



Field Path Detection for Tractors Based on Virtual Iteration in Time Domain



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Motivation: Reliable Input Data for FE-Analysis

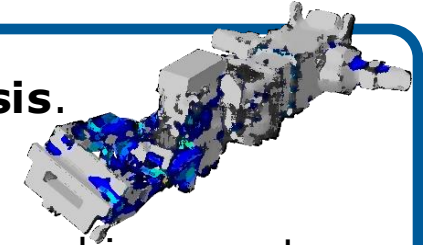
Accurate load case definition: Essential for FEA and mechanical fatigue analysis.

Required FEA-input data: Accelerations, wheel hub forces, etc.

Common source: Estimated on basis of experience → old fashioned and inaccurate.

Improved method: Use wheel hub forces as input data for **VMBS** (Vehicle Multibody System) simulation → Accurate input data for subsequent **FEA**.

At first glimpse this method seems to be clear and simple, or perhaps not?



Methods: Definition of VMBS Input Data

Wheel hub forces:

From measurements on similar, existing vehicle with measurement rim

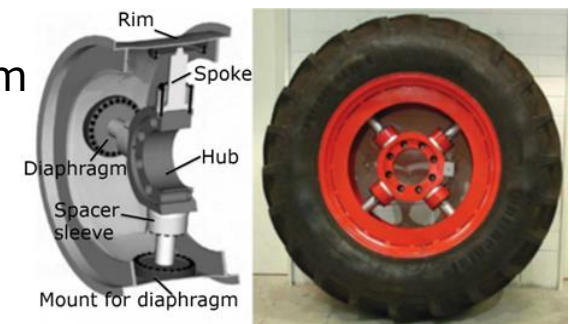
Disadvantage: Expensive and time-intensive,

Useable for only one tractor parameter set 🙅

Field path profile:

Field path profile input for VMBS simulation → wheel hub forces.

Advantage: Independent from tractor parameter set (different tractors can be simulated with or w/o implements, ballast mass, front loader, etc.) → **cost efficient** 👍



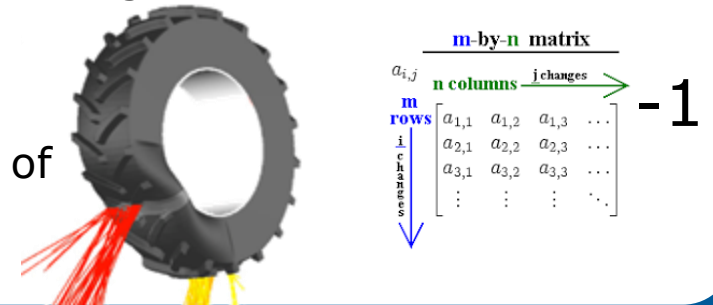
→ **Method for field path detection to be developed**

Method: Dynamic Inversion

Target and Challenges

- It is not highest priority that detected profiles are exactly identical with original ones in the field, which is not possible, anyway.
- Aim is that acceleration results achieved with identified profiles match very well with measured accelerations in the field.

- **Prerequisites: Accurate, refined vehicle multibody system simulation model with highly sophisticated tire model (FTire) → ECS Simulation Conference 2023.**
- **Complex nonlinear tractor** model in ADAMS replicates dynamic behavior of real tractor very **precisely**. However, complexity and non-linearity of systems means a challenge in view of inversion.
- Multiple contact areas at obstacles with sharp edges challenge inversion algorithm in addition, bijectivity is violated.
- Comparative simulations proved that **reasonable reduction** of degrees of freedoms (e.g.: cabin rigidly fixed to the tractor body) has negligible influence on the accelerations near the wheel hubs.



Simplified model is necessary for dynamic inversion

Simplified Model Without Tires

Reduced number of degrees of freedom:

- Cabin or hinges rigidly fixed to body, etc.

Degrees of freedom

Chassis assumed to be rigid body (proved by frequency check)

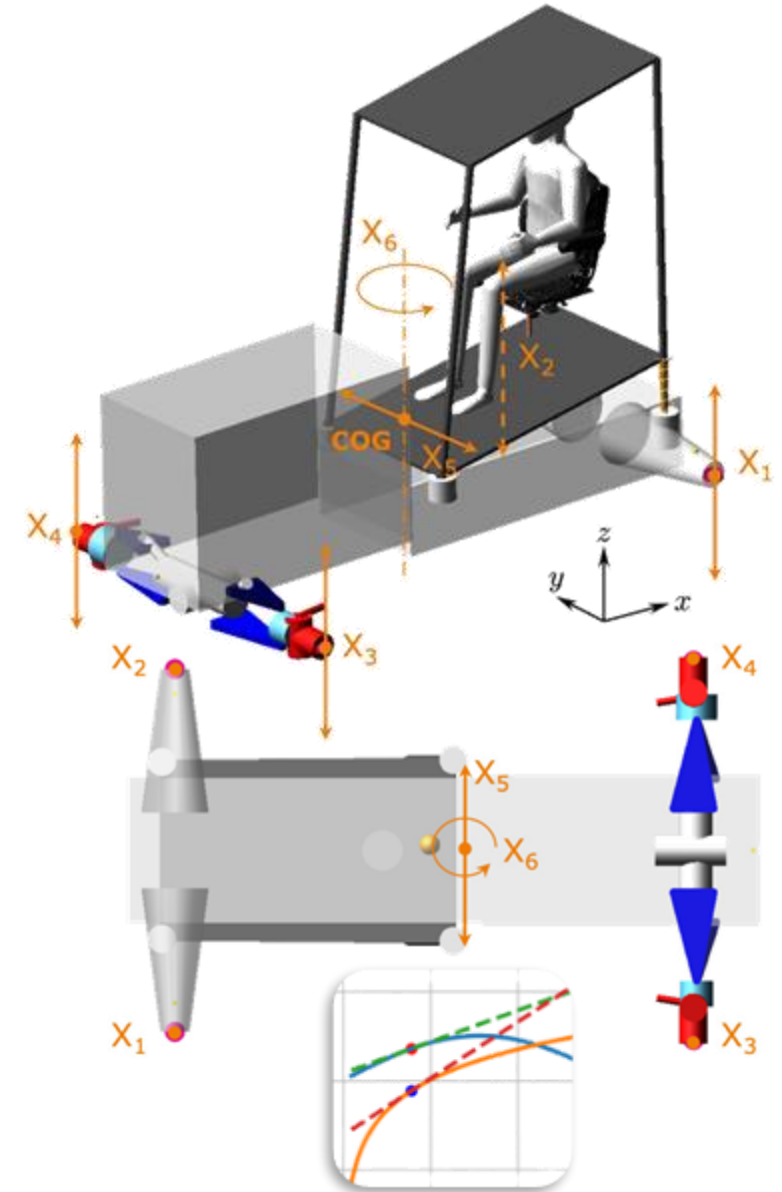
Chassis in longitudinal x-direction fixed!

- 1) Movement of chassis in lateral y-direction
- 2) Movement of chassis in vertical z-direction
- 3) Rot. of chassis about longitudinal x-axis
- 4) Rot. of chassis about lateral y-axis
- 5) Rot. of chassis about vertical z-axis
- 6) Rot. of front axle about longitudinal axis of chassis

DOF transformed to the six state variables of $X_1, X_2, X_3, X_4, X_5, X_6$ (as seen right).

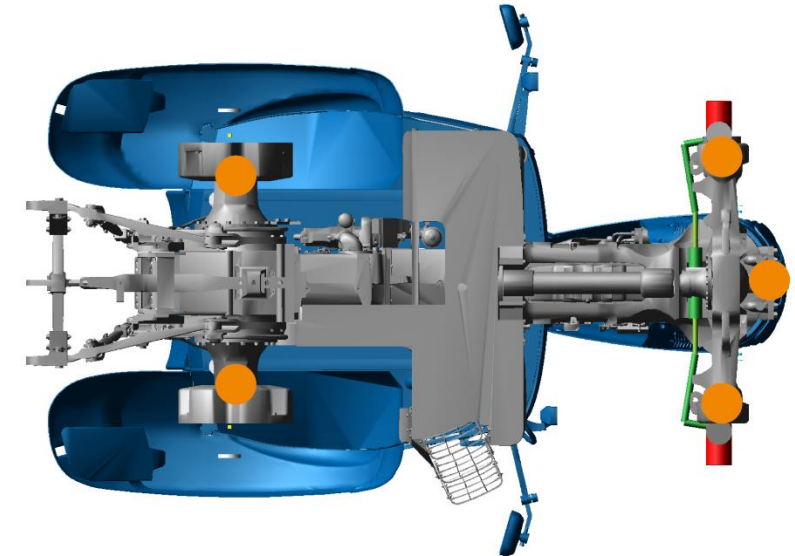
Linearization around equilibrium point

→ **Linear Time Invariant (LTI) System**



Sensor Positions

- **Four** sensor locations from nonlinear model are selected. (Sensor in the middle of the front axle is used for verifying the measurement results achieved by the left and right sensor.)
 - Sensors measure **accelerations** in x -, y - and z -direction.
 - Without loss of generality, sensor positions virtually shifted to **wheel center points**.
- ➔ Coordinate **transformation** is needed.
- This transformation reduces potential error sources during development, because movement of the wheel center points is integral to the identification process.
- System comprises six degrees of freedom and **six input parameters**:
 - four vertical forces and
 - two lateral forces (one lateral force per axle).



● Sensor positions

Mathematical Framework

LTI System $\mathbf{M}\ddot{\vec{s}} + \mathbf{D}\dot{\vec{s}} + \mathbf{K}\vec{s} = \vec{f}$.

q	number of degrees of freedom	$\mathbf{M} \in \mathbb{R}^q \times \mathbb{R}^q$	mass matrix
$\vec{s} \in \mathbb{R}^q$	generalized displacement vector	$\mathbf{D} \in \mathbb{R}^q \times \mathbb{R}^q$	damping matrix
$\dot{\vec{s}} \in \mathbb{R}^q$	generalized velocity vector	$\mathbf{K} \in \mathbb{R}^q \times \mathbb{R}^q$	stiffness matrix
$\ddot{\vec{s}} \in \mathbb{R}^q$	generalized acceleration vector	$\vec{f} \in \mathbb{R}^q$	external forces vector.

With $\dot{\vec{s}} = \vec{v}$, $\mathbf{M}^{-1}\vec{f} = \widehat{\mathbf{B}}\vec{u}$

$$\begin{bmatrix} \dot{\vec{s}} \\ \vec{v} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & \mathbf{E} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{D} \end{bmatrix}}_{\mathbf{A}} \begin{bmatrix} \vec{s} \\ \vec{v} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \widehat{\mathbf{B}} \end{bmatrix}}_{\mathbf{B}} \vec{u}.$$

1st order

With **state** vector $\vec{x}^T = [\vec{s}^T, \vec{v}^T]$, **input** variable $\vec{u}$ (wheel hub forces), and **output** variable $\vec{y}$ (sensor signals)

$$\dot{\vec{x}} = \mathbf{A}\vec{x} + \mathbf{B}\vec{u} \quad \text{with} \quad \vec{y} = \mathbf{C}\vec{x} + \mathbf{D}_T\vec{u}.$$

Without loss of generality: **C=E**

$\mathbf{A} \in \mathbb{R}^n \times \mathbb{R}^n$ system matrix

$\mathbf{C} \in \mathbb{R}^k \times \mathbb{R}^n$

output matrix

$\mathbf{B} \in \mathbb{R}^n \times \mathbb{R}^m$ input matrix

$\mathbf{D}_T \in \mathbb{R}^k \times \mathbb{R}^m$

direct transmission matrix.

Sensor locations =
wheel center points

Matrices obtained from Adams

Inversion

Direct transmission matrix $\mathbf{D}_T = \mathbf{0} \rightarrow$ output vector $\vec{y} = \mathbf{C}\vec{x}$

$$\dot{\vec{x}} = \mathbf{A}\vec{x} + \mathbf{B}\vec{u}$$

$$\dot{\vec{y}} = \mathbf{C}\mathbf{A}\vec{x} + \mathbf{C}\mathbf{B}\vec{u}$$

non-square $\mathbf{C}\mathbf{B}$ $k \times m$ – matrices

$$\vec{u} = (\mathbf{C}\mathbf{B})^{-1} \cdot [\dot{\vec{y}} - \mathbf{C}\mathbf{A}\mathbf{C}^{-1}\vec{y}]$$

$$\vec{u} = (\mathbf{C}\mathbf{B})^+ \cdot [\dot{\vec{y}} - \mathbf{C}\mathbf{A}\mathbf{C}^{-1}\vec{y}]$$

so-called Moore–Penrose pseudo-inverse:

$$(\mathbf{C}\mathbf{B})^+ = \underbrace{[\mathbf{B}^T \mathbf{C}^T \mathbf{C}\mathbf{B}]^{-1} \mathbf{B}^T \mathbf{C}^T}_{\mathbf{S}}$$

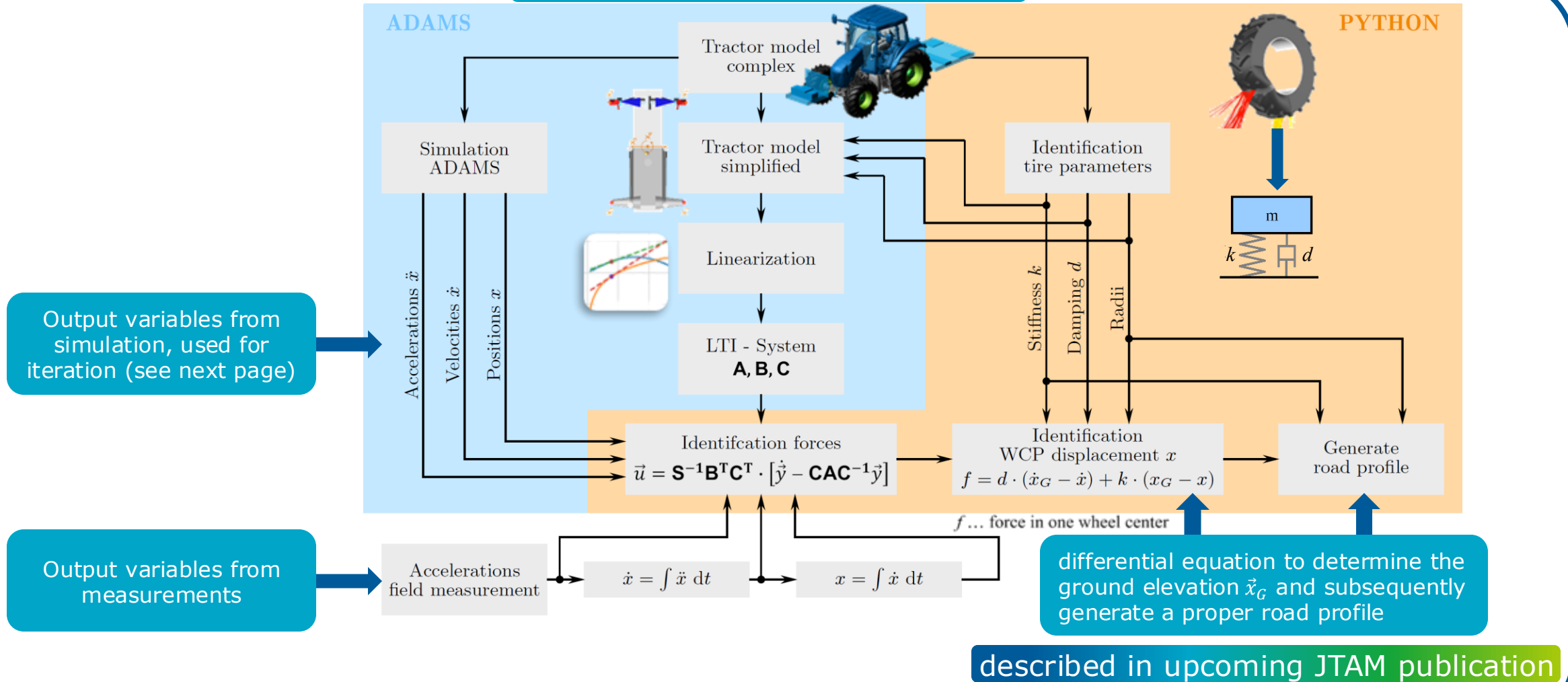
$$\vec{u} = \mathbf{S}^{-1} \mathbf{B}^T \mathbf{C}^T \cdot [\dot{\vec{y}} - \mathbf{C}\mathbf{A}\mathbf{C}^{-1}\vec{y}]$$

Condition for invertible matrix $\mathbf{S}$:
 $\rightarrow$ matrix $\mathbf{C}$ to be regular

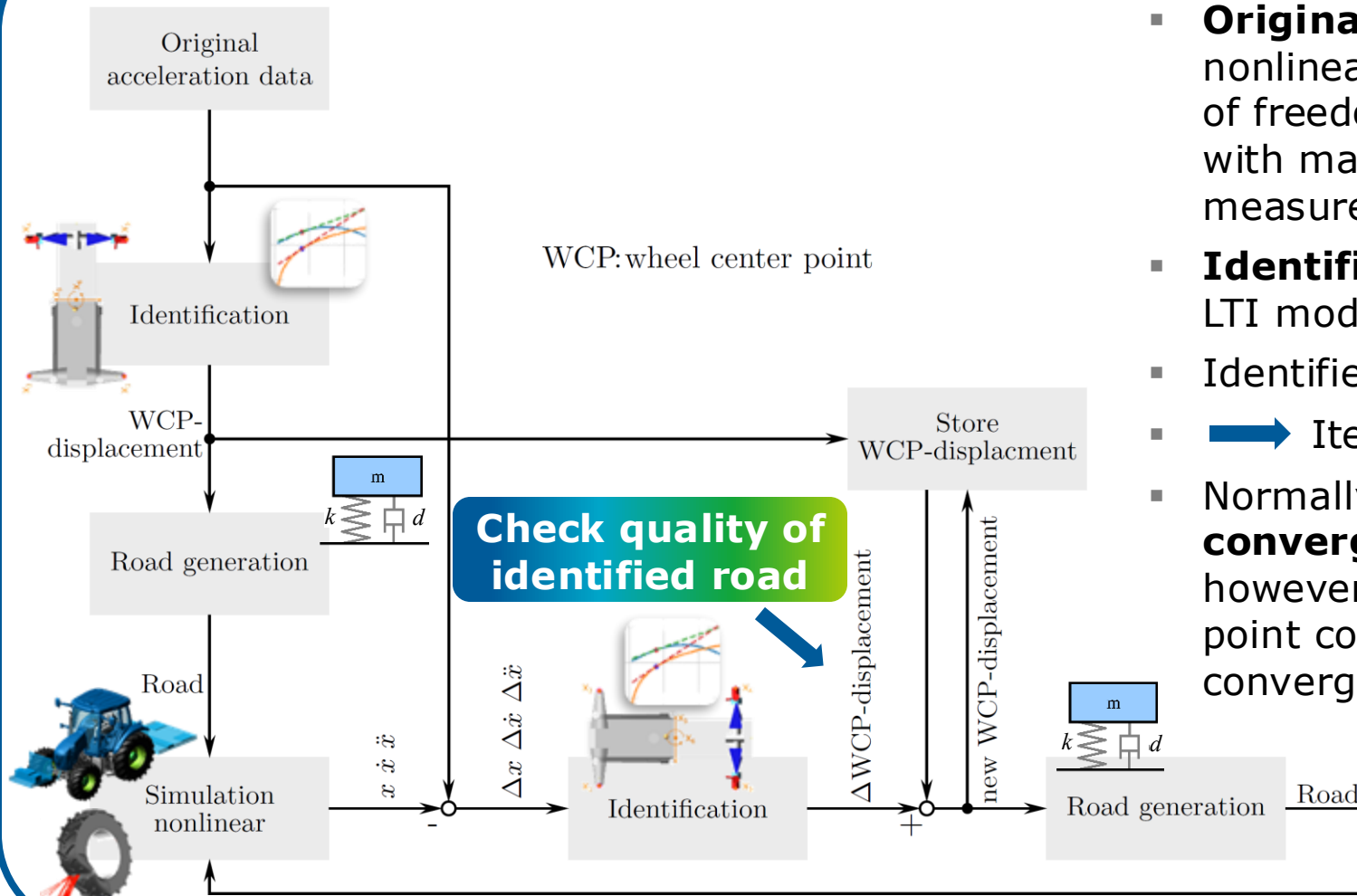
**Input vector (wheel hub forces)
as a function of output vector
(sensor signals)**

- Elimination of frequency domain transformations, $(\mathbf{C}\mathbf{B})^{-1}$ or $\mathbf{S}$ requires only **one single inversion**
- Second derivation of positions $\ddot{\vec{y}}$ measurable
 $\rightarrow$ **Signal integration** to obtain $\dot{\vec{y}}$ and $\vec{y}$ (stable process)

Identification Algorithm



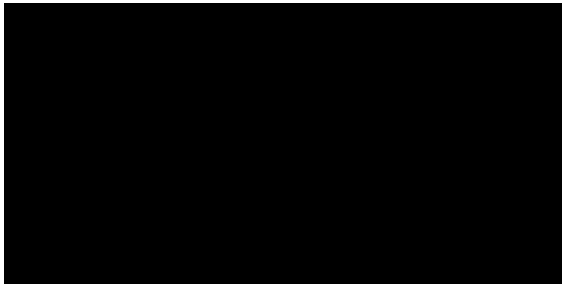
Iteration Process for Road Identification



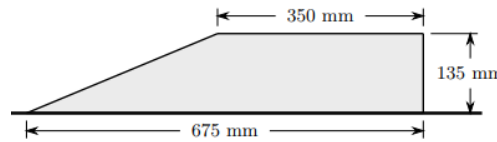
- **Original accelerations** refer to complex, nonlinear model (high no. of degrees of freedom, high sophisticated FTire model with many degrees of freedom) or measurements
- **Identification** is carried out with simplified LTI model.
- Identified **profile deviates** from original one.
- ➡ Iteration process to be developed.
- Normally, identified solution exhibits **convergence** against original profile, however, it **cannot be warranted** (multi-point contacts, lift-off, etc.). Therefore, convergence to be checked with a keen eye.

Validation on Known Path Profile, Example 1

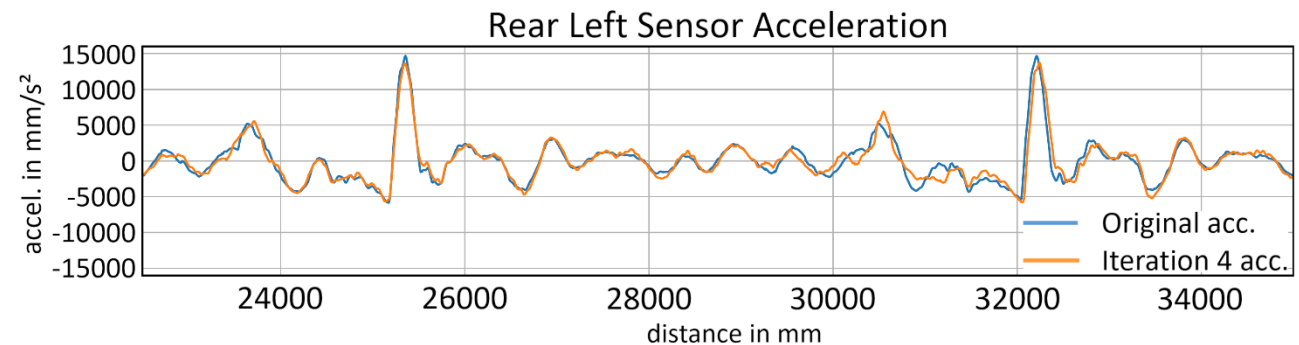
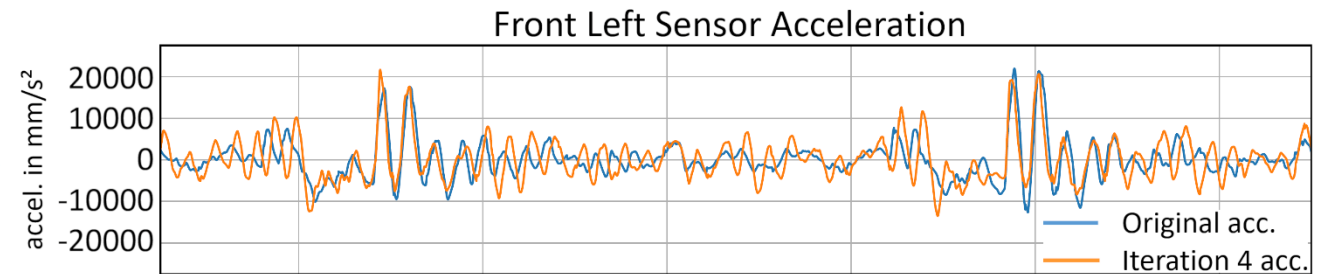
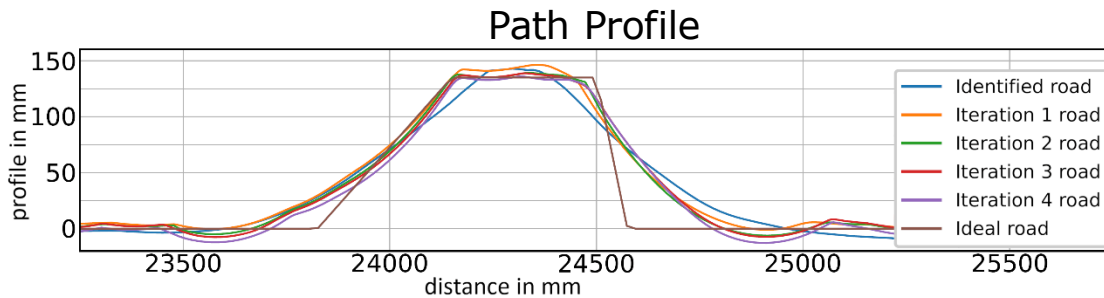
- Merry-Go-Round test (MGR): Tractor durability test procedure with periodical excitations
- Based on accelerations measured close to wheel hub centers, obstacle shape has been identified.



Merry-Go-Round test



Obstacle in detail



Iterated profile does not match original one exactly. ➡ However, accelerations achieved with identified profile correspond very well with measured ones.

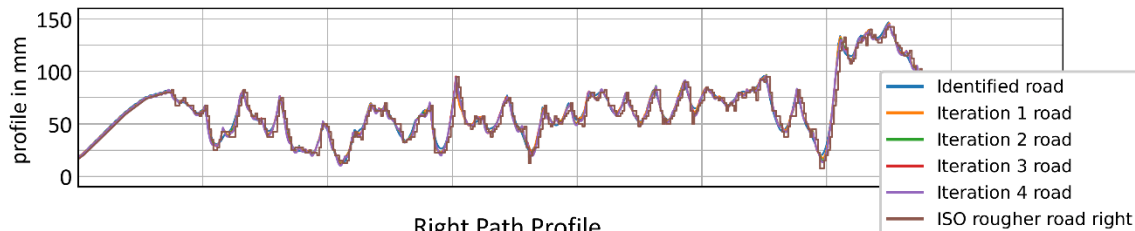
➡ Important for strength and mechanical fatigue.

Validation on Known Path Profile, Example 2

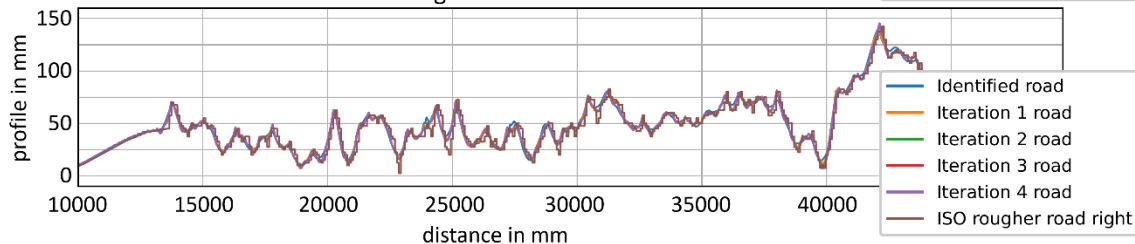
- Track: ISO 5008 rougher road course, Holperbahn-35 (jolting path ↔ "Sturzacker").
- ISO 5008 profile comprises sharp edges and corners.
➡ Challenge for inversion algorithm (multiple-surface contacts between tire and ground).
- Exact geometric match of road profile is not ultimate objective.
- Goal: Accelerations with identified profile **resemble original accelerations**. **Goal met!**



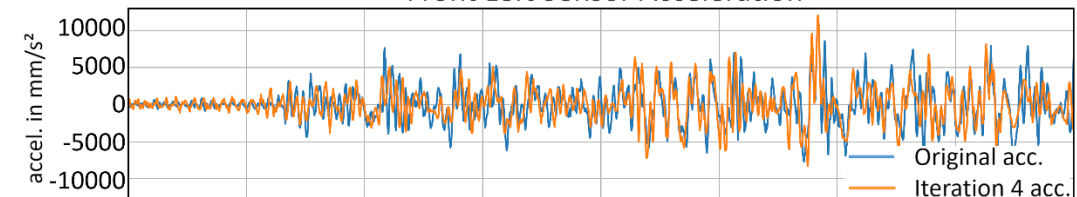
Left Path Profile



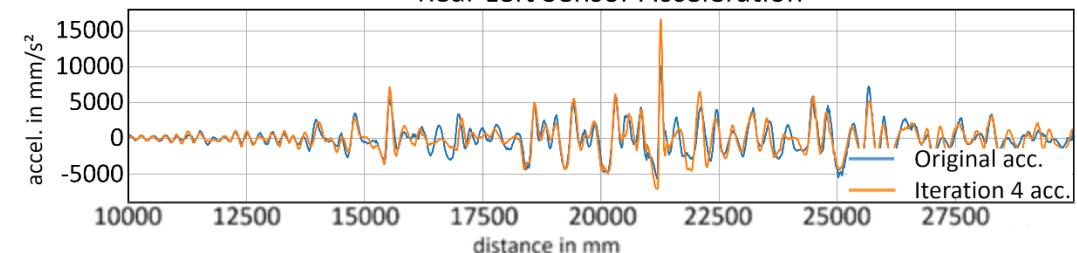
Right Path Profile



Front Left Sensor Acceleration

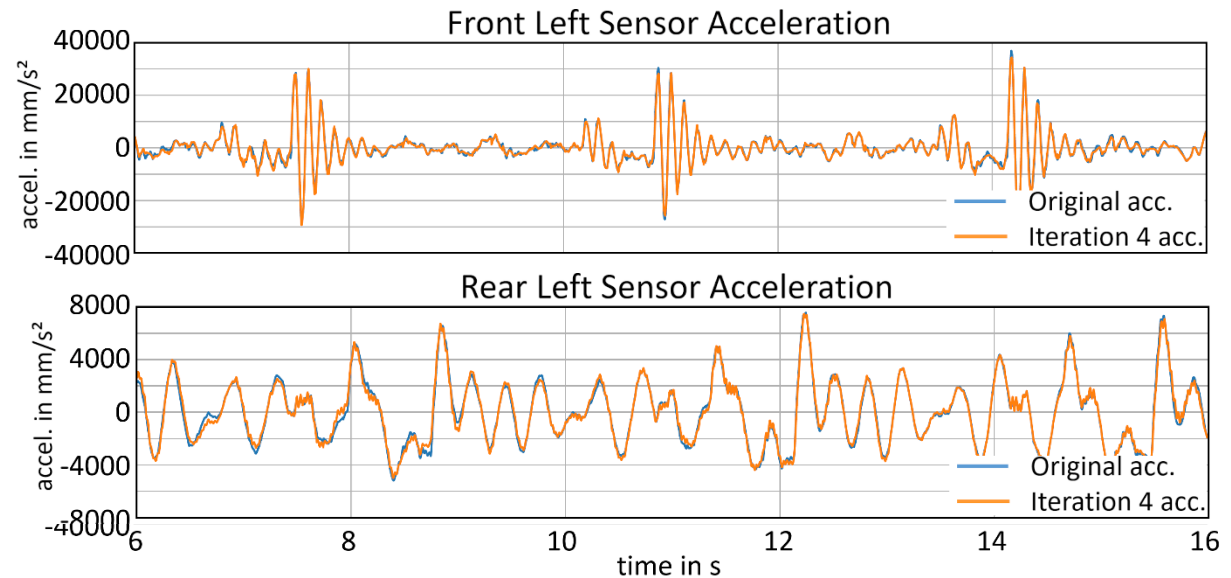
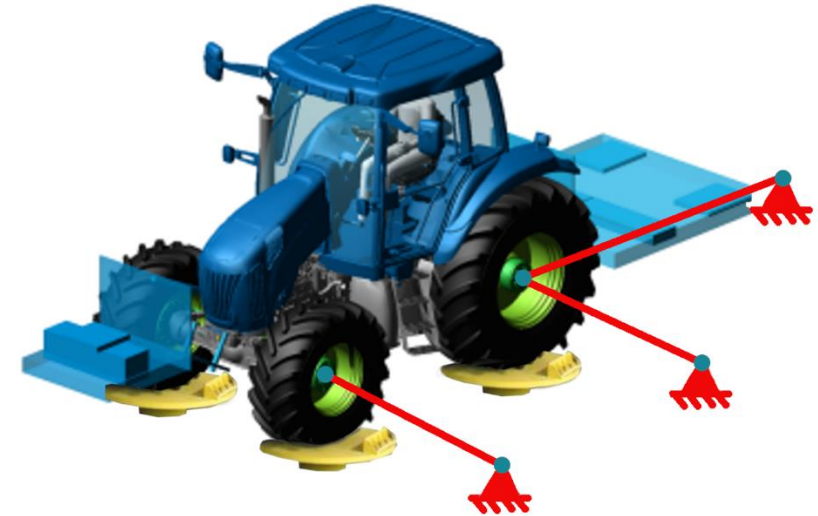


Rear Left Sensor Acceleration



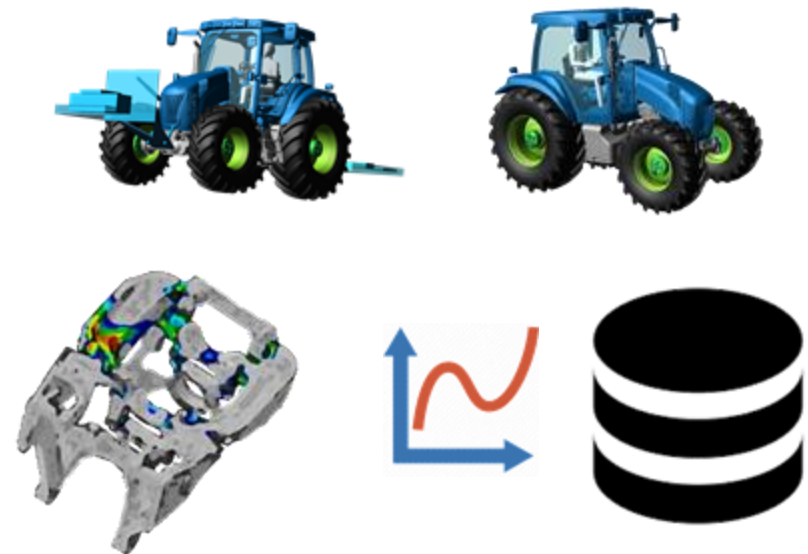
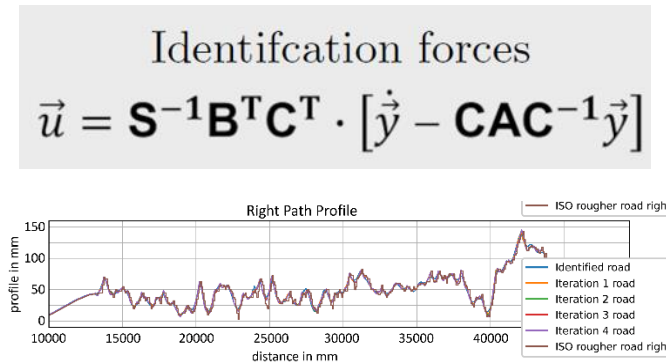
Application Example: Four-Poster Test Rig

- Consists of four **hydraulic actuators**, each positioned under a wheel.
- Objective is to achieve same vertical **accelerations as measured in the field**, in this case: MGR test.
- Presented **inversion algorithm** provides **input signals** for four-poster actuators.
- Model is adjusted to boundary conditions related to test bed (see red bars).
- Convergence** can be **warranted** because multiple tire contact surfaces cannot occur on test rig.
- Target** of reproducing original acceleration on test rig is **met** very well.



Conclusions

- **Iterative inversion method in time domain** has been established for **field path detection** based on measured accelerations. Method is **cost-effective** and sufficiently **accurate** (see examples).
- In contrast to measured wheel hub forces, **field path profiles** do **not depend on** certain **vehicle data**.
- ➡ Suitable for setting up a **field path data base** of **real and test tracks** as input for tractor multibody system simulations, which AVL has already started.
- Utilizing this data base one can **derive reliable and accurate load** case definitions for finite element and **mechanical fatigue** analysis, also in view of **parameter variation** (ballasted or unballasted, etc.), already during a **pure virtual development** phase, i.e.: before any prototypes exist.
- For the future it may be expected that AI-methods will provide further potential for process improvements.





Thank you for your attention!

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