 DOI: 10.1784/insi.2012.54.8.451

Rolling stock condition monitoring using wheel/rail forces

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Paper presented at CM 2012 & MFPT 2012, The Ninth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, London, UK, June 2012

Railway vehicles are efficient because of the low resistance in the contact zone between wheel and rail. In order to remain efficient, train operators and infrastructure owners need to keep rails, wheels and vehicles in an acceptable condition. Wheel wear affects the dynamic characteristics of vehicles and the dynamic force impact on the rail.

The shape of the wheel profile affects the performance of railway vehicles in different ways. Wheel condition has historically been managed by identifying and removing wheels from service when they exceed an impact threshold. Condition monitoring of railway vehicles is mainly performed using wheel impact load detectors and truck performance detectors. These systems use either forces or stress on the rail to interpret the condition.

This paper will show measurements taken at the research station outside Luleå in northern Sweden. The station measures the wheel/rail forces, both lateral and vertical, at the point of contact in a curve with a 484 m radius at speeds of up to 100 km/h. Data are analysed to show differences for various wheel positions and to determine the robustness of the system.

1. Introduction

Railways use the low resistance of movement between wheel and rail to create an energy efficient mode of transport. The most important element in the dynamics of a railway vehicle is the interaction between the wheel and the rail[1]. Keeping wheels and vehicles in an acceptable condition is therefore a major concern for both railway operators and infrastructure owners. Wheel impacts on a railroad track can cause extensive damage, the ultimate form of which is rail breakage. Apart from affecting the actual rail, dynamic impacts can also degrade and cause premature damage to the track's sub-grade. Depending on the track curvature and the type of bogie design, each wheel/rail system may exhibit significant differences in steering and dynamic stability[2].

To evaluate the loads generated by wheel/rail interaction, North American railways have adopted the use of detection and condition monitoring technologies[3]. The technique of placing condition monitoring equipment along the track is referred to as wayside detection[4]. Wayside detectors are mostly used for exception reporting; for example, determining large wheel impact forces from a wheel flat, which is the simplest use of these detectors[5]. A more sophisticated use of wayside detector data is to monitor the changes in forces over time, which in combination with temperatures and wheel position can be used to predict when a threshold condition will be reached.

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In a study performed on a metro line, only a few real-time alarms caused by traditional track force threshold limits were registered[6]. In this case, structured condition monitoring was used in combination with structured maintenance planning. There are also issues with differences in track structure and climate to consider when trying to compare data or information from different track systems or geographical locations. In this paper, an analysis of the different wheel/rail force data collected from the research station is carried out and the robustness of field measurements shown.

2. Condition monitoring of railway vehicles

Condition monitoring aims to record the current (real-time) condition of a system[1]. Traditional inspection techniques used in the railroad industry, such as drive-by inspection, are not as accurate and reliable as more rigorous and quantitative inspection methods[7]. Wayside detection systems provide a means of monitoring the condition of vehicles, ensuring that they are in a serviceable condition[4]. How track-friendly a vehicle is depends not only on its design, speed and axle load, but also on its maintenance condition[8]. It is not uncommon for wheels on both sides of a wheel axle to degrade differently, despite having the same axle load and initiating tread defect[6]. Wheel condition has historically been managed by identifying and removing wheels from service when they exceed a vertical impact load threshold[6]. These thresholds are typically based on when a wheel/rail impact is presumed to cause sufficient stresses to the track structure.

Force measurement detectors make it possible for vehicles with defective wheels, which are likely to cause damage to the permanent railway structures, to be identified and removed from service immediately[9]. Vertical impact loads between wheel and rail resulting from surface anomalies such as wheel flats have been used to create mathematical models of wheel-rail impact behaviour[10]. Systems that solely measure the axle load of wheel flats are mostly placed on a tangent track with no gradient, or a negligible gradient, where trains do not accelerate or brake[11]. When measuring the lateral forces, it is an advantage to perform measurements in narrow curves in which the vehicles can show their steering ability. Lateral forces are the result of a poorly-steering bogie and trains moving at speeds different from the optimal curve speed, but they are also the result of longitudinal buff and draft forces transmitted through train action and coupler angularity[12].

2.1 Wheel impact load detector

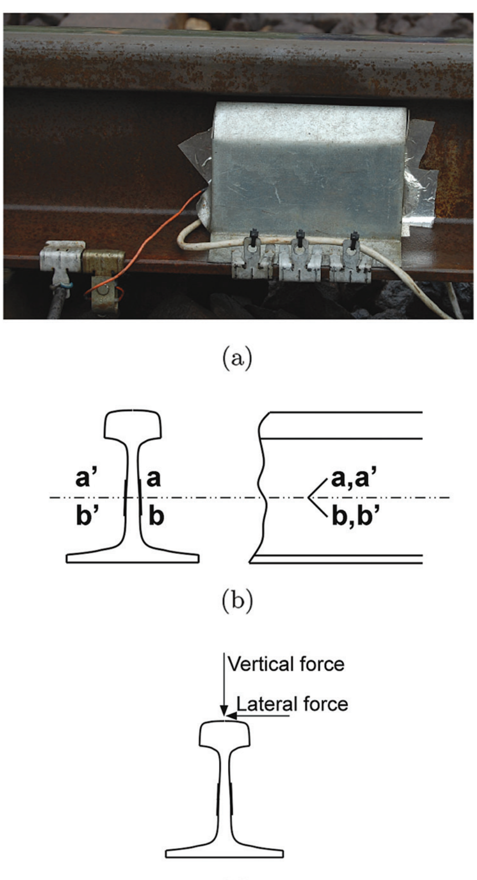
Increasing concern about damage to track components arising from high-impact loads generated by damaged wheels led to the installation in 1985 of the first wheel impact load detector (WILD) by British Rail[9]. The WILD system was originally installed to monitor damaging track forces; obvious benefits are obtained from the early detection of rolling-stock wheel defects.

The installation of WILDs requires no radical modification of the existing track structure[7]. WILD sites consist of strain gauges arranged along a 30-foot stretch of track, and the strain gauges are welded to the web of the rail[13]. WILDs have been depended on to identify wheels with shells, spall and out-of-rounds since the early 1990s, and have continued to protect railroads from damaging loads and derailments due to broken rails[5]. The impact load detecting system also offers the opportunity to define criteria for the removal of railway wheels, based not only on a visual inspection of wheel tread defects but also on the impact loads measured by the detectors[14].

2.2 Truck performance detector

Truck performance detectors (TPD) measure both vertical and lateral forces/stresses when a vehicle passes. TPDs can evaluate bogie performance, vehicle lubrication conditions, prevent derailment and increase the safety and efficiency of the railway as a whole[3]. Proper curving of vehicle bogies (trucks) is essential to insure proper system performance[15]. Conventional visual bogie inspection methodology cannot detect all bogie defects that cause poor curving performance.

A typical force-based TPD site designed for the evaluation of a three-piece freight wagon bogie consists of an ‘S’ curve arrangement where two narrow curves arc in opposite directions[16]. These curves should have a radius of between 291 and 436 m. The array consists of eight measurement zones (cribs) of gauge, three in each curve and two in the tangent section[13]. The TPD layout allows a thorough evaluation of the bogie’s ‘dynamic’ curving performance by checking left and right rotation as well as its ability to return to a neutral tracking position in the tangent section[17].



(a)

(b)

(c)

Figure 1. Measurement equipment, sensor placement and force definition: (a) measurement system placed on the rail; (b) measurement sensor placement; (c) definition of wheel/rail forces

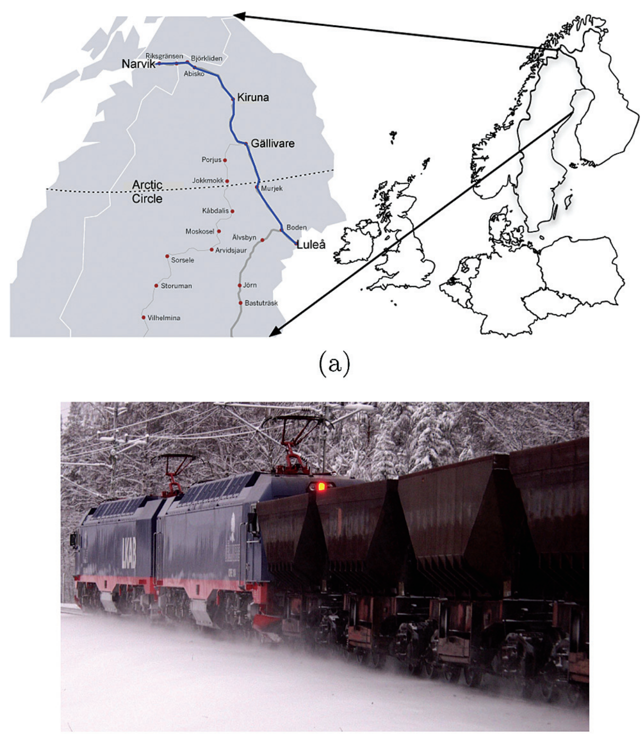
2.2.1 Research station outside Luleå, Sweden

In a research station outside Luleå, the wheel/rail forces are measured, both lateral and vertical, in a curve with a 484 m radius for speeds of up to 100 km/h[11,18]. The research station is a simplified version of a TPD, consisting of only one measurement zone. Due to the hostile environment of railroads, there is a weatherproofing shield on top of the strain gauges, see Figure 1(a).

The measurement system consists of several strain gauge sensors micro-welded to the web of the rail, as indicated in Figure 1(b). The measured forces are vertical and lateral, see Figure 1(c), with the positive lateral force outwards in the curve. Lateral forces are the result of a poorly steering bogie and trains moving at speeds different from the optimal curve speed, but they are also the result of longitudinal buff and draft forces transmitted through train action and coupler angularity[17].

3. Case study description

The only existing heavy haul line in Europe, called the Iron Ore Line (Malmbanan), stretches 500 km from Luleå in Sweden to Narvik in Norway, see Figure 2(a). On the line, there is mixed traffic consisting of both passenger and freight trains. The iron ore freight trains consist of two IORE locomotives accompanied by 68 wagons with a maximum length of 750 m and a total train weight of 8,500 tonnes, see Figure 2(b). In 2010, LKAB mining company transported 26 MGT (million gross tonne) from their two mines in Kiruna and Malmberget; of these, 6 MGT were shipped from Luleå harbour. The trains operate in harsh climate conditions, including snow in the winter and extreme temperatures ranging from –40ºC to +25ºC[19].



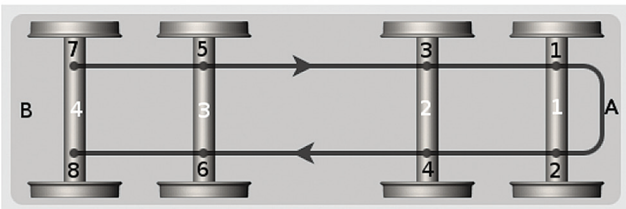
(a)

(b)

Figure 2. Malmbanan and trafficking iron ore train: (a) Northern Sweden with Malmbanan; (b) photo of an iron ore train

The results presented in this paper are recorded from two iron ore freight wagons with the Amsted three-piece bogie, designated 43 and 44. The wagons were followed for a period of 15 months, from March 2009 to May 2010. These wagons travel with an average axle load of 30 tonnes and a loaded top speed of 60 km/h from Malmberget towards Luleå. During the period, the wagons have random positions in the train, from right behind the locomotive to being the last two wagons. The iron ore trains are closely monitored; all vehicles have RFID tags for identification and are connected to the measurement system.

Figure 3(a) shows the set-up of a wagon with wheel, axle and bogie designation; as shown, the two wagons are always connected at the A-end with a steel rod. This means that our two wagons travel as a pair with one wagon having its B-end first and the other its A-end. If they travel in the other direction, this is reversed. This presents two different scenarios when passing the research station, as either 43 or 44 is travelling first. Figure 3(b) shows the designation for the wheels of a bogie when passing the research station.



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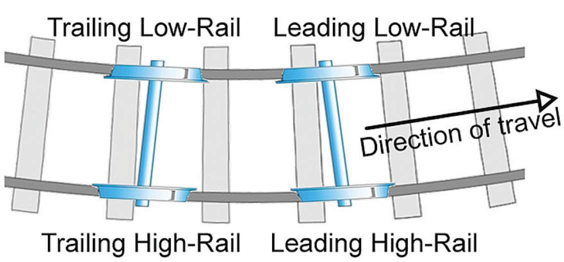
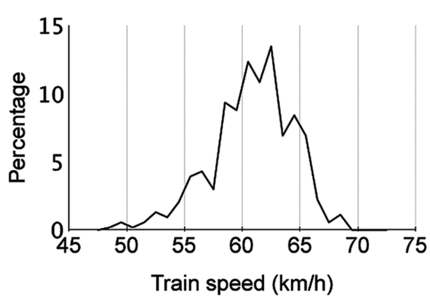


(b)

Figure 3. Wagon set-up and wheel position when passing the research station: (a) set-up of a wagon with A and B end as well as wheel and axle numbering; (b) wheel positions for a bogie in a curve

During the project time, both speed and vertical load varied. This variation can be seen in Figures 4(a) and (b). As is shown, train speeds are allowed up to 9 km/h over the set limit of 60 km/h. The restriction of 30 tonnes on the vertical load is an average for the whole train set.



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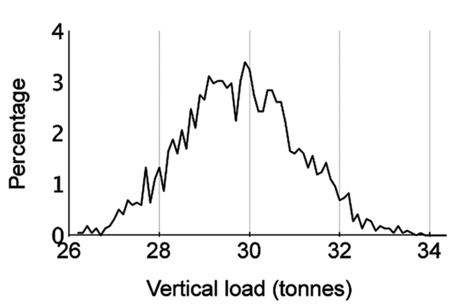


(b)

Figure 4. Speed and vertical load: (a) speed for loaded trains; (b) vertical load for loaded trains

For the test, the wheel axles on the two investigated wagons were put together as a mix of new and old, see Figure 5(b). This was done to collect data for a full wheel life cycle, between wheel turnings (re-profiling). During the project, two axles had to be exchanged for new ones due to wheel damage. In Figure 5(a), the monthly average temperature for Gällivare and the average, maximum and minimum temperatures from the research station are shown.

During two periods the wagons were stationary in the maintenance workshop, at 64,000 km or day 193 and 80,000 km or day 259, see Figure 5(b). The first stationary period was caused by wheel damage and the second was caused by bogie revision and inspection. During the revision, draft sills were measured and centre bowl liners in the bogie were inspected.

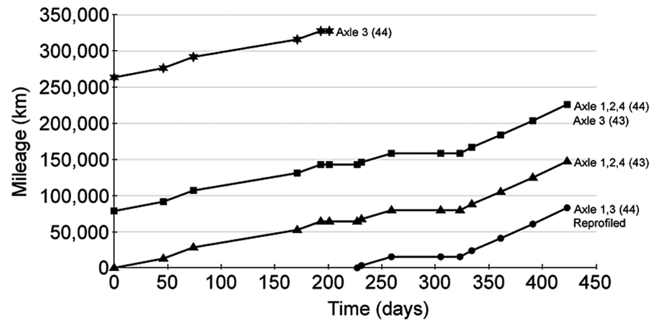


Figure 5. Mileage of wheel *versus* time of the project

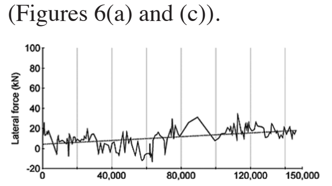
Between 80 and 100,000 km there are fewer force measurements due to a malfunction in the RFID-tag reading between the wagons and the research station. This was during February and March 2010.

4. Results and discussion

4.1 Lateral forces for different positions in bogie

The four different wheel positions of the bogie (see Figure 3(b)) show differences in the signature of the lateral forces. The leading axle is the first of the two to negotiate the curve and therefore usually has a larger lateral force. The trailing axle follows and thus has a lower lateral force. Figure 6 shows data from one bogie (43A) travelling loaded towards Luleå when it is the leading bogie of the wagon. The x-axis shows the distance the wheel has run since new, almost 150,000 km.

The leading high-rail consistently shows large lateral forces. This is expected since it is the first wheel of the bogie and wagon to steer through the curve. Table 1 gives the average values of each wheel in Figure 6. The wheels on the high-rail (Figures 6(c) and (d)) have the largest average values on the bogie. This is expected as they steer the wagon. Both wheels of the leading axle (Figures 6(b) and (d)) have larger average values than the trailing axle (Figures 6(a) and (c)).



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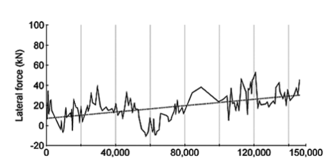

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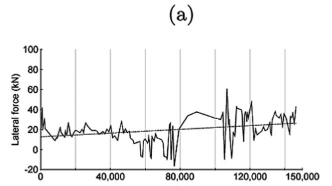

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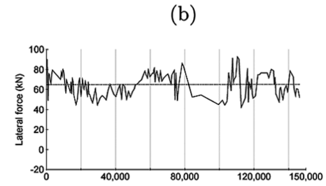


(d)

Figure 6. Lateral forces from all wheel positions in a bogie for 150,000 km of travel distance: (a) trailing low-rail; (b) leading low-rail; (c) trailing high-rail; (d) leading high-rail

Table 1. Average for graphs in Figure 6 in kN

Figure 6	(a)	(b)	(c)	(d)
$\bar{x}$	10.9	18.2	19.3	65.1

Another interesting parameter is the trend line in Figure 6. In Figure 6, (a)-(c) show increasing trends while (d) remains steady or decreases. This indicates a possible relationship between running distance and lateral forces for all wheel positions except the leading high-rail. This clearly indicates that to evaluate lateral forces instead of the running distance, the position in the bogie has to be known.

4.2 Robustness of field measurements

Looking at the measurements in Figure 6, there is a question about the lateral forces that the passing wheels generate from time to time, even if the wear of these wheels is approximately the same. There are several possible reasons for these variations, including placement in the train, friction coefficient, temperature, humidity and bogie configuration. However, in the project, all these factors were monitored and offer no explanation of the variation in lateral forces. To more accurately determine how the lateral forces compare between measurements, the leading high-rail wheels for all four studied bogies were collected while travelling loaded towards Luleå, always with the same wheel positions (wagon 43 first). In Figure 7, the data from these four wheels are plotted for the average of the wheels for each passage.

Figure 7 shows how these four wheels follow each other, even when two axles of one wagon had to be changed for new re-profiled wheels at 64,000 km, C and D from Table 2. The pattern of the peak forces on these wheels is very similar for each passage, and the patterns seen well duplicated between passings. However, the wheels are not consistently either the largest or smallest. The small variations might be from the dynamic force additive, friction coefficient, bogie condition and configuration or from speed changes. Some parameters that might change the friction coefficient are water, surface roughness, vertical load, dust or metal particles.

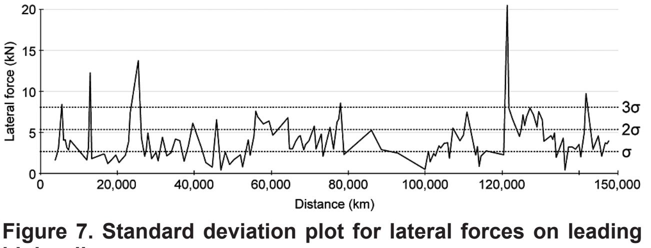


Figure 7. Standard deviation plot for lateral forces on leading high-rail

In Table 2, the average, maximum and minimum forces for the graphs in Figure 7 have been calculated to distinguish any differences or similarities. The variations for these four wheels and all measurements are σ = 2.7 kN. From the graphs in Figure 7 and Table 2, we see that these four wheels follow each other's forces well, even if D in Table 2 has a slightly lower average. One explanation for this behaviour is that this wheel was changed for a new one during the study. From Figure 7 and Table 2, it is apparent that the forces are not much different for these wheels, even if they have different running distances. A new wheel has forces similar to those of a wheel that has run 140,000 km. The data for these four wheels are consistently similar over 15 months for each time of measurement, even if they differ greatly between one measurement and the next. This indicates that the measurement system is ideal for repeated use on prolonged series of measurements.

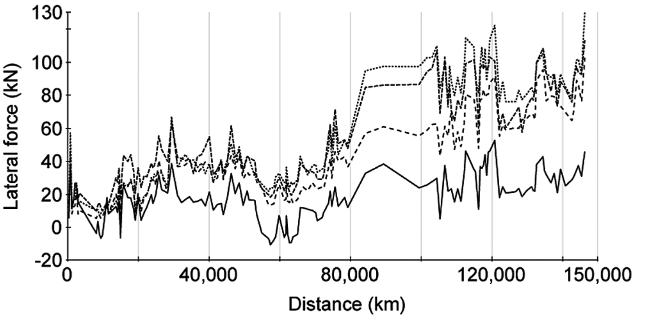
The main question is: what kind of data are most useful for condition monitoring of wheels and bogie?

Table 2. Max, min and average forces in kN and wheel starting km for Figure 7

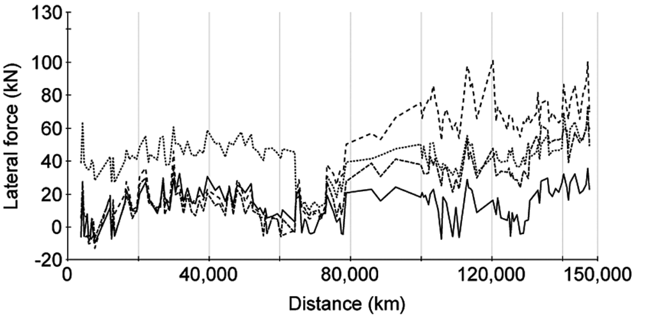
Figure 7	A	B	C	D
$\bar{x}$	63.5	62.4	63.3	60.8
Max	93.6	91.5	93.0	93.6
Min	40.3	39.3	39.6	38.7
Starting km	0	0	78,700	263,580

4.3 Changes in lateral forces due to direction of travel

From the data, the leading low-rail seems the most promising for condition monitoring. In Figures 8(a) and 8(b), the leading low-rail has been plotted for the two scenarios described earlier, for travel of loaded trains towards Luleå. In the first scenario in Figure 8(a), wagon 44 travels first; it travels second in the second scenario in Figure 8(b).



(a)



(b)

Figure 8. Lateral forces for leading low-rail: (a) Wagon 44 travelling first, scenario 1; (b) Wagon 43 travelling first, scenario 2

There are very different behaviours between the scenarios in Figures 8(a) and 8(b). From these Figures we may assume that the lateral forces of a single bogie or wagon may differ according to its direction of travel. This indicates a need to measure in two reverse curves (both left and right) to be able to collect data on both wheels of an axle as leading low-rail, depending on whether the bogie is leading or trailing. Such data should permit a better understanding of the condition of the wheels and bogie.

From the data collected for 15 months, there is no clear indication that weather or seasonal changes influence the lateral force for this wheel position. If they had an effect, there should be a similar magnitude of forces at the beginning and the end of the study.

5. Conclusions

The four different wheel positions in a bogie show significantly different force signatures. The leading high-rail has high forces that remain unaffected by the change in running distance, while the three others increase over the distance.

The measurement system at the research station is shown to be robust. During the 15 months of measuring, most collected data point to the leading high-rail, for the scenario whereby wagon 43 travels first and is within 3σ, the limit of variation. The mix of wheels, some starting at 0 km others at 78,700 km, seems to have no or very little influence on the lateral forces acting on the leading high-rail.

Directional changes of the wagon, for example turning around at loading or unloading, show distinctive differences in lateral forces for the leading low-rail with running distance. This might be because the dynamics of the wagon differ little from wear when turning left or right. In order to collect all possible data in one run, there is a need for a second measurement point in a reverse curve with the same radius.

Acknowledgements

The authors would like to thank Dan Larsson at Damill AB for his help, particularly his useful discussions about the research station. Then we would like to thank LKAB/MTAB for support and discussions about the iron ore wagons. We would also like to thank Luleå Railway Research Centre (JVTC) for its financial support.

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The evolution from e(lectronic) Maintenance to i(ntelligent) Maintenance

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