Synthesising Spatially Repeatable Tyre Forces from Axle Load Probability Distributions

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Outline

- **Background ➔ Costanzi (2008)**
  - Whole-Life Modelling of Spray-Sealed Roads
- **Current Work ➔ Heavy Duty Pavements**
  - Axle Load Probability Distributions
  - Vehicle Models and Traffic Modelling
  - Results
- **Summary & Conclusions**
Background
The Dynamic Load Coefficient

- **Dynamic Load Coefficient (DLC):**
  \[
  DLC = \frac{\sigma}{P_0}
  \]
- Typical: \( 0.1 < DLC < 0.3 \)
- Depends on surface, suspension, speed...
4th Power Law and the DLC

- 4th power law (AASHO Road Test, 1960s):

\[ N_{ESAL} = \left( \frac{P_{stat}}{P_0} \right)^4 \]

- Eisenmann, 1975, Assumed dynamic loads applied randomly along road:

\[ \phi = E \left[ P(t)^4 \right] = P_{stat}^4 \left( 1 + 6DLC^2 + 3DLC^4 \right) \]

Dynamic Road Stress Factor, \( v \)

\( v = 1.1-1.5 \) (typical)
Road Stress Factor Approach

Factors $\eta_I$ and $\eta_{II}$ for tyre and axle configurations

\[ N_{ESAL} = v \left( \eta_I \eta_{II} \frac{P_{stat}}{P_0} \right)^4 \]

- Suspension type (Leaf/Air/Rubber..)
- Tyre configuration (Single/Dual/Wide)
- Suspension configuration (Single/Tandem/Triaxle)

- Used for Legislation (EC:1992; Australia:1999)
- Payload advantage for air or ‘equivalent’ suspensions
The Trouble With ESALs

- Problems with ESALs
  - Assume a damage relationship
  - Is it 4? Is it 12? Is it 1?
  - Reject differences between vehicles
  - Ignore dynamic effects

\[ N_{ESAL} = \left( \frac{P_{stat}}{P_0} \right) \]
Axle Load Probability Distributions

- **Pros**
  - Based on *real* weights
  - Allows analytical calculation of pavement response
  - Traffic is *statistically* correct

- **Cons**
  - *Still neglect dynamic effects*
  - *Spatial repeatability?*
The Importance of Being Dynamic

Spatial Repeatability!

n = 1

n = 4
What is Spatial Repeatability?

- **Heavy vehicles apply their peak tyre forces at similar locations**
  - Similar dimensions
  - Similar weights
  - Similar speeds
- This has been measured →
- **Earlier failure at critical points!**
The Spatial Repeatability Index (SRI)

- Measures the **spatial correlation** between tyre forces of two vehicles

\[ SRI = \rho = \frac{E[(F_{ref} - \mu_{ref})(F_i - \mu_i)]}{\sigma_{ref}\sigma_i} \]

- Also called the ‘normalised covariance,’ or ‘correlation coefficient’
Spatial Repeatability Results

542 vehicles

- A2+2(steel), 81 vehicles
- A2+2(air), 38 vehicles
- A2+3(air), 57 vehicles
- A2+3(steel), 55 vehicles
- Rig2, 275 vehicles
- Other, 36 vehicles

± 1m (3Hz)
± 0.3m (10Hz)
Aggregate Tyre Force:  
Alternative Measure of Repeatability

\[ A_k^n = \frac{1}{F_{j,k}} \sum_{j=1}^{N} F_{j,k}^n \]

- Quantifies dynamic loading effects of a truck in the spatial domain at specific points along pavement
- Often normalised by static weight \( \rightarrow \) normalised aggregate tyre force (NAF)

k: particular point on road  
j: vehicle axle (1...N)  
n: power law exponent (i.e., 4)
Background
Costanzi (2008)

- Air spring suspensions “road-friendly”
  
  *(Fed. Off. of Road Safety, 1999; Same as EC Regulation)*

- Higher Mass Limits (HML)
  - Road-friendly suspensions
  - 6 axle tractor/semi-trailer
  - Allowable GVW raised from 42.5 to 45.5 tonnes

- No in-service suspension performance requirement
  - *Are these suspensions still ‘road-friendly?’*
  - *What effect does HML have on maintenance costs of spray-seal roads?*
Whole-Life Methodology
Costanzi (2008)

1. Create Road
2. Calculate Vehicle Forces
3. Calculate Deformation
4. Evaluate and Repair Damage (if necessary)
5. Cost of maintenance

Update Road

Vehicle Model Input
Road Deformation Model
Maintenance Model
Whole-Life Modelling Results
Costanzi (2009)

• Results
  • ‘road-friendly’ and CML $\rightarrow$ -14% cost ($AUD/tonne-km)
  • ‘road-friendly’ and HML $\rightarrow$ -1%
  • 50% non-functional dampers and HML $\rightarrow$ +21%
Current Work
Current Work

Framework (GUI, Storage, Plotting)

- Climate Models
- Granular Materials
- Pavement Damage
- Maintenance Model
- Traffic Model
Overview of Traffic Modelling

• GOALS
  – Create ‘spatially repeatable’ traffic models
    • from ‘ME-PDG style’ axle load probability distributions
    • derived from US LTPP, ‘per-vehicle’ WIM records
    • Three methods
      – direct from WIM
      – Monte Carlo randomisation
      – ‘phase shifting’ (Collop 1996)
  – Calculate measures of spatial repeatability
    • SRI [statistics]
    • NAF [spatial domain]
Vehicle Models

8-DOF, ‘Pitch-Plane’ Model

2-DOF, Quarter Car Model (QCM)
‘Reference’ Fleet Generation

Per-Vehicle WIM (Weights and Spacings)

Calculate C.G. Positions

Filter Spurious Vehicles

Calculate Inertial Properties

Estimate Suspension Parameters

Pass Input to Simulation

Class 9 Vehicles From US LTPP Database

- Determined from Statics
- Linear air suspension elements and nonlinear leaf springs
- Constant damping factors for air spring suspensions
- Tractors: 10% leaf sprung, Trailers: 30% leaf sprung

References
Correlation of Tandem Axle Groups

- Tandem groups are correlated!
- Arises from evenly loaded trailers
- Important for randomised generation of vehicle models
‘Target’ Fleet Generation

Calculate Params as for Reference

Pass Input to Simulation

‘N’ random samples

Assume correlation between tandems

Assume fixed wheelbases

Pitch – Plane Models
Randomised QCM Generation

- Trailer QCM
- Tractor QCM
- Steer QCM

Estimate Suspension Parameters

Pass Input to Simulation

‘N’ random samples

Correlated Samples

Same proportions as Reference
Phase Shifting Theory

\[ F_1(t) = \sin(\omega t) \]

\[ F_2(t) = \sin(\omega t + \phi) \]

\[ SRI = \cos(\phi) \]
Phase Shifting Theory

$$P(SRI) \quad \text{cosine} \quad P(\phi)$$
Phase Shifting Theory

180° (Note mirroring)
Phase Shifted QCM Generation

1. Discretise Target SRI Distribution
   - $\phi = \cos^{-1}(\text{SRI})$
2. Phase Shift Reference Tyre Forces
3. iFFT
   - SRI
   - Normalised Aggregate Force
4. FFT
   - Tand QCM
   - Steer QCM

- Mean laden weights
- Leaf and air sprung tandems simulated
Results & Conclusions
Traffic Modelling Results

- All Air (QCMs & Pitch-Planes)
- Tract. Air/Trail. Leaf (Pitch-Planes & P-S QCMs)
- Tract. Air/Trail. Leaf (Random QCMs)

Graph showing comparison of different traffic modelling results with SRI (Surface Roughness Index) on the x-axis and $\Phi$ (SRL) on the y-axis. Different lines represent Reference, Target, Random QCM, and Phase Shifted QCM.
Traffic Modelling Results

- Good phase agreement
- Range of magnitudes

Fleet Normalised Aggregate Force vs. Distance [m]
## Traffic Modelling Results

<table>
<thead>
<tr>
<th>Method</th>
<th>Number of Vehicles in Fleet</th>
<th>Simulation Time (One Run) [sec]</th>
<th>Simulation Time (20 years in weeks) [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>7000</td>
<td>147600</td>
<td>1777</td>
</tr>
<tr>
<td>Target</td>
<td>1000</td>
<td>26000</td>
<td>330</td>
</tr>
<tr>
<td>Random QCM</td>
<td>1000</td>
<td>24000</td>
<td>290</td>
</tr>
<tr>
<td>Phase Shifted QCM</td>
<td>3</td>
<td>90</td>
<td><strong>1.5</strong></td>
</tr>
</tbody>
</table>

Includes overhead of calculating ‘target’ distribution in first run.
Summary and Conclusions

• Spatial repeatability is important!

• Whole-life modelling accounts for:
  – Traffic fleet characteristics
  – Spatial repeatability

• Traffic modelling
  – Phase-shifted QCMs 99.5% faster than ‘target’ pitch-plane models
  – QCMs capture salient features of loading profile
Thank You!