RAIL CORRUGATION AND ROLLING NOISE
specifications, measurements and long term data

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scope of presentation

• Wheel/rail rolling noise
  – wheel and rail irregularities and noise

• Rail corrugation
  – huge contribution to rolling noise, “roaring rails”
  – “wavelength fixing mechanisms” relevant to noise

• Specification and control of rail irregularities
  – standards: EN13231-3, EN15610, EN ISO3095
  – implementation
  – measurements
    • post-reprofiling and difference pre to post reprofiling
    • train-borne during grinding

• “long-term” measurements
  – corrugation and noise

• conclusions and recommendations
• Introductory work was given in presentation last year to TRB conference
• This presentation follows from last year; it gives
  – practical recommendations
  – results from different railway systems (corrugation and noise)
  – conclusions and recommendations
model of wheel / rail rolling noise generation (DJT, 1991)

- excitation of dynamic behaviour by wheel/rail “roughness” i.e. irregularities
- control noise by
  - controlling roughness
  - modifying dynamic behaviour
  - affecting propagation

Model of Remington (1988) is similar
rail irregularities: corrugation
(quasi-periodic irregularity on the rail)

- there is a great variety of rail corrugation
- corrugation can occur on all types of track
“mechanism” causing rail corrugation

• general mechanism proposed in 1993 (and in different forms previously) is still valid


damage mechanisms (rail)

- **wear** is most common damage mechanism
  - wear \( \propto \) (tangential force) * slip

- other damage mechanisms (plastic flow etc) are not significant for types of corrugation that contribute to wheel / rail noise
<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength-fixing mechanism</th>
<th>Where?</th>
<th>Typical frequency (Hz)</th>
<th>treatments</th>
<th>Should be successful</th>
</tr>
</thead>
<tbody>
<tr>
<td>pinned-pinned resonance</td>
<td>pinned-pinned resonance</td>
<td>Straight track, high rail of curves</td>
<td>400-1200</td>
<td>Hard rails, control friction</td>
<td>Increase pinned-pinned frequency so that corrugation would be &lt;20mm wavelength</td>
</tr>
<tr>
<td>Rutting</td>
<td>2\textsuperscript{nd} torsional resonance of driven axles</td>
<td>Low rail of curves</td>
<td>250-400</td>
<td>Friction modifier, hard rails, reduce cant excess, asymmetric profiling in curves</td>
<td>reduce applied traction in curving, improve curving behaviour of vehicles dynamic vibration absorber</td>
</tr>
<tr>
<td>Heavy haul</td>
<td>P2 resonance</td>
<td>Straight track or curves</td>
<td>50-100</td>
<td>Hard rails</td>
<td>Reduce cant excess when corrugation is on low rail</td>
</tr>
<tr>
<td>Light rail</td>
<td>P2 resonance</td>
<td>Straight track or curves</td>
<td>50-100</td>
<td>increase rail strength and EI</td>
<td>Reduce unsprung mass</td>
</tr>
<tr>
<td>Other P2 resonance</td>
<td>P2 resonance</td>
<td>Straight track or high rail in curves</td>
<td>50-100</td>
<td>Hard rails, highly resilient trackforms</td>
<td>Reduce unsprung mass</td>
</tr>
<tr>
<td>Trackform-specific</td>
<td>Trackform specific</td>
<td>Straight track or curves</td>
<td>-</td>
<td>Hard rails, friction control</td>
<td>Avoid “peaky” resonances, improved steering</td>
</tr>
</tbody>
</table>
wavelength-fixing mechanisms

- fix wavelength and position along track
- *All* wavelength-fixing mechanisms are constant frequency, not constant wavelength
  
  \[ \text{wavelength} = \frac{\text{speed}}{\text{frequency}} \]

- Wavelength-fixing mechanisms relevant to noise and GBV are:
  - pinned-pinned resonance
  - “rutting”
  - P2 resonance: ground-borne vibration
• What standards / specifications exist to control or specify limits on corrugation and acoustic roughness?
  – is there any equivalence between these standards?
• What amplitude of corrugation and acoustic roughness exists?
  – before reprofiling
  – after reprofiling
• How can these be measured?
• Can corrugation removal be satisfactorily controlled during the reprofiling operation?
• What is the effect of reprofiling on noise?
EN / ISO standards relevant to irregularities and wheel / rail noise

• EN 13231-3:2006
  – reprofiling of rails

• EN 15610:2009
  – rail roughness measurement related to rolling noise generation

• EN ISO 3095
  – acoustic type testing of vehicles
wavelength ranges: noise and standards

- **human hearing**
  - 20Hz to 20kHz

- **Standards**
  - EN13231:3 reflects limitations of reprofiling
  - acoustic standards reflect
    - limitations of conventional equipment
    - effects of contact patch filtering on short wavelengths

<table>
<thead>
<tr>
<th></th>
<th>10m/s (22mph)</th>
<th>50m/s (110mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20Hz</td>
<td>500mm</td>
<td>2500mm</td>
</tr>
<tr>
<td>20kHz</td>
<td>0.5mm</td>
<td>2.5mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10mm</td>
<td>3mm</td>
<td>3.15mm</td>
</tr>
<tr>
<td></td>
<td>1000mm</td>
<td>250mm</td>
<td>630mm</td>
</tr>
</tbody>
</table>
### EN 13231-3:2006

#### Table 1 — Window lengths

<table>
<thead>
<tr>
<th>Wavelength range (mm)</th>
<th>0 - 30</th>
<th>30 - 100</th>
<th>100 - 300</th>
<th>300 - 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window length (m)</td>
<td>0,15</td>
<td>0,5</td>
<td>1,5</td>
<td>5</td>
</tr>
</tbody>
</table>

#### Table 2 — Moving average of RMS amplitude limits

<table>
<thead>
<tr>
<th>Wavelength range (mm)</th>
<th>10 - 30</th>
<th>30 - 100</th>
<th>100 - 300</th>
<th>300 - 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit of moving average of RMS amplitude (mm)</td>
<td>0,004</td>
<td>0,004</td>
<td>0,012</td>
<td>0,040</td>
</tr>
</tbody>
</table>

#### Table 3 — Moving average of peak-to-peak amplitude limits

<table>
<thead>
<tr>
<th>Wavelength range (mm)</th>
<th>10 - 30</th>
<th>30 - 100</th>
<th>100 - 300</th>
<th>300 - 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit of moving average of peak-to-peak amplitude (mm)</td>
<td>0,010</td>
<td>0,010</td>
<td>0,030</td>
<td>0,100</td>
</tr>
</tbody>
</table>

#### Table 4 — Acceptance criteria for longitudinal profile expressed in terms of allowable percentages of track exceeding moving average RMS or peak-to-peak amplitude limits

<table>
<thead>
<tr>
<th>Wavelength range (mm)</th>
<th>10 - 30</th>
<th>30 - 100</th>
<th>100 - 300</th>
<th>300 - 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>5 %</td>
<td>5 %</td>
<td>5 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Class 2</td>
<td>No requirement</td>
<td>10 %</td>
<td>10 %</td>
<td>No requirement</td>
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</tbody>
</table>

- **This is an excellent and practical basis for reprioring specifications to reduce wheel / rail rolling noise**

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0.010mm = 0.4thou

**Most significant wavelength ranges for noise**
corrugation / acoustic roughness measurements

- post-reprofiling measurements
- contributed by users of RailMeasurement equipment
  - worldwide
  - on all types of railway system
  - from major suppliers of reprofiling equipment (grinding and milling): all give both good and bad results
  - using same equipment (CAT)

- The best results (lowest irregularities, largest change with reprofiling) were obtained where there was a specification that was monitored
reprofiling standard, acoustic standards and post-reprofiling irregularities
• reprofiling
  – can (but doesn’t always) reduce irregularities below EN13231-3:2006 level (previous slide)
  – rarely reduces irregularities below ISO3095/EN15610 level for 10-30mm wavelength range (previous)
  – *usually* significantly reduces irregularities 30-300mm
  – usually increases irregularities 10-30mm
long-term monitoring of corrugation, grinding and noise (primarily ground-borne)

• Data from London Underground, with permission
• 4 lines on LU, 24 locations
  – specific locations are not shown
• The main justification for grinding on much of London Underground is noise reduction.
  – monitoring undertaken at some sites for more than a decade
  – first railway system to adopt a CAT for QA of grinding (in 1997)
Long-term monitoring of noise and roughness (courtesy of London Underground)

- One site: 3-7dB reduction from grinding or rerailing
- 30 months, two (partial) rerails (!), one grind
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>PRE-GRIND</th>
<th>GROUND</th>
<th>POST-GRIND</th>
<th>+6 MONTHS</th>
<th>PRE (dB)</th>
<th>POST (dB)</th>
<th>+6M (dB)</th>
<th>ΔdB</th>
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<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SB</td>
<td>07/05/2009</td>
<td>09/08/2009</td>
<td>24/08/2009</td>
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<td>43</td>
<td>41</td>
<td>40</td>
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</tr>
<tr>
<td>SB</td>
<td>26/05/2009</td>
<td>04/10/2010</td>
<td>no access</td>
<td>45</td>
<td></td>
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<tr>
<td>SB</td>
<td>04/03/2009</td>
<td>02/08/2009</td>
<td>14/09/2009</td>
<td>25/03/2010</td>
<td>38</td>
<td>36</td>
<td>36</td>
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<tr>
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<td>17/08/2009</td>
<td>25/08/2009</td>
<td>18/02/2010</td>
<td>45</td>
<td>44</td>
<td></td>
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<tr>
<td>Central Line</td>
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<tr>
<td>IR</td>
<td>14/05/2009</td>
<td>01/04/2010</td>
<td>11/05/2010</td>
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<td>44</td>
<td>47</td>
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<tr>
<td>EB</td>
<td>24/11/2009</td>
<td>26/02/2010</td>
<td>14/06/2010</td>
<td></td>
<td>39</td>
<td>31</td>
<td></td>
<td>-8</td>
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<tr>
<td>Bakerloo Line</td>
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<td></td>
<td></td>
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<tr>
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<td>21/03/2010</td>
<td>07/04/2010</td>
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<td>47</td>
<td>42</td>
<td></td>
<td>-5</td>
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<tr>
<td>SB</td>
<td>23/02/2010</td>
<td>21/03/2010</td>
<td>07/04/2010</td>
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<td>42</td>
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<td>01/05/2010</td>
<td>02/06/2010</td>
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<td>48</td>
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<tr>
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<td>08/04/2010</td>
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<td>56</td>
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<td>EB</td>
<td>09/12/2009</td>
<td>23/02/2010</td>
<td>19/03/2010</td>
<td></td>
<td>54</td>
<td>52</td>
<td></td>
<td>-2</td>
</tr>
<tr>
<td>WB</td>
<td>09/12/2009</td>
<td>03/03/2010</td>
<td>19/03/2010</td>
<td></td>
<td>54</td>
<td>52</td>
<td></td>
<td>-2</td>
</tr>
<tr>
<td>EB</td>
<td>01/02/2010</td>
<td>02/02/2010</td>
<td>19/03/2010</td>
<td></td>
<td>44</td>
<td>38</td>
<td></td>
<td>-6</td>
</tr>
<tr>
<td>WB</td>
<td>01/02/2010</td>
<td>11/02/2010</td>
<td>19/03/2010</td>
<td></td>
<td>46</td>
<td>38</td>
<td></td>
<td>-8</td>
</tr>
<tr>
<td>Circle Line</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR</td>
<td>01/02/2010</td>
<td>16/02/2010</td>
<td>19/03/2010</td>
<td></td>
<td>57</td>
<td>46</td>
<td></td>
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<tr>
<td>IR</td>
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<td>18/02/2010</td>
<td>19/03/2010</td>
<td></td>
<td>39</td>
<td>33</td>
<td></td>
<td>-6</td>
</tr>
</tbody>
</table>
Noise reduction (usually ground-borne noise i.e. relatively low frequency)

• reduction from grinding is significant, particularly given that noise is primarily ground-borne, therefore low frequency (underground)
• sometimes an increase immediately after grinding, but significant reduction after 6 months
• grinding undertaken to equivalent of EN13231-3:2006 for about a decade, and monitored (with CAT)
development of corrugation
(on metro)

- 30-100mm corrugation (measured with CAT)
  - well developed after only 2 months
removal of corrugation (same site)
Loram LR series grinder

• reduction in 30-100mm corrugation from more than 0.050mm RMS to less than 0.003mm (0.12 thou) RMS in 12 passes
• measurements (at 1mm interval) during grinding
Conclusions (1 of 4)

- model including “damage mechanism” and “wavelength fixing mechanism” provides a good method of understanding rail corrugation
- wear is the most common damage mechanism (and most relevant to short wavelength corrugation & noise)
- wavelength-fixing mechanisms most relevant to wheel / rail noise and GBV:
  - P2 resonance: 50-100Hz
  - “rutting” (axle torsion): 250-400Hz
  - pinned-pined resonance: 450-1200Hz
Conclusions (2 of 4)

- acoustics and reprofiling standards exist that are an excellent basis for controlling irregularities that contribute to wheel / rail noise
  - reprofiling standard (2006 version) and acoustics standards are substantially identical
  - all major suppliers *can* reprofile to requirements of the 2006 European reprofiling standard (also all suppliers *may not* do so)
  - a few reprofiling trains have on-board equipment that can demonstrate these standards have been achieved
Conclusions (3 of 4)

• comprehensive measurements (undertaken on London Underground) demonstrate:
  – 0-11dB reduction in noise (mainly ground-borne) following grinding on a wide range of sites
  – consistent increase in corrugation / roughness and noise under traffic, after grinding
    • noise measurements not as comprehensive (in-property noise levels)

• irregularities at levels of a few microns can be and are monitored routinely during reprofiling on some metro systems
Conclusions (4 of 4)

• reprofiling (typical grinding and milling)
  – greatly reduces irregularities in 30-300mm wavelength range
  – typically *increases* amplitude of irregularities at 10-30mm wavelength (“stone signature”)

• The best results from reprofiling are consistently obtained where and when there is an objective specification that can be and is monitored.
acknowledgements

• John Edwards and James Shepherd, Noise and Vibration Engineers, London Underground
• Prof Xuesong Jin and colleagues, SWJTU, Chengdu for post-grind monitoring of corrugation
• ARTC, Citirail, Corus/Tata, IRT, LU, Loram, Metro Medellin, QN, Schweerbau, Sumitomo, TTC, ...... for CAT measurements