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Development of railway track condition monitoring from multi-train in-service vehicles

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ABSTRACT

A cab-based track monitoring system has been developed which makes use of the existing on-board GSM-R cab radio present in the majority of trains operating in the UK. With the addition of a low-cost sensor, type, location and severity of the track defects are reported using the system. The system improves safety and network performance by efficiently directing maintenance crews to the location of defects, minimising time spent on maintenance and inspection. Initially, vehicle dynamic simulation was used to test the feasibility of the system for defect monitoring and to develop compensation factors for vehicle type and operating speed. Novel on-board signal processing techniques are also presented through comparison of vibration response from sites with known defects and outputs from Network Rail's (NR) New Measurement Train (NMT). Good agreement was reported for track faults in relation to vertical and lateral alignment and dip faults. Statistically, good agreement has been demonstrated, suggesting that the data acquired could be used to provide an indication of track quality thereby improving network performance, reducing rough ride and leading to improved passenger comfort. Improvements in the measured and statistical correlation are anticipated through the use, of multi-train / multi-journey and machine learning methods..

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Introduction

Typically track geometry maintenance is undertaken on a 'find and fix' regime, however in order to improve efficiency, and achieve the associated cost savings, infrastructure managers (IM) aim to move to a 'predict and prevent' regime. This requires more frequent monitoring of the condition of the track along with accurate prediction of the future degradation of track geometry.

Currently IMs operate a number of measurement trains to monitor the track geometry and detect track defects. The inspection frequency of measurements is governed by the line-speed and traffic density (gross tonnage) of a track section and therefore these vehicles are deployed more frequently on mainline routes, with higher speeds and traffic density,

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than secondary routes. To increase the coverage and frequency of track geometry monitoring, a range of unattended track geometry measurements systems (UGMS) have been developed [1] which can be fitted to passenger vehicles to collect data during normal passenger service. However, in many cases these systems can be cost prohibitive to retro-fit to current vehicle fleets.

In collaboration with Siemens and Rail Safety and Standards Board (RSSB), research has been undertaken to develop a low-cost remote condition monitoring (RCM) solution which makes use of the existing on-board GSM-R cab radio present in the majority of trains operating in the UK. The addition of a micro electromechanical system (MEMS) sensor in the cab radio through the fitment of a sensor card, provides the opportunity to monitor the vibration of the vehicle in three axes, which when combined with advanced on-board signal processing techniques, can be used to detect certain track features.

In this paper the research work undertaken to support the development of the in-vehicle system is described. This includes the use of vehicle dynamics simulations to test the feasibility of the concept system for the detection of track voids and to develop compensation factors for variations in vehicle type and operating speed. The development and testing of the on-board signal processing techniques are also presented through comparison of vibration response from sites with known defects and outputs from Network Rail's (NR) track geometry recording vehicle.

Vehicle monitoring the track

Acceleration response measured at the axlebox can be viewed as the closest true representation of the vibration at the vehicle-track interface. A small loss in signal strength is seen at the axlebox as compared to the wheel-rail interface. Condition of wheels, bearings as well as track irregularities can be monitored with a sensors mounted on the vehicle [2]; the commercial railway product summarised in [3] includes an electromagnetic energy harvester that can be retrofitted to the axlebox. The harvester has a dual purpose, using the accelerations at the wheelset to both harvest energy and sense the vibrations at the wheelset.

Several other studies have also been identified in literature that have reported vehicle based monitoring systems to infer the condition of the track with sensors [4], [5] and [6]. The detection of abnormal track features can, with some level of confidence, be inferred from the axlebox and bogie acceleration signals; however, a monitoring system with sensors located in the carbody is more challenging due to the suspension characteristics of the vehicle, particularly of those associated with the air suspension that are designed to improve passenger comfort but, as a consequence, eliminate high frequency vibrations. The filtering effect of the primary suspension into the bogie and the secondary suspension into the carbody almost entirely removes the majority of the high frequency components of the signal originating from the vehicle-track interface; however, the amplitude of a significant impact is still transferred into the carbody and this is validated to some extent from driver reported track faults. The challenges present for a carbody based track monitoring system have meant that very few studies have attempted to implement a viable solution for the problem.

In comparison, the track monitoring system presented in this paper is able to indicate the location and severity of irregularities at the vehicle-track interface through the assessment of the acceleration response measured in the vehicle cab, and also identify the type of track asset (e.g. switches and crossing (S&C), structure or plain-line track) where the irregularity is measured. Installation of a sensor card into multiple trains provides both monitoring of the entire rail network, including secondary lines, as well as the assessment of each track-section by multiple trains. With sufficient train installations, given the multiple journeys, by multiple trains, an automated assessment of the entire rail network could be provided within one day.

Measured data is sent to a ground system and assessed to take advantage of the multiple train journeys over the same track section. This allows the removal of false alarms, and improves the estimates of location accuracy and irregularity sizing.

The system has initially been developed to detect voids in the track structure (plain-line and at S&C), large amplitude irregularities in the vertical or lateral alignment which can be used to monitor and predict deterioration in track geometry.

Detection of track faults from in-vehicle data

An initial assessment of the feasibility of the proposed technology was undertaken using vehicle dynamic simulations. These simulations investigated the frequency response characteristics of the acceleration signals acquired from different locations on the vehicle when subjected to a variety of discrete track inputs. One of the main challenges to the success of this technology for the detection of track degradation (e.g. change in track condition over time) arises from the problems of differentiating the vehicles response to a track fault from the response generated during normal operation. Clearly, features seen at the wheelset and bogie level can be more readily attributed to abnormal track conditions (such as voided sleepers) but translation of those features in the carbody to abnormalities in the track are significantly more challenging. However, the simulation results showed that it is possible for the vehicles response to discrete track inputs to be transmitted through the vehicle suspension and observed within the cab of the vehicle. But the accuracy of the system for detecting the degradation of the track will depend on the sensitivity of the sensor to record the lower amplitude signals observed in the cab. The simulations concluded that, through the use of the proposed tri-axis accelerometer and some signal processing and detection techniques, it should be possible to differentiate between different types of anomalies and their severity.

As a means of recognising signature track features from in-service vehicle, a prototype device was used to acquire data on a number of routes on Network Rail (NR) infrastructure. Early fault recognition focused on void detection for which the acquired triaxial acceleration data was post-processed and analysed to identify the characteristics of the vehicle response to abnormal track features.

Signal processing techniques for detecting the time information in a signal was used to extract the location of the maximum signal strength in the time domain. The method uses a Continuous Wavelet Transform (CWT) that allows a windowed estimation to be applied to the signal where the window is automatically sized according to the frequency thereby preserving the time of the detected irregularity. The CWT is extracted using the equation

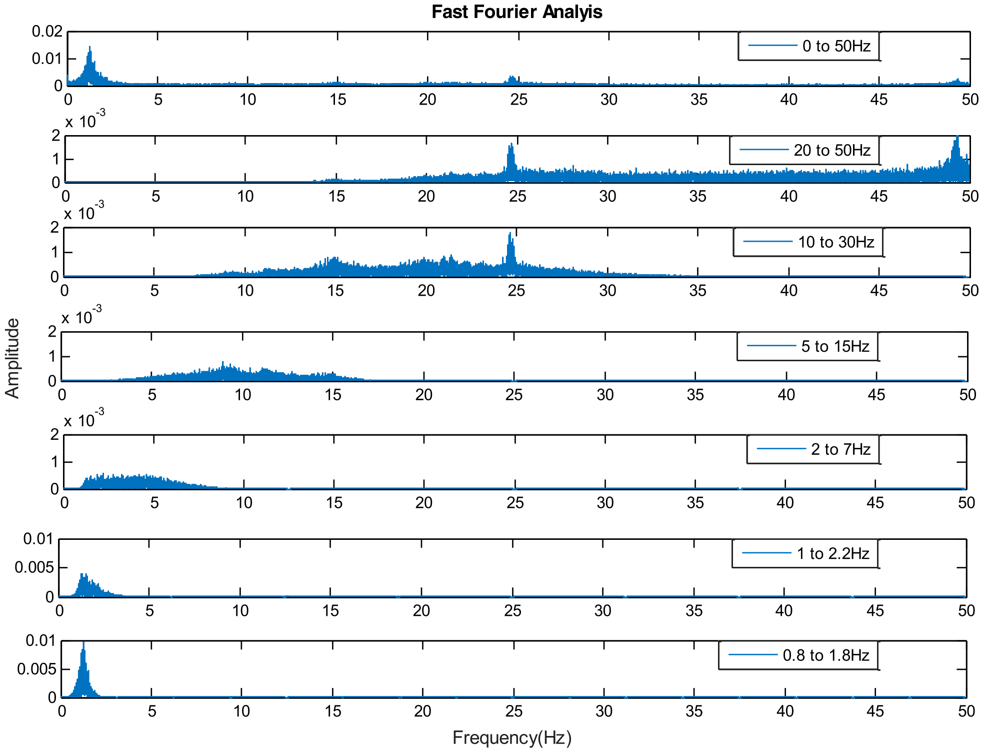

Figure 1. Vertical acceleration frequency analysis (Conference paper [8]).

below:

$$W_{\psi}f(b,a) = \int_{-\infty}^{\infty} \frac{1}{|a|} \psi\left(\overline{\frac{x-b}{a}}\right) f(x)dx$$

The selected mother wavelet $\psi(t)$ is shifted in time by b and modulated in frequency by $1/a$. A multi-resolution analysis (MRA) [7] separates the signal into frequency bands using the CWT as seen from the frequency analysis of the vertical acceleration data in Figure 1. The frequency spectrum in segmented into six bands, which correspond to the MRA shown in Figure 2.

The top subplot in Figure 2 shows the corresponding raw vertical acceleration data. Here the acceleration signal is further decomposed into discrete frequency bands in successive subplots, from higher frequencies in the top subplot to low frequencies in the bottom. As discussed, a discrete wavelet transform and a subsequent multi-resolution of the transform was used to produce these plots.

The subplots of Figure 2 show the vertical acceleration experienced in the carbody of the vehicle during prototype testing, with each subplot having the same frequency range used in the corresponding subplot of Figure 1. The bottom two plots in Figure 3 are very similar in acceleration peak amplitudes of approximately 1 m/s^2 which can be seen to have a corresponding frequency range between 0 and 4 Hz, as confirmed in the spectrogram of the vertical acceleration in Figure 3.

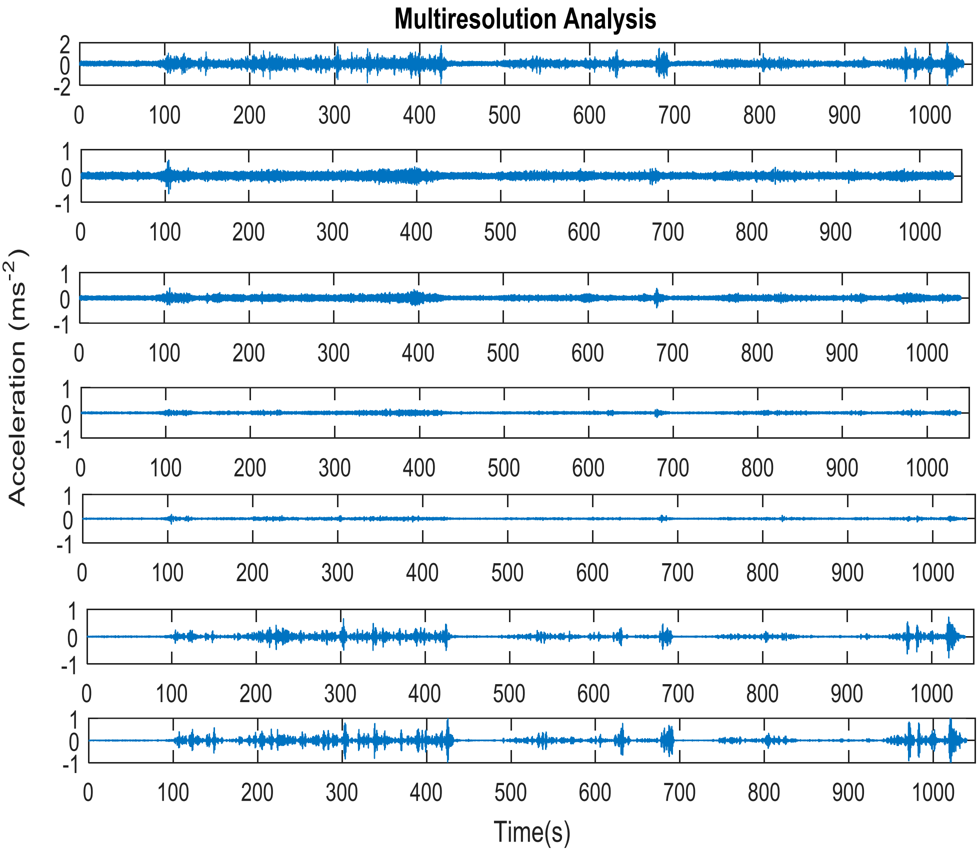

Figure 2. Multi-resolution analysis (Conference paper [8]).

As the initial aim of the system was to identify features relating to poor support (e.g. voids) and irregularities in the track, the vertical acceleration measured in the vehicle is greatly influenced by the low frequency (up to 4 Hz) vibration of the carbody. This vibration has been shown to be of value for detecting track irregularities, such as those generated at locations with poor support conditions or voided track. When analysed in a spectrogram, as shown in Figure 3, it can be seen that the majority of the power in the vertical acceleration signal resides within this distinct frequency range and the power suggests that the resonance is strong.

This frequency analysis showed that, by band-pass filtering the acceleration response at different frequency ranges could the allow the system to differentiate between various types of response e.g. lower frequency features such as voided sleepers and higher frequency features such as corrugation and wheel flats. Similar approaches have been identified by the authors in [9]; this approach would allow the detection algorithm to differentiate between a range of potential defect types.

The following section further examines the characteristics of the carbody vertical acceleration response to design the detection algorithm using a state machine.

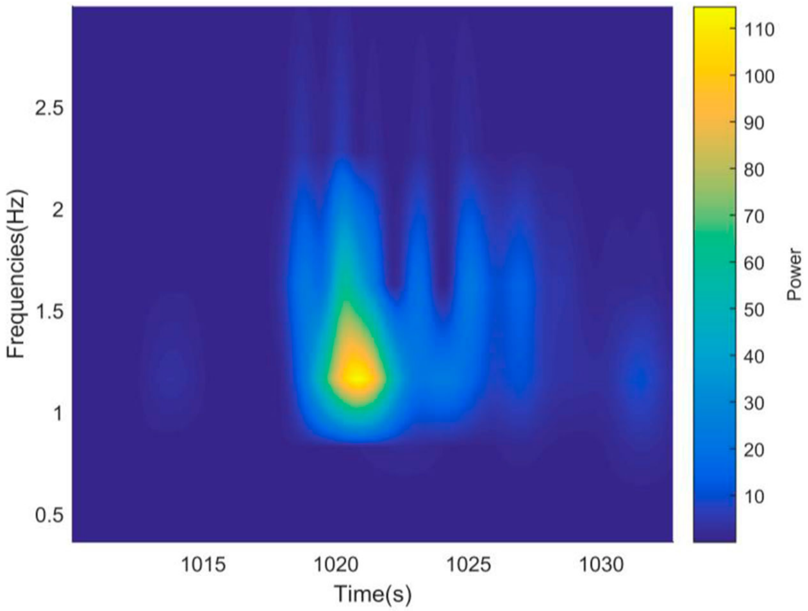

Figure 3. Spectrogram of Vertical Acceleration measured in the carbody (Conference paper [8]).

Detection Algorithm Development

Using dynamic modelling of the vehicle and track interaction, simulations were generated for passenger and freight vehicles travelling over voided tracks on plain line and at S&C. The frequency analysis, discussed in the previous section, supported the isolation of signals that were indicative of particular track faults. Consequently, a detection algorithm was developed, using a state-machine approach which could isolate the abnormalities, categorise them, and accurately report their GNSS location.

Speed compensation

Speed compensation is necessary to account for vehicles which are operating at a lower speed and therefore generate lower than anticipated acceleration levels over the same section of track. A detailed speed compensation methodology was derived from experimental and simulation acceleration data. Simulations were conducted using the VAMPIRE vehicle dynamics simulations software with a vehicle operating over measured track geometry data from a section of track with known voids at varying speeds. The simulated vertical acceleration output from the carbody were compared with measured carbody accelerations obtained from experimental testing operating over the same section of track at varying speeds.

It is important to note that the compensated acceleration values generated from the algorithm only provide an indication of track quality and are not the actual acceleration values that might be achieved when operating at a higher speed.

In simulation, vertical acceleration was seen to exhibit a square law proportionality to the speed of the vehicle which had to be evaluated and verified before an algorithm was

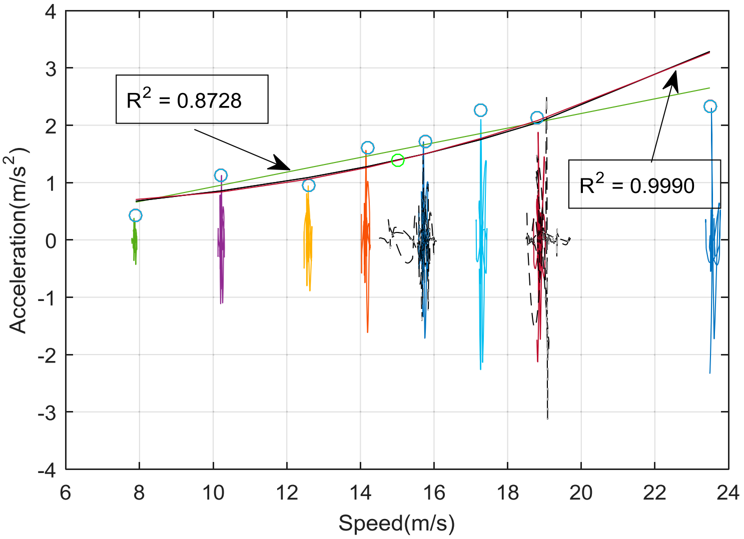

Figure 4. Speed Compensation Model Residuals Consideration.

developed to compensate for the observed relationship. Figure 4 shows both the simulated and experimental acceleration response of the carbody to a severe vertical irregularity in the track. The acceleration response, shown by the dashed lines, below each circle is the data gathered during experimental runs of the prototype system. The modelled response for the peak accelerations (circles) is shown by the continuous curves in the plot. The isolated acceleration responses of the simulated vehicle travelling over a severe to moderate irregularities in the track for a range of speeds is shown in the Figure 4. The blue circles mark the maximum acceleration in the simulation response and the measured results from early prototyping trials are shown as black dashed lines overlaid on the simulation results.

To determine the goodness of fit for the proposed mathematical models that represents the actual trend of the acceleration, the coefficient of determination R^2 for both a linear regression of the data and the exponential or square law fit of the data were determined. These indicate how closely the values obtained from curve fitting match the dependant variable (acceleration) which the model is intended to predict. It can be seen that although the linear fit, shown in green, exhibits good correlation to the data with a 0.873 (e.g. closer to 1 the better) it is not as good as the fit to an exponential model of the data shown in purple, giving an R^2 value of 0.999.

As the exponential model of the data provides the best fit a robust method of selecting an appropriate exponential that not only predicts the most severe irregularity case but also one that represents a range of irregularities had to be determined. Figure 5 shows a number of exponential models that predict the behaviour of the vehicle carbody whilst it travels over a range on irregularity with varying severity.

The green exponential is a fit of the entire data set that is representative of a mid-range acceleration profile for the speeds shown on the x-axis of the Figure 5.

To normalise the acceleration values at lower speed to that of those experienced by the vehicle at higher speed, the lower acceleration values are increased by a factor governed by the derived inverse exponential proportionality. Figure 6 shows the inverse exponentials

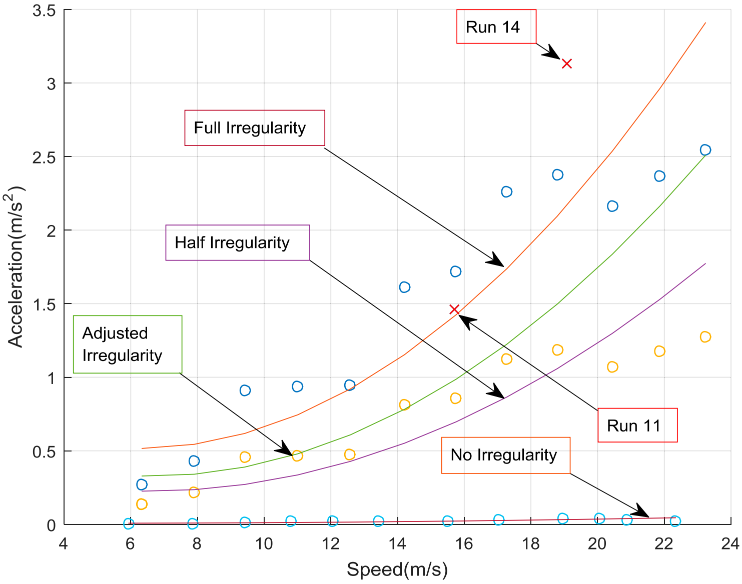

Figure 5. Speed Acceleration Plots for Various Severities of Irregularities.

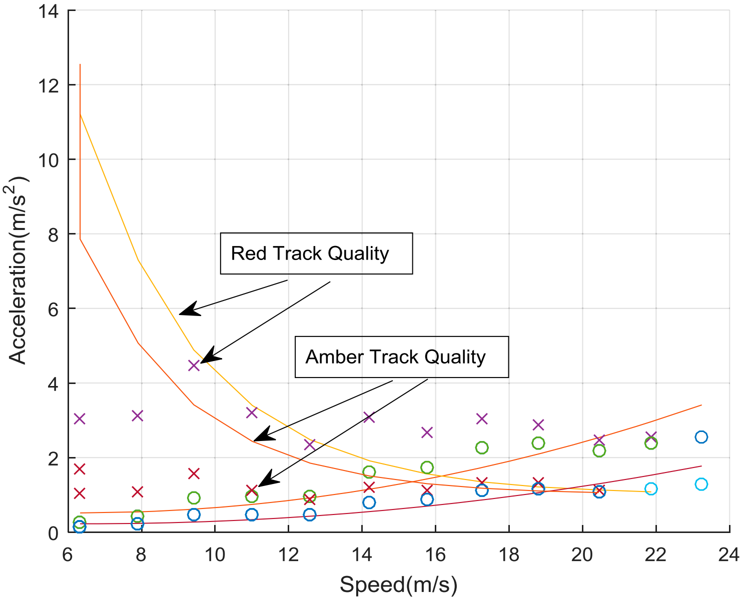

Figure 6. Compensated Acceleration Inverse Exponential Fits.

for the severe irregularity and a lower severity level rated at mid-range. The circles in the figure represent the acceleration values and the crosses represent the compensated values. It can be seen that acceleration values, shown as crosses, at lower speed are modified by the inverse exponential to a normalisation factor governed by the higher speed values.

The implementation requires the low speed acceleration values to be modified in a manner that can be correlated to the higher speed acceleration values. The higher speed acceleration values from the vehicle travelling over a section of poor quality track are a good representation of the vehicles dynamic behaviour in response to a particular irregularity in the track. In contrast, the response of the vehicle at lower speeds does not yield the acceleration amplitudes required with a good level of certainty to differentiate between good or bad track quality. It was therefore necessary to compensate for the lower acceleration values by a factor that normalised the acceleration values at lower speed to that of higher speed values transmitted into the vehicle carbody by the same irregularity. Compensated values were highlighted in the resulting outputs using a confidence level to illustrate that they are assumed values of acceleration and not actual values.

Trials on Network Rail infrastructure

A demonstrator system was trialled on the NR NMT operating on a number of routes. This included track sections from Derby and Crewe (trial 1 and 2), via Chester and Liverpool, and the Thameslink route (Hither Green to London Victoria, via London Blackfriars and London St Pancras Int., trial 3).

The data acquired by the in-cab system during the three trials was synchronised with the NMT measured track geometry data using the time and GNSS co-ordinates from the system processor. To ensure that the track geometry data recorded by the NMT and the acceleration data measured by the in-cab system were aligned correctly the vehicle speed measured by both systems was compared and the alignment adjusted as necessary. Figure 7 compares the vehicle speed measured by the NMT. The plot legend marks the NMT data as NMT(TT02), in red, and NMT(TT03), in green; for the NMT data files, TT02 and TT03, denote the track geometry data for the particular run in question. The corresponding in-cab data is shown by the dashed lines: in black for Run 25 and in blue for Run 36. Run 36 is a repeated run over the same section of track (while the NMT was on its return journey but not recording) corresponding to TT02 and TT03 shown in Figure 7. Run 36 was valuable as repeated detection of the same fault on two different runs, highlighting the repeatability of the system for detecting the same fault with a good level of accuracy. It can be seen that an excellent match in the vehicle speed is obtained from the selected NMT runs and in-cab data. This gives confidence that the correct sections of data has been selected in both datasets. These runs represent the data from Thameslink route where the NMT travelled from Hither Green to London Victoria, via London Blackfriars and London St Pancras Int., before returning to Hither Green via (via London Blackfriars).

The speed channel for the in-cab system is acquired from the GNSS signal on the NMT. Figure 7 shows the correlation between GNSS location information reported by the track monitoring system and that of the NMT. This was key in aligning the track geometry data and faults reported by NR NMT with the vertical exceedances from the track monitoring system. The trials also revealed, by the two independent runs over the same stretch of track, that the system was capable of detecting the same irregularity illustrating the potential repeatability of detecting the same track fault. It is conceivable that from multiple runs over the same section of track by the same and other vehicles reporting the same exceedance that the locational error with GNSS can be reduced to give more accurate locational information about track faults for directing maintenance actions.

The location and severity of discrete track faults determined from the NMT track geometry data and reported by NR were compared to the outputs from the detection algorithms

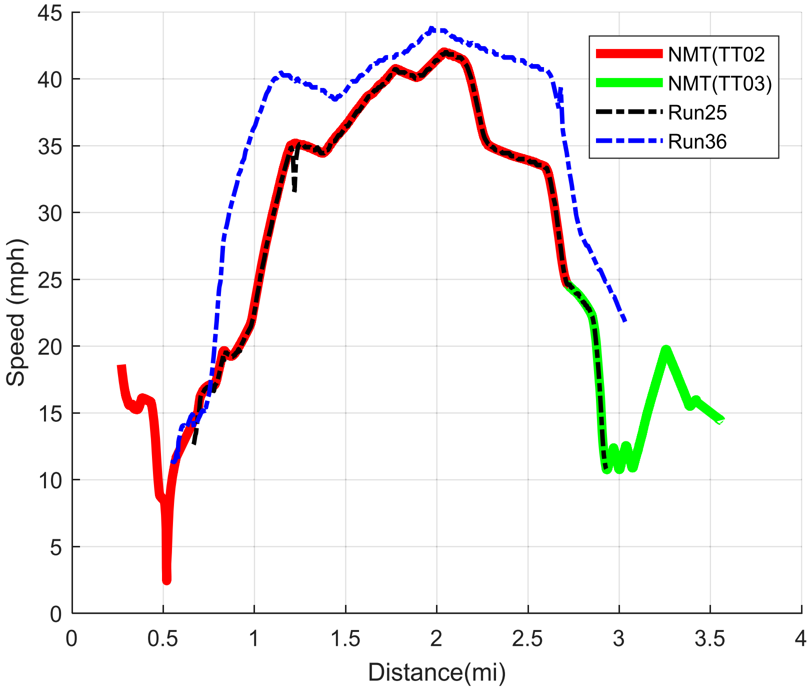

Figure 7. Correlation Vehicle Speed Recorded by NMT and In-cab System for Trial 3.

in track monitoring system. The distance history of the filtered acceleration signals, band-pass filtered at 1–4 Hz to remove features not associated with the vehicle response, were also compared to the measured track geometry data, along with appropriate statistical measures as reported in the following sections.

Detection of discrete faults

Amongst other measures, a key assessment criteria of the system are its ability to detect the appearance of discrete faults. Thresholds are defined in NR standards [10] for specific track geometry parameters acquired by the NMT to identify individual faults which require maintenance to ensure safe operation of the vehicles on the track. These are reported in a NR 'Track Geometry Fault Report' which includes details of the location (e.g. ELR, TID and GNSS), type, peak value and threshold of each fault identified in the track geometry data. Faults are either classified as Level 1 (alert limit, L1), features which should be corrected during routine maintenance plan, or Level 2 (intervention limit, L2), isolated defects which require more urgent attention.

A summary of the different track faults reported by Network Rail on track sections measured during trial 3 are summarised in Table 1 below. It is important to note that whilst it is not expected that the system will be able to directly detect track twist and gauge faults, the vehicles response to these features may translate into the vertical and lateral acceleration acquired by the track monitoring system and so could infer the presence of such faults.

Due to the absence of GNSS data from the first trial, the main focus of the discrete fault detection assessment has been the data acquired on the Thameslink route during trial 3.

Table 1. Summary of reported track geometry faults.

Type	Channel	Description
3 m Twist	TW3M	Difference in cross-level over 3 m length along the track, increasing the risk of wheel unloading leading and flange climbing
Gauge	GAUG	Variation in the distance between inside faces of the rails, from the standard gauge of 1435 mm
Cyclic top	CYC	Depressions in the rail that form a cyclic shape in the track, which can excite resonances in freight vehicle suspensions and increase the risk of derailment
Alignment 35m	AL35	Horizontal profile of the rails about the track centre-line
Top 35m	TL35 TR35	Vertical profile of the left and right rail
Dips	LDIP RDIP	Dips in the rail-head generally associated with bolted joints and measured as a dip angle

Table 2. Summary of NR reported track geometry faults and in-cab detection algorithm.

		Total No. NR Faults		Total Siemens Detections		% Match	
Type	Channel	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
3 m Twist	TW3M	9	0	7	0	78	–
Gauge	GAUG	9	2	2	2	22	100
Cyclic top	CYC	0	0	0	0	–	–
Alignment 35m	AL35	0	1	0	1	–	100
Top 35m	TL35	2	2	2	2	100	100
Total		20	5	11	5	55	100

The exceedances of each track fault threshold reported by NR for the selected track sections were combined and plotted on an interactive map along with the exceedances in the vertical and lateral acceleration automatically generated by the detection algorithms incorporated on the in-cab system. This provided an initial understanding of the level of correlation between the NMT and acceleration data.

To demonstrate the level of correlation, the total number of track faults and peak acceleration exceedances have been summarised in Table 2. This shows that 55% of the L1 track faults were detected by the track monitoring system, whereas 100% of the L2 faults corresponded to a location where a high peak acceleration exceedance was reported by the track monitoring system. It is important to note that at some locations high vertical or lateral accelerations are measured by the track monitoring system which do not correspond to any faults recorded by the NMT. This suggests that the vehicle is responding to features (or combination of features) in the track which are either just below the alert threshold or are not currently assessed in track maintenance standards. The response of a vehicle (and the accelerations experienced within the vehicle) to a particular track geometry feature will depend on the vehicles suspension characteristics and some vehicles may be able to tolerate larger variations in track alignment than others. Therefore, it may be more appropriate to target maintenance based on the response of the vehicle (as recorded by the track monitoring system for example) rather than apply the same track maintenance standards to all vehicles. Performance related track maintenance has been considered in previous research [11] and would need to account for the vehicles response to different track features and wavelengths.

The track geometry fault report for trial 3 showed two L2 exceedances in the railhead top profile threshold. To illustrate that the in-cab system can detect these faults, Figure 8

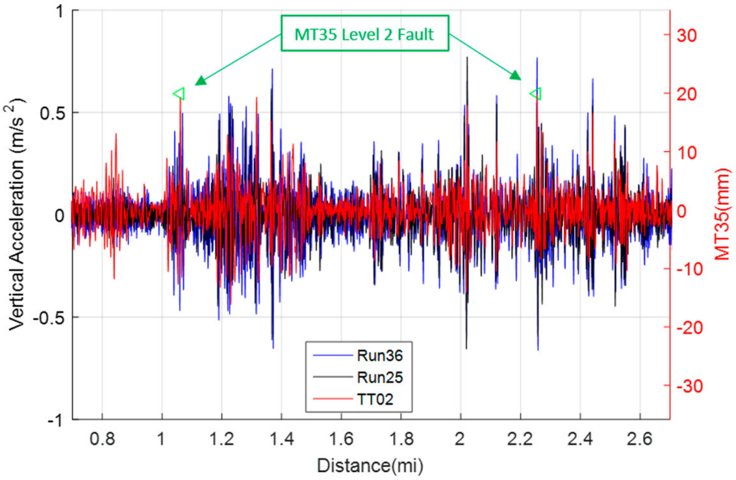

Figure 8. Comparisons of Vertical Acceleration and 35 m Mean-top with GNSS location.

shows a comparison of the vertical acceleration measured from the in-cab system and the mean top of the left and right railhead profile measured in the longitudinal vertical plane and filtered at 35 m wavelength (MT35), derived from the NMT data. The comparison is plotted on a dual y-axis; the left y-axis representing the vertical acceleration for Run25 and Run36 from trial 3, shown in blue and black respectively; the right y-axis representing the NMT measured MT35. Although the units of the acceleration and MT35 data are different the emphasis here is the proportionality of the two datasets, differing scales are used to give the appearance of normalised data without losing the units.

Figure 9 shows a closer look, at the same data as Figure 8, revealing that, overall, the general shape of the distance histories of the vertical acceleration and MT35 show very good agreement, with peaks in the acceleration response, generally, occurring at locations with high peaks in MT35. The exceedances in the MT35 discussed above are shown as green triangles. The zoomed-in plot verifies, firstly, that the acceleration recorded during the first run (Run 25) captures the fault and, secondly, that the subsequent run over the same track section (Run 36) captures the same fault verifying the repeatability of the system for detecting faults (and to monitor any changes in the fault severity over time). The longitudinal offset in the position is due to differences in the GNSS antenna positions on the vehicle used by the track monitoring system and NMT.

A similar comparison was seen for the MT35 and the vertical displacement, for Run25 and Run36, derived by double integrating the vertical acceleration measured by the in-cab system. It has been noted in some cases, when using displacements, a better comparison is seen as the amplitudes of the NMT and in-cab system are both in millimetres (Figure 10).

The lateral acceleration (low-pass filtered to remove the response due to vehicle curving) measured by the in-cab system also shows good agreement when compared to the track lateral irregularity (AL35) channel from the NMT data. Figure 11 (Figure 12 zoomed-in) shows the lateral acceleration (Run25) and AL35, measured by the NMT, for the same track section described in the vertical analysis above. It can be seen that there is generally a good agreement between the peaks in the AL35 data and the lateral acceleration measured by

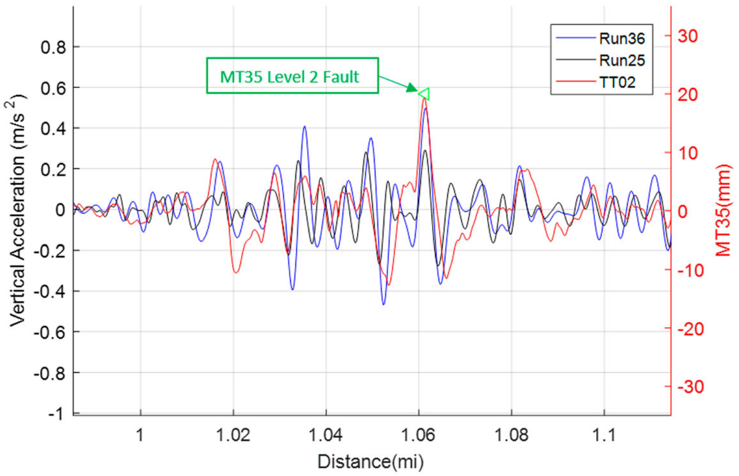

Figure 9. Comparisons of Vertical Acceleration and 35 m Mean-top – Zoomed-in.

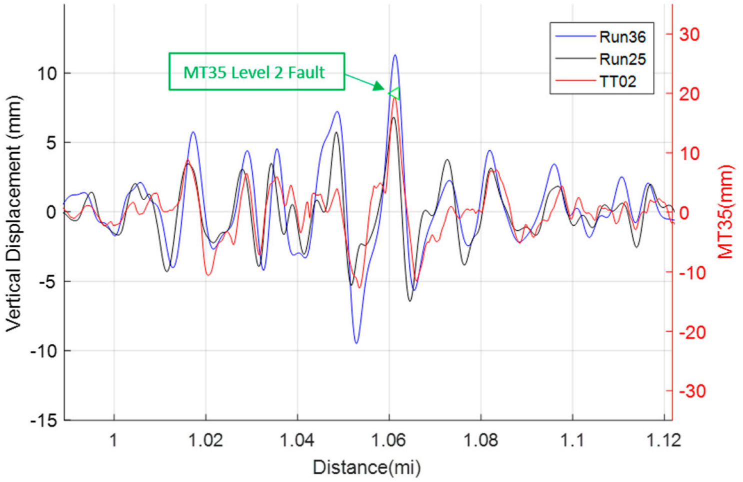

Figure 10. Comparisons of Vertical Displacements and 35 m Mean-top.

the in-cab system, particularly at the location of the reported exceedance at approximately 1.26 miles along the track section. A revised band-pass filter for the lateral acceleration, between 0.5 and 2 Hz, was found to give the best correlation to the NMT recorded lateral alignment data.

Track quality assessment

In the previous section the capability of the system for detecting discrete track faults was assessed, in this section the acceleration data acquired by the system is analysed to support the assessment of track quality and future degradation.

Previous research [11] to [12], has shown that track geometry deterioration is driven by a number of factors which typically include the tonnage of traffic carried, the unsprung

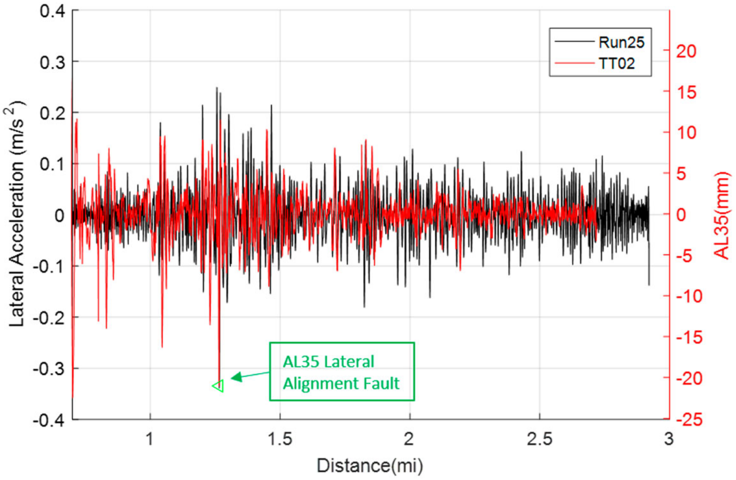

Figure 11. Comparison of Lateral Acceleration and AL35 for Run 25 – Zoomed-in.

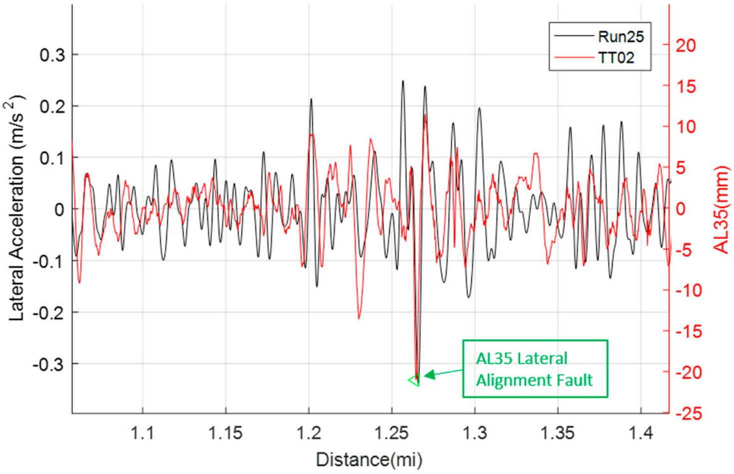

Figure 12. Comparison of Lateral Acceleration and AL35 for Run25 – zoomed-in.

mass of the vehicles and the local condition of the track, ballast and sub-grade. Additionally, research has attempted to define alternative methods for describing track geometry which considers the typical vehicle behaviour. However, these alternative proposals of track geometry descriptions have been shown to not improve the regression model [13].

In GB mainline railways, track geometry quality is assessed by calculating the SD of the track vertical and lateral alignment over a defined length (e.g. 1/8th mile, approx. 200 m) and is used to monitor track degradation and for maintenance scheduling, as illustrated in Figure 13.

It is valuable to note, that although the Standard Deviation (SD) may not be the most accurate statistical measure to describe the variation and magnitude of track irregularities, it is still a commonly used parameter to assess track geometry quality and is included in

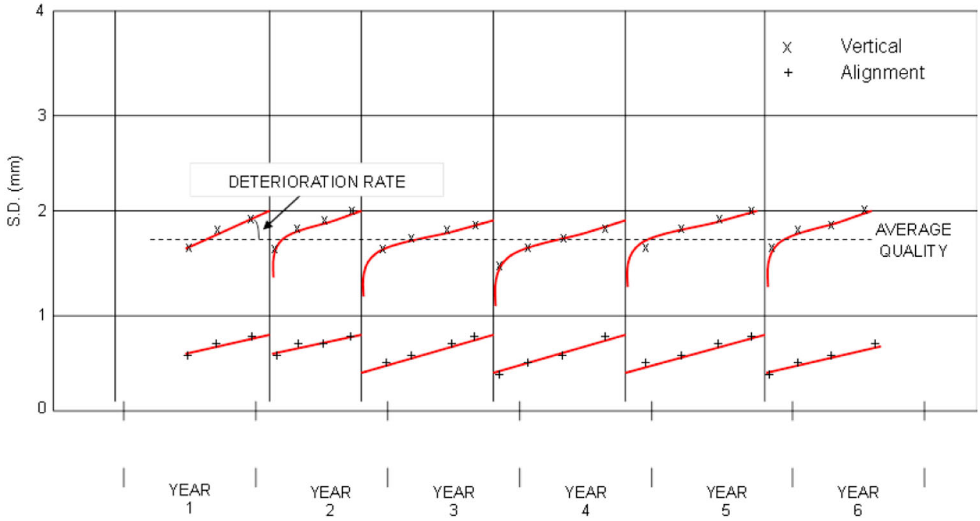

Figure 13. Track Geometry Deterioration Cycles Measured by Standard Deviation.

a number of EN standards for the approval of rolling stock (EN-14363) and assessment of track geometry quality (EN-13848-5).

From the comparisons of the NMT and acceleration signals presented in the previous sections, it is clear that there is generally a good agreement between the vertical (MT35) and lateral (AL35) track irregularities (for wavelengths up to 35 m) derived from the NMT data and the vertical and lateral acceleration recorded by the track monitoring system. To observe this correlation statistically the normalised 1/8th mile SD of both the NMT and acceleration data have been calculated for both trials two and three.

Figure 14, shows a comparison of the normalised 1/8th mile SD values for the vertical data from Run2c of trial 2. Run2c, from trial 2 (Derby and Crewe) is used here, as the track section is a particularly long run, consisting of 14 miles of data, enabling the value of the SD to be seen more clearly. Figure 15 below shows the same analysis for the lateral acceleration compared to AL35 (WDB3 in the legend is the Engineering Line Reference for the track section) within trial 2. A good agreement between the SDs can be seen, demonstrating the potential for the system to monitor future track degradation and the effectiveness of maintenance actions. It can be seen that the correlation at approx.13-miles deteriorates significantly; this was investigated further and was found to be as a result of a reduction in vehicle speed, thereby reducing the magnitude of the resultant acceleration seen in the vehicle.

To illustrate the repeatability of statistical measures from trial three, the normalised 1/8th mile SD of the vertical acceleration and the MT35 channels are shown in Figure 16 below; the NMT data shown in red and acceleration data for the two runs (Run 25 and 36) shown in black and blue respectively. It can be seen from that, statistically, there is generally good agreement between the vertical alignment (MT35) derived from the NMT and the vertical acceleration data measured by the track monitoring system. It should be noted that correlation between the lateral alignment (AL35) and lateral acceleration measured by the track monitoring system, provided a less definitive a comparison.

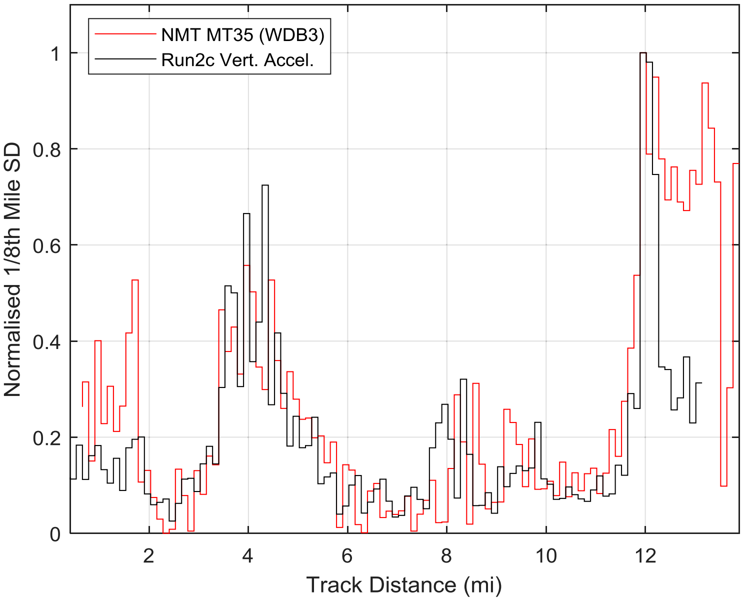

Figure 14. MT35 and Vertical Acceleration 1/8th Mile Standard Deviation Against Track Distance.

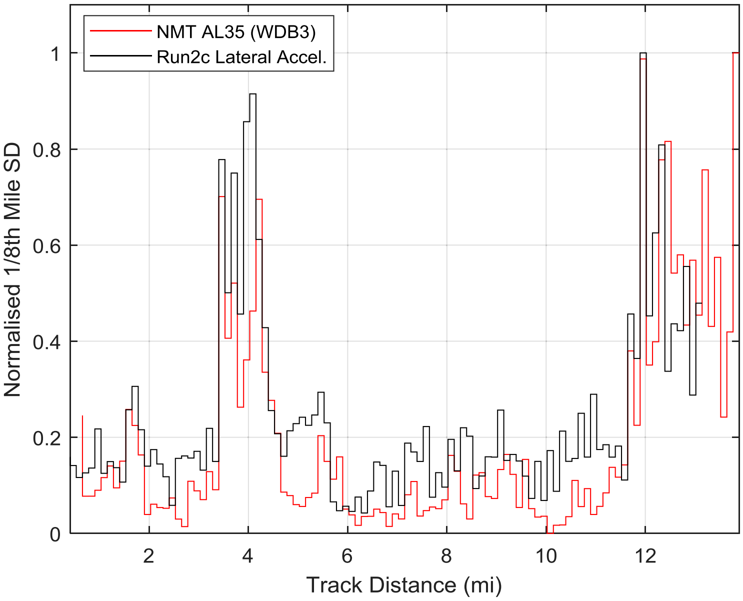

Figure 15. AL35 and Lateral Acceleration 1/8th Mile SD (WBD3) Against Track Distance.

To further illustrate the relative correlation of the normalised SDs calculated from the vertical (MT35) and lateral (AL35) alignment and acceleration data, the SDs calculated from the vertical and lateral acceleration from trial three have been plotted against the corresponding data from the NMT in Figures 17 and 18, respectively.

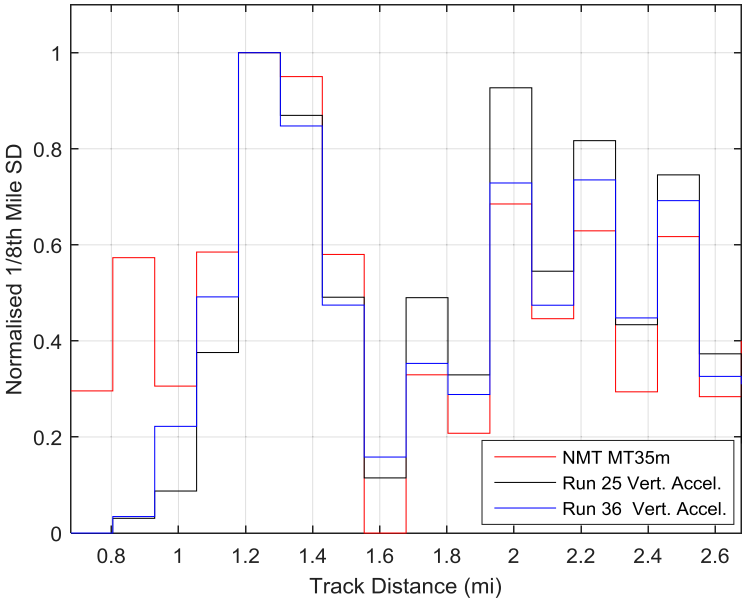

Figure 16. Normalised 1/8th Mile SD for Run25, Run36 MT35 Vertical Acceleration Against Track Distance.

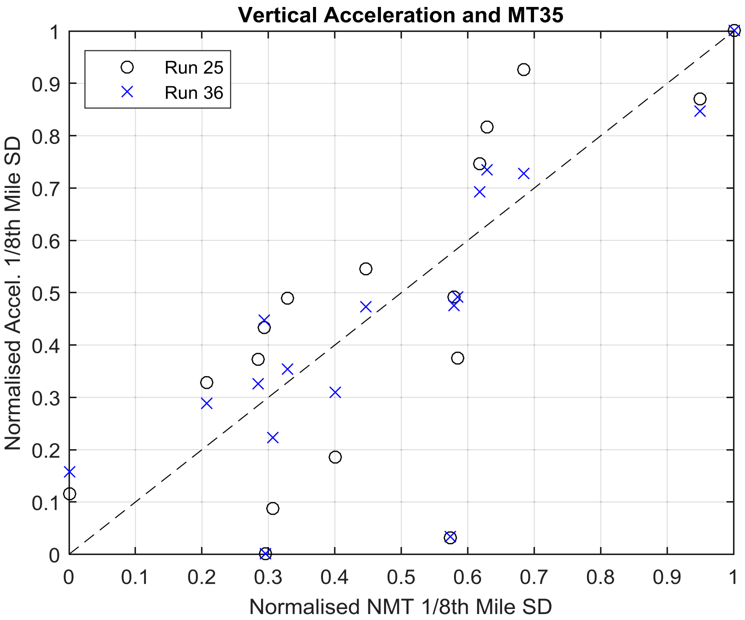

Figure 17. Normalised 1/8th Mile SD for Run25 and Run36 MT35 and Vertical Acceleration.

The dashed line indicates a perfect correlation between the SDs therefore the closer the data to this line the better the match between the datasets. Generally it can be seen from Figure 17 that a good correlation is obtained between the SDs of the vertical acceleration and the vertical alignment (MT35).

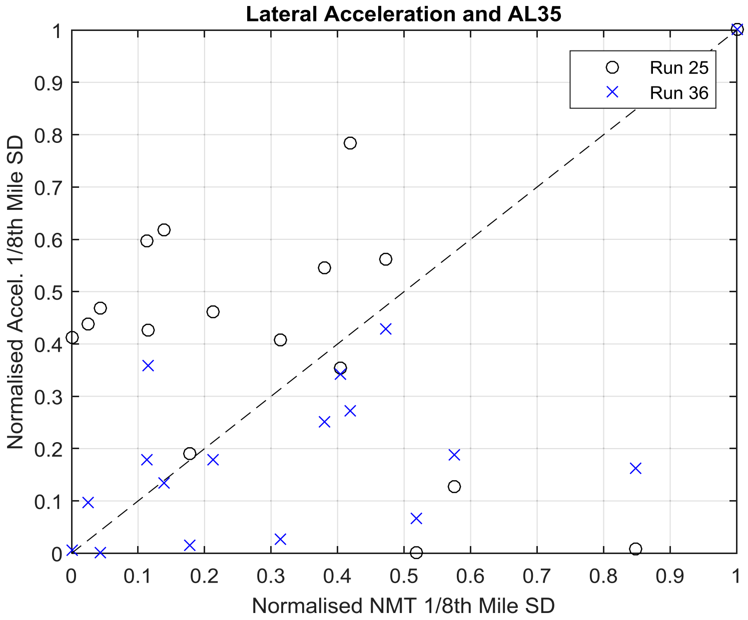

Figure 18. Normalised 1/8th Mile SD for Run25 and Run36 AL35 and Lateral Acceleration.

However, as illustrated in Figure 18, an observably weaker correlation is obtained between the lateral acceleration and lateral alignment (AL35). This agrees with previous research which has shown that track geometry SDs may not provide a good correlation with the vehicle response [13]. However, no alternative methods, examined by the authors, have been proposed for describing variations in track irregularities. Further examination of Figure 18 reveals considerable scatter in the normalised acceleration SDs and the SD calculated from the lateral track alignment. This suggests that the amplitude of the measured acceleration is influenced by the operating speed of the vehicle over the track geometry. It is worth noting that no speed compensation was applied during the trials of the monitoring system to correct for reduced acceleration at lower speeds and increased acceleration at higher in the vehicle car-body.

Not compensating for the affect of speed variations on the acceleration response reduces the confidence in the current system for detecting changes in track geometry quality; however, it is possible the system could be improved through additional simulation and experimental work to further understand the vehicle response due to variations in track inputs (e.g. magnitude and wavelength) and operating speed.

Conclusion and future developments

Recent developments of the Siemens in-cab GSM-R system has included the addition of a, commercially available, low-cost solution for the monitoring of track defects and degradation. The incorporation of a MEMS sensor and associated processing capabilities provides the opportunity to measure the acceleration response in three axes that when combined with signal processing and fault detection can identify features in the data associated with a range of track defects.

Vehicle dynamics simulations were undertaken to support the development of the system. The simulations showed that although the magnitude and frequency of the acceleration response is filtered through the primary and secondary suspension, useful information can still be gained from the in-cab response. The placement of the system within the cab was verified and initial detection algorithm development was completed based on the simulated response.

Prototype trials of the system on vehicles operating over track sections with known features provided further evidence of the potential benefits of the system. Through these trials, locations with known voided sleepers were a detected by the algorithm and used to develop thresholds in acceleration response for future deployment.

A demonstrator system was subsequently trialled on the Network Rail NMT. In the most part, arguably, good agreement was observed between the track irregularities measured by the NMT and the acceleration response measured by the in-cab system. The outputs from the detection algorithm incorporated in the system generally showed good agreement with the location of reported track faults derived from the NMT data, particularly in relation to the vertical top, and dip faults, with exceedances in peak acceleration reported at the location of the majority of Level 1 (Alert Limit L1) and Level 2 (Intervention Limit L2) reported track faults. Discrete lateral faults were examined extensively with less correlation being found. It is possible with improved speed compensation algorithms and the future implementation of a multi-train / multi-journey approach that the correlation with reported track faults (in particular the lower magnitude alert limits, Level 1) **could** be improved.

A more detailed assessment of the track irregularities and acceleration signals showed that, overall, the general shape of the distance histories of the acceleration and track irregularities have good agreement, in the vertical response of the vehicle, with peaks in the acceleration response generally occurring at locations with high irregularity peaks.

Further statistical analysis of the vertical and lateral acceleration response acquired by the system was shown to provide a good correlation with the common statistical measures used to assess track quality, particularly in the vertical direction. Statistical measures of correlation in the lateral response of the vehicle showed significantly less agreement than the vertical. With further development, the potential benefits of the system in terms of monitoring track degradation and evaluating the performance of corrective track maintenance from in-service vehicles could be realised but particular focus will need to be placed on finding better methods of improving the reduced lateral correlation in vehicle response.

As the system uses acceleration measurements from in-vehicle sensors, the accuracy of the system (or confidence of detection) will inevitably depend on the response of the vehicle to the track features and how this energy/excitation transfers through the primary/secondary suspension into the vehicle. Therefore, the system may not be able to detect the very early onset of a fault where the vehicle response to this fault is small, however with multiple journeys by the same vehicle and multiple vehicles travelling over the same section of track it should be possible to measure a change in a given fault whether for track degradation assessment or the evaluation of corrective track maintenance. Due to the absence of speed compensation in the recent trials much of the results showed less observable correlation particularly when the vehicle was running at low speeds or experiencing a change in velocity. It is anticipated that further machine learning methods to compensate for speed variations will enable a multi-train and multi-journal calibration of vehicle response enabling further improvements to be made.

The outputs from this research have provided useful information on the current capabilities of the system and potential for future developments. This will include the inclusion of algorithms to quantify passenger ride comfort and multi-train assessment to enhance the capabilities of the system.

Overall the system has shown good agreement between the locations of peak exceedances in acceleration response and discrete track faults measured by the NMT. Statistical analysis of the acceleration data acquired by the system has also shown reasonable correlation, particularly in the vertical direction, with SD of track irregularities commonly used as an indicator of track quality and degradation. However, further work is required to understand the vehicle response due to variations in track inputs (e.g. magnitude and wavelength) and, crucially, operating speed.

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Disclosure statement

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