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Wayside Train Monitoring Systems: A State-of-the-Art and Running Safety Implications

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Abstract

The appearance of railway undertakings in Europe led to an enormous increase in rolling stock operators: mainly in the freight sector. To keep these vehicles under control, and to limit as much as possible the consequences of accidents arising from failures, fires, exceeded gauge, *etc.,* it is necessary to consider the possibility (and the need) to check rolling stock conditions from stationary measuring equipment, *i.e.* at wayside train monitoring systems (WTMS). After the analysis of the literature on railway accidents, this paper aims to classifying safety-related and maintenance-related train-environment interactions, discussing the implications and the capabilities of existing WTMS systems.

Keywords: railways, rolling stock, wayside monitoring, accidents, safety, review.

1 Introduction

Safety, regularity and cost effectiveness have been mandatory requirements of railways since they were first invented. It is not surprising that the three mentioned characteristics, in the above mentioned order, were at the basis of all regulations and training every railway system around the world.

Today we face a world that has dramatically changed in the last two decades. In Europe: after the Maastricht agreement, the free circulation of people and goods have become (or should have become) a reality that completely changed the approach to national railways as we used to consider them. The “White Paper on Transport” of the European Union introduced a package of measures to revitalise the rail sector through the rapid creation of an integrated European rail network. The objective was to speed up market integration by removing major barriers to cross-border services, guaranteeing a high level of safety on the railways, and reducing costs as a result of greater harmonisation of technical standards in the rail sector.

That document opened the market to new subjects previously unknown (Railway Undertakings, RU [1]) whose only goal was to make a profit from both passenger and freight services. As a counterpart, these new subjects did not have the engineering knowledge and safety culture of previously existing national railways.

In general, more traffic means more vehicles, more mileage, increased use and, in mechanical terms, greater potential wear and fatigue problems. Higher efficiency measures also mean fewer personnel for ordinary inspections and checks, and a potentially higher risk of unexpected and undesired accidents arising from catastrophic failures of safety-related components.

An improved design of vehicles is certainly possible because more advanced resources are available (finite element codes, experimental stress analysis, *etc.*), however they are not by themselves sufficient to ensure *a priori* that the aforementioned accidents cannot happen in practice. For some classes of vehicle, such as freight wagons, actual operational conditions are still largely unknown: *i.e.* real routes that the wagon will travel on are not predictable (if not for really a few instances), and loads cannot be safely predicted. Unlimited life approach, which was used until a few years ago, is today believed to be too conservative, but the practical applicability of damage accumulation arising from time-varying loads still suffers from the uncertainty of input parameters.

An automatic and unmanned survey is necessary to maintain the leadership that the railways still have in terms of safety. This is possible today thanks to the advances in sensor technology, database size, and the computer network distribution throughout the European territory. Both web and satellite communications offer the possibility of checking the status of a network, or a fleet of vehicles, virtually from any position on Earth.

This paper focuses on the requirements for wayside train monitoring systems: addressing their potential and limits, and therefore depict where the application is trivial or where it is still a matter of research and development.

2 Train-side monitoring and wayside monitoring

Safety can be achieved by monitoring both vehicle and infrastructure conditions. It is, in fact, from the interaction of the two that risks may generate a danger to people travelling on the train, and to people living close to railway lines.

When the number of employees was large enough (and computers were still in the cradle), patrolling was the usual way to check the integrity of the railway network. Large efforts were made, starting in the 1960s, with the first Shinkansen monitoring train (called *Doctor Yellow*) [1]. Nowadays most infrastructure owners have one or more recording trains (see, for instance, the Network Rail New Measurement Train (NMT) [3]; the SNCF TGV Iris 320 [4]; the RFI Archimede; and Y1/Y2 trains [5]): there are also companies that offer diagnostic services by means of measuring trains (see *i.e.* the Dutch company Eurailscout [6]). These measuring trains have the dual purpose of both reducing the number of people needed to visually check the conditions of the track, and to guarantee that the infrastructure quality level is sufficient to ensure the safe running of trains throughout the network, the latter being a duty of the (state based) infrastructure owner.

It can be said that the field of network conditions monitoring, which is outside the scope of this paper, is well established and that a number of competing companies offer complete subsystems including hardware (sensors, signal conditioners) and software (visualization, storage and data management applications) to check track geometry, rail wear, overhead line conditions, and so on.

One of the dual aspects of track monitoring is vehicle inspection. This was traditionally carried out in workshops at fixed times or distance intervals, but, for the reasons described in the introduction, this is not automatically done by national railways anymore. With the revision of the Directive on Railway Safety in Europe, the EU introduced the term “Entity in Charge of Maintenance” in 2008 [7]. This “Entity in Charge of Maintenance” must ensure that all wagons assigned to it in the national vehicle registers are serviced in accordance with the regulations in force [8].

3 Railway disasters analysis and prevention

The European Railway Agency has a research project which has gathered information about serious accidents for the period 1990-2009. The project identified 402 serious accidents: of which 385 were not previously known to the ERA (Figure 1). The archive contains fatal train collisions, derailments and fires, level crossing accidents with on-train fatalities, and other accidents with four or more fatalities. For a project brief see [9], while the full document can be downloaded from [10]. In twenty years of service in Europe, there were 100 such disasters with 979 fatalities, and 1343 injured people.

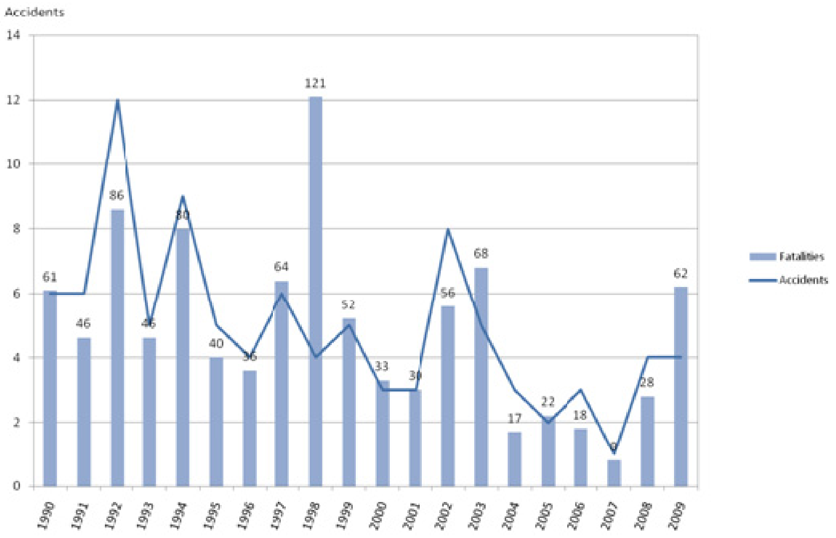


Figure 1: Accidents in Europe with five or more fatalities since 1990 [9]

This official and authoritative source of data classifies accidents in six categories listed below in alphabetical order (for each the total number of fatalities and injured people is reported):

- Accident to person caused by RS in motion (fatalities: 24, injured: 3);
- Fire in rolling stock (fatalities: 21, injured: 10);
- Level-crossing accident (fatalities: 349, injured: 143);
- Train collision with an obstacle (fatalities: 32, injured: 120);
- Train derailment (fatalities: 269, injured: 417);
- Trains collision (fatalities: 284, injured: 650).

It is important, for the scope of the present paper, to assess which of these accidents happened because of either track or rolling stock direct failure, or for reasons arising from failures in their interaction. At a first glance, some accident classes are most likely a result of human behaviour (accidents to persons caused by rolling stock in motion, level-crossing accidents); some others to signalling related problems (trains collisions); and some other to infrastructure problems not directly related with track specific features (train collision with an obstacle, as fallen trees, landslides, *etc.*).

There are apparently only two classes which are interesting in this context: fire in rolling stock, and train derailment. Fatalities arising from derailment are 27.4 % of the total number of fatalities; it is, therefore, interesting to look in more detail at the reasons for the most important accidents in this category. Figure 2 shows that the derailments, sorted by the number of casualties, were mostly brought about by reasons which were related not to the direct running dynamics of the vehicles, but to other infrastructure failures, excess speed, or broken components.

Date	Country	Place	Fats.	Inj.	Reason	Avoidable with WTMS?
03/06/1998	DE	Eschede	101	87	Broken composite wheel	No
29/06/2009	IT	Viareggio	32	27	Broken axle	No
02/12/1994	HU	Szajol station	31	54	Switch set incorrectly	No
31/03/1997	ES	Uharte Arakil station, Pamplona, Navarra	18	40	Speed excess	No
05/05/1997	PL	Reptowo, Szczecin	12	40	N/A	N/A
15/11/1992	DE	Northeim	11	0	Fallen steel bar caused derailment	Probably Yes
06/03/1998	FI	Jyväskylä	10	8	N/A	N/A
06/02/2000	DE	Brühl	9	52	Speed excess	No
12/01/1997	IT	Piacenza	8	30	Speed excess	No
20/07/2002	IT	Messina, Sicily	8	2	Track conditions	No
10/05/2002	UK	Potters Bar	7	32	Points equipment failure	No
21/08/2006	ES	Between León and Palencia.	7	6	Speed excess	No
30/11/1992	NL	Hoofddorp	5	6	N/A	N/A
11/09/1994	EL	Tithoréa	5	0	N/A	N/A
27/02/1995	ES	San Sebastian	5	33	N/A	N/A

Figure 2: Derailments in Europe with 5 or more fatalities since 1990 (data reprocessed from [9])

The biggest ever disaster in modern railways, the Eschede derailment in 1998, was caused by the failure of a "composite wheel", *i.e.* a wheel made of a steel web-hub part, a rubber intermediate element, and an outer steel tread. After a tyre failure, a part of the train hit a motorway bridge which, when it had collapsed, acted as a barrier for the remaining vehicles. After the accident all wheels of that kind were withdrawn from service, thus avoiding further possible accidents of the same kind.

The second accident, in terms of importance, was the Viareggio disaster (29 June 2009), which was, to some extent, the trigger for a set of actions taken at a European level to limit, as much as possible, the consequences of accidents involving dangerous goods. The accident, arising from a broken axle, led to the fracture of a tank containing LPG that caught fire: burning a noticeable part of the city; killing residents that were mostly sleeping in their houses. After the accident, the ERA set up a task force made up of experts in the field of freight wagon maintenance and railway axles, which included all the stakeholders (RUs, keepers, ECMs, suppliers, NSAs, etc.), with the aim of developing (1) urgent measures to follow-up information on problems with broken axles, and (2) to review the different maintenance regimes existing across Europe: drawing up a programme for further harmonisation [12].

In any case, it seems, from the available information, that disasters arising from exceptional situations can hardly be prevented by using wayside inspection systems; as long as they are not related to train interactions with the infrastructure that can be detected and modified by using the usual concept of wayside monitoring that will be discussed below.

Fire accidents occupy a much smaller class: with 21 casualties (2.1% of the total) and 10 people injured in only two accidents (06/11/2002, Nancy (FR), with 12 casualties; and 28/02/2008, between the railway stations Kunino-Cherven Briyag (BG), with 9 casualties and 10 people injured). In this case the incidence of fire in causing large disasters seems residual.

It could be concluded that investing large resources to prevent derailments and/or to avoid fires seems out of proportion to the danger. For derailment-related disasters it would appear to be absolutely useless, and, in the case of fire, there are other measures that could be more effective at a lower cost: such as on-board fire extinguishing systems for passenger cars. The rest of the paper, however, will show that the use of wayside monitoring systems can, nevertheless, be of great importance and effective, not only for safety, but also for the cost effectiveness of the railways.

4 Railway accidents: risks and dangers

Analysing the full ERA database, broadening the data to include those accidents with less than 5 fatalities, leads to a much larger number of accidents. Limiting the selection to derailments, for example, leads us to find that from 30.04.2003 to 30.01.2012 there were 310 derailments in the European network, while in the same period there were only two “serious accidents” arising from the same cause. Apparently the ratio of “normal accidents” and “serious accidents” is in the order of 1:150, leading to interesting considerations, which could be summarised as follows:

- a large number of derailments lead to a low number of fatalities
- this arises from the fact that derailments often happen at low speeds (on switches in stations, depots, and marshalling yards) in locations where track defects (twists) are typically found
- vehicles more subject to derailment are freight wagons which are stiffer (only one stage of suspension for two-wheel-set cars), possibly unevenly loaded and certainly less overlooked
- civilians and staff are affected by these "normal" derailments only when local conditions become particularly unfavourable.

Having said this, the importance of prevention seems crucial for railway operations, costs, effectiveness, and regularity. The consequences of a railway accident of any kind, and derailments are a particularly important case, can be measured by the immediate loss of regularity of the service and the enormous costs to restore the infrastructure. It should also be noted that most of the time the vehicles that were involved in an accident must be withdrawn as it is not economically viable to repair them; and the cost for a locomotive alone may amount to several million Euros.

Looking at the risk of a derailment as a statistical parameter, results in a very low figure. It would be hard to sum up all ton-kms run every day in Europe, however the number of derailments seems very low. The danger to people associated with derailments is not proportional to the risk. A trains mass and speed is such that no preventative measures can be taken to limit the consequences of an accident whose dynamics remain largely unpredictable. Therefore, we can never predicted when an apparently "normal accident" can turn into a "serious accident", or a disaster. If the axle in Viareggio had fractured some hundred meters away from where it did, then the racking pain of counting 32 people dead would probably not have been necessary.

This consideration alone therefore requires the deepest attention in looking carefully at the interaction of a running train: not only at the infrastructure, but also at the entire environment; including people who normally have nothing to do with railways.

5 Train interaction with the environment

A running train interacts mainly with the track and, for electric traction, with an overhead line or third rail. Therefore, it would seem that the most important parameters to check, in order to avoid undesirable consequences and potentially heavy losses, should be in these areas.

Nevertheless, an attempt was made to consider all possible interactions with the environment of a train pass-by, including those that are not apparently directly related to safety. Figure 3 shows a broad set of undesirable features, *i.e.* deviations from the "normally operating vehicle" with some additional properties and comments as follows:

- Localization: indicates where the problem is located on the vehicle. This may help to group sensors devoted to investigating a particular area of the vehicle.
- Safety related: indicates whether the consequences of the undesirable features may lead to a hazard for humans.
- Regular in-workshop maintenance: indicates if the parameter is subject to check, adjustment or repair during scheduled maintenance operations.
- Wayside detection: indicates weather the undesirable features are detectable with currently available combinations of sensor-processing techniques, regardless of the fact that a commercial system exists.
- Commercial system availability: indicates if one or more references were found on the Internet for measuring systems which claims to be capable of detecting undesirable features.

Generally speaking, a wayside train monitoring system (WTMS) has the highest value when it is able to avoid a potentially dangerous feature from resulting in fatalities or injuries. It must be said that the ALARP (as low as reasonably practicable) approach should be used throughout (in this area it has the recommendation of several inquiry commissions after some accidents, see *e.g.* [14]). For a risk to be ALARP, it must be possible to demonstrate that the cost involved in reducing the risk further would not be grossly disproportionate to the benefit gained. The ALARP principle arises from the fact that infinite time, effort, and money could be spent in the attempt to reduce a risk to zero. It should not be understood as simply a quantitive measure of benefit against detriment. It is more a best common practice of judgement in the balancing of risk and societal benefit (the reader is referred to [15] for an example of the implications on the British health and safety system).

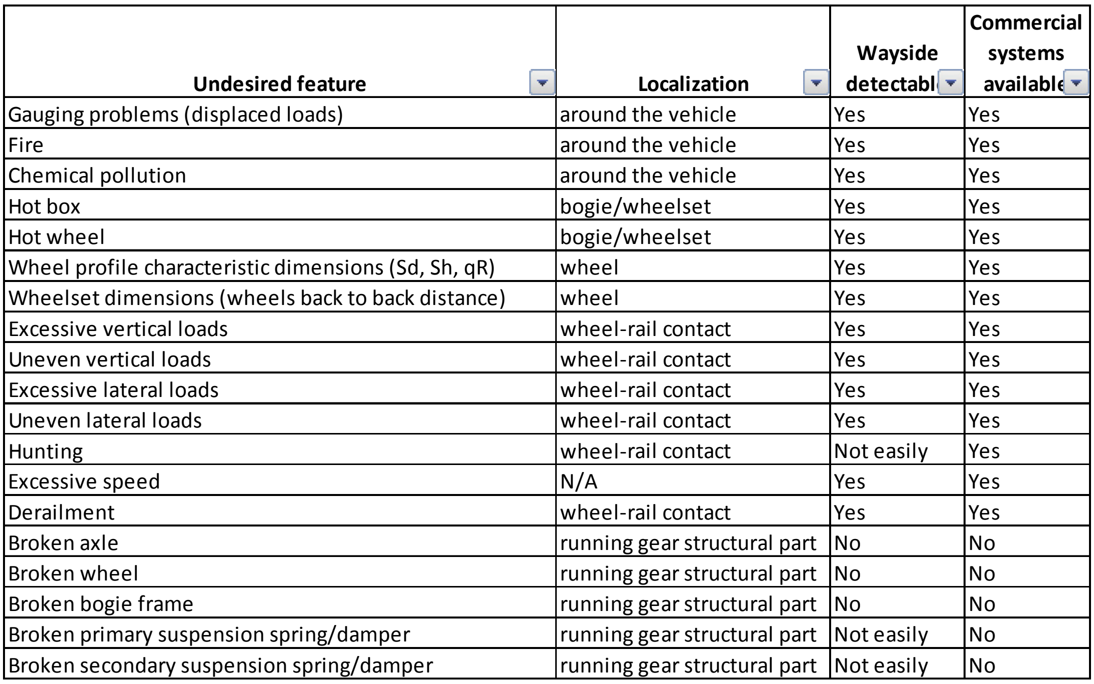
Figure 4, which is a subset of Figure 3, shows only the features that are potentially dangerous. It can be seen that the current market situation is relatively fair as long as commercial systems already exist for many of the features. Furthermore, for broken suspension components, that could possibly be inspected by image processing techniques, a large area remains to be researched in the structural area of running gears in the form of workshop NDT tests (like ultrasonic testing, magnetic particle testing, penetrant testing), which are normally used on wheel-sets and bogie frames. Apparently, they are unlikely be replaced by WTMS systems.

6 Safety-related wayside-detectable features

Although the main goal of this paper is to give the reader an overview of accidents, causes, and possible philosophies to reduce residual hazards to a minimum, it is nevertheless worth taking a look at some problems which may have potentially extreme consequences, *i.e.* those features that are directly related to safety. In the following paragraphs the possible causes indicated in Figure 4 are discussed and some examples are given of existing equipment that is currently available on the market. Note that there is no intention to be exhaustive in terms of possible suppliers and equipment; the devices reported below are intended only as a first glance at the market.

Undesired feature	**Localization**	**Safety related**	**Regular in-workshop maintenance related**	**Wayside detectable**	**Commercial systems available**
Broken pantograph	vehicle roof	Not normally	No	Normally not	No
Worn pantograph strips	vehicle roof	No	Yes	Yes	Yes
Strong EMI (Elecro-Magnetic Interference)	N/A	Not normally	No	Yes	Yes
Excessive pollution from Diesel loco/DMU	vehicle roof	No	Yes	Not easily	No
External noise	N/A	No	Not directly	Yes	Yes
Gauging problems (displaced loads)	around the vehicle	Yes	No	Yes	Yes
Fire	around the vehicle	Yes	No	Yes	Yes
Chemical pollution	around the vehicle	Yes	No	Yes	Yes
Groundborne noise and vibrations	far from the track	No	Not directly	Yes	Yes
Hot box	bogie/wheelset	Yes	No	Yes	Yes
Hot wheel	bogie/wheelset	Yes	No	Yes	Yes
Hot brake disk	bogie/wheelset	Not immediately	No	Yes	Yes
Wheel profile characteristic dimensions (Sd, Sh, qR)	wheel	Yes	Yes	Yes	Yes
Wheel tread roll-over	wheel	No	Yes	Yes	Yes
Wheelset dimensions (wheels back to back distance)	wheel	Yes	No	Yes	Yes
Out-of-roundness (in general) and polygonization	wheel	Not immediately	Yes	Yes	Yes
Wheel flats	wheel	Not immediately	Yes	Yes	Yes
Excessive vertical loads	wheel-rail contact	Yes	No	Yes	Yes
Uneven vertical loads	wheel-rail contact	Yes	No	Yes	Yes
Excessive lateral loads	wheel-rail contact	Yes	No	Yes	Yes
Uneven lateral loads	wheel-rail contact	Yes	No	Yes	Yes
Excessive angle of attack	wheel-rail contact	Not immediately	No	Yes	Yes
Squeal noise	wheel-rail contact	No	No	Yes	Yes
Flanging noise	wheel-rail contact	No	No	Yes	Yes
Hunting	wheel-rail contact	Yes	No	Not easily	Yes
Excessive speed	N/A	Yes	No	Yes	Yes
Derailment	wheel-rail contact	Yes	No	Yes	Yes
Broken axle	running gear structural part	Yes	Yes	No	No
Broken wheel	running gear structural part	Yes	Yes	No	No
Broken bogie frame	running gear structural part	Yes	Yes	No	No
Broken primary suspension spring/damper	running gear structural part	Yes	Yes	Not easily	No
Broken secondary suspension spring/damper	running gear structural part	Yes	Yes	Not easily	No

Figure 3: List of potential interactions of a running train



Undesired feature	Localization	Wayside detectabl	Commercial systems available
Gauging problems (displaced loads)	around the vehicle	Yes	Yes
Fire	around the vehicle	Yes	Yes
Chemical pollution	around the vehicle	Yes	Yes
Hot box	bogie/wheelset	Yes	Yes
Hot wheel	bogie/wheelset	Yes	Yes
Wheel profile characteristic dimensions (Sd, Sh, qR)	wheel	Yes	Yes
Wheelset dimensions (wheels back to back distance)	wheel	Yes	Yes
Excessive vertical loads	wheel-rail contact	Yes	Yes
Uneven vertical loads	wheel-rail contact	Yes	Yes
Excessive lateral loads	wheel-rail contact	Yes	Yes
Uneven lateral loads	wheel-rail contact	Yes	Yes
Hunting	wheel-rail contact	Not easily	Yes
Excessive speed	N/A	Yes	Yes
Derailment	wheel-rail contact	Yes	Yes
Broken axle	running gear structural part	No	No
Broken wheel	running gear structural part	No	No
Broken bogie frame	running gear structural part	No	No
Broken primary suspension spring/damper	running gear structural part	Not easily	No
Broken secondary suspension spring/damper	running gear structural part	Not easily	No

Figure 4: List of safety-related undesirable features and corresponding detection equipment

Information for equipment and manufacturers is commonly found on the Internet by using a search engine. To write this paper, the review [16] and the proceedings of the international conference that followed [17], were extremely helpful.

6.1 Gauge

Gauging problems can be serious for open freight wagons loaded with bulky goods (trunks, pipes, coils, etc.) that can displaced in service because of poor fixings to the car's superstructure. Generally speaking, other types of vehicles can also suffer from displacement of external surfaces (doors, panels of various kinds).

The most dangerous effect of exceeding a gauge is the possible collision with an oncoming train, or with a tunnel portal. It is not surprising, therefore, that profile detection systems are preferably installed at a short distance from the tunnel entrance: although this is not mandatory.

Profile measuring systems are typically made of laser scanners, either optical or radar [18, 19]. In some cases the resolution and the hardware/software processing capabilities are such that a very realistic image of the passing rolling stock can be achieved, from which it is also visually clear which part of the vehicle generated the alarm of "displaced object".

6.2 Fire and chemical substances

Fire detection is fundamental to avoiding terrible accidents inside tunnels. It is clear that stopping a train with a developing fire before it enters a tunnel is the best way to avoid the consequences of fire and (even more important) smoke to drivers and passengers. It should be said that, in the future, all passenger trains are likely to be equipped with fire suppression systems, but this remains a problem for freight trains in long tunnels with double tracks.

The philosophy of managing a fire inside a tunnel is based on the obvious conclusion that, if possible, a burning train should be brought out of the tunnel as soon as possible, and the entrance of other trains into the tunnel should be prevented. To limit the consequences of fires, all new base tunnels under the Alps will be built with two single tracks.

Fire detectors are normally constructed by using infrared sensors. Considering that the thermal power of a fire can vary between 0.1 and 150 MW, infrared emissions are therefore compared to a threshold (which, *e.g.* is set at 0.5 MW by SBB), and a decision is taken immediately whether to stop the train or allow it to proceed on its route.

An interesting discussion of infrared radiation wavelengths and practical detectability under solar exposition is given in [19], while a description of typical fires is given in [20].

While thermal checks are relatively well established, chemical hazard sources are not as well known. An analysis of the admissible concentration (TLV, Threshold Limit Values) of dangerous gases like methane, propane, chlorine, and ammonia, is given in [20]. It is clear that such concentrations can be reached after a leak from a freight car only in an environment which allows such a situation (*i.e.* typically in a tunnel and not in open air). The difficulty of measuring some substances (ammonia, chlorine) promoted a suggestion to limit the detection just to the total amount of hydrocarbons (a limit of 10 ppm is indicated in [20]), however, in the same reference an interesting risk assessment is made for the Swiss case.

6.3 Hot box/wheel/disc

The detection of hot axleboxes is probably the oldest wayside safety check regularly carried out by railway administrations. Hot axlebox detectors, HABD for short, are spread throughout the network of all the most important lines in Europe.

Their technology is well assessed and there are a number of suppliers of different systems in Europe. The development of this branch of WTMS is linked to the relatively frequent possibility that an axlebox is overheated by lubrication problems. Roller bearings are nowadays supplied with seals and a predetermined quantity of special grease. If, for any reason, grease leaks out of the seals, the temperature of the bearings increases due to the higher friction. This process inevitably leads to the destruction of the axlebox and to the consequent derailment of the axle concerned. It is, therefore, not hard to understand why, by the 1960s, research had started on the practical applicability of HABD.

Generally speaking, the concept of HABD can be implemented to check other parts that may be involved, although, to some extent, less directly related to safety in the sense that they are less likely to lead to derailments.

Tread (or block) braked vehicles may suffer from leverage blocking because of rust or other reasons, thus causing a freight car or a locomotive to continuously brake. This condition may lead to abnormal stresses in the wheels, to the possible loss of the wheel tyre (clearly only for composite wheels), and to high stresses in the wheel and the tyre (it is worth remembering that block braked wheels are painted with thermally sensitive paint, which reveal if a high temperature has been reached; and they are also painted with white signs showing if the tyre has rotated on the web).

Similarly, disc-braked wheel-sets may suffer from pad losses and brake cylinder malfunctioning. Consequences may be less severe for safety, but equally important for regularity: and in any case the technology to assess this problem is already available.

It is not surprising that HABD systems can also be extended to become HWD (Hot Wheel Detector), and/or HDD (Hot Disc Detector). Several suppliers can be found in the European market: the recent European Standard [21], dealing only with HABD systems, mentions the HWD systems as an extension, although it is not directly covered by the standard. A thorough review of the HABD, HWD and HDD systems in Europe can be found in [22], which discusses the approach of the various manufacturers (single beam, dual beam, multi beam and wide scanning by mechanically oscillating mirror systems are described in detail).

6.4 Wheel profile and wheel-set dimensions

Wheel profile measurement supplies some of the most important parameters for both safety and maintenance. Dimensions Sd, Sh, and qR: *i.e.* wheel flange thickness, height, and the size of the active flank of the flange, are directly related to both the safe passing through switches and crossings, and the scheduling of regular reprofiling maintenance operations.

The basic principle is the use of laser-optic modules activated by treadles which, by illuminating the wheel profile, can derive, by triangulation, the desired parameters. Conversely, for HSBD, which have to work at full speed on main lines, checking geometrical parameters is easier at low speeds and, as long as these geometrical characteristics vary slowly in time, a regular check at borders, main stations, or depots is normally more than sufficient. It could be said that a reasonable top speed for these systems should be in the order of 60 km/h.

Several suppliers offer systems with such capabilities, which can offer great advantages to the main infrastructure managers in assessing the status of the rolling stock travelling on their network. Smaller networks normally perform these checks by using manual instruments during regular, ordinary checks of rolling stock.

Concerning wheel-set dimensions, the only interesting dimension is the back-to-back wheels distance, which for standard wheel-sets on a standard gauge, is nominally equal to 1360 mm. It is trivial that when the profiles of the two wheels of a wheel-set are known also their distance will be also known. Less trivial is the consideration that this distance should not vary along the circumference but this condition is really quite rare and this is of lesser importance.

6.5 Lateral and vertical loads, hunting

Safety against derailment is conventionally expressed by the ratio Y/Q of the lateral force Y to the vertical force Q. Although this ratio is not sufficient to explain in full detail the mechanism of derailment, as many parameters (actual speed, suspension stiffness, dynamic effects, local value of the coefficient of friction, *etc.*) influence the phenomenon, it is clear that both lateral and vertical loads must be measured in order to estimate the Y/Q ratio.

The measurement of wheel-rail forces is possible through the measurement of the effect of these forces on the track. Several wheel load detectors have been developed around the world, based on the measurement of the vertical displacement of the track (or of the rail with respect to the sleepers), of the stresses in various parts of the rail, or of direct rail-sleeper force by means of load cells.

Fewer devices were developed to measure lateral loads: for several reasons. First of all, while the vertical load is a constant value on a straight track, lateral loads depend on speed and on many other characteristics of the vehicle (suspension longitudinal stiffness of the primary suspension, bogie-body rotational torque, *etc.*). The measurement of lateral force is therefore much more “local” than the vertical load: which can also be used as a “legal for trade” measurement of the net weight loaded on a freight wagon.

Vertical Q loads are particularly important in case the load can be displaced on a freight wagon, or in case a suspension is defective or broken. In these cases the distribution of the gross weight of the wagon is not even and this can lead to low local values of the Y/Q ratio, as long as Q decreases it becomes easier to exceed prescribed limits. This condition may degenerate when track twists are found with high wheel-rail friction coefficient and low dynamic actions: a situation that is typical of stations and marshalling yards where it is well known that the majority of derailments happen. Keeping freight car loading under strict control is therefore fundamental.

Abnormally high vertical loads can be given by local out-of-roundness of a wheel, normally due to sliding during braking. Wheel flats, as they are known, generate one impact per wheel revolution, and while their effect on the track is normally negligible, it can be harmful for bearings and wheel-sets. Data recorded at different times can easily highlight how vertical loads evolve with the evident implications on maintenance operations [17].

Some special considerations should be given to hunting phenomena. Hunting is a complex feature that happens when the so-called *equivalent conicity* γ_{eq} reaches locally high values. Like all instability phenomena, once started it only stops by noticeably lowering the speed; and if no special devices are installed on the vehicles to detect this condition, serious possibilities of damages or derailment exist.

High-speed passenger cars are all equipped with hunting detectors, while freight cars have no such devices. Moreover, freight cars have a mechanical arrangement of running gears which is less sophisticated than passenger cars (friction vertical dampers, only one stage of suspension, no anti-yaw dampers) and they run with extremely variable loads between tare and laden.

As with all phenomena, it cannot simply be stated that "if hunting does not happen here, it will not happen anywhere else", because the possibility cannot be eliminated in principle. Nevertheless, as long as a vehicle runs at reasonable speed in the conditions of loading which are known to be critical for that vehicle, an attempt to induce hunting can be done by locally modifying wheel-rail contact conditions, by increasing the locally equivalent conicity. It should be noted that γ_{eq} depends on the coupling of the profiles, and it is therefore impossible to have the same conditions for all vehicles as each of them will have, in practice, different wheel profiles. Nevertheless, there are some arrangements that are known to give *a priori* a higher equivalent coefficient, and this should be implemented in a measuring site to promote hunting. Between these, the simplest is to tighten the track gauge by keeping all the other parameters constant: although this measure is normally more efficient for rail inclination of 1:40 than for 1:20; the most efficient and elegant solution is to grind the rail to a specific profile in combination with the gauge tightening option.

Several systems exist to measure vertical loads, lateral loads, and hunting phenomena. The reader is referred to [23] for a description of the approach followed by Austrian railways to develop such a system.

6.6 Speed

Speed measurements, although extremely easy at a fixed location, are not considered as a required feature of a WTMS system. Speed is normally recorded in order to relate it to the measurement of performance, because many parameters are more or less directly related to it, but it is not by itself the reason for installing a WTMS. Speed is governed by the signalling system, which is far more complex and continuously distributed over a territory.

Saying how a WTMS system should be interfaced to a signalling system is a complicated task. The main question is whether the indications given by a WTMS system should be used to automatically restrict the speed of a train: for example when a hot wheel or a fire is detected. Signalling systems are extremely reliable, with redundant hardware and certified software, and must work in a fail-safe condition: *i.e.* if a signalling system fails, trains should stop safely without consequences other than service disruption.

False positives are always possible in any detection and analysis system, and would not be tolerated by railway users. The costs to link WTMS systems to local signalling devices could be even more costly than the WTMS itself when looking, for example, for a SIL4 (Safety Integrity Level 4) architecture. It is still being debated whether a system that is not intrinsically safe can be turned off without consequences for its owner in the case of an accident happening; certainly a fine balance of good sense and engineering knowledge will be required to carefully list all the requirements within the limits of the available budgets. It is a matter of fact that with a few exceptions (like HABD systems), the outputs of WTMS systems are analysed and "filtered" by the operators who judge the following actions in a non-automatic way.

6.7 Derailment

Once in progress, a derailment cannot be stopped. Many derailments have only limited consequences since, as previously mentioned, they happen at low speeds; when they happen, for various reasons, at high speeds and involving freight cars carrying dangerous goods, the consequences may be tragic: as in the accident in Viareggio.

It is well known that freight cars do not have any electrical systems, and that any vehicle-mounted device must be either mechanically or pneumatically actuated. Derailment detectors, which have been available for many years, are based on the principle that during the derailment the vehicle structure is subjected to extreme acceleration levels: large enough to active an automatic valve which discharges the brake pipe into the atmosphere. The train driver receives no information about what is happening to his train, and the train may stop anywhere. A large debate still exists in the railway sector about the efficiency and the applicability of such derailment detectors, and also the costs related to the application of such devices. Furthermore, the forecasted use of this equipment on wagons carrying dangerous goods may have limited efficiency as long as such wagons run in conjunction with other wagons that are not equipped with derailment detectors.

Restricting the field of the subject to the goal of this paper, it should be said that while a train may run for many kilometres with a fire on it, it will certainly stop within a reasonable distance after a derailment. When a train "breaks", in fact, the brake pipe is interrupted and the train stops in the shortest possible distance. The author carried out an investigation on a tank carrying 26 t of phosphoric acid which travelled for about 4.5 km after a derailment caused by a broken suspension leaf spring; but this is believed to be quite an extreme case. To the author's knowledge, only the "level 1" system described in [23] is currently offered on the market as a WTMS capable of detecting derailments at a fixed site. Nevertheless, the incidence of derailments is so low that the real effectiveness or need of such devices should be carefully considered.

6.8 Broken axle, wheel, bogie frame, suspension components

While some suspension components can be inspected automatically by means of an image processing technique: *i.e.* by automatically analysing the images provided by a high speed and high resolution camera; structural components cannot be inspected by WTMS.

This limitation is intrinsic to the kind of defects that cause failures of axles, wheels, and bogie frames. Cracks of a limited size normally start in the mechanical discontinuities (fillets, welds) for high stress or thermal reasons (wheel treads), and can be observed only by using the methodologies available: such as NDT (Non-Destructive Testing). In the aforementioned case of a broken leaf spring, such failures could not have been detected either by a WTMS system or by an operator during normal checks in service.

This field remains open to research and development, but unless there are dramatically new technologies, it will be confined to maintenance workshops.

7 Vehicle identification

Before concluding, it should be highlighted that until now one of the most important reasons preventing the large scale use of WTMS systems in Europe is the absence of a common vehicle identification procedure which can be used when a train passes in front of a WTMS.

Tags/readers and RFID systems have non-negligible costs when applied to large fleets, while optical recognition of international marking has to face the enormous variety of shapes, colours and positions of vehicles and markings.

Until a unified approach to vehicle marking has been decided and implemented, a truly automatic vehicle detection service remains an almost impossible task: virtually impairing all the efforts made to build and deliver reliable and low cost advanced WTMS systems.

8 Conclusions

This review paper aimed at describing the current Wayside Train Monitoring System technology with particular reference to devices and technologies which are readily available on the market.

After a first general description of the interaction of a train with the environment and the analysis of officially available data on accidents, a distinction was made between safety critical and maintenance related characteristics exhibited by a train during a pass-by. The rest of the paper was devoted to the analysis of safety related issues which, in some terms, require that WTMS systems should be implemented throughout Europe; the analysis of those parameters that are related only or mainly to maintenance, which only suggest that WTMS systems could be implemented, was not considered here.

The attempt to give a reasonably complete description of the current scenario is further complicated by a reality which is extremely dynamic, and by the fact that the whole world, and Europe in particular, is facing a financial and political crisis which will force all the players in railways to re-consider policies and strategies. It is, nevertheless, hoped that the curious reader will look for updated information and characteristics by browsing the Internet and participating in conferences and trade fairs in the railway sector.

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