A Rail-Road Hybrid Vehicle: *Dynamic Stability Analysis*

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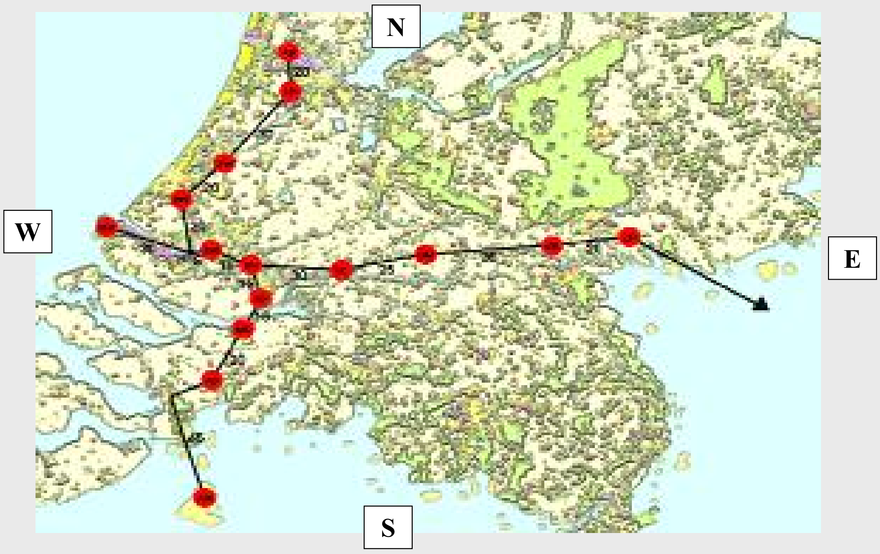
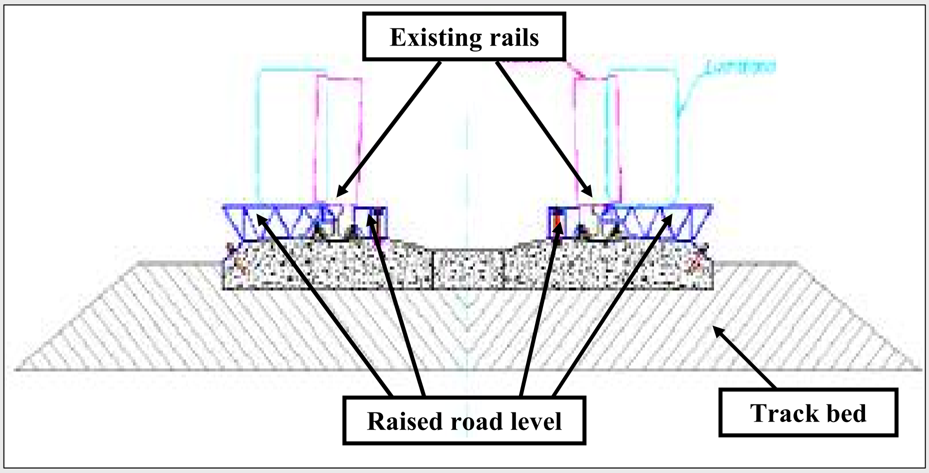
Introduction: Rail-Road Hybrid Betuwe Route



Combining Rail & Road

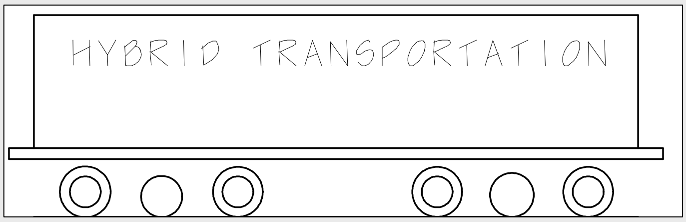
- Rail vehicles:
  - + Low rolling resistance
  - - Switching / flexibility
- Road vehicles:
  - + Flexibility in manoeuvring
  - + Door-to-door transport
  - - High rolling resistance
- → The rail-road Hybrid vehicle
  - Road vehicle with up to 60 % of vehicle load on simple and light rail axles.

Proposed Rail-road hybrid track



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

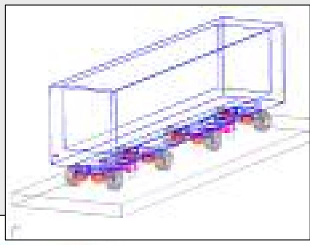
- Autonomous, on-board power source
- General air spring suspensions applied
- Total vehicle mass approx. 45 tonnes

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

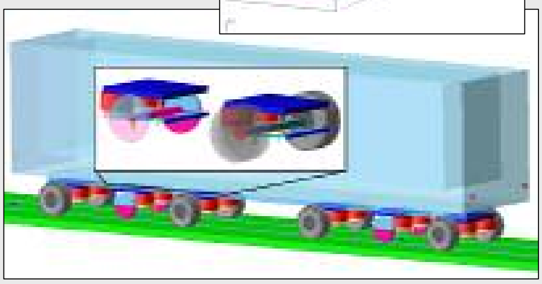
- Point follower steering on axle 1 and 6
- Ackermann steer angles on axles 3 and 4.

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



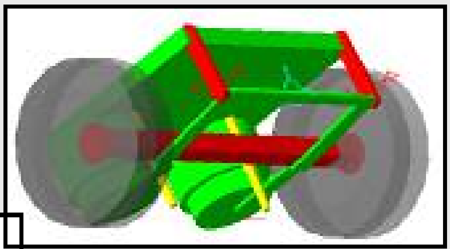
- Rail axles *go-with-flow*
- Generalised rail contact
- Possible zero-friction & conicity in rail wheels
- Vehicle load from 0 to 100 % on rail axles.

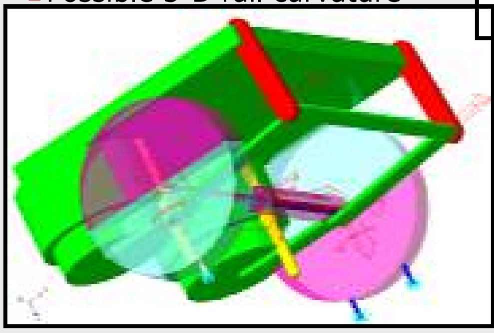


Axle suspension models

Rail axles

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



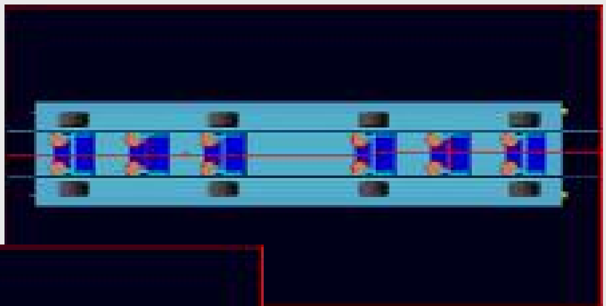


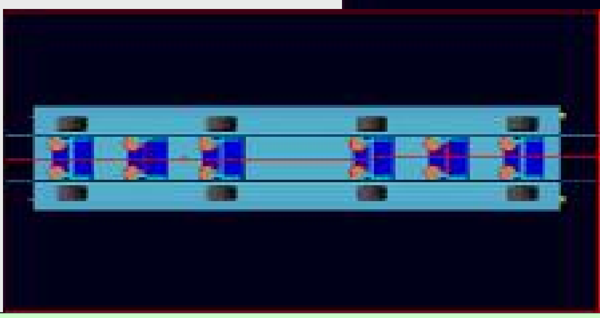
Road axles

- 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

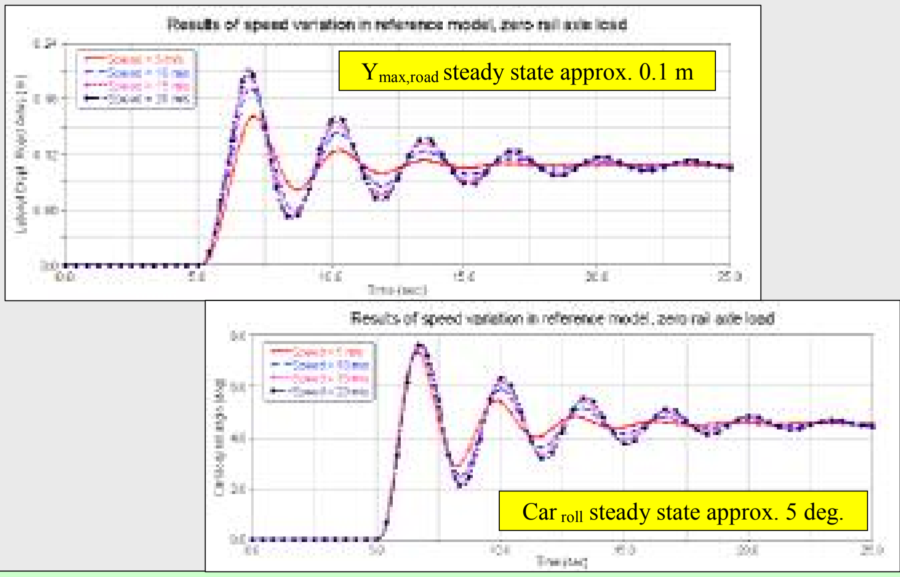
Simulation approach

- 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: → reference case
  2. Rail wheels: zero α & μ rails: → worst case (level icy rail)
  3. Steering system optimal parameters (PID required ?)
  4. Complete system verification on rails.

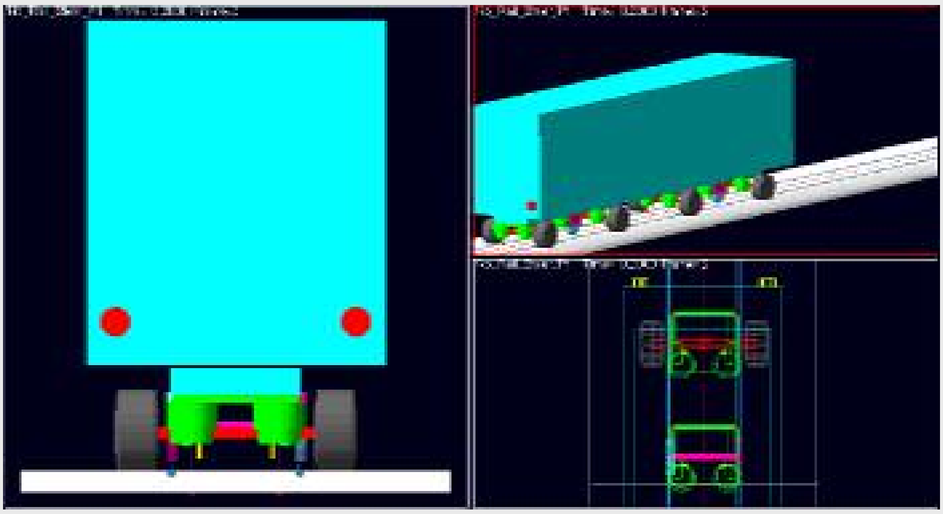
Simulation output

- Signals:
  - $Y_{max,road}$: max lat. displ. of any road axles
  - $F_{z,rail,\%}$: sum of rail axle forces vertical, % of total
  - Car_{roll} : dynamic car body roll angle
- Design parameter studies: → tendencies
- Methods:
  - Peak value (overshoot)
  - Steady state (static response).

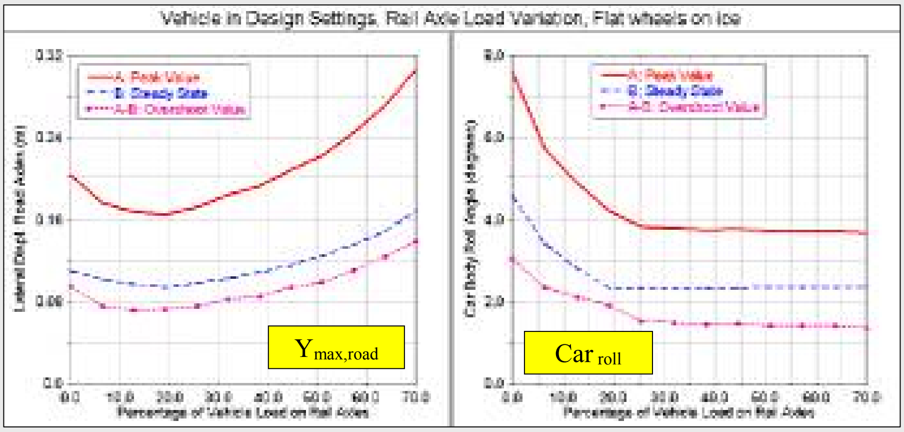
1. Reference car: simulation results



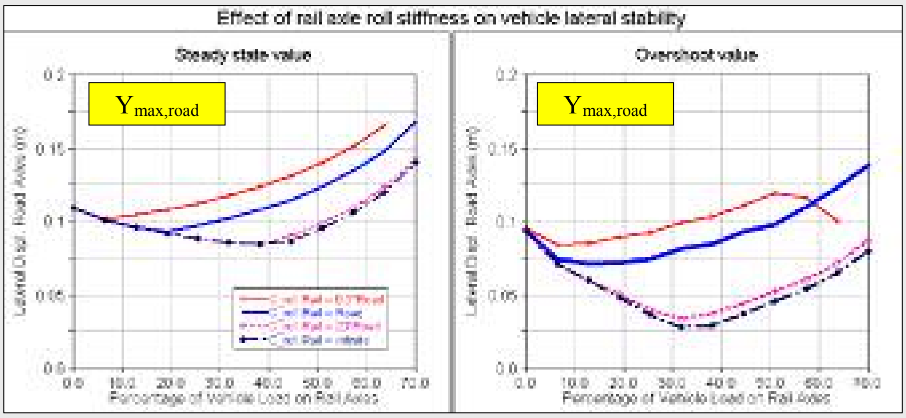
Reference vehicle at zero vertical rail forces



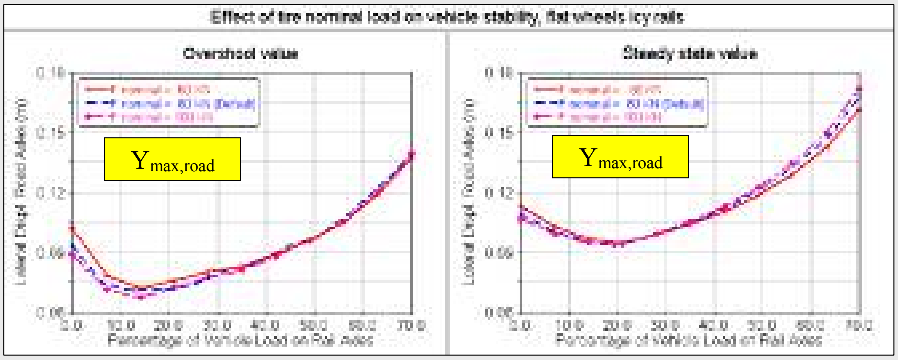
2. Level icy rail: design study results

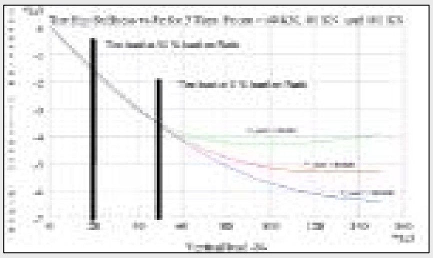


- $Y_{max,road}$ steady state & overshoot show a minimum for $F_{z,rail,\%}$
- Transfer from road to rail axles increases C_{roll} (at C_{roll} rail = road).



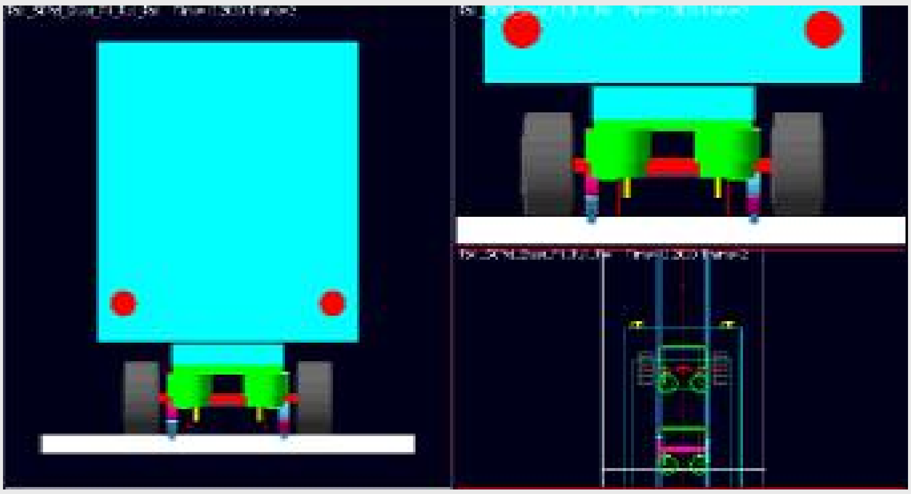
- High body roll stiffness improves vehicle stability
- Rail axle C_{roll} must be at least equal to road axle C_{roll}.



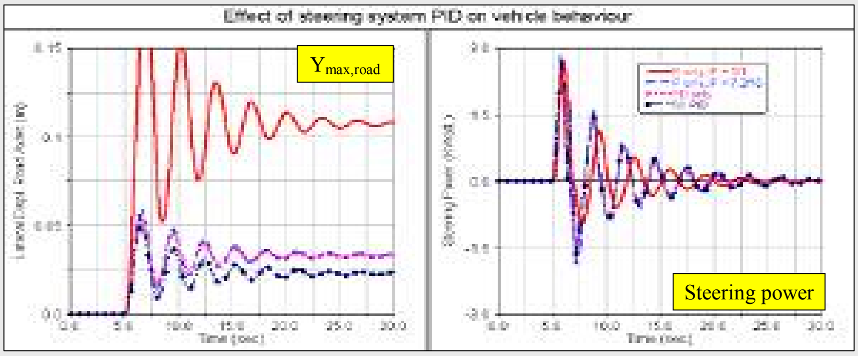


- Variation of tire nominal load
- → Slight sensitivity to tire slip stiffness
- \+ Vehicles with overloaded tires benefit more of hybrid use.

Level icy rail surface: vertical rail forces 50 %



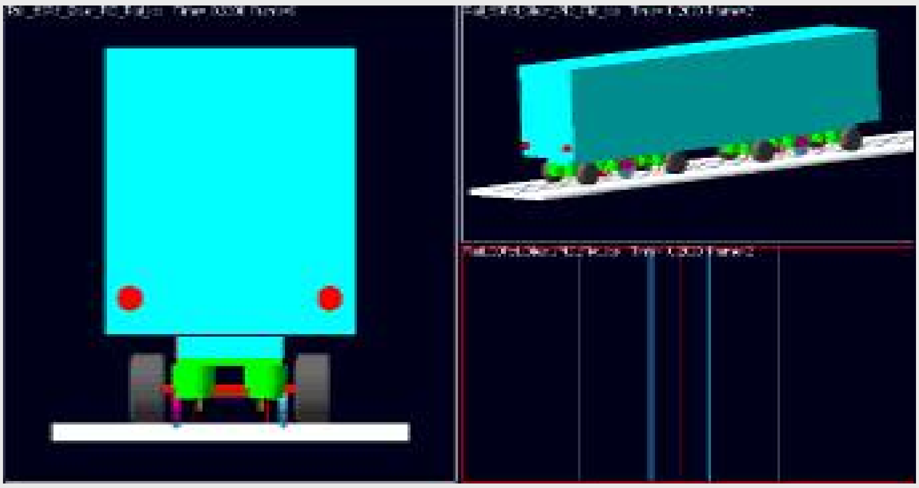
3. Steering parameter design study



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

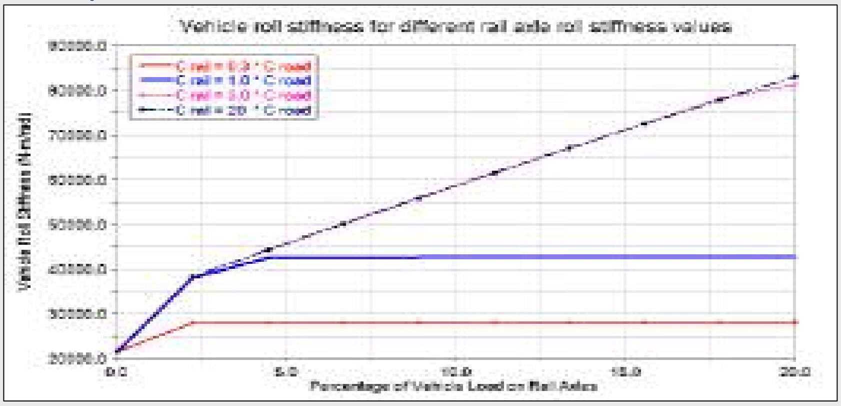
- Factor 3-4 improvement of $Y_{max,road}$ with no extra steering power.

Hybrid with full steering PID, vertical rail forces 50 %



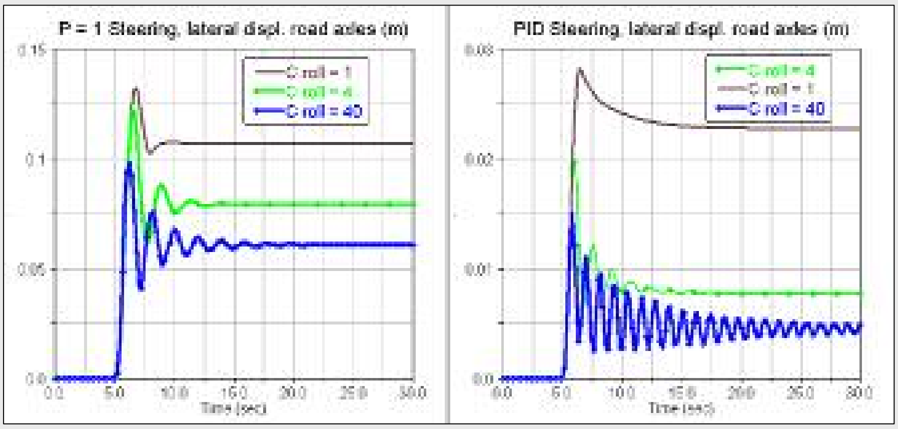
4. Complete system verification

System roll stiffness as a function of Rail %



- Roll stiffness doubles at default setting: C rail = C road axles
- At C rail >> C road: asymptotic behavior at high % rail load.

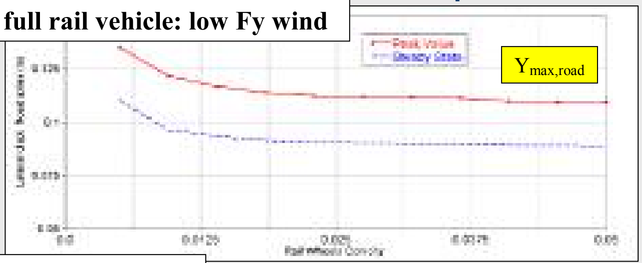
Effect of car roll stiffness to $Y_{max,road}$



- High roll stiffness reduces $Y_{max,road}$ for both P=1 and PID.

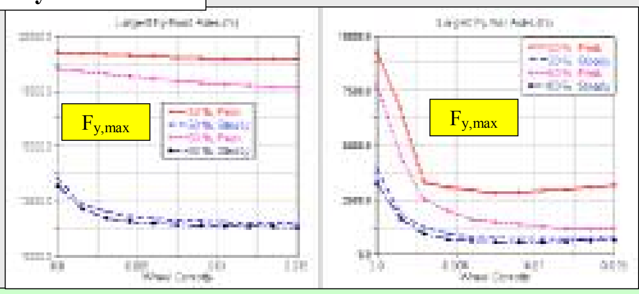
Effect of rail parameters

full rail vehicle: low Fy wind



→ Conicity 0.01 to 0.04 is OK

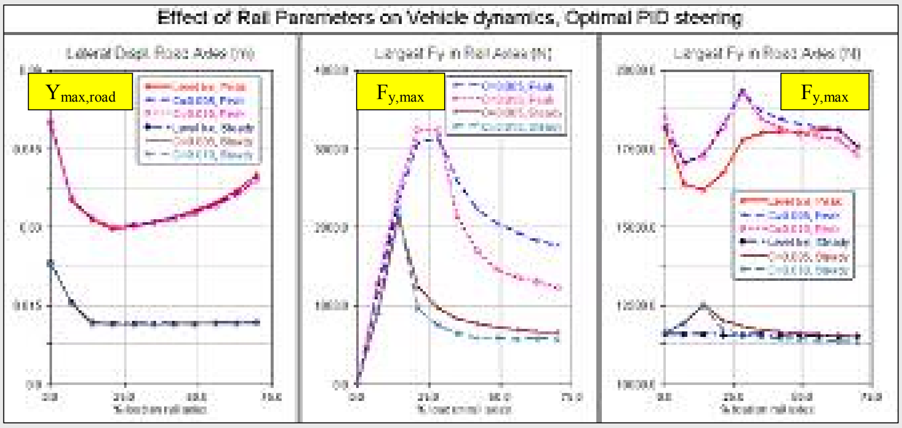
Hybrid vehicle



→Conicity around 0.01 is OK

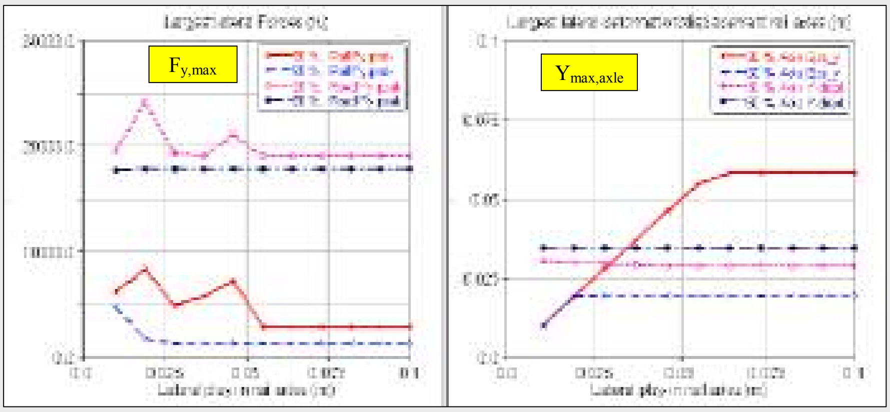
→ High % rail, low peak forces.

Gain from Rail Fy: 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.

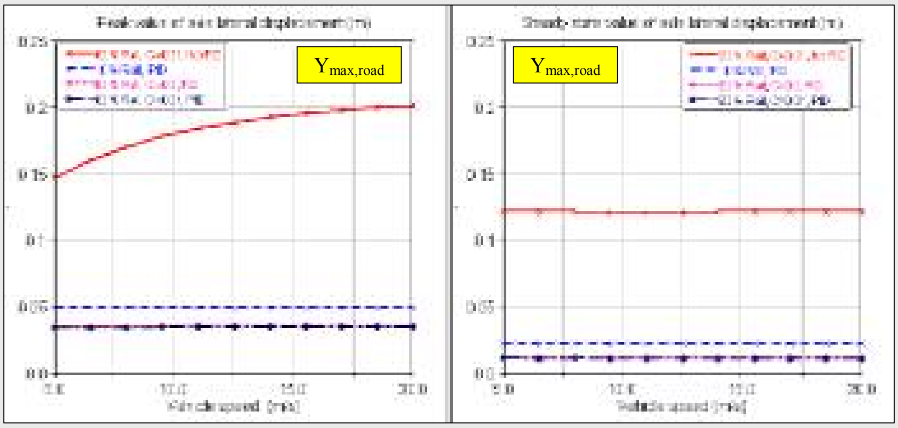
Variation of bump stop engagement for rail axle lat. play



- → 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.

7 ISHVWD 2002 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.

7 ISHVWD 2002 Results: 4 complete system

Side wind input 0.1 G: comparing three settings

P=1, no rails | P=1, 50 % rails | PID 50 % rails

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.