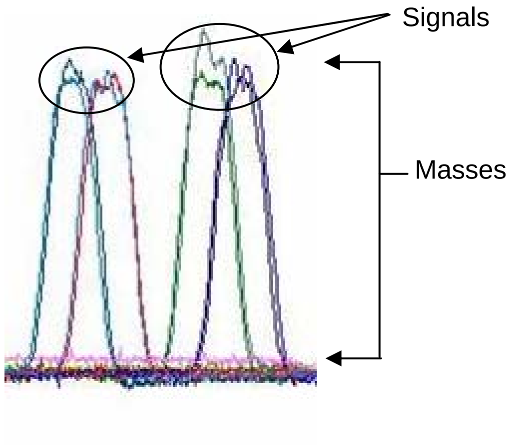


*Figure 1 : Strain Gauge Signal Quality*

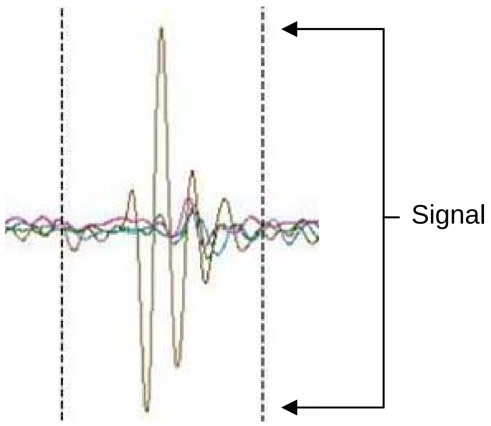


*Figure 2 : Accelerometer Signal Quality*

Characteristics of the Wheel Condition Monitor are:

- defects as small as 3 mm are identified
- operates between 30 and 180 km/h
- data are gathered for each wheel in a train.
- accelerometer arrays yield continuous and linear coverage of the entire wheel circumference, independent of wheel diameter.
- in-motion weighing by load cells provides quasi-static masses
- impacts reported are <u>independent</u> of axle mass. Separation of impacts from mass allows high S/N and obviates the need for normalisation factors, such as impact factors.
- defects detected include spalls, shells, out-of-round (OoR) wheels and long-period defects.
- velocity and axle spacing data permit reconstruction of trains with integrated AVI tag data; defect data are assigned to appropriate axles and wheels.
- after processing, the Teknis WMS data system trends wheel defects.
- Train-level dynamic parameters can also be derived; these include speed, axle load, vehicle loading balance – front to rear, gross vehicle weight, train impact force, total train forces, train load, length and power-to-weight analysis consist loading analysis, driving patterns, and so on.

A key feature of predictive monitoring detectors is the goal of uniform performance throughout the network and during changing climatic conditions. Strain gauge and accelerometer methods can both be sensitive to changes in track modulus. WCM is unique in that it automatically calibrates as track modulus and/or local geometry changes, maintaining consistent performance.

**1.3 Bearing Acoustic Monitor** Vipac Engineers and Scientists developed the RailBAM® System for monitoring the health of rolling stock bearings via acoustic means. The system and its performance are described in detail by Southern <u>et</u> <u>al</u> in the CORE 2004 Conference on Railways Engineering. Unlike a bearing acoustic monitor, a hot-box detector (HBD) is a reactive method for bearing monitoring which might detect the infrared signature of a bearing nearing imminent failure at speed, necessitating an urgent alarm. The alternative predictive monitoring method utilises sensitive acoustic techniques to examine bearings at speed for characteristic <u>signatures</u>, as faults develop. Trending of tagged vehicles with bearing faults can occur for many thousands of kilometres after fault signatures are first detected and long before bearings overheat.

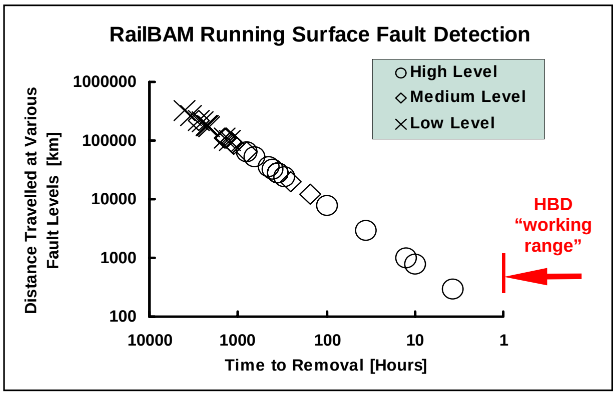


*Figure 3 : Plot of Detection Trending Distances at Various Fault Levels*

Figure 3 presents a limited dataset of the distances travelled by bearing faults at various severity levels (High, Medium and Low) as their condition is trended by several RailBAM® Systems – due to lack of wagon histories at this time, distances travelled are conservative minimum estimated values and times have been derived using a mean speed of 80kmph. However it is clear that faults are consistently trended for many thousands of kilometres, well before the time of bearing overheating.

As observed for other predictive monitors, this permits rolling stock owners to schedule maintenance in advance of outright component failure. RailBAM® uses a sensitive acoustic array and advanced signal processing algorithms to track and identify characteristic signatures of specific bearing faults and acoustic wheel faults. RailBAM® detects acoustic signals emanating from wheels and bearings travelling at 30 to 130 km/h through the site. Signals are specific to the identified bearing or wheel, with little contamination from neighbouring axles. Bearing faults are specified as raceway (cup or cone spalls, roller faults) or potential fretting and looseness faults. Signal amplitudes allow quantification of fault severity. At the lowest levels, trending is started and bearings and wheels are watched for worsening condition or more complex acoustic signatures. As bearing condition deteriorates and reaches a high severity, maintenance can be scheduled.

Other acoustic events are identified by RailBAM®; optimally, acoustic fault data for tagged vehicles can be correlated with results from the wheel condition monitor (WCM), the vehicle geometry (TBOGI) or wheel profile (WheelSpec) detectors.

RailBAM® provides the following detection capability:

- Early detection of outer/inner ring, roller faults in axle box and cup, cone, roller faults for package bearings
- Early detection of looseness and fretting faults in axle box and package bearings.
- Detection of wheel/rail flanging and certain types of wheel impacts.
- Train speed and approximate wheel diameter

RailBAM® provides the following features:

- Reliable measurement at 30 to 130 kph
- Analysis reporting within 10 to 15 minutes of train pass-by.
- Comprehensive database for condition trending purposes.
- Ability to track fault development over 1000's of kms due to early detection
- Alarm reporting to customer requirements.
- Self checking systems with automatic system fault alarms

**1.4 Vehicle Geometry** Wayside Inspection Devices (WID) developed TBOGI - the laser-based apparatus for measuring numerous aspects of bogie geometry at line speed. The system is able to derive the following core values from vehicles travelling between 30 and 240 km/h on tangent track:

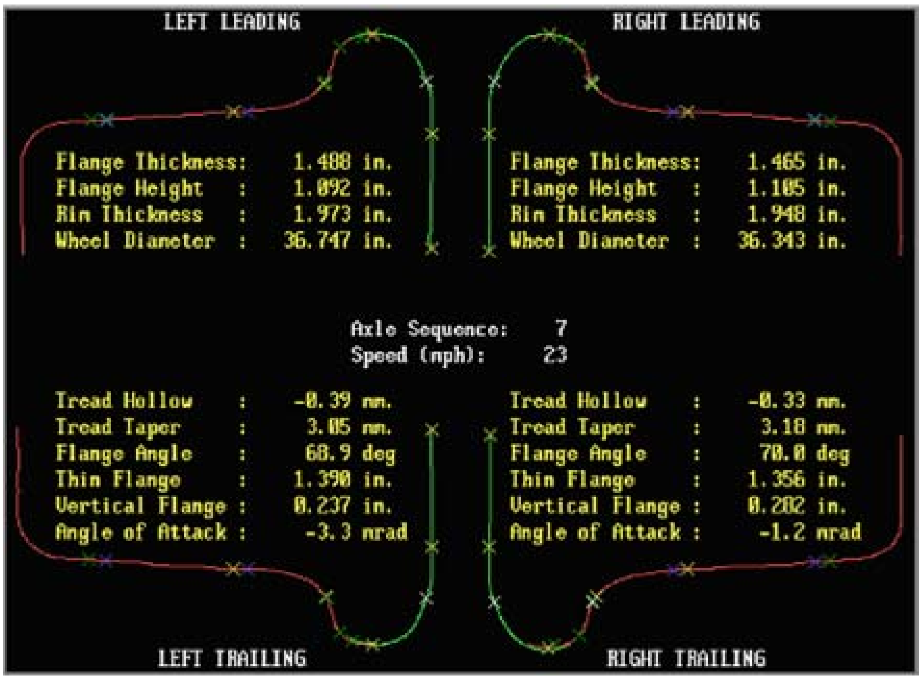
- Angle of attack (AoA) – orientation of the axle relative to the track
- Tracking Position – position of the wheel set relative to the track centreline
- Inter-axle misalignment – orientation of both axles of the bogie in relation to each other
- Tracking Error – difference in tracking positions of the bogie axles
- Hunting – lateral instability of a bogie
- Truck rotation – evaluation of steering ability of the bogie

WID conducted extensive research on bogie performance in a number of field applications. The conclusion was that measuring performance on tangent track with optical means is the most reliable, most accurate method of monitoring. Measurements in S-shaped curves are subject to environmental and physical variables. Changes in the wheel/rail interface due to the rail surface contamination and/or lubrication, weather conditions, variations of train speed from balance speed affect adversely the results of bogie performance monitoring in curves. All of these studies led WID to choose a laser-based method for direct measurement of axle angle and tracking position on tangent track. Data are reproducible, specific and of a very high resolution, as required of a predictive monitor.

**1.5 Wheel Profile** ImageMap's laser-based WheelSpec is an automated wheel inspection system. The apparatus resides beneath the rails and sleepers and upward-pointing lasers illuminate the running surfaces of wheels travelling at up to 100 km/h. High-speed cameras capture specific illuminated points on the wheel, permitting computer generation of highly accurate (nominally 0.1 mm) generation of the wheel profile. Measured and calculated parameters from the cross-section profiles include:

- Flange thickness
- Flange height
- Rim thickness
- Vertical flange
- Built-up & grooved tread
- Tread taper (hollow)
- Back-to-back gauge
- Wheel diameter
- Wheel flange angle

Figure 4 depicts the output from the WheelSpec system for a typical pair of wheels on one axle. The measured parameters are reported within the output shown.



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LEFT LEADING                                      RIGHT LEADING

Flange Thickness:    1.488 in.      Flange Thickness:    1.465 in.
Flange Height    :   1.092 in.      Flange Height    :   1.105 in.
Rim Thickness    :   1.973 in.      Rim Thickness    :   1.948 in.
Wheel Diameter   :  36.747 in.      Wheel Diameter   :  36.343 in.

                      Axle Sequence:    7
                      Speed (mph):     23

Tread Hollow     :  -0.39 mm.       Tread Hollow     :  -0.33 mm.
Tread Taper      :   3.05 mm.       Tread Taper      :   3.18 mm.
Flange Angle     :   68.9 deg       Flange Angle     :   70.0 deg
Thin Flange      :  1.390 in.       Thin Flange      :  1.356 in.
Vertical Flange  :  0.237 in.       Vertical Flange  :  0.202 in.
Angle of Attack  :   -3.3 mrad      Angle of Attack  :   -1.2 mrad

LEFT TRAILING                                     RIGHT TRAILING
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*Figure 4 : Profiles of a typical pair of wheels on one axle*

Measurements outside of specification can be used to predict maintenance scheduling. Wheel profiles gathered by these means can be used to flag out-of-specification wheels that are at or near the condemn limit or which represent potential safety risks. Maintenance depots have the option of manual measurement of such wheels to confirm damage and to examine other components of trucks for potential damage initiators. For example, the WheelSpec provides a means to check wheels on trucks that have been flagged with aberrant tracking geometry by TBOGI.

Accurate measurements of wheel profiles at speed enables trending of specific measures that are hallmarks of accelerated or abnormal wheel wear (e.g. flange, tread hollow). Trending of wheels can yield estimated remaining life and is useful for issuing alerts on rapid changes in profile. The latter might be observed if rail lubrication or rail profile changes, and additionally might flag sensitive vehicles in a fleet.

## 2. PREDICTIVE CONDITION MONITORING

Reproducibility is a hallmark of an effective predictive rolling stock monitor. Figure 5 illustrates the AoA and tracking position results for a train passing the TBOGI 6 times at speeds between 65 and 204 km/h over 14 days. The traces are overlapping and are essentially indistinguishable from pass to pass.

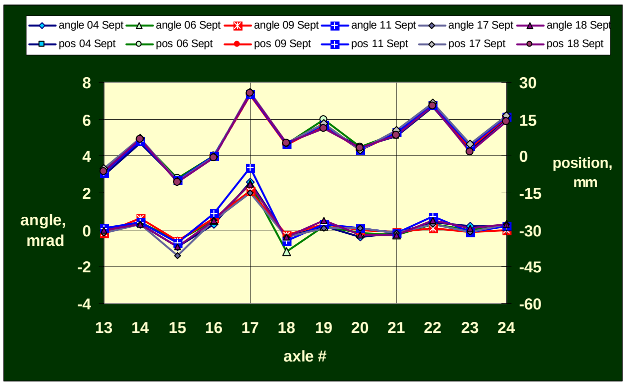


*Figure 5 : Reproducibility of Geometry Data*

Critical goals of predictive rolling stock monitoring are to prevent further damage to a vehicle once faults are found and to allow timely predictive maintenance of that vehicle (scheduling for anticipated service and repair). An essential tool for effective rolling stock monitoring is computer trending of fleets and timely reporting of data (and alarms) to the relevant groups. Root data are provided to users, not symptomatic or estimated values. A central data management system, the Teknis Wayside Monitoring System (WMS) is one tool at the disposal of the Alliance. Separate feeds from each detector system can be fused in WMS for management by the respective detector suppliers and by operators assigned by rolling stock owners. Trending tools are available to rolling stock owners to track data from the wayside detectors. Additionally, independent data feeds and management tools are available for each detector.

The model shown in Figure 6 is a working hypothesis developed by the Wayside Monitoring Alliance. It provides a pictorial means to develop concepts and testable hypotheses. By first considering the major forms of damage observed (wheel surface, bearings, bogie geometry and wheel profile/wear) the Alliance has begun to show causal relationships that create a positive feedback loop.

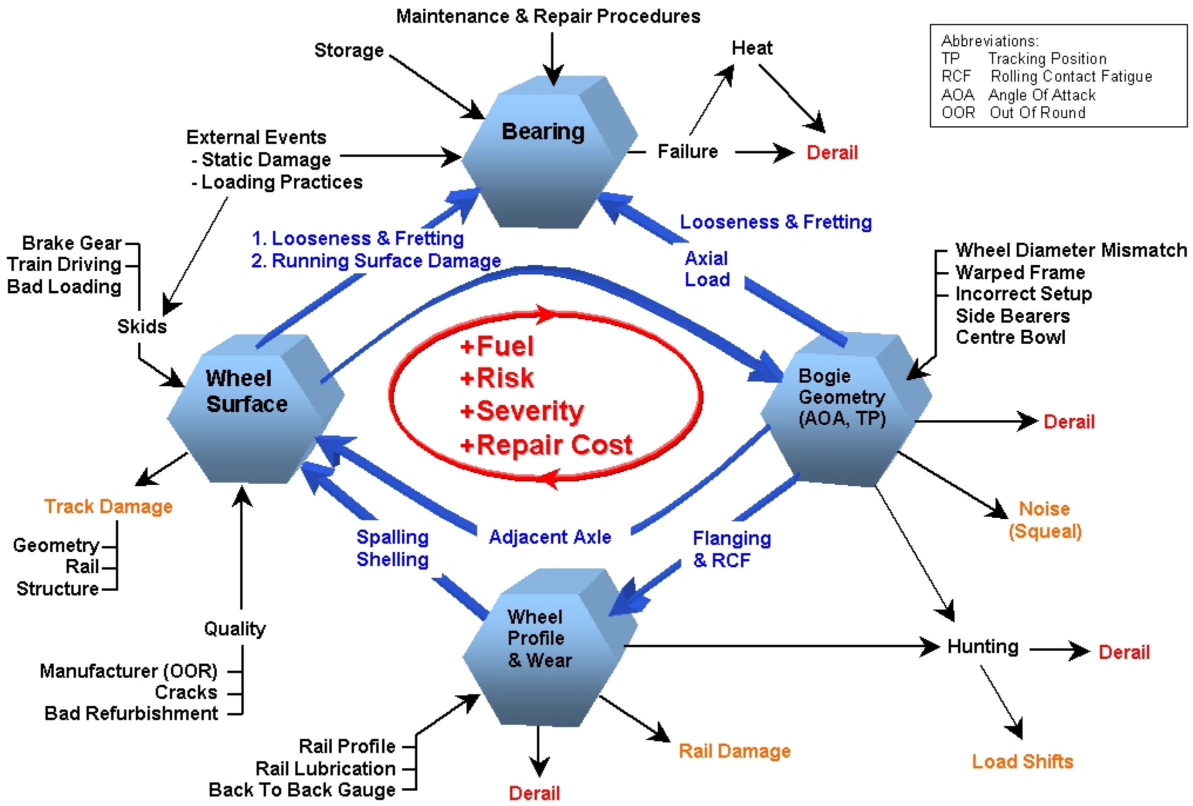


***Figure 6 : Wayside Monitoring Alliance Model of Wheel, Bearing and Geometry Damage***

Arrows which point toward the hexagonal areas of damage suggest initiators of said damage. Arrows pointing from the hexagons suggest effects of the damage, either on other components of the vehicle (heavy arrows) or in terms of consequences. These arrows are based on observations of the Alliance over several years. One consequence of not repairing geometry and wheel damage is indicated by the pair of heavy arrows inside the hexagons, which suggests that inaction leads to damage initiation on the adjacent axle of a bogie.

The core of the model, literally and figuratively, is the area in red. This highlights the consequences of not utilising detector information to effect timely repair or predictive maintenance on identified defects. As the cycle continues, increased forces acting on components due to growing damage ultimately means higher forces are acting on the rails too, leading to infrastructure damage. All of these forces are fed by increased fuel consumption. The end-points on the outer perimeter all represent cumulative and increasing risk to rolling stock owners and operators. As time passes, the defects and risk increase in severity because of the positive feedback nature of the cycle. This ultimately translates to much higher repair costs. In the sections following the authors have provided some examples of typical relationships that reinforce this model.

As mentioned above, some of the potential initiation and end-point effects of the damage found by predictive wayside monitors are listed on the outer perimeter of the drawing. Initiators vary depending on the damage being observed and these are discussed in some detail below.

As an example, a wheel skid can cause a small defect that grows into a long period defect of increasing impact. There is a chance that wheel impacts will have a direct effect on the running surfaces of wheel bearings, leading to cone, cup or roller faults. A minor wheel defect will grow into a larger wheel defect; it will not heal. Left long enough (usually less than 8 weeks), a very frequent observation is that the adjacent wheel on the same axle develops a growing impact fault.

This implies that truck geometry has been adversely affected by the wheel defect and forces are acting on both wheels of the same axle. Simultaneously, the altered geometry often causes measurable effects on wheel profile by flanging and rolling contact fatigue (RCF). This accelerates wheel wear and leads to spalling and shelling of the wheels, worsening impact forces, and so on. It is also hypothesized that aberrant truck geometry leads to elevated lateral forces acting on the rails and increasing axial loads cause stress on wheel bearings. This manifests itself in looseness and fretting faults in bearings (which to date can only be measured by the RailBAM detector). There have been numerous observations of noisy wheels predating looseness and fretting defects. It is important to consider that looseness and fretting are major causes of heat in bearings. Many initiators of damage are listed in the model and the cycle can start at any point.

## 2.1 Bogie Geometry

Geometry defects arise from multiple causes. An example of a vehicle with a steering problem is illustrated in Table 1. The initial rotation is in red and the rotation after repair is in blue.

| **Car** | **Bogie** | **dir** | **leadEnd** | **Pass Date** | **Rotation** |
|---|---|---|---|---|---|
| 4xx9 | A | N | A | 2003-06-07 | **1.15** |
| 4xx9 | A | N | A | 2003-06-08 | **1.20** |
| 4xx9 | A | N | A | **2003-08-20** | **0.40** |
| | | | | | |
| 4xx9 | A | S | A | 2003-06-06 | **-2.35** |
| 4xx9 | A | S | A | 2003-06-08 | **-1.85** |
| 4xx9 | A | S | A | 2003-06-09 | **-1.55** |
| 4xx9 | A | S | A | **2003-08-20** | **-0.05** |

***Table 1: Repaired Vehicle with Steering Problem Identified by TBOGI***

Truck 4xx9 showed excessive positive rotation while in the northbound direction and high negative rotation while travelling southbound. This truck was flagged by TBOGI. After repairs the truck showed nominal behaviour. Maintenance records indicated all wheels were in good condition but the side bearing gaps needed adjustment and the centre plate required grease. Timely repair of these problems likely prevented further negative consequences.

A commonly held belief is that lateral forces only act to a significant degree on rails via trains travelling through curves. Figure 7 illustrates a typical train with a "bad actor" truck with aberrant geometry (left axis angle of attack (mrad); right axis Force (kips)).

The lateral forces exerted on the rails on tangent track are highly significant and this is a characteristic signature of a truck with improper angle of attack. In this case the axle had an angle of -6 mrad on tangent track and the lateral force exerted into the rail was 8 kips. These data show the urgent need to quickly and reliably detect improperly tracking vehicles before they lead to infrastructure damage and before they initiate damage to other components of a bogie. As discussed above, the increased axial loads shown by this truck can damage certain types of wheel bearings, particularly by causing looseness and fretting.

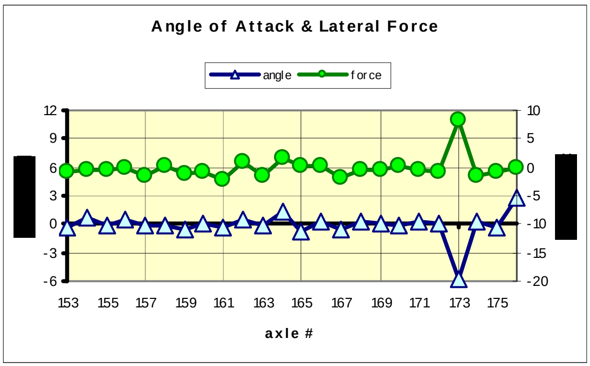
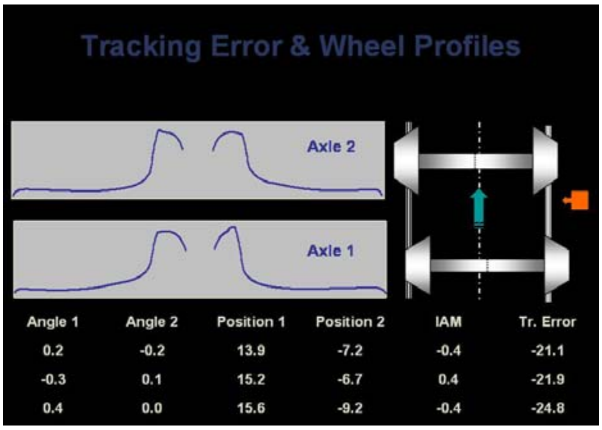


***Figure 7 : Lateral Forces Exerted on Rails by Vehicle with High Angle of Attack***

Wheel, bearing and geometry damage that is trending does not spontaneously heal. It will worsen with time, sometimes slowly and other times very rapidly. Trending helps to predict end points. In the past, where some detectors showed variable results, "bad actors" would sometimes erratically appear and then disappear. For wheel condition this might have been due to a sharp short-period defect (impact) developing into a long-period defect with a lower apparent impact over some types of detectors. The erroneous conclusion was that the wheel was "healing". Similarly, certain types of vehicle geometry detectors might yield different results depending on environmental conditions, etc., leading to the conclusion that perhaps aberrant geometry had corrected itself without maintenance. Predictive monitoring and trending of defects allows long-term observation of defects and they invariably worsen with time, perhaps with a period of slow defect growth. Figure 8 illustrates a typical example of this phenomenon. A truck with combined geometry defects led to severe wheel damage. The geometry defect had been followed for some time but it was not quickly acted upon by the vehicle owner. The result of this vehicle having a large uncorrected tracking error for an extended time was severe wheel damage, indicated by sharp flanges on diagonally-opposed wheels of the bogie, on adjacent axles.



Tracking Error & Wheel Profiles

| Angle 1 | Angle 2 | Position 1 | Position 2 | IAM | Tr. Error |
|---|---|---|---|---|---|
| 0.2 | -0.2 | 13.9 | -7.2 | -0.4 | -21.1 |
| -0.3 | 0.1 | 15.2 | -6.7 | 0.4 | -21.9 |
| 0.4 | 0.0 | 15.6 | -9.2 | -0.4 | -24.8 |

***Figure 8 : Misalignment and Wheel Damage***

In this example, TBOGI measured a large tracking error and a small inter-axle misalignment. The wheels on these 2 axles showed asymmetric wheel wear (flanging). Effects of out-of-specification tracking geometry are being analysed by the Alliance for initiation of bearing defects. To date there is increasing evidence that noisy wheels (flanging or high angle of attack) which are detected by RailBAM® can precede bearing damage. A goal of the Alliance is to co-locate a TBOGI and a RailBAM® system to trend geometry defects and bearing damage within the same vehicles.

## 2.2 Wheel Surface

Based on practical experience over ten years, the common type of wheel running surface defects are:

- Spalling from rolling contact fatigue or induced by poor bogie geometry
- Shelling from localised heating (small skids)
- Spalling from sub-surface defects (wheel quality or from previous damage)
- Skid flats
- Out of Round

Without exception, once a wheel defect occurs, the severity of the impacts from that defect increase over time.

Sudden large impacts caused by skidded wheels are not typical. Wheel defects normally develop from small defects in the wheel's running surface. These defects typically grow and pass through stages as they mature into high-level alarm events.

Some, but not all, wheel defects can be shown to have speed or direction dependence after analysis. In general, it is evident that such dependencies are just an indication of the maturity of the defect.

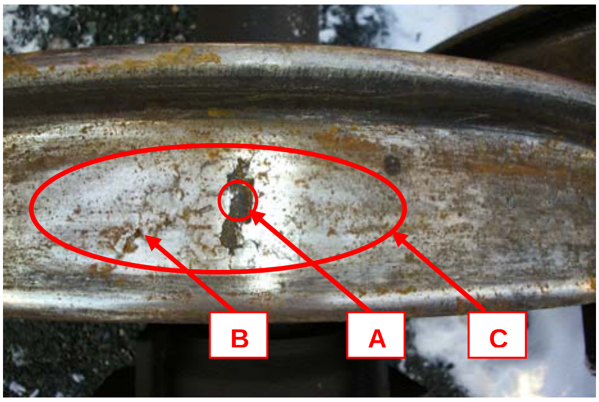


***Figure 9 : A Typical Mature Wheel Defect***

The wheel in Figure 9 shows an old (8 month) and mature wheel defect that progressed from a small (20mm) skid. Progression of this type of defect is typically:

1. Very small skid, high heat, metallurgical damage to localised area (A).

2. Shelling initiates, sharp edges. Decreasing severity with speed.

3. Extremely high dynamic loading on damaged section.

4. Shelling worsens and sharp edges round off. Typically not speed dependent at this stage.

5. Possible re-skidding on same area of wheel under heavy braking, deeper heat damage.

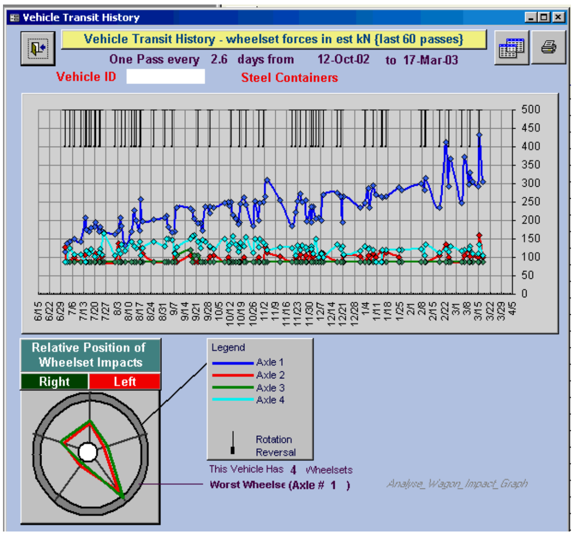
6. More shelling. Collapsing of metal around the impact area and subsurface cracking causing more metal to fall out (B).

7. Repeated impacts on the same point cause collapsing of wheel tread over long period. Sometimes these are only apparent with a run-out check. Wheels at this stage show increasing severity with speed. In the example in Figure 9 the impacts reached about 400kN at 100 km/h and the long-period damage area finally spanned 200mm (C).

Figure 10 illustrates this type of defect progression with increasing variability due to speed as it matures into a long period defect.

Machining this type of wheel at such a late stage results in both significant loss of wheel life and a high risk that the damage has extended well into the wheel rim. There is a higher likelihood that damage to this wheel will recur when placed back in service.

Grinding the edges of a wheel defect simply creates a long period defect that is more speed dependent and does not break the positive feedback cycle (Figure 6).



Vehicle Transit History

Vehicle Transit History - wheelset forces in est kN {last 60 passes}

One Pass every 2.6 days from 12-Oct-02 to 17-Mar-03

Vehicle ID Steel Containers

Relative Position of Wheelset Impacts

Right Left

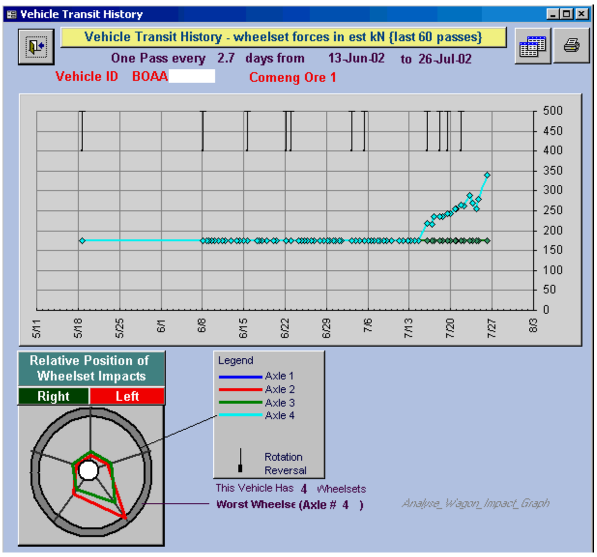
Legend
Axle 1
Axle 2
Axle 3
Axle 4
Rotation Reversal

This Vehicle Has 4 Wheelsets

Worst Wheelse (Axle # 1 )

**Figure 10 : Wheel Defect Progression**

An example of a typical but rapidly worsening wheel defect is shown in Figure 11. In this example the alternate points represent passes over the WCM site at axle loads of 5 tonne and 35 tonne and the immunity of the WCM from the sprung mass is clear. This axle developed OOR wheels and the extreme axle loads led to the rapid rate of deterioration (two weeks).



Vehicle Transit History

Vehicle Transit History - wheelset forces in est kN {last 60 passes}

One Pass every 2.7 days from 13-Jun-02 to 26-Jul-02

Vehicle ID BOAA Comeng Ore 1

Relative Position of Wheelset Impacts

Right Left

Legend
Axle 1
Axle 2
Axle 3
Axle 4
Rotation Reversal

This Vehicle Has 4 Wheelsets

Worst Wheelse (Axle # 4 )

***Figure 11: Rapidly Worsening Wheel Defect***

When a wheel with a defect is left in service for a long time it is not unusual for the adjacent wheel-set in the bogie to develop defects. Figures 12 and 13 show small skids worsening over a six month period (A). By the time the impact levels reach a moderate level (250 kN or three months) the adjacent wheel-set (B) shows developing faults. The increasing variability in the latter passes of the Figure 12 (C) is speed related and is typical of a long period and well worn defect that is difficult to locate on visual inspection

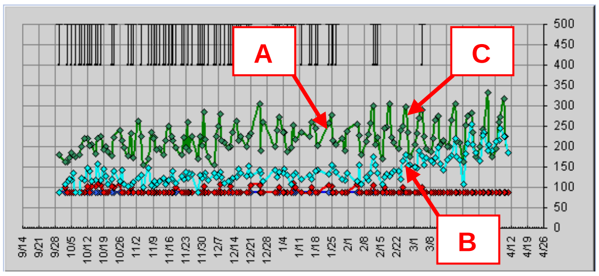


***Figure 12 : Damage to Adjacent Wheelset***

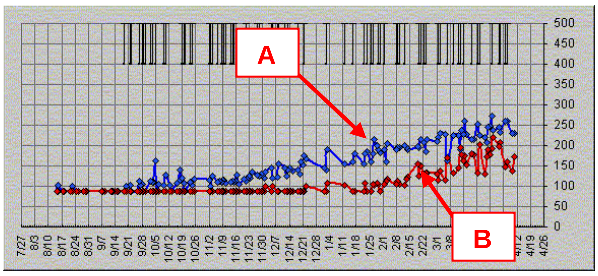


***Figure 13 : Damage to Adjacent Wheelset***

It is not possible to quantify the bogie geometry in this example because the tBogi and WheelSpec systems were not co-located at these sites but the hypothesis is that the wheel defect introduces drag and perturbs the tracking, ultimately causing damage to the adjacent wheelset tread and accelerated wear on all four wheels of the bogie.

## 2.3 Bearings

Bearing failures have been observed and trended that appear to arise without noisy wheels or wheel impacts (potential geometry issues). The example in Figure 14 illustrates a bearing with a running surface defect.

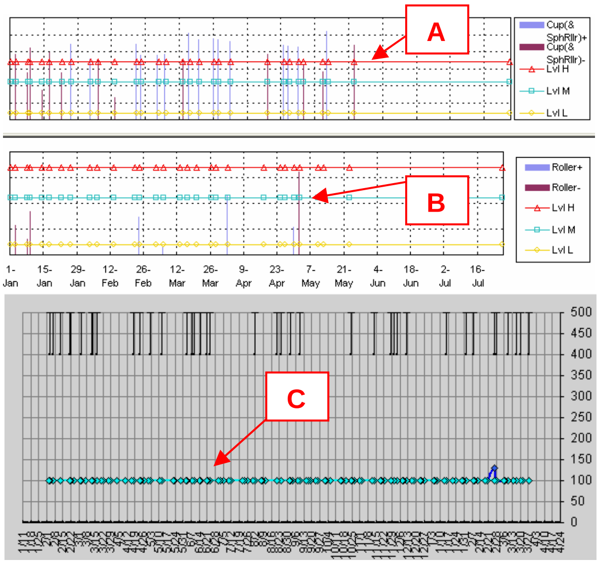


***Figure 14: Bearing Running Surface Defect***

The WCM plot (lower) shows no wheel impacts were found for the vehicle over a long history (C). The bearing defect grew gradually over time, which illustrates the sensitivity and reproducibility of the RailBAM method.

The fault signature suggested a High level cup and spherical roller bearing fault which had appeared before January and continued through May. The upper plot shows the acoustic data exceeded the red (High) zone during several passes (A). There is little trace of a roller defect (middle plot; B) and no evidence of looseness and fretting (not shown), although by May the roller bearing fault has approached the High damage level and action is required.

Another mode for a failed wheel bearing is shown in Figure 15. For this vehicle the WCM measured a wheel defect, with trending starting (A) on about April 5. RailBAM began to trend acoustic wheel sounds (B) by May 21. As indicated, the time courses for the bearing and wheel impact plots are different. The wheel impact measured approximately 200 kN by May 24. There was no signature for running surface (cup, cone, roller) defects for the bearing (not shown) but on May 14th a serious high level looseness and fretting trend started (C) and this continued for 10 weeks at a consistent and High level. Since a TBOGI and WheelSpec were not installed at this site it is not possible to determine whether the wheel impact caused a geometry or wheel profile defect (or vice versa). The bearing damage was most likely initiated by impact forces acting through the wheel on the bearing structure.

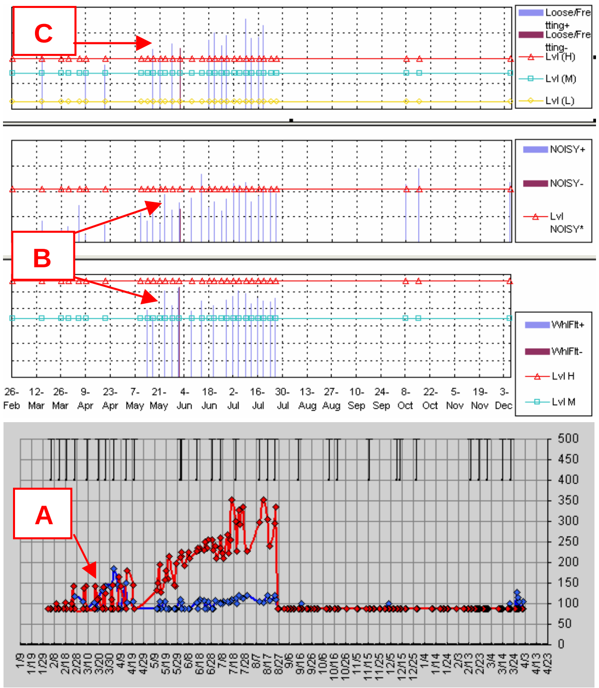


*Figure 15: Wheel Damage Preceding Bearing Failure*

Certain bearing types might be more susceptible to this form of damage. This is only one example from an emerging repetitive pattern that the Alliance is following closely.

We note that there is a greater percentage of bearing faults in otherwise perfect wheelsets where these faults may have arisen from damaged seals, water ingress, poor assembly and/or handling (see Figure 14 and upper portion of Figure 6).

## False Economy

There are concerns in the industry regarding “premature” replacement or repair of failing components (wheels, bearings, bogies, etc.). The Alliance believes this practice needs to be critically examined by railroads. VIPAC is trending various types of bearings and defects and is working closely with vehicle owners to evaluate which fault types and fault levels can be left in service to maximise useable lifespan, without inducing collateral damage. On the other hand, the cost of waiting to repair identified wheel and geometry damage is significant. There is little “residual value” in a defective wheel left in service for a significant time after it has been flagged. Far more material must be machined off defective wheels left in service, shortening their useful effective lifespan. As has been found in numerous instances, once rolling stock faults are found, they do not improve without corrective measures (i.e. service).. For example, leaving a defective wheel in service once a reproducible fault has been shown inevitably leads to more serious damage to that wheel, to wheels on adjacent axles and to initiation of damage in other components.

A scenario observed repeatedly with the Wheel Condition Monitor and RailBAM is as follows. A small defect appears in a wheel and it gradually grows over time. Left in service as it worsens, the adjacent wheelset then shows a growing defect (Figures 12 and 13). If left further, wheels on an adjacent axle begin to deteriorate. It is hypothesized at this time that the worsening wheel defects are causing vehicle tracking errors and subsequent wheel profile damage. Early maintenance of a modestly damaged wheel can prevent deeper and more costly repair.

Another common observation is that wheel defects left running in a fleet can lead to bearing damage. A typical example is shown in Figure 16. A wheel with a small defect, which was far below typical “exception alarms” (A), showed a steady worsening over time. Within four to eight weeks a bearing fault (B) was detected. The bearing’s health deteriorated over time, leading to ultimate failure.

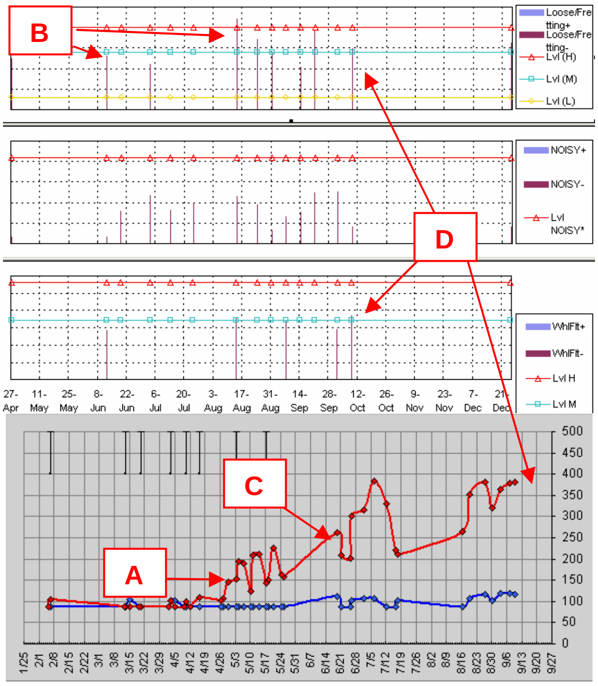


*Figure 16: Wheel Damage Leading to Bearing Failure and Derailment*

In this case the authors reviewed the data after this specific vehicle derailed and concluded a small skid likely occurred due to faulty loading of the vehicle. The WCM showed that the skid grew at a moderate rate. By the time it measured approximately 200 kN (C), which is far below typical alarm levels, the damage had been done to the wheel and to the bearing. The damaged wheel initiated looseness and fretting (B) in the bearing on the same axle. The bearing deteriorated over three months and it ultimately failed at speed (D). The time frames in practice are somewhat variable but the result is consistent. Once a fault has been found, leaving that component in service leads to further and more extensive damage. In this example the TBOGI and WheelSpec were not installed on the rail line and data are not available to combine with the wheel and bearing detector results. The authors believe that wheel profile damage and vehicle geometry changes typically appear to varying degrees in scenarios like the one discussed above, hastening damage growth, particularly in certain bearing types. Ongoing research will test this hypothesis.

## 2.5 Geometry → Bearing → Wheel Surface

An example of multiple defects that reinforces the model presented in Figure 6 is shown in Figure 17.

RailBAM trended acoustic wheel "noise" (A) most likely emanating from a wheel (flanging?) before January 1. This noise continued and grew steadily through July. Looseness and fretting (B) reached a high level by early March, coinciding with the appearance of wheel impacts (C). The looseness and fretting signature grew through July (B), exceeding the "High" alarm level.

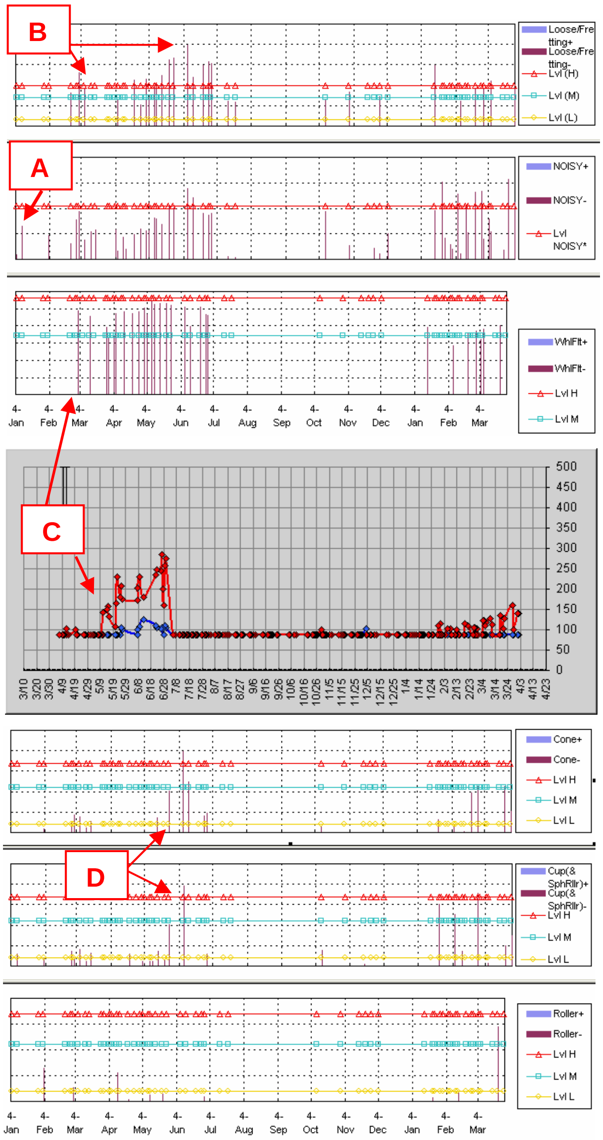


*Figure 17 : Complex Defect Progression*

As the wheel impact reached 200 kN in May, unconfirmed bearing rolling surface defects (cone and cup) could have been initiated (D). This vehicle was repaired in early July and all detector readings dropped to nominal levels.

The time course of defect appearance suggests a potential process:

- acoustic "noise" signatures imply a wheel flanging or geometry defect was the first event
- within 2 months the wheel surface was damaged and impacts were measured
- simultaneous with the wheel surface damage, axial loads from the presumed geometry issue had caused looseness and fretting in the bearing
- the damage levels grew

- the bearing running surface might have been damaged

What is highly significant is the course of events after the vehicle returned to service. Within seven months the entire process repeated with an almost identical time course and sequence. A conclusion is that the root cause of this vehicle's damage was not addressed during maintenance. If a problem with the truck's frame, geometry and/or steering were not corrected in July, that root defect likely seeded new damage in the replaced components. Therefore it is essential for maintenance depots to understand the nature of emerging defects so that proper repair can be carried out to effectively prevent expensive ongoing cycles of damage and risk. A TBOGI instrument at this location would have confirmed a geometry problem. And a WheelSpec would have pinpointed a wheel profile abnormality. The use of combined data from complementary and sensitive wayside monitors is a powerful tool for evaluating damage and seeking root causes of vehicle defects.

## 3. SUMMARY

Many factors besides initiation of novel truck damage need to be carefully considered when flagged defective components are left in service:

- Risk management is a constant concern in a litigious environment. Improving the health of a fleet by predictive maintenance reduces risk of equipment failure at speed.
- If equipment reaches alarm levels on line, the expense of traffic delays is considerable and the cost of preparing vehicles for safe transport to maintenance depots at a later date is high. The overall cost of vehicle repair is several-fold higher if failures occur on track. A recent paper presented to the Transportation Research Board in January 2004 by Randolph Resor and Allan Zarembski (Zeta-Tech, Associates, Inc.; "Factors Determining the Economics of Wayside Defect Detectors") documents this phenomenon. A wheel or bearing repair that causes an alarm that requires cut-out in the network costs approximately six- to eight-fold as much to effect as a repair performed at a depot through predictive maintenance.
- Wheel impacts, aberrant wheel profiles, bearing damage and/or poor vehicle tracking geometry lead to environmental noise and to increased fuel consumption.
- The positive feedback nature of the cycle of damage discussed above leads to escalating repair costs the longer that defective vehicles are left in circulation in the network.

Predictive rolling stock condition monitoring helps to minimise these concerns.

The Wayside Monitoring Alliance continues to refine the detectors discussed here. As more detectors are co-located, it is anticipated that the working model in Figure 6 will be refined. Installation of all four Alliance detectors in one location, a "Supersite", will provide reinforcing data that will enable more accurate modelling. Relationships between components will be better defined and hypotheses will be critically evaluated.

A development of the cooperation between the Alliance members is the belief that the rail industry should consider the implications of not embracing predictive monitoring. Existing policies appear to concentrate on gross alarms (Interchange Rules) and on forces acting on the rails and infrastructure. The assumption that rolling stock defects below current alarm thresholds are not economically significant to the rolling stock owner must be reconsidered now that technologies are available to quantify the forces and effects of rolling stock defects.