Design case studies B: Eurostar and Class 91 retrofit

Engr 514:2014 Design of safety-critical systems

Roger Kemp, January 2014

Eurostar

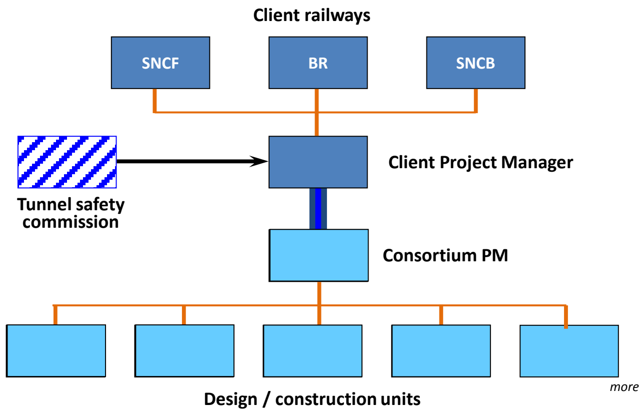
A few safety issues

Hazard	Risk level
Basic structure of train	Low
Signalling interference (particularly on UK "classic" routes)	High
Train fire in tunnel	Potentially catastrophic
Hazards incurred in attempt to mitigate fire hazard	Likely
Operational problems for drivers in "foreign" country	Possible
Faults in new design of train management system	Moderate
Terrorist threat	On the cards
etc.	

The *Eurostar* project

- 3 public-sector customers – single point contact
- Private sector design/development involving 3 national consortia and 17 main sites
- Based on proven TGV technology
- 4 safety authorities – SNCF, SNCB, UK and the Tunnel Safety Commission

Eurostar organisation



Eurostar in context

Fleet	Number of sets	Delivery
TGV-PSE	109	1978
Postal TGV	2	1984
TGV-Atlantique	105	1988
AVE (Spain)	24	1991
TGV-Réseau	90	1992
Eurostar	**38**	**1993**
PBKA (Thalys)	17	1996
Korean TGV	46	1998
TGV Duplex	30	1995
TOTAL	**461**	

Managing hazards in the Tunnel

- TSC dominated by the fire brigades

  Note: in France, the *Sapeurs Pompiers* are a more general emergency service, unlike Kent Fire Brigade

- The scenario envisaged:

  Power car catches fire – passengers unable to get to service tunnel

- The solution:

  Fire doors to be provided between cars and closed when in tunnel (except when people need to pass). Gangway down full length of train.

  If one power car is on fire, whole train exits the Tunnel powered by the working power car – and assume one motor bogie has failed

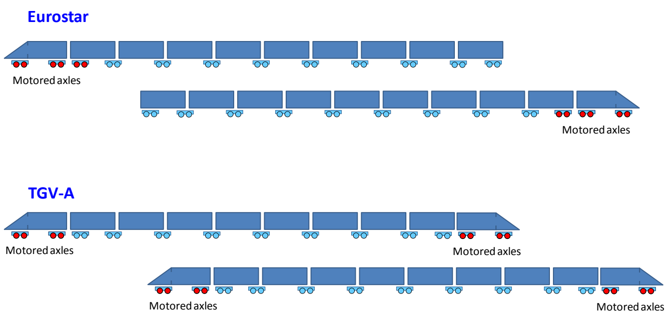
  Train to be separable into two sections from cab; in event of a serious fire, passengers herded into the safe section, train separates, and good half leaves tunnel under its own power

Saloon doors

Toughened glass, designed to resist fire. Power-operated controlled by handle to prevent inadvertent opening

Additional fire doors near gangway connection close in tunnel (visible at far end of car)

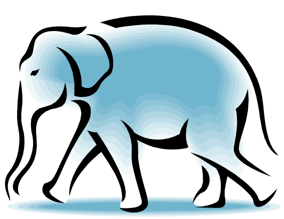
Train formations due to TSC policy



Implications of TSC policy

- Train power reduced from 17.6 MW (16 motors) on TGV-A to 13.2 MW (12 motors)
- Train has to be able to exit tunnel (1% gradient) using only 4 motors.
- Power car designed to produce 6.6 MW at the rail (4 motors under power car + 2 under adjacent car) which is 50% more than other TGVs. ***Challenging design project***.
- Lower level of duplication than other TGVs so ***greater chance of total failure***.

The elephant in the room



Any serious fire in a stationary train is likely to result in a stream of ionised gases above the fire which will cause a flash-over from the 25kV line to earth and loss of all power.

Effect seen in the two fires involving freight trains.

Security issues

23 May 1977

Nine Indonesian youths hijacked a train near Punt in the Netherlands. After a 3-week siege, 6 hijackers and 2 hostages killed.

Security services keen to avoid a similar occurrence in the Tunnel

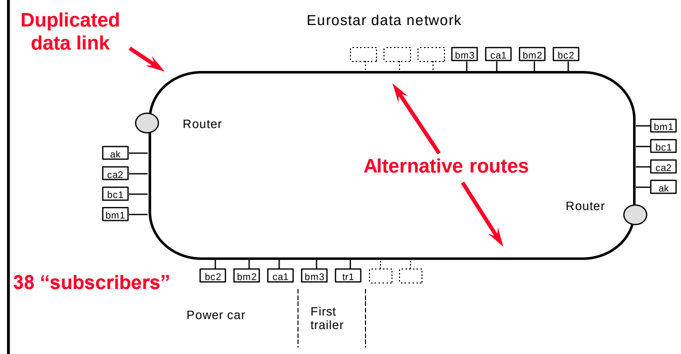
[details not included in PowerPoint]

Train management system

Discussed in more detail in Engr 529

- Objective to produce a high integrity system
  - Duplicated transmission links down different sides of the train.
  - Alternative message routing
  - Token bus system deemed more reliable than *Carrier sense multiple access* (CSMA) protocols, like Ethernet

Eurostar data network

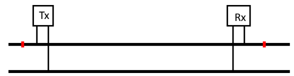


Static testing

It didn't work like that

- Quadruplicated data links only gave increase in reliability of part of the system
- The control and signalling equipment cubicle did not have adequate snow-proofing, resulting in a common-mode failure
- Several trains became stuck in Tunnel when electrical systems short-circuited due to melted snow

ICMU (interference current monitoring unit)



Possibility that drive system could fail in such a way it produced currents that interfere with signalling system.

Cannot demonstrate by analysis that risk is ALARP. Therefore UK safety authorities insisted on ICMU to detect currents that might cause problems.

But remember, traction current can be up to 6,800A DC with high harmonic content. Right-side failures are highly probable.

100 circuit breaker resets on Royal Train, thanks to ICMUs

More details in Engr 529

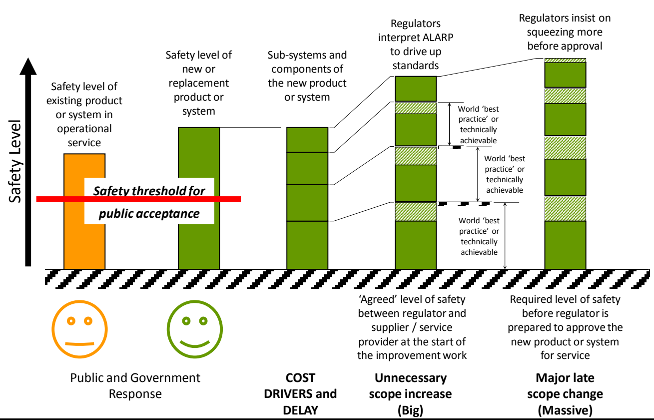
How widely is ALARP accepted ?

- France uses GAME (*Globalement au moins équivalent*)
- To most Southern Europeans the concept of ALARP is not accepted.

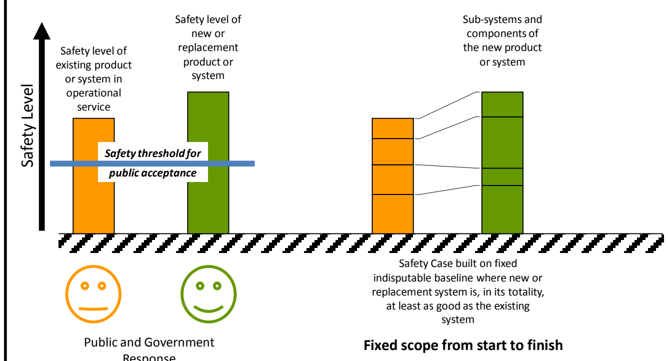
	ALARP	GAME
Reference system	☑	☑
Statistics & probability	☑	☒ ?
Consideration of costs	☑	☒
Value on "a life"	☑	☒

Safety in UK's Railways – the vagaries of applying ALARP

PA Consulting Group



The value of GAME is that there is a clear baseline that is not open for interpretation



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The regulatory bodies apply the ALARP principle onerously, inflexibly and inconsistently

- The UK regulatory requirements place a huge burden on the industry:
  - By applying ALARP for each component of the system, and applying it at the time of commissioning, the overall effect is to add much more delay, cost and uncertainty than would result from a GAME approach applied at the overall system level and mainly at the design stage
  - ALARP is appropriate for improving safety performance that is near the intolerable level, but GAME is more appropriate where the risk is at least in the middle of the tolerable range, (as it is for rail)
- We don't achieve a balance between the workload and the available effort. We are chasing perfection at the expense of pragmatism

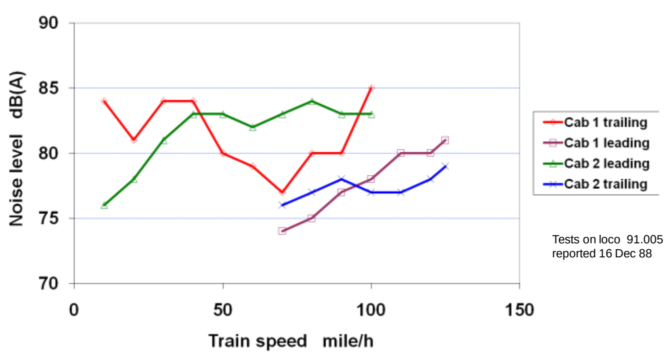
PA Consulting Group

Class 91 locomotives **"We have a problem"**

- Thirty trains built or in production
- Each cost approx. £20 million (at 2014 prices)
- Noise level in drivers' cab "up to 85dB(A)"

"Situation completely unacceptable"
– Sir Bob Reid, BR Chairman

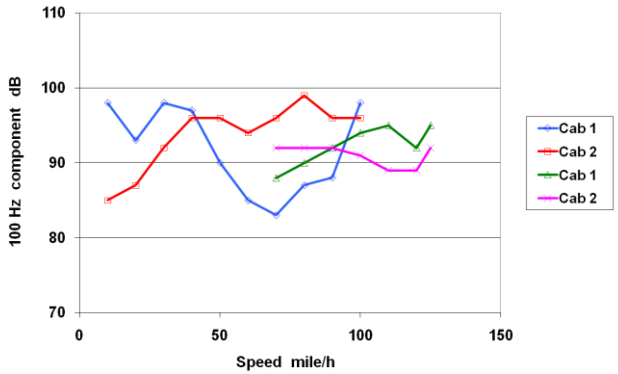
Step 1 – make some measurements



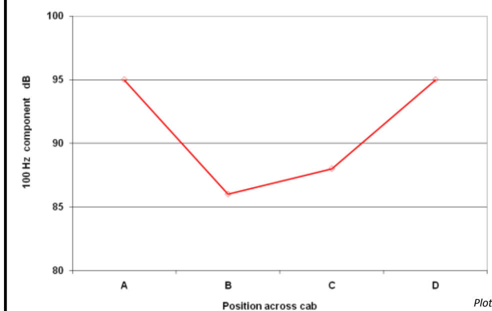
Step 2 – summarise the problem

- Noise level between 74 and 85 dB(A)
- Strong 100Hz component
- No obvious correlation with speed
- No obvious correlation with loco direction

Further analysis of 100 Hz component



100 Hz values across cab



Conclusion :

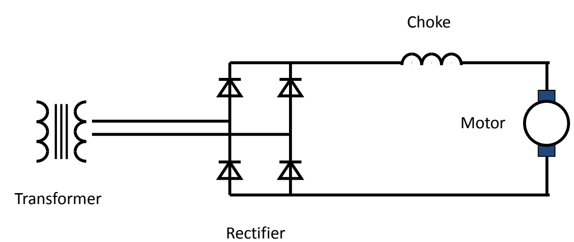
There is a standing wave amplifying 100 Hz at certain positions in cab

Plotted values average of 7 sets of tests at speeds up to 100 mile/h and different power levels

Brainstorming – what do we know ?

- Noise only occurs when loco taking power
  – Roughly proportional to power
  – Independent of speed
- Frequency independent of speed
  – Therefore probably linked to electrical equipment, not gearboxes, drive shafts, bogies, etc.
- Resonances amplify 100 Hz sound level

Simplified power circuit



Possible noise sources

- Transformer
  - 8 MVA, iron-cored, 15 tonnes
- Main smoothing chokes
  - One per motor, air-cored, taking 2000A, 30% ripple
- Traction motors
  - Four motors, each 1.5 MW, 3.5 tonnes
- Fans, pumps and other auxiliaries

Possible transmission paths

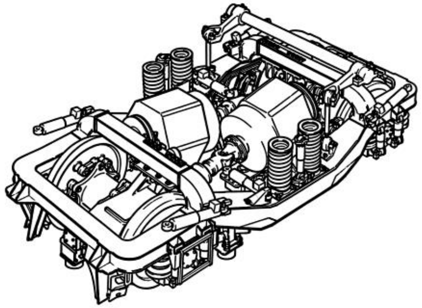
- Transmission to, and through, the structure
- Electromagnetic forces on structure
- Air-borne noise from fans
- Resonances in structure
- Resonances in cab panels
- Air-resonance in cab (organ pipe)

More tests

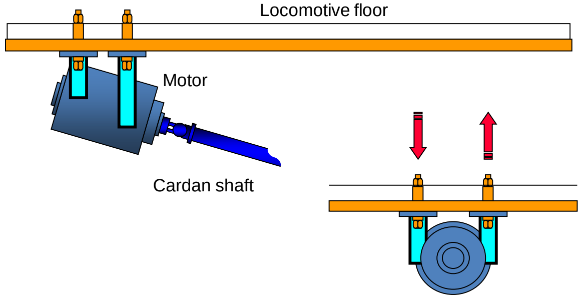
- Static tests "disconnect everything in turn" to identify noise source
- SDRC* commissioned to investigate structural resonance amplifying the noise
- Building acoustics consultant retained to advise on cab acoustics

* Structural Dynamics Research Corporation

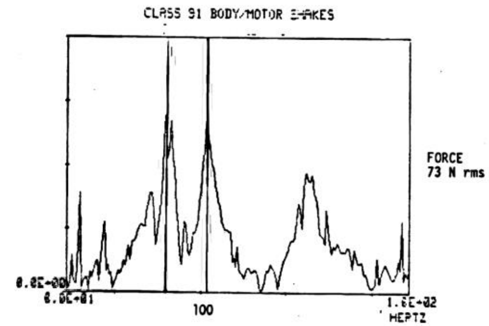
Bogie layout



Motor mounting

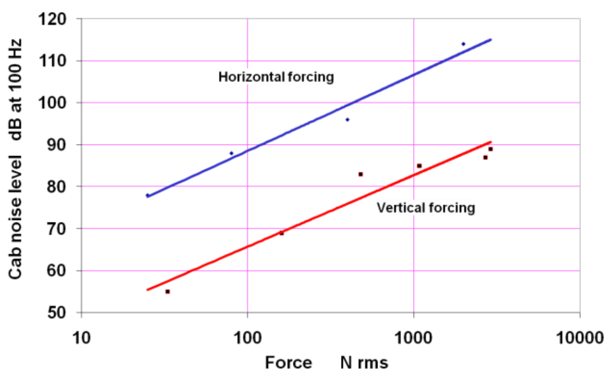


More tests – body resonance



100Hz transmission

Motor (foot) to cab (driver's left ear)



Preliminary conclusions

- Forcing energy : 100 Hz motor ripple current
- Ripple current translates into anti-phase forces on motor feet - transmitted to loco structure
- Body structure resonant at 100 Hz and transmits noise to cab supports
- Cab acoustic isolation not as good as specified
- Cab has 100 Hz air resonance

Stage 3 – develop solutions

- Fundamental investigations
  - Vibration tests
  - Static power tests
- Pursuing most likely culprit
  - Initial design of motor isolation mounts
- Investigating possible "quick fixes"
  - Active noise cancellation
  - Cab acoustic treatment
- Check impact on product safety?

Active noise cancellation

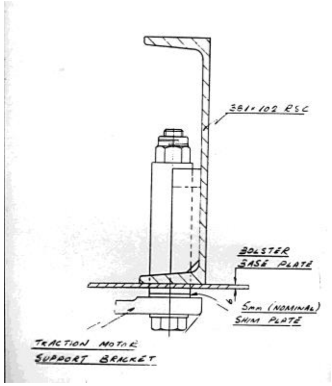
- Use microphone to measure noise
- Use loudspeakers to produce equal noise in anti-phase to cancel out original noise
- Proved in Lotus sports cars
- Problem in 2-man cab : can compensate for one or other - not both !

Motor mounts - conflicting requirements

- Flexible to isolate vibration
- Transmits full load torque of motor (10kN-m)
- Motor movements must be restricted to prevent hitting other components
- Must be capable of withstanding >3g in a crash
- Must avoid body bending frequency (12Hz) and bogie kinematic frequency (8Hz)
- Must fit in very restricted space

Original motor mounts

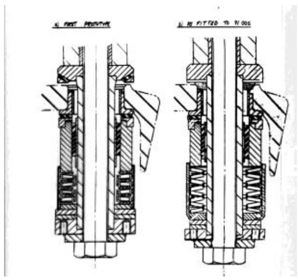
- Existing mount solidly bolted to 380 x 100mm chassis structure
- 28mm high-tensile bolts
- It seems likely that the noise is caused by varying torque transmitted by the motor feet to the chassis



Alternatives considered

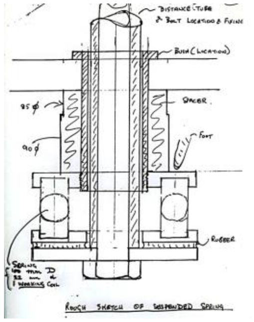
- **Air springs** – too big
- **Rubber springs in shear** – unsafe failure modes
- **Coil springs** – worth investigating, if we can find a solution that “fails safe”
- **Belleville washers and rubber in compression** – worth investigating

Belville washer spring



- Dished washer works in vertical.
- Doesn’t give lateral suspension – shorts out isolation
- Tends to be unstable

First ideas of coil spring mount

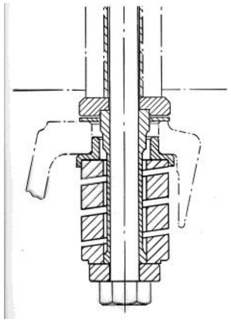


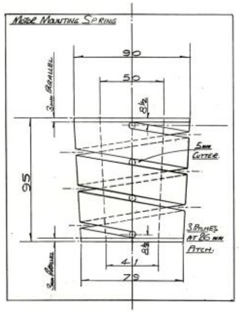
Problems:

- Spring needs to provide resilience in vertical and lateral directions
- Quasi-static force >10kN
- No manufacturer wants to make spring that short

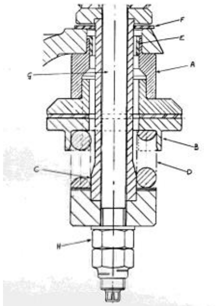
But design gives positive retention in case of spring failure

Spring machined from solid





Stage 4 – focus on final design



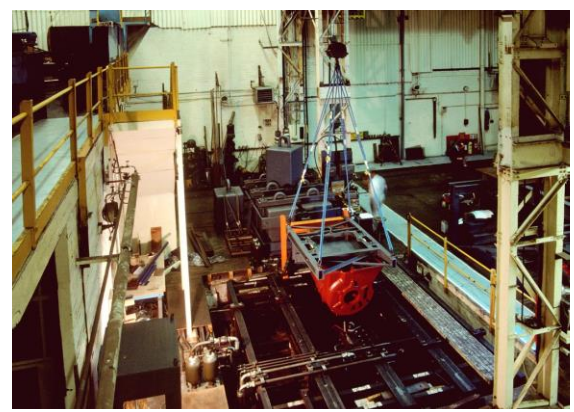
Check modification process

- Mount can be installed on site
- Does not require cutting and welding operations

Stage 5 – intensive tests: static performance

Check design can withstand proof stresses anticipated in crash situations

Dynamic testing



Stage 6 – safety validation: simulation of 3g

Suspend motor and swing against 200t mass

Stage 6 contd.

Conclusions

- 100 Hz noise level reduced by 20dB.
  - *BR management and unions satisfied*
- Retrofit could be done in depot - no need to return locos to build works
- Safety tests demonstrated that new design could withstand crash forces
- Work completed in 3 months
  - *Did not delay entry into service*

Methodology

→ Define the problem

→ Analyse the problem

→ Confirm the analysis by tests

→ Brainstorm alternative solutions

→ Test these alternatives

→ Decide on best option

→ Prove option

Possible lessons from these case studies?

- Avoid fixating on improbable hazards (Tunnel fire, signalling interference) as the solutions might exacerbate other more mundane risks.
- Consider a wide range of possible hazards – not just those that are “traditional” to the industry.
- The best solution is the least-bad compromise between technical performance, safety, timescale, cost and practicability.