MONITORING AND MANAGING WHEEL CONDITION AND LOADING

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KEYWORDS

Rail, Wheel, Defect, Weighbridge

INTRODUCTION

Damaged wheels, hot bearings and bad loading practices are increasingly recognized as major contributors to the hazards and costs of the rail industry.

To improve both safety and economy, rail operators need vehicle condition data. A combination of wheel, bearing and load monitoring integrated by an effective database application can present the necessary information in a way that can be used productively.

Teknis has developed a system that provides accurate in-motion weighing and comprehensive analysis of load distribution plus defect detection and classification at wheel, bogie, wagon and train levels.

Teknis' Wheel Impact Load Detector (WILD) is designed to allow track & structure owners to monitor the vehicles running on their rails and rolling stock owners to optimize their maintenance scheduling. The system is low-cost, quick to install and maintain and requires no modification to the track.

This paper presents an overview of the technology and operational results reported by National Rail.

SYSTEM OVERVIEW

The basic components of the WILD system are the track mounted sensor array, on-site processing rack (CSU) and control PC.

The WILD system is modular. All configurations use the same software. The system dynamically senses the configuration so increased capability can be added by plugging in the appropriate hardware. Power can be AC or DC (including solar). All sensor units perform a range of self-test functions and return status in real-time to the control PC.

Sensors are mounted in pairs, one on each rail, between the sleepers. Depending on requirements a WILD array may contain:

- 10 -12 Accelerometers
- 4 -12 Load Gauges
- 2 - 4 Temperature Sensors
- 4 Wheel Flange Detectors
- Automatic Vehicle Identification Tag Reader
- Hot-Box/Hot-Wheel Detector
- Out-of-Gauge/Dragging-Equipment Detector
- Lateral Tracking Sensors

Accelerometers and load gauges measure impact and axle load respectively. Temperature sensors measure rail temperature. The wheel flange detectors sense the direction and speed of the train passing over the array. The AVI tag reader allows defects and data to be associated with particular vehicles, independent of consist.

Lateral tracking sensors quantify sideways movement of wheelsets to detect problems such as faulty side bearers and 'warped' bogies.

Hot-box/hot-wheel detectors use thermal data to target faulty bearings and brakes. Out-of-gauge/dragging-equipment detectors look for shifted or badly arranged loads and other objects that project outside of the nominal cross-section of railway vehicles. WILD can integrate the output from these sensors via a direct interface module at the CSU or through networked data files at the control PC.

Defect measurement and classification are independent of speed and load. This makes artificial normalization techniques such as 'Impact Factor' redundant.

Load measurement comes in two levels. Level 1 uses 4 load gauges and provides measurement accuracy of +/-5%[8]. Level 2 load measurement uses 12 load gauges to give +/-1%[8]. All load measurement is independent of speed up to 130km/h[8].

The upper speed limit is set at 130km/h because there has, as yet, been no opportunity to test at higher speeds. The system itself is capable of operating at speeds in excess of 250km/h[11].

SENSOR ARRAY AND PROCESSING RACK

Standard defect and load sensors are placed between the sleepers in 6 pairs as shown in Figure 1. The wheel flange detectors are then positioned at either end of the array. This makes 10 sleeper spans, or about 7 meters, for the full array. This excludes the AVI, lateral, hot-box and out-of-gauge sensors which tend to be located adjacent to the array. Sensors are clamped to the track using specialized mounting blocks designed for ease of installation and maintenance. This provides solid connection to the rail without drilling, welding, or as required in some cases, replacing entire sections of track. This method of attachment has proven absolutely reliable.

There have been no signs of any loosening or slippage shown by any mounting block on any WILD array over the full operational life of all existing sites.

The CSU contains interface boards for each group of sensors in a standard 19" rack. Signals from the array are processed by the CSU. Combined with the further processing in the database, this removes variations due to track modulus, wagon suspension, speed and static load.

Data is organized into messages, then sent to the control PC. The CSU and control PC use a secure HDLC link to transfer data, operator commands and system status. The communications medium can be dialup PSTN, leased line or radio link. If required, data can also be transferred via LAN, WAN, intranet or Internet. In the event of communications failure the CSU has sufficient battery backed memory to store full data on 64,000 wheels for up to 3 months[11].

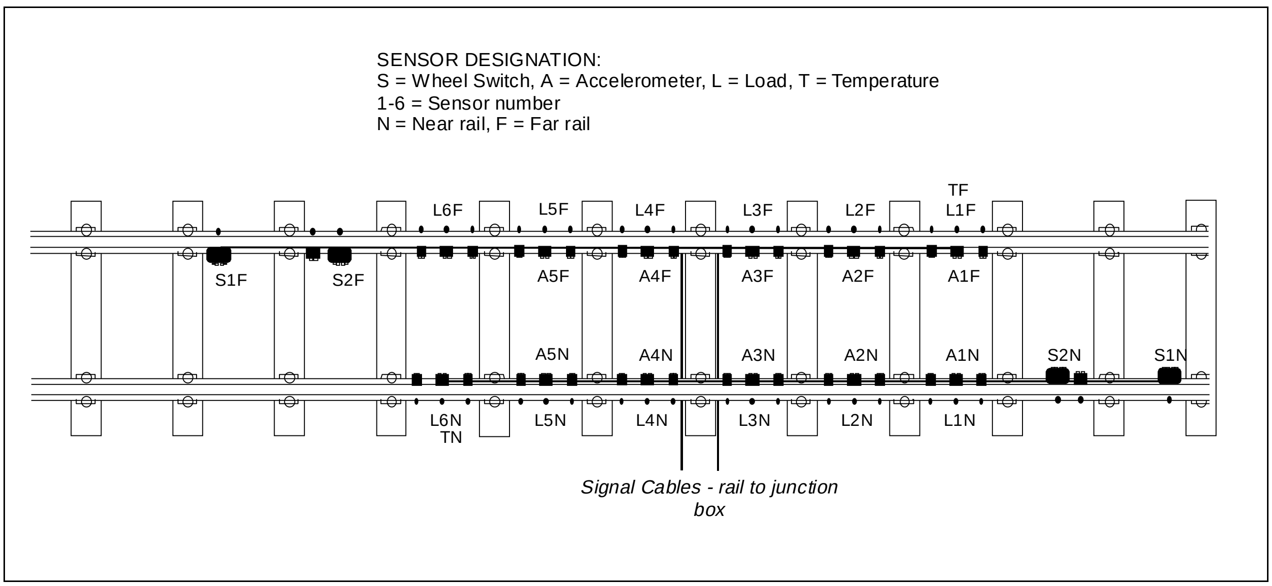


FIGURE 1: Schematic of Array Sensor Positions

CONTROL PC AND DATABASE

Data sent to the control PC is kept in the WILDDB database application. This can be networked to other PCs to automatically forward selected data. In order to cater for the wide variety of requirements characteristic of railway operations WILDDB has been designed to allow extensive user-configuration. Once data for a train has been received it is processed collectively to classify defects and analyze loading patterns. Consequent actions, such as automatically printing a report or sounding an alarm, are user-definable. Processing algorithms are fully parameterized so that changes can be made without rewriting any software. All data can be reprocessed at a later time to verify improved algorithms and/or alter parameters.

None of the original information is lost or changed at any stage of the processing. This data can be reprocessed in part or whole at a later date. If any aspect of the analysis is enhanced or if fine-tuning of the system is desired, it is not necessary to wait for a valid statistical sample of trains in order to verify improvements.

LOAD MEASUREMENT AND PATTERN ANALYSIS

Figure 2 shows measurements of total train mass. Figure 3 shows fully loaded, 50% loaded and empty (TARE) wagon masses. The data is taken from a calibration trial of a new WILD system with Level 1 (+/-5% rated accuracy) load measurement[1]. The maximum line speed for the site was 80km/h. The reference train mass was given as 412.1 tonne. The mean of the data below is 412.3

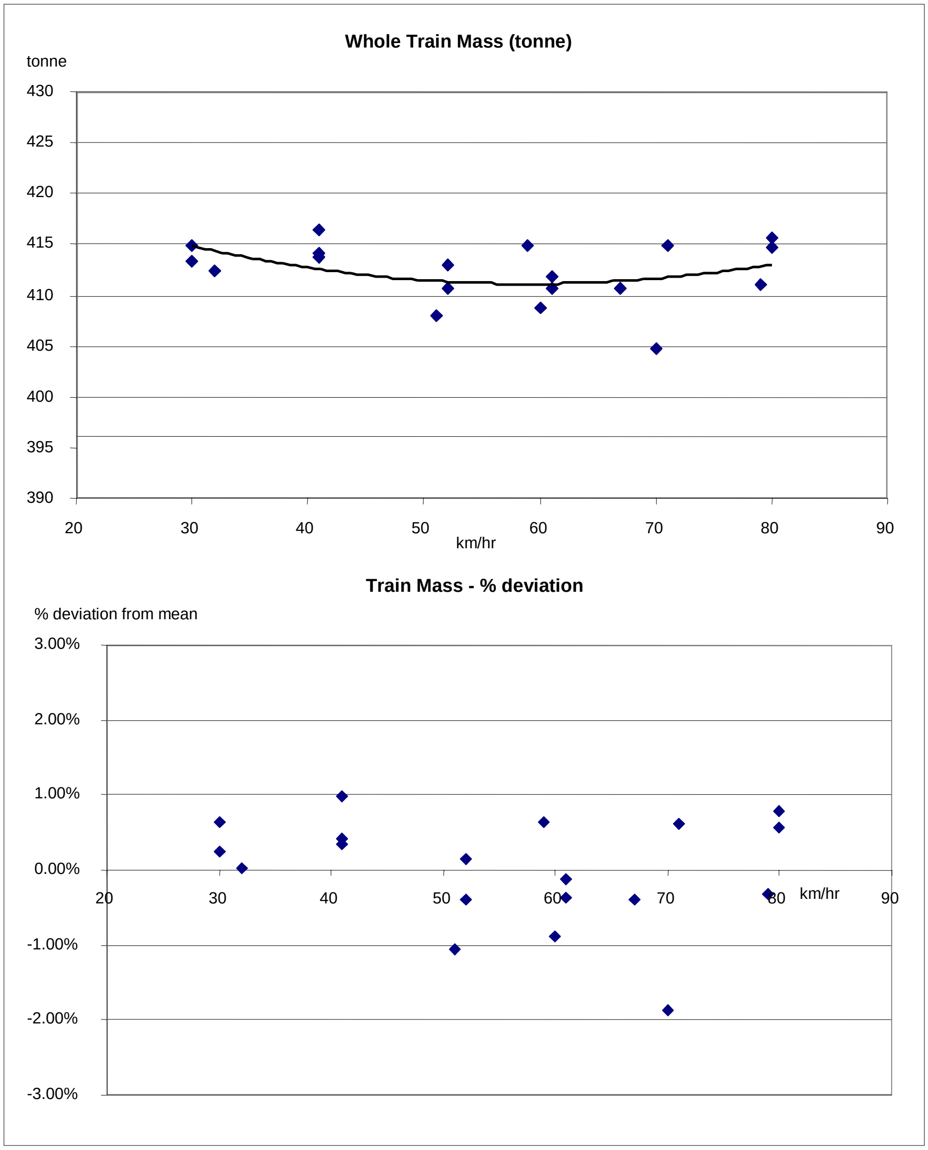
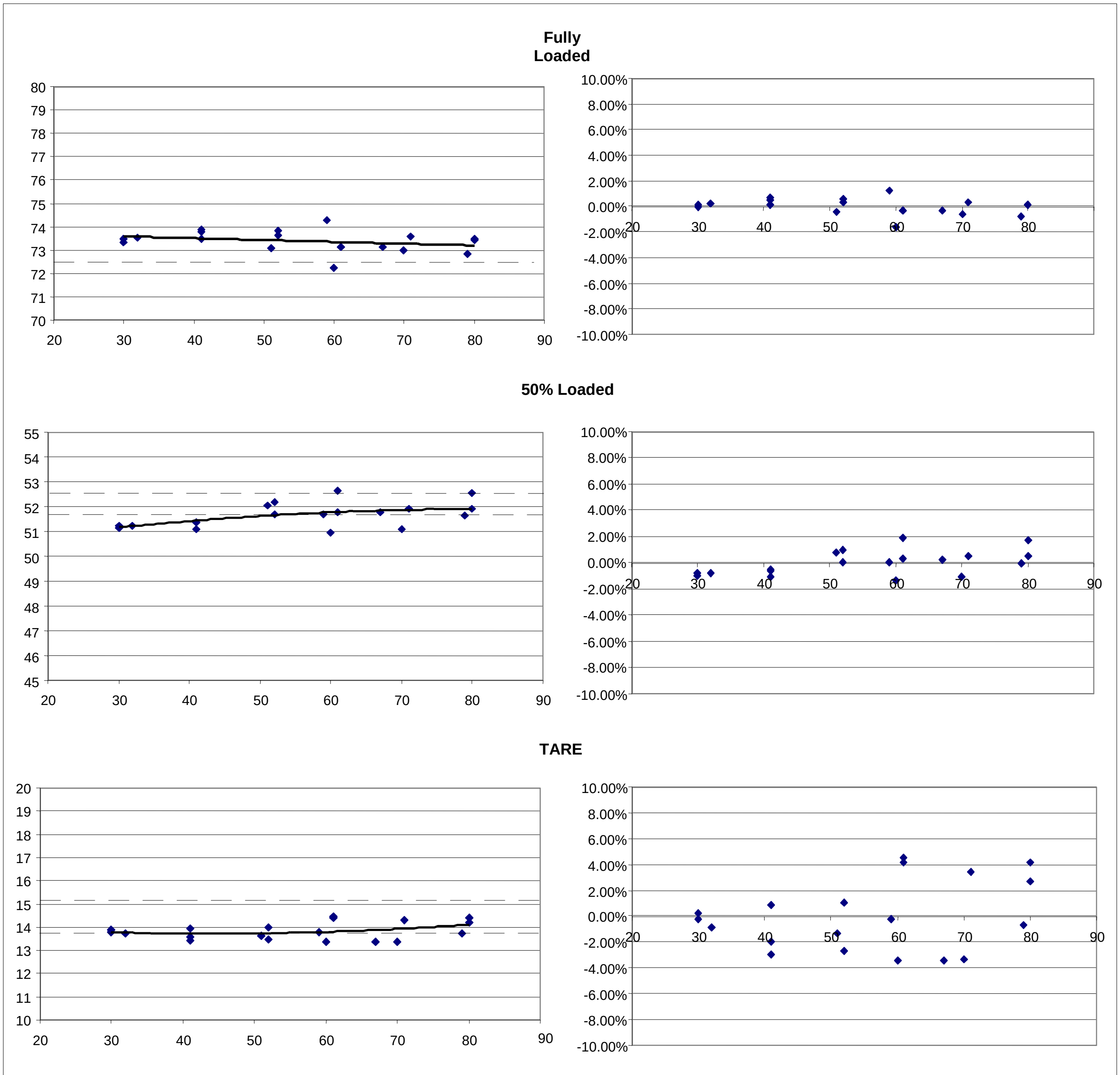


FIGURE 2: Total train mass and percentage deviation with Level 1 load measurement

The following series of graphs show data for three load reference vehicles. The graphs on the left show mass as measured verses speed. Those on the right show deviation from measured mean as a percentage. The x axis on all graphs is km/h. Dotted lines represent weights obtained from a quasi-static reference weigh-bridge.



<u>FIGURE 3: Wagon mass and percentage deviation for fully loaded, half loaded and empty reference wagons with Level 1 load measurement</u>

The deviation on the TARE vehicle, when specified as a percentage, is noticeably greater. However, the deviation in terms of tonne is comparable and better than the variance of the reference weigh-bridge. Table 1 lists mass and deviation data for these test runs. At the bottom of the table are summary measures including standard deviation, mean, minimum, maximum, the reference value and the mean difference from the reference value. All values are measured in tonnes.

km/hr	Full	50%	TARE
30	73.3	51.1	13.8
30	73.5	51.2	13.9
32	73.6	51.2	13.7
41	73.5	51.1	14.0
41	73.9	51.3	13.4
41	73.8	51.4	13.6
51	73.1	52.0	13.7
52	73.8	51.7	13.5
52	73.6	52.2	14.0
59	74.3	51.7	13.8
60	72.2	51.0	13.4
61	73.1	51.8	14.5
61	73.1	52.6	14.4
67	73.2	51.8	13.4
70	73.0	51.1	13.4
71	73.6	51.9	14.3
79	72.8	51.6	13.7
80	73.5	51.9	14.4
80	73.5	52.5	14.2
mean	**73.4**	**51.6**	**13.8**
std dev	0.45	0.49	0.38
min	72.3	51.0	13.4
max	74.3	52.6	14.5
reference	**72.4**	**52.3**	**14.5**
delta mean	1.0	-0.7	-0.7

TABLE 1: Level 1 load measurement data for calibration trials

LOAD ACCURACY

Results of these trials showed typical vehicles with nominal wheels displayed +/-2.5% variance over 25 tonne and +/-900 kg under 25 tonne[1].

As shown in Table 1, the standard deviation does not increase with load. The variability is not a function of mass or speed and system performance actually improves with load. In other words, variability can be defined as +/- kg instead of as a percentage. This translates into the following performance:

		Full	50%	TARE
	mean	73.4	51.6	13.8
	Std dev	0.45	0.49	0.38
1 Confidence Level				
95%	Low	72.5	50.6	13.1
	High	74.3	52.6	14.5
	+/- kg	882 kg	960 kg	745 kg
	+/- %	1.2%	1.9%	5.4%
98%	Low	72.4	50.5	12.9
	High	74.4	52.7	14.7
	+/- kg	1049 kg	1142 kg	885 kg
	+/- %	1.4%	2.2%	6.4%
99%	Low	72.2	50.3	12.8
	High	74.6	52.9	14.8
	+/- kg	1161 kg	1264 kg	980 kg
	+/- %	1.6%	2.4%	6.7%

1. *95 % level of confidence = mean mass as measured +/- 1.96 sigma*
2. *98 % level of confidence = mean mass as measured +/- 2.33 sigma*
3. *99 % level of confidence = mean mass as measured +/- 2.58 sigma*
4. *all figures are in tonne unless otherwise denoted*

TABLE 2: Level 1 load variance expressed in kg rather than percentage

Measuring the mass of axles that have significant defects decreases accuracy by a few percent. Figure 4 shows load data for vehicles with moderate-high level defects.

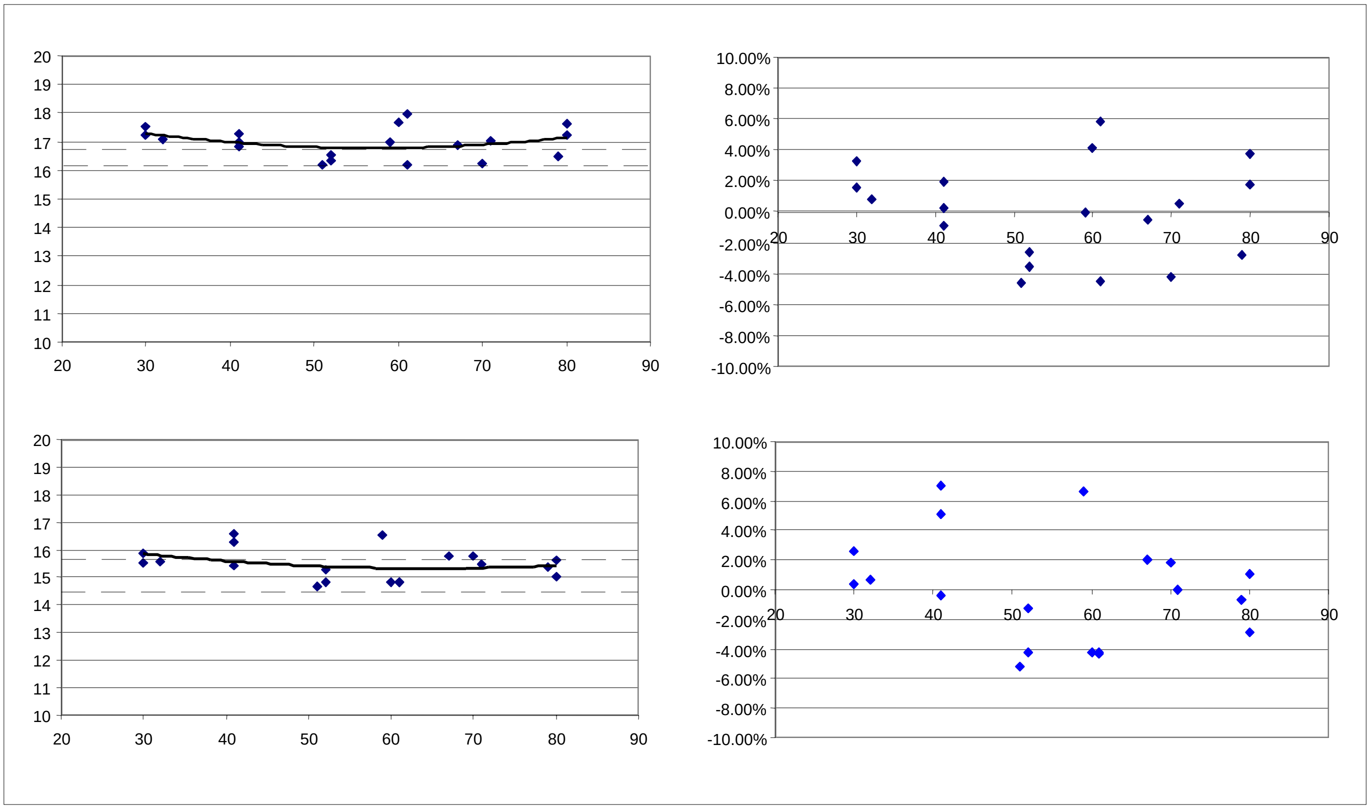


FIGURE 4: Level 1 load measurement on wagons with defective wheels

In addition to in-motion weighing, the WILD system analyzes load balance in wagons and load distribution over an entire train. This can be further refined to include overload limits based on wagon type or even individual wagons within the fleet that require special attention. Speed can also be factored in. For example, the system can be configured to automatically generate an alarm and print a report when a particular type of wagon with a certain type of bearing is detected with a combination of load and speed above certain limits. The system can also alarm on hazardous conditions such as empty vehicles within a heavy consist.

WHEEL DEFECT CHARACTERIZATION

WILD can detect and classify defects from a few millimeters in size up to large (>10cm) skids[10]. Standard defects such as skids, built-up treads, cracks and spalling can be differentiated and graded. The system is also capable of detecting long-period defects such as out-of-round wheels, sub-surface defects and collapsed wheel tread due to cracking[7, 10]. The system can discriminate multiple defects on the same wheel and can provide separate classifications and relative positions of each. Defect measurement is reported in terms of impact force in kiloNewtons (kN). While all raw data is stored, reporting tends to be on the basis of 'normalized' values that have had the effects of speed and load removed. Normalized magnitudes are repeatable to within +/-5%[10] independent of speed (30-130km/h) and load (empty up to 38tonne axle load).

The normalizing reference function is based on the smooth tread of a new or freshly machined wheel, fully loaded and traveling at 80km/h. It has been repeatedly shown that this process results in the consistent and repeatable grading of wheel defects[10, 15].

It is very important that the system reports the same wheel defect at the same level regardless of axle load. Otherwise a wagon with a defective wheel might pass over the site without incident when empty only to cause an alarm and require change-out when loaded.

Figure 5 shows both tabular and graphical representation of normalized data from multiple runs of the same defect at different load levels. This data was obtained during normal operations at a heavy-haul WILD site in Western Australia. Speed is effectively constant. The only variables are direction and load. Direction alternates for each successive data point and load varies from 22 tonne to 130 tonne. The left-hand graph plots impact against speed. The graph on the right shows the impact level at each run. This is a good example of a skid that is 'freshened' or renewed occasionally.

Below is a list of column headings for the table in Figure 5.

Car ID	-	AVI tag ID for vehicle
Car#	-	The position of the wagon in the consist
Dir	-	Direction of travel. User-defined designation.
Date	-	The date the train crossed the array
Time	-	The time the train crossed the array
km/h	-	The average train speed over the array in km/h
Load	-	Wagon mass in tonnes
Index	-	Estimated track damage potential of the defect
Axle1 kN – Axle4 kN	-	Normalized kN impact data for axles 1 to 4

Carr ID	Carr #	Dir	Date	Time	km/h	Load	Index	Axle 1 kN	Axle 2 kN	Axle 3 kN	Axle 4 kN
551	102	N	25-Aug	0:54	73	22	24			238	
551	102	H	25-Aug	21:57	74	131	24			250	190
551	102	N	27-Aug	10:35	71	21	18			246	
551	102	H	28-Aug	1:22	73	134	23			262	
551	102	N	28-Aug	12:05	73	21	20			267	
551	102	H	29-Aug	5:40	73	129	22			257	
551	102	N	29-Aug	12:46	75	20	17			246	
551	102	H	31-Aug	10:54	73	126	23			242	
551	103	N	31-Aug	18:48	72	21	20			242	198
551	103	H	01-Sep	9:21	74	130	23			234	
551	103	N	01-Sep	17:30	73	22	20			234	
551	103	H	02-Sep	8:28	74	133	24			248	
551	103	N	02-Sep	18:20	75	23	20			245	
551	103	H	03-Sep	8:49	67	129	19			234	
551	103	N	03-Sep	18:36	74	22	19			234	
551	103	H	04-Sep	8:48	73	134	22			246	190
551	103	N	04-Sep	20:13	76	21	16			256	
551	22	H	05-Sep	14:34	71	127	25			240	
551	23	N	06-Sep	1:57	73	22	16			238	
551	23	H	06-Sep	16:44	71	130	17			230	194
551	102	N	08-Sep	7:21	72	21	24			242	
551	102	H	09-Sep	6:10	71	132	21			230	

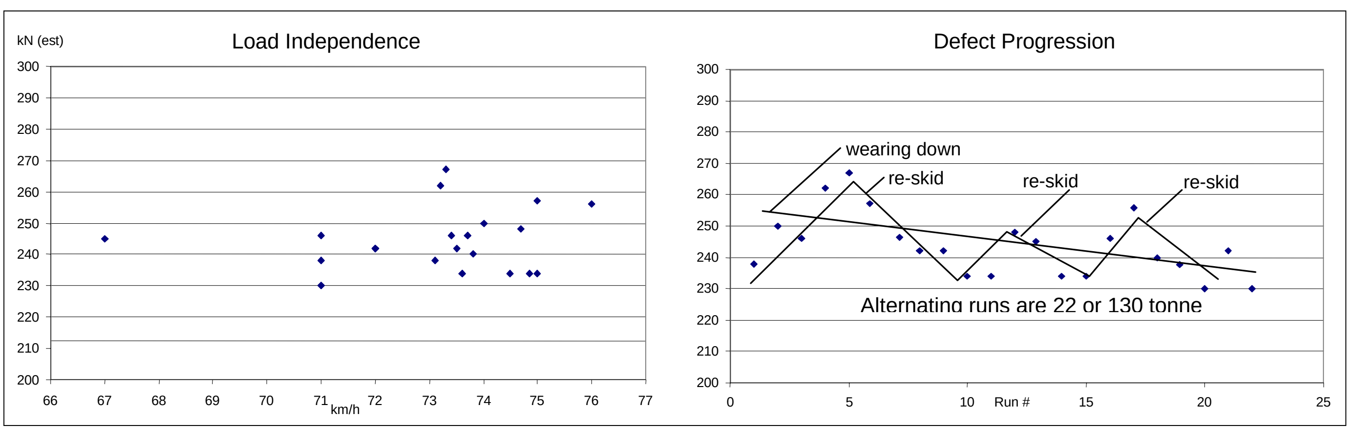


FIGURE 5: Defect data showing load independence and skid progression

Figure 6 shows normalized data from a 75mm flat at different speeds. The data was obtained during standard calibration trials run as part of the commissioning of a new WILD system.

FIGURE 6: Impact data from 75 mm flat

In addition to the basic defect classification, the severity of a WILD alarm can take into account other factors such as combined number/severity of defects on any/all wheels in a wagon, vehicle type, tag or the owner of the train.

DEFECT PROGRESSION AND VARIABILITY

Detection of wheel defects requires that the defect be running on the rail/wheel contact surface when the wheel crosses the array. A defect that is very small or not on the normal running area of the wheel can sometimes evade detection.

Variation in readings from one pass to the next is usually caused by:

1. Normal defect progression or creation of a new defect
2. Sharp edged, very small defects near the edge of the normal rail/wheel contact area
3. Particularly narrow rail/wheel contact area
4. Defects with a ‘resonant’ speed. At this speed, usually well over 80km/h, wheel/rail contact at the defect is momentarily zero. In this situation the data is effected by the way the wheel ‘lands’.
5. Reversal of wheel rotation, when a vehicle is turned around or a train reverses over a WILD array. This becomes more apparent in highly complex or asymmetric defects.

WILD sites with vehicle tag identification have allowed study of long term trends in defect progression. These suggest that:

- Spalls remain stable and constant but increase the chance of skid formation at that point on the wheel[10]
- Skids (or flats) periodically ‘freshen’ or sharpen, then wear at the edges, then sharpen again at the next heavy braking, etc (see Figure 5). Such flat spots tend to skid more easily. This is especially apparent on locomotives. Skids can also degenerate into long period defects through sub-surface heat damage[7, 9, 13, 14]
- Long-period defects are stable if caused by machining but tend to increase steadily when formed under a skid[7, 9, 13, 14] (see above)
- Cracks increase exponentially[7]

DEFECT ISOLATION – WHEELS ADJACENT TO IMPACTS

Association of defects with specific wheels is very strong. Severe impacts on one wheel are isolated to one or two zones on a wheel (wheels are divided into 5 zones). However, such high-impact cases can cause a small amount of ‘bleed through’ to other wheels in the same bogie. Figure 7 shows all zone readings for the wheel adjacent to (and in the same bogie with) a wheel exhibiting a severe impact.

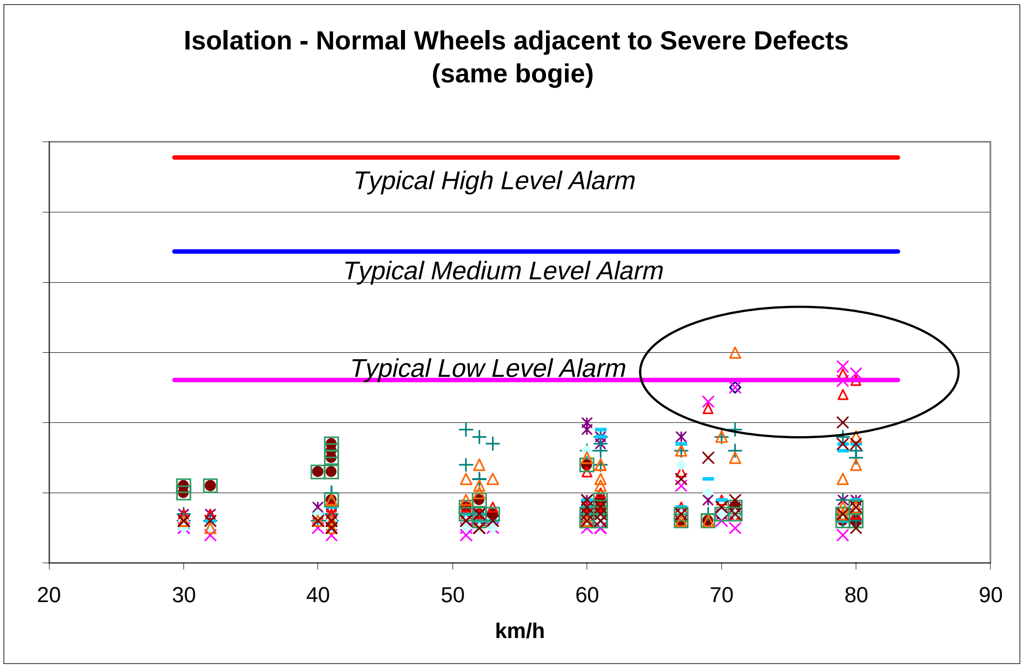


FIGURE 7: Examination of impact levels registered on one wheel from a high impact on the adjacent wheel in the same bogie

Note that there are some readings, which are elevated to the point where they will register low level alarms. This is not considered to be a problem because the adjacent wheel has already caused a high level alarm on the train.

OTHER DATA

The system provides other data that can be of particular interest to operators. Rail and ambient temperatures are measured for each train to provide additional environmental and structure related data.

Speed measurement is accurate to 0.3%[1, 10]. Inter-bogie spacing is measured in millimeters and total train length can be measured to within 0.1%[1,10]. Figure 8 shows trial data for the measurement of a locomotive wheelbase. Figure 9 shows total train length measured while the train coasted across the site and then again when the train was accelerating in reverse (i.e. under compression). In some operations train length must be below a specified maximum for certain turn-outs or unloaders. The WILD system can be configured to alarm on trains exceeding a user-specified length restriction.

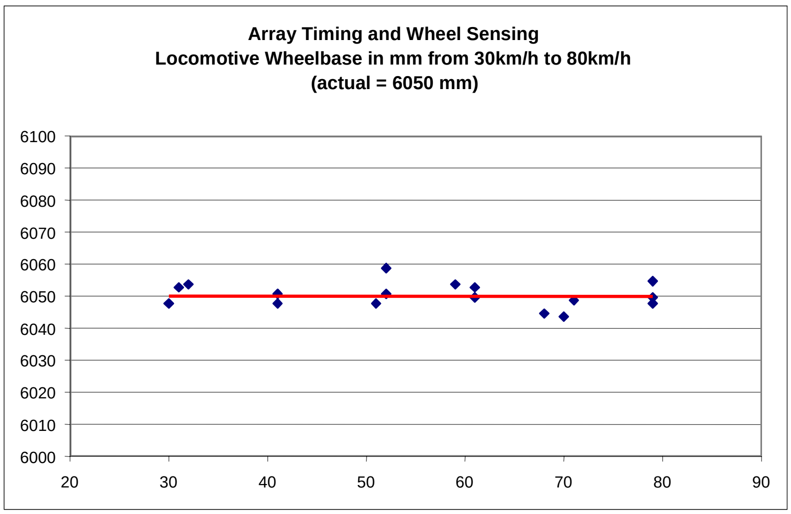


FIGURE 8: Axle spacing measurements for a locomotive wheelbase

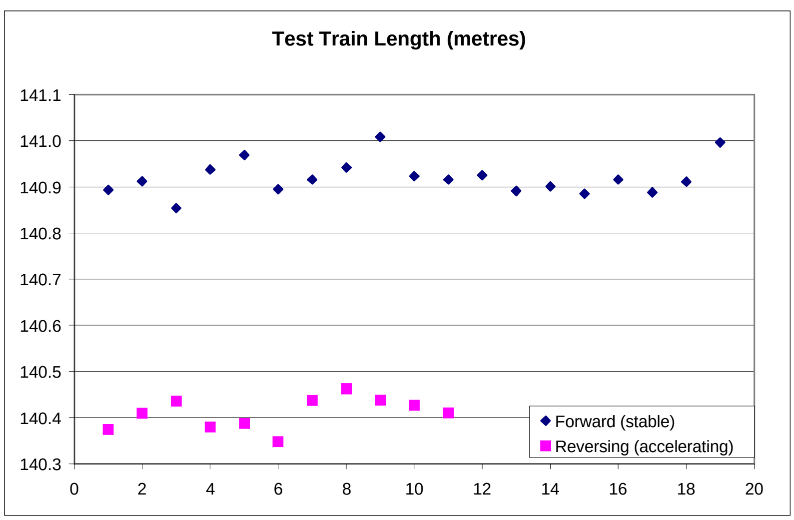


FIGURE 9: Total train length during coasting and compression

SYSTEM PERFORMANCE ISSUES - ENVIRONMENTAL NOISE

Railway lines are not noted for being benign environments, particularly from an electronics point of view. Electromagnetic noise, up to and including lightning strikes, is a common fact of life.

The connection from the on-track array to the processing rack passes through a bulkhead of transorbs and gas arrestors to protect against transient surges. WILD installations have been functioning for several years in some of the worst lightning areas in Australia.

Also important is the ability to function with high levels of non-destructive day-to-day noise. All array sensors are separately grounded back to a single-point earth that serves as the reference for all equipment.

One installation in particular serves as a proving ground. Located in tropical Queensland, the CSU processor rack sits between two 50,000Volt step-down transformers. In addition to overhead electrification the rail carries a return current fluctuating between 0 and 300 Amps depending on train location and traction. Figure 9 shows both raw and filtered wheel switch signals from this site.

FIGURE 9: Raw and filtered wheelswitch signals

NATIONAL RAIL - SYSTEM AS INSTALLED

WILD systems are in use around Australia: in New South Wales, Queensland, Western Australia and South Australia.

National Rail (NR) is an Australian rail carrier. The NR WILD system is located near Port Germein, approximately 300km north of Adelaide, South Australia. In addition to the basic defect sensors the system includes full Level2 load measurement, AVI tag reader and lateral sensor array. Figure 10 shows a photo of the site.

The CSU processor rack is housed in a standard equipment hut with two PSTN phone lines. One line is used by the WILD to automatically dial out to the control PC on detection of a train. The other line provides a dial-in interface to the maintenance PC. This PC is permanently connected to the CSU as a secondary interface to the WILD.

Due to data privacy issues among the various operators that run traffic over the site, the control PC is housed at Teknis. Once the ownership of a train is established the control PC dials out to download the data to the specified recipient (either National Rail or Australian Rail Track Corporation).

FIGURE 10: Photo of National Rail WILD site

DESCRIPTION OF TRIALS

Calibration trials are performed as part of commissioning for every WILD site. Known consists, specially assembled to provide a mixture of good wheels, defective wheels and vehicle loads are run over the WILD array at speeds from 30 up to 130km/h (or the maximum line speed). This provides specific data concerning the structural response so that normalizing reference functions can be fine tuned.

OPERATIONAL METHODS

As with other systems, the effectiveness of the WILD depends on two things; what it can do and how it is used.

The National Rail fleet is made up of approximately 4,500 vehicles with a total of approximately 27,000 wheelsets. NR purchased a WILD system in August 1998. Since then they have worked closely with Teknis in order to gain the most out of the system.

As a joint effort Teknis and National Rail have undertaken an ongoing research and development program, looking at both the technical and operational aspects of the system.

The main areas of study to date are:

1. Wheel defects and their effect on bearings
2. Analysis of lateral tracking data to discriminate between types of tracking defects such as misaligned (or 'warped') bogies and faulty side bearers.

Other areas of interest include:

1. Wheel defects and loading related to safety
2. Affect of wheel and bearing defects on fuel consumption
3. Evaluating wheel defects and lateral ‘hunting’ as causes of load shifting
4. Average distance traveled between occurrence of a wheel defect and failure of the bearing
5. Relationship between wheel defect severity and average distance to failure (as described above)
6. The characteristics of different bearing types in response to similar wheel defects

The most important issues emphasized by National Rail have been:

1. Identification of vehicles by AVI tag enabling defect tracking and trend analysis over extended periods.
2. The ability to configure the system to raise alarms on serious defects that, by nature, do not have significant impact levels.
3. Separating vehicle data from different owners to safeguard confidentiality.
4. The ability to reprocess all original data in a separate database and so not risk losing current settings or results.
5. Reliability, accuracy and robustness.

In the first month after commissioning of the WILD, National Rail implemented an operational structure for managing the system. The current structure, refined over the 8 months since, is shown in Figure 11. The results of this approach are described in the following sections.

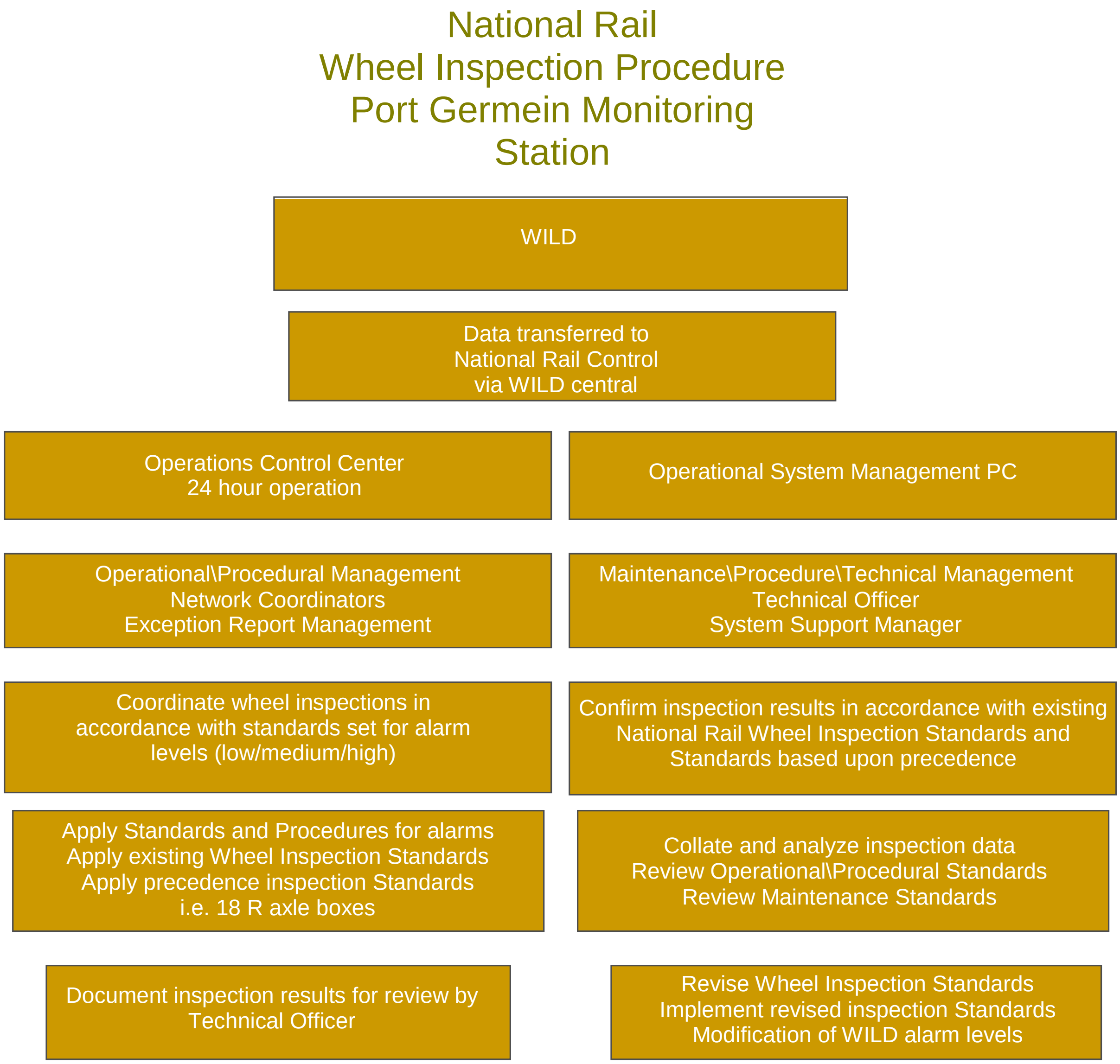


FIGURE 11: National Rail - WILD system management schematic

METHODS OF EVALUATION

WILD is a preventative system. Evaluating such a system, whose effect is the absence of something (e.g. bearing failures), is inherently less direct than evaluating a system that directly produces an output.

To quantify the effectiveness of the NR WILD we looked at:

1. Number of bearing failures before and after the system became operational.
2. Number of defects reported by the system
3. Comparison of reported defects with inspection results and proportion of defects so reported that result in a wheelset change-out.

NATIONAL RAIL - OPERATIONAL RESULTS

National Rail maintains a continual regimen of wheel inspection using accepted, industry standard techniques. This accounts for most serious wheel defects. However, the inherent limitations of visual and aural (or ‘roll-by’) inspections are well known.

Before the WILD system came into operational use National Rail had a highly seasonal bearing failure rate. In the cooler months (May to September) the rate would peak to 1 or more per week[4, 6]. During summer, the frequency was far lower. Averaged over an entire year, there would be approximately 2 bearing failures per month. Of these, approximately 75% were associated with 18R type bearings. It was thought that the great majority of these failures could be attributed to one of two causes; loss of bearing grease, or damage to bearings due to wheel defects. To combat the first, NR introduced a concerted program of preventative maintenance involving re-greasing all bearings. This began in June of 1998 and was completed in the first half of September. At the same time (August) the WILD system was commissioned. In the 8 months since there have been a total of 3 failures. All 3 were detected by WILD. As described later, these failures came about due to procedural issues characteristic of any new operation, rather than technical deficiency. Out of all defects detected by the system, the only three that were not reported caused derailments within weeks of first alarm. This, along with the number of defects reported, strongly suggests that re-greasing did not target the major cause of bearing failures.

The total number of incidents each month, reported by the WILD system, are shown in Figure 12. An ‘incident’ in this context represents a medium or high level alarm. In summary this graph represents a real reduction in serious defects of 90% over 6 months[4]. In January of this year the alarm criteria were changed to include lower level defects. This appears as a jump in the number of reported defects for February and March. There have been no defects reported by WILD that have been regarded as false alarms. All defects reported are inspected in accordance with current NR defect standards. These standards are, at present, in accordance with worlds best practice. National Rail plan to update these standards to take advantage of the new information generated through WILD. A reported defect that meets the NR inspection criteria for ‘condemnable’ is removed immediately. All high alarms, and about 35-40% of medium level alarms, fall into this category. Other wheels reported by WILD that do not conform to the standard are generally marked for continued observation to gather data on defect progression. Increasingly, the WILD data has been used to override the inspection results. Because of the relative newness of the system, this has only been done when it was felt that the defect presented a serious hazard even though it did not meet the standard for removal. In the case of 18R bearings the standard procedures have already been changed to adopt the WILD system as primary indication of a condemnable wheel defect[2, 3, 4] (see Table 4).

Table 3 is taken directly from an NR report[4]. It shows the comparison between defect data and visual inspection for the 23 wheelsets reported by WILD during September 1998, one month after the system was commissioned. Table 4 shows a similar excerpt, this time from January 1999. In many cases, the WILD defect classification matches closely with the observed defects. Where the defect data and inspection do not agree, the growing trend (as seen in Table 4) is for WILD to override the inspection results. This is due to the repeatability of the data from one pass to the next plus the fact that trains that produce alarms have been inspected and confirmed as OK only to derail soon afterward (see Table 5 and Figure 13). This strongly supports the system's ability to detect defects that cannot be detected by visual inspection methods.

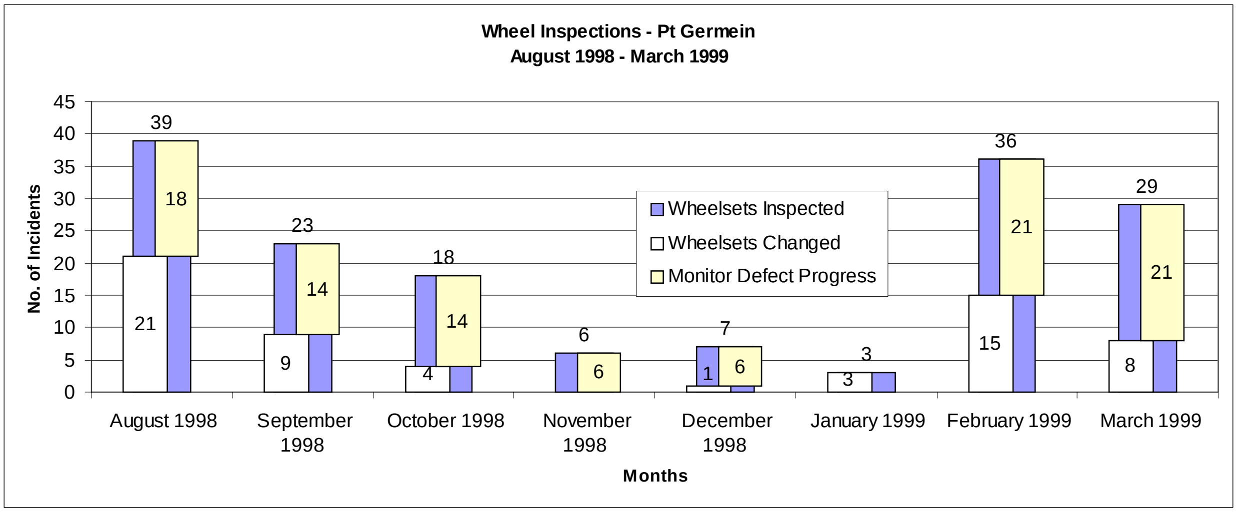


FIGURE 12: Defects reported and action taken for each month since commissioning

Defect Measurement and Classification	Action Taken	Description from examination
371kN Spall	Change	Wheelset impact for 18 R box over 300kN, change out wheelset. Wheel pitting approx. 3 mm in depth thermal cracking approx. 30 mm in length propagating from pits.
321kN Skid	Change	Shift Diary item refers to wagon having handbrake released at Bowmans, wagon detached and reattached at AFT, handbrake most likely left on at this location. Extensive skidding on wheels.
270kN Skid	Monitor	Morandoo Flying Gang to monitor wheelset condition.
264kN Skid	Change	Inspection of wheelsets indicated wheels pitted to approx. 3mm and thermals to approx. 30 mm in length. Wagon to be deployed to maintenance for wheelset change.
350kN Spall	Change	AFT Maintainers inspected wagon and advised hole the size of 20 cent piece approx 2 - 3 mm in depth, relatively thin wheel, wheelset changed out.
264kN Skid	Monitor	AEI tag on 'B' end repaired, no defects observed on wheelset, monitor wagon.
323kN Spall	Change	Hole in tread 80 mm x 40 mm 1.5 - 2 mm in depth. Network Coordinators notified requested to remarshall wagon to front of consist as safety precaution, red card on arrival into Sydney for wheelset change.
293kN Skid.	Change	Examination indicated extensive skidding over half wheel diameter, wagon carded to Whyalla for wheelset change.
315kN Skid	Monitor	G. Thorogood to determine condition of wheelset and advise course of action taken. Data to be obtained for loco's, table to possibly introduced to WILD system for loco alarm levels.
275kN Skid	Change	Wagon due for PM, deploy to maintenance for PM and wheelset change.
267kN Skid	Change	Wagon identified as being in the o\due category >50 000 km for PM, B. Benbow advised to remove wagon for wheelset change and PM.
285kN Skid	Monitor	Chullora Maintainers arranged wagon to be inspected by TO's at Cooks River, wagon deployed to Melbourne for inspection by WMC Flying Gang, no defect located on wagon, monitor wagon.
277kN Skid	Monitor	TX. Alice Springs to inspect wagon upon arrival.
285kN Skid	Monitor	Perth Maintainers advised to inspect wagon, inspection has indicated no fault with wheelsets on this wagon, monitor next time over site.
269 kN Skid	Monitor	Advised G. Thorogood, inspection to be arranged in Perth by Graham.
293kN Skid	Monitor	Advised TraileRail Perth to inspect wheelset on arrival into Perth and advise outcome of inspection.
266kN Skid	Monitor	Advised TraileRail Perth to inspect wheelset on arrival into Perth and advise outcome of inspection.
264 kN Skid	Monitor	AFT Maintainers to inspect on arrival into Adelaide, monitor over site to determine if magnitude of defect increasing.
264kN Skid	Monitor	Mick C to arrange inspection of wagon in Melbourne.
268kN Skid	Monitor	Crossing inspection indicated potential fault with consist, train speed reduced to 80 km\hr. Subsequent roll-by and visual inspections indicated no problem with wheelset. Monitor wheelset over site.
270kN Skid	Monitor	Wheel to be checked on arrival into ACR to confirm magnitude of defect on wheelset.
286kN Skid	Change	Wagon due PM, inspect Perth and confirm condition 'ok' to travel back to WMC for PM.
267kN Skid	Monitor	Wagon inspection arranged by Network Coordinators at Pt Augusta, wheel condition confirmed as 'ok'. Monitor next time over site.
315kN Skid	Monitor	Forwarded 'e' mail to T\Rail Perth to inspect bogie on arrival into Perth and advise condition of wheelset.
294kN Skid	Monitor	Forwarded 'e' mail to Maintainers Perth to inspect bogie on arrival into Perth and advise condition of wheelset.

TABLE 3: National Rail WILD inspection report - September 1998

Defect Measurement and Classification	Action Taken	Description from examination
382kN	Change	Wheelset changed on arrival into AFT due to 18 R box > 300 Kn. Two skids approx 50 mm in diameter noted and minor spalling. Wagon checked over site upon repair 16/1/99, 6AL7, wheel condition 'ok'.
277kN	Change	Perth Maintainers advise wheel displayed minimum spalling, no greater than ten cent piece. Wheelset changed due to high impact reading over site & 18 R box.
310kN	Change	Perth Maintainers to inspect\change wheelset also advise nature of wheel defect. Minimal visual spalling, normal inspection standards would not have changed wheelset.

TABLE 4: National Rail WILD inspection report - January 1999

Another NR report, this time from February 1999, is summarized as follows:

1. 36 wheelsets inspected, increased from 4 inspected in January due to reviewing inspection standards as a result of characteristics displayed (via WILD) by wheelset/hot-box failures at Tottenham and Port Augusta in early January (1999)
2. 15 (or 42%) of wheelsets inspected were replaced. Of these 12 were 18R bearings, 2 were 50t bearings and one was a 70t bearing
3. *Most, if not all, were not picked up during train examination*
4. Most were changed out in accordance with NR standards
5. All displayed similar impact characteristics

Point 3 from the summary above bears special mention. Regardless of the diligence of the train examiners, manual examinations, both aural and visual, are prone to letting through significant numbers of defective wheels. Some of the main reasons for this include:

1. The large number of wheels to be inspected necessitate a quick examination
2. Often wheels are partially obscured by brakes, bogie etc so that the examiners cannot clearly observe significant portions of the circumference
3. Some defect types cannot be seen when stationary nor heard when the train is moving at normal roll-by inspection speeds. This is especially true of sub-surface and long-period defects[10].
4. The severity of many defects is not proportional to the sound produced. Long-period defects especially, can hit the rail with extreme force while only dissipating a small fraction as sound[10].

LEARNING FROM FAILURES

As mentioned above there have been 3 instances where the data from the WILD system did not prevent a serious bearing failure. While unfortunate, this has allowed us to collect a small amount of data on the distance traveled between occurrence of a wheel defect and resultant bearing failure. On each occasion the failed bearing was of the type 18R.

The first such event occurred shortly after the WILD was commissioned. Because the operational framework was not in place the wagon proceeded for roughly 2000km before derailing.

In the second instance the wagon passed over the array 12 times prior to failure and 4 times after being repaired[2]. The data from each pass is shown in Table 5. On two occasions prior to failure the WILD system reported a medium level alarm (requiring immediate inspection at the next depot). The wheelset was inspected twice in accordance with National Rail standards. Results of the first inspection found 'minimal spalling'. On both occasions the vehicle was deemed safe to proceed. On the third occasion that an alarm would have been generated, the vehicle crossed the array during a system upgrade that delayed the incident report. After the final array crossing the vehicle traveled a further 2000km before the bearing failed and the vehicle derailed. The data from the final pass again indicated a moderate alarm level but, due to the upgrade, the report was not printed until after the failure and derailment. It is unknown whether a third inspection would have resulted in removal of the wheelset. The data shows a distinct trend; Figure 13 shows kN impact values for all passes. The total distance traveled by the vehicle from first defect alarm to eventual failure was more than 7,000 km. However, the data shows clearly the presence of the defect 2 months earlier.

The data in Table 5 also demonstrates defect measurement consistency at various loads and speeds. The column headings are listed below. It is worth noting that this level of analysis would not be possible without AVI tagging to identify individual vehicles over time.

Dir	- Direction of train travel. Defined as Up (U) and Down (D)
Date	- The date the train crossed the array
Speed	- The average train speed over the array
Car#	- The position of the wagon in the consist
Load	- Wagon mass in tonnes
Dam	- Estimated track damage potential of the defect
A1k – A4k	- Normalized kN impact data for axles 1 to 4

The inspection results indicated a small amount of tread build up on the first axle in the wagon. This would account for the low-level data shown on Axle 1 of the wagon[2].

Dir	Date	Speed	Car#	Load	Dam	A1k	A2k	A3k	A4k
U	16 Aug	101	29	64.8	6		142		
D	22 Aug	83	64	46.1	9		162		
U	30 Aug	106	34	59.2	8		174		
U	13 Sep	109	28	69.7	17	140	213		
U	01 Nov	91	23	88.3	29	144	267		
D	07 Nov	93	55	45.7	35	146	290		
U	12 Nov	104	25	74.5	43	150	323		
D	10 Dec	78	56	54.1	40	141	325		
U	13 Dec	102	27	59.3	45	138	331		
D	16 Dec	93	11	76.0	39	146	336		
18/12/98 Wagon Inspected – "Minimal Spalling"									
U	20 Dec	99	20	56.3	49	149	354		
22/12/98 Wagon Inspected – "Deemed OK to travel"									
U	31 Dec	104	31	52.8	56	144	373		
06/01/99 Bearing collapse									
D	24 Jan	98	66	51.8	0				
U	28 Jan	107	18	42.3	0				
D	06 Feb	90	51	52.7	0				
U	12 Feb	106	14	76.5	0				

TABLE 5: Defect history for wagon RQPW 60078

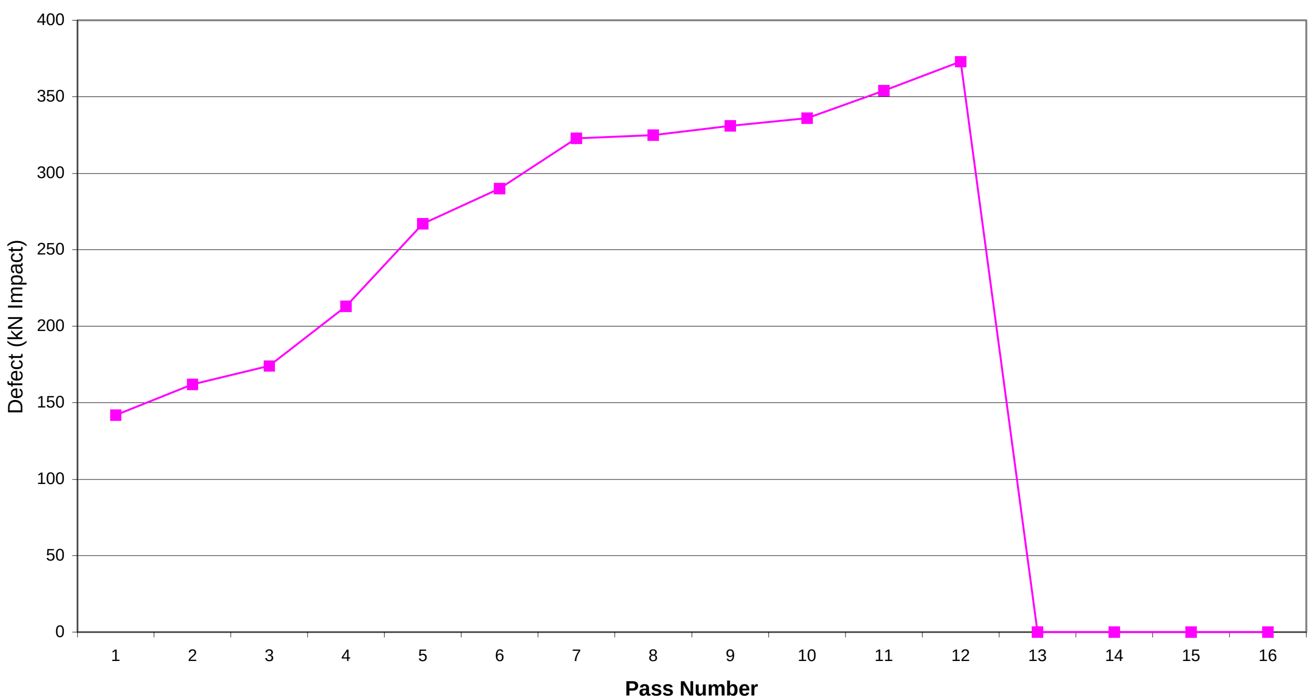


FIGURE 13: Plot of defect data for each pass of wagon RQPW 60078 over the array

The third failure occurred due to a missed tag that prevented the vehicle from being identified correctly[3]. Missed tags are rare. By chance, of all the vehicles in that consist this was the only one not to record tag information. Again, the distance traveled by the defective wheelset was several thousand kilometers.

In response to these incidents, National Rail has instigated systemic changes.

1. Alarm criteria have been lowered to encompass lesser defects.
2. Alarm levels for 18R bearings are lower than general levels to take into account the demonstrated higher susceptibility to wheel defects.
3. A second PC has been configured as backup to the main control PC so that real-time alarms are not interrupted.
4. Defect standards have been reviewed with regard to 18R bearings to incorporate the information gained from the WILD as primary indication of a condemnable wheel defect. A general review of defect inspection standards is also planned[4].

While these 3 cases by no means constitute a valid statistical sample, they do suggest that distance-to-failure may be as large as several thousand kilometers, depending on the severity of the defect. This is also supported by the practical elimination of failures with only one WILD system in place. An average train travels more than 2000 km between one pass over the WILD array and the next. If the distance-to-failure were orders of magnitude less than the distance between passes then there would still be a significant number of failures that occurred ‘between passes’.

In contrast, the distance from onset of detectable temperature increase (i.e. hot-box) to bearing burn-off can be less than 20km[12]. This means that, for bearing failures where the ultimate cause is a wheel defect, the detection of the wheel defect may provide far earlier indication of eventual bearing failure than standard hot bearing detectors.

ANALYSIS OF COST PER FAILURE AND CORRESPONDING SAVINGS

In purely economic terms, to translate these results into dollars requires an average total cost per failure. To be at all realistic, this must include both direct and indirect costs. Examples from both categories are listed below.

Direct Costs	Indirect Costs
Increased fuel consumption	Loss of business through increased costs
Part replacement, Vehicle damage	Labor, Transport, Equipment (i.e. cranes)
Track and structure damage	Schedule delays and loss of revenue
Damage to private property and freight	Compensation, Litigation

Data for such a cost analysis is difficult to obtain and estimates vary widely. Ironically, a true assessment of these costs has the potential to generate substantial savings through improvements in management targeting. A first pass would require only that all work relating to a particular incident be grouped under a separate project or job number.

As a starting point, the cost of removing and servicing a wheelset during routine maintenance is approximately US$7,000[4, 5, 6]. At the other end of the scale, a catastrophic derailment can range up to and beyond several million dollars. The average cost of a derailment has been estimated in a Canadian paper, at US$160,000[12]. National Rail however, believe that this does not take sufficient account of structure damage. The NR routes covered by the WILD system are all concrete sleepered. When a vehicle derails it will often be dragged for several kilometers, causing damage to a large number of sleepers etc. In terms of structure repair alone, NR estimates an average of US$190,000 per kilometer of track damage[6]. Recently, the Times of India newspaper reported a vehicle with a severe wheel defect causing "around 100 fractures" along more than 100 miles of track between Delhi and Ambala.

Although admittedly simplified, an approximate distribution of failures based on inverse proportionality between cost and frequency seems to agree reasonably well with available data[2, 3, 4, 5, 6]. This is shown in Figure 14 with failures divided up into 4 'classes'. The classes are described below.

Class1	-	Minor incident (e.g. bearing failure near depot) involving little collateral damage or associated costs
Class2	-	Moderate failure - some delays and or incidental costs incurred (e.g. crane, transport)
Class3	-	Major incident involving extensive damage to rolling stock and structure. Corresponding delays and indirect costs.
Class4	-	Catastrophic failure. Extensive damage to a large amount of rolling-stock and structure, possible injuries or loss of life

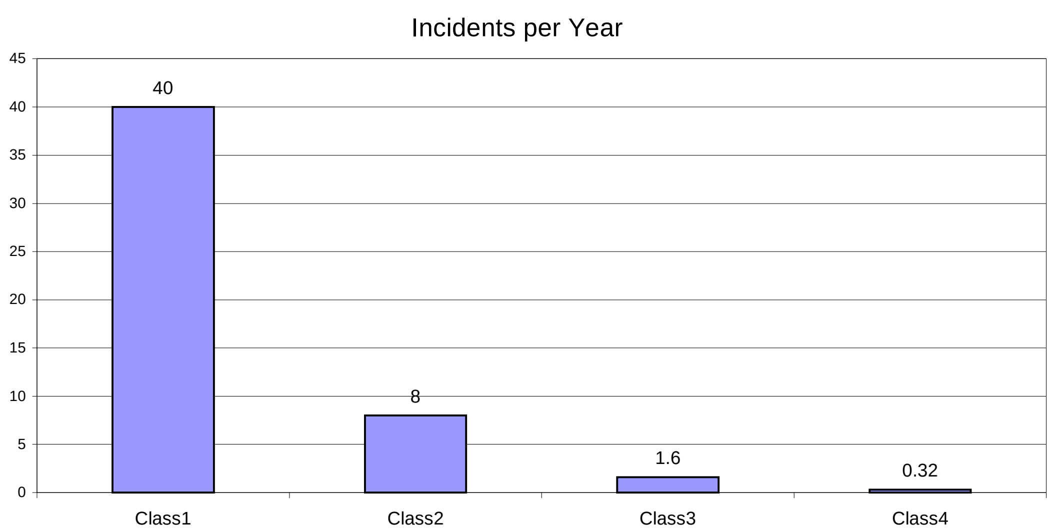


FIGURE 14: Estimated distribution of failures by class

Table 6 shows average cost per failure versus dollar value assigned to each class if we assume this distribution of failures.

	Average cost of failure in class (US$)				
	Class1 'minor'	Class2 'moderate'	Class3 'major'	Class4 'catastrophic'	Average cost per failure (US$)
Lower boundary estimate	$7,500	$37,500	$187,500	$937,500	$24,000
Middle level (NR) estimate	$12,500	$62,500	$312,500	$1,562,500	$36,000
Upper boundary estimate	$17,500	$87,500	$437,500	$2,187,500	$48,000

TABLE 6: Average cost per failure for various cost-of-failure-in-class values

If we subtract a base cost per wheelset of US$7,000 that would be spent on replacement regardless, then we are left with the difference in cost between detecting and preventing the failure and allowing the failure to occur.

The number of defects detected each month, that resulted in wheelset change-out, are shown in Figure 12. Aggregate totals for the first 6 months are listed below.

- 96 defects reported by WILD at or near the level reported for vehicles prior to recorded derailments
- 38 wheelsets changed out in accordance with NR standards or as a result of WILD data
- 3 derailments as a result of early procedural problems or delayed reporting as described above

From this large number of total defects and the decline in defects detected per month it would seem that the system was not only detecting potential failures for that 6 month period, it was also culling out wheels that would have failed later, say in 12 months or more.

Having calculated the average cost per failure we are faced with deciding how to use this to estimate savings. We could look at the question from the point of view of failure prevention. Effectively, this model translates into; "we usually get this many failures per six months. How much do we save if we prevent them from happening?" However, this becomes complicated when trying to deal with variations over time. Another way to express the problem would be, "I have 'x' defective wheels that will fail some time within the next 12 months or more, and new defects are being produced to replace the old ones that have been 'removed' through failure. How much do I save if I can stop the defective wheels currently in the system from failing *and* keep detecting the new ones before they have a chance to fail?"

This second model provides the simplest method and makes best use of the real data we have. In this model we can look at the early phase, just after installation of a defect detection system. We can also estimate the savings generated in the long term once the existing defects have been culled from the fleet.

As mentioned previously, National Rail used to average approximately 2 failures per month[4, 6]. For such a ‘steady state’ system this also represents the rate of new defects appearing. This agrees well with Figure 12. Therefore, a reasonable estimate of the savings generated can be obtained by multiplying the number of defective wheelsets removed by the average cost per failure minus the base cost of repair. The results of this are shown in Table 7

	Savings			
Average cost per failure – base repair cost (US$7000)	First 3 months (34 wheelsets changed)	First 6 months (38 wheelsets changed)	First 12 months (70 wheelsets changed*)	‘Steady state’ annual (24 wheelsets per year)
$17,000 (low)	$578,000	$646,000	$1,190,000	$408,000
$29,000 (NR)	$986,000	$1,102,000	$2,030,000	$696,000
$41,000 (high)	$1,394,000	$1,558,000	$2,870,000	$984,000

* Number of wheelsets for 12 months projected from 61 at 8 months

TABLE 7: Estimate of savings for various intervals and average-cost-per-failure values

Of course, this does not take into account that some defective wheelsets were not changed out because they did not fit the NR defect inspection standards.

Using this model with the mid-level cost-per-failure assumed for NR operations, the estimated saving generated in 6 months amounts to US$1,102,000. Table 7 also shows the savings using higher and lower estimates of average cost per failure.

It is relevant to note that even the lowest savings figure (US$646,000) is several times the maximum (i.e. fully optioned) cost of a WILD system.

It should also be noted that these figures only relate to basic defect detection. They do not include benefits from load measurement or lateral tracking, neither of which has yet been modeled or quantified.

SAVINGS AS RELATED TO FLEET COVERAGE

National Rail currently has one WILD site, located so as to give maximum coverage. They estimate that this site sees approximately 60% of their fleet. Placed appropriately, an additional site could increase fleet coverage to 95%[6]. If the failure rates for traffic on different tracks were consistent then the total savings could be multiplied by a factor of 1.6 resulting in an increase in projected savings from US$2,030,000 to US$3,248,000 for the first 12 months. Steady-state annual savings would increase from US$696,000 to US$1,113,600. However, the routes up and down the eastern seaboard do not produce anywhere near the number of failures that occur on the east-west routes across the country. As to why this should be the case, there are several factors that seem relevant.

On the east-west lines:
1. Average line speed is higher (100km/h against 80km/h)
2. The structure is more rigid (concrete sleepers)
3. Runs are dryer, dustier and far longer between stops (the Nullabor plain)

Normally vehicles stay on one or the other section of the network. When vehicles do move from the eastern seaboard to the cross-country lines they are just as prone to failures and show similar defects to the vehicles that normally run on those lines.

This is not to say that the savings would not increase with greater fleet coverage. It is just not possible to use bearing failures to estimate benefits in the way we have done for the existing site.

CONCLUSIONS

The WILD system provides integrated data encompassing in-motion weighing, load pattern analysis and a range of wheel defect classifications.

Operational results show that this can provide rail operators with accurate, reliable condition monitoring information in a way that can be used productively.

By actively looking for and implementing improvements, both technical and procedural, National Rail have gained a significant improvement in fleet wheel condition plus a return on investment estimated at several times the cost of the WILD system within the first 6 months of operation. Because the system has displayed consistent ability to detect serious defects that cannot be found via normal inspection National Rail is using the WILD system as the basis for an enhancement of their defect inspection standards.

The data obtained suggests a strong connection between bearing failure and wheel defects. There is also clear indication that wheel defect detection may provide a far earlier warning of potential bearing failure than thermal ‘hot-box’ systems.

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UNITS OF MEASUREMENT

Throughout this report there are several areas where measurements are quoted. The units used, along with conversion to imperial measures where applicable, are listed below.

Unit of Measure	Abbreviation	Description	Conversion
kiloNewton	kN	Metric unit of force	1 kN = 0.225 kips
kip	kip	Rail industry unit of force	1 kip = 4.448 kN
tonne	tonne	Metric mass	1 tonne = 2205 lbs
kilometer	km	Metric distance	1 km = 0.62 miles
meter	m	Metric distance	1 m = 39.4 inches
millimeter	mm	Metric distance	1 mm = 0.039 inches
U.S. dollar	US$	U.S. currency	1 US$ = 1.59 A$ at 3/99
Australian dollar	A$	Australian currency	1 A$ = 0.63 US$ at 3/99

GLOSSARY OF TERMS

18R bearing	A type of bearing used by NR highly susceptible to wheel defects
50t bearing	A type of bearing used by NR
70t bearing	A type of bearing used by NR
Accelerometer	A sensor unit used to measure force
AEI	See Automatic Vehicle Identification
Ambient temperature	Temperature of the surrounding air
Array	See sensor array
ARTC	Abbreviation of Australian Rail Track Corporation
Australian Rail Track Corporation	Australian owner of track structure
Automatic Equipment Identification	See Automatic Vehicle Identification
Automatic Vehicle Identification	In this context a combination of UHF tag sensor and radio reflective tags. The tags are attached to individual vehicles and are read as the train passes the radar tag sensor in order to uniquely identify a vehicle in a consist
AVI	See Automatic Vehicle Identification
Axle	Either the solid axle joining the wheels in a wheelset or another term for the entire wheelset
Bogie	Usually two or three wheelsets integrated with bearings, suspension, brakes etc to form a support platform for a rail vehicle.
Bulkhead	Electronic assembly designed to separate and protect sensitive equipment from potentially damaging environments
Burn-off	Describes a situation where a bearing has over-heated to the point of failure
Change-out	Refers to a defective wheelset being removed from a bogie for repairs
Class	See failure class
Collapsed wheel tread	Formed when the surface of a wheel is not sufficiently supported by the underlying metal due to cracking or cavities
Condemnable defect	A defect that requires the wheelset be removed and repaired or scrapped
Consist	A combination of motive stock and rolling stock that makes up a train
Contact patch	See rail/wheel contact surface
Control PC	The PC that contains the software required to control the WILD processor rack
Crack	A fracture in a wheel
CSU	Control Status Unit - a term used to refer to the WILD processing rack
Defect progression	The changes that occur over time to alter a defects characteristics from those of the original defect
Dialup	A communications link formed by a modem automatically dialing a pre-defined number. Also another term for PSTN.
Distance-to-failure	The distance a wheel travels between occurrence of the defect and eventual failure
Dragging Equipment	Anything attached to a train that is dragging along. Often, parts of the train that have broken but not fallen off completely
Failure	A situation where a wheelset is damaged so that it must be removed from the bogie. Often causes other damage
Failure class	A grouping of failures based on a defined average total cost per failure in the group
Flat	See skid
Gas Arrestor	High power shunt for excessive voltages
HDLC	High-Level Data Link Control. A robust synchronous communications protocol
High level defect	A defect which presents a high risk of derailment if the vehicle is not stopped immediately
Hot-box	Term used to refer to a railway wheel bearing that has over-heated due to internal friction caused by some fault in the bearing
Hot-wheel	Term used to describe a wheel that has had the brakes left on or dragging while travelling and so become hot. Used to detect sticking brakes.
Hunting	A vehicle moving from side to side until its wheels contact the gauge face of the rail. See tracking defect

Impact factor	Ratio of a measured impact value over the mass in an attempt to remove the variation in impacts produced by different masses
Impact force	The vertical force that occurs when a wheel that has a defect rolls along the rail
Incident	A defect or condition detected by the WILD system that warrants immediate attention
Incident report	Report generated automatically that describes a serious wheel defect or other serious alarm condition
In-motion weighing	In the context of the WILD this refers to weighing rail vehicles at normal line speeds
kiloNewton	Metric unit of force.
kN	Abbreviation of kiloNewton.
LAN	Local Area Network
Lateral tracking	The measurement of horizontal force designed to detect train wheels hitting the inner edge of the rail as they run along it
Leased line	A dedicated PSTN line
Level 1 load measurement	Basic in-motion weighing option in the WILD system. Uses 4 load gauges to provide +/-5% accuracy.
Level 2 load measurement	Full in-motion weighing option in the WILD system. Uses 12 load gauges to provide +/-1% accuracy.
Load balance	See load distribution
Load distribution	The balance of mass in a rail wagon from front to rear or side to side. Also, the weight of vehicles at various positions in a consist.
Load gauge	A sensor unit used to measure mass
Load pattern analysis	Examines load distribution to detect bad loading practices or shifted loads
Load shifting	A movement of load being carried in a wagon. Can be caused by wheel or bearing defects or warped bogies. Can damage freight and, in extreme cases, cause a derailment
Low level defect	A small defect with little damage potential. Important for analysis of defect progression.
Medium level defect	See moderate level defect
Moderate level defect	A larger defect often associated with wheels that have just become condemnable
National Rail	Short for National Rail Corporation Ltd
Normalization	Mathematical technique of removing the effects of variables so that data values can be directly compared
Normalizing reference function	A function applied to normalized data to some specific criteria
NR	Abbreviation of National Rail
Out-of-gauge	Anything attached to a train that projects outside a specified cross-section
Out-of-round	A defective wheel that is not circular. Can be caused by bad machining or by collapse of the wheel surface due to sub-surface defects
Overload	A vehicle carrying weight over the specified limit for the line or for its type
Processing rack	The signal processing hardware that converts sensor array signals into data to be sent to the control PC
PSTN	Short for Public Switched Telephone Network. Refers to the international telephone system based on copper wires carrying analog voice data.
Rail temperature	Temperature of the rail
Rail/wheel contact surface	The line that runs along the rail and around the circumference of a wheel that defines the normal points of contact between the two surfaces.
Return current	The current flowing through the rail that completes the circuit formed by overhead electrification and an electrically powered locomotive
Roll-by inspection	An inspection method whereby a train rolls slowly past a train examiner who listens for defects
Sensor array	The various sensors attached to the rails at a WILD installation
Severe defect	See high level defect
Side-bearer	Provides lateral stabilizing between carriage body and bogie frame
Single-point earth	Radial grounding scheme where every return line is physically connected to the same point

Skid	A flat spot on a wheel caused when the brakes lock up and the wheel slides along the rail
Spall	A defect produced when a part of the wheel surface breaks away forming a depression
Step-down transformer	Equipment used to convert a higher voltage to a lower one
Sub-surface defect	Cavities or cracks under the surface of the wheel
Tag	A radio reflective identification badge attached to a vehicle
Tag reader	UHF sensor placed at the side of a track, used to read AVI tags as vehicles pass
Teknis	Short for Teknis Electronics Pty Ltd
Total cost per failure	The total of direct and indirect costs associated with a failure
Tracking defect	A defect that causes a bogie not to run straight with respect to the track
Traction	An electric locomotive applying power to increase speed
Transient surge	A sudden change in current and/or voltage
Transorb	High speed semi-conductor device that shunts excessive voltages to ground
Unloader	Refers mainly to the machinery used to automatically unload coal or minerals from a wagon
WAN	Wide Area Network
Warped bogie	A bogie in which the wheelsets are not properly aligned
Wheel condition	General term encompassing all aspects of wheel quality esp. to do with wheel defects
Wheel defect severity	The magnitude of risk associated with a wheel defect
Wheel flange detector	A sensor unit used to detect a train wheel passing
Wheel Impact Load Detector	A system designed to measure rail vehicle loading and wheel defects
Wheel switch	See wheel flange detector
Wheel zone	See zone
Wheelbase	The distance between the center of the inner wheels of two adjacent bogies on the same vehicle
Wheelset	Comprises two train wheels joined by a solid axle
WILD	Wheel Impact Load Detector manufactured by Teknis Electronics
WILD array	See sensor array
WILDDB	The WILD database application
Zone	Roughly equivalent to dividing a wheel into 5 equal segments. For purposes of detecting wheels with multiple defects

ABOUT THE AUTHORS

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