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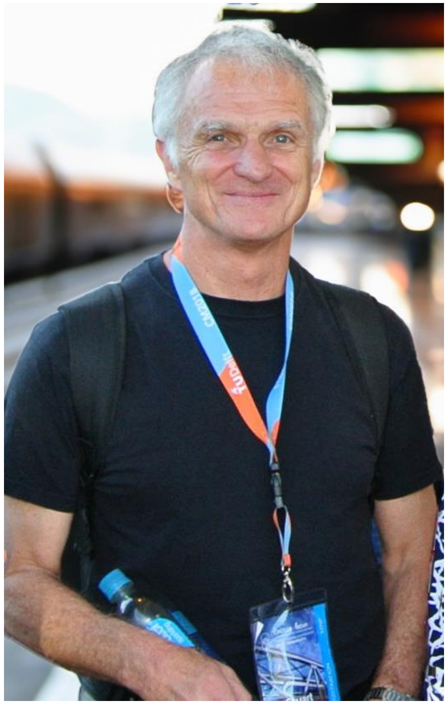

Rail corrugation: a problem solved?

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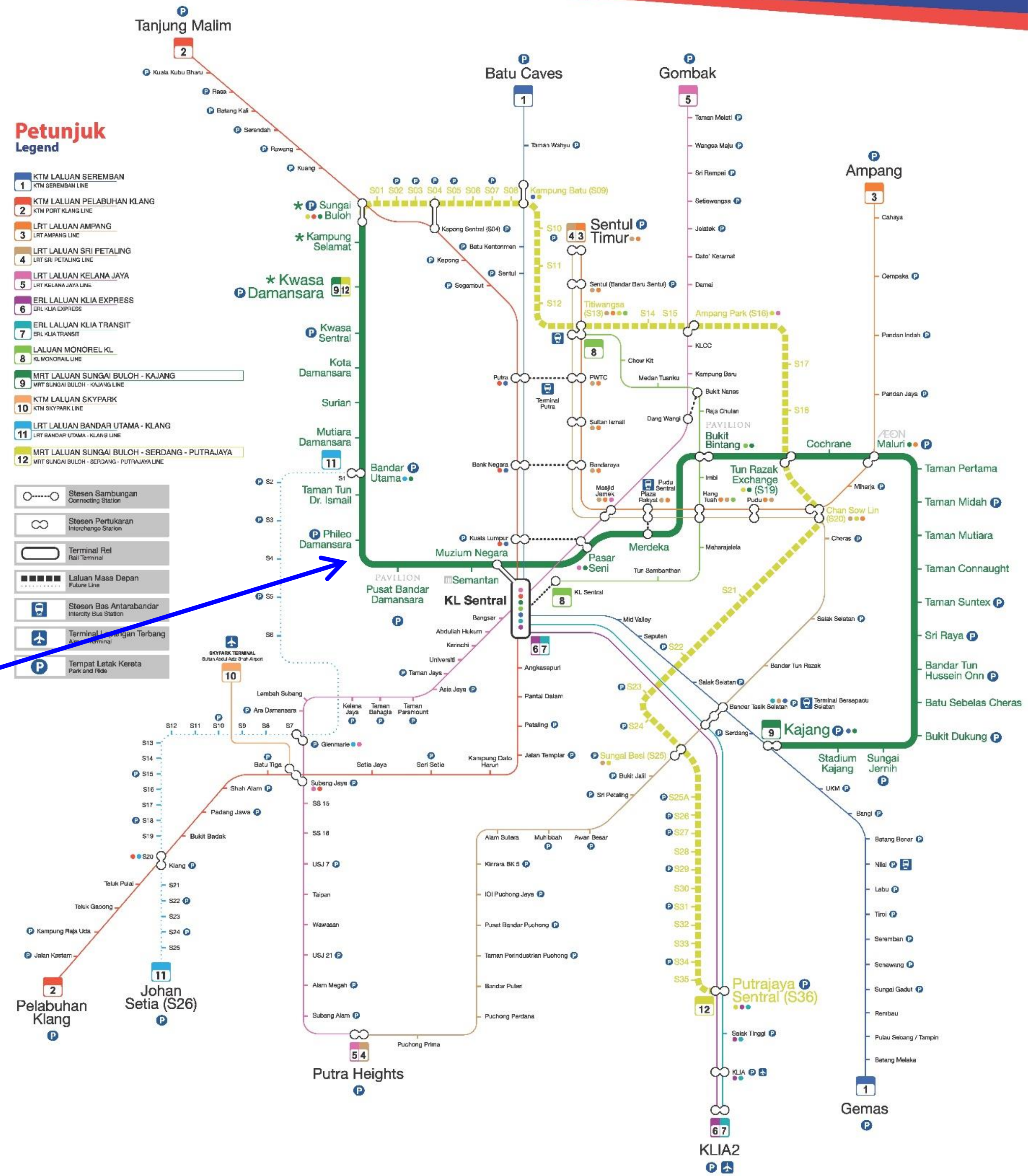
scope of presentation

- rail corrugation
  - examples, consequences
- The project and challenge presented here.
- "corrugation mechanism"
  - classification of 4 types of corrugation relevant to the project
- mechanism and (possible) methods of prevention
- monitoring
- results
- conclusions

- I’ve been working on rail corrugation for 45 years.
- When I started, we knew almost nothing about the cause of rail corrugation: indeed, we thought this was a single phenomenon.
- We’ve come a long way from there to do what has been achieved in the project discussed here

Kuala Lumpur transit lines

Kajang Line



Kajang Line: some basics

- route length = 51km (track = 102km)
- underground for 9.5km, elevated for 41.5km
- 31 stations
- opened Phase 1 in Dec 2016, Phase 2 in mid-2017
- entirely "non-ballasted track"
  - two different "trackforms"
- driverless, computer-controlled trains (ATO)
  - speed varies little at a site
- steep gradients (for a railway): 3.5%
- tight curves: 150m radius, often on exit from stations

These conditions are conducive to corrugation formation.

challenge of this project

- "The Works Package Contractor shall produce and submit for Approval a report clearly showing he has considered all known corrugation forming mechanisms and taken due mitigation measures for each in his designs."
- "Where the corrugation causing mechanisms are discovered to be due to the Works Package Contractor’s omission during the design stage or errors in construction they shall be rectified by the Works Package Contractor at his own expense."

In other words:

- ensure that the track is built so that there is no corrugation during operation
- if there is corrugation, the Contractor shall remove it at their cost

Neither of these had been done before.

examples

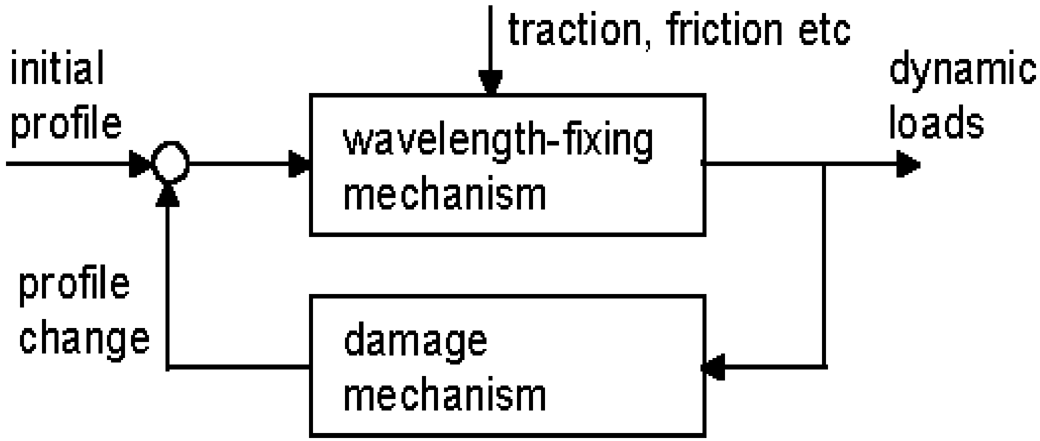
- corrugation
  - is varied in appearance and wavelength
  - occurs on almost all types of track
  - is particularly prevalent on metros

why is it a problem?

- excessive noise and vibration
  - intrusive noise at higher frequency: examples
  - ground-borne vibration for low frequency/long wavelengths

- increased maintenance of track and vehicles
  - accelerated fatigue damage e.g. rail breaks, broken axles
  - increased track maintenance e.g. "white ballast"

“mechanism” for corrugation formation



- simple but useful
- proposed in 1993
- wear is the "damage mechanism" for all corrugation of interest here
- classification used here is based only on the “wavelength-fixing mechanism”

wavelength-fixing mechanisms

- *all* wavelength-fixing mechanisms are constant frequency phenomena

$$\lambda = v/f$$

- essentially resonances (and associated anti-resonances)
- corrugation develops more quickly where trains speeds vary little e.g. metros
- similar wavelengths on very different types of track because
  - both f and v increase
  - so λ changes little
- Why did it take 100+ years to discover this?

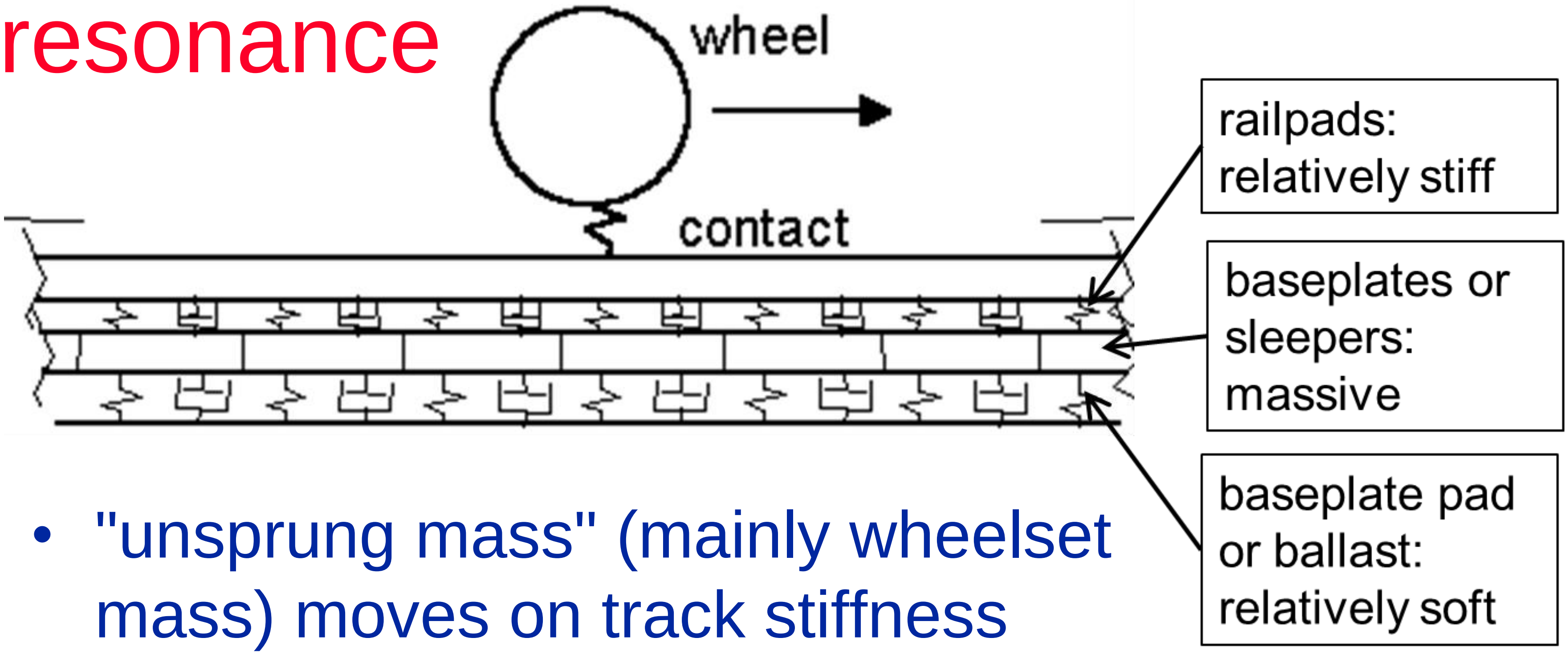
classification based on "wavelength-fixing mechanism"

1. P2 resonance
2. trackform-specific resonance

   1. and 2. are particularly dependent on the trackform.

3. pinned-pinned resonance
4. rutting

P2 resonance



- "unsprung mass" (mainly wheelset mass) moves on track stiffness
  - mainly baseplate pad / ballast
  - typically 50-100Hz
- this resonance exists on all railways
  - but does not always form corrugation

1. P2 resonance corrugation

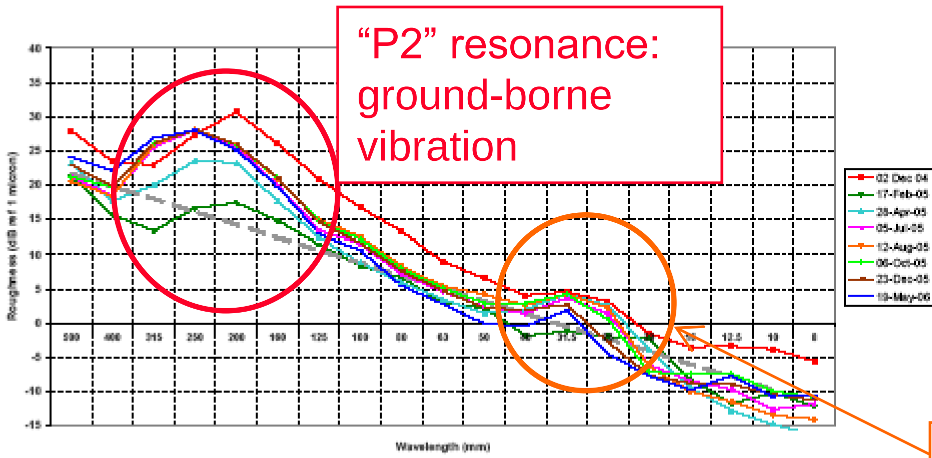
- can occur on all types of track, but is particularly prevalent on metros
- If it "can occur", how can it confidently be prevented?

This was the most challenging and risky corrugation for which to propose mitigation measures: almost entirely "engineering judgement".

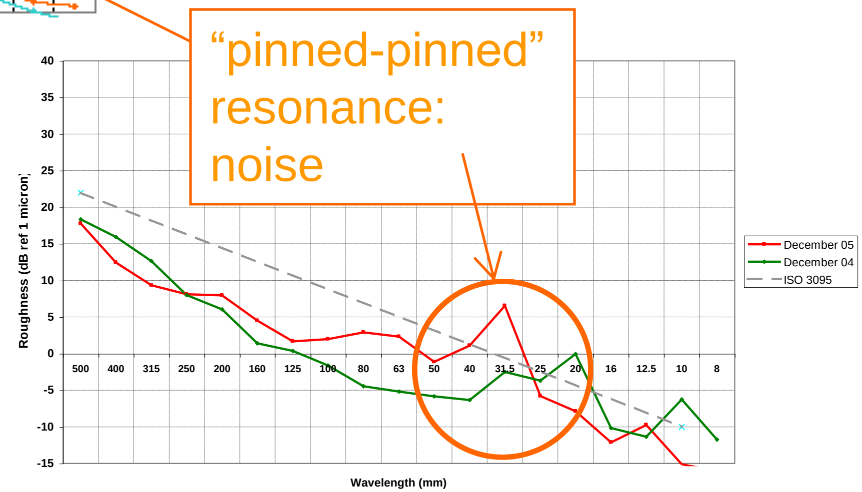
If advice on this had been wrong, almost the entire metro could have been corrugated.

P2 resonance corrugation: presence and absence on the same inter-station section of the same railway line

amplitude



- “traditional” trackforms
  - corrugation at short <u>and</u> long wavelengths



- very resilient trackform (“Pandrol Vanguard”)
  - corrugation at short wavelength <u>only</u>

avoidance of P2 resonance corrugation

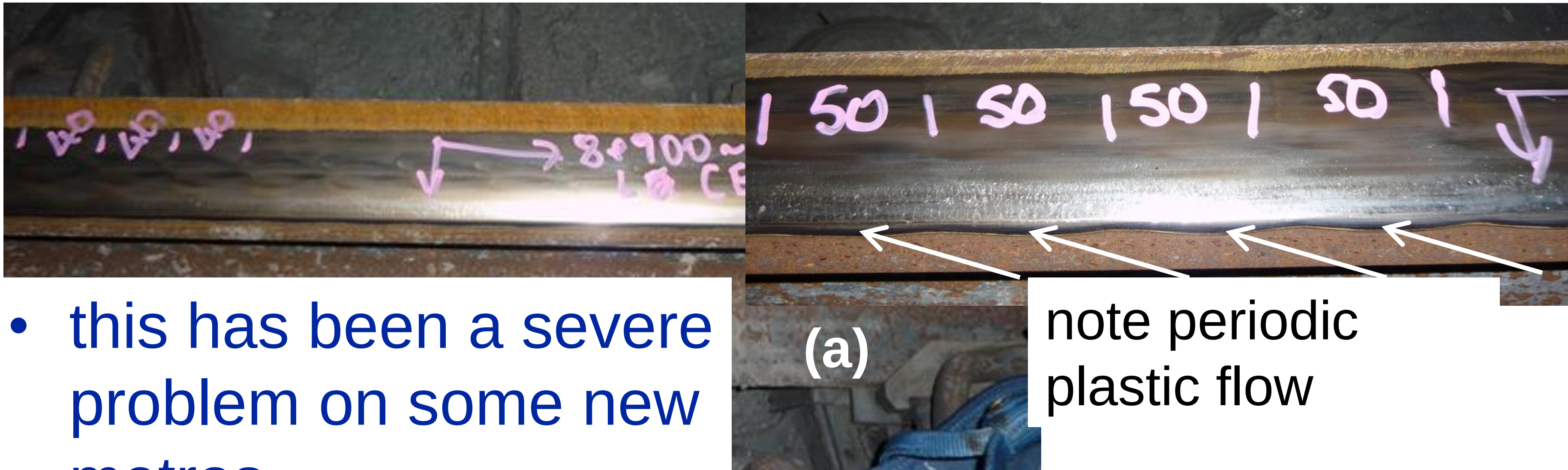
system	fastener stiffness (MN/m^2)	fastener damping (kNs/m^2)	spacing (m)	P2 corrugation ?
(A)	80.3	8.4	0.76	yes
(B)	19.8	9.6	0.91	no
(C)	39.5	9.7	0.76	no
(D)	25	4.6	0.76	no

Note: Stiffness and damping are given per fastening per unit length of track.

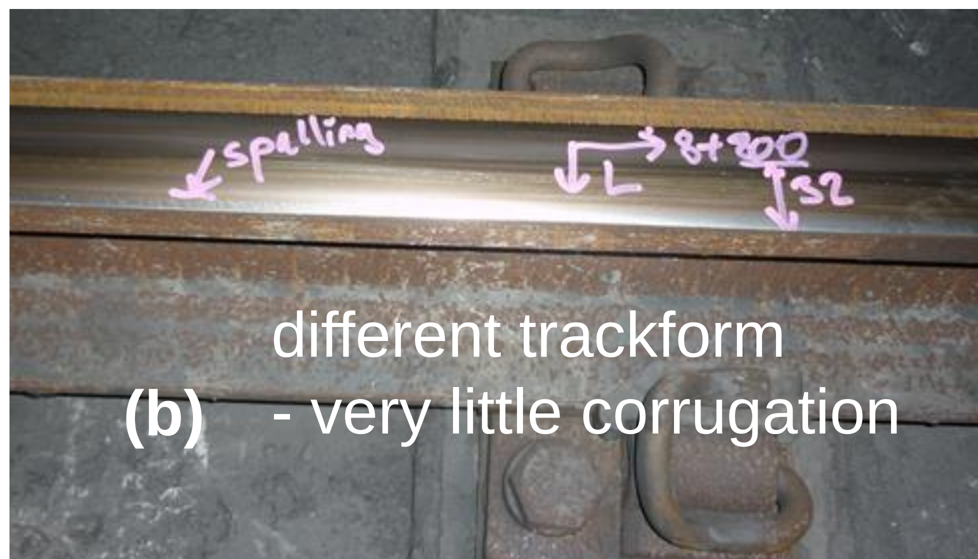
- general advice based on TRB project in USA in 1990s
- don’t need Pandrol Vanguard to avoid P2 resonance corrugation

fastening system stiffness of 28MN/m for spacing of 0.7m (40MN/m^2) <u>should be </u>OK, but best to be well below this

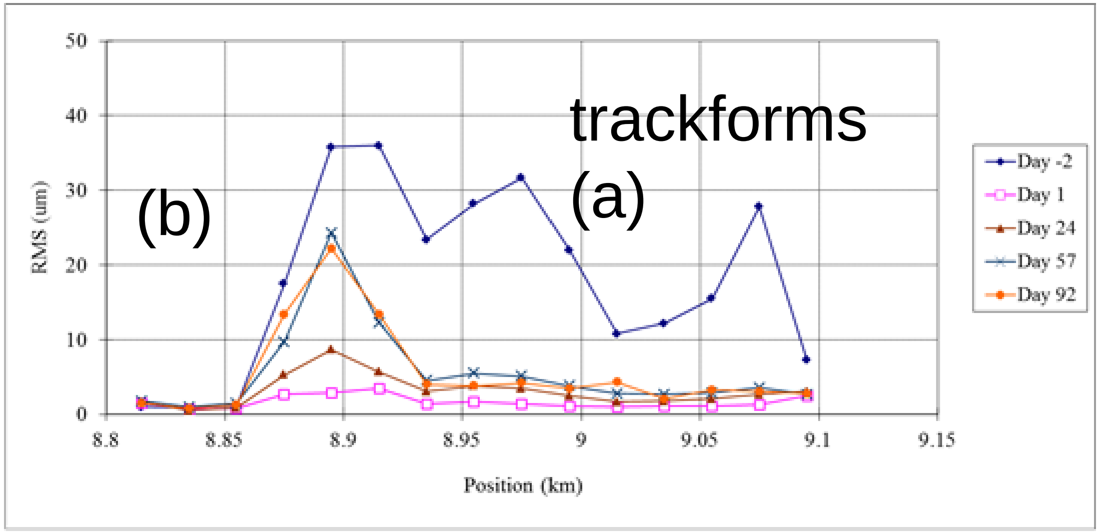
2. “trackform-specific” corrugation



- this has been a severe problem on some new metros
- track here was ground 6 months previously
- typically, this type of corrugation occurs *very quickly* and is extremely periodic



How quickly can this type of corrugation develop?



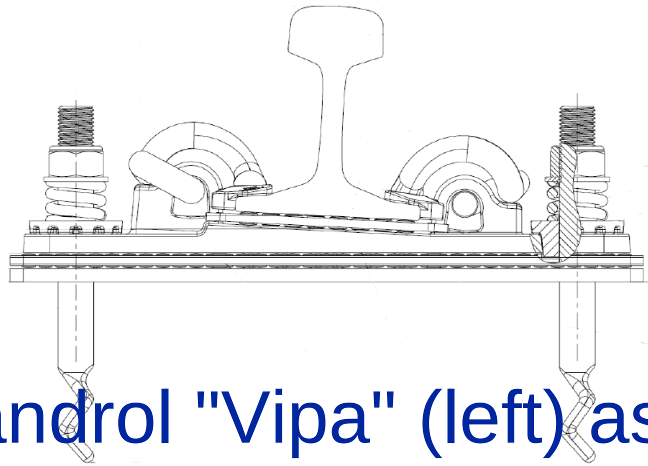
- measurements taken at the site in previous slide
- 57 days (< 2 months) after the site was ground
  - corrugation on trackform (a) developed to >10 times the amplitude of corrugation on adjacent "standard" trackform (b)

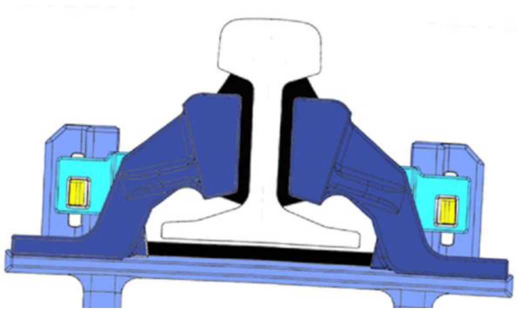
“trackform-specific” corrugation

- neither the precise mechanism nor preventative measures have yet been identified
  - suppliers appear surprisingly unconcerned
  - proposal was that this results from baseplate or sleeper acting as a dynamic vibration absorber on the railpad
- not all trackforms of the same generic type do corrugate
- critical things to avoid are
  - high mass baseplate (this exists on trackform (a))
  - resilient pad between rail and baseplate (reduces resonant frequency)

These conclusions and recommendations were based largely on "engineering judgement".

trackforms proposed for KVMRT





- Pandrol "Vipa" (left) as "standard"
  - HDPE (very stiff) railpad
  - baseplate pad selected from those offered based on relatively low stiffness specified and experience of previous installations (from Pandrol and elsewhere)
- Pandrol "Vanguard" (right) for noise-sensitive sites
  - demonstrated to have negligible P2 or trackform-specific corrugation

3. “pinned-pinned resonance” corrugation

- This is the usually the highest frequency resonance giving rise to corrugation
  - therefore, shortest wavelength for a given speed
- exists on metros, but uncommon
  - two of the above examples, in different countries

“pinned-pinned resonance”

- rail vibrates as if there were nodes at sleepers/fastenings
  - conceptually similar to a guitar or violin string
    - but a beam in bending, not a string in tension
- there is easy movement of the rail under the wheel between fastenings
- conversely, when wheel passes over the fastenings, the support appears dynamically “stiff” (anti-resonance)
- dynamic forces are high
- these dynamic forces initiate corrugation

How do we avoid p-p resonance corrugation?

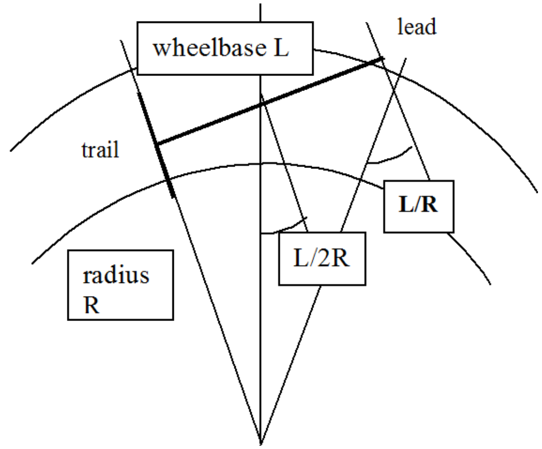
- ensure that frequency is sufficiently high that a corrugation would be of similar dimensions to the contact patch between wheel and rail
- there is no evidence to suggest that p-p resonance corrugation occurs on any railway with 60kg/m rail, 100km/h trains, 0.7m fastener spacing
  - sufficiently high frequency that $\lambda = v/f$ is very small
- there is considerable evidence to suggest that p-p resonance corrugation does <u>not</u> occur in these conditions

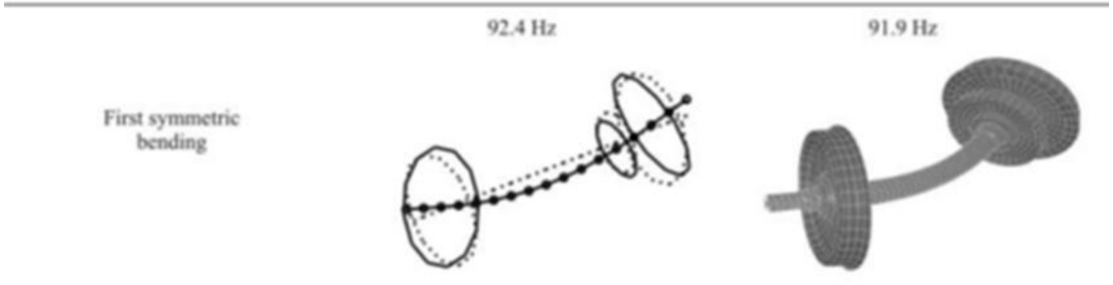
4. “rutting”



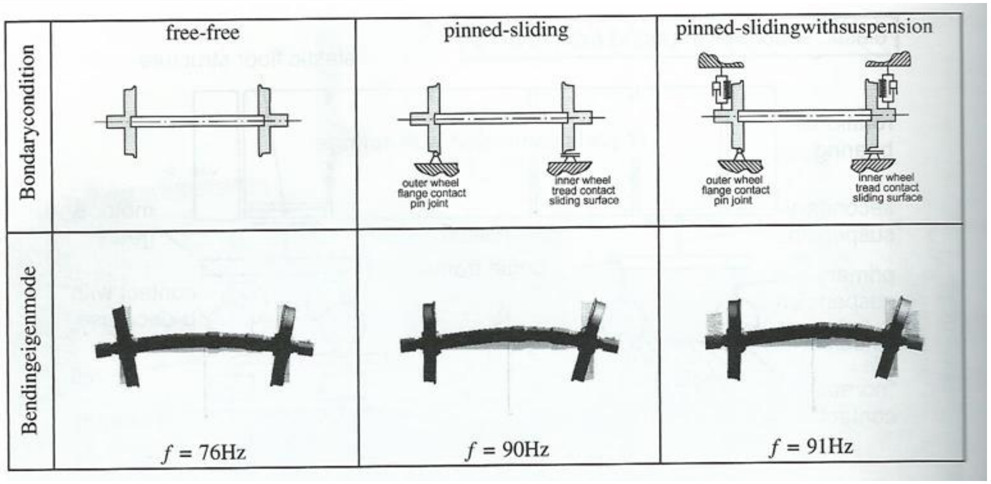

- associated primarily with low rail in curves
- also high rail in some circumstances (example on right)
- wavelength-fixing mechanism appears to be flexural resonance of wheelset
- very common on metros

what causes rutting?





- Tassilly&Vincent , RATP (1989)
- Chalmers University (above),
- Stuttgarter Strassenbahn (below)



- flexural resonance of wheelset
- excited by high lateral creep (angle of attack): see Figure showing bogie in a curve
- frequency (about 100Hz) is similar to P2 resonance
  - this resonance is fundamental to design of railway vehicles

mitigation measures for rutting

- The most successful treatment has been "friction modifier"
  - changes friction characteristics
  - reduces "stick-slip"
- several others could have been proposed for KVMRT, but impractical
- The following was proposed:
  - do nothing initially
  - see if rutting develops
  - if it does, install friction modifier where required, and only where required

What were the results?

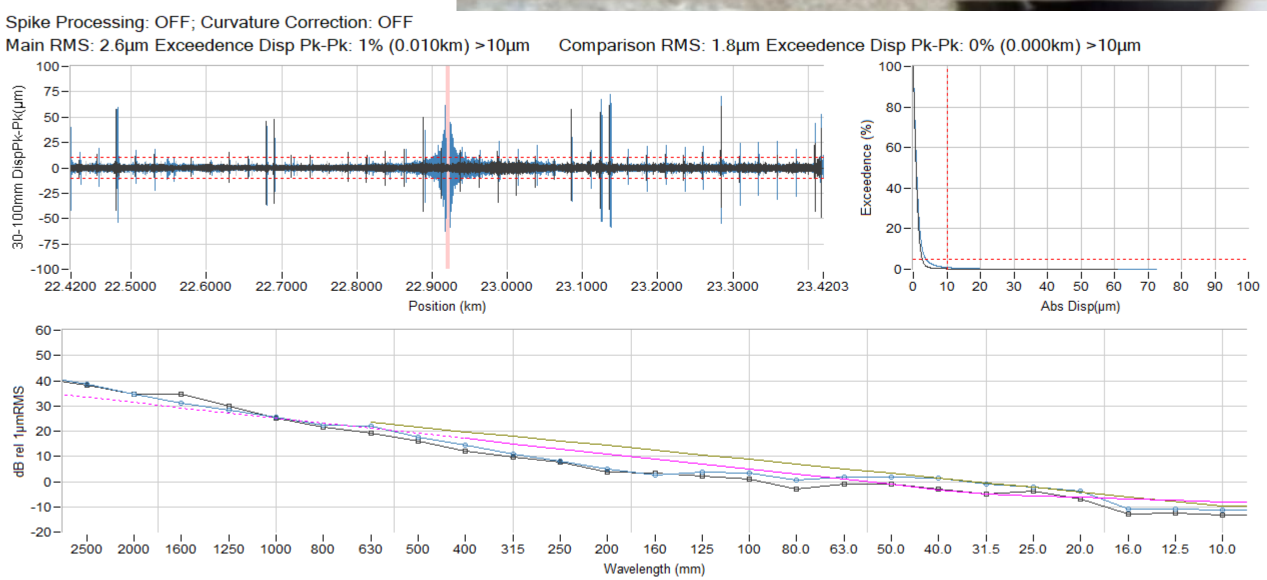
- monitoring
  - twice annually from before introduction of service traffic
  - maximum of 2 years of service traffic
  - 9 sites
    - selected because of conditions conducive to corrugation formation e.g. exit from stations, tight curvature, high speeds, steep gradients (3.5%)
    - both trackforms
    - all sites were >500m long, measure both rails

a more severe site

- very tight curves e.g. 155m
- exit from station
- both trackforms

results

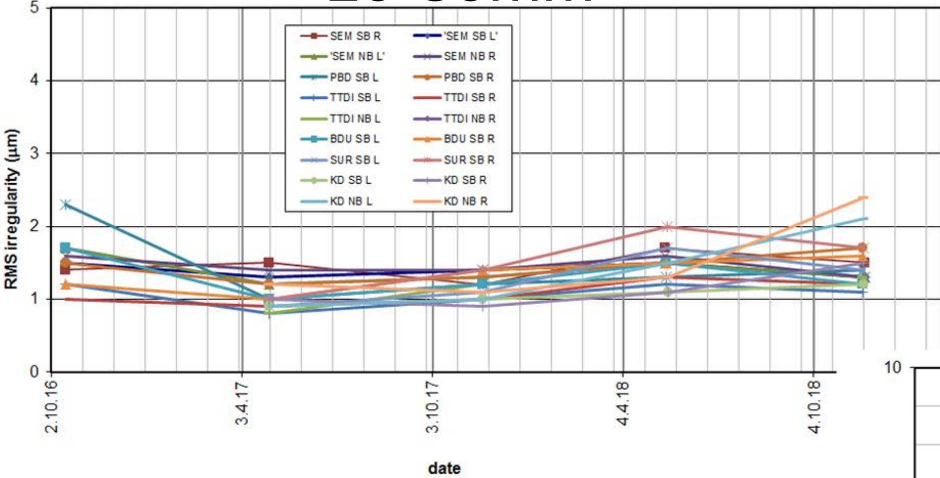
- after 2 years of intensive traffic



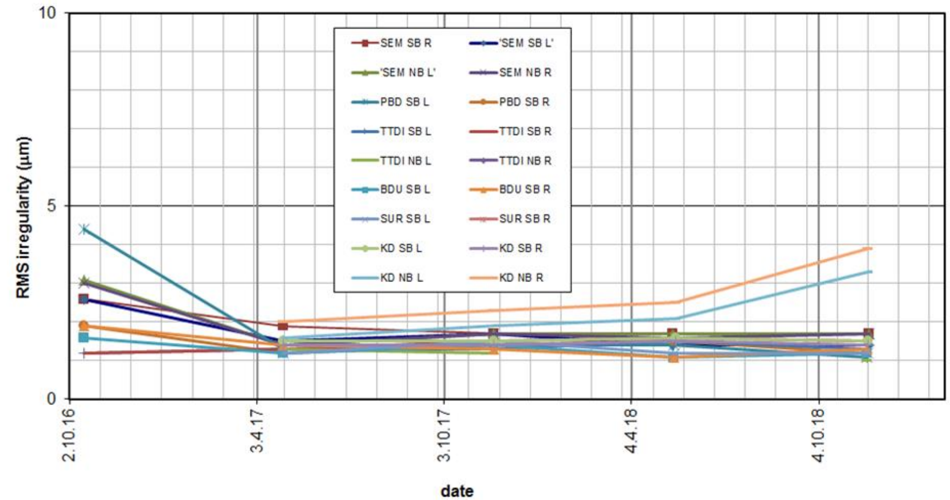
these results are typical

development of irregularities in time

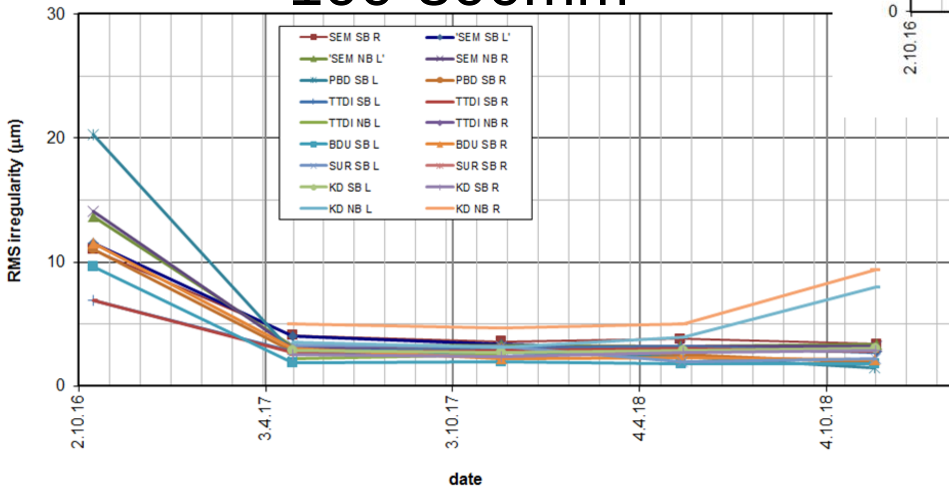
10-30mm



30-100mm



100-300mm



measurements made over the complete system

- used Spectral Analysis app on a mobile phone during a train ride
  - check for constant frequency peaks
- There was a perceptible peak in only 7 of 60 inter-station sections.
  - all were in tight radius curves
  - would correspond to a tiny amplitude of corrugation
  - <2.5% of the length of the line

Conclusions

- A metro system has been built according to a requirement that no rail corrugation should occur.
- The work that was undertaken relied on a great deal of engineering judgement and rudimentary calculation or mathematical modelling.
- Monitoring has demonstrated
  - corrugation has not occurred after 2 years of extremely severe service traffic
  - the level of irregularities over the entire track is similar to that for "acoustically ground" track
- This is the first time that such a project has ever been undertaken, let alone successfully.
- The criteria could be applied relatively simply elsewhere.