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THE EFFECT OF TOP OF RAIL FRICTION CONTROL ON A EUROPEAN PASSENGER SYSTEM: THE HEATHROW EXPRESS EXPERIENCE

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ABSTRACT

Top of Rail (TOR) Friction Modifier (FM) has been investigated as a practical means of addressing a number of wheel rail issues occurring on curves on Heathrow Express, an airport express shuttle in London. Issues of concerns included excessive clip breakage, corrugations, and differential wheel wear. A staged trial plan first addressed safety concerns, and systematically measured the effect of two different wayside TOR FM application Phases. Lateral force measurements were used as a primary indicator providing immediate feedback on TOR effectiveness. Significant reductions in lateral forces were recorded, particularly on the low rail, with the best results obtained with FM application from each end of the test zone. A corresponding reduction in clip breakage occurred, resulting from the reduced rail base deflection from lower lateral forces. Wheel wear reductions were also observed despite the limited test area, likely because this section incorporates most of the sharp curves on the system. Throughout the trial, progressively reduced corrugation growth rates were recorded. With optimum FM coverage, the corrugation growth rate was reduced by 80%. Ongoing work is addressing long term corrugation growth rates, and effects on RCF.
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1 INTRODUCTION

Heathrow Express (HEX) operates a frequent shuttle service from central London to Heathrow airport using five-car Siemens Class 360 and nine-car Class 332 trains, with axle loads ranging from 11 to 14 tonnes.

Trains travel from Paddington Station in central London about every 15 minutes, arriving first at the Central Terminal Area (CTA) providing service to Terminals 1 to 3. Some trains then continue to Terminal 4 (inbound), primarily on single track in this section (bi-directional running) until 8225 Points and Crossing around 450m before Terminal 4 (T4) when the track splits into two tunnels to T4 Platforms 1 and 2. These trains then return from Terminal 4 (outbound). On leaving Heathrow, trains join the mainline Network Rail track for the rest of the journey to Paddington. The net result is that the area from CTA to Terminal 4 sees about 8 trains an hour for nineteen hours a day.

In recent years a number of issues related to wheel / rail condition have become apparent, particularly on track in the immediate vicinity of the airport. These issues include excessive clip breakage, corrugation growth, differential wheel wear and RCF. It was thought that many of these problems might relate to significant lateral loads believed to occur on a few relatively sharp curves between CTA and T4. Vehicle dynamics modelling provided support to this view[1].

Standard wayside gauge face grease lubrication is used on the system.

1.1 Vehicle Type / Configuration

Two different train configurations were used through the course of this trial:

Class 332 trains (8 or 9 car) are formed by combining two four or five car units. The four car units are configured: Motor-Pantograph car-trailer-Motor. The five car units are configured as Motor, Pantograph – Trailer – Trailer – Motor. Only the end cars of the train are driven. Axle loads for motor and pantograph cars are 12.7 tonnes, and 10 tonnes for trailer cars.

Class 360 trains are single five car units configured as Motor – Pantograph – Trailer – Trailer – Motor. Axle loads and speeds are similar.

1.2 Clip Breakage and Track Structure

Clip breakage had become a serious issue for Heathrow Express, particularly in the tunnel areas. The track structure is rather stiff and non resilient. Concrete sleepers are used on Pandrol studded rubber pads with concrete slab track. The clip type used is Pandrol e-clip 2000 series. Alternative e-plus clips were considered but replacement of existing clips was considered impractical. The failure mechanism of the clips is believed to be through fatigue, induced by high lateral deflections of the rail foot. The high deflections in turn are a result of the fundamental problem, high lateral forces on the rail. Figure 1 shows a typical example of clip failure.

Prior to the trial, clip breakage rates of up to 50 per week were recorded in this area, with average values of around 30. Two staff members were required to visit once per week, with a trolley containing a large number of new clips. Clip breakage normally declined after grinding, as the correct transverse rail profile was restored, and corrugations removed. Generally this improvement was lost within a relatively short period as corrugations returned within a matter of weeks, and wear on the top of the low rail caused loss of the transverse profile.

Figure 1 Example of typical broken clip

1.2 Wheel Wear and Differential Wheel Diameter

The target for wheel reprofiling is 402000 km. Depending on wheel condition, reprofiling can be as soon as 370000 km. Flange wear is not a significant factor for wheel life. Rather, tread wear and differential (side to side) wheel diameter are of more significance. Differential wheel diameter on these vehicles has been cited as a factor promoting RCF on the NR mainline[2] and also in the Heathrow airport area. Additional metal also must be removed during reprofiling if there is a large wheel diameter difference from side to side. Differential wheel diameter can also increase flange wear and affect ride quality, and was a concern for Heathrow Express.

It is not physically possible for the Heathrow Express trains to be turned end to end. Since the sharp curves are predominantly in one orientation (left handed coming from London) this leads to differential wear from one side of the train to another.

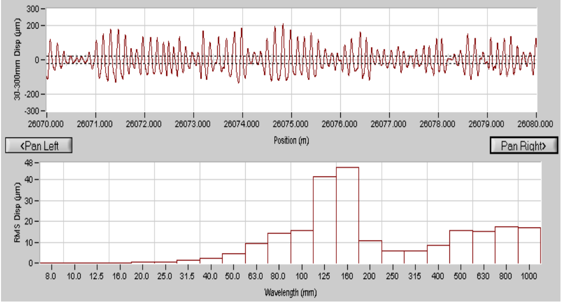
Wheel wear is significantly higher for driving axles (motor cars), and lower for trailer cars due to the higher longitudinal creepage and consequent friction forces. Wheel wear on pantograph cars is also relatively high. Wheel wear is monitored using a laser based measurement on the wheel reprofiling machine. Wheel profile is the standard UK P8 profile (conicity 1:20).

1.3 Corrugations, Transverse Rail Profiles, and RCF

Typical low rail corrugations between CTA and T4 are shown in Figure 2 below. The Corrugation Analysis Trolley (CAT) profile of a typical corrugated section is shown in Figure 3. All data is for low rail, no significant high rail corrugation was noted during the baseline or trial periods. Median wavelengths of 125 to 160 mm were recorded, with peak to valley depth of up to 0.8mm. This corrugation is likely a result of the P2 resonance of the unsprung mass on the track stiffness[3].

Figure 2 Typical low rail corrugations between CTA and T4

Figure 3 Typical CAT profile of corrugated rail



Wear of the top of the low rail leading to non-optimal wheel rail contact, together with the growth of corrugations were each factors which had been identified as contributing to high rates of clip breakage. Corrugations were in themselves one of the primary reasons for grinding. The rail profile is UIC54 (UK equivalent BS113A).

1.4 Potential of TOR Friction Modifiers.

Heathrow Express became aware of previously published work on the use of Top of Rail friction modifiers (FM) to reduce lateral forces and rail wear[4,5,6]. Prior published information on lateral force reduction was mostly limited to heavy haul freight operations in North America, except for results at Tokyo Metro with a train mounted application system[7]. Results on FM effects on short pitch corrugation growth in metro system curves have been reported[8,9].

It was decided to assess this technology as a means to improve management of the wheel / rail interface to mitigate the identified operational and maintenance issues. Prior published work in this area has used KELTRACK® top of rail FM[4-9]. This is a water based suspension of polymers and inorganic materials that provides (on evaporation of the liquid phase):

1. An intermediate coefficient of friction (0.3-0.4) between the wheel and rail[10,11], such that braking and traction are not affected. This controllably reduced friction is believed to reduce the wear component of the corrugation mechanism. The wheel / rail frictional force (in combination with lateral creepage) is directly related to lateral forces, and these are expected to be correspondingly reduced.
2. Positive relationship between traction and creepage ("positive friction")[12] which has been identified as a possible contributor to interrupting the dynamic component of the short pitch corrugation mechanism.

In this case it was chosen to apply the FM by wayside application using a Portec Rail Protector IV device. This equipment uses applicator bars mounted to the field side of the rail. FM is pumped to the railhead on triggering by a wheel sensor, and picked up by passing wheels. This method provided a convenient way to assess the potential of this technology and appropriate to deal with the limited number of problem curves.

2 TRIAL OBJECTIVES, PLANNING AND METHODOLOGIES

2.1 Objectives

Heathrow Express's primary objectives for this trial were to determine the effect of TOR FM on the various identified wheel / rail related issues.

The specific trial success criteria were:

1. Reduced clip breakage
2. Reduced rates of corrugation growth and ultimate amplitude development
3. Positive or nil effect on train wheels (tread wear)
4. Reduced rail head transverse profile degradation
5. Positive or nil effect on RCF

2.2 Trial Planning, Monitoring and Execution

The Heathrow Express track is maintained by Network Rail, the infrastructure operator in the UK. Since TOR FM had not previously been used in UK mainline systems, a detailed risk assessment was first carried out. Because of little prior UK experience and because the line at T4 ends at a dead stop, it was decided for risk mitigation purposes to initially apply friction modifier to the top of the low rail only. It was noted that most FM applications globally apply to the top of both rails for optimum results.

As part of this approval process a braking trial was carried out using a 4 car Class 332 train[13]. FM was applied manually and through wayside application bars to the top of the low rail. Stopping distances with the friction modifier were well within the proscribed standards, and similar to those recorded without FM application.

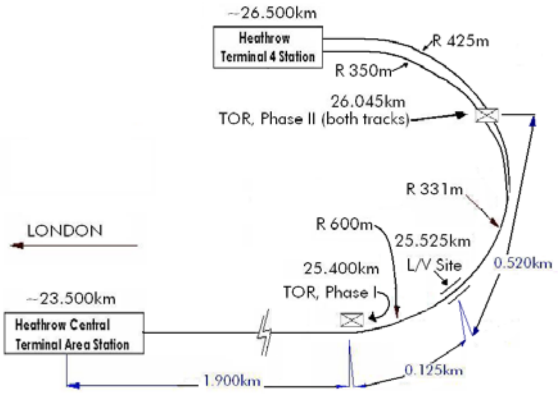


Figure 4 Schematic of test area from CTA to Terminal 4

Figure 4 shows a schematic of the test area between CTA and T4. In this section trains run bi-directionally, inbound and outbound from T4. Normal guidelines for application of FM in bi-directional traffic are for wayside application at each end of the track to be treated. It was decided to initially install just one wayside applicator, referred to the "Phase I" unit, in the location shown in Figure 4. This unit will apply FM to trains inbound to T4 and outbound to CTA. However when only this unit is operational trains outbound from T4 will not be treated until they pass this application unit, heading out of the test area. The intention with Phase I was to gain experience of TOR, establish safe operation, and gather initial results. Phase II was to add a second unit at T4 to treat trains outbound from T4. Guidelines for installation of TOR applicators specify that the applicator should be installed in tangent track at least 30m from the start of the spiral[14]. For the Phase I unit practical issues related to site access / space precluded this, and the unit was installed at one end of a 600 m radius curve. In practice this location did not pose any major application issues.

All application units in the test area apply FM to trains travelling in both directions.

The trial plan included:

1. Monitoring clip breakage intensively for the initial period of the trial by weekly inspection.
2. Regular monitoring of corrugation / longitudinal profiles using a CAT device (Corrugation Analysis Trolley from RailMeasurement Ltd.).
3. Installation and calibration of equipment for rail strain gauge based measurement of lateral and vertical forces within the body of the 600 m radius curve, located 125m "downstream" (West) from the Phase I unit (Fig 4). LVDT based monitoring of rail deflection was also employed.
4. Installation of a single wayside TOR application system for Phase I of the trial in December 2006.

5. Subsequent installation of a second wayside applicator for Phase II in July 2008. The Phase II unit is a "dual" unit, capable of applying to trains on different tracks exiting from the two platforms at T4.

In the initial stages of the trial, the TOR application unit was monitored every 1-2 weeks. A number of issues related to consistency of application and application rate optimization were addressed in the early stages, and further equipment upgrades were installed from October to December 2008. Since these upgrades the application equipment has functioned reliably.

In March 2008 Terminal 5 at Heathrow airport was opened, resulting in a significant change of service between CTA and T4. Train service to T4 was changed from 8 and 9 car Class 332 trains to 5 car Class 360 trains, with the same service frequency. This resulted in a reduction of 44% in the number of axles per week over the site. Class 360 vehicles have greater acceleration and braking capabilities than Class 332. Class 360 vehicles were believed from prior Network Rail experience to be more damaging to track structure as a result of these traction / braking capabilities.

3 RESULTS AND DISCUSSION

3.1 Lateral Forces

Lateral force measurements were carried out in a series of campaigns in 2007 (Phase I, nine car Class 332 trains) and 2008 /09 (Phase I and Phase II conditions, five car Class 360 trains). Initial checks showed that, as expected:

1. No changes in vertical forces were observed under different FM conditions or non FM (baseline) conditions.
2. For a given frictional condition the forces were generally very consistent from train to train, although it took two full days of operation to re-establish stable lateral forces on changing friction conditions.

2007 results (Class 332 trains, Phase I unit only)

Figure 5 shows the average lateral forces for leading axles, low rail and high rail, for inbound and outbound traffic. Leading axles only are analyzed as these exert the largest lateral force due to lateral creepage induced by the angle of attack of the leading axle wheel to the high rail.

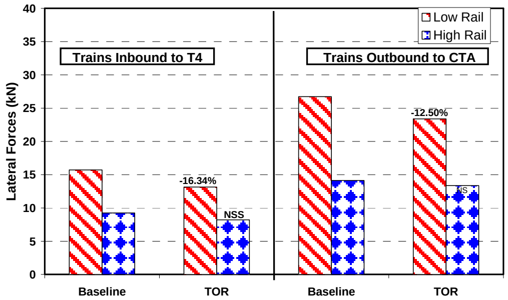


Figure 5 Phase I average leading axle lateral forces, inbound and outbound trains.

The following observations can be made:

- ➢ Outbound trains exert considerably higher lateral forces particularly on the low rail, either with or without FM application. This was an unexpected result.
- ➢ With Phase I FM application, both inbound and outbound trains experienced a 12 to 16% reduction in average leading axle lateral forces on the low rail.
- ➢ Forces on the high rail were typically lower than on the low rail. No statistically significant difference was recorded for average leading axle forces on the high rail between baseline and FM.

Further analysis of lateral forces on an axle by axle basis (Figure 6) indicated that the individual axles with the highest base line lateral forces (leading axles on driving cars) showed a much higher reduction in lateral forces (40-50%). These will be the wheels leading to the greatest rail deflection and causing the most track structure damage.

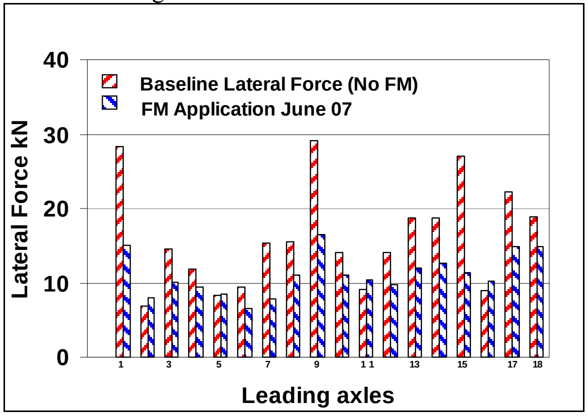


Figure 6 Leading Axle by Axle comparison inbound Class 332 trains, Phase I application versus baseline

Whereas with FM application the lateral forces on the low rail were consistent, the high rail forces showed oscillations between negative and positive values. This suggests that the leading wheels are not in saturated lateral creepage, but that the leading high rail wheels are oscillating on and off flange. Absolute force values were used to determine average values. It is hypothesized that the large difference in lateral forces between inbound and outbound trains is because braking of the inbound trains provides improved bogie steering, compared with acceleration of outbound trains.

2008 /09 results (Class 360 trains)

Figure 7 compares baseline (no FM) conditions for Class 332 trains (May 2007) and Class 360 trains (October 2008). The outbound Class 360 trains show very similar forces to corresponding Class 332 trains. However inbound Class 360 trains show much higher forces on the low rail than corresponding Class 332 trains. Class 360 trains are capable of higher braking and acceleration rates. At close to the measurement point, Class 360 vehicles are travelling 4-8kph faster than Class 332 for both inbound and outbound trains.

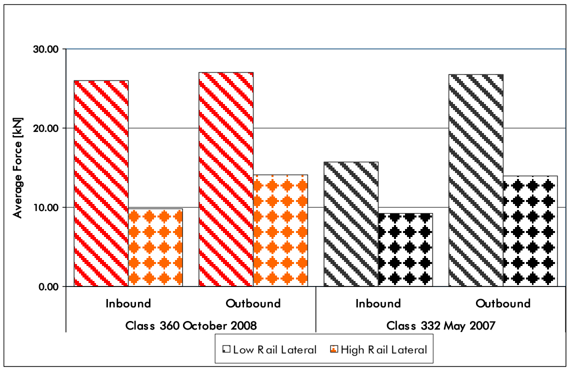


Figure 7 Leading Axle Average Lateral forces for Class 332 and Class 360, no FM

This information suggests that the Class 360 vehicles will be more damaging to track structure (e.g. clip breakage) in the test zone than the Class 332.

Figure 8 summarizes the lateral forces for Phase II results, comparing baseline forces (Class 360 trains), for inbound and outbound trains with application from both the Phase I and Phase II units. Comparison with Figure 5 clearly shows the much greater lateral force reduction with application of FM from both ends of the test zone. This optimized arrangement has become the standard on-going configuration. The results indicate that average lateral force reductions of ≥ 50% resulted from application of TOR FM under these conditions.

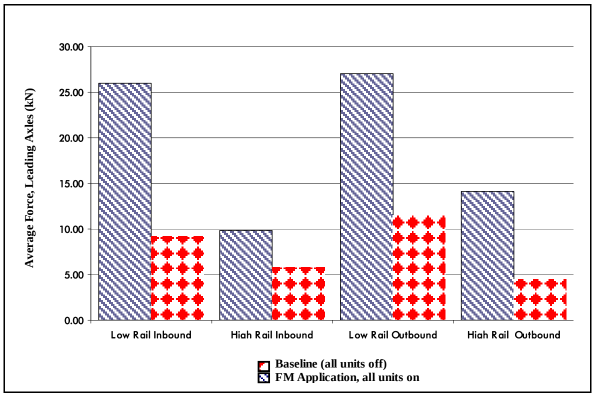


Figure 8 Average leading axle lateral forces, with and without FM (Phase I and Phase II units operating), Class 360 vehicles

3.2 Clip Breakage

Clip breakage was monitored by routine reports from Network Rail (NR) inspectors. A more intensive clip breakage monitoring program over a limited test area was also carried out during Phase I. The NR results shown in Figure 9 illustrate the whole trial period. The clip breakage data has been normalized to account for the change in traffic pattern with the opening of Terminal 5 (reduced number of axles per day).

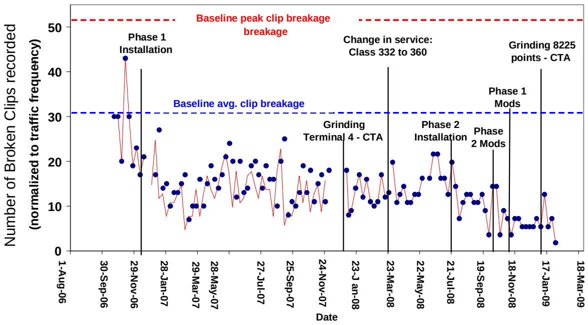


Figure 9 Clip breakage rate (adjusted for traffic frequency)

Clip breakage of the type shown in Figure 1 is likely due to fatigue induced by a large number of lateral deflections exceeding the threshold for the clip. It was anticipated that if TOR friction control reduced lateral forces, that this in turn would reduce clip deflection and fatigue failure. Given that the population of clips at the start of the trial will have experienced a range of deflections depending on both their location in the track (lateral forces / deflection experienced) and the length of time the clip had been in track, it might be expected that the effect of reduced lateral forces on clip breakage might be gradual.

The intensive monitoring showed a reduction in clip breakage within the first few weeks of the start of Phase I, declining from an average of about 30 per week to about 10- 20. The more intensive monitoring also showed that after FM, clip breakages were primarily in locations at the T4 end (further from the Phase I applicator).

Through the course of Phase 1, clip breakage rates continued at a much reduced rate. For two weeks in the middle of February 2007, the application was inadvertently stopped, as the unit had not been refilled with FM. A second two week interruption occurred in mid May 2007due to an inadvertently disconnected wheel sensor cable. An increase in clip breakage was noted in this period, peaking at about 25 in early June. Once stable application was re-established, the clip breakage rate returned to an average of about 15 per week until the start of Phase II.

The change in vehicle type did not cause any change in the rate of clip breakage on an axle adjusted basis. Due to the shorter trains being run, the absolute rate of clip breakage was reduced proportionally to the number of axles. With the startup of the Phase II unit close to Terminal 4, a further reduction in clip breakage rate was recorded to an axle adjusted average of 5 per week, as expected based on the lateral force results. By this point it can be expected that much of the clip breakage that was significantly fatigued but not yet broken prior to the introduction of TOR FM will have been removed through breakage, and the remaining population should have experienced much less deflection induced stress.

3.3 Rail corrugations

Assessment of rail corrugation indicated that between the Phase I site and T4 these occurred predominantly on the low rail. The dominant corrugation wavelengths were between 30 –300mm and this range is used in the present analysis. Corrugation at 125mm and 160mm wavelength were most significant in the tunnels approaching T4. Data was analyzed using Root Mean Square Moving Average corrugations for each wavelengths using a 10m window to compare before and after FM application.

Phase I application was initiated in December 2006, 0.7 km from the measurement point, and 1km from T4. Phase II application commenced in October 2007, close to the corrugation measurement point (Fig. 3). Rails were ground in August 2006, January 2007 and January 2008.

Figure 10 shows the results of corrugation monitoring (160 mm wavelength) at the specified location, from December 2006. All measurements except October 2008 were taken a few weeks prior to the next scheduled grind. Essentially identical results were obtained for 125 mm wavelength, which are not reproduced here.

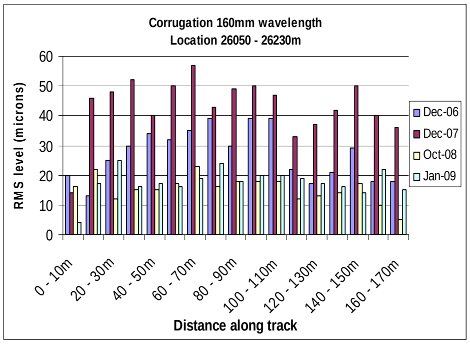


Figure 10 RMS Corrugation amplitude (160mm Wavelength) at 26050-26230m before and after FM application

From the data in Figure 10, average corrugation growth rates in microns per month can be calculated, and are shown in Table 1. The data has been normalized in the same way as the clip breakage data to take into account the change in traffic pattern after the opening of Terminal 5 (44% axle reduction). The calculations assume a linear increase in corrugation amplitude with time after grinding, which may be questionable. These factors do not change the overall conclusion.

	Amplitude, microns	Corrugation growth, Microns per month	Microns per month (axle adjusted basis)
After August 06 grind	**3.6**		
Aug 2006 to Dec 2006 (Baseline)	**23.5**	**5.9**	**5,9**
Dec 06 grind	**3.6**		
Jan 2007 to Dec 07	**43.2**	**3.3**	**3.3**
Dec 07 grind	**3.6**		
Jan 08 to Oct 08	**15.4**	**1.18**	**1.6**
Oct 08 to Jan 09	**17.8**	**0.73**	**1.11**

Table 1 Average corrugation growth rates

The data shows that at the monitoring point 0.7 km from the Phase I unit, the corrugation growth rate was reduced by about 45% compared to the baseline (pre-FM period) with Phase I operation only. With the addition of the Phase II unit, corrugation growth rate further decreased. Although only a three month period has been measured so far when both Phase I and Phase II units have been fully operational, this shows a growth rate reduced to 1.11 microns per month, an 81% reduction from the baseline period. This result is somewhat lower than the 8-12 fold reductions recorded previously on European and Japanese metro systems[8], but still a significant improvement from a practical maintenance standpoint.

Similar corrugation growth rates were measured at locations between the Phase I and Phase II application points.

3.4 Rail transverse profiles and wear

During the trial it was observed that the rail head transverse profile was better maintained with FM application compared to past experience. This result can be anticipated[4,10] due to the reduced vertical wear expected particularly on the low rail. This change should allow for optimum wheel rail contact to maintained, with resulting improvements in steering through the curve.

3.5 Wheel tread wear and differential wheel diameter

Wheel wear was measured for a number of vehicles whose service intervals matched before and after application of FM. The numbering convention is wheels 1-4 wheel sequentially on Side 1, wheels 5-8 sequentially as shown below in Figure 11. Figure 12 shows baseline (pre FM) wheel wear (2004 to 2006) after 370000 km for motor and pantograph cars.

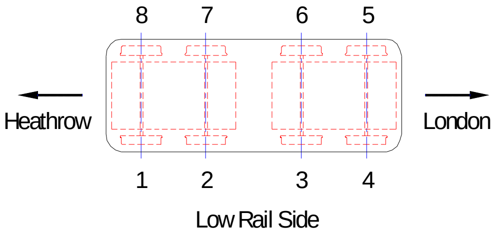


Figure 11 Wheel numbering convention

The wear pattern within a given car generally follows the expected pattern of higher wear for leading wheelsets, and higher wear on the left hand wheels (low rail) heading towards Heathrow (section 1.2).

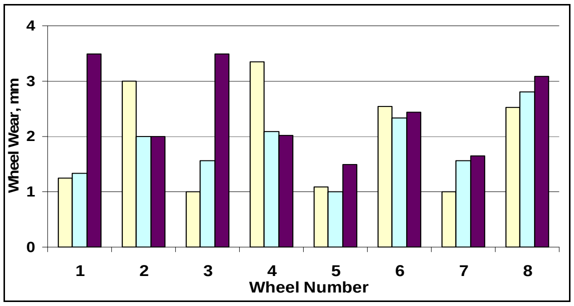


Figure 12 Wheel tread wear after 370000 km, baseline (pre FM) (2004 to 2006), motor and pantograph cars.

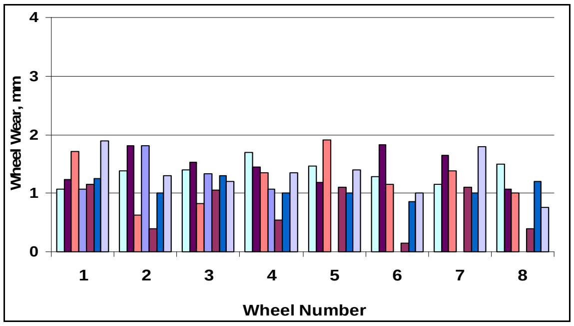


Figure 13 Wear after 370000 km with FM application (2006 to 2008), motor and pantograph cars.

Figure 13 shows corresponding data for motor and pantograph cars from 2006 to 2008, again after 370000 km, with FM application. A comparison between Figures 12 and 13 reveals a significant reduction in wheel wear between the two periods. In 2004-2006 wear of over 3 mm occurred on several wheels of the data set examined. During 2006-2008 wear on all wheels was less than 2 mm.

No other changes were identified between these two periods other than the initiation of TOR FM. For example, there were no changes in wheel profile or rail profiles (standard UK P8 profile), traction control etc that could explain this difference. It is remarkable that a change in the frictional conditions in just the 0.6 km test zone could result in such a large reduction in wheel wear, considering that the overall route from London is about 16 km. However it had been believed from dynamic modeling that the sharp curves in the tunnel area were the major cause of wheel wear. These results substantiate that view.

Trailer cars have lower wheel wear and so are not included in this analysis, but a significant reduction in wear was also recorded on trailer car wheels.

A corresponding comparison of side to side differential wheel diameter is shown in Figure 14. During the FM period the differential wheel diameter has been greatly reduced. This is presumably because the wear on the left hand wheels (driving towards T4) has been reduced proportionately more than the lower wearing right hand wheels.

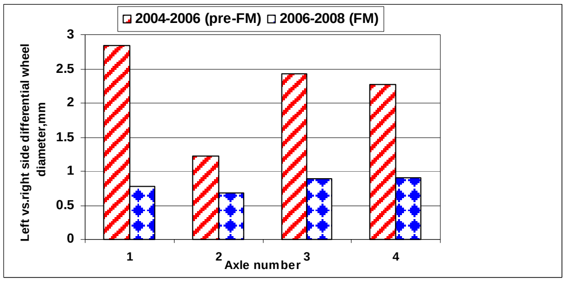


Figure 14 Side to side differential wheel diameter, before and after FM

SUMMARY AND CONCLUSIONS

This paper describes an extensive trial on Heathrow of the effect of TOR friction control to address wheel rail related issues of clip breakage, corrugation and wheel wear.

The results of the trial indicate that:

- No safety related issues (e.g. wheel slip related, braking distances, signaling etc) have been reported after more than two years continuous application of TOR FM on Heathrow Express.
- Lateral forces on leading axles are significantly reduced by FM application, by as much as 50%. Percent reductions are highest on the axles which generate the highest forces.
- Clip breakage is greatly reduced as a result of FM application. This is very likely due to a reduction in fatigue related failures caused by excessive deflection of the foot of the rail. The deflections are in turn a result of the high lateral forces imparted at the wheel / rail interface.
- Wheel tread wear was substantially reduced on introduction of FM. This allows for maintenance efficiencies to be realized.
- A similar reduction was observed in differential wheel diameter (side to side), resulting from differential wheel wear. This allows for less metal removal during reprofiling, as well as less tendency for RCF generation on rail.
- A substantial reduction in the rate of corrugation growth was recorded. This has allowed for less grinding, both in terms of grinding frequency, and amount of metal removed. The corrugation reduction is noteworthy considering that the likely corrugation generation mechanism is P2 resonance of the unsprung mass. The corrugation reduction must then be primarily related to reduction of the wear component of the corrugation mechanism. Other case studies

showing reduction in corrugation growth rates with FM may have involved both wear reduction and also reduction of stick-slip associated with torsional oscillation of the axles.

TOR FM is now part of standard track maintenance practice Heathrow Express. Additional wayside application units have been installed on the inbound line to Terminal 5, and on the line inbound from the tunnel portal to CTA.

FUTURE WORK

Ongoing work will continue long term corrugation monitoring with full Phase II operation. In addition, the ability of TOR FM to reduce growth of rail RCF is being assessed. This Phase III trial is being carried out on inbound track from the tunnel portal to CTA, an area which is subject to RCF / head checks.

Vehicle dynamic modeling is also being undertaken to compare predicted lateral force with measurements under the various frictional scenarios encountered during this trial.

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