A Rail-Road Hybrid Vehicle: Dynamic Stability Analysis

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Introduction: Rail-Road Hybrid Betuwe Route

Combining Rail & Road

- Rail vehicles:
  - + Low rolling resistance
  - - Switching / flexibility

- Road vehicles:
  - + Flexibility in manoeuvring
  - + Door-to-door transport
  - - High rolling resistance

- The rail-road Hybrid vehicle
  - Road vehicle with up to 60 % of vehicle load on simple and light rail axles.
Hybrid vehicle concept

- Rail-road hybrid vehicle:
  - intelligent autonomous road vehicle (agv)
  - Active steered & driven road wheels
  - electronically lateral guiding
  - light rail axles: no brakes & self centring
  - vertical force control on rail wheels.
The Hybrid: system layout

- Autonomous, on-board power source
- General air spring suspensions applied
- Total vehicle mass approx. 45 tonnes

- 4 road axles: 1 – 3  4 – 6
- 2 rail wheel sets: 2  5

- Point follower steering on axle 1 and 6
- Ackermann steer angles on axles 3 and 4.

ADAMS model approach

- Fully parametrised model using UDE’s
- 2 Axle groups, each 2 road & 1 rail axle
- Template based model components
- Generic axle models applied
- Pivot steered axles with torsion spring
- State-of-the art Magic Formula tires

- Rail axles go-with-flow
- Generalised rail contact
- Possible zero-friction & conicity in rail wheels
- Vehicle load from 0 to 100 % on rail axles.
Axle suspension models

**Rail axles**
- Airspring with rigid link
- Axle lift (0 % rail load)
- Conical wheels – single point contact wheel-to-rails
- Possible 3-D rail curvature

**Road axles**
- Airspring with rigid link
- Axle lift (0 % road load)
- Range of MF tyre models
- Variable steering method
- Applied: Point follower with 2 m and 3 m lead point.

Axle steering system

Axle 1 steer input ➔

⇤ Axle 6 steer input
Simulation approach

- Analyse stability using lateral wind input:
  - Wind force amplitude equal to 0.1 G lat. acc.
  - Good system damping around speed of 55 km/h
  - Max. lateral deviation must be smaller than 0.10 m

- Assess vehicle and steering control parameters

- Model settings used:
  1. Completely on road wheels: \( \rightarrow \) reference case
  2. Rail wheels: zero \( \alpha \) & \( \mu \) rails: \( \rightarrow \) worst case (level icy rail)
  3. Steering system optimal parameters (PID required ?)
  4. Complete system verification on rails.

Simulation output

- Signals:
  - \( Y_{\text{max,road}} \): max lat. displ. of any road axles
  - \( F_{z,\text{rail},\%} \): sum of rail axle forces vertical, % of total
  - \( \text{Car}_{\text{roll}} \): dynamic car body roll angle

- Design parameter studies: \( \rightarrow \) tendencies

- Methods:
  - Peak value (overshoot)
  - Steady state (static response)
1. Reference car: simulation results

- $Y_{\text{max,road}}$ steady state approx. 0.1 m
- Car$_{roll}$ steady state approx. 5 deg.

Reference vehicle at zero vertical rail forces
2. Level icy rail: design study results

- \( Y_{\text{max,road}} \) steady state & overshoot show a minimum for \( F_{z,\text{rail}} \% \)
- Transfer from road to rail axles increases \( C_{\text{roll}} \) (at \( C_{\text{roll, rail}} = \text{road} \)).

- High body roll stiffness improves vehicle stability
- Rail axle \( C_{\text{roll}} \) must be at least equal to road axle \( C_{\text{roll}} \).
Variation of tire nominal load
- Slight sensitivity to tire slip stiffness
+ Vehicles with overloaded tires benefit more of hybrid use.

Results: 2 Level icy rail

Level icy rail surface: vertical rail forces 50 %
3. Steering parameter design study

1. Red: Y deviation point follower to input angle axle 1/6: P=1
2. Blue: P-factor axle 1/6 = 7.2/16: strong improvement
3. Cyan: 2 +D-factor axle 1/6 = 2.7/4.0: slightly better
4. Black: 3 + I-factor axle 1/6 = 8.0/5.0: better static offset

- Factor 3-4 improvement of $Y_{\text{max,road}}$ with no extra steering power.

Hybrid with full steering PID, vertical rail forces 50%
4. Complete system verification

System roll stiffness as a function of Rail %

- Roll stiffness doubles at default setting: \( C_{\text{rail}} = C_{\text{road axles}} \)
- At \( C_{\text{rail}} \gg C_{\text{road}} \): asymptotic behavior at high % rail load.

Effect of car roll stiffness to \( Y_{\text{max,road}} \)

- High roll stiffness reduces \( Y_{\text{max,road}} \) for both \( P=1 \) and PID.
Effect of rail parameters

**full rail vehicle:** low $F_y$ wind

- Conicity $0.01$ to $0.04$ is OK

**Hybrid vehicle**

- Conicity around $0.01$ is OK
- High % rail, low peak forces.

Results: 4 complete system

Gain from Rail $F_y$: Level Ice / conicity $= 0.005$ / conicity $= 0.01$

- With PID control hybrid improves at increase of rail load % !!
- Small differences due to wheel conicity & rail friction
- No extra stabilisation from rail axles required
- Light rail axles with zero lateral forces can be achieved.

Results: 4 complete system
Variation of bump stop engagement for rail axle lat. play

- 30 % rail: > 0.06 m play, 60 % rail: > 0.02 m play
- Self centering effect of rail helps at higher % rails
- 0.075 m play is sufficient for most circumstances.

Results: 4 complete system

Final variation of velocity in various system settings

- Hybrid design is stable & predictable in desired speed range
- Speed dependency disappears due to PID steering control
- With PID control, 60 % hybrid is better than 0 % hybrid.

Results: 4 complete system
Conclusions & further work

- The hybrid combines the benefits of road & rail vehicles
- No dynamic problems where found in operation speed range
- W.R.T. vehicle component design:
  - Improved response is dominated by roll stiffness increase
  - System is robust w.r.t. tire mismatch problems
  - Simple P.I.D. control gives significant improvement
  - Extra stabilisation from rail guidance is small, thus minimisation of rail axle weight is feasible.
- TU Delft is now looking for partners to built a physical prototype for further tests and feasibility analysis.