SIMPACK User Meeting

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Multiphysics Modeling of Railway Pneumatic Suspensions

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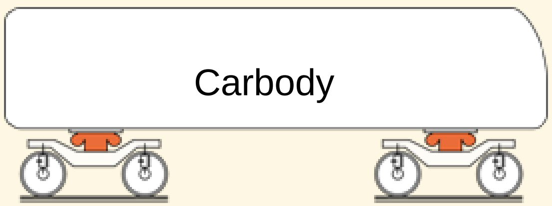
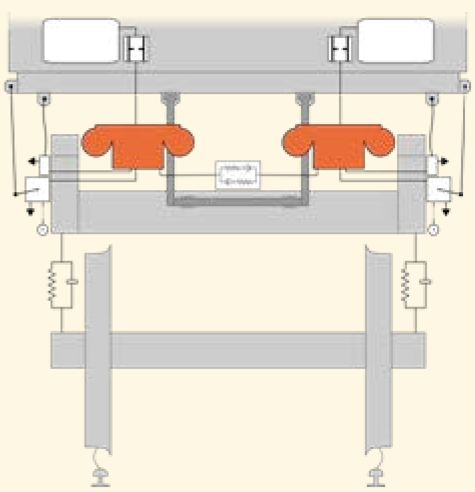
Secondary suspension dynamics





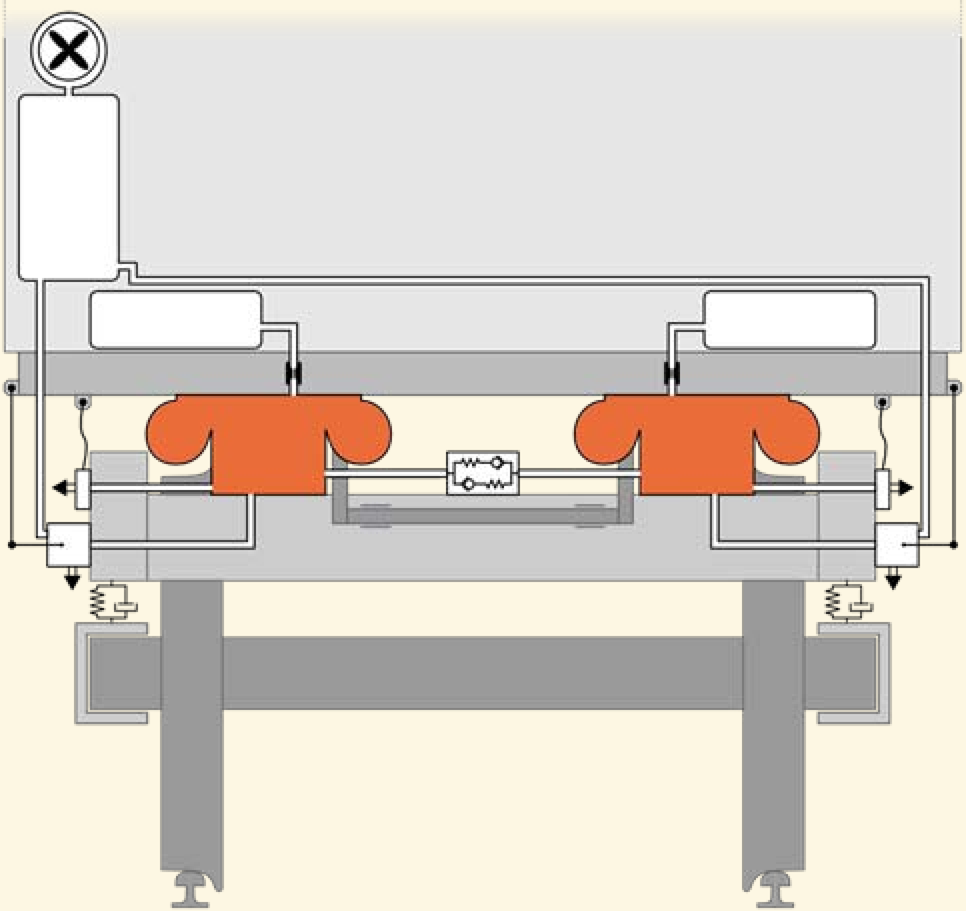
- **Industrial context**
  - A full pneumatic circuit
  - Various morphologies
  - Increase in design complexity
- **Scientific motivations**
  - Deep understanding of the dynamic behaviour
  - Development of accurate models including the complete pneumatic circuit
  - Multibody and pneumatic dynamics coupling
  - Optimized suspension design tool

Contents

- **Description of pneumatic suspension circuits**
- **Comparison of pneumatic component models**
- **Experimental validation**
- **Analysis of a complete metro car**
  - Multibody and pneumatic coupling
  - Influence of heat transfer
  - Comparison of various suspension morphologies
- **Conclusion**

Pneumatic suspension components

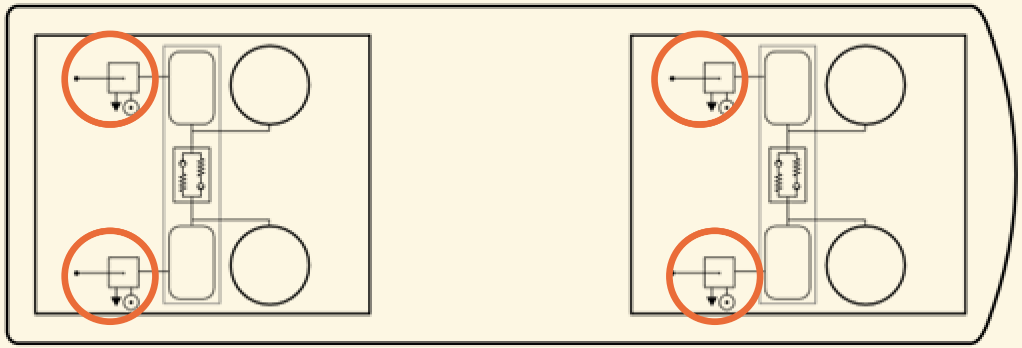
- Air spring
- Auxiliary tank
- Connecting pipe
- Orifice
- Valves
  - Levelling valve
  - Exhaust Valve
  - Differential valve
- Pressure source



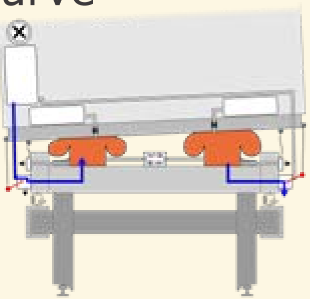
Many possible configurations

Levelling configurations

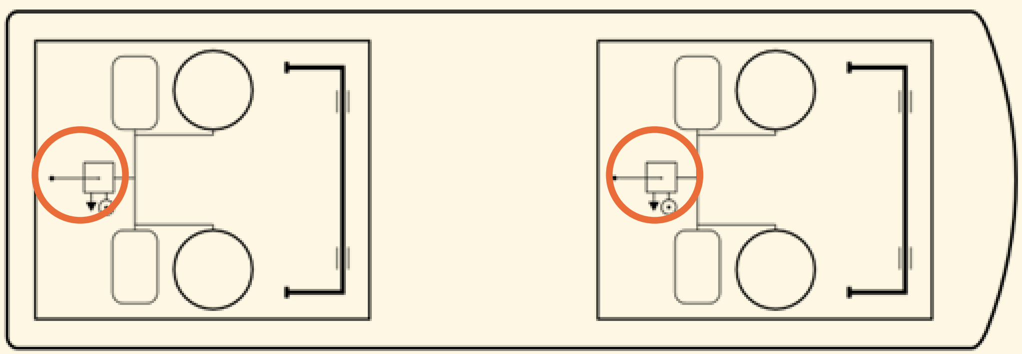
- **4-point suspension**



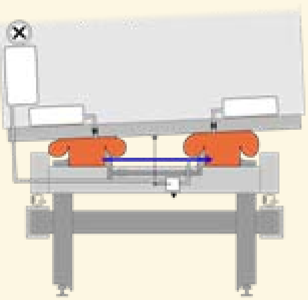
- 4 levelling valves per carbody
- 1 levelling valve per bellows
- Differential valve is necessary
  - rail twist, punctured bellows
- Anti-roll action in curve



- **2-point suspension**

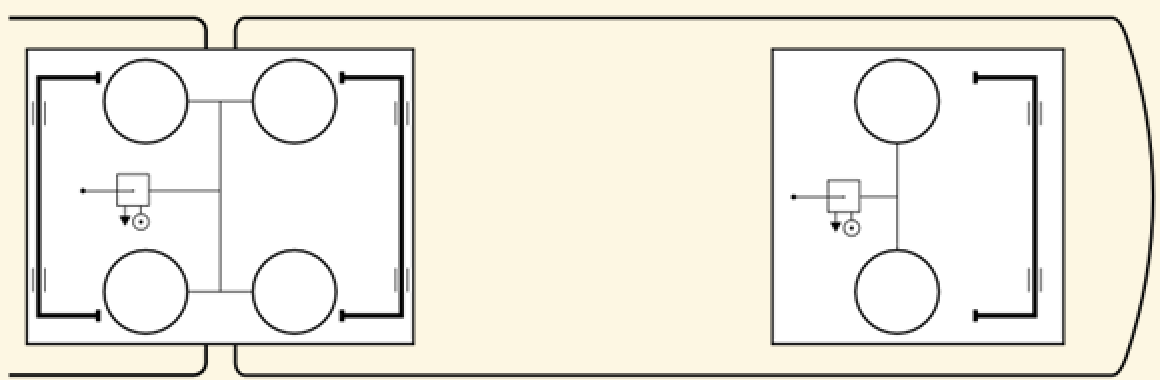


- 2 levelling valves per carbody
- 1 levelling for 2 bellows
- Anti-roll bar needed



Suspension configuration

Kind of bogie	Conventional	Jakob's bogie	
Number of bellows per bogie	2	4	
Levelling configuration	2-point	3-point	4-point
Anti-roll bar	With	Without	
Auxiliary tank	With	Without	
Hydraulic damper	With	Without	



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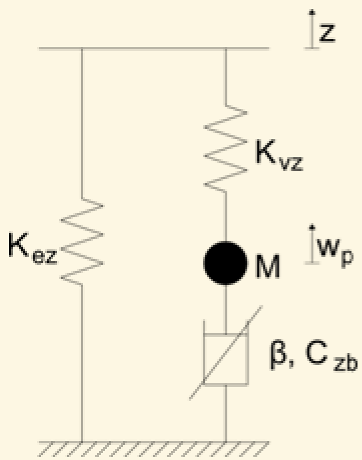
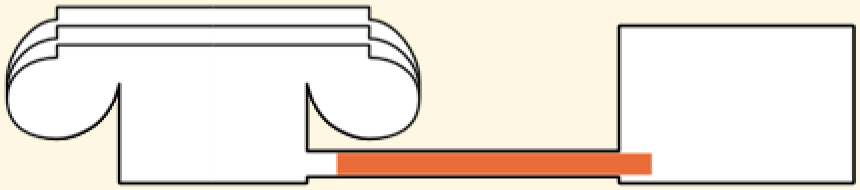
Bellow-tank models

- **Spring-mass system**



- **Oscillating air mass**



$$m_p\ddot{y} + \frac{\rho_p}{2}\left(\lambda\frac{L_p}{d_p} + \zeta\right)A_p\dot{y}^2 sign(\dot{y}) + (p_b - p_t)A_p = 0$$

Volume variation in bellow and tank

Pressure variation

$$pV^\gamma = p_0V_0^\gamma$$

- Suitable for multibody software
- Difficult to complete with valve models
- Difficult to adapt for various topologies

Component specific model

- **Bellows and tanks: pneumatic chambers**
  - Continuity equation ➔ mass variation

$$\dot{M} = \sum_i q_i$$

  - Energy equation ➔ temperature variation

$$\dot{T} = \frac{\gamma - 1}{RM}\left(\sum_i q_i h_i - \frac{RT}{\gamma - 1}\sum_i q_i + \dot{Q} - p\dot{V}\right)$$

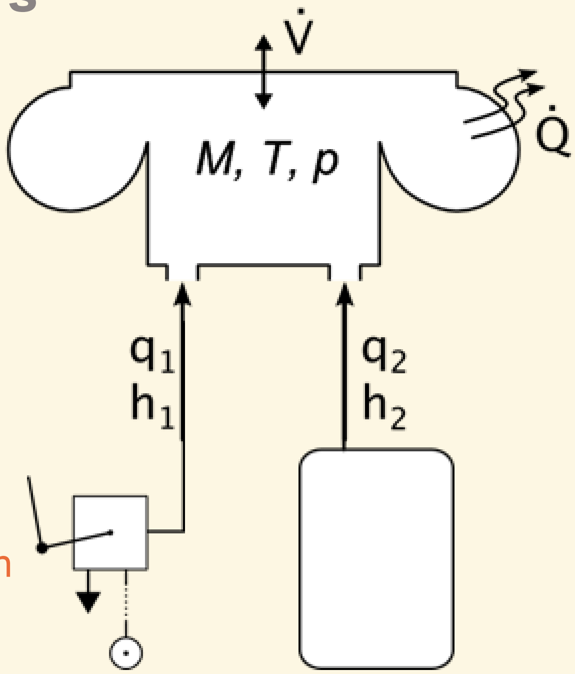
Entering enthalpy — Mass variation — Heat transfer — Volume variation

  - Perfect gaz equation ➔ pressure

$$p = \frac{MRT}{V}$$

➔ Easy to connect with other components

  - Bellows reaction force: $F = A_e(p_b - p_a)$



Component specific models

- **Bellow and tank: pneumatic chambers**
  - Continuity equation → mass variation

$$\dot{M} = \sum_i q_i$$

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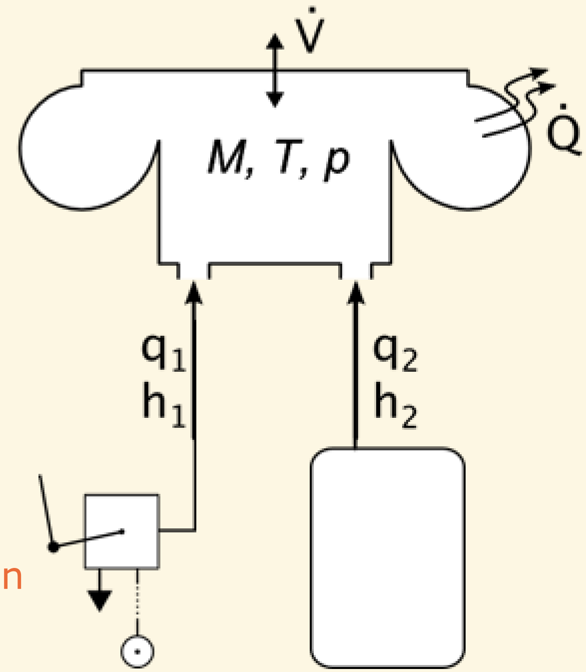
Entering enthalpy — Mass variation — Heat transfer — Volume variation

  - Perfect gas equation → pressure

$$p = MRT/V$$

→ Bellow reaction force: $F = A_e(p_b - p_a)$



- **Pipe**
  - Differential model $\dot{q} = f(p_1, p_2, q)$
  - Algebraic model $q = f(p_1, p_2)$

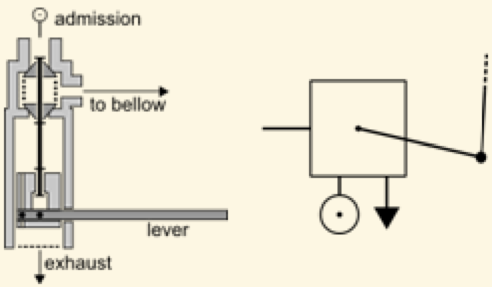
Incompressible flow case:

$$\dot{q} = \frac{A}{L}\left(\Delta p - \frac{1}{2\rho A^2}\left(\frac{\lambda L}{d} + \zeta\right) q^2 sign(q)\right)$$

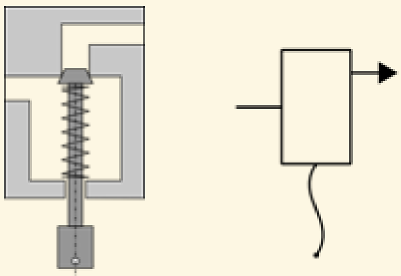
$$q = \sqrt{\frac{2\rho A^2}{\lambda L/d + \zeta}\left|\Delta p\right|}\, sign(\Delta p)$$

Valve modeling

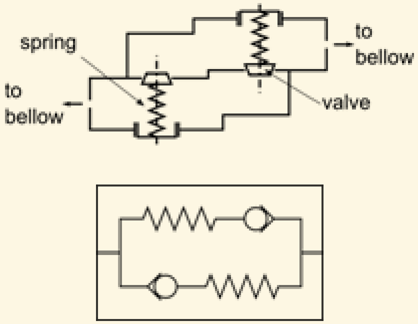
- **Levelling valve**



- **Safety valve**

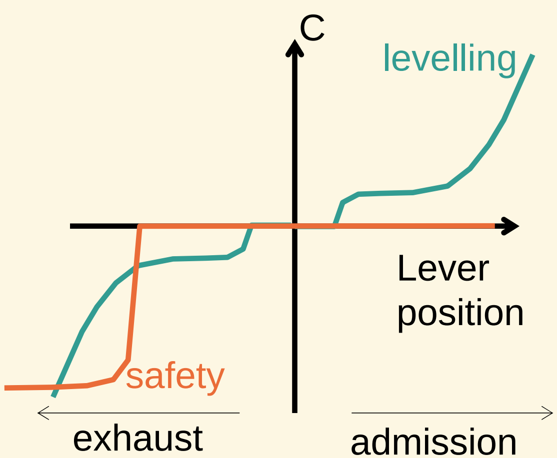


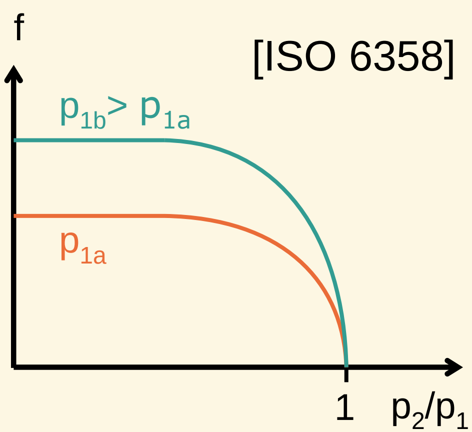
- **Differential valve**

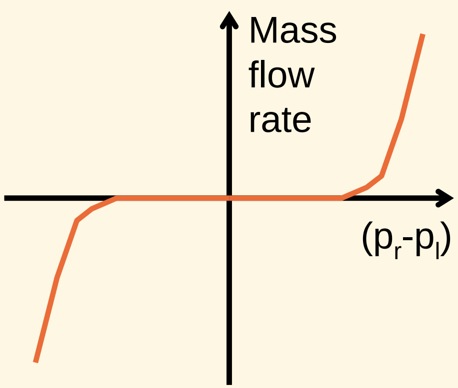


$$q = C(position) \cdot f(p_2, p_1)$$

$$q = f\ (p_r, p_l)$$

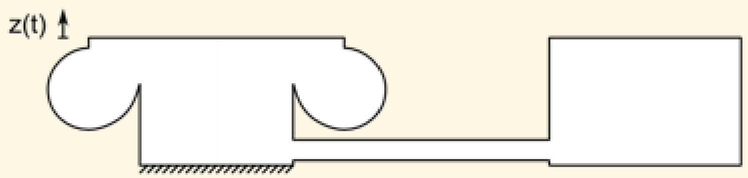


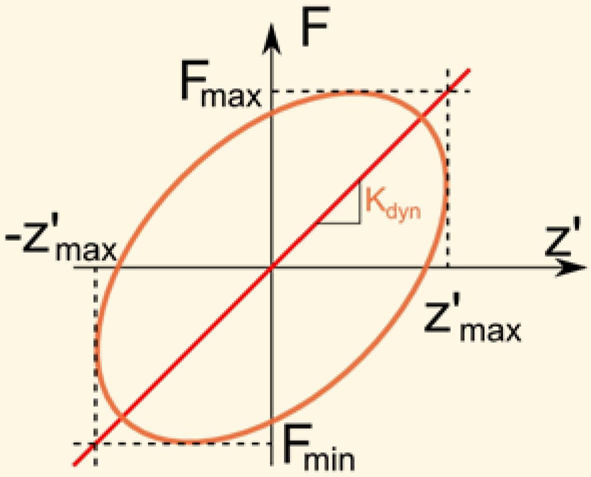




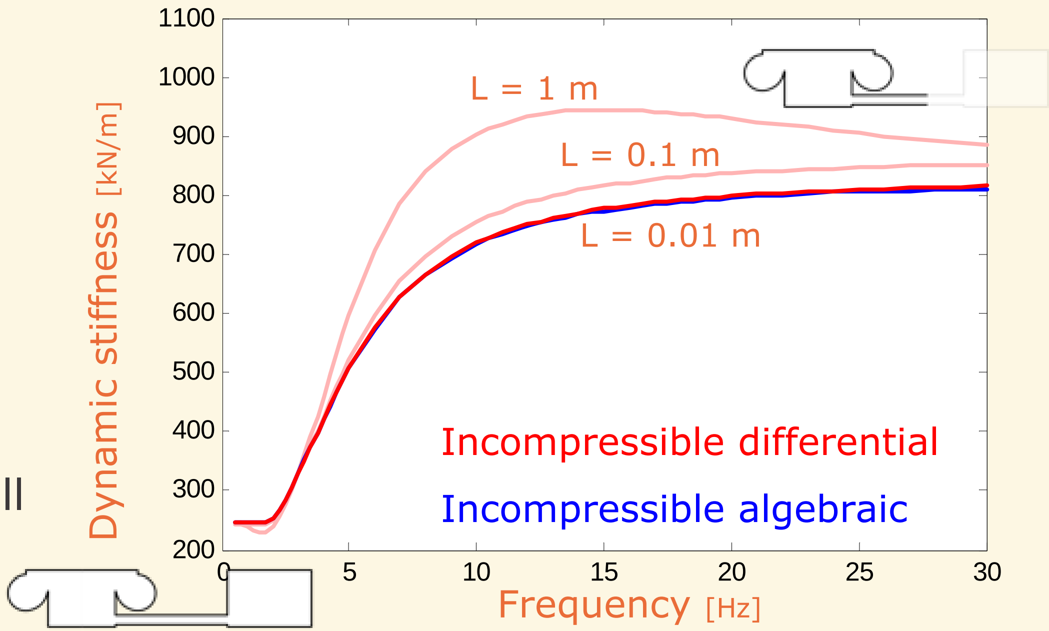
Frequency analysis

- **Dynamic stiffness analysis**
  - bellow-tank subsystem
  - displacement sinusoidal excitation





- Two constant levels
  - low frequencies: bellow and tank excitation
  - high frequencies: bellow excitation only
- Air mass inertia not taken into account by the algebraic model
- Inertia effects negligible for small pipe lengths



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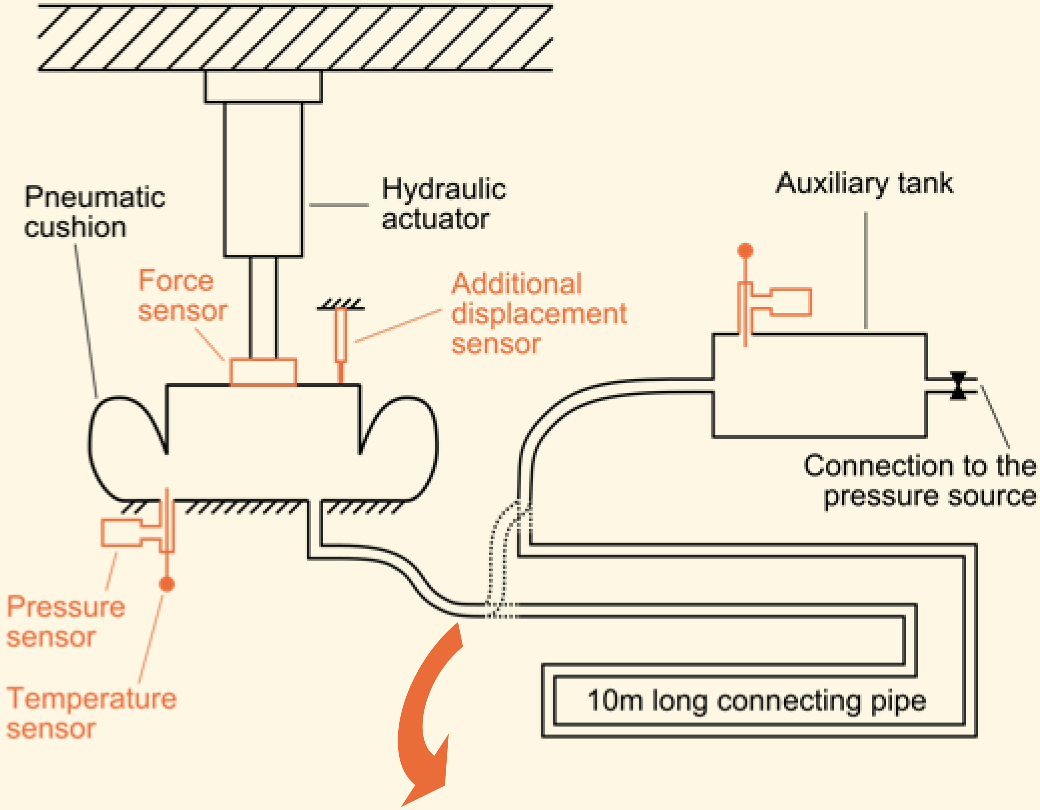
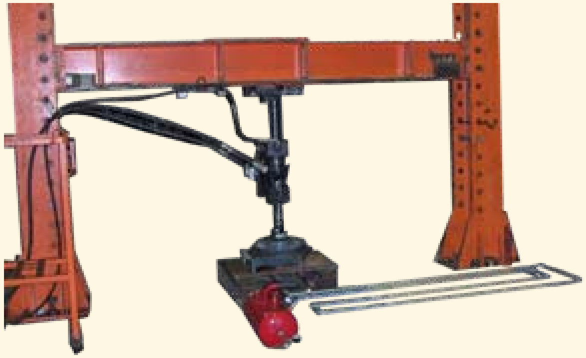
Experimental setup





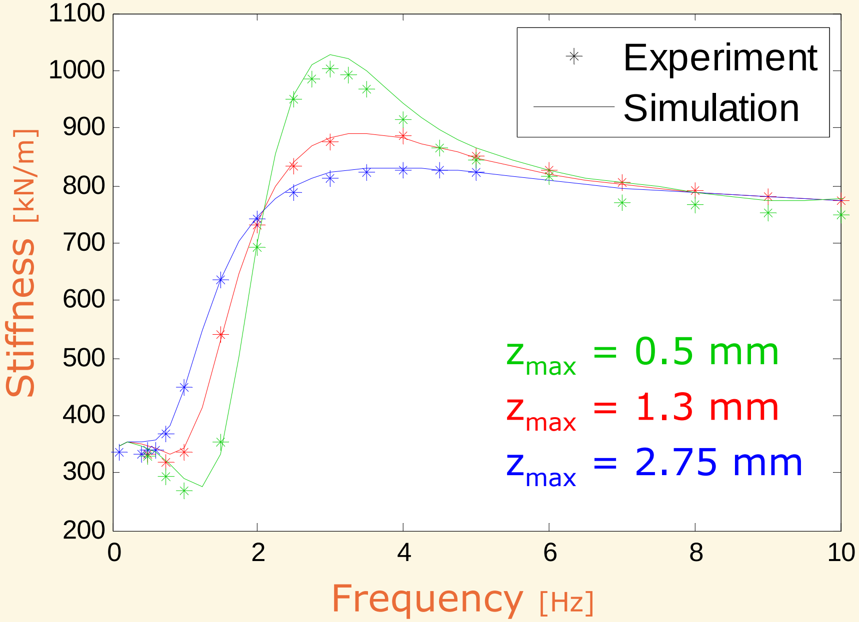
- Several pipe configurations

Collaboration with:

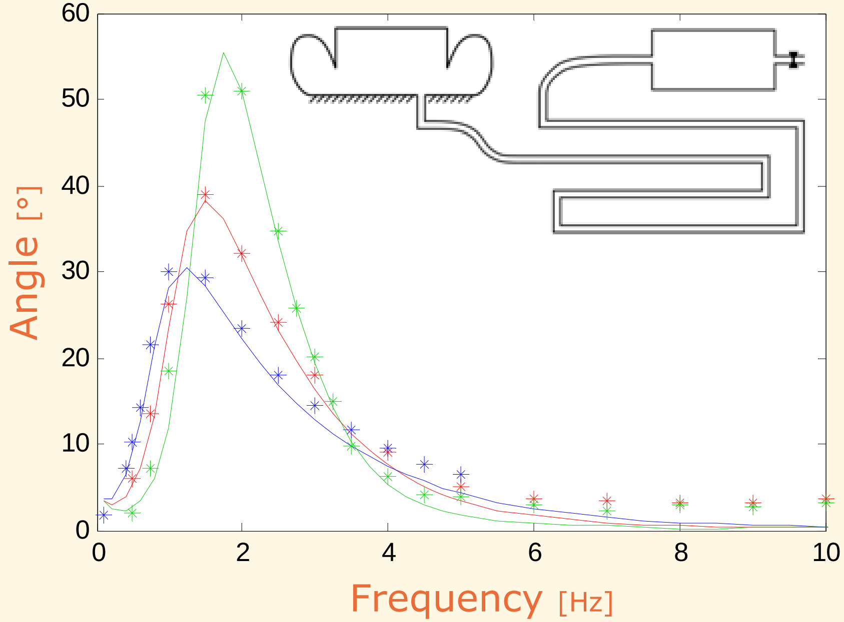
Laboratoire d'Essais Mécaniques, Structure et Génie Civil (LEMSC, UCL/iMMC)

Dynamic tests: Excitation amplitude

Dynamic stiffness

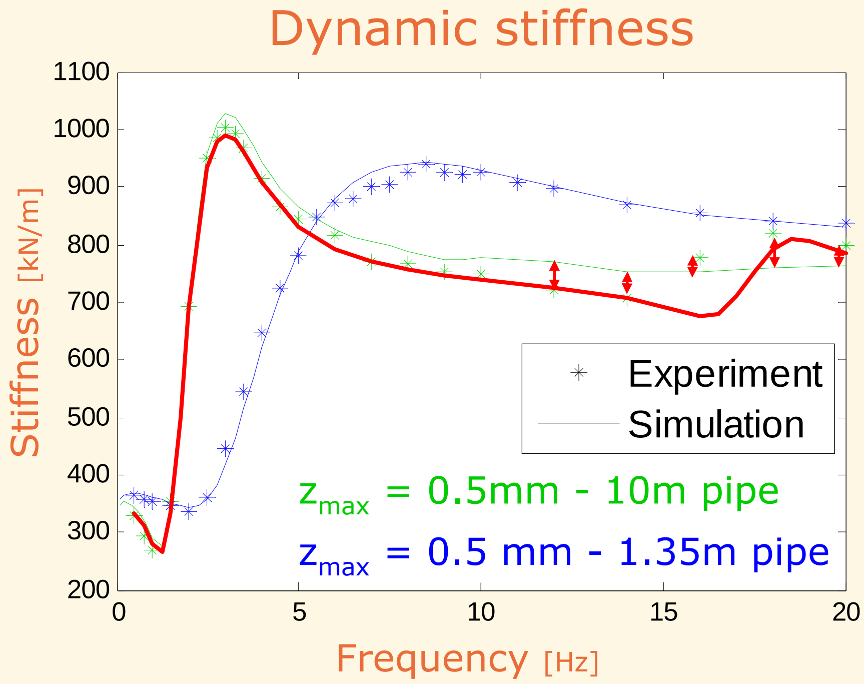


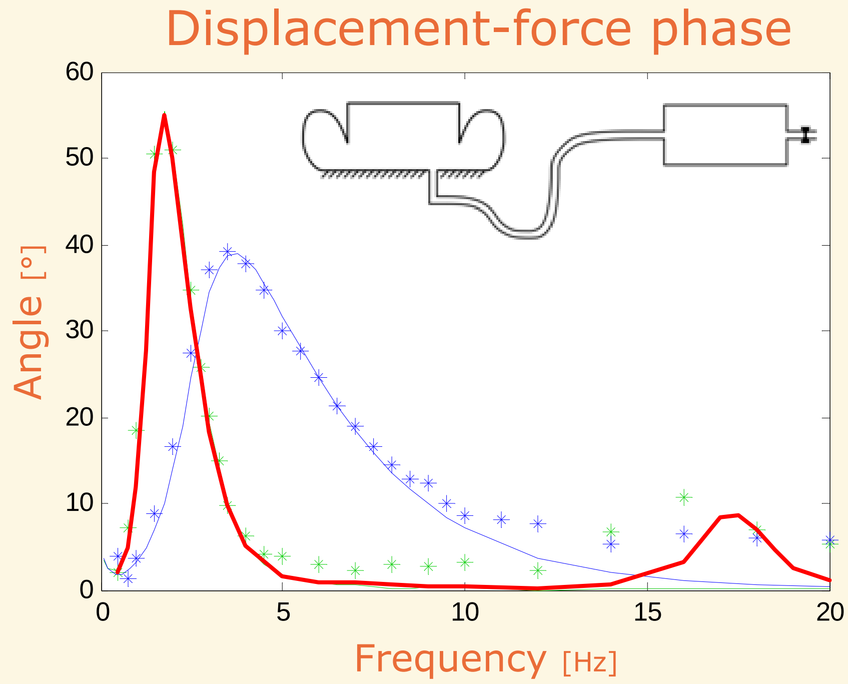
Displacement-force phase



- Incompressible differential model is suitable
- Pipe volume added to the bellows and to the tank volume
- Loss coefficient estimated for z_{max} = 1.3 mm
- Good match with experimental results for the 2 other amplitudes
- Phase error

Dynamic tests: Pipe length





- Pipe length ↘ ➡ Resonance frequency ↗
- Incompressible model is still suitable
- For higher frequency: 2^{nd} resonance effect ➡ Discretized model

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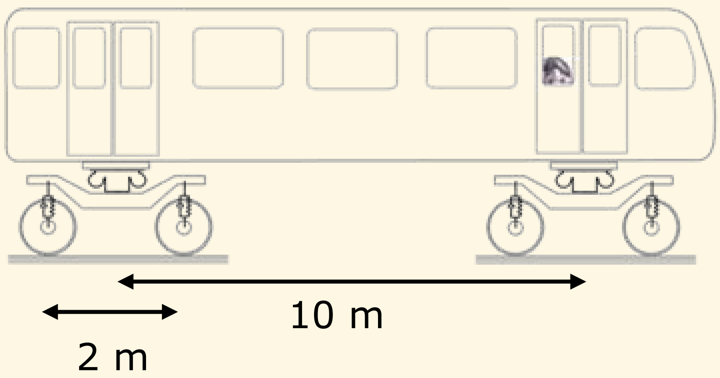
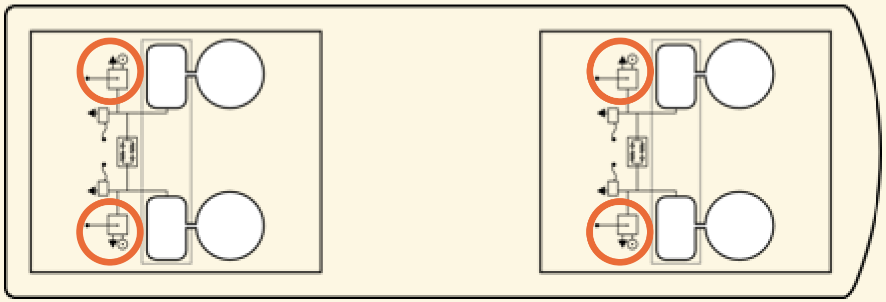
Application to a metro car

- **Vehicle main properties**
  - Carbody mass 17 tons
  - Bogie mass 3.5 tons
  - Bogie centre distance 10 m



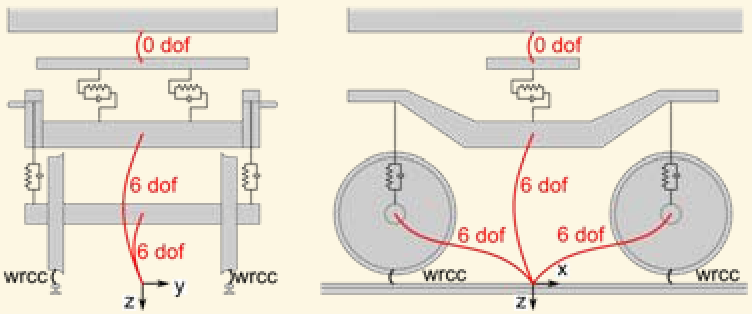
- **Modeling assumptions**
  - Perfectly rigid carbody
  - Rigid bogie frame

- **2^{nd} Suspension characteristics → full pneumatic**
  - 4-point configuration
  - No anti-roll bar
  - No hydraulic damper
  - Bellows directly connected to tanks
    ↳ no pipe



Hybrid simulation via co-simulation

- **Multibody (Newton-Euler)**



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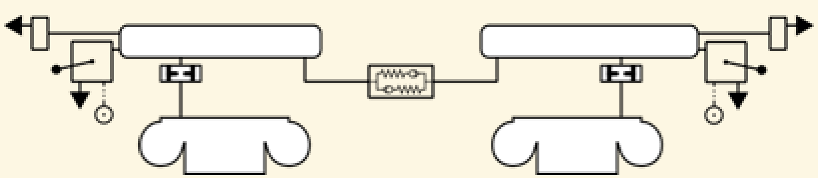
- **Pneumatics**



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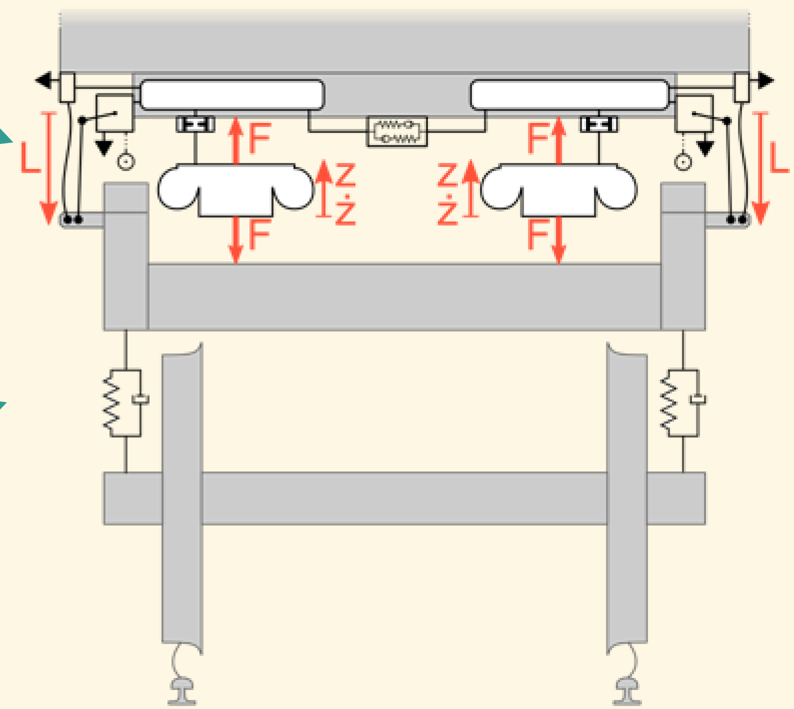
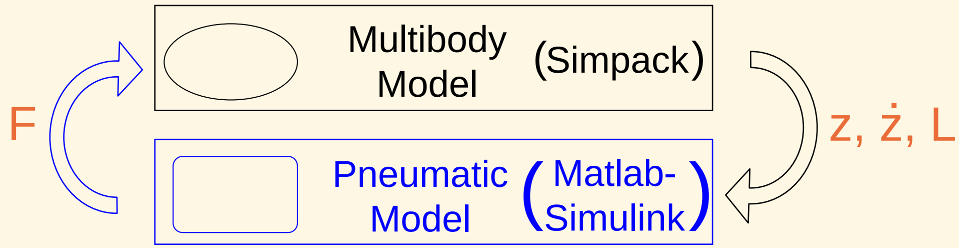
Hybrid model

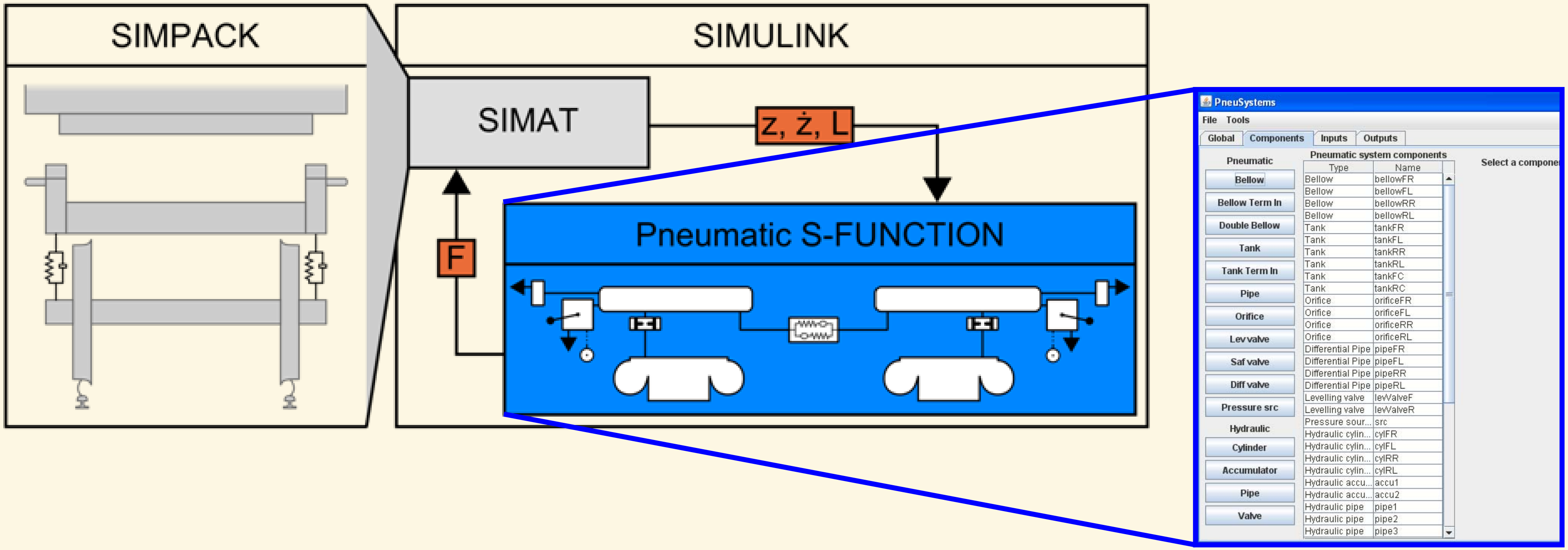


Hybrid Simulation by co-simulation

- **Co-Simulation**
  - 2 process integrated in parallel
  - Interaction at fixed time step

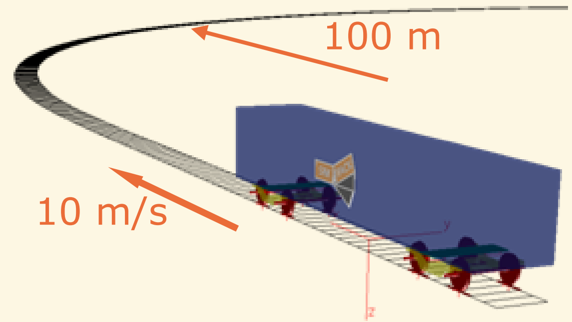


SIMULINK diagram

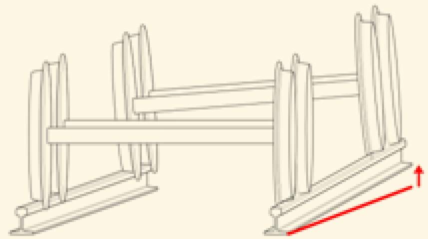


Various situations to be analysed

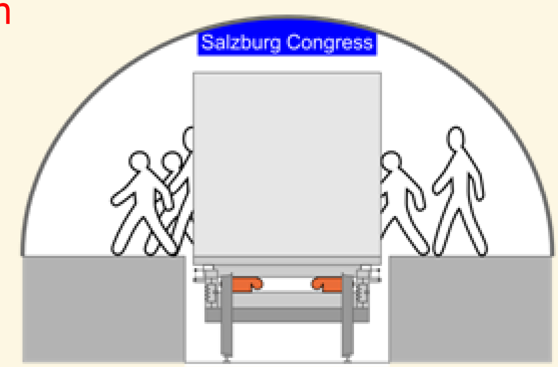
- Curve passing



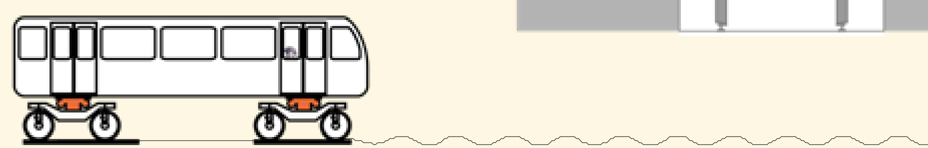
- Rail twist



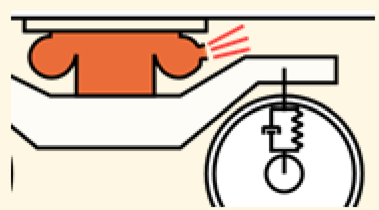
- Station loading / unloading



- Passanger comfort

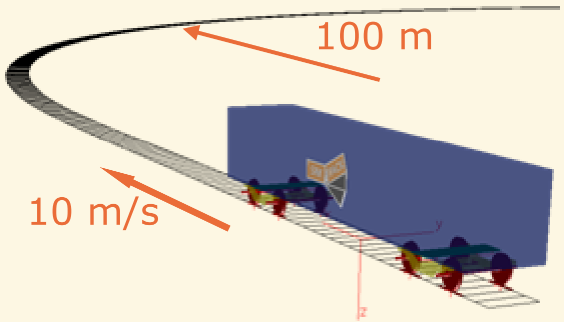


- Failure mode (leakage, …)

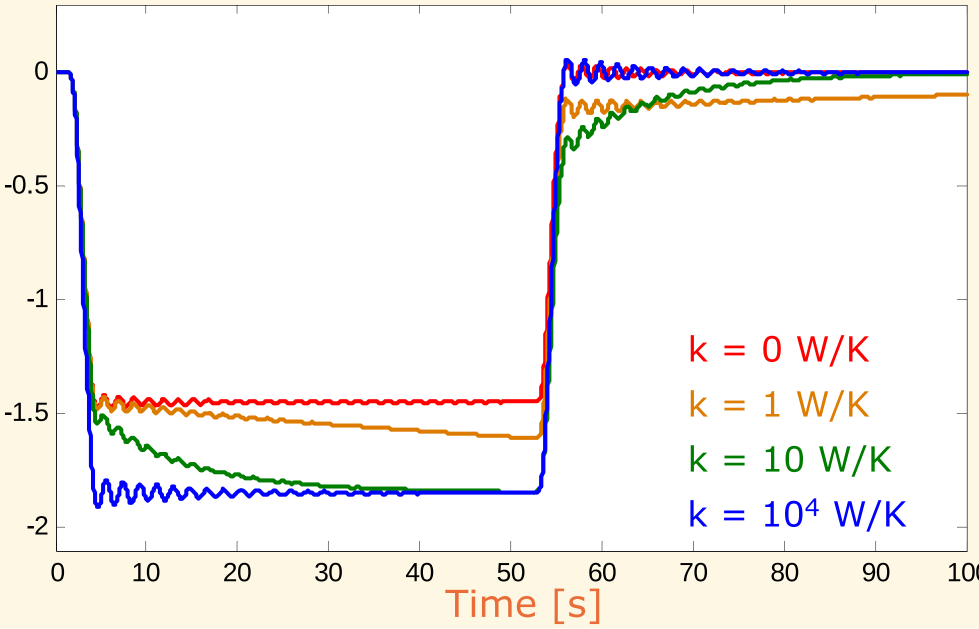


Influence of the heat transfer

- **Without valves**
  - k=0 W/K (adiabatic)
    - larger stiffness
      - smaller roll angle
  - $k=10^4$ W/K (≈isotherm)
    - smaller stiffness
      - larger roll angle
  - k=1 W/K … 10 W/K
    - close to the adiabatic case at first
    - tends toward the isotherm case after a longer time

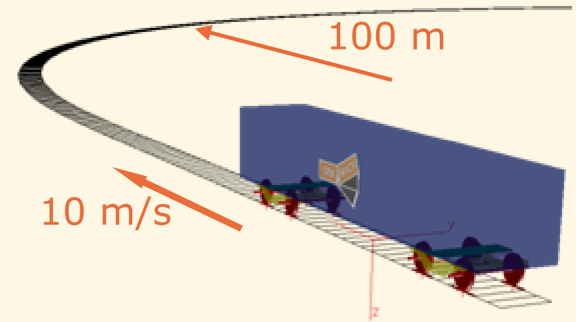


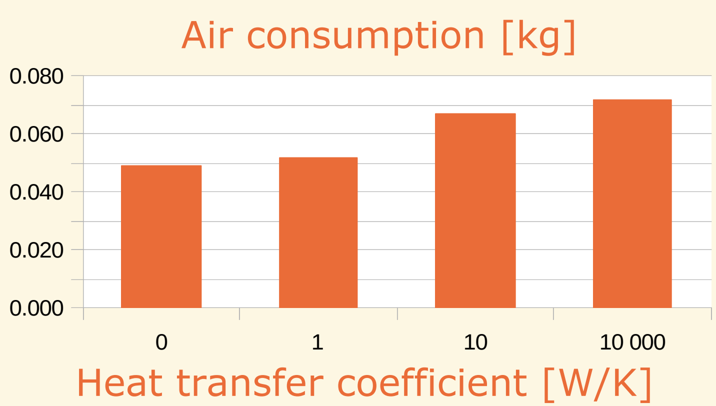
Carbody roll angle [°]

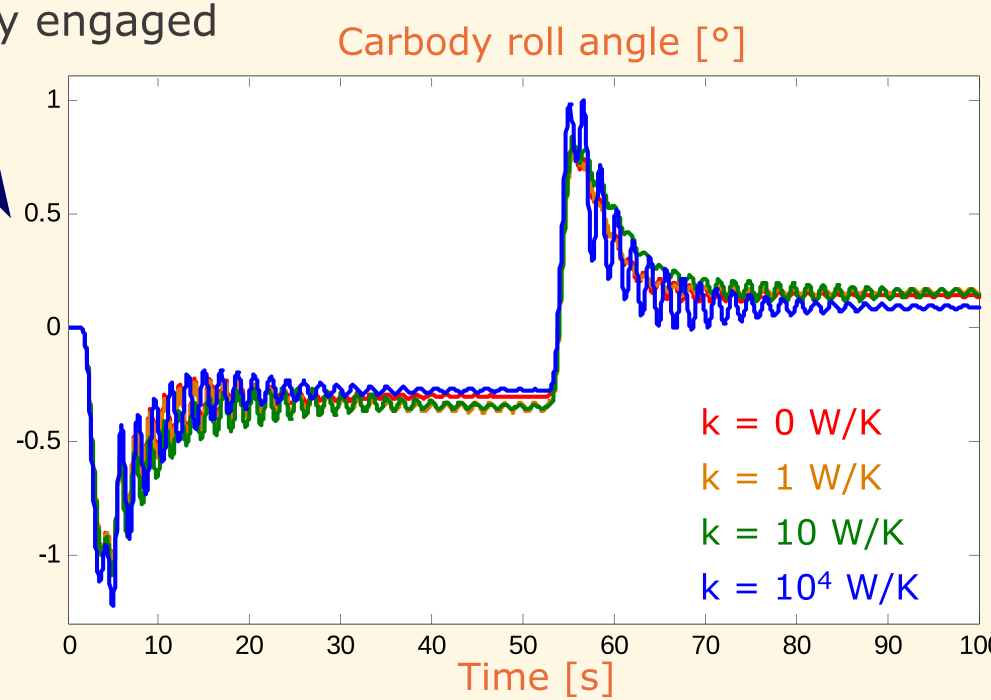


Influence of the heat transfer

- **Valves connected**
  - Levelling valves ➡ reduced roll angle
  - Levelling action
    - ↳ less influence of heat transfer
  - Intermediate k values
    - ↳ temperature and stiffness progressively decrease
      - ↳ levelling valve periodically engaged
        - ↳ 0.1° oscillations
  - k ↗ ➡ air consumption ↗

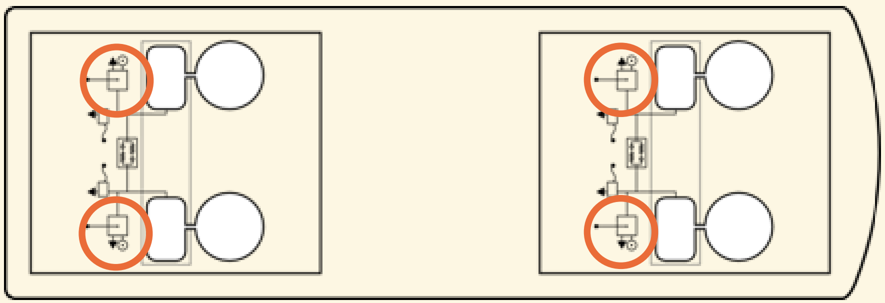


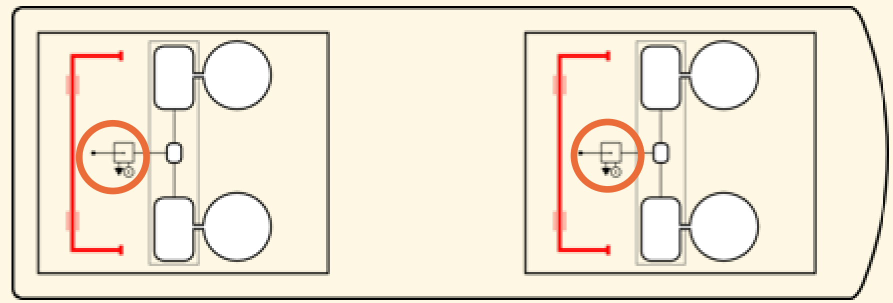




Configurations comparison

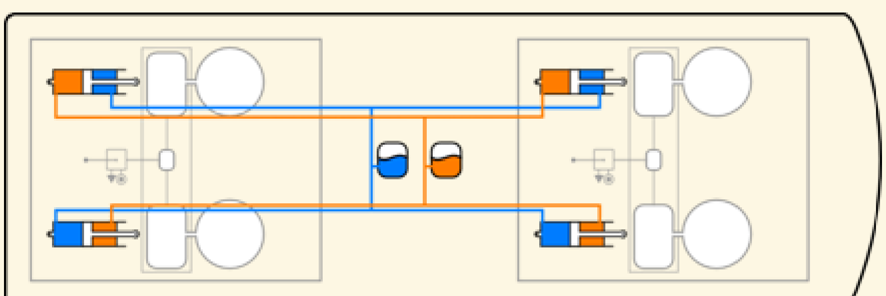
- **Classical configurations**
  - 4-point suspension
  - 2-point suspension + classical anti-roll bar



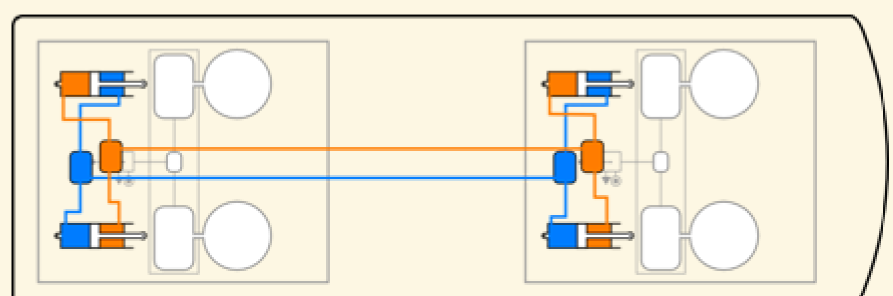


- **Novel configurations**
  - 2-point suspension + Kinetic H2 anti-roll system

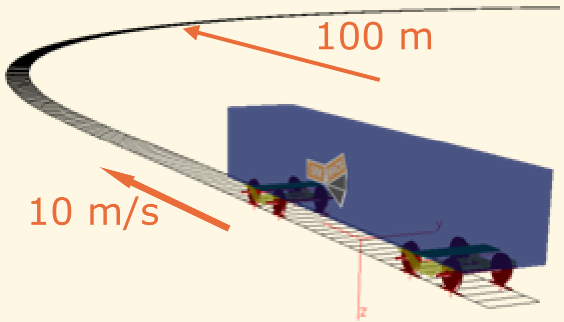
Hydraulic version



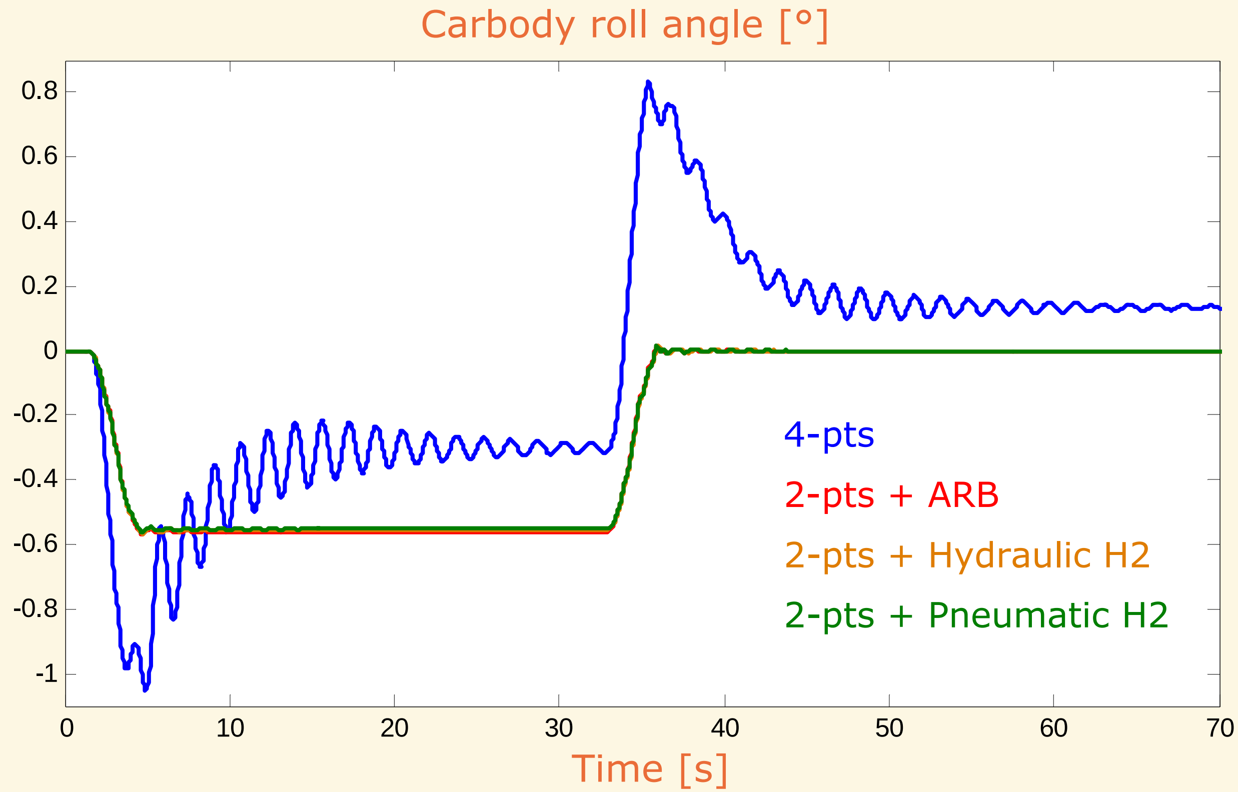
Pneumatic version



Curve entry

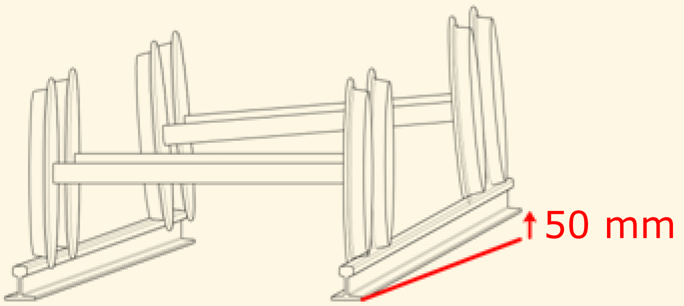


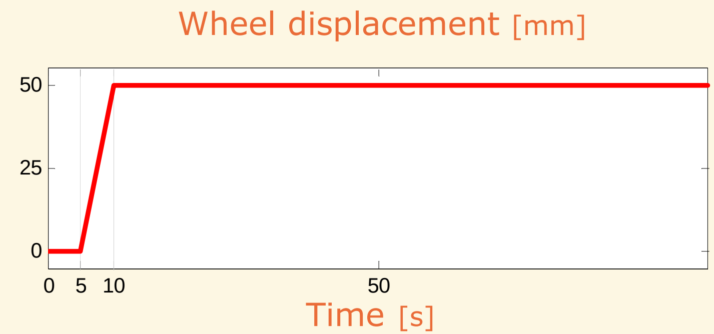
- Anti-roll bar and H2 systems:
  - set so as to obtain a comparable roll angle as for the 4-point case

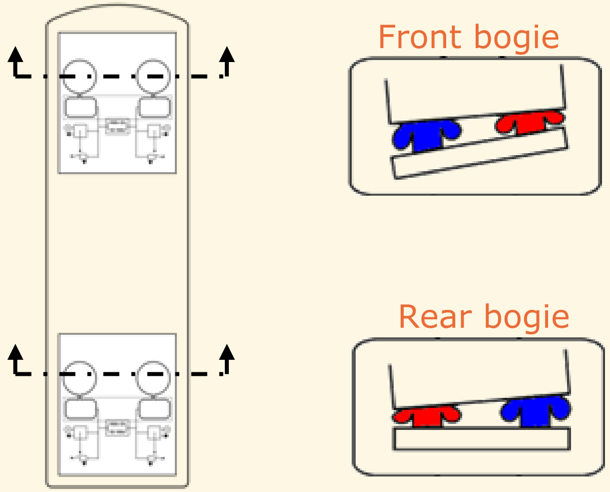


ΔQ/Q test

- **Rail twist excitation**
  - Measurement of the wheel/rail force vertical component variations
  - Stationary vehicle
  - Wheelset motion imposed
    ➔ no wheel/rail contact calculation
  - Wheel displacement: 50 mm
- **Secondary suspension reaction**
  - Crushed diagonal
  - Extended diagonal

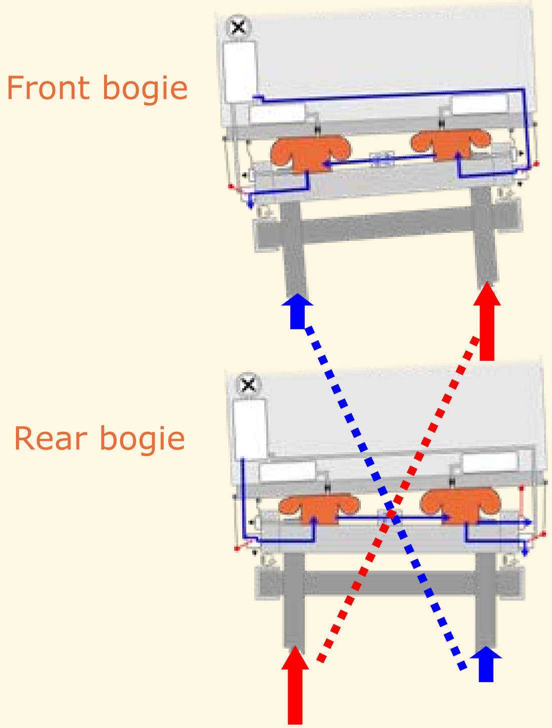




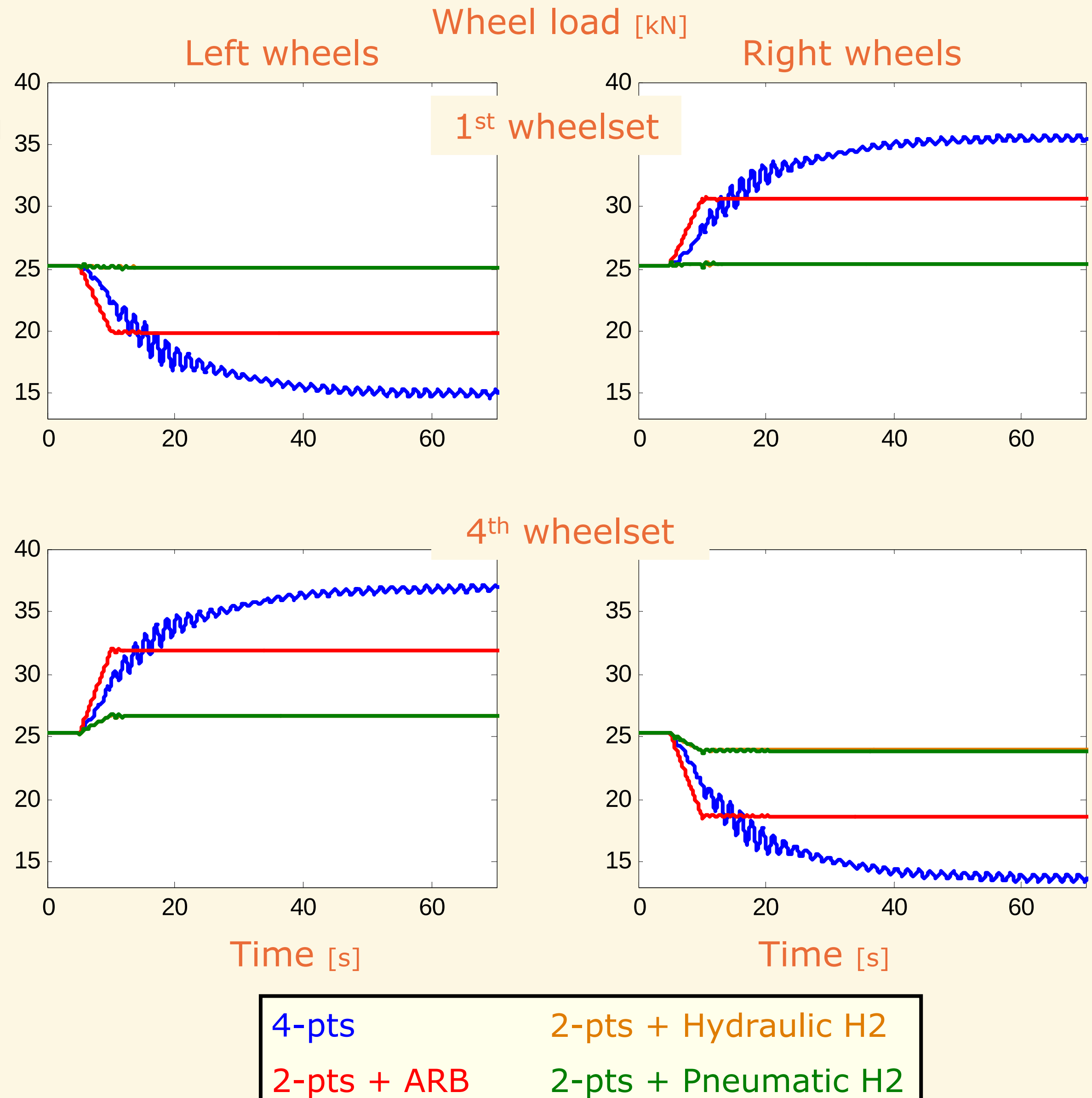


ΔQ/Q: wheel load variations

- For the 4-point suspension
  - Increased wheel unloading due to the leveling system



- For H2 systems:
  - Small unloading
  - Possibility of increased roll stiffness



Contents

Conclusion

- **Industrial demand** ⟷ **Scientific approach**

  Pneumatic suspension analysis ⟷ Advanced modeling techniques

- **Model comparison**
  - Suspension design and morphology → Choice of the model
- **Experimental analysis**
  - Heat transfer assessment
  - Model validation
- **Generic tool for suspensions**
  - Analyses of multibody-pneumatic interactions in complex situations
  - Comparison of various configurations
  - Investigation for new pneumatic circuit morphologies

Prospects

- **Multiphysics modeling**
  - For systems with higher dynamics
    - Investigation of pressure wave effects
    - Refinement of valves modeling
    - Influence of multibody coupling techniques → strong coupling?
- **Railway pneumatic suspension**
  - How to avoid many experimental tests for determining model parameters?
  - Use the developed models in a mechatronics approach within an industrial framework
    - Detect earlier unexpected behaviour
    - Optimization of existing suspension configurations
    - Investigation of novel configurations

Conclusion

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