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Perspectives on railway track geometry condition monitoring from in-service railway vehicles

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This paper presents a view of the current state of monitoring track geometry condition from in-service vehicles. It considers technology used to provide condition monitoring; some issues of processing and the determination of location; how things have evolved over the past decade; and what is being, or could/should be done in future research. Monitoring railway track geometry from an in-service vehicle is an attractive proposition that has become a reality in the past decade. However, this is only the beginning. Seeing the same track over and over again provides an opportunity for observing track geometry degradation that can potentially be used to inform maintenance decisions. Furthermore, it is possible to extend the use of track condition information to identify if maintenance is effective, and to monitor the degradation of individual faults such as dipped joints. There are full unattended track geometry measurement systems running on in-service vehicles in the UK and elsewhere around the world, feeding their geometry measurements into large databases. These data can be retrieved, but little is currently done with the data other than the generation of reports of track geometry that exceeds predefined thresholds. There are examples of simpler systems that measure some track geometry parameters more or less directly and accurately, but forego parameters such as gauge. Additionally, there are experimental systems that use mathematics and models to infer track geometry using data from sensors placed on an in-service vehicle. Finally, there are systems that do not claim to measure track geometry, but monitor some other quantity such as ride quality or bogie acceleration to infer poor track geometry without explicitly measuring it.

Keywords: condition monitoring; track geometry; fault detection; fault diagnosis; maintenance

1. Introduction

This paper presents a view of the current state of monitoring track geometry condition from in-service vehicles. It considers technology used to provide condition monitoring; some issues of processing and the determination of location; how things have evolved over the past decade; and what is being, or could/should be done in future research.

Monitoring and inspection are different things. Railway track inspection focuses on the safety of the track, traditionally assured by the use of a dedicated track recording vehicle (TRV) or hauled track recording coach (TRC) running around the rail network gathering track geometry data. Monitoring, on the other hand, focusses on faults and supports efficient maintenance. It is interested in identifying faults, diagnosing the causes of faults, and predicting when an irregularity will become a fault.

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Modern electronics and the development of robust sensors made possible track geometry inspection systems that are compact and robust enough to be mounted underneath in-service vehicles. In June 2002, Network Rail promised unattended geometry measurement systems (UGMS) to be placed on in-service vehicles to survey heavily used lines without interrupting the normal traffic. There are now unattended track geometry measurement systems running on in-service vehicles in Britain that are collecting full track geometry. The data are saved in large databases from which geometry can be viewed.

Despite the push for UGMS on in-service vehicles, many track condition monitoring systems that do not give full geometry have been developed, and a few commercialised. For example, left and right accelerometers and displacements transducer measure the vertical rail profile on the channel tunnel rail link (CTRL) with the 200 m section standard deviations and spot faults transmitted to a central server.[1] Deutsche Bahn (DB) have been successfully running ICE 2 trains with accelerometers on for some time.[2] In Japan, axlebox accelerometers have been used on high-speed trains for a long time.[3] However, the use of accelerometers on axleboxes seems to be falling out of favour because of issues with maintaining them. More examples appear in Section 2.4.

There is also the possibility of measuring the movement of a bogie or even the car body from which the track geometry can be estimated using an inverse model and advanced mathematics. The choice of sensors and their positioning on the in-service vehicle is an important consideration, both from the point of view of what type of track geometry can be detected and practical issues to do with maintainability and robustness. The authors of the current paper started experimenting with sensors on an in-service vehicle in the mid-2000s [4]. There is a question over whether the track geometry is explicitly needed. If the bogie follows a smooth trajectory down the track, then the track geometry must be reasonably good. Conversely, poor track geometry almost always leads to something detectable in the trajectory of the bogie. Some effort has gone into turning sensor data into pseudo-geometry, that is, the geometry as experienced by the bogie ignoring the primary suspension.[5,6]

London Underground experimented with accelerometers on the bogie and body of metro vehicles where the acceleration itself was viewed against distance along the track.[7] There was no attempt to reconstruct geometry. Instead, high accelerations were associated with poor track geometry. The problem of different acceleration with different vehicle speed was dealt with by virtue of the fact that the speed profiles between platform stops on a metro tends to be the same. Recently, however, London Underground has started to fit UGMS systems to its vehicles.[8]

A large quantity of data can be collected from sensors mounted on an in-service vehicle, but this needs to be reduced to useful information locally as it is not practical to transfer all the raw data from the vehicle to a central server. Some information that was present in the sensor data can easily be lost if the data reduction is too great, but this problem is becoming less as mobile communications technology improves. The server needs to be able to handle large quantities of data as in-service vehicles typically cover the same track many times each day compared to a dedicated TRV that traverses the track only once every few weeks.

Condition monitoring of fixed assets, such as point machines, track circuits, and so on, does not rely on location to identify the asset. Similarly, collecting data on assets fixed to a moving platform is not a problem. However, data collected about the fixed infrastructure from a moving platform require that the line, location, and direction of travel associated with the data are known.

Track condition information gathered from multiple passes over the same track in the same, or opposite direction, needs to be collated and processed jointly to obtain information about the progress of faults and to identify when maintenance might become necessary. This applies

to track geometry or pseudo-geometry. Mutual alignment between data from different runs needs to be carried out accurately so changes can be quantified by an automatic system.

Additional information may be needed, such as the location, time, and description of maintenance activities, not just on the track, but also on the instrumented vehicle itself. Wheel turning reduces noise in the pseudo-geometry for systems that are not independent of wheel condition. By knowing what track maintenance has occurred, it should be possible to see if that maintenance was effective and whether the improvement lasts.

The first part of this paper reviews sensor systems that have been developed for gathering track condition information from in-service vehicles. A range of systems from full UGMS mounted on the bogie of an in-service vehicle to a lone accelerometer are discussed. The next part of the paper discusses some issues that are common to many sensors placed on in-service vehicles to look at track condition, including the issue of localisation of the collected data. Following this, a discussion of the processing that takes place in a central location is presented. Finally, the potential use of data and what could be done to improve the data are discussed.

2. Systems

Track geometry condition monitoring systems suitable for application on in-service vehicles, or being researched, are discussed in this section. The sensors used range from full UGMS to 'single sensor' solutions. The track geometry is either measured using UGMS; estimated using some mathematics and model-based estimation; or the track condition is inferred and no attempt is made to describe the underlying track geometry, just that the response of some part of the vehicle was exceptional so there must be a problem with the track.

2.1. Track geometry defects

Typical track geometry parameters collected during inspection include: left and right vertical rail profile, lateral alignment, gauge, cross-level, twist, dipped joints, corrugation, and cyclic top.[9] There are thresholds defined for individual faults, and statistical measures of track quality such as standard deviation of 35 m top over 200 m sections (1/8 mile). These specifications for track geometry inspection equipment have been driven by the reports that have historically been required to assure safe running of vehicles on the track. Meeting the track geometry requirements is not necessarily a guarantee of safety. More advanced tools such as VAMPIRE, which is used to simulate trains on measured geometry to predict potential problems such as wheel climb, are used to develop a detailed understanding of track–train interactions.

2.2. Inspection or monitoring of track geometry or condition

One of the oldest in-service vehicle track condition monitoring approaches relied on the influence of the track condition on the ride quality as observed by the passengers or by the train driver. A damped pendulum with an inky tip drew a line on a moving piece of paper, providing indications of large lateral body movements that indicated that the track condition was poor. The means of knowing the location of the fault is not clear, but presumably relied on an operator marking the position of station stops and mile markers on the paper. By knowing the approximate speed of the vehicle, or the line speed profile, the location of a fault could be identified with some degree of accuracy.

Traditionally, a TRV or TRC travelled over the railway network to measure the track geometry. While not an in-service solution, the modern TRCs are effectively fitted with track geometry recording systems that could be fitted to in-service vehicles.

The custom built measurement train can be maintained regularly and during data collection, it does not have to stop very often. An in-service measurement system is more difficult to maintain as it is a specialist piece of equipment, and while taking measurements the in-service vehicle is likely to come to a halt much more frequently than a dedicated measurement train. The consequence of moving slowly and coming to a stop is a loss of accuracy in the geometry data.

The remainder of this section gives information on the current state of track measuring/monitoring systems, starting with full UGMS, going on to give details of industrial use of other sensors sets, and ending with academic sensor set systems.

2.3. UGMS

New fleets in the UK are specified to have UGMS installed on a proportion of a new fleet. For example, the tender for the new intercity express programme (IEP) vehicles includes the requirements to monitor the infrastructure.[10] Of relevance here is the requirement that a proportion of the fleet must be fitted with a UGMS capable of obtaining the parameters listed in Table 1. In addition, ‘train speed with ± 2 mph and train position by differential global positioning system (DGPS)’ must be recorded, and

the location of the geometry systems must be repeatable to 1 m (run on run) with absolute location of the network being determined to within 3 m in terms of miles and yardage. All data must be attributed with the correct Engineers Line Reference/Track ID.

Data must be saved every 0.2 m along the track being monitored. The UGMS requirements give a good idea of what data will be collected and how much will be saved, but it does not give exact details on the filtering processes that might be required. If the geometry is available every 0.2 m and can really be identified in position within 3 m of an absolute position, then the system will be doing very well. DGPS can give a theoretical position accuracy of around 1.0 m, but this is not easy to achieve from a moving railway vehicle, even in ideal conditions without reflections or obstructions. It is difficult to imagine the localisation requirement being met consistently by a UGMS in practice.

2.4. Track condition monitoring systems on in-service vehicles

There are remote track condition monitoring systems running on in-service vehicles without a full UGMS system. A sample of these is discussed in this section.

Table 1. Requirements of UGMS fitted to IEP fleet.[10]

Parameter	Repeatability of geometry signal (mm)	Repeatability of statistical data (1/8th mile standard deviation) (mm)
35 m top (left and right rail)	± 1	0.1
70 m top (mean)	± 1	0.1
35 m alignment	± 2	0.2
70 m alignment	± 2	0.2
Gauge	± 0.5	0.1
3 m twist	± 1.5	0.15
Curvature (versine from a 20 m chord)	± 1	0.1
Cross-level	± 1.5	0.15

A remote condition monitoring system mounted on Acela trains (USA) monitors accelerations on the body and bogie, reporting high values.[11] This is mandated by the FRA (US Federal Railroad Administration) for high-speed trains. This system provides measurements of car body vertical acceleration, car body lateral acceleration, and bogie lateral acceleration. The paper presents the system as being appropriate for 'inspection' of track parameters, but in reality the results are more aligned to monitoring. Events are triggered by excess acceleration, and reported using mobile phone technology. A GPS module is used to tag the data with time and location information, claiming only to be within 200–300 ft (60–90 m) of the correct location. This error is significant and could be because of the position of the GPS antenna which appears to be on the side of the bogie.

Vertically and laterally sensing accelerometers have been added to in-service London Underground vehicles to monitor track geometry.[7] One problem seems to be that the speed of the vehicle is not taken into account in the processing, so the accelerations will increase with vehicle speed. Comparisons between runs are only possible as most underground trains follow more or less the same speed profile between station stops.

A track geometry monitoring system that is not a full UGSM is the TrackLine system from AEA technology (now DeltaRail).[12] This provides accurate vertical rail profiles using vertical acceleration on the bogie above the axlebox together with a vertically sensing displacement transducer to the axlebox. The vertical track geometry with standard deviations over 200 m sections is computed on board and sent over GPRS. The results can be compared in the office to see degradation in track geometry over time, to enable tamping or stoneblowing to be scheduled. This system is used on the CTRL between London and Paris/Brussels.[1]

DB have had an accelerometer-based system running on ICE 2 trains since 2004.[2] The measurement system is based on accelerometers alone, avoiding the use of optical technology due to in-service robustness issues and the need for lenses to be cleaned. The experience with accelerometers has been favourable. This is an example where a full UGMS has not been used, but the results have been trusted to give sufficient information on track geometry to be a useful tool for planning maintenance.

In [13], is described a system that attempts to identify vertical and lateral track geometry irregularities using accelerometers placed on the body of Japanese in-service vehicles. This approach requires modelling the dynamics of the primary and secondary suspension systems, and also has an acoustic sensor (a microphone) to listen for corrugation faults. This system relies on irregularities in the track geometry passing into the vehicle body, which is found to be possible on high-speed lines, but the newer N700 Shinkansen trains have such good suspension that this was no longer adequate. In response to this, a new system 'RAIDARSS-3' was made from 2009 with axlebox-mounted, vertically sensing accelerometers. These are doubly integrated and treated with a 10 m versine measurement processing to obtain geometry. This has been validated against dedicated TRV results.[14] Events are defined as accelerations exceeding a threshold level, or track irregularities exceeding given threshold levels. A unique sensing feature of this system is detecting trains passing, presumably as these cause significant body accelerations that might otherwise be identified as track irregularities. However, the authors report that axlebox-mounted accelerometers are difficult to maintain, so there is currently a renewed effort to reconstruct track geometry from car-body accelerations, using a Kalman filter and inverse modelling.[15] This system is still evolving.

SNCF (France) have been experimenting with accelerometers mounted on an in-service vehicle to measure track geometry parameters.[16] This was partially in response to the difficulties of running the existing TRV at a high enough speed to fit on the high-speed TGV trains, although a higher speed dedicated inspection train was being developed at the time.

Data are tagged with Global Navigation Satellite System (GNSS) position information and sent via 3G link to a central server.

The systems described above, and, no doubt, other similar ones, have been applied to in-service railway vehicles in an industrial way. The systems described in the next section are grouped together as more experimental, temporary, and one-off systems.

2.5. Academic and experimental systems

The Japanese research reported in [3] describes the use of a bogie-mounted, vertically sensing accelerometer on the bogie plus a vertically oriented displacement sensor from the bogie to the axlebox to observe vertical rail geometry. This paper contains interesting technical information on the processing of the accelerometer data to give versine (chord) type data. The system is similar to the vertical monitoring described in [12].

The authors of the current paper have been experimenting with in-service track geometry monitoring since 2003. A large number of sensors were attached to a Tyne and Wear Metro (heavy metro in Newcastle, UK) to observe track geometry from an in-service vehicle. Some results from this trial were published in [4–6,17]. A system based on an inertial measurement unit (IMU) alone has been trialled on Merseyrail (a heavy metro in Liverpool, UK) and also is in use on the Southern network in the UK as part of a third rail condition monitoring system.[18,19]

A tri-axis accelerometer has been fitted in the body of a Japanese in-service vehicle running on a local line (regular stops) with GNSS.[20] There is no connection to a tachometer signal, instead the speed is generated from a combination of GNSS, double integration of longitudinal acceleration, and identifying when the vehicle has stopped at a station stop. The rms vertical and lateral accelerations are taken as indicators of vertical and lateral track geometry. The thresholds for acceptable rms accelerations increase with increasing vehicle speed.

Vertically and laterally sensing accelerometers mounted on the body and axleboxes of a Japanese mainline railway vehicle, in addition to a microphone, have been used to detect track geometry faults and vehicle faults.[21] In this case, there are no sensors on the bogie frame. This is the research part of the ongoing Japanese in-service track geometry monitoring system. The objective was to move towards a track condition monitoring system that could operate using sensors mounted only inside the vehicle body. In the paper, the data processing involves multiresolution analysis of the data, using wavelets.

Track irregularities with wavelengths greater than 20 m are identified from accelerometers mounted on the body, bogie, and axleboxes of an in-service high-speed train in Italy.[22] The processing described in this paper is carried out in the frequency domain, with an attempt to invert the dynamics of the train suspension. The paper includes detail about the issues with sensor noise from accelerometers mounted in various locations on the train and also considers the effects of uncertainty in the suspension system parameters.

An experimental set-up on an Italian metro vehicle has left and right vertically and laterally sensing axlebox-mounted accelerometers to identify corrugation problems as well as accelerometers on the bogie and inside the body that are used to identify track condition.[23] A few other sensors help to identify curving to get some idea of location as GNSS is not possible underground. Corrugation is not addressed by most UGMS, only those augmented with axlebox-mounted accelerometers. The paper comments on the need to ensure that the wheel treads are in good condition to avoid contaminating the data with unwanted noise signals.

An in-service Korean high-speed vehicle used axlebox- and bogie-mounted inertial sensors to monitor the condition of track.[24] The results were compared to a UGMS attached to the same vehicle. The simplified sensor set system is able to detect track geometry irregularities

reasonably well, but the focus is on reproducing the UGMS track geometry. Another paper by the same team compares the use of axlebox accelerometers to the use of bogie-mounted accelerometers.[25]

Bogie-mounted, laterally sensing accelerometers and body-mounted accelerometers placed on a Chinese railway vehicle together with complex processing are used to identify track geometry anomalies in [26].

In India (presumed), the vertical and lateral accelerations on axleboxes and on the bogie frame of an in-service vehicle are being trialled to provide track geometry irregularity warnings with position straight from GNSS.[27] A fuzzy logic system is taught to recognise various geometrical fault conditions. The accelerometers used are low-cost micro-electro-mechanical system (MEMS) devices that seem to provide enough signal to noise ratio to allow for double integration. However, low-cost MEMS sensors generally have significant noise levels and poor long- to medium-term stability so are generally best for identifying only shorter wavelength irregularities.

A German in-service regional railway vehicle with an IMU in the body can identify many track features.[28] The positioning is based on GNSS, and there is no connection to a tachometer. This system is at an early stage and the IMU picks up locomotive vibrations and other unwanted signals.

As part of the European Commission Framework Programme 7 (EC FP7) AUTOMAIN project, a freight train was instrumented with vertically sensing accelerometers attached to a freight locomotive. This provided vertical left and right rail geometry that could be mutually aligned and compared.[29]

It has been found in the literature that sometimes a solution to a particular problem is described. For example, the use of vertically sensing, axlebox-mounted accelerometers to identify corrugation, or to monitor joints.[30] By focussing on one aspect of track geometry, the sensors can be chosen to work for the particular application but generally cannot then be used to achieve additional functions. An accelerometer that is very good for identifying corrugation may not be able to, nor need to, have low enough drift to be useful for identifying long wavelength geometry.

2.6. Conclusion

Axlebox accelerometers for vertical track geometry are often thought of as being a good way to identify the vertical rail profile. However, the required double integration gives rise to some problems, and maintaining the sensors on axleboxes has proved difficult in practice. A more robust solution has the sensors on the bogie, including the full UGMS solution with an IMU on the bogie and optical sensors looking at the rails. An even more robust solution is to place the sensors on the car body, but then there are some problems caused by the isolation of the primary and secondary suspension systems. The next section looks at common problems with sensors and some common issues experienced with track geometry monitoring systems such as sensor errors and location problems.

3. Sensors

Sensors, when placed on a rail vehicle, do not always perform perfectly. There are problems common to different sensor types and systems. This section will look at how data are collected on the train and how local processing can be used to turn raw sensor data into information that can feed into the decision-making processes of a maintenance engineer.

3.1. *Tachometer/odometer*

A tachometer measures the speed of rotation, an odometer measures the distance travelled. Typically on a road or rail vehicle, the tachometer measures the speed of rotation of an unpowered wheel and the odometer is the integration of the tachometer with respect to time multiplied by the wheel circumference to convert rotations per unit time into distance.

Older tachometers are often based on an inductive sensor closely coupled to a toothed gear. Pulses generated as each tooth of the gear passes the inductive sensor are detected and converted into an analogue signal proportional to speed. This signal can directly drive an analogue indicator in the driver's cab. Alternatively, the analogue speed signal from one tachometer can be combined with others to provide wheel slip detection as well as a driver speed indication. This sort of tachometer has several problems when used for determining the distance moved along the track between two events. At low speeds, the analogue signal is typically dead as the inductive sensor does not detect slowly moving teeth. If detection is made the analogue signal is not proportional at low speeds due to inaccuracies in the analogue circuitry. The constant of proportionality between the analogue signal and speed is often adjustable so that the analogue signal output can be adjusted when the wheels are turned and their diameter goes down. Inaccuracies remain from the wheel wear, and from the fact that the rolling radius of the wheels varies along the track and there is some slip at the wheel–rail contact point. The wheel may even slide along the track when adhesion is poor, resulting in poor distance measurement.

More modern tachometers use more direct digital signals, for example a magnetic ring magnetised with an alternating direction magnetic field with a magnetic field detector. This is incorporated into the bearing structure and provides hundreds of pulses per revolution and may even give the direction of rotation. The pulses can be counted directly without needing to generate an analogue signal.[19] Changes in wheel diameter can be known from maintenance activities such as wheel replacement or turning, but there remains uncertainty of rolling radius and changes in wheel diameter through wear and the effects of loss of adhesion.

Sometimes it is assumed that a tachometer together with an approximate starting position solves the problem of localising events, but tachometers have problems. The tachometer can, at best, only identify the distance between events. It cannot even do this very accurately over long distances (km). Problems include wheel slip or slide, changing wheel diameter, varying rolling radius. There is a variable creep at the wheel–rail interface. Another problem is that the distance travelled by the wheel does not match the track length as the wheelsets do not travel exactly along the track but tend to wander left and right, taking a slightly longer path.

Even if the odometry was exact, there is another more fundamental problem in that the distance along the track between two locations on the ground along the track is not known exactly. When the track was designed, there would have been a good idea of the length of rails needed, but the actual installation results in a distance that is not known precisely. The mile markers along the side of the line cannot be accurate for all tracks, and in some cases the mile markers are quite in error because of changes to layouts. At the decimetre level, temperature changes affect the distance between two marks drawn on a rail, so the distance along the track between two places can never be truly known.

Hence, measuring the distance between events starts to appear to be a hopeless exercise. While the tachometer gives a good observation of the distance between two events, it does not provide an error-free measurement. The accumulating error must be included in any processing that uses the tachometer signal for distance estimation.

Odometry problems and algorithms for solving these problems have been discussed by Allotta et al. [31] where the importance of localisation with regard to signalling is the main

concern, in particular when there is a loss of adhesion and, therefore, loss of positional accuracy. This technology can be used to assist with the general location problem as required when identifying the location of track geometry defects.

Radar-based speed measurement systems allow the train speed to be measured by detecting the motion of the ground under the train with a forward-facing radar system. The system can be mounted underneath a vehicle and operates fairly well. This system is robust in the face of wheel slip, but may be confused in the presence of flat lying snow, for example.

A novel use of data from on-board inertial sensors is the estimation of absolute speed based on correlation of the input from the track to the leading and trailing wheelsets on a bogie.[32,33] An inertial sensor is placed on the bogie of the vehicle. By knowing the bogie wheelbase and the delay between the same input exciting the leading and trailing wheelsets, the vehicle speed is computed. This results in a good estimate of the speed of the vehicle that still works if either wheelset slips.

Techniques to correct distance errors for mileposts that are described as being up to 200 m in error by using the position of what is termed 'key equipment', meaning turnouts, curves, metal between the rails as found at switches and on steel bridges and elsewhere.[34] DGPS is cited as a method for correcting location information that can be used when the infrastructure is set up for this, and another method cited for more accurate positioning is the use of radio frequency identification (RFID) tags. However, these two innovations are discounted for reasons of cost in the railway line of interest to [34] in favour of using features in the track itself. In the paper, extensive examples of alignment of collected data to the reference map are shown, but the results are still in error by between 1 and 7 m (approximately). It is noted that the reference map often contains slight errors and potential inconsistencies. What is striking about the example plots is that the human eye can see exactly how to mutually align two TRC geometry traces with great precision, that is, better than a fraction of a metre. Mutual alignment between runs is much easier and more accurate than matching each run to a reference map. This is particularly true for in-service data where the data can come from the same track many times in a single day and the change in geometry is small (except after maintenance activities).

3.2. *Inertial sensors*

Inertial sensors include accelerometers and gyroscopes. With the introduction of MEMS technology, inertial sensors have become smaller, use less power, have better performance, and are lower cost. However, budget MEMS accelerometers and gyroscopes are not of sufficient quality to measure track geometry. The majority of the work carried out by the authors of the current paper has used tactical-grade MEMS inertial sensors that cost hundreds of pounds per channel but not thousands. If good quality sensor data are collected initially, it is possible to add noise artificially to see what would have happened if a noisier sensor had been used. Academic papers that present the results of real-world trials on railway vehicles rarely reveal the specifications of the sensors used.

The acceleration caused by track geometry is proportional to the square of the longitudinal speed, proportional to the amplitude of the geometrical irregularity, and inversely proportional to the square of the wavelength. A sinusoidal vertical geometrical irregularity with an amplitude of 10 mm and a wavelength of 50 m gives an acceleration of 0.32 ms^{-2} at 45 ms^{-1} , but gives 0.0032 ms^{-2} at 4.5 ms^{-1} . The vertical acceleration on an axlebox can be up to 100 g, occasionally exceeding this if a wheel hits a badly aligned rail joint at speed. Compared to an axlebox acceleration range of $100 \text{ g} = 981 \text{ ms}^{-2}$, it is not surprising that trying to observe long wavelength geometry from an axlebox-mounted accelerometer is technically

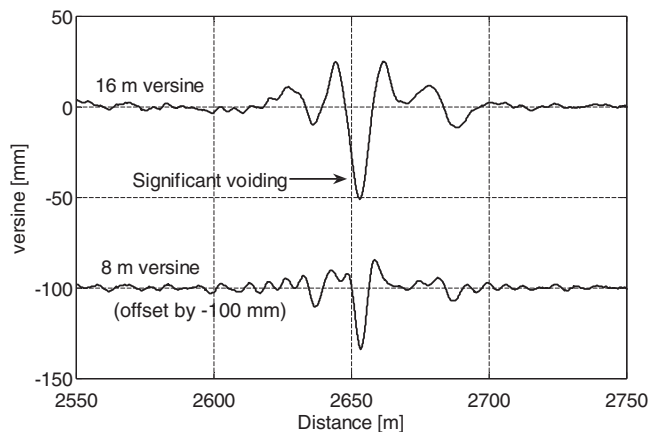


Figure 1. Tyne and Wear Metro, significant voiding.

challenging, especially at low speeds as may be encountered as an in-service vehicle slows down for station stops. Grassie [35] describes vertically sensing axlebox-mounted accelerometers as a practical way to measure vertical rail profile, but the requirements on the axlebox accelerometer in terms of offset and drift are severe if this is to reveal vertical track geometry at long wavelengths.

AEA's now retired Lab5 TRC had vertically sensing accelerometers mounted on the body and the displacement across the primary and secondary suspensions was measured. The accelerometer on the body only needs a range of less than $1\text{ g} = 9.8\text{ ms}^{-2}$, so the small accelerations associated with long wavelength geometry are relatively easier to measure. Improvements in accelerometer technology mean that AEA's TrackLine system places the accelerometer on the bogie, where vertical accelerations are typically no more than $10\text{ g} = 98\text{ ms}^{-2}$, and measures the displacement to the axlebox.

Historically, gyroscopes were sensitive to accelerations, but improvements mean that it is practical to operate a gyroscope on the bogie of a railway vehicle, but it is not yet practical to operate one on an axlebox. Fortunately, this is not required in relation to track geometry, but it might be desirable for other purposes. Yaw rate and roll rate gyroscopes have been used on track geometry measurement systems for a long time,[36] but the authors have found that using pitch rate gyroscopes on the bogie of in-service vehicles provides really useful information, in particular in comparison to accelerometers at low speeds as are often found in in-service vehicles that make station stops.[5,6]

Figure 1 shows 16 and 8 m versines computed from the pitch rate gyro mounted on the bogie of a Tyne and Wear Metro vehicle. As described by Weston et al. [5], the versine is computed from the pitch rate gyro and tachometer data by converting to a pseudo curvature signal and then to a versine value. The 16 m versine is almost 50 mm down, which is a significant depression in the track over a 16 m chord. It is most likely associated with voiding or a wet spot. The 1 m versines from the axlebox (not shown here) do not indicate any short wavelength anomaly, so the depression is not associated with a joint or other discontinuity. The 8 m versine shows about a 30 mm dip, which is consistent with significant voiding.

3.2.1. Sensor offset drift

Gyros, accelerometers, and most other sensors have an offset that can be nulled during initial calibration. However, the offset tends to drift over time mainly because of changes in

temperature, but also because of supply voltage variations or environmental factors, or simply because of aging of materials. Changes in offset over a period of tens of seconds have been seen by the authors on accelerometers attached to axleboxes every time the vehicle came to a stop. This was identified as a thermal effect linked to the axlebox warming the sensor while the train motion through the air generated a cooling effect. On reaching a stop, the sensor would rapidly warm up as the cooling effect of the air had disappeared and, as a result, its offset drifted rather quickly. This effect was eventually avoided by placing the sensor inside a plastic box. Offset drift is generally slow, but when looking for geometrical effects with 70 m wavelength a slow offset drift can still be a problem. The offset has a profound effect on the results of, for example, double integration from acceleration to displacement. Temperature changes found outside of the vehicle body, exposed on the bogie frame or on the axlebox, can be considerable. For example, a sensor can be frozen in winter, or be in a 140 mph air stream, or a sensor on an axlebox can be warmed from the bearing. Typically, higher specification sensors have small offset drift.

Gyroscope and accelerometer offset (drift) can be compensated for in a frequently stopping in-service vehicle by assuming that the gyro signal should be zero when the vehicle has been stopped for a short time. Assuming that the bogie becomes essentially stationary when the vehicle is at a stop, the offset can be modelled and forced to go through zero at a station stop. Rather than resetting the offset to zero when the vehicle stops, introducing step changes in sensor readings that are not good, this problem is an ideal application for modelling, estimation and Kalman filtering, or, better, optimal smoothing. In effect, one is providing the additional observations that when the vehicle speed is zero, the turn rate of the gyro will be zero (allowing some time for the bogie to settle).

3.2.2. *Integration and double integration*

Double integration of acceleration to obtain position is always needed. It is sometimes assumed that if the acceleration error has zero mean, then doubly integrating it with respect to time to give position will result in a position with zero mean error. In fact, it gives position plus the integration of a random walk, which is an out of control error that grows very rapidly. Double integration is only stabilised by adding a high-pass filter, but this cannot remove the problems caused by any amount of offset drift, which by its very nature is a slow phenomenon.

Many different techniques to deal with the problems of double integration of inertial sensors are described in [37]. There is, however, a limit to what can be extracted from double integrating an accelerometer. The noise from an accelerometer (and from the signal processing chain including the analogue to digital conversion) will always have some effect on the results.

An example of processing of doubly integrated accelerations is to give versine results.[17] The axlebox accelerometer signals are turned into 1 m versine results using a simple processing chain that converts from acceleration to curvature (using the vehicle speed) and from curvature to 1 m versine. Figure 2 shows an example of dipped joints. There are dipped joints following a regular pattern of 18 m spacing (60 foot rail lengths) with some joints better than others. An extra joint is visible in the data, providing a potentially useful reference position. The raw accelerations are less good for condition monitoring as they vary considerably with vehicle speed and are more affected by high frequency vibrations. For the example given, the wheel condition of the vehicle is not very good, so the results are quite noisy.

Figure 3 shows 1 m versines from an axlebox accelerometer over a pair of switches and crossings that form a crossover. There is a crossing in the left rail first, and then a crossing in

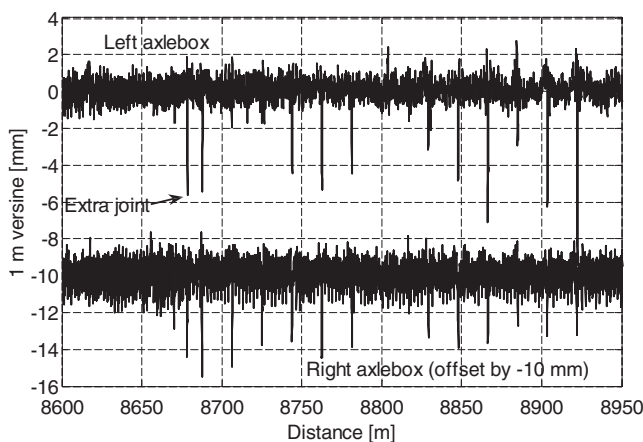


Figure 2. Dipped joints, Tyne and Wear Metro.

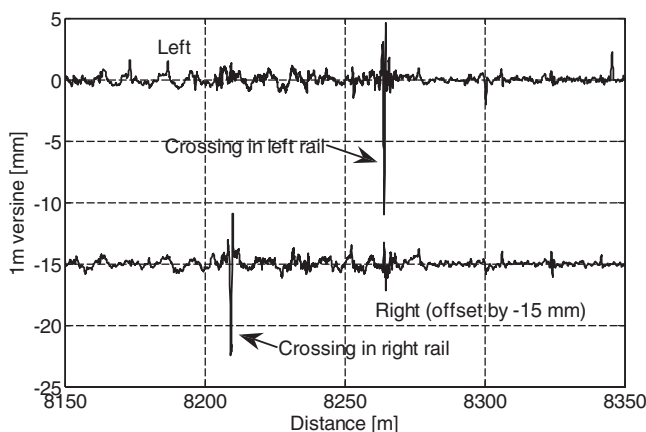


Figure 3. Pair of switches and crossings forming a crossover.

the right rail. The crossings show a significant dip over a 1 m versine, but this is a metro line with a maximum speed of 50 mph. The crossings provide features that can be used to give positional information.

Figure 4 shows the same 1 m vertical versines computed from Tyne and Wear Metro vehicle axlebox accelerometer data when passing over a level-crossing. The results are, at first sight, strange. The first two dips in the left and right rails are deformations in the rails corresponding to the places where the left and right wheels of road vehicles cross the track. The second pair of dips are deformations in the rail for the opposite carriageway. There is a central reservation between the two carriageways. The road does not cross the tracks perpendicularly but is at a noticeable angle, which explains why the right rail sees the deformation of the road wheel paths slightly before the left rail. These deformations in the rails can be monitored in time, and five months later were observed to be essentially unchanged.

All three of these example features, the joints, the crossings of S&C work, and level-crossings, all help to identify the position of other data along the railway. Note that these

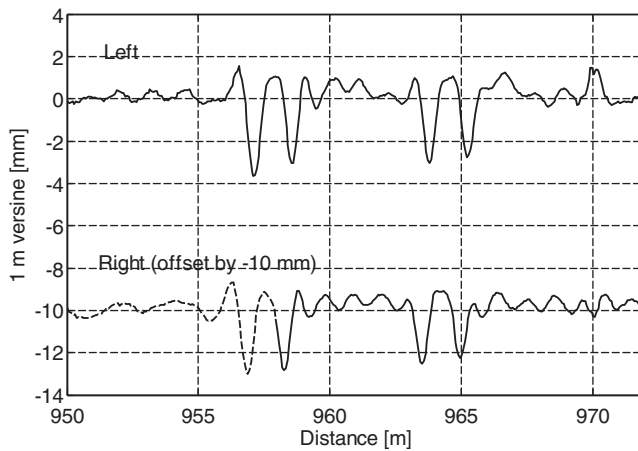


Figure 4. Left and right 1 m versines over a level-crossing.

features are all much less clear without axlebox accelerometers. The raw accelerations are related to the features, but by normalising the accelerations into a geometrical equivalent, the features can be compared much more easily at different vehicle speeds.

3.3. Displacement sensors

Displacement sensors measure a distance directly as the distance between two end fixings, or contain a draw string with a rotary component to measure displacement. These types of displacement sensors are inevitably in the way at some point during maintenance as they attach to items together and need to have one end or the other removed from time to time. It can be difficult to ensure that the sensor measures, for example, only the vertical component of displacement when the two ends of the sensor have some relative lateral or longitudinal movement. Capacitive or inductive displacement sensors are more robust but can only measure small displacements.

Laser-based distance sensors are highly accurate, but are difficult to get to work properly on an in-service vehicle because of the dirty railway environment and issues with robustness of the laser source itself. A pair of laser displacement sensors used in a third rail condition monitoring system have to be cleaned regularly to keep it working.[18]

3.4. 2D optical sensors

The retired Lab5 coach from AEA technology (rail) used a video camera and a white light shining through a slot to form a line on the rail that could be seen through a video camera and processed to identify the gauge corner for determining the lateral track geometry, and the rail top for the vertical profile, and the rail cross-section at the same time. A direct laser-based replacement is available but with better resolution and more frames per second.

The old Lab5 coach continuously blew a jet of air past the optical sensors to avoid getting dirt into the optical system, and laser-based systems need the same treatment. Hence, optical systems on an in-service vehicle are awkward to maintain.

3.5. Global Navigation Satellite System

GNSS is the generic term for a satellite-based positioning system of which GPS (Global Positioning System, USA) was the first, but there is Glasnost (Russian), Beidou (Chinese), and soon Galileo (Europe).

It is generally assumed that by attaching an antenna to the roof of a railway vehicle and connecting it to a GNSS module, the position information will come in with the accuracy stated in the manufacturer's data sheet – this is often not the case. However, for comparing standard deviations over 200 m sections, exact positioning is not critical. For specifying where a spot fault is located it is more important, but a maintainer can probably find a fault with a position error of 10 m. For these purposes, tagging the data with a GNSS satellite fix is enough. However, for monitoring the evolution of geometrical faults over time, accurate location information is critical. This information need not come from GNSS, but can be calculated in post-processing of the data.

Defining 'location' on a railway is a problem. Traditionally, the location of something on the railway infrastructure would have been denoted in miles and chains (or yards), with the miles being defined by mile markers. The mile markers are not exactly one mile apart, and with changes to the track layout and inside and outside curves, the mile markers cannot give an accurate measurement along the track.

The requirements for the UGMS on (a proportion of) the new IEP trains are for a location from run to run within 1 m, and within 3 m of absolute position, with a position in terms of engineering line reference or track ID and miles and yardage. This requirement seems to be based on assumed GNSS performance.[10]

It should be possible to use local correction signals broadcast over radio links over the railway infrastructure from reference-based stations placed on railway land so that the position on board a train is known significantly more accurately (differential GNSS), but the use on a moving platform needs to be verified. There is little point in trying to achieve an accuracy of less than 1 m as the antenna is on the roof and the roof also moves laterally. The antenna is the best mounted above the centre of a bogie to give the least motion.

Combining a tachometer output with GNSS data using a Kalman filter provides a considerable improvement in identifying the position of track condition data, but getting an absolute position for the data is still difficult.[38] The relative positions of things become a lot better, but the absolute position remains elusive.

There is a real possibility of combining GNSS data with inertial navigation system sensors and tacho in a deeply integrated way rather than as a post-processing activity, or even more superficially by tagging sensor data with GNSS time and location. Many GNSS modules on the market today are available in variants that accept a yaw rate gyro input and a tacho input. The provision of these two inputs improves the position estimates for a rail vehicle considerably and should be seriously considered.

A little appreciated aspect of GNSS modules is that they have an internal Kalman filter for tracking position that makes some important assumptions about its motion. There are generally two models used: one is the stationary model in which it is assumed that the antenna is not moving; and the second is a motion model with limited acceleration. In the face of no other data, the accelerations are typically assumed to be up to 4 g. When the antenna does not appear to have moved significantly for 3 min, the mode changes to stationary mode. In this mode, the assumed accelerations of the antenna are zero, or very small. The Kalman filter takes observations of the satellites and makes sure that the best stationary position estimate is made. One of the by-products of the Kalman filter is that it is possible to test the assumption that the antenna is not moving. When this is proved to be false, the antenna is assumed to be moving and the Kalman filter switches to the dynamic mode. In this mode, accelerations

in any direction are assumed to be up to 4 g, which is far too high for a railway vehicle. It can be observed in dynamic mode that once the train is moving, the GNSS positions are often following a credible path that looks like a railway line. This is because the heading is not changing quickly and the Kalman filter is content to predict the next position based on the projection of the two previous points. The observation from the satellites is typically quite poor for each individual second, so the dynamic model is essential. The GNSS internal kinematic model does not use the fact that a railway vehicle follows railway lines. This means that acceleration is limited, and the largest acceleration occurs in the longitudinal direction (ignoring the lateral motion of the antenna on the roof as the body sways). In the lateral direction, there is acceleration to go around corners, but this is modest. There is little vertical acceleration and trains change altitude very slowly. These assumptions can be built into a better model if the raw (internal) GNSS information is available.

3.6. Other sensors

Other sensors used in practice include:

- Metal detectors, which can be used to identify passage over a switch rail while measuring track geometry from dedicated TRVs or UGMS. This provides positional information, and also flags the locations of switches and crossings where optical geometry measuring equipment can get confused by the switch geometry.
- Sensors that identify signalling components, such as automatic warning system (AWS) magnets or other inductive devices in the track, can be useful for pinning down location information occasionally, but the position of the items in the track may not be exactly known.
- Sensors that detect RF ID tags placed at known points on the infrastructure to define reference locations (used by London Underground).
- Video recordings, which are useful for identifying missing rail clips that might be causes of track geometry problems, but is not otherwise considered relevant to this paper.

3.7. Sensor combinations

The vertical acceleration at an axlebox can be used raw, but the speed of the vehicle affects the meaning of the vertical acceleration – the faster the vehicle moves, the higher the acceleration is likely on the same piece of track. This was found in London Underground's accelerometer monitoring solution.[7] Hence, almost all useful information is based on a combination of sensors as the vehicle speed is generally required as well as a means of identifying the position along the track.

Vertical rail profile is probably best measured with acceleration on the bogie over the axlebox, and the vertical displacement to the axlebox from the accelerometer.[12] Moving the accelerometer from the axlebox to the bogie isolates the accelerometer from the worst impulsive accelerations, and reduces the range with which the accelerometer has to contend. However, the displacement transducer is then vulnerable.

Lateral alignment is hard to measure accurately without optical sensors. Lateral acceleration at the bogie plus lateral displacement from the bogie to the wheelback has been tried, but the displacement component was found to be small and could be done without. The lateral alignment is then the lateral alignment according to the plan view trajectory taken by the wheelsets, which is not the same as the lateral alignment of the track. Determining track lateral alignment and gauge without optical sensors is not practical.

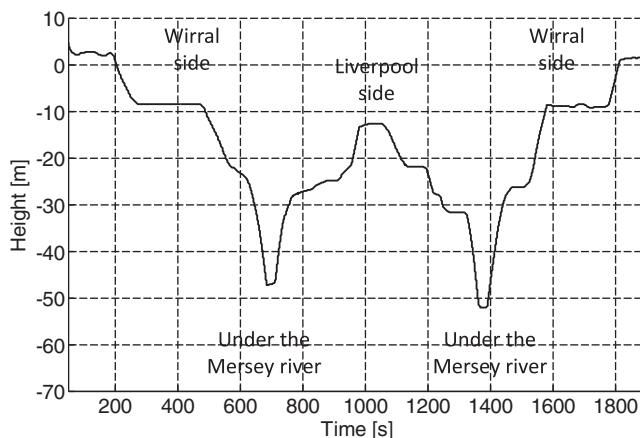


Figure 5. Estimated height of Merseyrail Metro vehicle passing under the Mersey river.

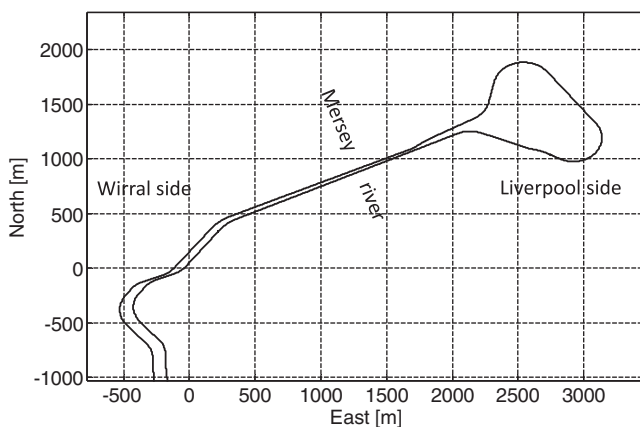


Figure 6. Plan view for Merseyrail Metro vehicle passing under the Mersey river.

An excellent example of sensor fusion is used to obtain cross-level from a yaw rate gyro, roll rate gyro, laterally sensing accelerometer, and vehicle speed.[36] Another example is combining acceleration at the bogie above the axlebox with displacement to the axlebox to give the vertical profile at a rail.[12]

Figure 5 shows the estimated height of a Merseyrail metro vehicle as it passes under the Mersey river and back again, generated by fusing the results from five of the six inertial sensors in an IMU mounted on the bogie as well as the tacho signal. Ironically, the vertically sensing accelerometer is not used here. The vehicle passes from the Wirral side under the Mersey river to the Liverpool side, and then back again to the Wirral side. Figure 6 shows the corresponding plan view of the trajectory taken by the vehicle. These are particularly challenging estimation problems as the vehicle is underground with no access to GNSS position estimates and the sensor data require careful treatment to avoid the accumulation of large errors over the 25 min or so taken to complete the part of the journey shown. On exiting at the Wirral side of the underground section, a sizeable error is developing, caused mostly by accumulated tacho errors (the heading is only slightly in error). The resulting position error

will be corrected when the GNSS position estimates become available once again. In all of these cases, a clear understanding of the sensor capabilities and limitations is needed so the sensors can be combined using formal methods such as a Kalman filter.

Sensor fusion can be used to improve the results compared to using a single sensor, but this fusion also provides the possibility of detecting failures in one sensor. Rather than using GNSS solely to tag interesting events found in inertial sensor data with time and location, by integrating GNSS with inertial sensors a failure in one of the sensors can be detected.[39] Self-monitoring is important for a track geometry fault detection system as unchecked, and a faulty sensor could generate large amounts of false information misinterpreted as real track geometry problems.

For research purposes, it is useful to record raw sensor data, but this is generally not practical for commercial systems. A UGMS does processing on board so that only the track geometry comes out of the system, or even, potentially, reports of standard deviations and exceedances, tagged with GNSS information for time and position. The lack of raw data makes testing new ideas difficult without building new instrumentation. It would be useful if a UGMS system could output raw data for development purposes.

3.8. *Model-based processing*

A set of sensors that identifies the track geometry by combinations of sensor outputs does not need to be aware of a local dynamic model. UGMS measures track geometry independent of the motion of the bogie platform from which it is mounted, as long as the optical sensors can see the rails.

When a reduced set of sensors is used, there are two approaches possible. One is to take the data from the sensors and use it as it is. For example, accelerations in the car body or lateral accelerations on the bogie can be noted as being too high in some places. There is no model required. However, by making use of a dynamic model, certain quantities that are missing from the measurement of track geometry can be estimated. The quality of the estimation depends partly on the theoretical possibilities of the given model and sensor combination, and partly on the extent to which the model accurately reflects the true dynamics. An example of this is the use of a simple inverse dynamics model used to convert yaw rate gyro data or lateral acceleration data into an approximation of lateral track alignment.[6]

Figure 7 shows lateral 35 m alignment derived from the yaw rate gyro mounted on the bogie of a Merseyrail vehicle (in combination with the tacho signal) without inverse model processing, with an inverse model, and from a TRV. Bogie yaw rate gyro-derived lateral alignment typically amplifies wavelengths around 30 m and reduces wavelengths shorter than 16 m. A Kalman filter estimates the lateral track alignment that would result in the observed bogie yaw rate assuming a simple dynamic model relating the track input to the sensor output. This results in a significant improvement in the lateral alignment estimates.[6]

Data from different sensors can be combined to improve considerably the accuracy of some measurement. For example, combining GNSS data with data from a yaw rate sensor and a tachometer to give a measurement of curvature that is almost entirely bias-free.[40] In principle, the curvature is the yaw rate divided by the vehicle speed. At low speeds the result is affected by errors in the speed, and drifting offset in the yaw rate gyro produces a speed-dependent drifting offset in the curvature estimates. The GNSS data provide the long-term curvature information that can correct this offset almost entirely when the correct model is used and the mathematics is set up correctly. The authors of Trehag et al. [40] use linear and nonlinear filtering with a model-based approach.

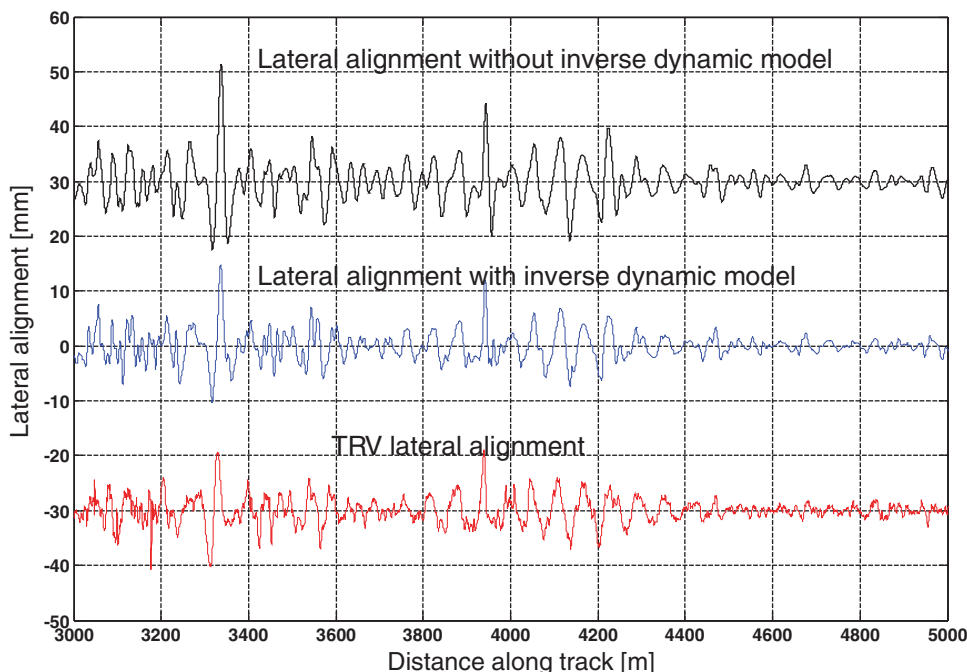


Figure 7. Lateral alignment with and without inverse dynamic model.

3.9. Other opportunities using the same or similar sensor sets

Given certain sensor combinations on the bogie of an in-service vehicle, it may be possible to identify other things that were not originally considered. For example, there has been progress on identifying the parameters such as adhesion and effective conicity at the wheel–rail interface using a model-based approach.[41,42]

As well as monitoring the track geometry, a combination of axlebox, bogie- and body-mounted sensors can be used to identify the condition of the bogie components as well as the possibility of identifying the absolute speed of the vehicle.[9]

Monitoring systems are likely to be compromised if a wheel flat were to occur, so it is worthwhile being able to detect this and report it. However, a wheel flat generates characteristic signals that can easily be detected in vertical accelerometer signals when the vehicle speed is known. Hence, a system can identify that there is a problem with the wheels rather than with the track and report this.

3.10. Excessive data

There is a recognition that condition monitoring systems located on in-service vehicles produce large amounts of data that have to be handled using emerging techniques. Núñez et al. [43] describe a system for handling the large amount of data coming from ABA (Axlebox acceleration) systems. An example of the raw data rates that might be anticipated from an IMU placed on the bogie of a railway vehicle is given by the following calculation. Sampling 6 inertial sensors at 256 times per second with a 16 bit resolution generates 3072 bytes per second, 11 MB per hour, and nearly 180 MB of data in 16 h of operation. It is practical to save this raw data locally, on a 32 GB SD card, for example, for a few weeks. Although raw data at this rate can theoretically be transmitted over a radio link, in practice the cost of doing

this is prohibitive, and the server would be overrun with data if there were more than a few vehicles producing data at the same time.

The typical way of dealing with the high raw data rate is to process the data on board so only the required information is transmitted. For example, the authors typically generate raw data at a rate of 256 Hz, downsampled from a higher initial sampling rate. The 256 Hz raw data rate was chosen as it allows the data to be locally processed to give geometric parameters every 0.125 m at 70 mph (32 ms^{-1}). For higher vehicle speeds, a higher raw data rate would be better.

Molodova et al. [44] report the detection of defects at short wavelengths from axlebox-mounted accelerometers. The paper shows that the frequencies generated over a short wavelength defect such as a squat can exceed 500 Hz. This means that the axlebox accelerometer has to be sampled over 1 kHz to avoid missing important data. During trials on the Tyne and Wear Metro, the authors of the current paper found that sampling the axlebox-mounted accelerometers at 1 kHz was not enough and on subsequent trials increased the sampling rate to 4 kHz. This high sampling rate results in large quantities of data being collected, much more than from 0.2 m spaced geometry samples. A lot of data can be discarded as being not of interest, leaving only the defect samples. However, if the measuring wheel develops a flat then the axlebox data may be rendered useless and may not be discarded, leading to an excess of data being saved locally.

The next section looks at the issues of getting data off the vehicle and further processing that takes place on a central (or distributed) server.

4. Off-board processing

This section describes issues with getting the data from the vehicle to a central location, and the processing that needs to be carried out at a central server. The outputs of the system depend on what information is transferred from the vehicle to the central location, and getting the most out of this information may require the addition of external data sources, such as maintenance records.

4.1. Data communication

GSM-R provides a means of moving small amounts of data from an in-service vehicle to a remote server. However, the data rates are limited, and there is competition with other sources of data that may well be more important. This has been used at least as far back as 2004 on the CTRL between London and Paris (and Brussels).[12] The amount of data coming off the train over a radio link must be small, for example the standard deviations over each 200 m section.

As mobile phone communication data rates increase, sufficient for streaming live video in the case of 4G, a normal 3G or 4G data connection may be usable from a moving vehicle. This provides for a significantly enhanced amount of data to be offloaded from an operating railway vehicle. However, the 3G coverage of the railway network is incomplete and the 4G coverage very poor at the moment. Typically, the coverage is good in built-up areas, but is incomplete in the countryside between large cities. Mobile phone coverage in an underground railway varies from excellent to non-existent, but is becoming more common.

Wifi connections made at certain stations or in depots can provide a mechanism for data to be removed from an in-service vehicle to a server with more bandwidth than a mobile link. This involves storing large amounts of data on-board the vehicle that is offloaded only at the

end of the day, or potentially offloaded bit by bit at some station stops (but these stops may not be long enough to allow for a connection to be made and a useful amount of data to be transferred).

It is possible to record large amounts of data to SD cards, or local hard disks, and to transfer the information off the train manually. This method of data transfer is only really suitable during the development of systems where all raw data are collected initially and used to refine the system so that events can be identified.

4.2. Map matching

Track condition information can be shown against position from GNSS and simply located on a traditional cartographic map. This is done for many systems and is sufficiently accurate for many purposes. The trajectory of the vehicle is given by plotting successive GNSS location points on the map and joining the dots. The corresponding geometry data are matched to the railway lines by eye. The GNSS data points are not generally accurate enough to determine the line on which the vehicle is travelling, but the direction of travel is evident so a sensible guess may be possible. At least the line on which the vehicle should have been is generally known. In practice, it has been found that the position information in open ground from a vehicle moving at around 100 mph is often 15 m or more ahead or behind the true position.[19] This happens even when the lateral position of the trajectory is accurate to within a few metres. The reason for this may be that the GNSS module makes a position fix and then transmits it by a serial data stream to the logging equipment. The serial link has a low baud rate and there is a delay of a few hundred milliseconds between the position fix being computed and the data reaching the logging equipment. This is sufficient to give a longitudinal error of 15 m. In principle, this delay can be compensated for, or there are other means of avoiding this error.

However, there is an increasing requirement to locate geometrical faults more accurately than a GNSS tag can manage. For comparing the degradation of 200 m standard deviations, GNSS locations are probably accurate enough, but to track the degradation of individual features such as voids, a much more accurate position is required.

It might be assumed that track geometry condition monitoring information should be aligned with a master digital map, and an electronic database assumed to contain all tracks with their design geometry and distances, and all the places where a vehicle can change from one track to another, amongst other things such as stations, signals, track circuits, and so on. The provision of a digital map for map matching is discussed by Gerlach and zu Hörste.[45]

Map matching means matching the trajectory taken by a vehicle and ‘matching’ it up to a digital map. The map matching needs to take place in real time for command and control applications, but can take place off line and use all available information for some applications such as locating geometrical features. The requirement is to figure out which of the tracks the vehicle was on at any given time in its journey, and where on the track the vehicle was located. This means that a geometrical feature of interest can be related back to an absolute point on the digital map. Maintenance teams use the same digital map to find any place, generally based on GNSS coordinates, but alternatively based on distance (and direction) from a reference item such as a mile post or a certain location cabinet.

One approach to tracking which path a vehicle is following (on a digital map) relies on GNSS data alone, as described in [46]. A highly accurate digital map is assumed to be available and it assumes that GNSS information with a standard deviation of 0.2 m is available (using a ‘real-time kinematic’ GNSS receiver). The track on which the vehicle is located is based on comparing the incoming position samples to the digital map to find the best match.

The primary limitation is linked to the rate at which GNSS data are available. This approach to map matching seems to be not feasible in reality.

The use of curvature information in combination with tacho and GPS information provides enough information to identify position relative to a digital map within a few metres, at least when there are significant curves present. Saab [47,48] provides a comprehensive description of the theory and practice of tracking a railway vehicle around a digital map. A limitation is that the beginning and end of curves are often not very well defined and may move slightly with maintenance activities.

Gerlach and Rahmig [49] describe map matching using GNSS, radar, and IMU data. There is a hypothesis that a branch was taken or not taken that is then determined. Problems are identified with closely spaced switches and the requirements for the GNSS data to be reasonably accurate. Using a camera to detect switches is suggested. Lüddecke and Rahmig [50] present an improved version where the uncertainty in the GNSS information is shaped according to the direction of travel of the railway vehicle. This improves the results. Heirich et al. [51] describe a probabilistic approach to tracking the position of a railway vehicle against a digital map using particle filtering. Crespillo et al. [52] describe merging GNSS and IMU information in a tight and loose way to obtain precise localisation information with reference to a master digital map.

Long straight (featureless) track presents more of a problem. Other sources of information about position could be AWS magnets in the track, or other discrete detectable features deliberately placed in the track such as RFID tags.

Despite the progress being made on map matching, the accuracy that will be achieved is unlikely to achieve better than 1 m error. However, for the purposes of tracking the degradation of individual geometric features, such as a developing void, it is not actually necessary to find the position of the feature on a digital map in order to get further. In fact, identifying position on a digital map does not allow comparison very well at all. What is really needed is the ability to compare run after run with mutually consistent position information. For condition monitoring mutual alignment is more important than precise localisation.

4.3. *Mutual alignment*

Mutual alignment means taking geometrical data against distance along the track, as measured by the on-board measuring system, and trying to overlay two or more data sets so that the same place on the same line appear at the same x coordinate. This allows differences in geometry to be calculated. It does not mean that the final position is known accurately, it is simply known accurately relative to another run.

In principle, mutual alignment could be done on board a vehicle, but in practice it will be done off board as there may be data from more than one vehicle that need comparing, and there is a need to find absolute position against an up-to-date reference map.

Mutually aligning data is critical for obtaining the changes in track condition over time. Mutual alignment of data from different runs over the same track presents a serious challenge. It sounds as if the mutual alignment needs only to shift the data to the left or to the right so as to remove a distance offset caused by an initial mismatch in position. However, this is only one part of the problem. If the tachometer is on a wheelset with a slightly different radius, then there is an accumulation of distance error. This can be considered as a distance scaling problem that can also be dealt with.

The alignment of two plots can be done straightforwardly by human operators as the human brain does pattern matching autonomously.

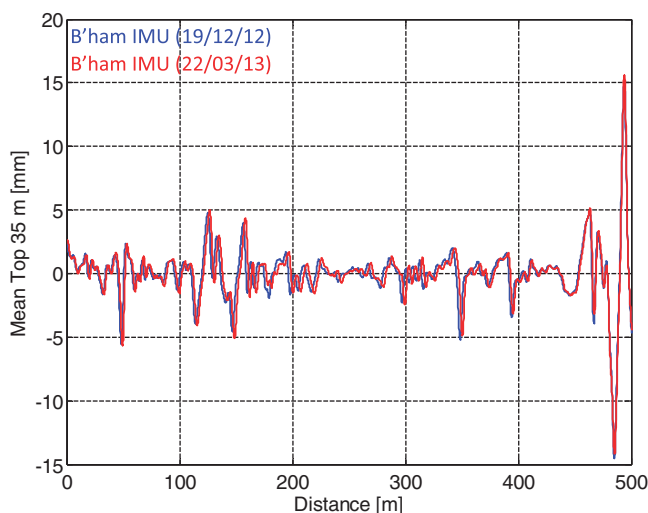


Figure 8. Mutual alignment by eye.

Rome [53] gives a mathematical process for mutually aligning data from multiple runs, which has been used for data from Amtrak (USA). It claims to ‘allow change and degradation analysis to be performed on a massive scale’. The conclusions suggest that in the future the changes detected will be correlated with types of maintenance, soil conditions, and environmental conditions to proactively predict problems before they become critical. This appears not to have happened yet, but is an objective to be realised sometime in the not too distant future.

An interesting relatively early paper about autonomous processing of track geometry data processing is presented by Madejski.[54] In this paper, the location of a piece of track geometry recording is identified by comparing the record with existing records. In this way, the data from TRC runs are mutually aligned and analysed automatically.

A computer can be programmed to perform mutual alignment between different runs and to identify how to stretch or shrink position information so that records are mutually aligned in a reasonable way. Sections with significant differences can be identified and linked to a change in line, or maintenance activity, or error.

Rough alignment can be done using location information, and the exact alignment is done by the human brain and never explicitly carried out.

An example of mutual alignment carried out by eye (Figure 8) shows an additional problem that has to be solved during mutual alignment. The 500 m of data taken one day has been scaled very slightly in the distance axis to obtain the best match with the data from another day and the alignment is good at the start and the end. The data in the middle are up to 3 m out of alignment. If the difference between the two plots is computed as it is, then the difference will appear to be significant where there are short wavelength features. It is critical that the traces are allowed to stretch or shrink in a small way to compensate for tachometer errors. When the alignment is correct, the differences are meaningful.

Figure 9 shows results from Network Rail’s new measurement train (NMT) and from in-service bogie-mounted IMU before and after renewal took place. The track beyond 480 m was not tamped, so the traces look similar, although one is from the NMT while the other is from an IMU mounted on a Class 377. The mutual alignment is possible over the unmaintained part as the traces are similar, but mutual alignment over the renewed section is

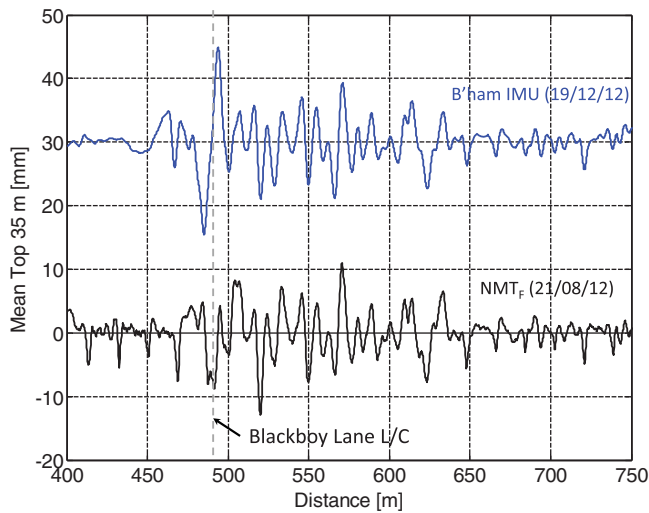


Figure 9. Alignment of data from different sources, before and after tamping.

impossible. It is necessary to know that maintenance has been carried out and to try to align the traces before and after the maintained section (not shown in the figure). The sections where there has been significant change cannot be aligned, so the alignment in the future has to be done relative to only the post-maintenance data.

Mutual alignment should be done based on all things that are computed, but taking into consideration their relative accuracies and mutual dependencies. Mutual alignment should also take into account the relative accuracies at different distance scales. Curvature information is more useful over longer distances while axlebox accelerometers are useful over shorter distances. The vertical geometrical data are generally better than the lateral data, even from UGMS, so in mutual alignment the vertical information should be given more weight than the lateral information.

4.4. Monitoring changes over time

Quantities such as standard deviation over 1/8 mile (200 m) can be computed from returned track geometry, assuming this is all returned to a central server, rather than computed on board. These can be compared from run to run, but what is really needed is identification of degrading track condition based on individual geometrical irregularities.

A quantity that might be derived from the geometry data is 3 m twist (where there are axlebox accelerometers or bogie accelerometers plus displacement transducers to the axlebox). This might be alternatively computed on board and only parts of interest transmitted to a central server.

A high twist in combination with other geometry irregularities can result in derailment. Figure 10 shows 3 m twist derived from the left and right vertical profiles over a pair of switches and crossings. Also shown are the three limiting thresholds that require maintenance intervention in differing time frames. The first pair is caused by a crossing in one rail, one wheel of the leading wheelset dips at the crossing and then the trailing wheel on the same side dips, causing the twist to show the opposite sign. At the next crossing, which is in the other rail, the twist appears in the opposite direction. The first crossing causes a significant twist, but well within the inner maintenance thresholds. The second crossing causes a twist

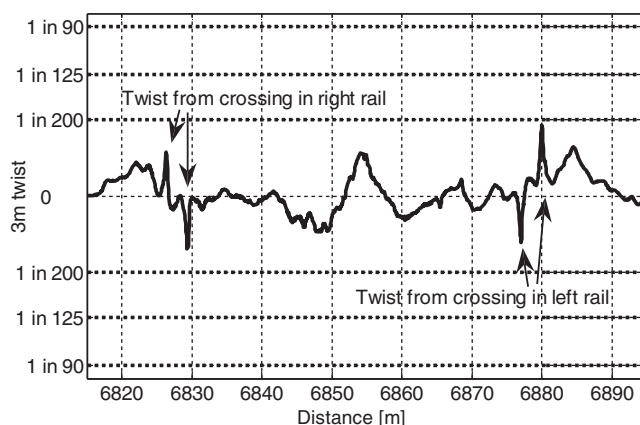


Figure 10. Twist computed from left and right vertical profiles.

in one direction that is close to the first maintenance threshold. Currently, this would not be flagged in a report as it has not reached the first threshold, but once it does cross the threshold it forces maintenance to be scheduled. Instead, the degradation of the twist can be monitored in an attempt to predict when maintenance will be required.

Andersson et al. [55] describe, among other things, how data collected from the Australian railway, including geometry data, are (or was at that time) being used to inform maintenance decisions. The standard geometrical quantities are collected: left and right top; alignment; twist; curvature; cross-level; and gauge. Other quantities reportedly collected include bogie and body accelerations, rail corrugation, and lateral jerk. One conclusion from the paper is that while organisations are collecting and archiving large amounts of geometry data, the computer systems are not yet ready to handle the task of examining deterioration rates in different places. This is now changing.

Faiz and Singh [56] provide a good summary of track geometry faults and suggest that it would be beneficial to move from a maintenance regime based on reacting to faults to a predictive maintenance scheme, but the details of how this should be done are missing. Currently, UGMS make a lot of measurements, but do not do well at the predictive part, that is, predicting how assets will degrade in the future. This is the next stage in railway track maintenance.

There is a need to develop models of how track degrades over time to make better predictions of the remaining life of an asset, or how long it might be before maintenance will be required. Some work has been done on this, for example, Andrade and Teixeira [57] discuss the development of a Bayesian model of track geometry degradation. The model is developed based on the incoming measurements of track geometry degradation, so the model evolves and becomes better at predicting the future behaviour as more data are gathered. It is suggested that for new lines the model must be learnt from the initial observed degradation, so contracts between railway vehicle operators and railway infrastructure operators may need to be renegotiated as the data become available following the opening of a new line. Vale and Lurder [58] discuss the development of stochastic models for track geometry degradation.

As well as monitoring degradation of track condition from in-service vehicles, it would be useful to monitor the effectiveness of maintenance. Did the maintenance operation fix the original problem and was the fix sustained, or did the problem reoccur? To do this implies that the automated processing has access to a database containing records of where, what, and when maintenance took place.

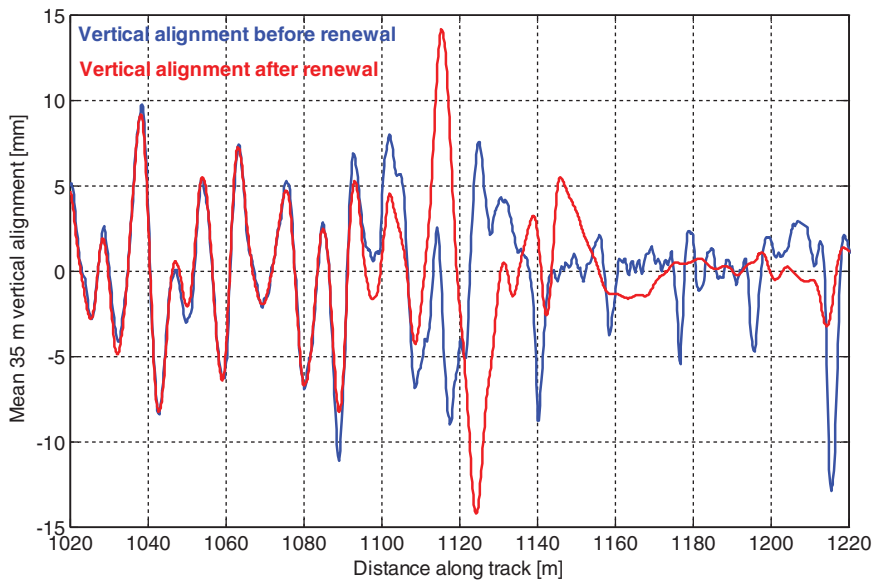


Figure 11. Mean 35 m vertical alignment before and after renewal.

Figure 11 shows the mean vertical (35 m) alignment before and after renewal, one data set taken from a TRV, another from an IMU on the bogie of an in-service vehicle. The track on the right hand half of the figure was renewed after the first vehicle had passed through, resulting in the removal of several dips and an overall improvement in the vertical alignment. The left-hand half of the figure shows a vertical alignment that remains essentially unchanged as it was not part of the renewal work and was not touched. In the middle, there is a level-crossing that appears to have become worse after the tamping that finished off the renewal work stopped just short of the level-crossing. Comparing the before and after alignment, the effectiveness of the maintenance activity can be assessed, but this process needs to be automated. Much more information about this level-crossing can be found in [59].

4.5. Links to other data sources

The railway system has a lot of disparate sources of data. Other data sources that may be used when monitoring changes in track condition include:

The UGMS specifications for the new IEP fleet state that the data sent must know which line the vehicle is on and which direction it is travelling, and the vehicle location within a few metres. This would probably be derived from information in the vehicle train management system that downloads key information from the train operator before each journey commences. However, an external server could just as well get this information directly from the train-operating company and link it to the geometry data from the vehicle.

Access to a digital map with design geometry would be useful to enable map matching for data from an in-service vehicle where the vehicle has only GNSS position information. Alterations or additions to the track layout need to be accommodated. A change in track geometry, for example, after straightening some curves to enhance the line speed, affects the distance along the track as well as the underlying geometry.

Information on maintenance activities needs to be available so that changes in track geometry can be related to a cause. The cause might be degradation, but improvement is normally

because of maintenance activity. In some cases, maintenance activity causes a worsening of the geometry, for example, at the end of a stretch of tamping.

Information on the weather and environmental factors such as flooding might be considered. High temperatures might cause changes in lateral alignment that can be picked up in the track geometry, but do not develop into track buckling.

5. Discussion and further work

The typical UGMS spatial resolution of 0.2 m is too coarse to identify geometry of interest over features with wavelengths less than 0.4 m. There is potential for adding vertically and laterally sensing axlebox accelerometers to UGMS for the purposes of identifying short wavelength corrugation and looking at dipped joints and the detail passing over switch blades and switch crossings. The Chiltern line (in the UK) has in-service UGMS with vertically sensing axlebox accelerometers added. The raw acceleration information is probably too detailed to be kept, but interesting portions can be logged and transmitted.

On board, it would be useful to integrate raw GNSS data with inertial sensor data to give a much better tracking of position. The IMU sensor information and tacho data can be used as part of the GNSS tracking algorithm. Alternatively, matching position to a digital map has the potential to be as accurate, and potentially more useful if it relates track problems to features that can be seen on the ground.

If UGMS is not required, so only monitoring is needed, then a system based on an IMU on the bogie of a vehicle (preferably with a stiff primary suspension) is reasonably useful. It does not see gauge and it does not see twist. The addition of axlebox accelerometers would help to fill in missing short wavelength detail, but this may be a luxury that can be done without.

6. Conclusions

There is a movement, certainly in the UK, to add UGMS to in-service vehicles, compute track geometry on board, and transmit the information to a central server where it can be viewed and used. However, the data are not used as much as they should be. When the full UGMS is not used, industry prefers to use something that sees vertical and lateral geometry if possible. There is always comparison between such systems and the results from a full geometry recording vehicle. Axlebox accelerometers provide a good view of real top profile, but lateral alignment is more difficult without optical sensors. Vertical acceleration at the bogie plus displacement to the axlebox provides excellent vertical rail profile.

Academic solutions tend to involve a smaller set of sensors that may be more robust, but cannot measure all track geometry parameters and suffer from uncertainty that is not welcomed by industry. However, the in-service systems run over the same track repeatedly, so achieving inspection quality accuracy may not be necessary.

There is a danger that UGMS is rolled out to in-service vehicles without planning the purpose for which the data are required. The geometry data are generated according to the traditional requirements of track geometry from a safety point of view without regard for what is actually required or useful.

Additional sensors could be added to a UGMS, such as axlebox-mounted accelerometers to enable the condition of switches and crossings and corrugation and joints to be monitored. If so, then the vehicle speed should be used to normalise the accelerations and allow computation of versines or similar quantities that are more or less independent of vehicle speed.

The potential for tighter integration between GNSS raw data and inertial sensor raw data should be given serious consideration to reduce the problems associated with cuttings and built-up areas where the GNSS alone can be poor. This could improve the navigation performance in tunnels.

There is a difference between inspection and monitoring. Accurate track geometry is not really needed to allow for comparisons from run to run over the same track. The extra frequency of incoming data makes up, to some extent, for the lack of accuracy.

The next step in track maintenance will be to take the information being recorded from in-service vehicles, in combination with other data sources, and to predict when assets will need maintaining rather than scheduling maintenance based on the detection of a fault. Predictive maintenance has been promised for nearly 20 years, but it has not really materialised. Systems sometime claim to be able to do this job, but often, in practice, the operation requires considerable manual input. A human operator is required to look through the data, which is not practical. It should be possible to automate much more of the condition monitoring and predictive maintenance tasks. One of the most important issues is to compare geometry condition between different runs automatically, which involves mutual alignment.

Gathering of a lot more data will make it possible to identify more accurate degradation models so predictive maintenance can be improved.

The server has to handle large volumes of data and process the data to provide reports of what is happening. Research is continuing into the use of distributed servers that can process data automatically and flag up important information.

It should be possible to use the collected data to determine if certain maintenance interventions have been successful. If the problem occurs again a short time later, perhaps the maintenance was not cost-effective. This requires integrating information about maintenance activities into the data processing.

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References

- [1] Scott G, Chillingworth E, Dick M. Development of an unattended track geometry measurement system. *Proceeding of the 2010 Joint Rail Conference*, Vol. 1; 2010 April 27–29; Urbana, IL, USA.
- [2] Erhard F, Wolter KU, Zacher M. Improvements of track maintenance by continuous monitoring with regularly scheduled high-speed trains. *Railway Engineering – 10th International Conference & Exhibition*; 2009 June 24–25; London.
- [3] Yazawa E, Takeshita K. Development of measurement device of track irregularity using inertial mid-chord offset method. *Quarterly Report of RTRI*. 2002 September; Vol. 43, No. 3.
- [4] Roberts C, Weston P, Ling CS, Goodman C. New methods for track monitoring. *IEE seminar on Railway Condition Monitoring (RCM2004)*; 2004 Feb 25; Derby, UK. p. 64–78.
- [5] Weston PF, Ling CS, Goodman CJ, Roberts C, Li P, Goodall RM. Monitoring vertical track irregularity from in-service railway vehicles. *IMEchE Pt F: J Rail Rapid Transit*. 2007;221(1):75–88.
- [6] Weston PF, Ling CS, Goodman CJ, Roberts C, Li P, Goodall RM. Monitoring lateral track irregularity from in-service railway vehicles. *IMEchE Pt F: J Rail Rapid Transit*. 2007;221(1):89–100.
- [7] McAnaw H. The system that measures the system. *NDT&E International*. 2003;36:169–179.
- [8] Mermec group press release. London underground choose MERMEC unattended geometry measuring system (UGMS) from line inspection. July 2012.

- [9] Ward C, Weston P, Stewart E, Li H, Goodall R, Roberts C, Mei T, Charles G, Dixon R. Condition monitoring opportunities using vehicle-based sensors. *Proc IMechE: Part F – J Rail Rapid Transit*. 2011;225(2): 202–218.
- [10] Department for Transport, UK. Train technical specification. Document No: IEP-TECH-REQ-35. 2012 Issue 05.
- [11] Ackroyd P, Angelo S, Nejtkovsky B, Stevens J. Remote ride quality monitoring of Acela train set performance. *Proceeding of the 2002 ASME/IEEE Joint Rail Conference*; 2002 April 23–25; Washington, DC.
- [12] King S. The UK's fastest track monitoring system as used on the channel tunnel rail link. *IEE Seminar on Railway Condition Monitoring (RCM 2004)*; 2004; Derby, UK. p. 11–32.
- [13] Tsunashima H, Naganuma Y, Matsumoto A, Mizuma T, Mori H. Japanese railway condition monitoring of tracks using in-service vehicle. Paper presented at the 5th IET Conference on Railway Condition Monitoring (RCM 2011); 2011 Nov 29–30; Derby, UK.
- [14] Tsunashima H, Naganuma Y, Matsumoto A, Mizuma T, Mori H. Condition monitoring of railway track using in-service vehicle. In: Perpinya X, editor. *Reliability and safety in railway*. InTech; 2012. Available from: <http://www.intechopen.com/books/reliability-and-safety-in-railway/condition-monitoring-of-railway-track-using-in-service-vehicle>.
- [15] Tsunashima H, Naganuma Y, Kobayashi T. Track geometry estimation from car-body vibration. *Veh Syst Dyn: Int J Veh Mech Mob*. 2014;52(Sup1):207–219. doi:10.1080/00423114.2014.889836
- [16] Henoret BL, Gignoux H. Track condition monitoring at SCNF: an introduction to methods, tools and perspectives. Paper presented at the 7th European Workshop on Structural Health Monitoring; 2014 July 8–11; Nantes, France.
- [17] Weston PF, Roberts C, Goodman CJ, Ling CS. Condition monitoring of railway track using in-service trains. *IET Conference on Railway Condition Monitoring (RCM 2006)*, 2006; Birmingham, UK. p. 26–31.
- [18] Green S, Hickson D, Ward D, Roberts C, Weston P, Stewart E. Monitoring the DC third rail interface using an in-service train. Paper presented at the 5th IET Conference on Railway Condition Monitoring and Non-destructive Testing; 2011 Nov 29–30; Birmingham, UK.
- [19] Stewart E, Weston P, Hillmansen S, Roberts C. Using bogie-mounted sensors to understand the dynamics of 3rd rail current collection systems. *Proc IMechE: Part F – J Rail Rapid Transit*. 2011;225(2):219–227.
- [20] Ishii H, Fujino Y, Mizuno Y, Kaito K. The Study of Train Intelligent Monitoring System using acceleration of ordinary trains. *Proceedings of the Asia-Pacific Workshop on Structural Health Monitoring*; 2006; Yokohama Japan.
- [21] Hayashi Y, Kojima T, Tsunashima H, Marumo Y. Real time fault detection of railway vehicles and track. *IET Conference on Railway Condition Monitoring (RCM 2006)*; 2006 Nov 29–30; Birmingham, UK.
- [22] Alfi S, Bruni S. Estimation of long wavelength track irregularities from on board measurement. Paper presented at the 4th IET International Conference on Railway Condition Monitoring; 2008 June 18–20, Derby, UK.
- [23] Bocciaolone M, Caprioli A, Cigada A, Collina A. A measurement system for quick rail inspection and effective track maintenance strategy. *Mech Syst Signal Process*. 2007;21:1242–1254.
- [24] Lee JS, Choi S, Kim SS, Park C, Kim YG. A mixed filtering approach for track condition monitoring using accelerometers on the axle box and bogie. *IEEE Trans Instrum Meas*. 2012;61(3):749–758.
- [25] Lee JS, Choi S, Kim SS, Kim YG, Kim SW, Park C. Track condition monitoring by in-service trains: a comparison between axlebox and bogie accelerometers. Paper presented at the 5th IET Conference on Railway Condition Monitoring (RCM2011); 2011 Nov 29–30; Derby, UK.
- [26] Wang C, Xiao Q, Liang H, Liu Y, Cai X. On-line monitoring of railway deformation using acceleration measurement. *Proceedings of the 6th World Congress on Intelligent Control and Automation*; 2006 June 21–23; Dalian, China.
- [27] Chellaswamy C, Akila V, Dinesh Babu A, Kalai Arasan N. Fuzzy logic based railway track condition monitoring system. *IEEE International Conference on Emerging Trends in Computing, Communication and Nanotechnology (ICECCN 2013)*; 2013 Mar; Tamilnadu, India.
- [28] Heirich O, Lehner A, Robertson P, Strang T. Measurement and analysis of train motion and railway track characteristics with inertial sensors. Paper presented at the 14th International IEEE Conference on Intelligent Transportation Systems; 2011 October 5–7; Washington, DC, USA.
- [29] AUTOMAIN project. Inspection of track from in-service freight trains. Final report for deliverable 3.1, www.automain.eu, 2013.
- [30] Molodova M, Oregui M, Núñez A, Li Z, Moraal J, Dollevoet R. Axle box acceleration for health monitoring of insulated joints: a case study in the Netherlands. *IEEE 17th International Conference on Intelligent Transportation Systems (ITSC2014)*; 2014 Oct; Qingdao, China.
- [31] Allotta B, Pugi L, Ridolfi A, Malvezzi M, Vettori G, Rindi A. Evaluation of odometry algorithm performances using a railway vehicle dynamic model. *Veh Syst Dyn: Int J Veh Mech Mob*. 2012;50(5):699–724. doi:10.1080/00423114.2011.628681
- [32] Mei TX, Li H. A novel approach for the measurement of absolute train speed. *Veh Syst Dyn: Int J Veh Mech Mob*. 46(S1):705–715. doi:10.1080/00423110802036984
- [33] Mei TX, Li H. Measurement of absolute vehicle speed with a simplified inverse model. *IEEE Trans Veh Technol*. 2010;59(3):1164–1171.
- [34] Xu P, Sun Q, Liu R, Wang F. Key equipment identification model for correcting milepost errors of track geometry data from track inspection cars. *Transport Res Part C*. 2013;35:85–103.

- [35] Grassie SL. Measurement of railhead longitudinal profiles: a comparison of different techniques. *Wear*. 1996;191(1–2):245–251.
- [36] Lewis RB, Richards AN. A compensated accelerometer for measurement of railway track crosslevel. *IEEE Trans Veh Technol*. 1988;37(9):174–178.
- [37] Naganuma Y, Kobayahi M, Nakagawa M, Okumura T. Condition monitoring of Shinkansen tracks using commercial trains. Paper presented at the 4th IET International Conference on Railway Condition Monitoring (RCM 2008); 2008 June 18–20; Derby, UK.
- [38] Mirabadi A, Schmid F, Mort N. Multisensor integration methods in the development of a fault-tolerant train navigation system. *J Navig*. 2003;56(3):385–398.
- [39] Mirabadi A, Mort N, Schmid F. Fault detection and isolation in multisensory train navigation systems. UKACC International Conference on Control '98; 1998 Sep 1–4; Swansea, UK.
- [40] Trehag J, Händel P, Ögren M. Onboard estimation and classification of a railroad curvature. *IEEE Trans Instrum Meas*. 2010;59(3):653–660.
- [41] Charles G, Goodall R, Dixon R. Model-based condition monitoring at the wheel–rail interface. *Veh Syst Dyn: Int J Veh Mech Mob*. 2008;46(S1):415–430. doi:10.1080/00423110801979259
- [42] Bruni S, Goodall R, Mei TX, Tsunashima H. Control and monitoring for railway vehicle dynamics. *Veh Syst Dyn: Int J Veh Mech Mob*. 2007;45(7–8):743–779. doi:10.1080/00423110701426690
- [43] Núñez A, Hendriks J, Li Z, De Schutter B, Dollevoet R. Facilitating maintenance decisions on the Dutch railways using big data: the ABA case study. *IEEE International Conference on Big Data*; 2014 Oct; Washington, DC.
- [44] Molodova M, Li Z, Dollevoet R. Axle box acceleration: measurement and simulation for detection of short wavelength track defects. *Wear*. 2011;271:349–356.
- [45] Gerlach K, zu Hörste MM. A precise digital map for Galileo-based train positioning systems. *IEEE 9th International Conference on Intelligent Transport Systems Telecommunications*; 2009 Oct; Lille, France, p. 343–347.
- [46] Yan X, Wang J, Cai B, Wei S. A novel automatic track identification algorithm based on LTS-Hausdorff distance. Paper presented at the 14th International IEEE Conference on Intelligent Transportation Systems; 2011 Oct 5–7; Washington, DC.
- [47] Saab SS. A map matching approach for train positioning Part I: development and analysis. *IEEE Trans Veh Technol*. 2000;49(2):467–475.
- [48] Saab SS. A map matching approach for train positioning Part II: application and experimentation. *IEEE Trans Veh Technol*. 2000;49(2):476–484.
- [49] Gerlach K, Rahmig C. Multi-hypothesis based map-matching algorithm for precise train positioning. Paper presented at the 12th International Conference on Information Fusion; 2009 July 6–9; Seattle, WA.
- [50] Lüddecke K, Rahmig C. Evaluating multiple GNSS data in a multi-hypothesis based map-matching algorithm for train positioning. *IEEE Intelligent Vehicles Symposium (IV)*; 2011 June 5–9; Baden-Baden, Germany.
- [51] Heirich O, Robertson P, García AC, Strang T, Lehner A. Probabilistic localization method for trains. *Intelligent Vehicles Symposium, Alcalá de Henares*; 2012 June 3–7; Spain.
- [52] Crespillo OG, Heirich O, Lehner A. Bayesian GNSS/IMU tight integration for precise railway navigation on track map. *IEEE Position, Location and Navigation Systems Symposium, PLANS*; 2014 May; IEEE/ION, Monterey, CA.
- [53] Rome HJ. Degradation and change analysis of aligned and merged data. *TRB Annual Meeting*; 2001 Jan; Washington DC.
- [54] Madejski J. Autonomous track geometry diagnostics system. *J Mater Process Technol*. 2004;157–158:194–202.
- [55] Andersson M, Murray M, Ferreira L, Lake N. Collection and use of railway track performance and maintenance data. *Conference on Railway Engineering*; 2004 June 20–23; Darwin.
- [56] Faiz RB, Singh S. Time based predictive maintenance management of UK rail track. *International Conference on Computing, Engineering and Information (ICC 2009)*; 2009; Fullerton, CA.
- [57] Andrade AR, Teixeira PF. A Bayesian model to assess rail track geometry degradation through its life-cycle. *Res Topics Transport Econ*. 2012;36:1–8.
- [58] Vale C, Lurder M. Stochastic model for the geometrical rail track degradation process in the Portuguese railway Northern line. *Reliab Eng Syst Saf*. 2013;116:91–98.
- [59] Le Pen L, Watson G, Powrie W, Yeo G, Weston P, Roberts C. The behaviour of railway level crossings: insights through field monitoring. *Transport Geotech*. 2014;1(4):201–213.