VDCA Swedish Vehicle Dynamics Competence Area

Proceedings from
2025 Vehicle Dynamics seminar
Model exchange for virtual pre series

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The contents of these proceedings include both **presentations and poster material** and are published at https://www.sveafordon.com/, https://research.chalmers.se/en/publication/541312, and https://kth.diva-portal.org/.

The seminar was arranged by the workgroup Vehicle Dynamics Competence Area in Swedish Vehicular Engineering Association (SVEA, https://www.sveafordon.com/).

VDCA Swedish Vehicle Dynamics Competence Area

VDCA is a workgroup in:

SWEDISH VEHICULAR ENGINEERING ASSOCIATION

SVERIGES FORDONSTEKNISKA FÖRENING

SVEA is a member of:

FISITA

Contents

Note that the pdf file is generated with these "headings as pdf bookmarks", so you can also navigate via the "bookmark pane" in your pdf reader.

Announcement of the Seminar

Vehicle Dynamics 2025 – Model exchange for virtual pre series

You have already registered for this event.

Vehicle Dynamics 2025 – Model exchange for virtual pre series

568

The seminar has two pages, one with Swedish flag and one with English flag. This is the main page for detailed updates of the announcement and registrations of participation.

Fordonsdynamiksseminarium 2025 – Modell-utbyte för virtuella förserier

Date And Time

May 7, 2025 09:00 AM to
May 7, 2025 04:15 PM

Registration End Date

May 8, 2025

Location

Vera Sandbergs Allé 8, Göteborg.
Plus code from google maps: MXVG+85 Göteborg

virtuella förserier

Vehicle Dynamics 2025 — Model exchange for virtual pre series

Vehicle development increasingly utilizes models and simulations to reduce the dependency on building real world prototypes. One can compare the A-, B-, and C-samples for real pre-series with exchange of models of vehicular sub-systems to a complete vehicle model. Such model exchange requires compatibility between model formats, which is a problem since one cannot expect all vehicle manufacturers and system suppliers to ever use the same format. For exchangeability, one would need acausal physical interfaces, well-defined model parameters, and signal interfaces. One would also need model integrating engineers, corresponding to real prototype workshops.

The presentations and poster this year are not all focusing model exchange, but we have asked these to address model exchange as one aspect of their topic.

Wednesday 7 May

The seminar will be in "hybrid format", meaning that participation is possible both in-real-life and on-line.

In-real-life:

Room Vasa C, Chalmers, Campus Johanneberg, Vera Sandbergs Allé 8, Göteborg

Plus code from google maps: MXVG+85 Göteborg

On-line:

Link to on-line meeting will be sent to those who register as on-line.

Registration

Registration is made via https://www.sveafordon.com/en/?post_type=event_listing&p=4926&preview=true.
If you are member, it is easier to register if you log in before registration.

You will get a confirmation that you are registered.

Initial registration deadline is 2025-05-05, we will order light lunch and fika for those registered until then plus some in reserve.
We will re-open the registration after that and for those who register after this, we cannot promise light lunch and fika.

2025-05-06: Registration is now re-opened, new deadline 2025-05-08 (=day AFTER seminar). If you register for on-line participation and very late, I might miss to send out on-line link to you. For those (few?) please late, I might miss to send out on-line link to you. For those (few?) please give me an SMS or call at +46 70 3821383 and I will try to send you link.

Seminar costs

The seminar is free for SVEA members. SVEA will sponsor food (fika and light lunch) for members (incl. pending membership applicants) who attend in-real-life.
For non-members attending in-real-life there will be a fee of 210 SEK (>membership fee).

Presenters (incl. poster presenters) attend for free.

We encourage to apply for SVEA membership (https://www.sveafordon.com/en/for-members/register/). SVEA membership fee is 200 SEK/year (junior 0 SEK, senior 100 SEK).

Purpose with the seminar

- Present and discuss interesting issues within and challenges for *Model exchange for virtual pre series*
- Create understanding and interest for vehicle dynamics
- Develop, increase, and spread competence
- Networking between engineers, organisations, and students

SVEAs objectives

- To make vehicular technology's voice heard in an increasingly more challenging debate among different vehicle types and transport modes both domestic and globally
- To build a network for efficient distribution of technological information
- To attract the next generation of Swedish vehicular engineers

Poster exhibition

There will be an exhibition of posters. It can be, e.g., master theses or PhD theses, either concluded or almost concluded. Please contact Lars Drugge larsd@kth.se or Bengt Jacobson bengt.jacobson@chalmers.se if you would like to propose a poster.

Each poster presenter should do a poster and a "micro presentation" with a few slides. Then the presenter should also be available for questions at the poster stands.

Proceedings

There will be proceedings from the seminar. This means that the presenters, including poster presenters, are welcome with a paper, or at least a public version of their presentation material. The proceedings will be published on the SVEA web. It will include a list of seminar participants, unless you ask us to not list your name.

Agenda

Moderator: Matthijs Klomp, Volvo Cars

09:00-09:45	**Coffee and registration**	
09:45-09:55	**Welcome**	Matthijs Klomp (Moderator), Bengt Jacobson (SVEA, VDCA)
09:05-11:00	**Session 1:** Presentations (20+10 min each):	
	Pres1: *FMU factory from CAE to SAE*	Edo Drenth, Volvo Autonomous Solutions
	Pres2: *Dynamic simulation and beyond*	Peter Sundström, Modelon
11:00-11:05	**Short break**	
11:05-12:00	**Session 2**: Presentations (20+10 min each):	
	Pres 3: *Target Cascading from Full Vehicle Dynamics Targets to System & Subsystem Vehicle Requirements*	Axel Villandseie, Volvo Cars
	Micro presentations of posters (5 min each):	
	Post1: *Reversing A-double using steerable axle on the last semi-trailer*	Pavan Kumar Adiga Nagaraj, Niveditha Krishnakumar, Chalmers, Volvo Trucks
	Post2: *Onboard Estimation of Center of Gravity in Heavy Vehicles*	Alfred Aronsson and Fabian Fagerlind, Chalmers and Volvo Trucks
	Post3: *Development and validation of a friction estimation model for collision avoidance maneuvers in autonomous trucks*	Ganapati Girish Kamat, Chalmers, Scania
	Post4*: Physics-Informed Neural Networks for Vehicle Lateral Dynamics Modelling*	Rishikesh Vishnu Sivakumar, Yuchuan Dong, Chalmers and Zeekr
	Post5*: Real time model for predictive axle load estimation*	Ajhay Babu Jagadeesan Karthik Babu, Mayank Vijay, KTH and Scania
12:00-13:30	**Light lunch** with networking and manned posters in seminar room.	
13:30-14:30	**Session 3:** Presentations (20+10 min each):	
	Pres 4: *about rolling resistance on roads with various weather and surface condition*	Mikael Askerdal, Volvo LV och Chalmers
	Pres 5: *FMU-based co-simulation for autonomous vehicle dynamics control*	Wenliang Zhang, KTH
14:30-15:00	**Coffee** with networking and manned posters	
	Session 4: Presentations (20+10 min each):	

	Pres 6: *Braking Distance Minimization on Roads with Varying Friction*	Ektor Karyotakis, Volvo Cars and Chalmers
15:00-16:00	Pres 7: Swedish vehicle engineering education:	
	Pres 7a: *KTH, Vehicle engineering* Pres 7b: *Chalmers, Mobility engineering* Pres 7c: *LiU, Vehicle engineering courses* Discussion	Mikael Nybacka, KTH Dag Henrik Bergsjö, Chalmers Jan Åslund, LiU All
16:00-16:15	**Wrap-up** · Overall technical questions from today's presentations and posters? · Feedback on present years seminar. Proposals for next year's seminar. · Discussion on other	

The seminar is arranged by the Swedish Vehicle Dynamics Competence Area (VDCA) and Swedish Vehicular Engineering Association (SVEA). The seminar is arranged with VDCA representatives from:

AFRY Automotive
AstaZero
Chalmers
KTH
LiU
Polestar
Scania
Volvo Cars
Volvo Trucks
VTI
Zeekr Technology Europe

SVEA is the society member for Sweden in FISITA:

Do not hesitate to contact us with questions and suggestions to
info@sveafordon.com

Swedish Vehicular Engineering Association

Participations

51 participants

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Introduction to the seminar

Introduction to

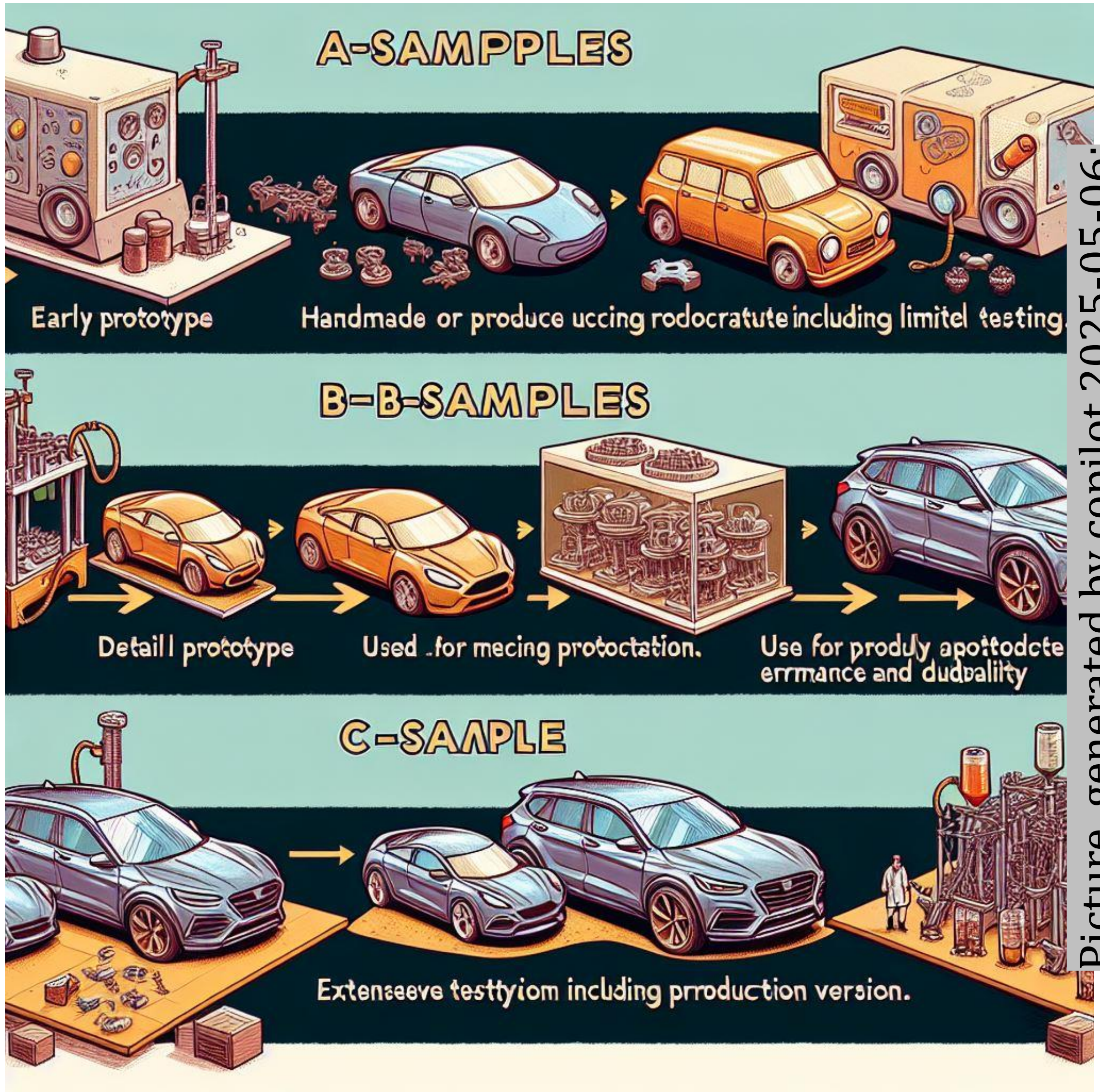
Vehicle Dynamics Seminar 2025

Model exchange for virtual pre series

Wednesday 2024-05-07 hosted by Chalmers, Göteborg, Sweden

About this year's seminar topic

- **Model exchange for virtual pre series**
- System suppliers deliver virtual A-, B-, C-samples to automotive developers
- Automotive developers compile the samples to complete vehicle models, "virtual pre-series"
- How to handle portability between the submodels? Challenges:
  - Parameterisation,
  - physical connections, and
  - signal connections
  - (Version management, over development time and different use)



Picture generated by copilot 2025-05-06:

Purpose with the seminar

- **Present and discuss** interesting issues within and challenges for Vehicle Dynamics within a topic which is selected each year
- Create **understanding and interest** for vehicle dynamics
- Develop, increase, and spread **competence**
- **Networking** between engineers, organisations, and students

Arrangement of the seminar

- Annual since 2013
- Arranged by **VDCA**,
  - which is a workgroup in **SVEA**
  - which is Sweden's "society member" in **FISITA**

SVEAs objectives

- To make **vehicular technology's voice heard** in an increasingly more challenging debate among different vehicle types and transport modes both domestic and globally
- To build a **network** for efficient distribution of technological information
- To attract the **next generation of Swedish vehicular engineers**

What have we achieved with our seminars

Year	Topic	Location
2013	Vehicle Dynamics Challenges	Lindholmen, Göteborg
2014	Vehicle Dynamics in a Cooperative Environment	Scania, Södertälje
2015	Vehicle Dynamics for Energy Efficient Mobility	Chalmers, Göteborg
2016	Functional Architectures and Virtual Methods for Efficient Vehicle Dynamics Development	NEVS, Trollhättan
2017	Vehicle Dynamics for Automated Driving	Scania, Södertälje
2018	Model Fidelity for Vehicle Motion Predictions	Chalmers, Göteborg
2019	<replaced by IAVSD international conference>	Göteborg
2020	<cancelled>	Cancelled, due to pandemic
2021	Future Mobility …and not only Lateral	Online, due to pandemic
2022	Connected and Electric	KTH, Stockholm and on-line
2023	Testing, development, and verification	AstaZero, Sandhult and on-line
2024	Virtual verification	Linköping and on-line
2025	Model exchange for virtual pre series	Göteborg, Chalmers and on-line
2026	(to be discussed at the wrap-up of 2025's seminar)	

About VDCA

VDCA Swedish Vehicle Dynamics Competence Area

VDCA "core group" has representatives and contributions from vehicle manufacturers, university groups in the subject Vehicle Dynamics, and VTI:

AFRY Automotive
AstaZero
Chalmers
KTH
LiU
Polestar
Scania
Volvo Cars
Volvo Trucks
VTI
Zeekr Technology Europe

Let's enjoy the day and do networking

Presentation 1:

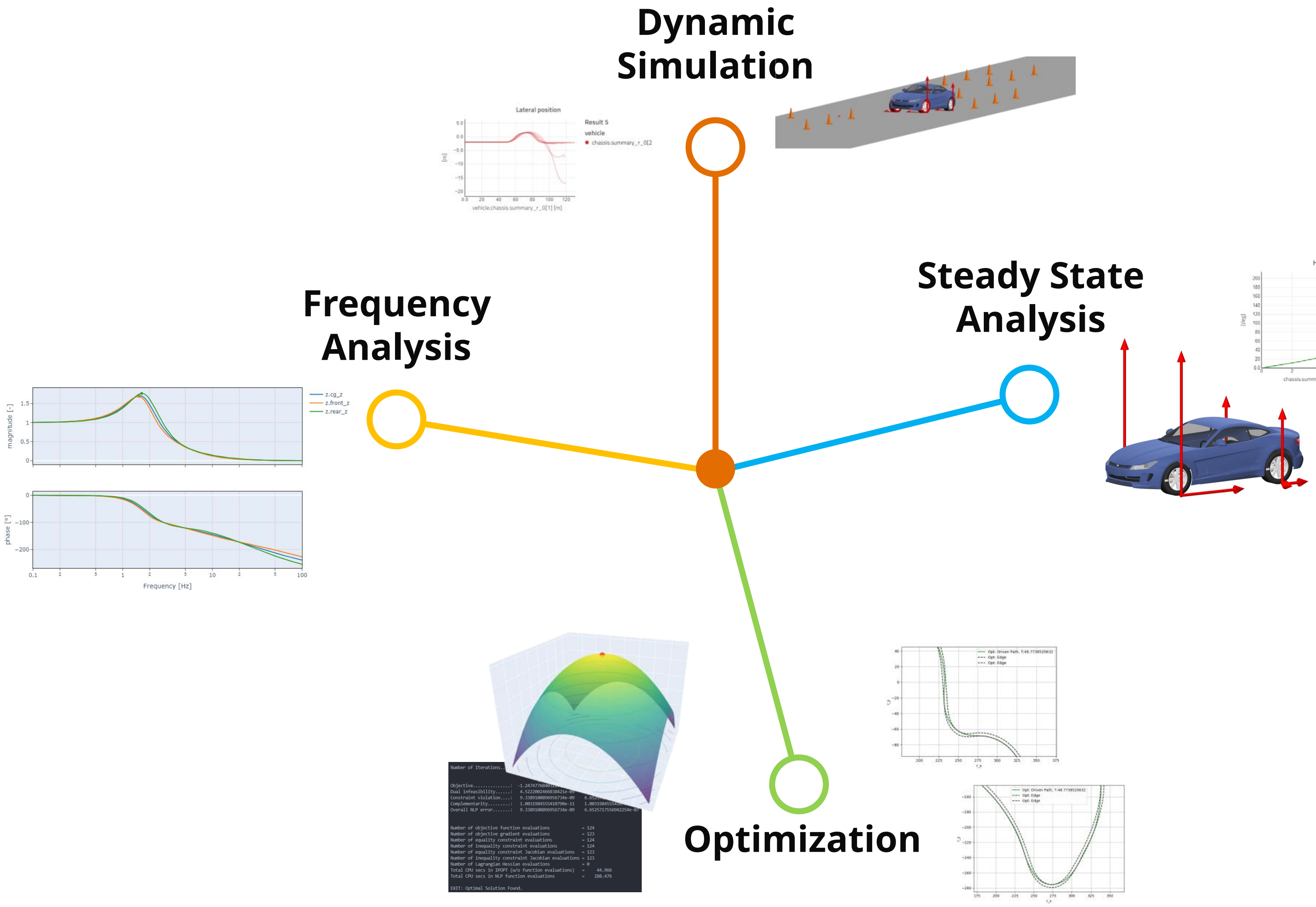
Dynamic simulation and beyond

Peter Sundström, Modelon

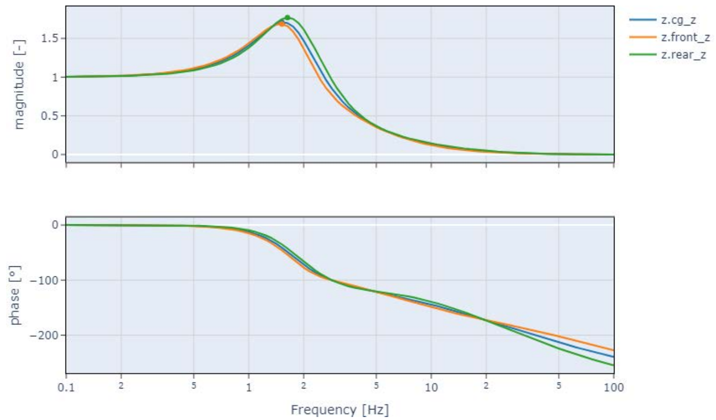
Dynamic simulation and beyond

Modelon

Peter Sundström


Dynamic Simulation
Lateral position
Result 5
vehicle
Frequency Analysis
magnitude [-]
phase [°]
Frequency [Hz]
z.cg_z
z.front_z
z.rear_z
Steady State Analysis
Handling Diagram
Result 45
chassis
Optimization
EXIT: Optimal Solution Found.

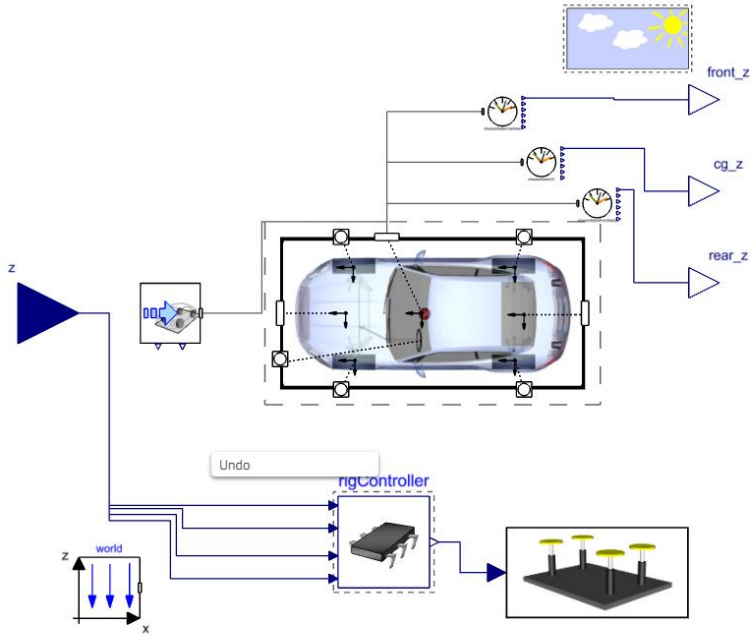
Frequency Analysis



Frequency Analysis

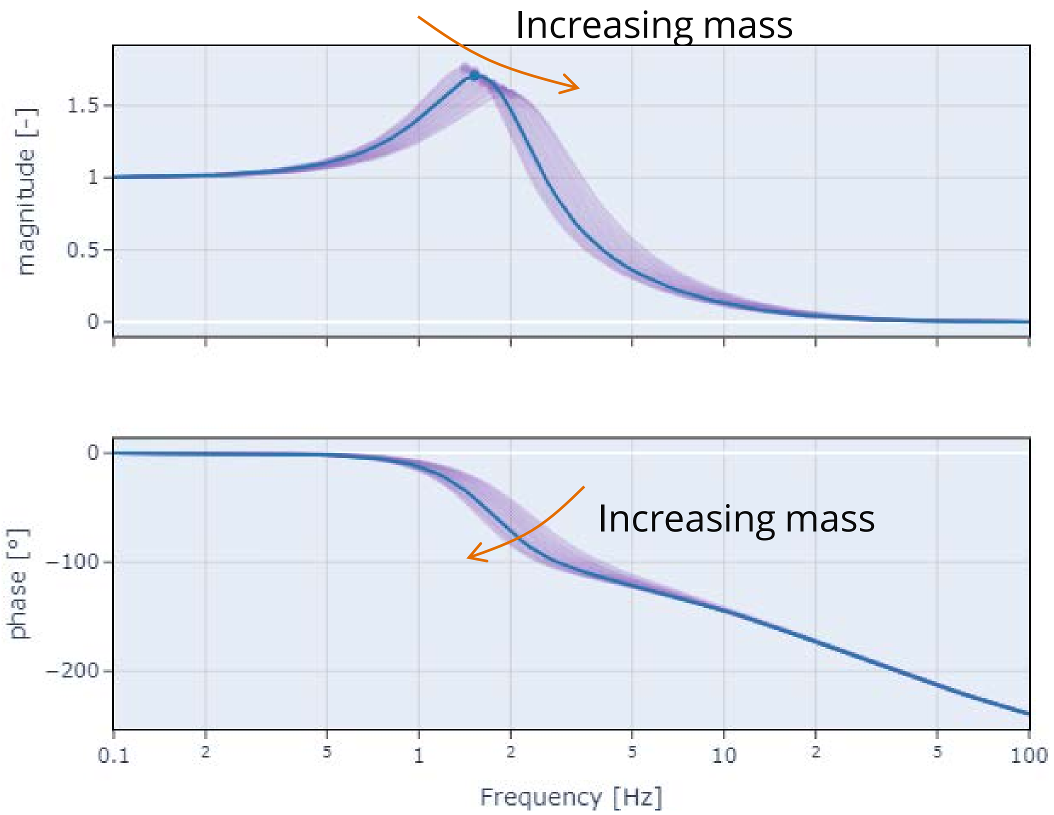
Vertical inputs at each wheel

Outputs at front, rear and c.g.

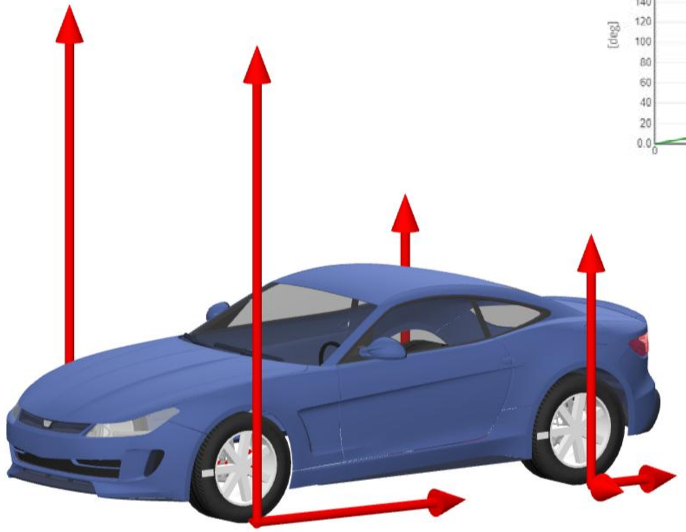


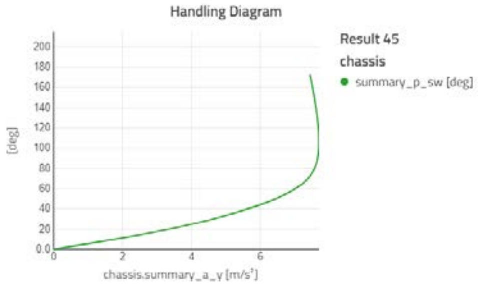
Vertical output at cg, response to uniform vertical input at wheels

Sweep total vehicle mass



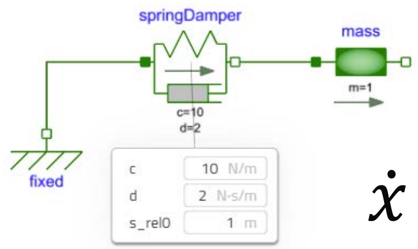
Steady State Analysis





$$\dot{x} = 0$$

Steady State Analysis

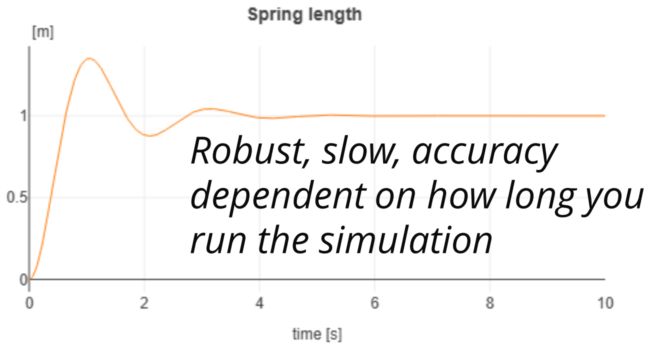


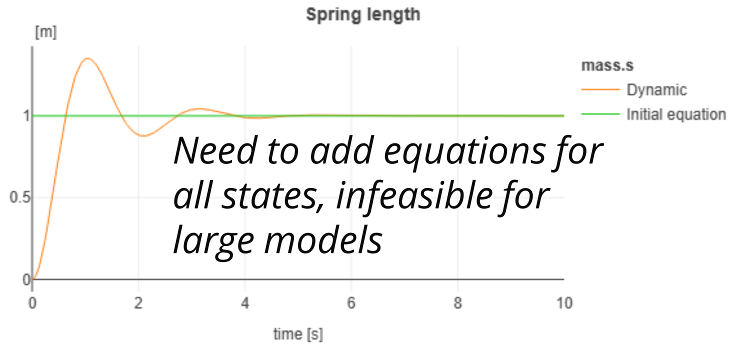
$$\dot{x} = 0$$

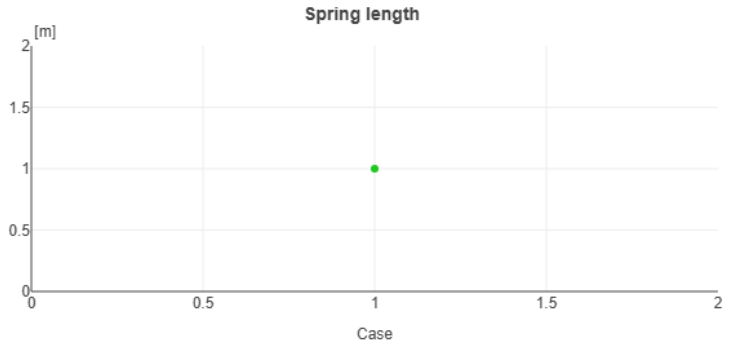
Run dynamic sim until steady-state is reached

Add equations for steady state

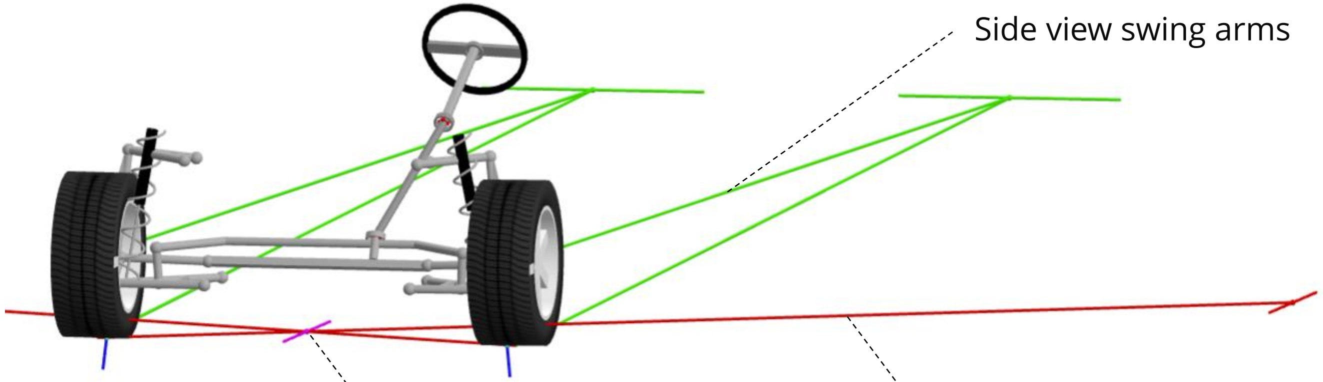
Use external solver to solve dynamic model for steady state
x such that der(x)=0

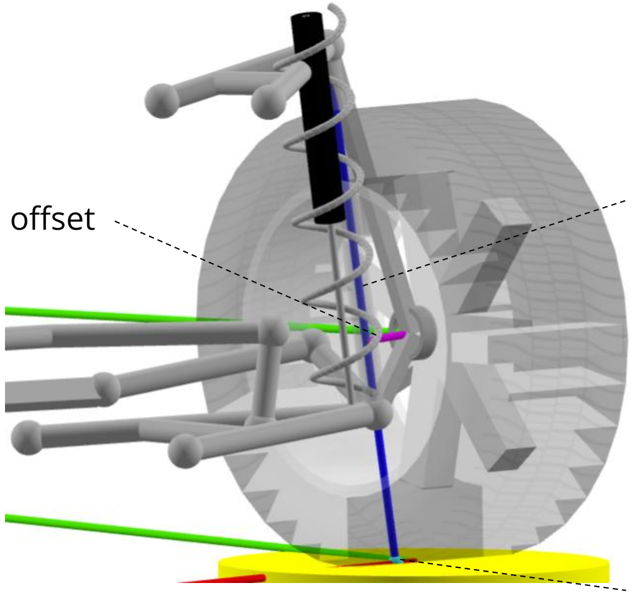


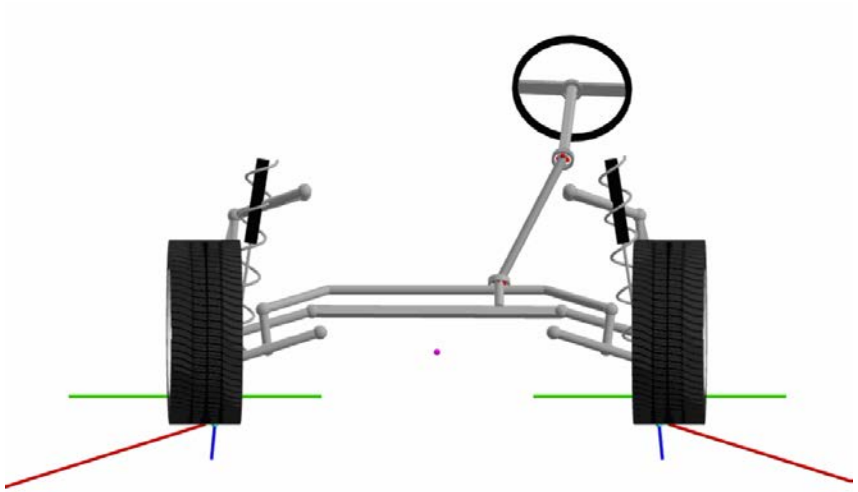




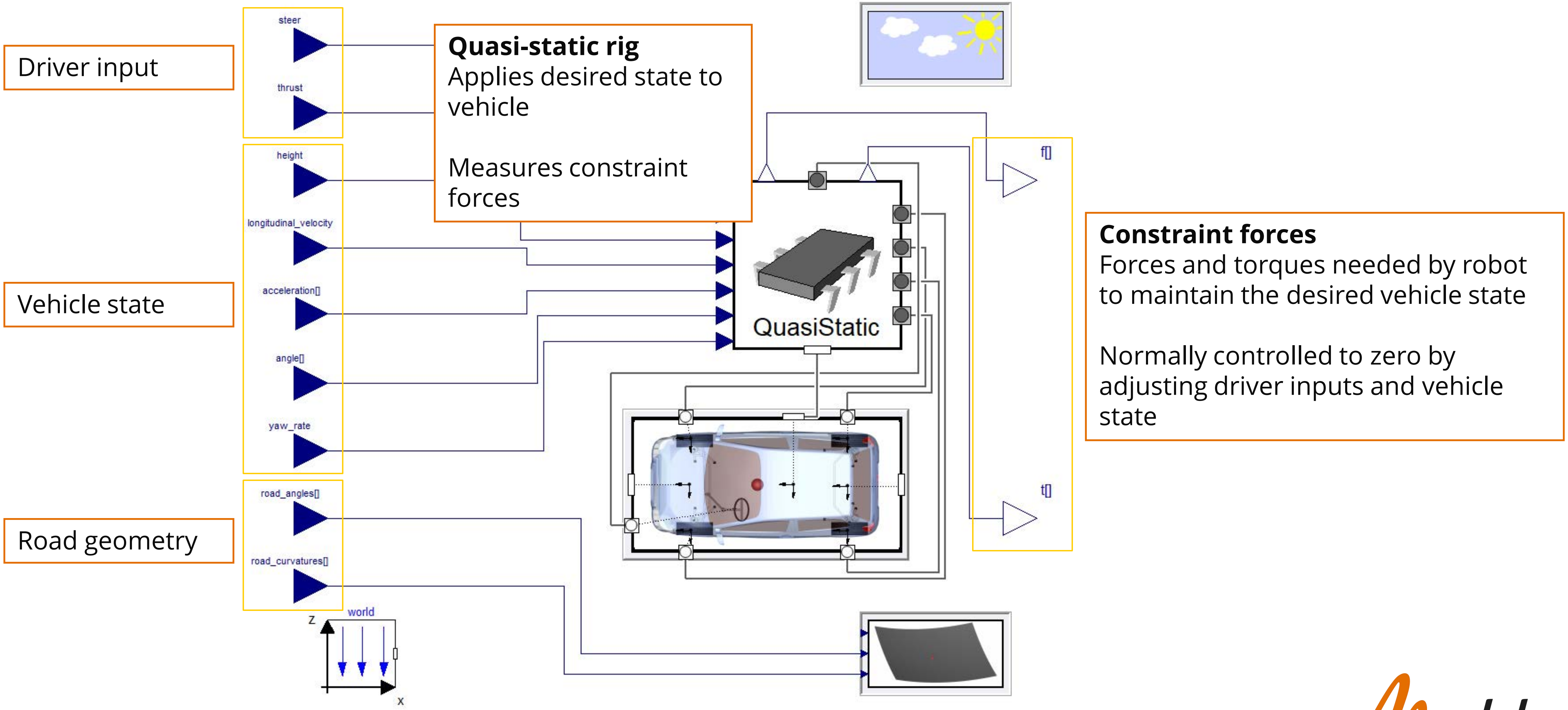
Suspension Analysis



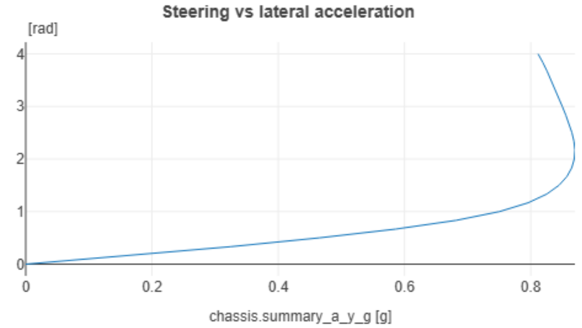


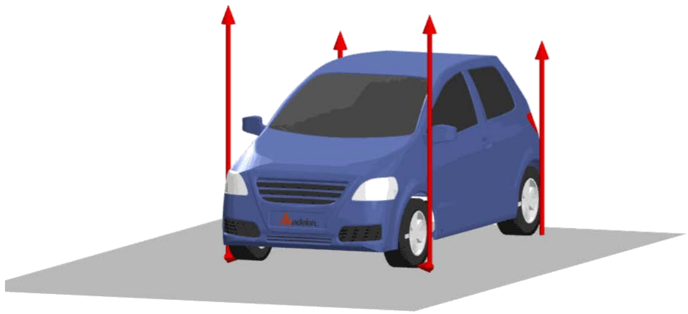


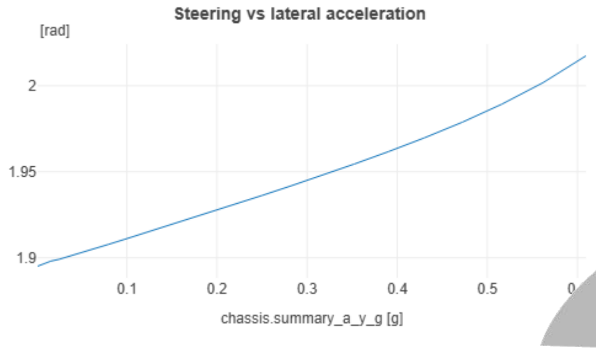
Chassis Analysis

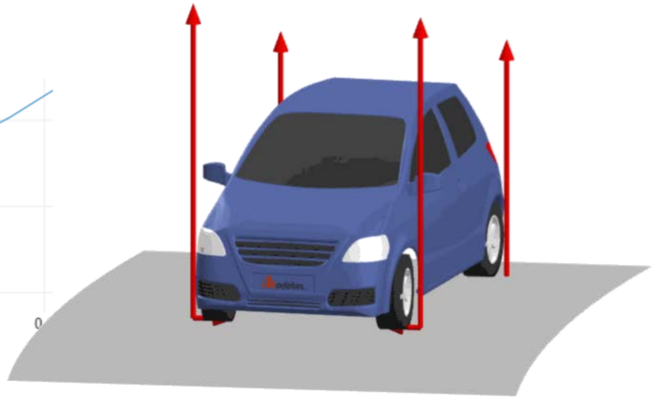


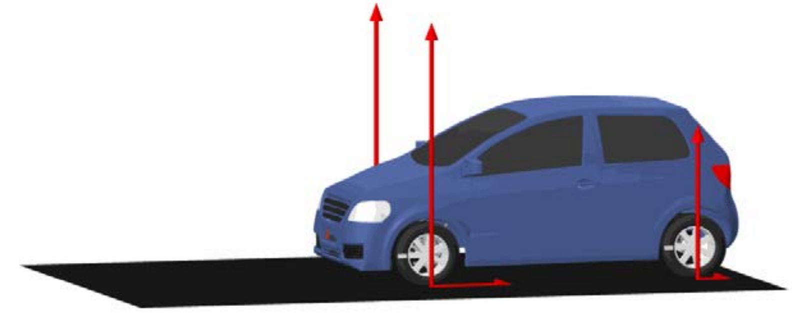
Chassis Analysis



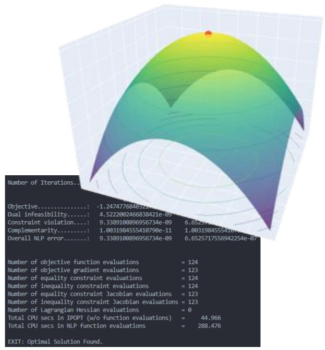


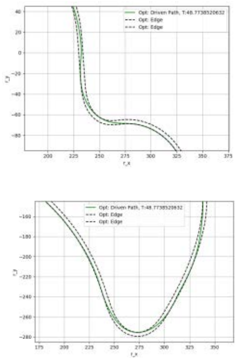






Modelon

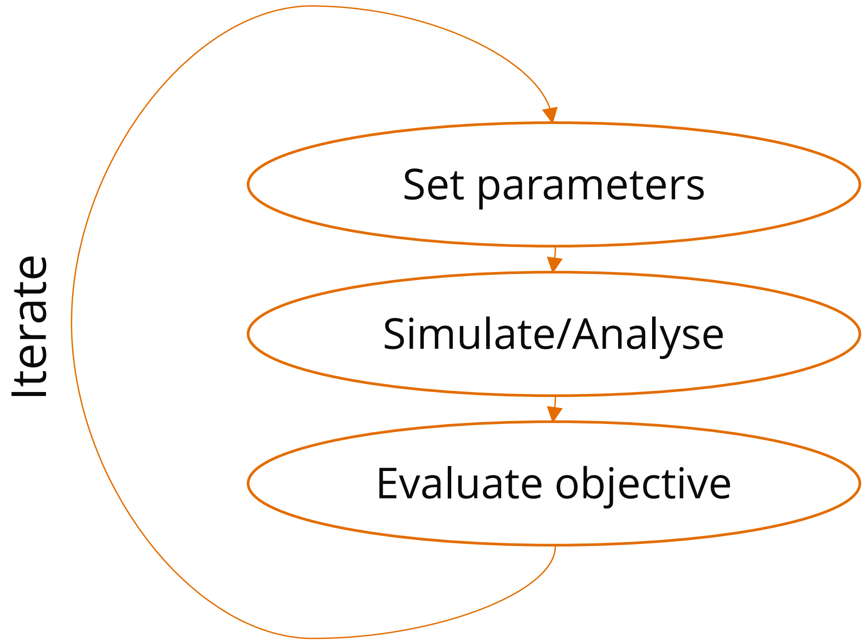




Optimization

Optimization

Derivative free optimization



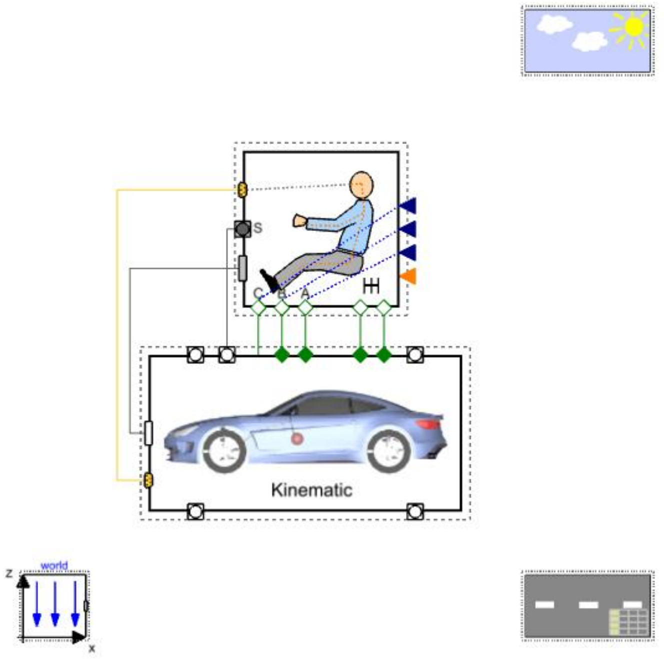
Gradient based/Trajectory optimization

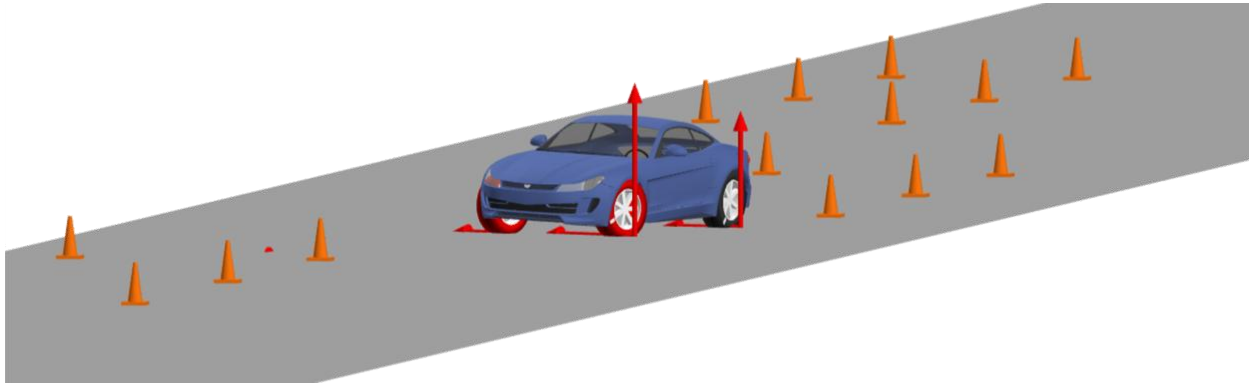
Optimize trajectories using collocation

Need first and second order derivatives from inputs -> objective and constraints

Divide into time segments, optimize objective such that segments line up and constraints are fulfilled

Derivative free optimization





Driver model follows prescribed path

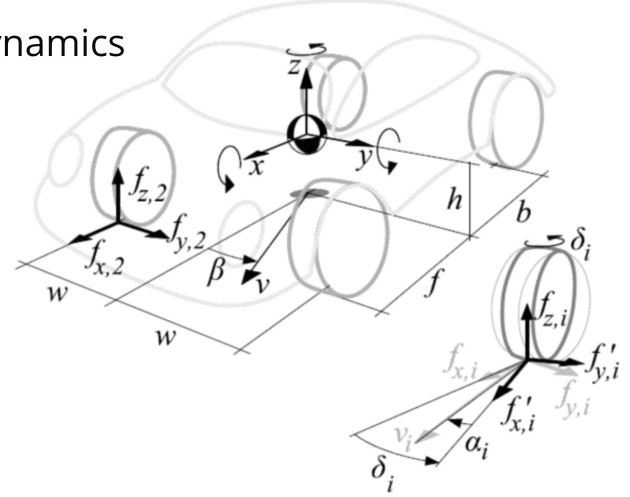
Condition to stay within cones

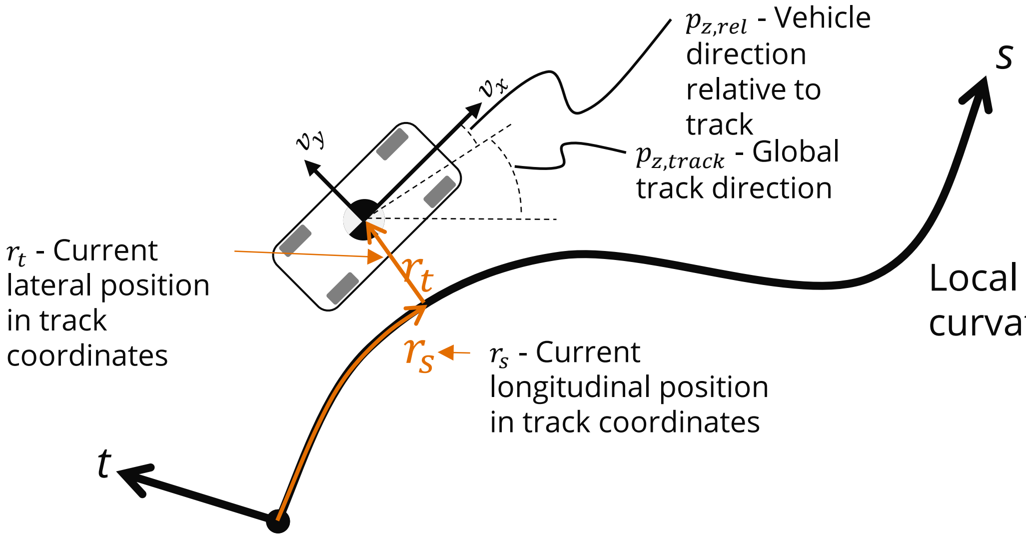
Use optimization algorithm (Nelder-Mead implementation in SciPy) to find highest initial velocity that doesn't violate constraints

For <5 parameters, this is robust and can handle many types of models, though it's not very fast

Trajectory optimization with Optimica and CasADi

Two-track vehicle model with
combined slip and relaxation dynamics
(**not multibody based**)



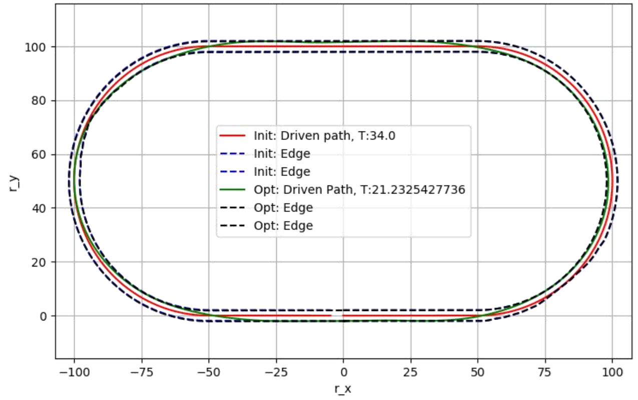


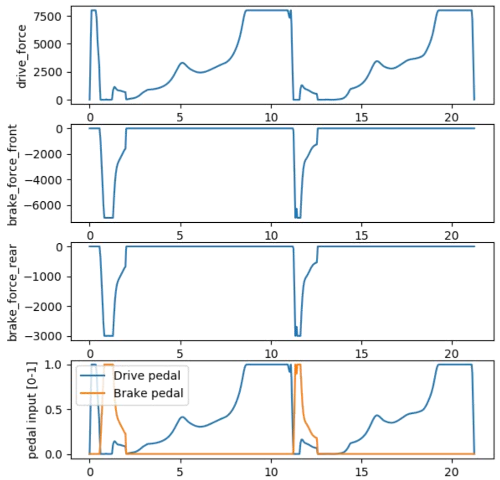
Local track coordinate system based on curvature and distance along track

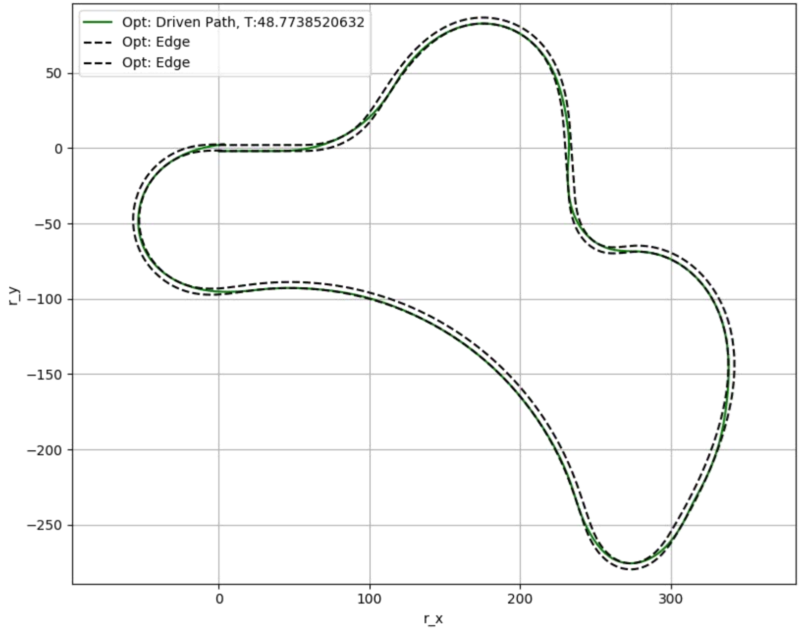
Simple optimization formulation, cost on lap time + small cost on actuator usage

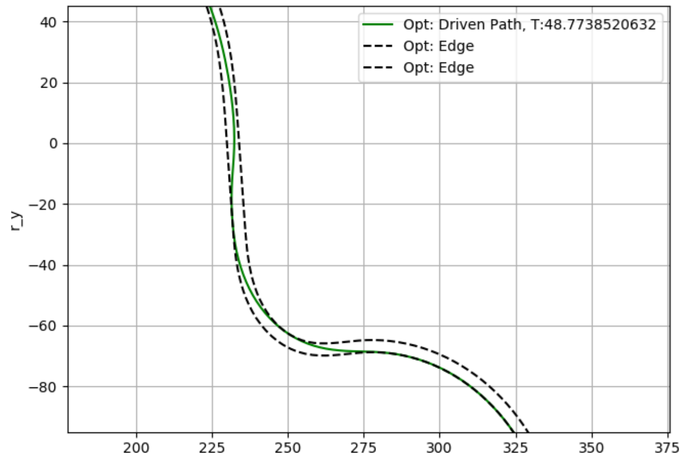
```
optimization LapTimeMinimization(
   objective=100*finalTime+1*icost(finalTime),
   startTime = 0,
   finalTime(free=true,max=160,min=10,initialGuess=122))
```

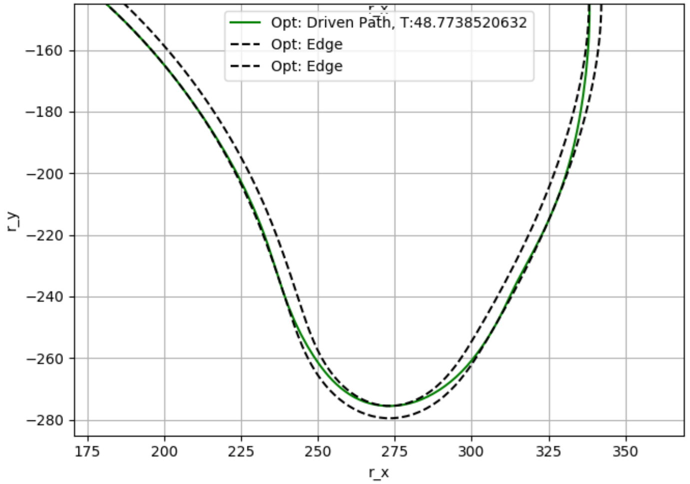
Trajectory optimization with Optimica and CasADi







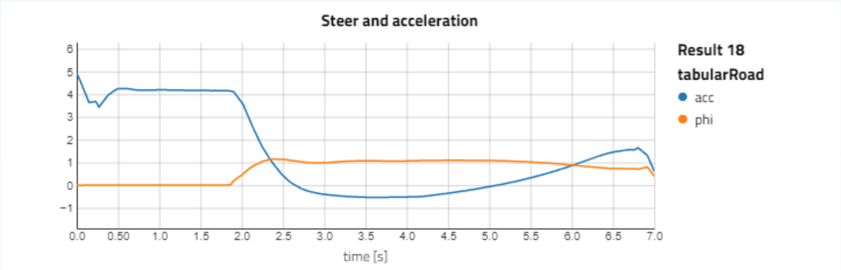


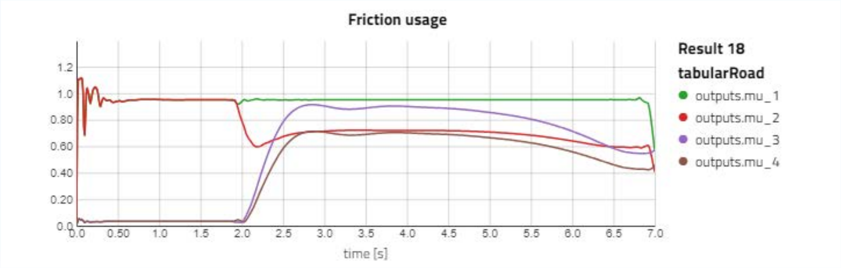


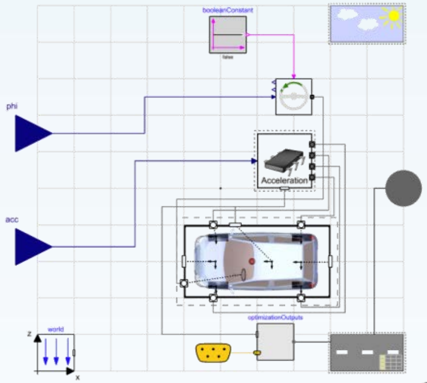
Very capable, but places high demands on model formulation (continuous derivatives, all Modelica constructs are not supported)

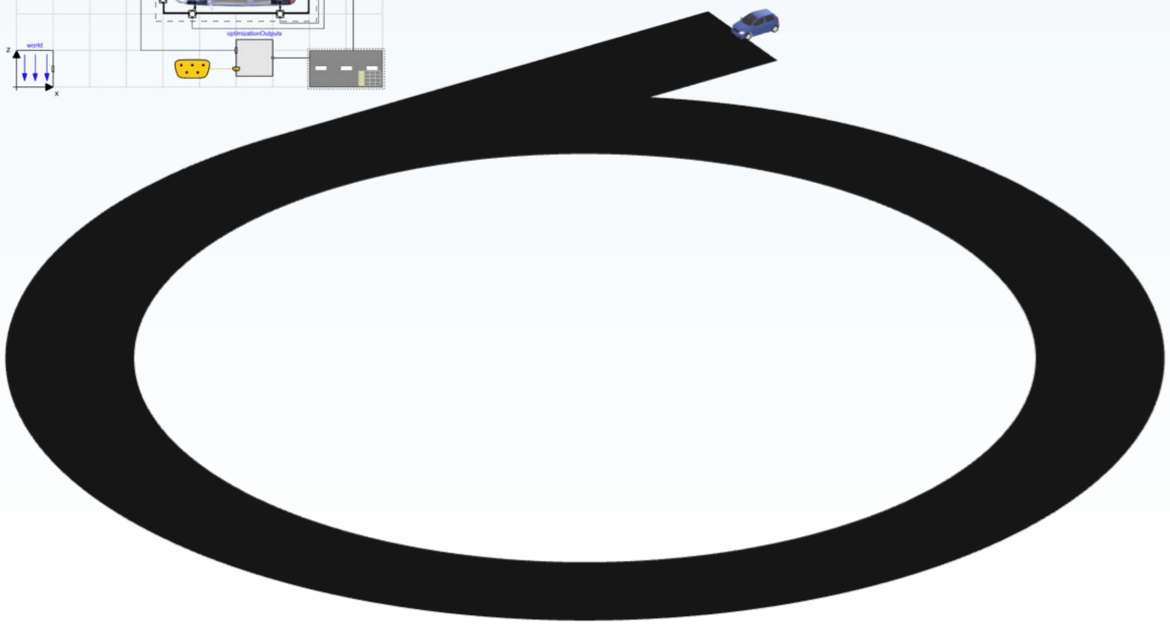
Trajectory optimization with Pyomo

```
Number of Iterations....: 122

                                   (scaled)                 (unscaled)
Objective...............:  -1.2474776840322713e+02   -1.2474776840322713e+02
Dual infeasibility......:   4.5222002466838421e-09    4.5222002466838421e-09
Constraint violation....:   9.3389100896956734e-09    6.6525717556942254e-07
Complementarity.........:   1.0031984555410790e-11    1.0031984555410790e-11
Overall NLP error.......:   9.3389100896956734e-09    6.6525717556942254e-07


Number of objective function evaluations             = 124
Number of objective gradient evaluations             = 123
Number of equality constraint evaluations            = 124
Number of inequality constraint evaluations          = 124
Number of equality constraint Jacobian evaluations   = 123
Number of inequality constraint Jacobian evaluations = 123
Number of Lagrangian Hessian evaluations             = 0
Total CPU secs in IPOPT (w/o function evaluations)   =     44.966
Total CPU secs in NLP function evaluations           =    288.476

EXIT: Optimal Solution Found.
```



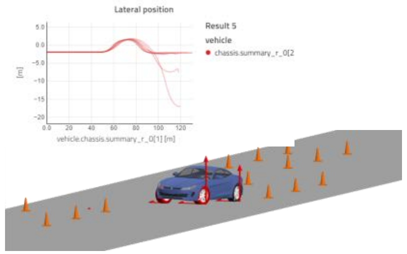




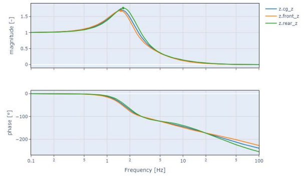


Early development, FMU based workflow allows more types of models to be used at the cost of optimization performance

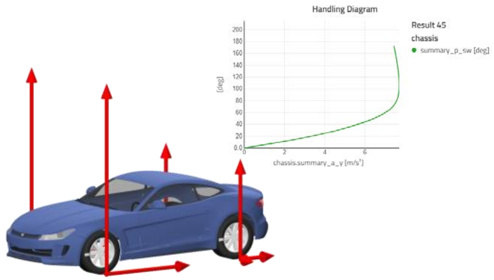
Dynamic Simulation



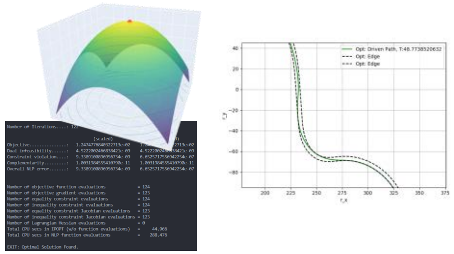
Frequency Analysis



Steady State Analysis



Optimization



Modelon Impact

Modelon

Accurate Simulations. Better Decisions.

Presentation 2:
FMU factory from CAE to SAE
Edo Drenth, Volvo Autonomous Solutions

VOLVO

FROM COMPUTER- TO SOFTWARE AIDED ENGINEERING

Quality, Traceability, and Speed

Volvo Autonomous Solutions

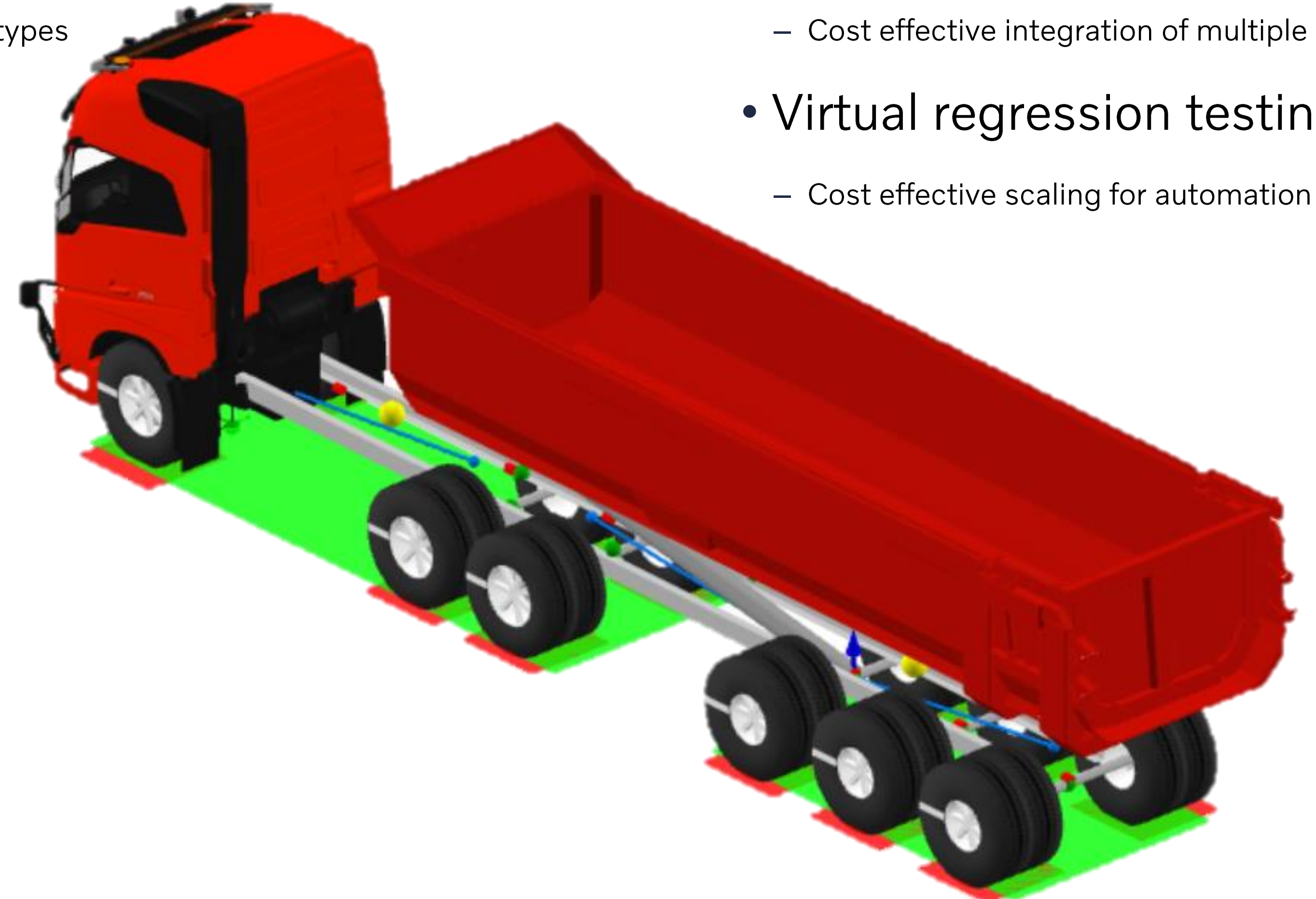
Vehicle Domain | Vehicle Models Team | Internal | ©2025

2025-05-07

The Purposes of Modelling

The promises of simulation

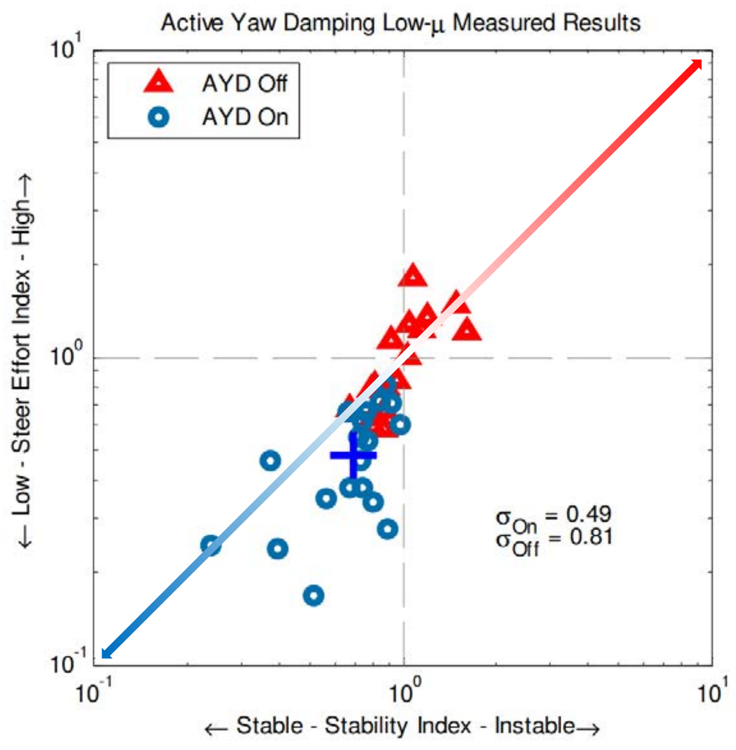
- Cost reduction
  - Reduced number of expensive physical prototypes
- Cut development time
  - Quicker turn around on design changes
- Measure the immeasurable
  - All signals are available
- Create better understanding



- Virtual integration
  - Cost effective integration of multiple embedded systems
- Virtual regression testing
  - Cost effective scaling for automation

Purpose Driven Model Fidelity

Models may only answer questions you modelled in the first place



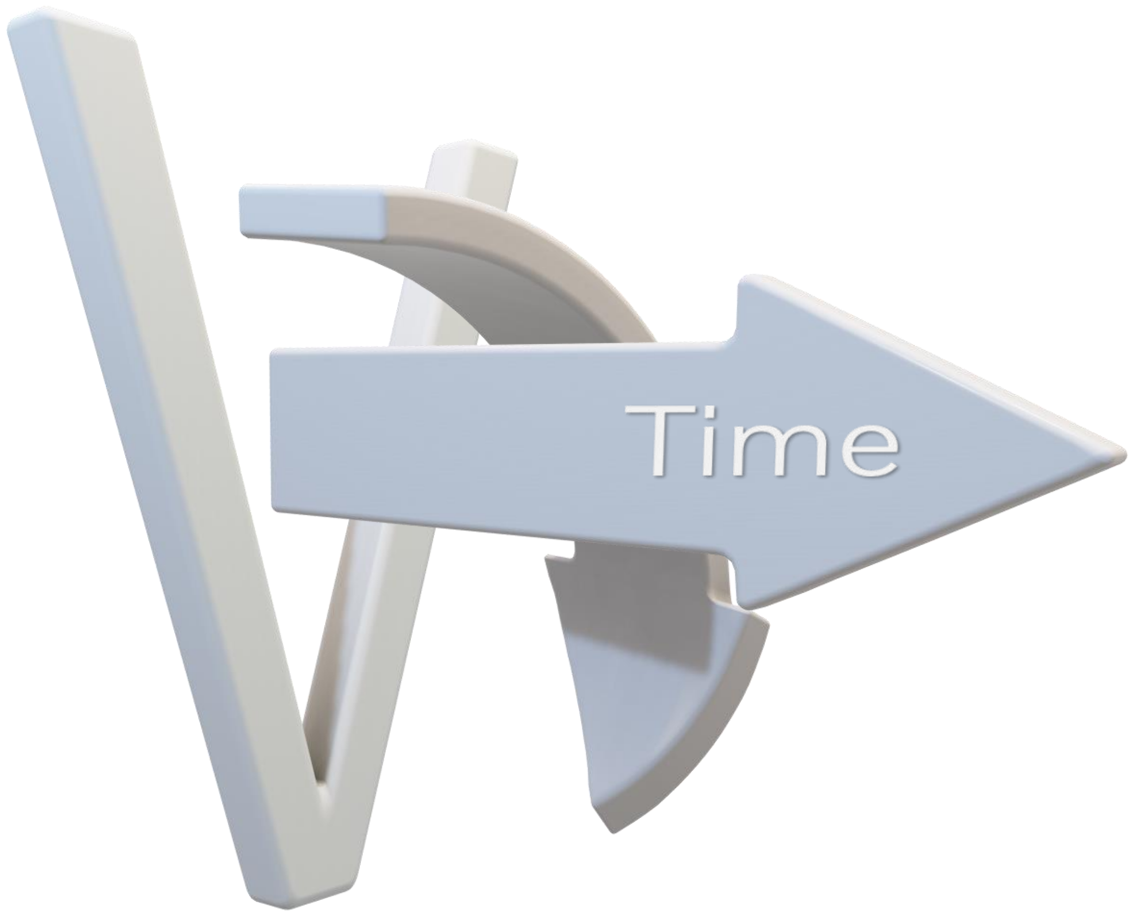
Source: Drenth, Haldex Cross Wheel Drive

"All models are wrong, but some are useful"

- George Box

Systems Engineering

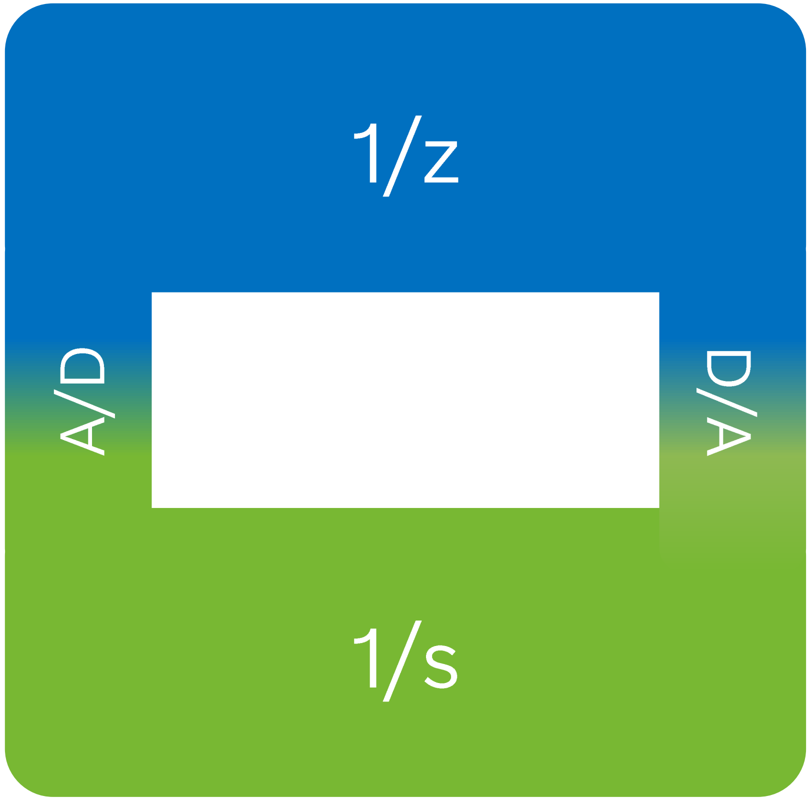
- Verifiable Requirements
- Break down
- Iterations
- Implementation
- Integration
- Modelling & Simulation



Automotive modelling and simulation historic view

Hardware in the Loop

- Vehicle Dynamics
  - Multi-body simulation
- ABS standard
  - Controllers
- Co-simulation
  - Hardware in the Loop

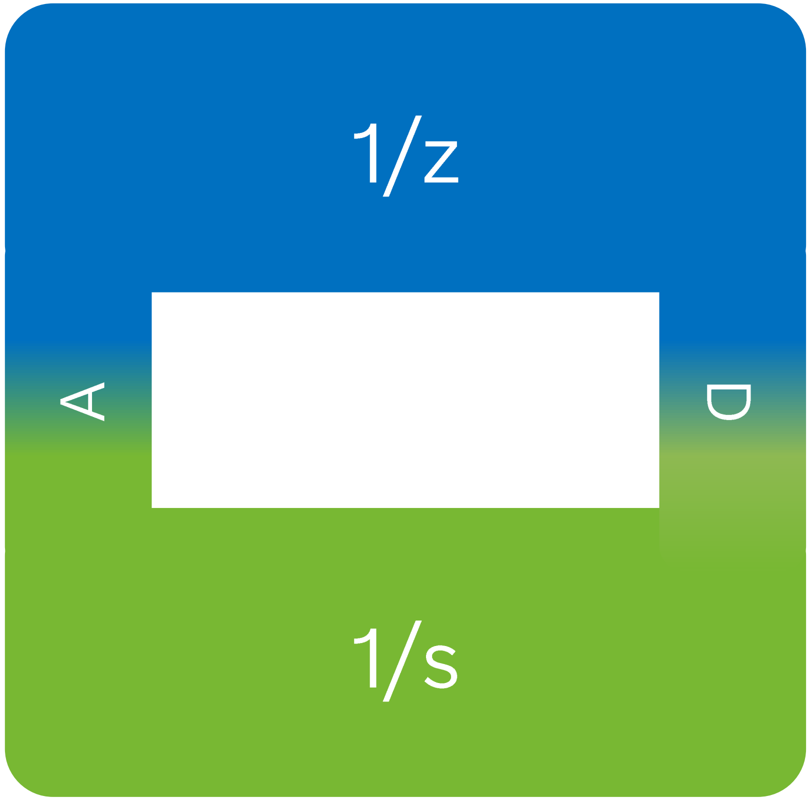


- A/D
  - Anti-aliasing
  - Sampling
- D/A
  - Sampling
  - Reconstruction

Automotive modelling and simulation historic view

Controls/actuators in the Loop

- Vehicle Dynamics
  - Multi-body simulation
- ABS standard
  - Controllers
- Co-simulation
  - Software/Model in the Loop



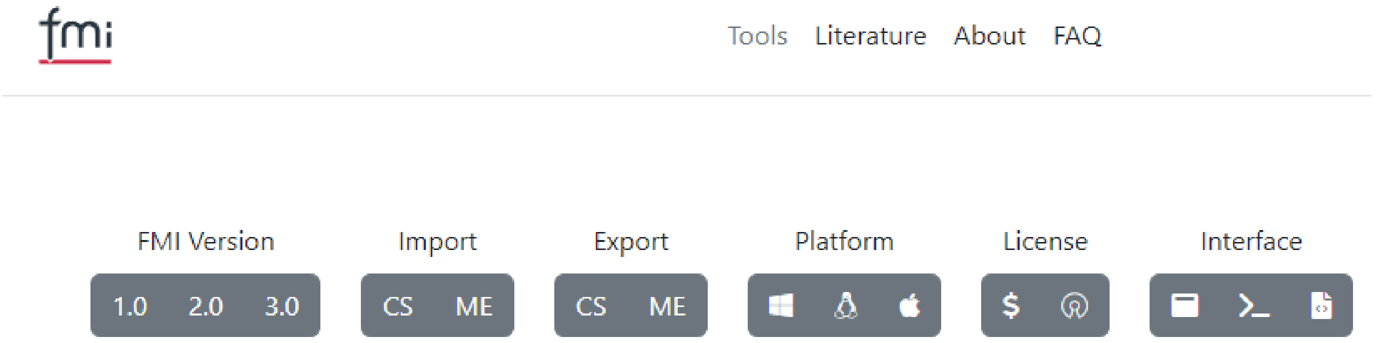
- D
  - Sampling
- A
  - Sampling

- Limited frequency content
- Mathematical ‘glue’

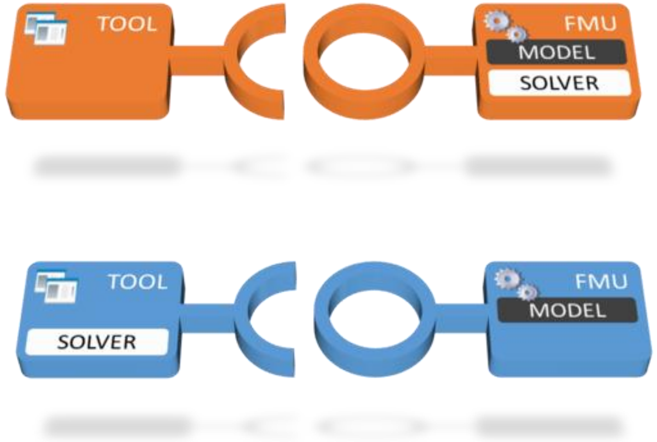
Automotive modelling and simulation historic view

Functional Mock-up Interface

Source: https://fmi-standard.org/tools/



- Functional Mock-Up Interface
  - Open, non-proprietary, interface standard



1.0 – 2010

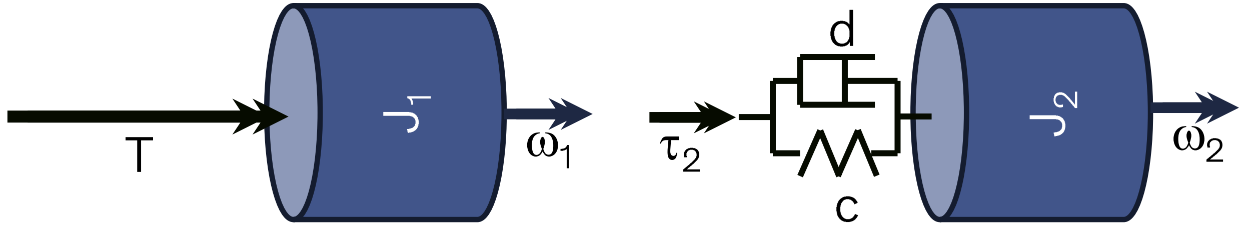
2.0 – 2014

3.0 – 2022

- Good slow specification progression
- Maintains a small compatibility matrix
- Many vendors support standard

Co-Simulation - Stability Analysis

The Model



Transfer function with ZOH Padé approximants inserted

$$H_0 = \frac{J_2(ds + c)}{J_1 \left(\frac{h}{2}s + 1\right)^2 (J_2 s^2 + ds + c)}$$

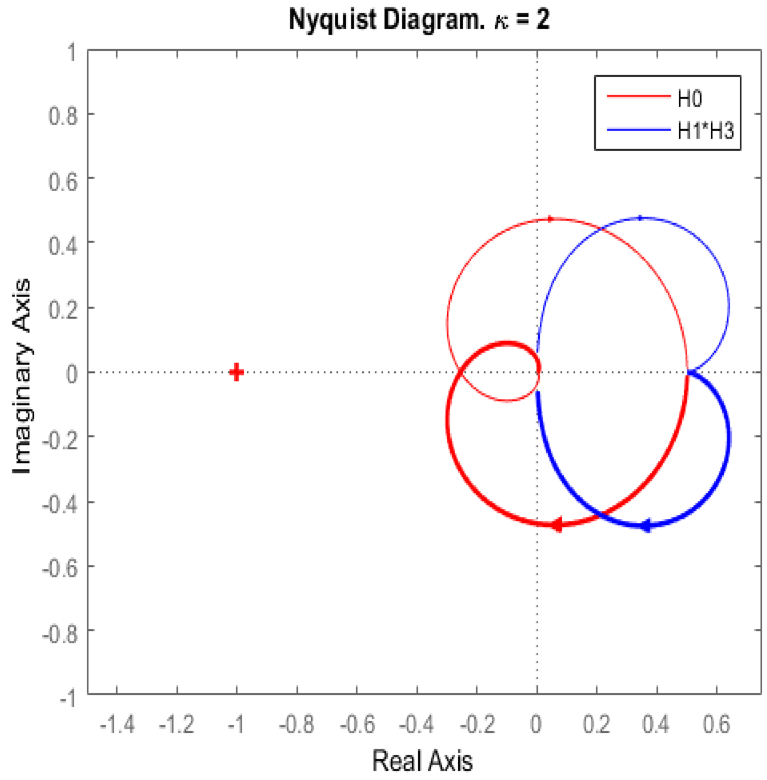
Inertia ratio dominant factor of open-loop gain

$$H_0(0) = \frac{J_2}{J_1} = \frac{1}{\kappa}$$

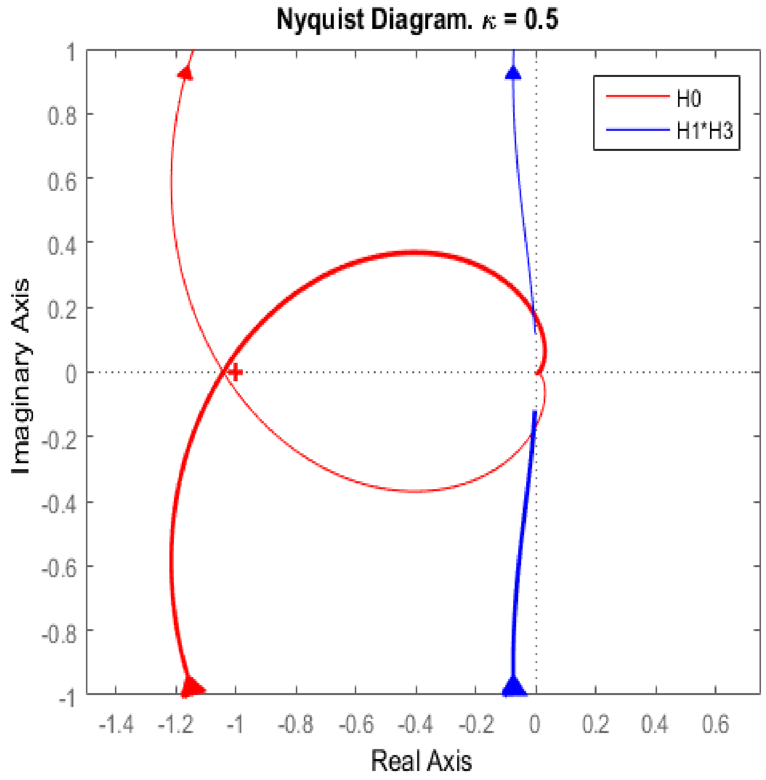
Co-Simulation - Stability Analysis

Open-loop Nyquist

Stable



Unstable

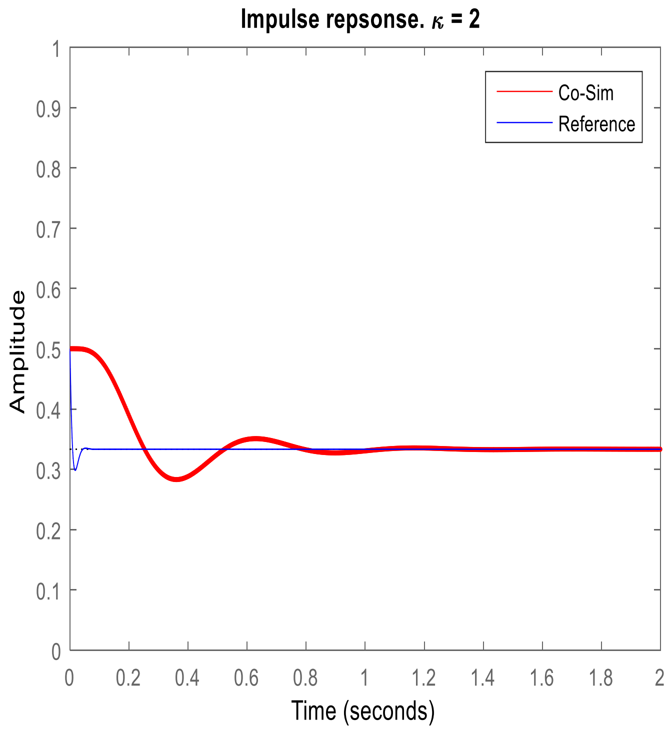


Inertia ratio to determine causality

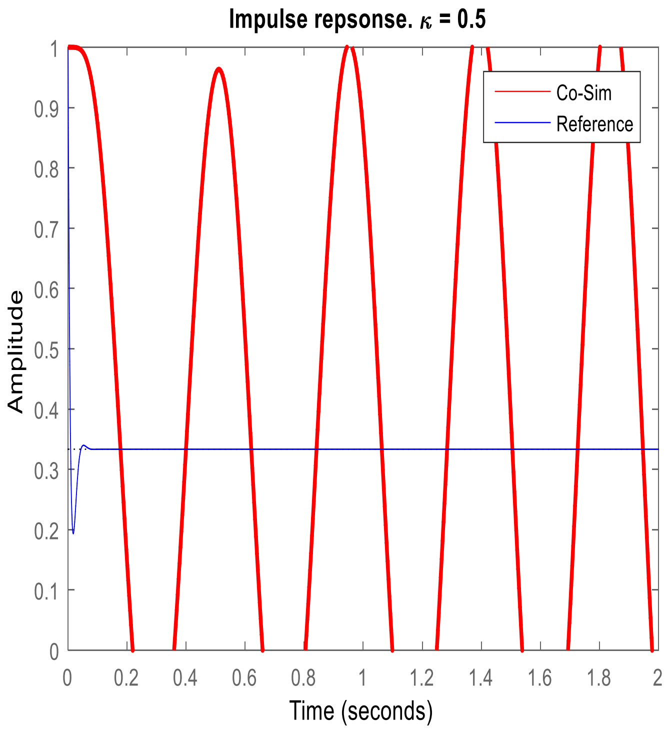
Co-Simulation - Stability Analysis

Impulse Responses – Energy Preserving Connector Elements

Stable

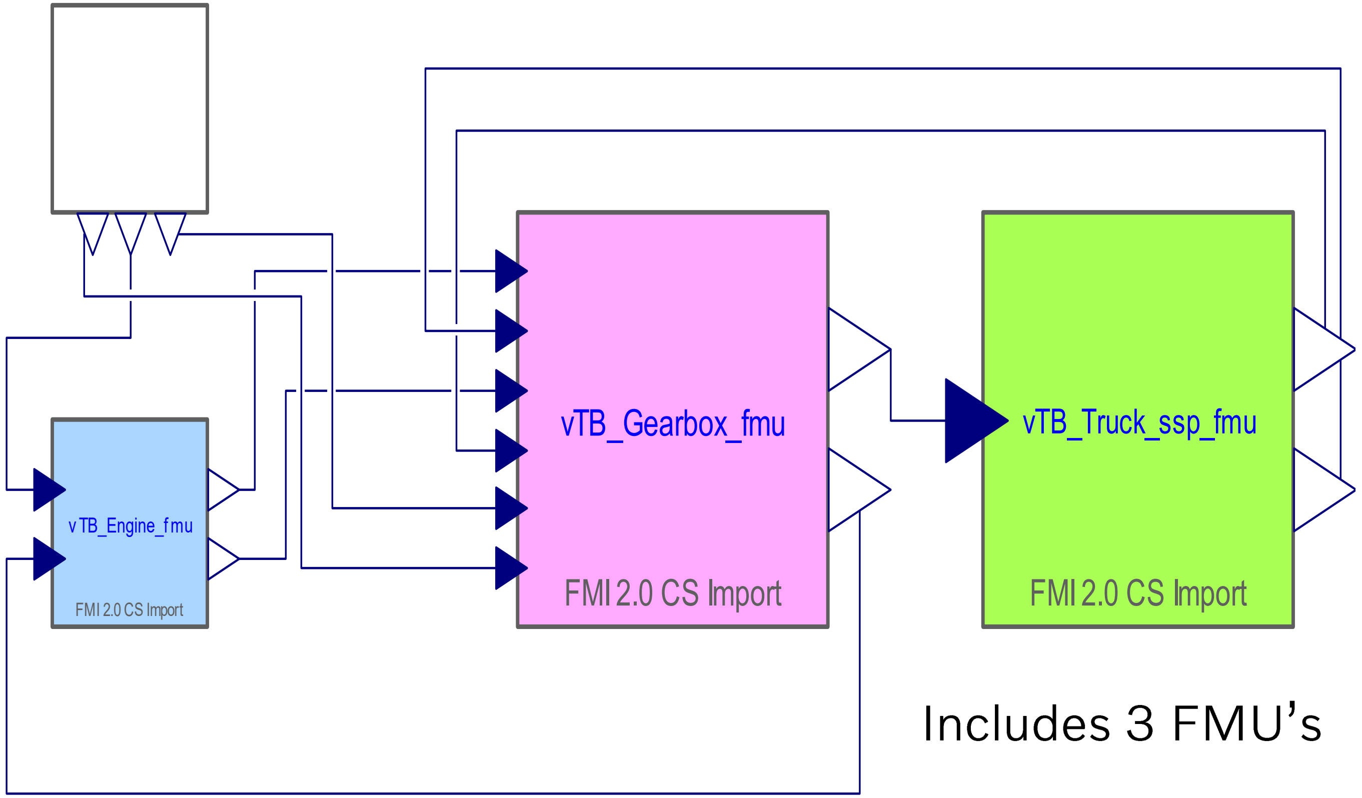


Unstable



Co-Simulation - Architecture

Chained sub-systems - Energy Preserving Connector Elements

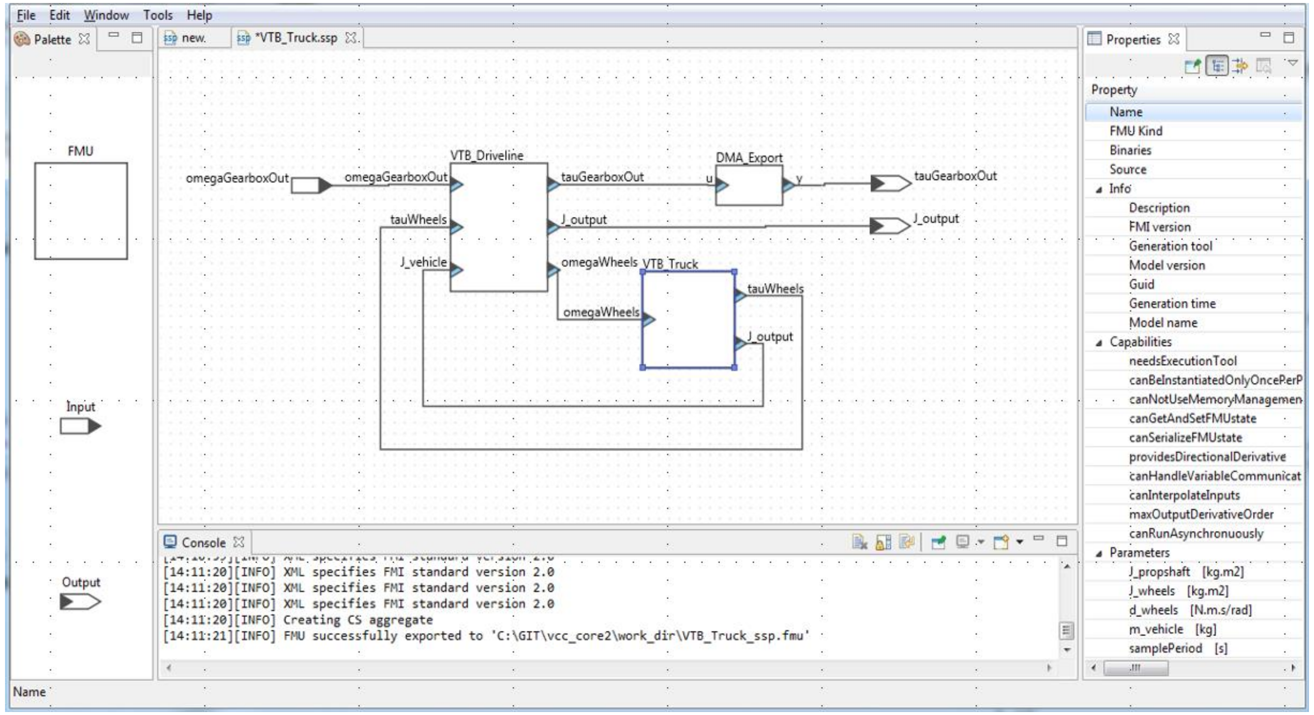


Includes 3 FMU's

Source: "Virtual Truck & Bus" (2014- 007465)

Co-Simulation - Architecture

Aggregate FMUs - Energy Preserving Connector Elements

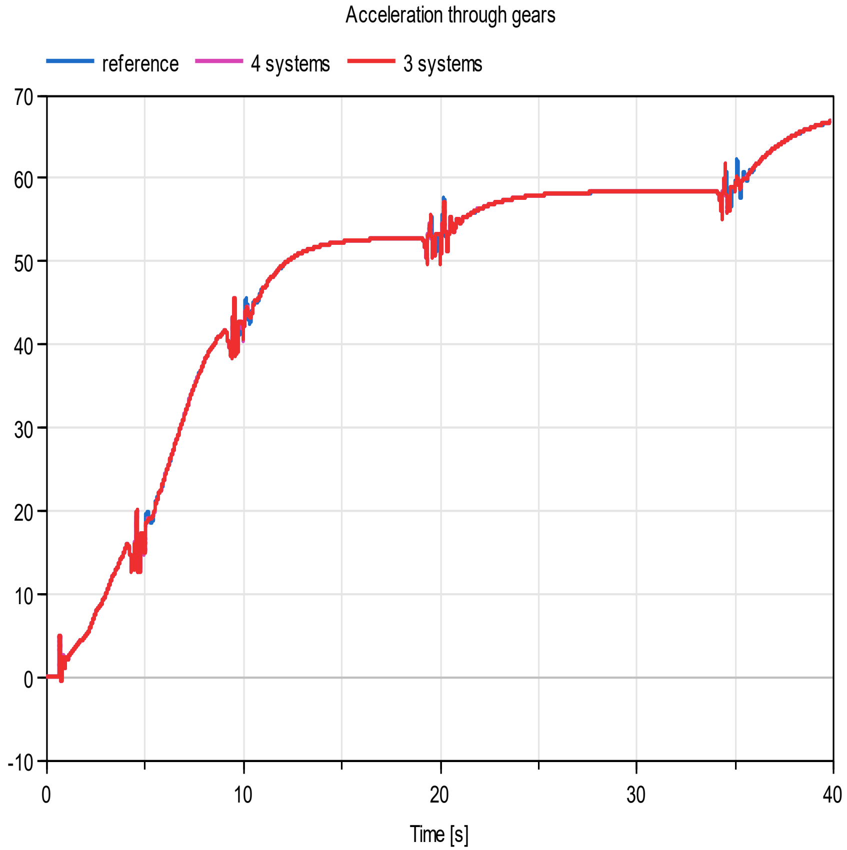


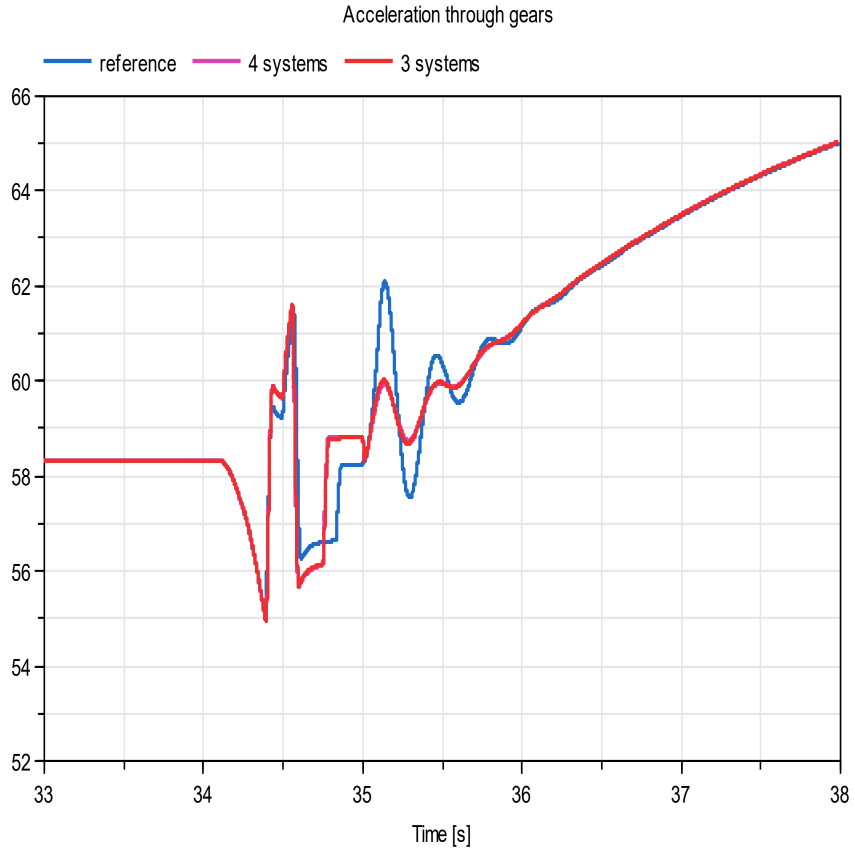
System Structure and Parameterization (SSP)

Source: "Virtual Truck & Bus“ (2014- 007465)

Co-Simulation – Results

Acceleration Through Gears





Transient signal distortion

Quick signal recovery

3- and 4-systems co-simulation basically identical results

4-systems has a performance penalty

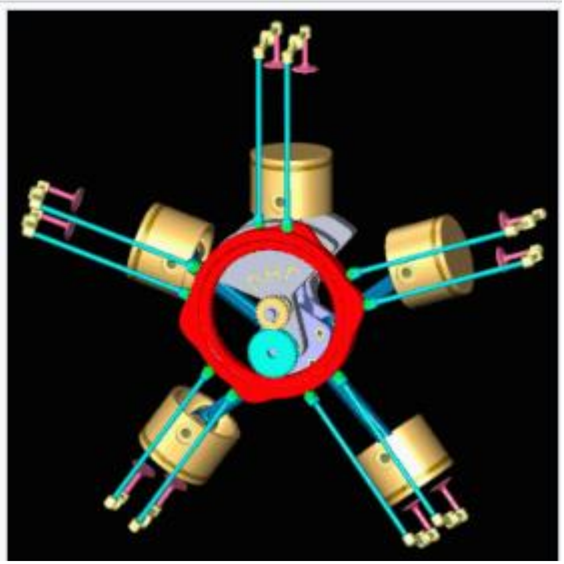
This is by no means trivial due to varying effective inertias

Source: "Virtual Truck & Bus“ (2014- 007465)

Conclusions

Non-iterative co-simulation is control engineering

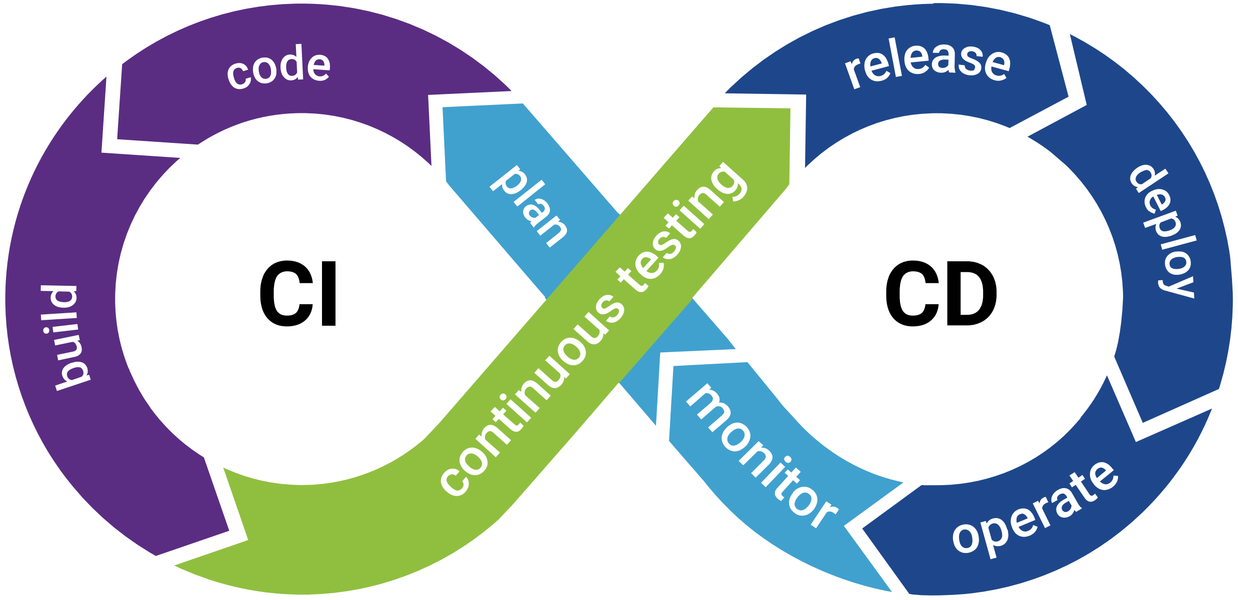
- Impedance ratio determines causality and stability
- One chained element determines flow
  - The remainder are effort loads
- System energy conservation required for asymptotic (steady-state) results
- Strict systems engineering required to design co-simulated plants

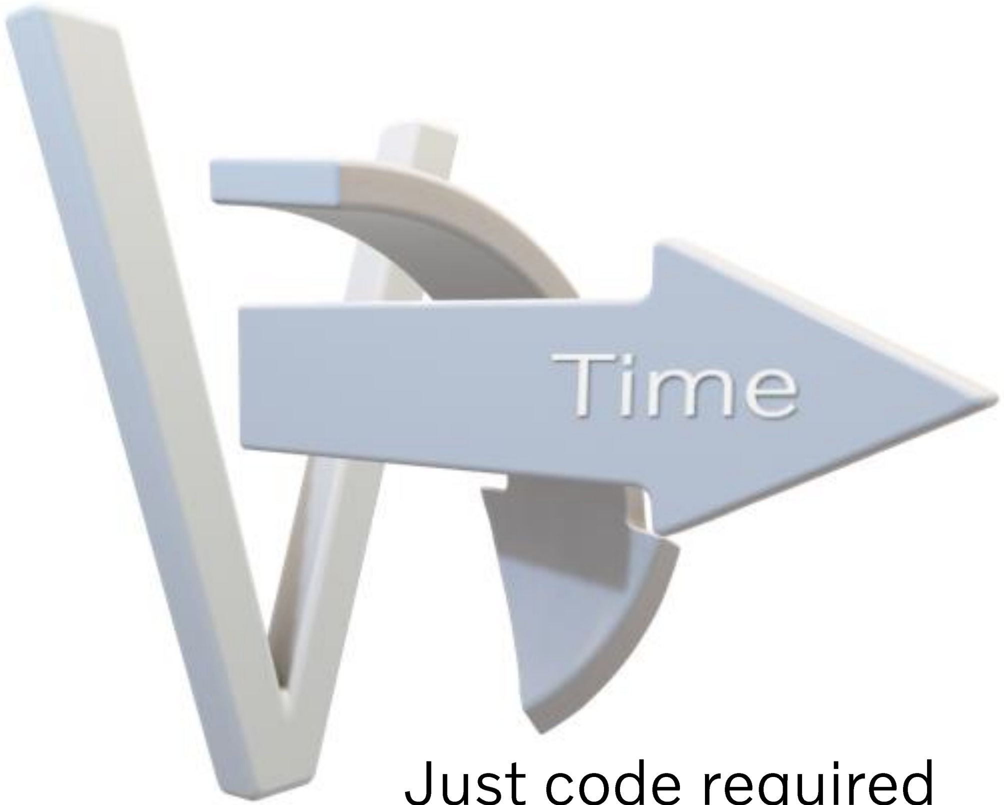


Source: Radial engine, Wikipedia

Software defined systems

Verification speed is key





Just code required

Systems simulation in automation

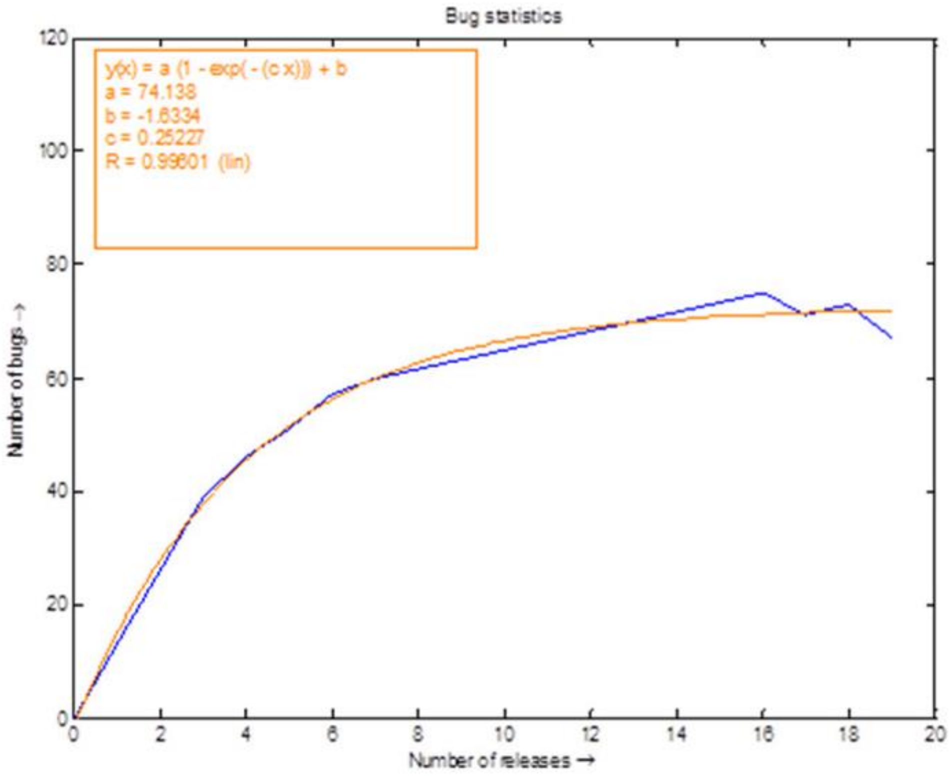
FMU-factory

- Virtual development is **a must** for reaching vehicle/machine automation goals
- Physics modelling and co-simulation is not trivial. Conservation of energy!
- Model development requires regression and CI/CD for assured quality and robustness
- FMU-factory to govern model proliferation for virtual development in multiple integration platforms

Mileage is everything

Acausal paradigm

- Plant model (code) re-use
- Incremental changes with regression
- Declarative (acausal) models are reusable assets in multiple load/test cases
- Imperative (causal) models may require substantial rework even with minor updates

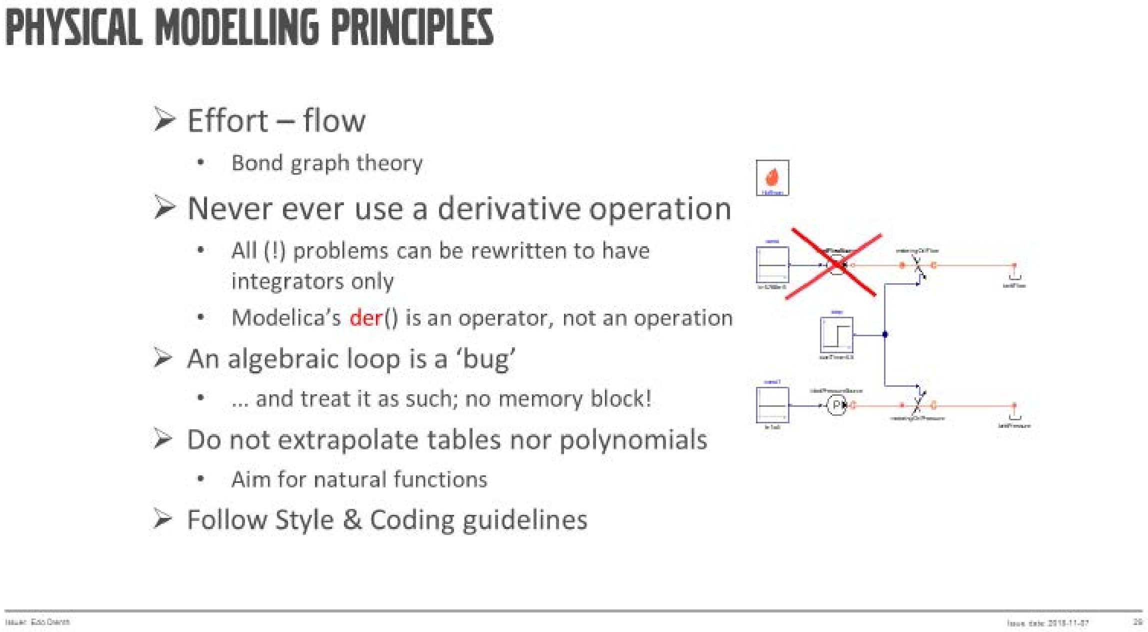


Source: https://www.linkedin.com/pulse/heterogeneous-robust-design-edo-drenth

Plant model requirements

Robust models

- Whatever happens, the simulation needs to carry on
  - A roll-over or a "physical" crash is a possible simulation outcome
    - It may not lead to a premature simulation execution failure
- Model requirements
  - First principles physics
  - Sound extrapolation
    - No use of tables
- Execution requirements
  - Faster than real-time



Source: Automotive Modelling and Simulation - Chalmers

Vehicle/machine model definition

Dynamic agent

– Mathematical description of the **real-world vehicle** behavior.

Constructed of:

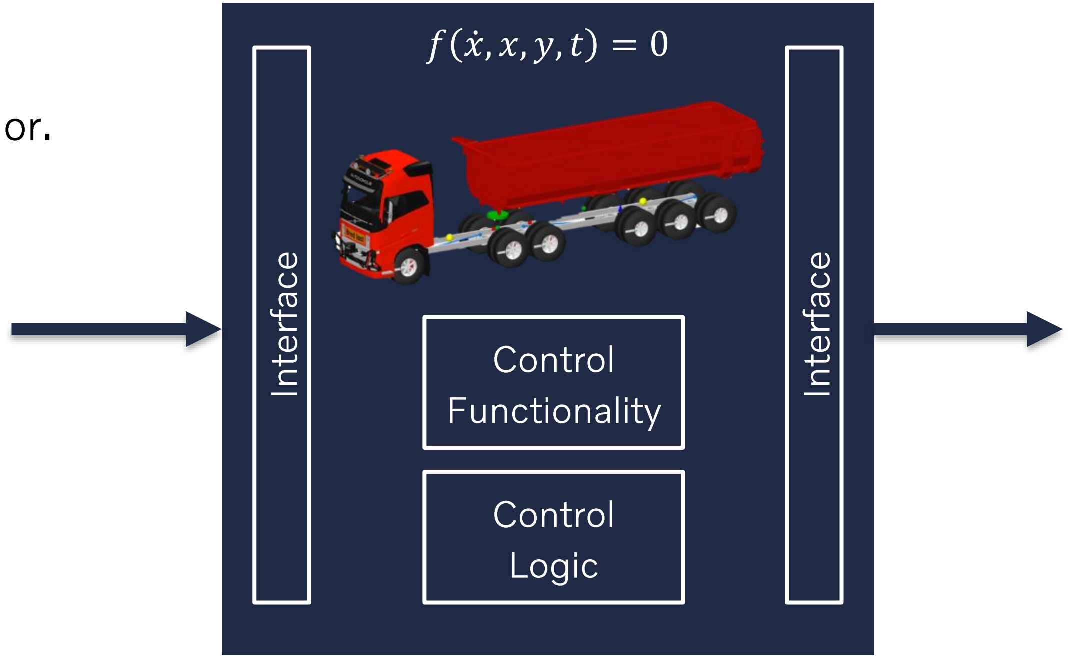
– Plant model: Differential-algebraic equations

– Base vehicle control logic

– Base vehicle control functionality

– Signal/message interfaces

– Simulation interfaces

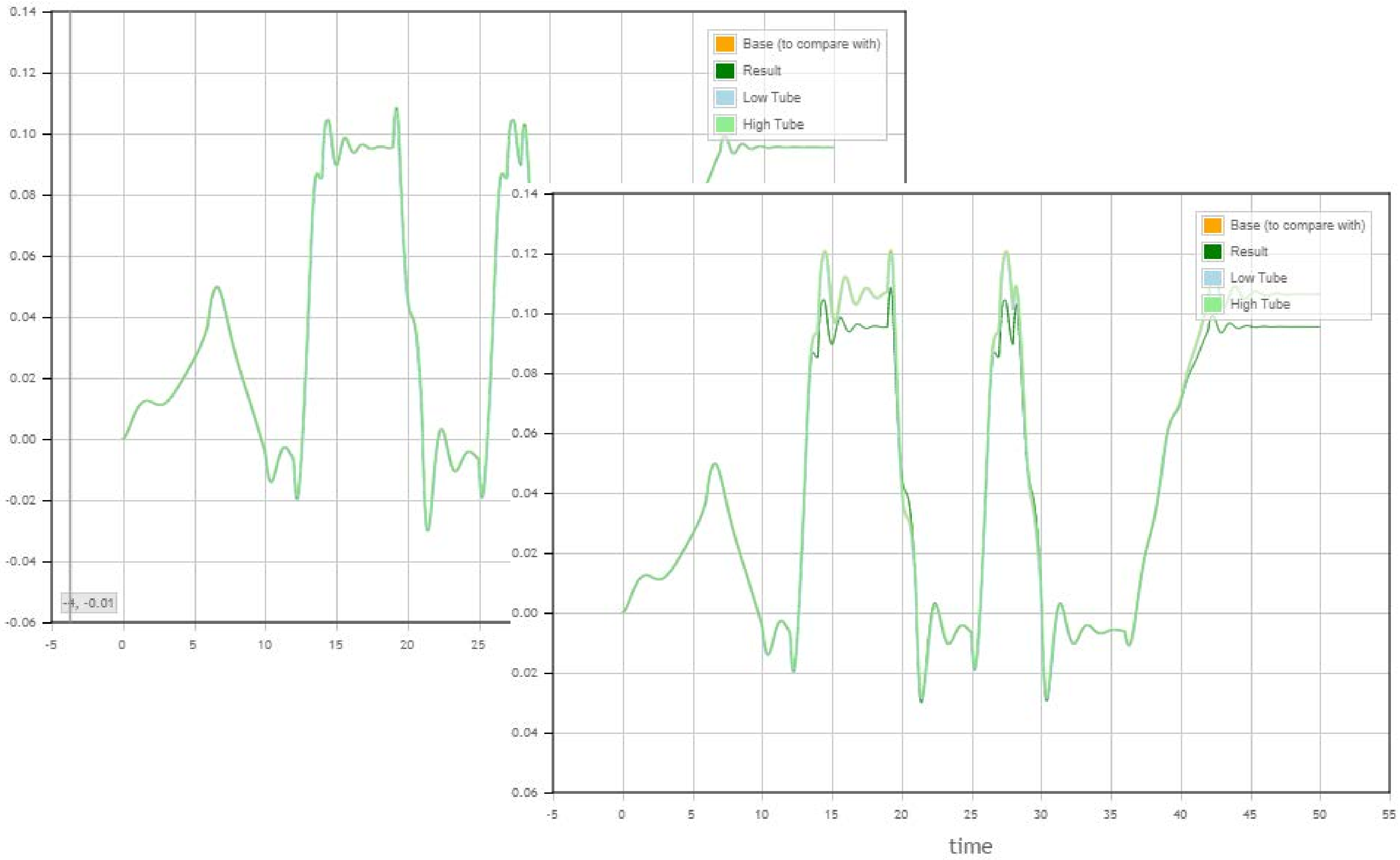


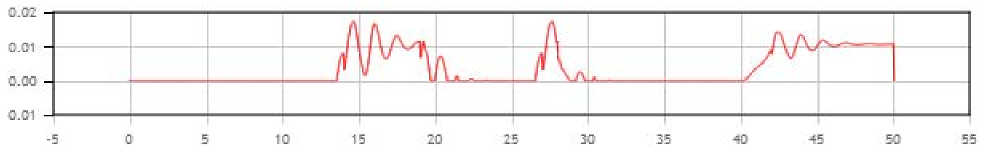
- Single executable: non-iterative co-simulation

Library regression

Controlling model evolution

- Reference results
- No commits on master
- Automatic pipelines per branch
- Merge requires approved
  - – Code review
  - – Regression



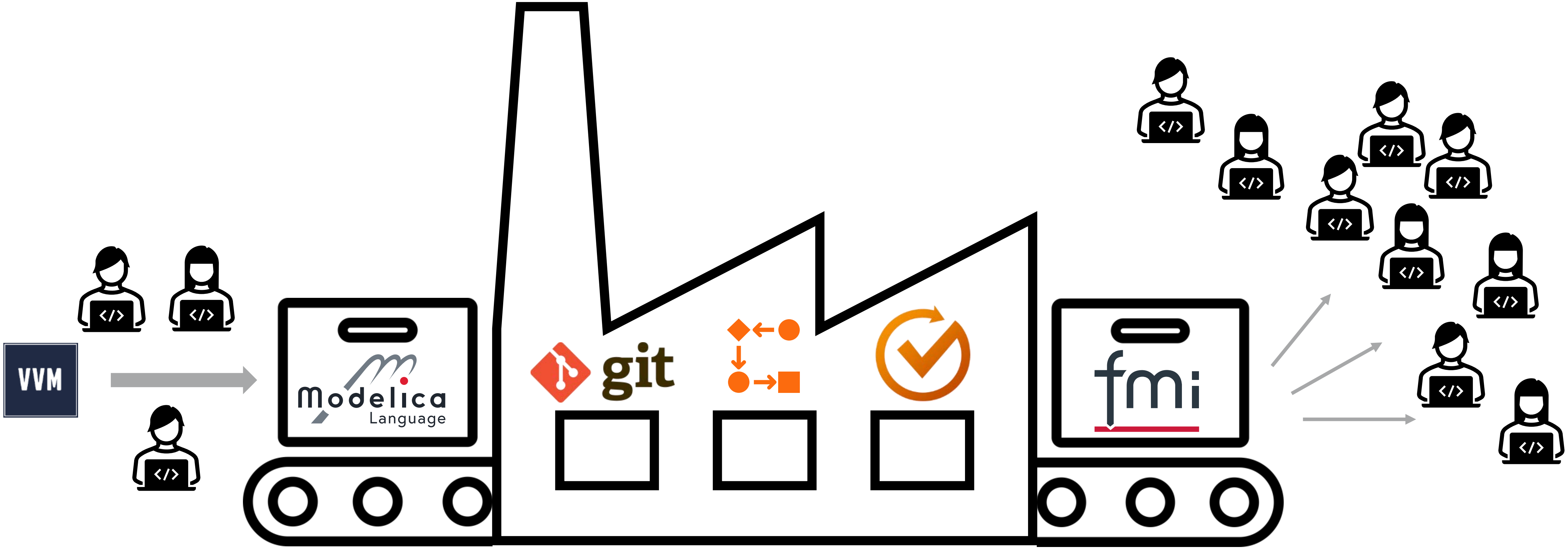


- Just code → Version control → Incremental quality control

It's
just
code

V.A.S FMU-Factory

Software Aided Engineering

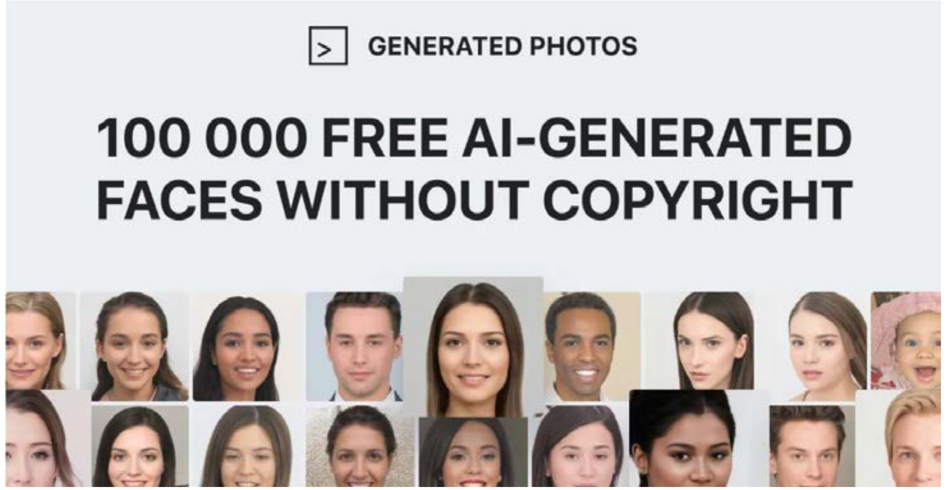


Where do we go from here?

Augmented model automation

- Purpose driven fidelity models
- First principal physics is combined ancestors' intelligence
- ML/AI to find fidelity discrepancies

The model at hand
represents
a possible outcome of a real system



Systems simulation

The essence

“If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.”
— Nikola Tesla

“If you want to find the secrets of *systems simulation*, think in terms of energy, frequency and vibration.”

VOLVO

Presentation 3:

Target Cascading from Full Vehicle Dynamics Targets to System & Subsystem Vehicle Requirements

Axel Villandseie, Volvo Cars

VOLVO

Target Cascading from Full Vehicle Dynamics Targets to System & Subsystem Vehicle Requirements

Target Cascading from Full Vehicle Dynamics Targets to System & Subsystem Vehicle Requirements,
Axel Villandseie, Volvo Cars

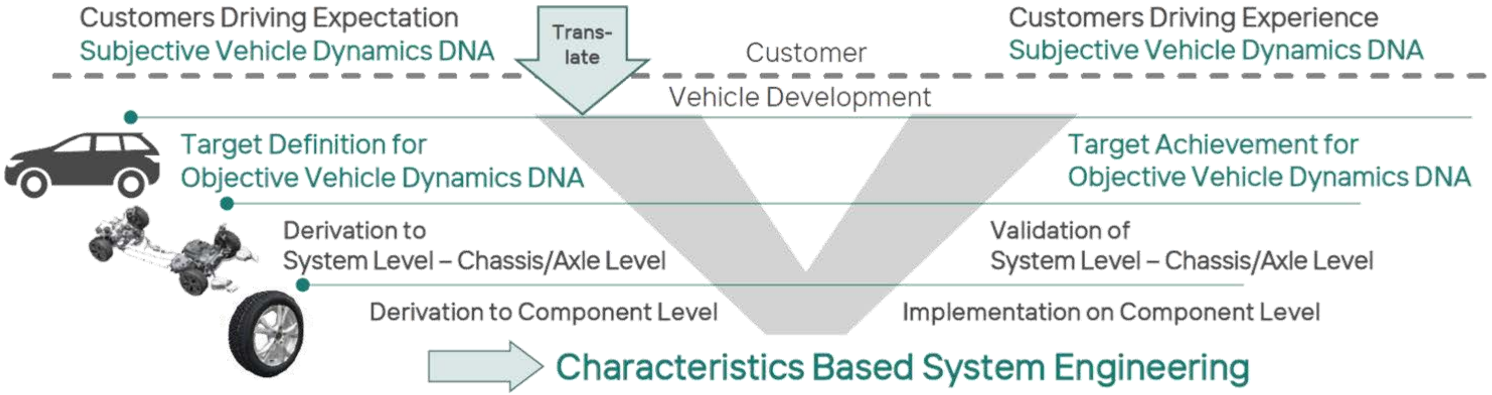
2025.05.07

About the project

Systematic design process for the concept phase that asserts fulfillment of overall vehicle dynamics targets.

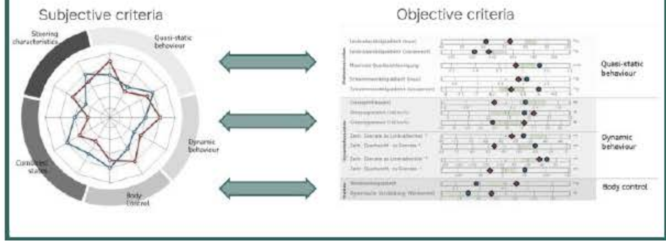
- Eliminates the need for complex (MBS) models for concept design
- Removes the need of component parametrization in early phases
- Cascade full vehicle targets into system & subsystem requirements

Developed together with FKFS in Stuttgart, based on the dissertation *Entwicklung einer fahrwerkauslegungsmethode für pkw zur anwendung in der konzeptphase (Hendrik Abel, 2019) (Development of a chassis design method for cars in the concept phase)*

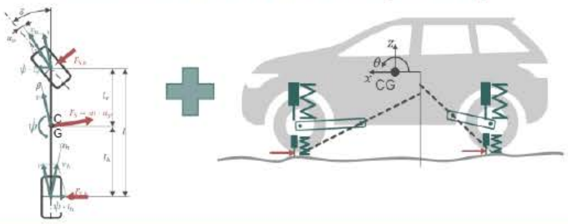


About the project

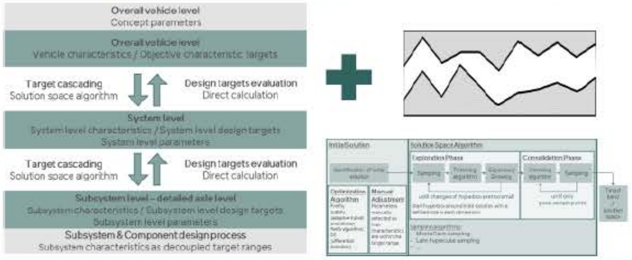
1. Objective full vehicle criteria



2. Efficient vehicle models with reduced complexity



3. Target cascading + solution space

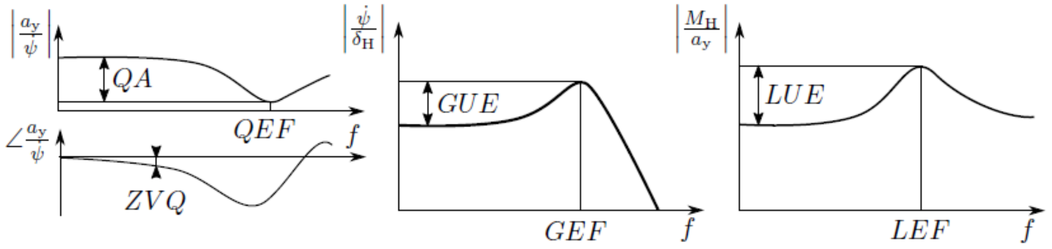


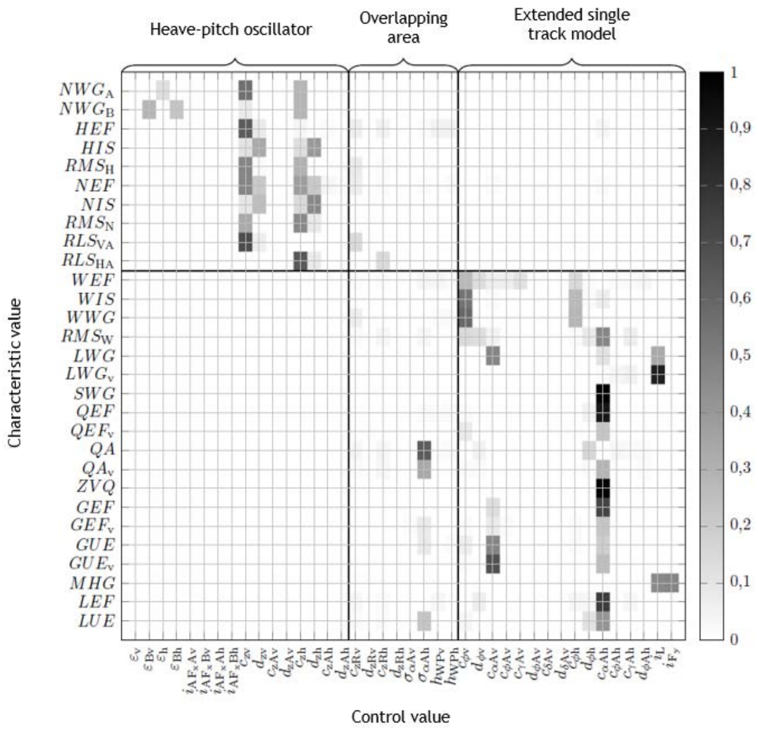
Tool developed in Python

The objective criteria

Special care to develop a new (limited) set of objective criteria that describe the full vehicle dynamics behavior in a logical manner without redundancy.

- Possible to define a preferred design sequence

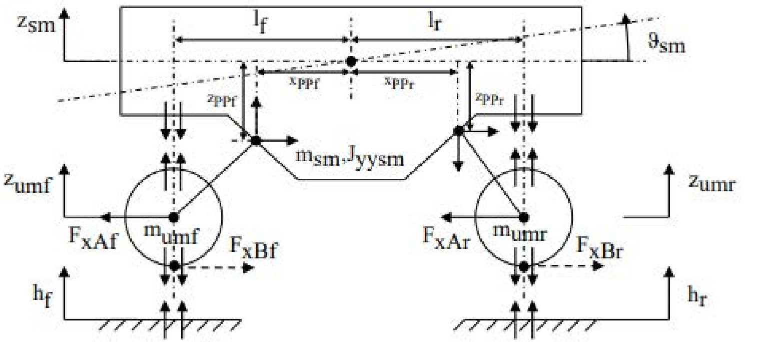


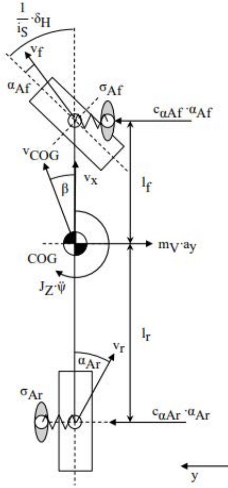


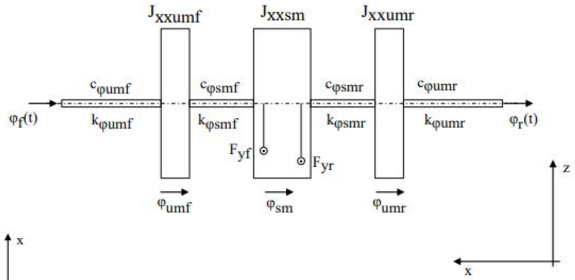
The models

Linear models

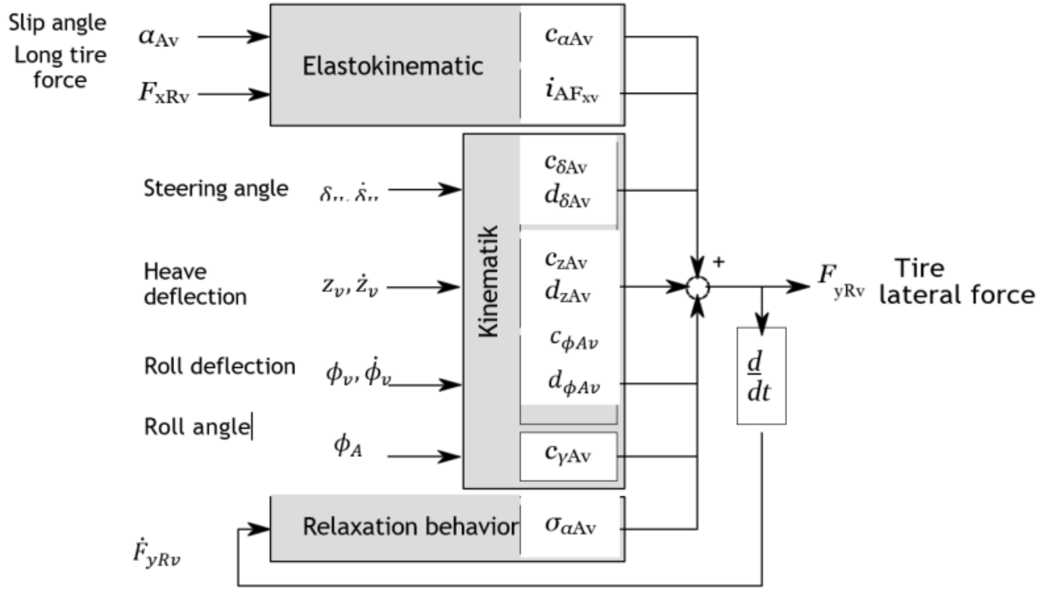
- Ride model
  - Heave & pitch oscillator with longitudinal dynamics (anti-squat & anti-dive)
- Lateral models
  - (Enhanced) Single track model with effective axle characteristics
  - Roll oscillator





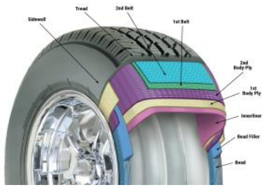


Enhanced Single track model

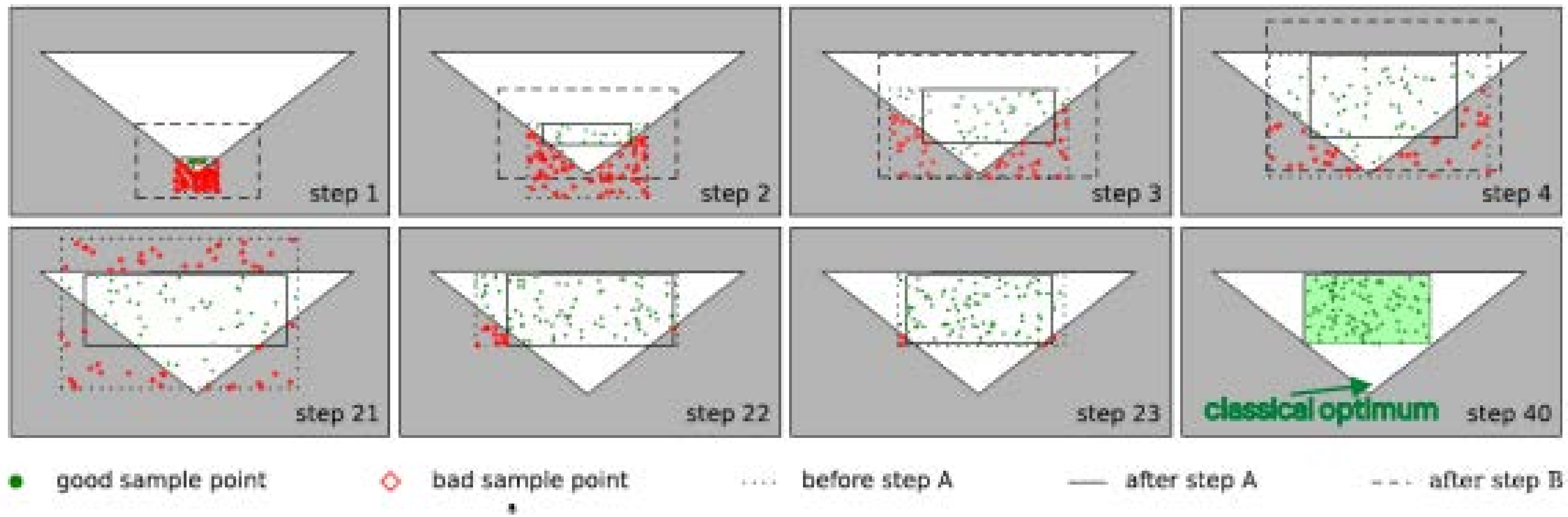


System to subsystem (effective axle characteristics)

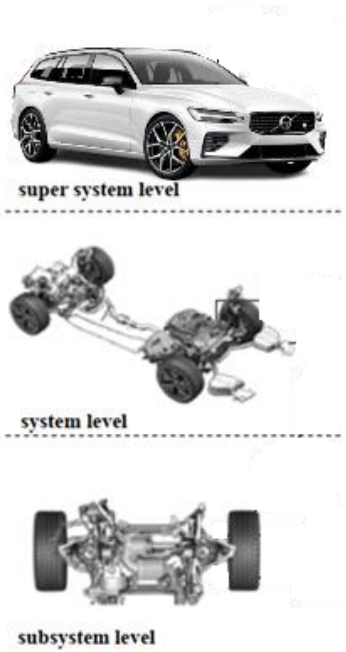
$$c_{\alpha\mathrm{A}} = c_{\alpha\mathrm{R}} \left(1 - \frac{c_{\alpha\mathrm{R}}}{c_{\delta\mathrm{F}_{y,\mathrm{Di}}}} - \frac{c_{\alpha\mathrm{R}}}{c_{\delta\mathrm{F}_{y,\mathrm{In}}}} - \frac{c_{\alpha\mathrm{R}} n_\mathrm{R}}{c_{\delta\mathrm{M}_{z,\mathrm{Di}}}} - \frac{c_{\alpha\mathrm{R}} n_\mathrm{R}}{c_{\delta\mathrm{M}_{z,\mathrm{In}}}} - \frac{c_{\gamma\mathrm{R}}}{c_{\gamma\mathrm{F}_{y,\mathrm{Di}}}} - \frac{c_{\gamma\mathrm{R}}}{c_{\gamma\mathrm{F}_{y,\mathrm{In}}}} - \frac{c_{\gamma\mathrm{R}} n_\mathrm{R}}{c_{\gamma\mathrm{M}_{z,\mathrm{Di}}}} - \frac{c_{\gamma\mathrm{R}} n_\mathrm{R}}{c_{\gamma\mathrm{M}_{z,\mathrm{In}}}} + \frac{c_{\alpha\mathrm{R}} i_{\mathrm{F}_y}}{c_\mathrm{L} i_{\delta*}} + \frac{c_{\gamma\mathrm{R}} i_{\mathrm{F}_y}}{c_\mathrm{L} i_{\gamma*}} \right)^{-1}$$



Solution space algorithm



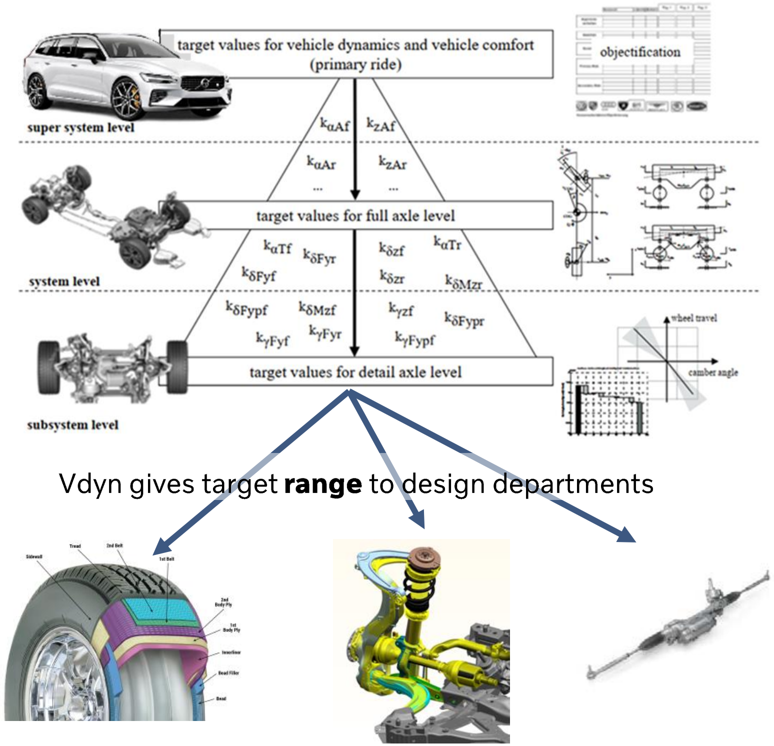
Visualization



Concept level:	Overall vehicle parameters, such as mass, wheelbase, inertias, cog-heigh etc.
System level:	Overall system characteristics, such as vertical stiffness, roll stiffness, damping, roll center height, steering ratio
Subsystem level:	Linearized suspension characteristics, such as tire cornering stiffness, tire relaxation length, bump steer, compliance steer, EPAS assist, etc.
Effective axle characteristics:	Input to the vehicle model. Calculated based on subsystem parameters. For example, axle cornering stiffness, axle relaxation length, axle camber stiffness, axle roll kinematic stiffness + damping
Objective requirements:	Can be calculated as a result from the vehicle model. If the solution space algorithm is to be used, the objective requirements act as the cost function.

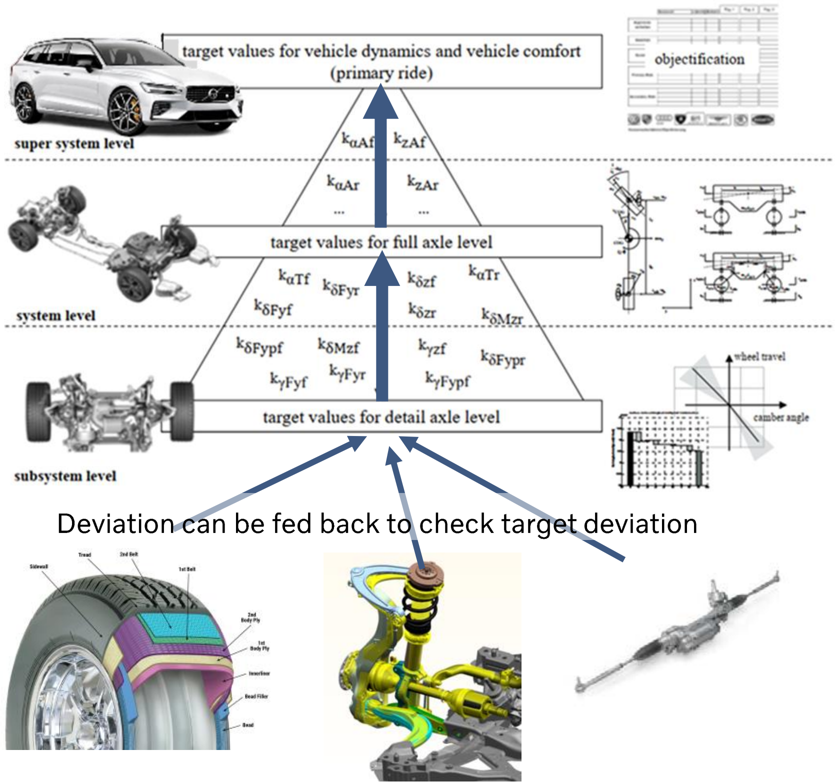
VOLVO

Top-down

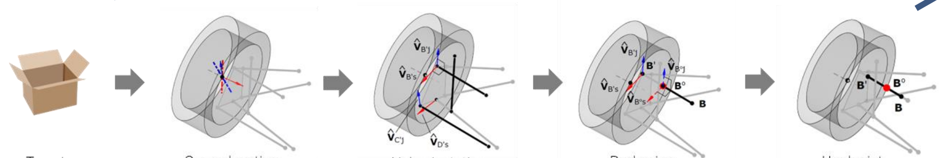


Vdyn gives target **range** to design departments

Bottom-up



Deviation can be fed back to check target deviation



Cascading to suspension hardpoints & flex elements

VOLVO

Thank you for your attention!
Questions?

Presentation 4:

Rolling resistance on roads with various weather and surface conditions

Mikael Askerdal, Volvo LV and Chalmers

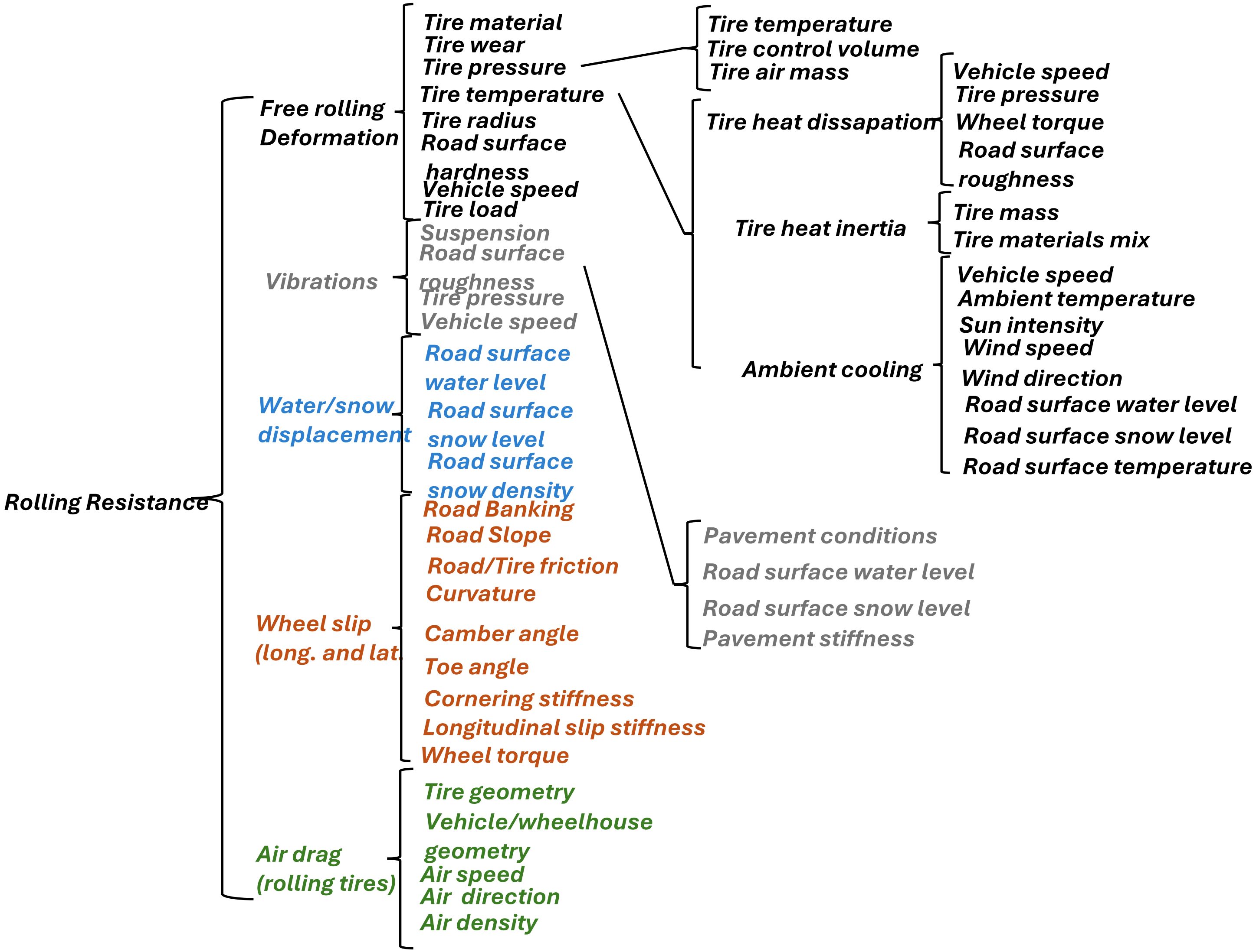
Rolling resistance on roads with various weather and surface conditions

Mikael Askerdal, AB Volvo

Content

- Rolling resistance model overview
  - static and dynamic
- Tire temperature measurements in different weathers and road conditions
- Implications of a linear heat dissipation model
- Conclusions

Overview and definitions of rolling resistance



Overview and definitions of rolling resistance

How is rolling resistance defined?

RR modeled from operating conditions / tire temperature

RR modeled from residual motion resist.

ResidualRR =

- $\sum$ ***TireRR***
  - ***Tire Hysteresis Losses (reported to be 80-90% of total rolling resistance)***
  - *Road/Surface Slip/Friction*
- \+
- *ExtendedRR*
  - *Road Surface Compression*
  - *Water/Snow Displacement*
  - *Suspension Losses*
  - *Bearing Losses*
  - *Cornering resistance*

(Hyttinen et. al (Scania))

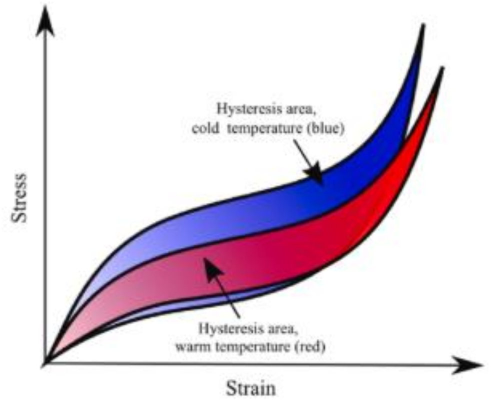


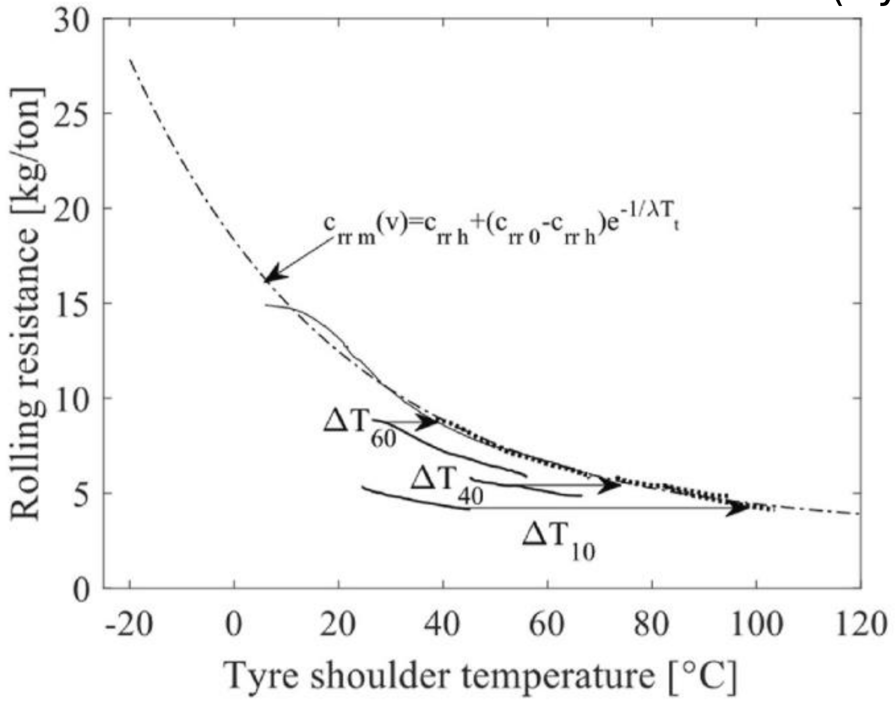
Fig. 2. Filled rubber hysteresis at different temperatures. The increase in temperature causes a decrease in hysteresis area and stiffness.

"the mechanical energy converted into heat by a tire moving for a unit distance on the roadway"

Tire rolling resistance model development

RR as a function of operating conditions / tire temperature

(Hyttinen et. al (Scania))



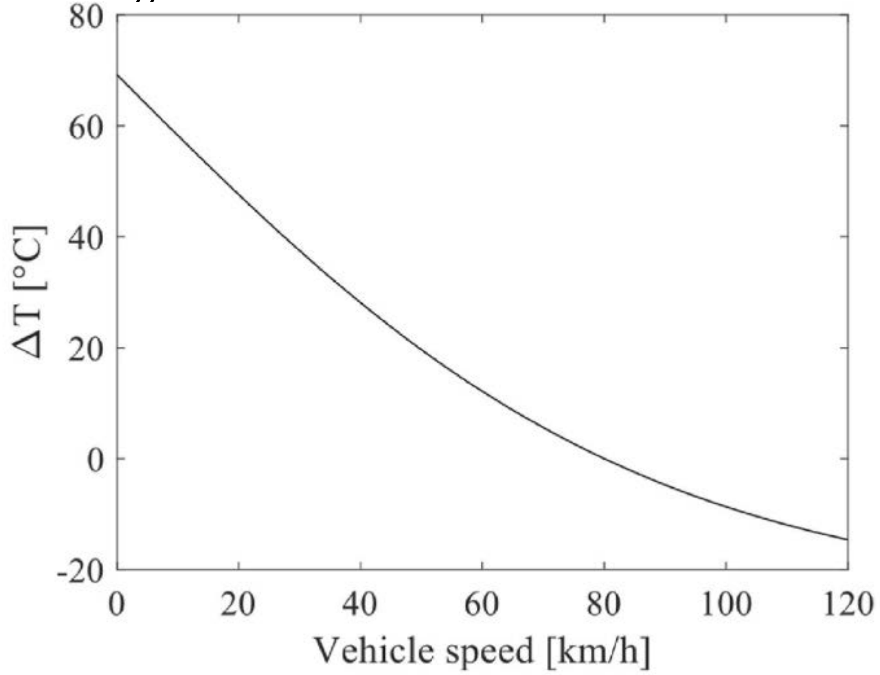


Fig. 27. The shift temperature (ΔT) at different speed levels.

$$c_{rr}(T_t, P_t, v) = \frac{||F||(c_0 + c_1 e^{-c_2 T_t} + c_3 e^{-c_2 T_t} \log(v+1))P_t^{-0.5}}{F_z}$$

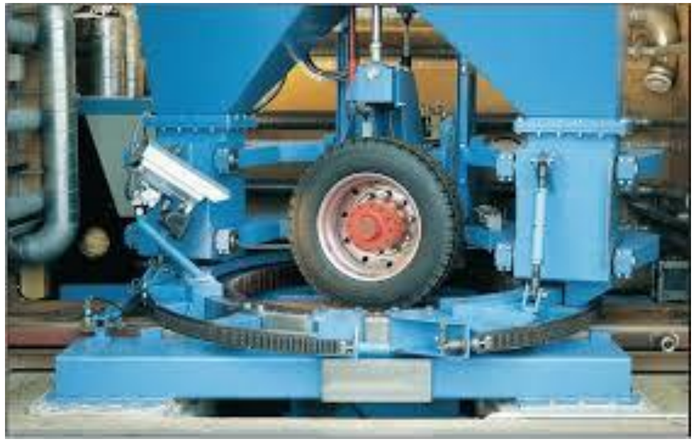
Ongoing work

Create a dynamic rolling resistance and tire temperature model taking road weather into account

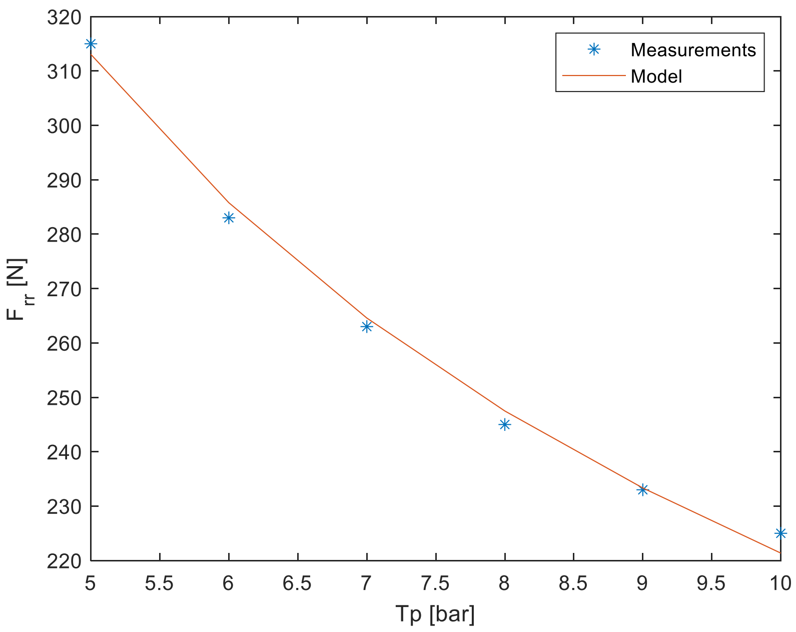
Tests at ”långa banan”, VTI, Linköping, to find a model on

how rolling resistance depend on operating conditions, i.e.

- Tire temperature
- Tire pressure
- Vehicle speed (5-36 km/h)

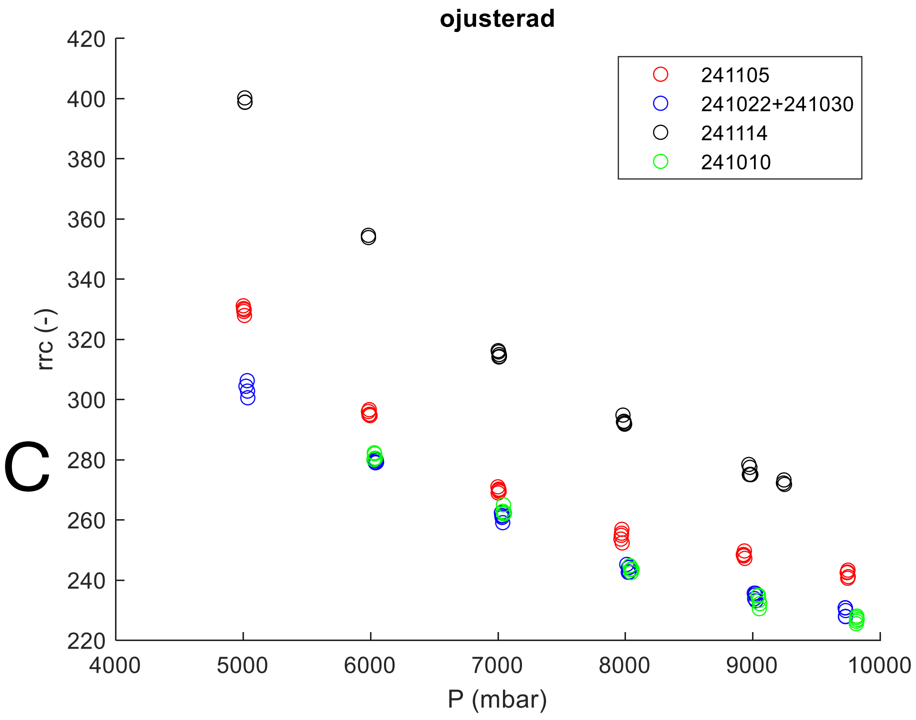


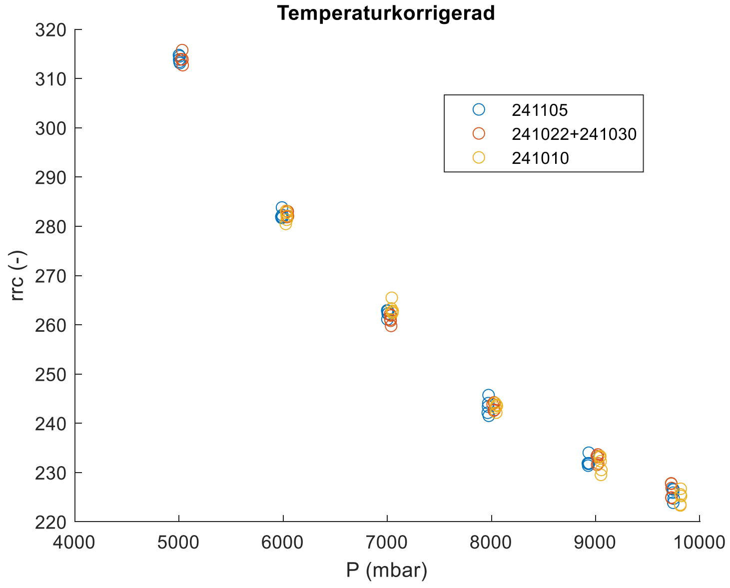
RR vs tire temperature



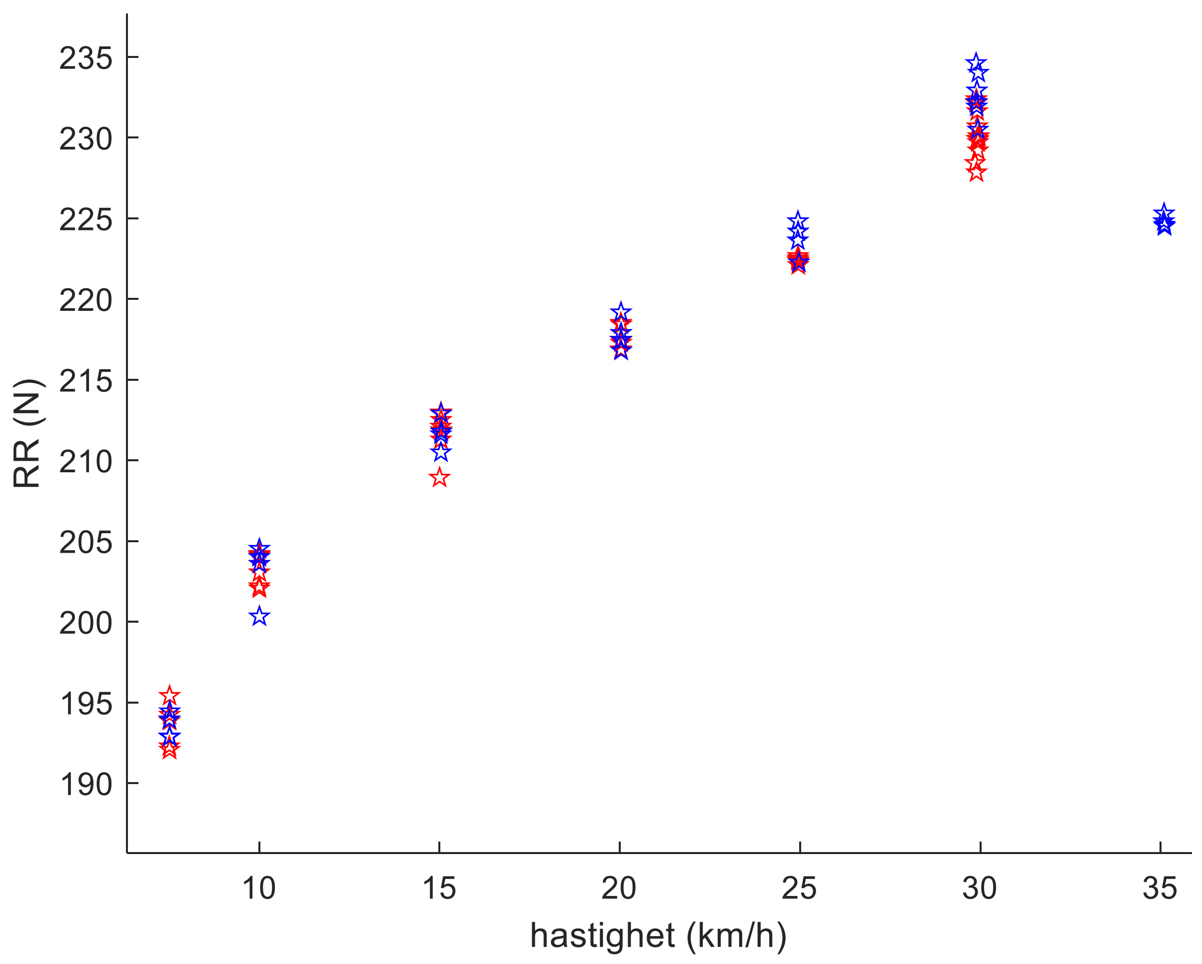
$$c_{rr} \approx C \; * \; P_t^{-0.5}$$

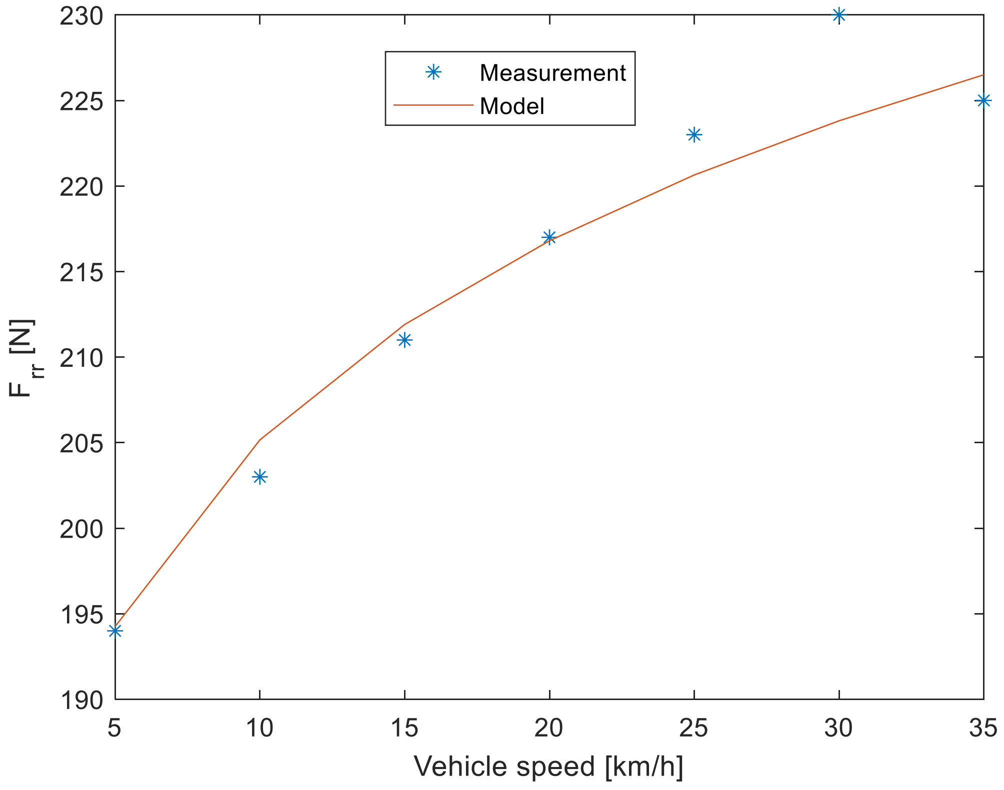
- Black - 6.8°C
- Red – 16.7 °C
- Green – 20.3 °C
- Blue – 20.6 °C





Vehicle speed

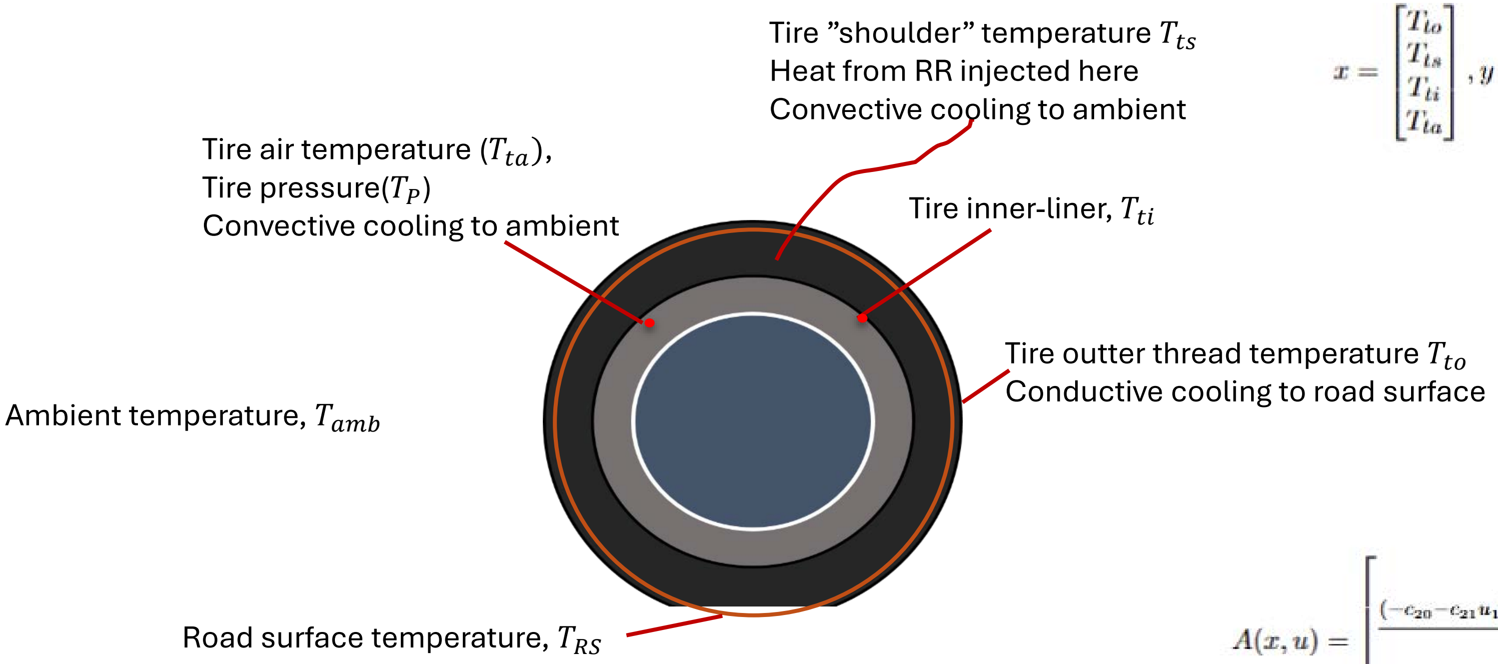




$$c_{rr} \approx C * \log(v+1)$$

Next steps

Create a dynamic rolling resistance model and a rolling resistance observer that take various road weather into account



Conductive heat transfer between different parts of tire

$$x = \begin{bmatrix} T_{to} \\ T_{ts} \\ T_{ti} \\ T_{ta} \end{bmatrix}, y = Cx + D; C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & n_{air} \end{bmatrix}, D = \begin{bmatrix} 0 \\ 0 \\ n_{air} * 273.15 \end{bmatrix} \quad (1)$$

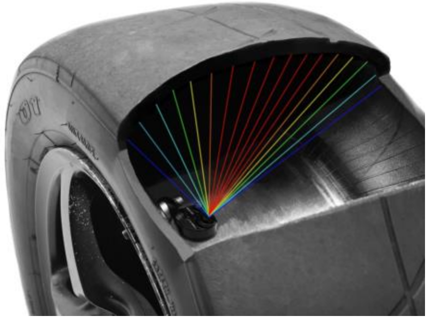
$$u = \begin{bmatrix} v_v \\ F_{tot} \\ T_{rs} \\ T_a \end{bmatrix} \quad (2)$$

$$\dot{x} = A(x, u); \quad (3)$$

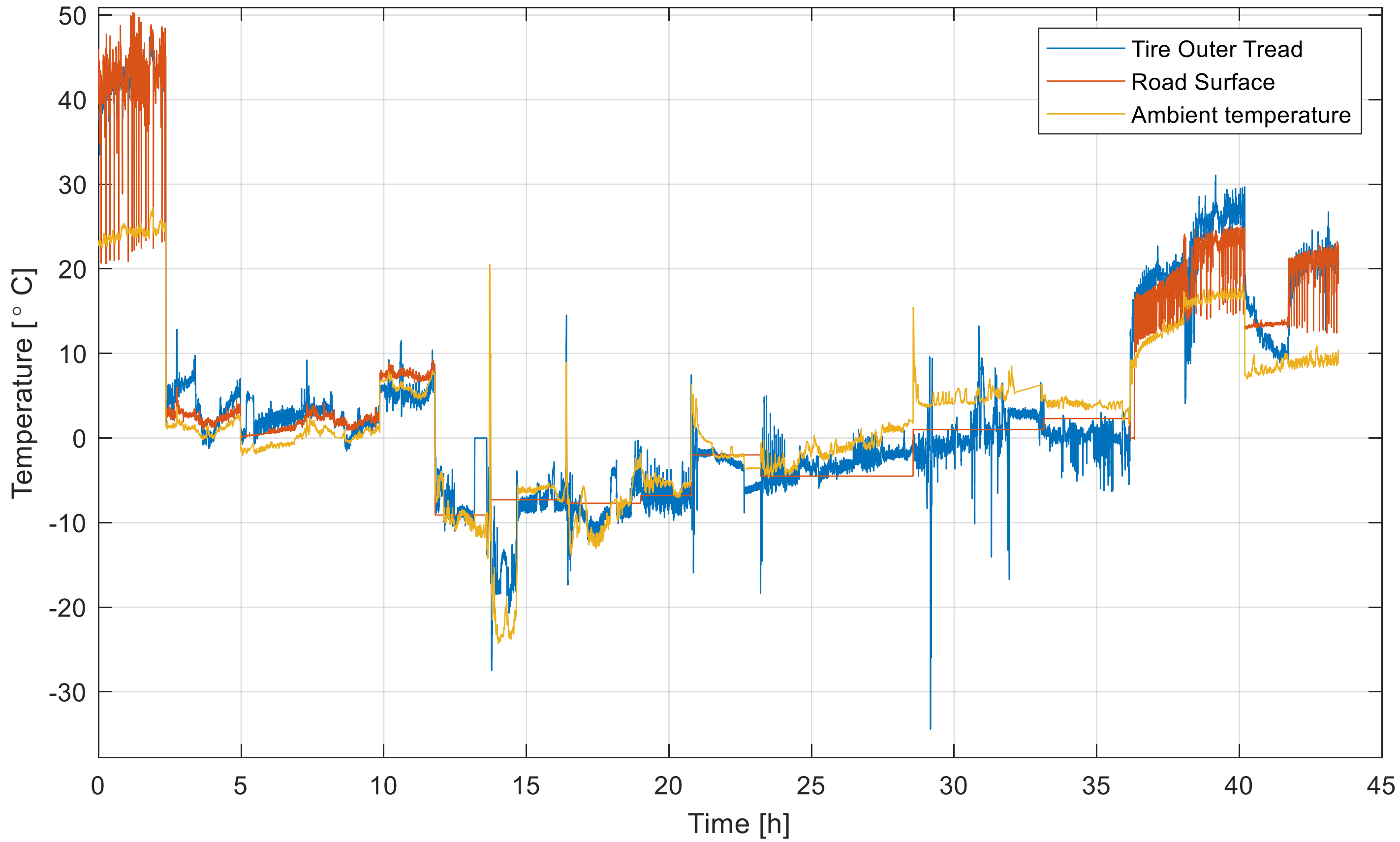
$$A(x,u) = \begin{bmatrix} \frac{(-c_{10} - c_{11}u_1 + c_{13}u_1^2)(u_3 - x_1) + c_{12}(x_2 - x_1)}{mc_{t1}} \\ \frac{(-c_{20} - c_{21}u_1)(u_4 - x_2) + c_{12}(x_1 - x_2) + c_{22}(x_3 - x_2) + u_1 u_2 (c_0 + c_1 e^{-c_2 x_2} + c_3 log(u_1 + 1) e^{-c_2 x_2}) \frac{P_t}{P_0}^{-0.5})}{mc_{t2}} \\ \frac{c_{22}(x_2 - x_3) + c_{30}(x_4 - x_3)}{mc_{t3}} \\ \frac{c_{30}(x_3 - x_4) + (c_{40} + c_{41}u_1)(u_4 - x_4)}{mc_{t4}} \end{bmatrix} \quad (4)$$

Temperature measurements

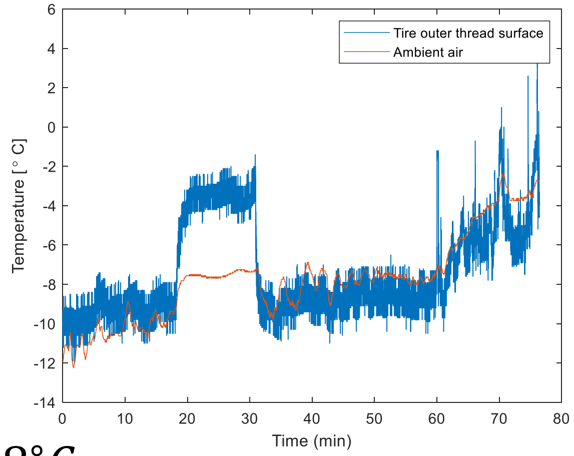
Test vehicle



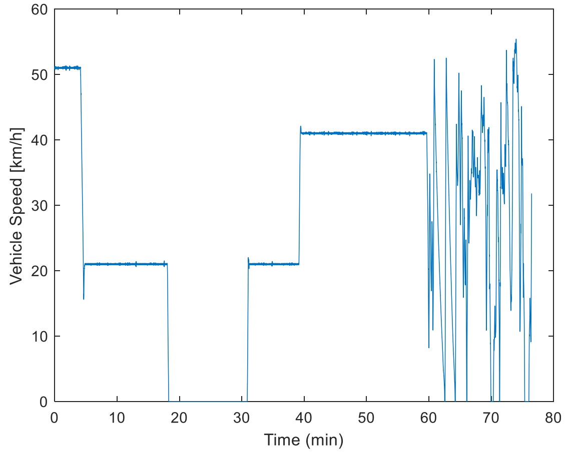
Temperature measurements

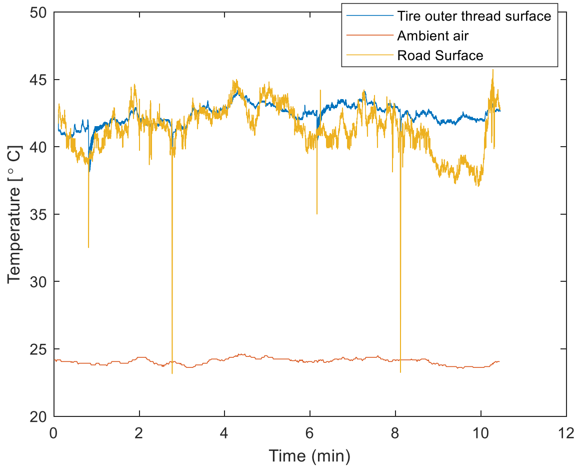


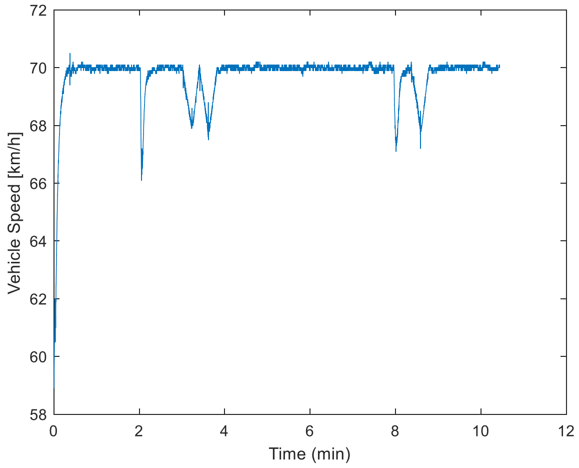
Tire outer tread and road surface temperature

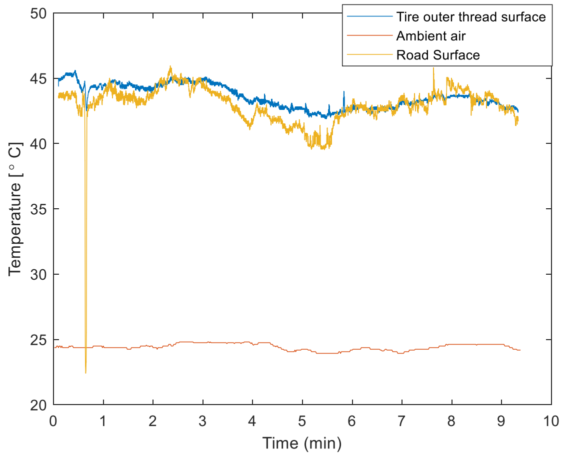


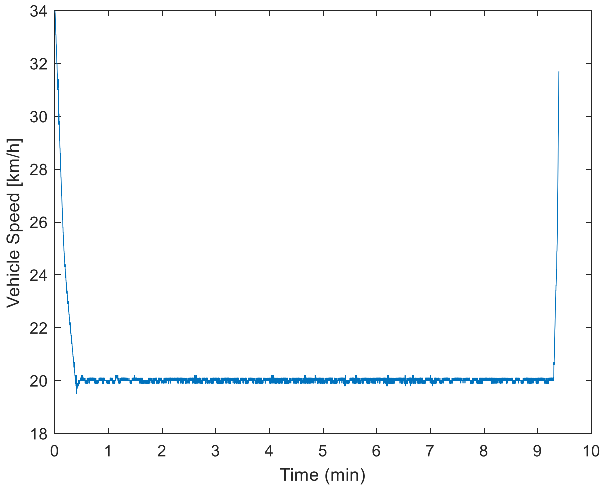
$T_{RS} \approx -8°C$



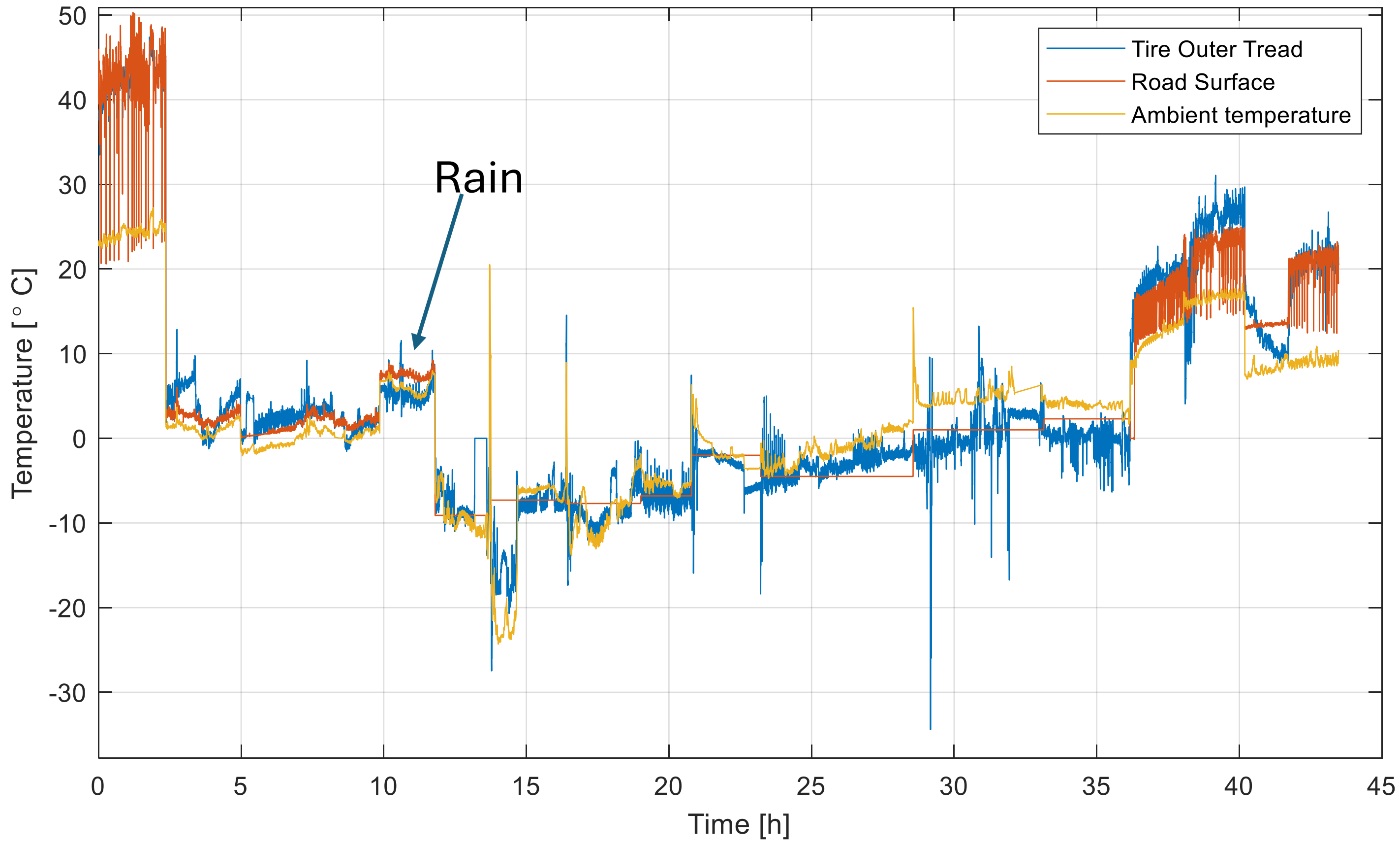




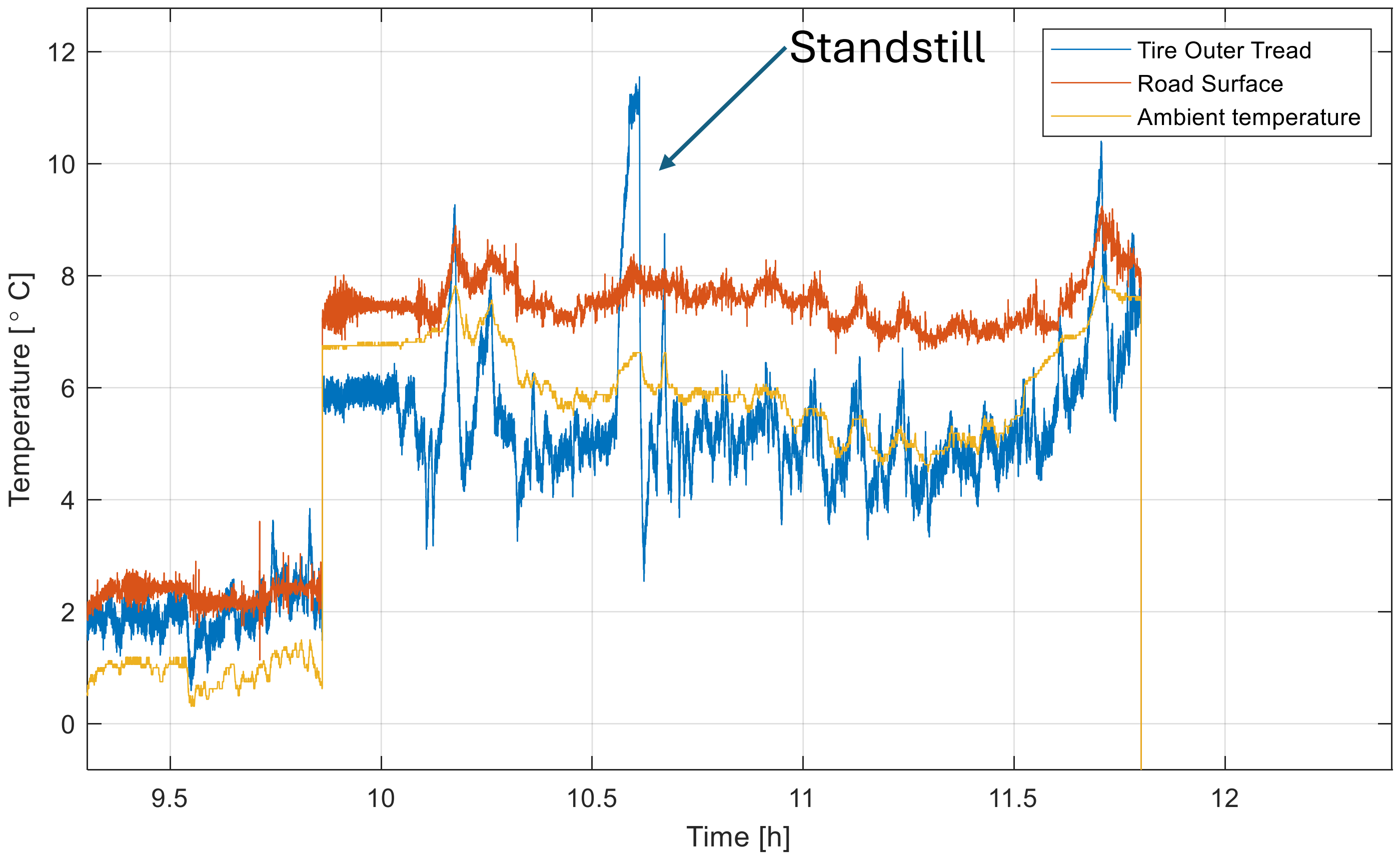




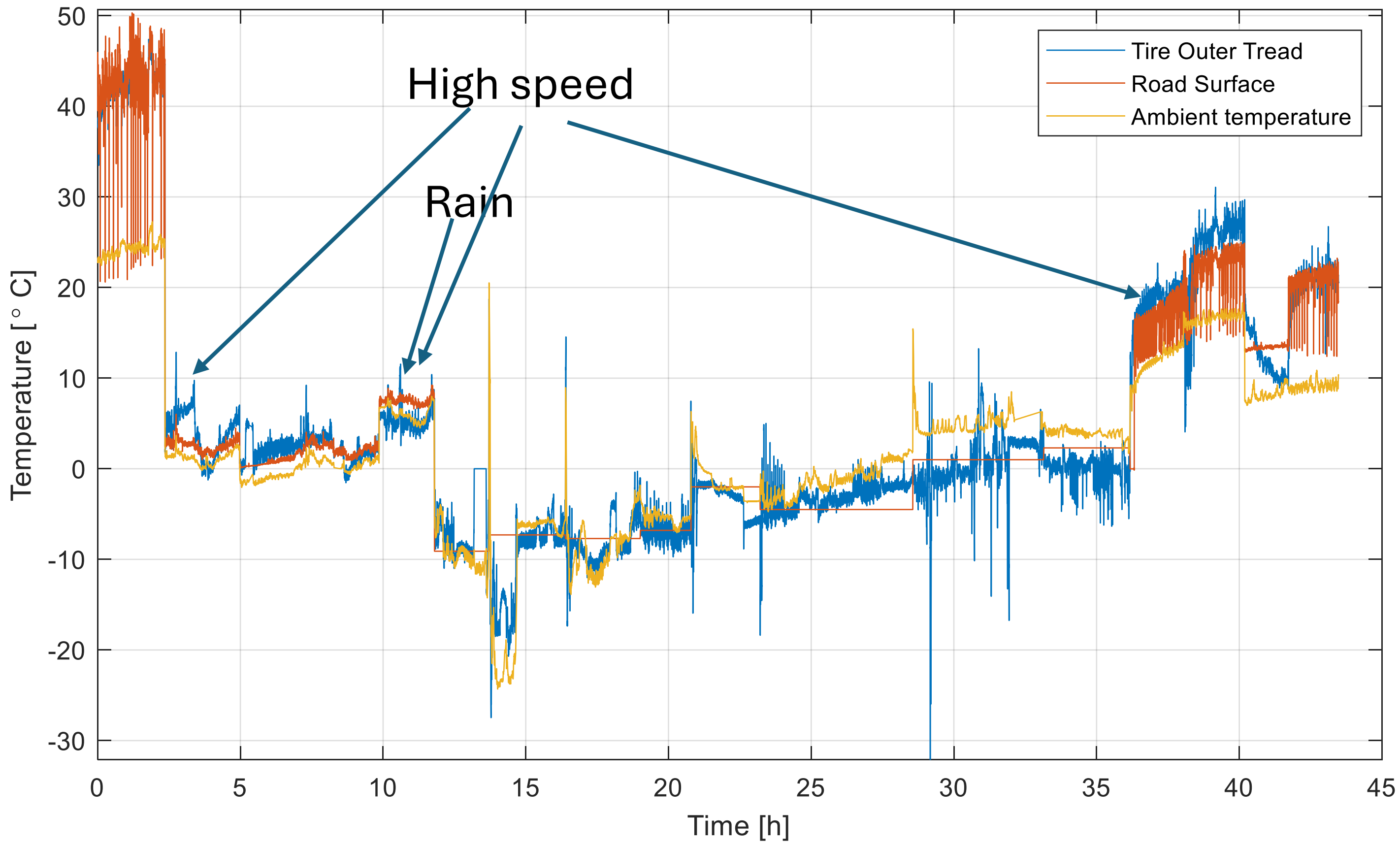
Temperature measurements



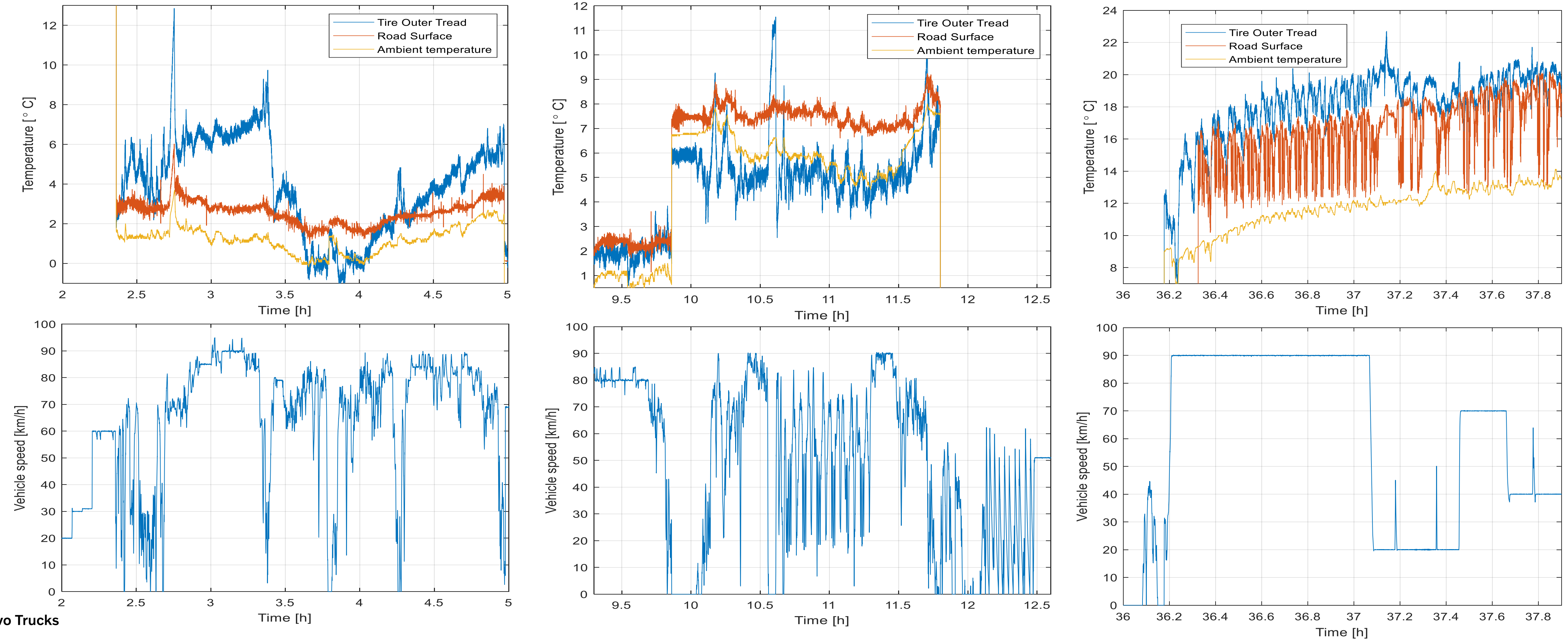
Temperature measurements - Rain



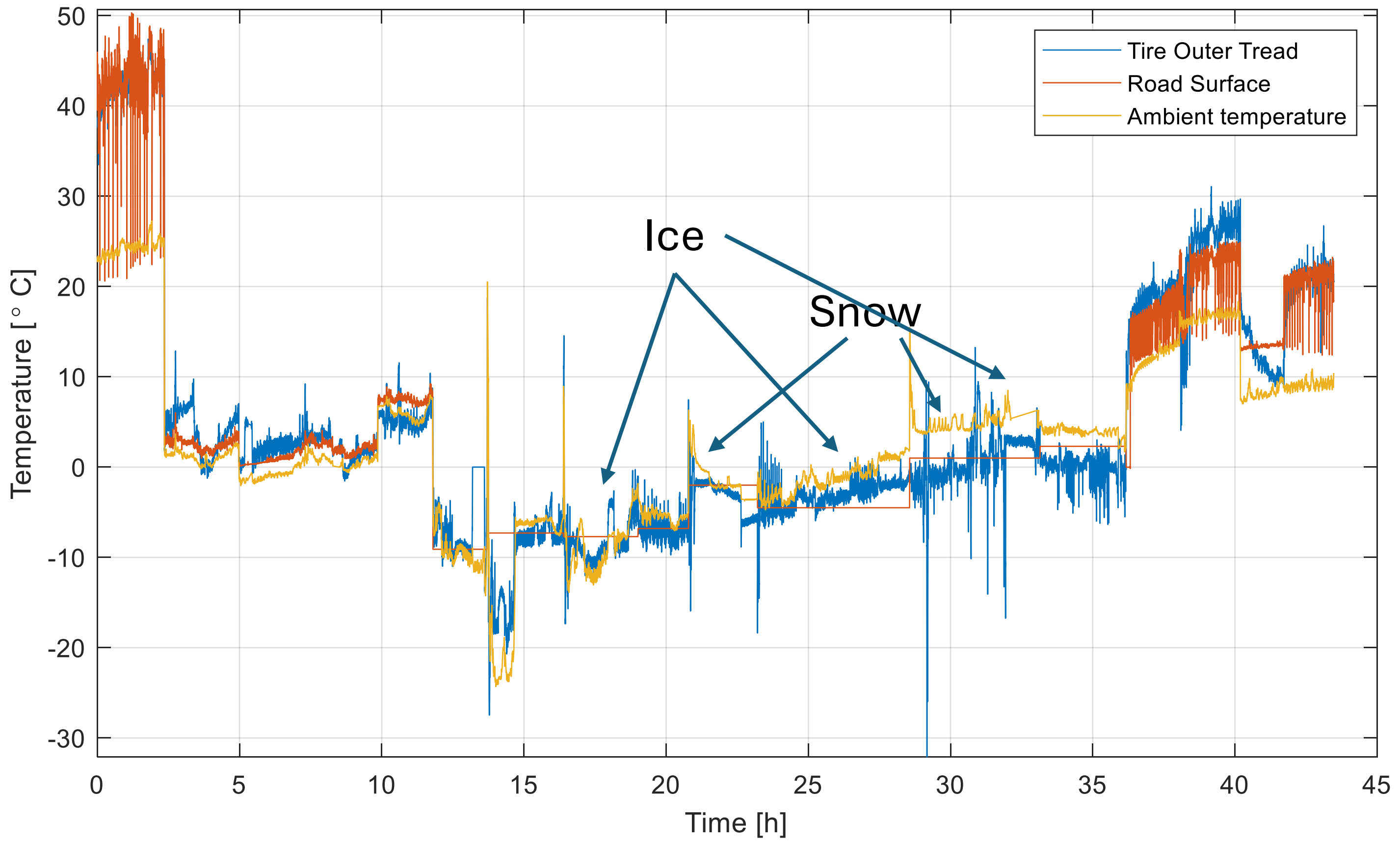
Temperature measurements



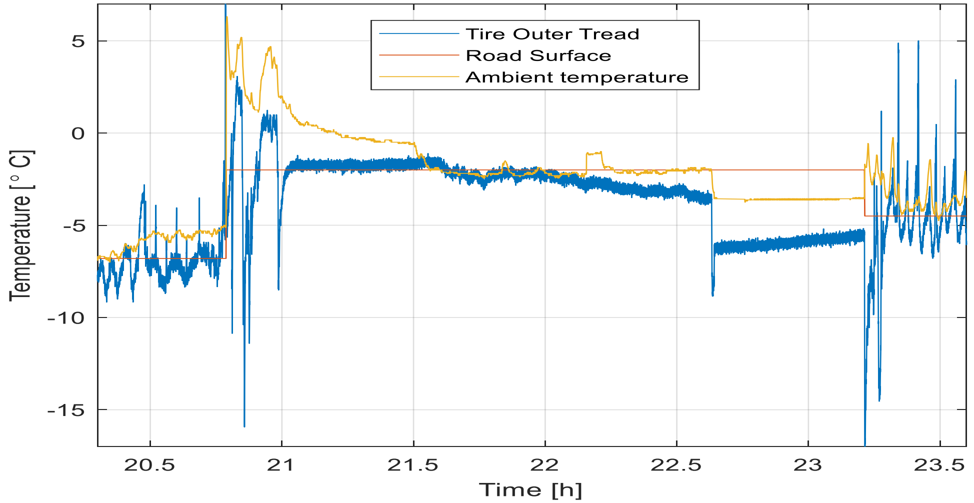
Temperature measurements – High speed

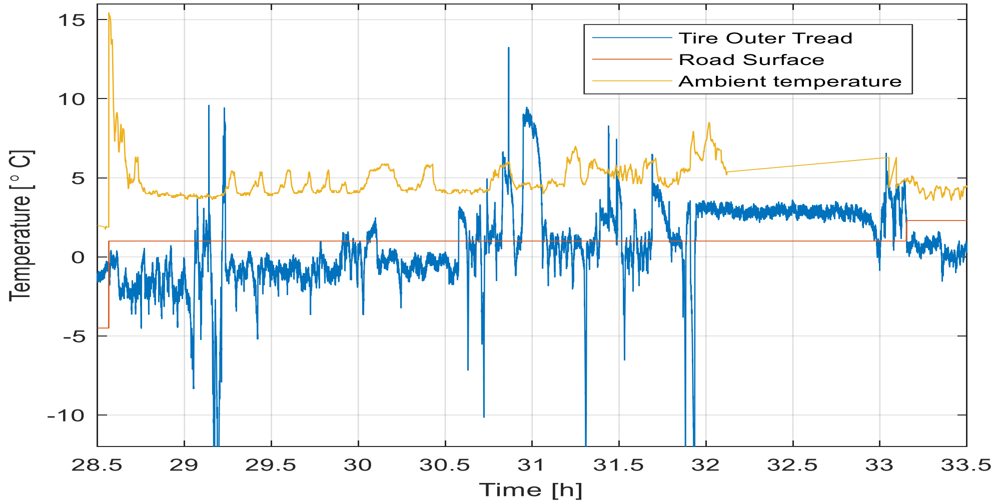


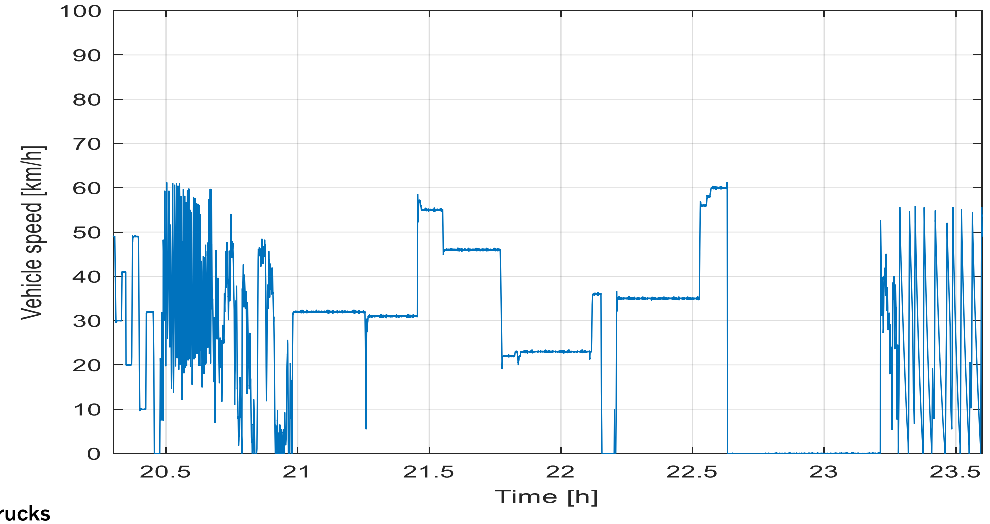
Temperature measurements

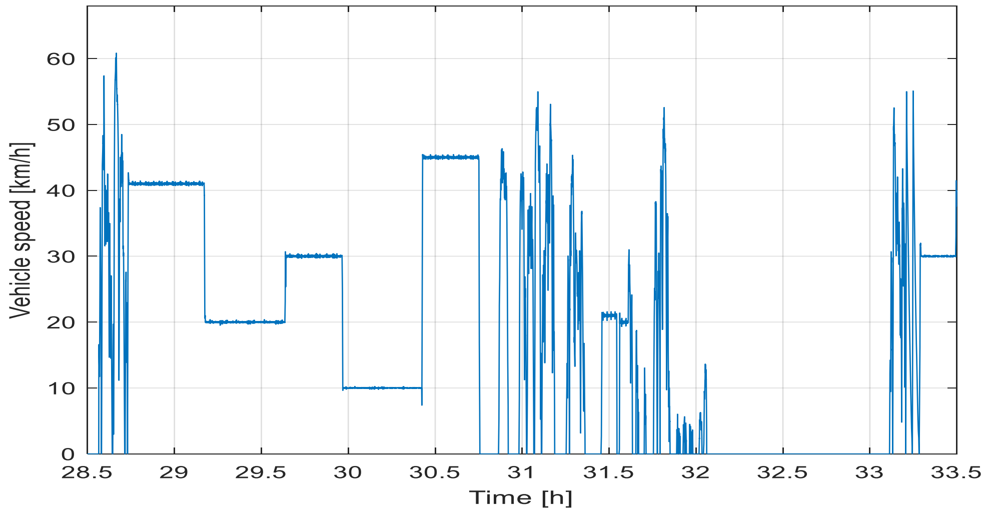


Temperature measurements - Snow

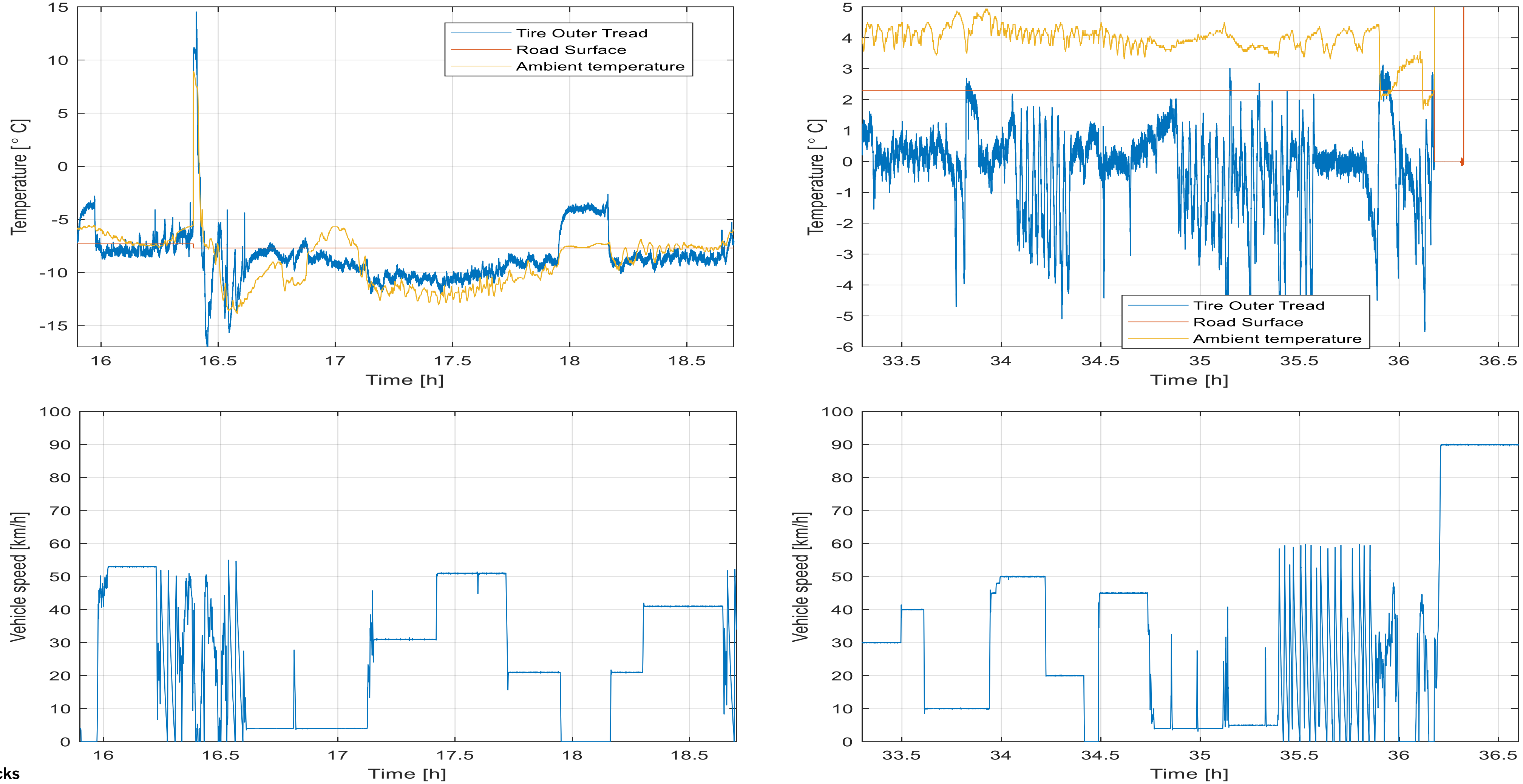




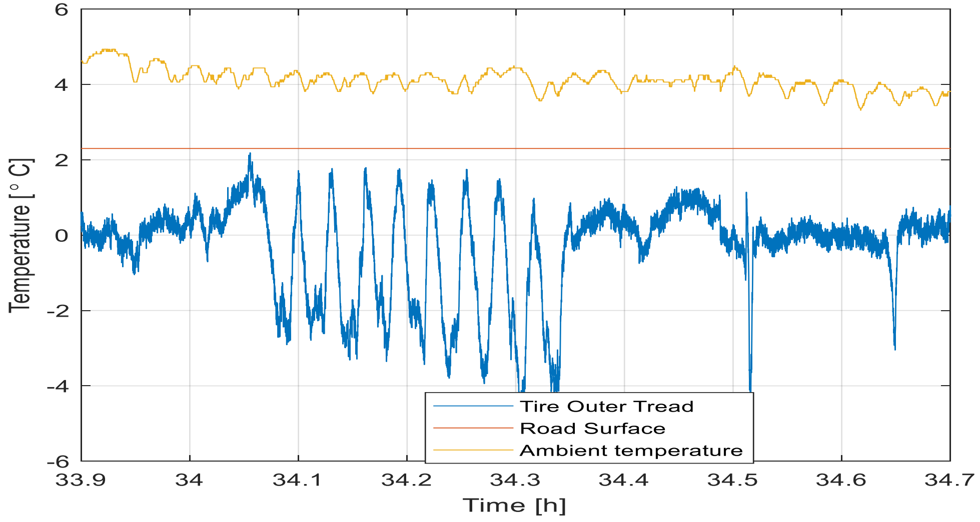


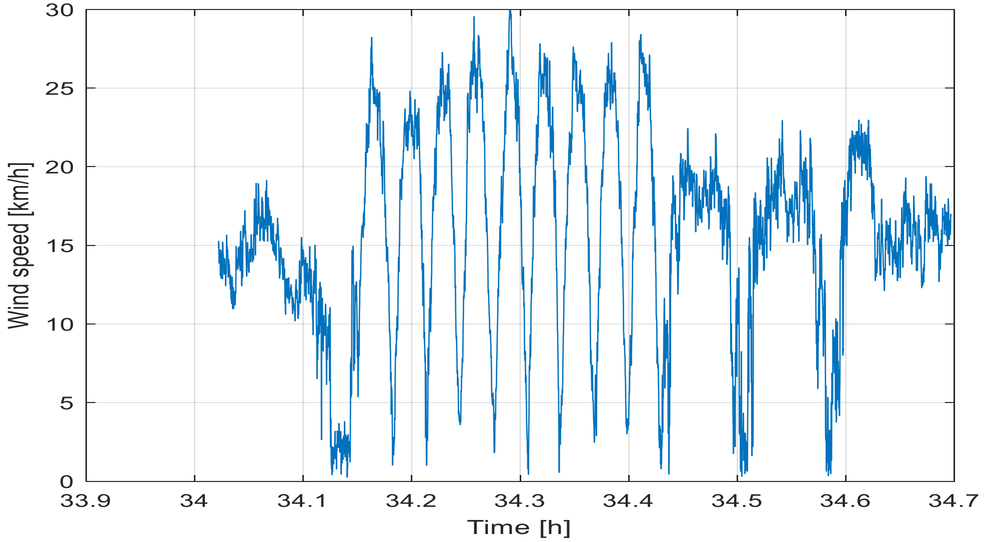


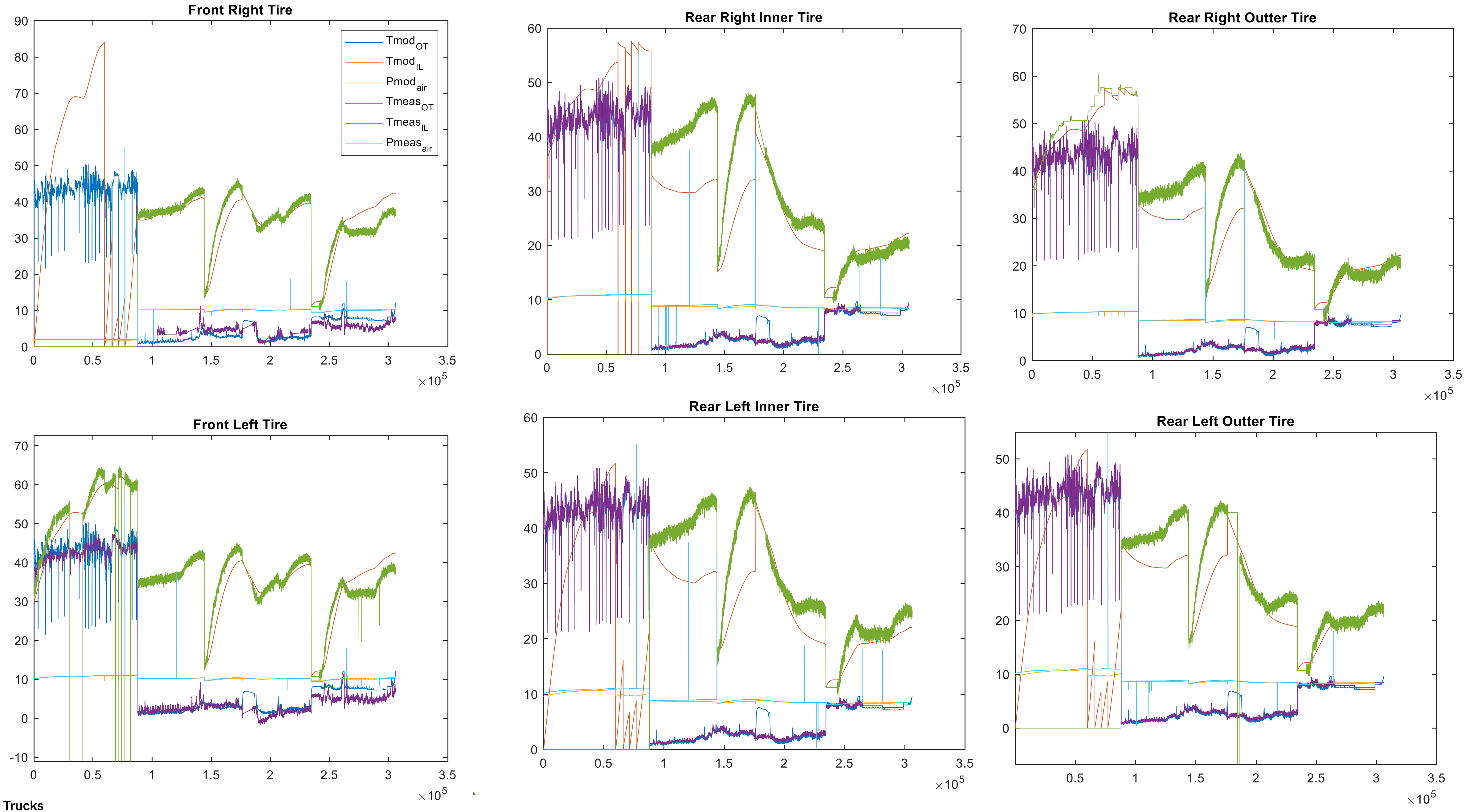
Temperature measurements - Ice



Temperature measurements - Ice

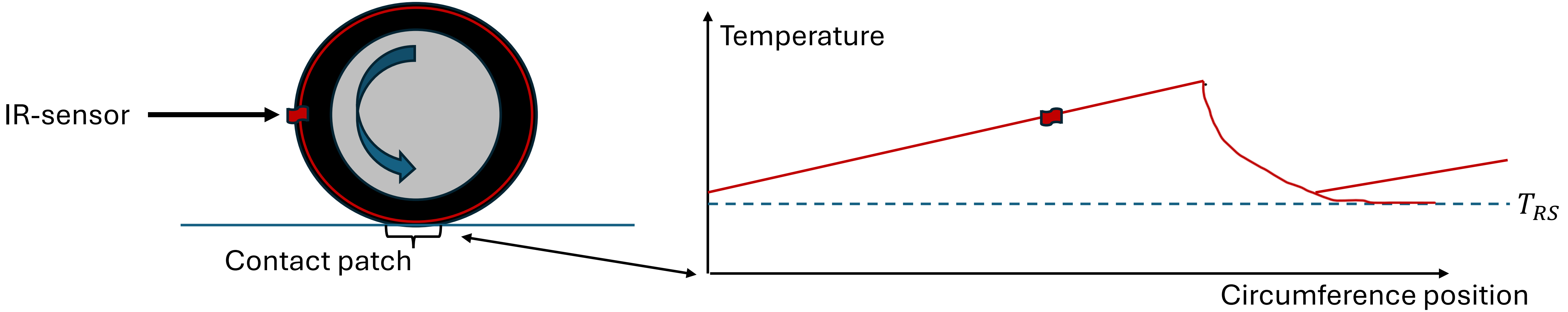


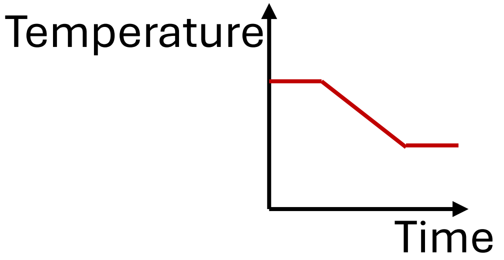



Front Right Tire
Rear Right Inner Tire
Rear Right Outter Tire
Front Left Tire
Rear Left Inner Tire
Rear Left Outter Tire
$Tmod_{OT}$
$Tmod_{IL}$
$Pmod_{air}$
$Tmeas_{OT}$
$Tmeas_{IL}$
$Pmeas_{air}$
$\times 10^5$

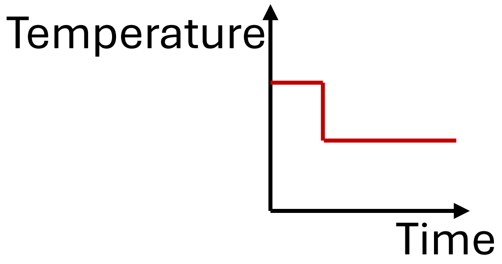
Implications of a linear heat dissipation model

Outer tread temperature model





Heat loss in contact patch linear in time ->
P_{HD} independent of speed



Heat loss in contact patch as step function ->
P_{HD} linear in speed

A linear heat dissipation model!?

Assumptions based on findings

- Majority of heat is dissipated through contact patch
- Outer tread temperature is independent of (low and moderate) speed and close to road surface temperature
- Tire heat dissipation increases linearly with vehicle speed, i.e. $P_{HD} = f(RS, RSC, \dots)(T_{RS} - T_{OT})v$

A linear heat dissipation model!?

- $P_{in} = F_z c_{rr}(T_t, P_t, v)v$
- Stationary conditions: $P_{in} = P_{HD} \rightarrow$

$$F_z c_{rr} v = f(RS, RSC, \dots)(T_{RS} - T_{OT})v \rightarrow$$

$$c_{rr}(T_t, P_t, v) = \frac{f(RS, RSC, \dots)(T_{RS} - T_{OT})}{F_z}$$

- c_{rr} is independent of speed in stationary conditions!
- or equally, if c_{rr} is independent of speed in stationary conditions, then heat dissipation is linear in speed.

Conclusions

- For low and moderate vehicle speeds, tire outer tread temperature tend to be close to road surface temperature
- At high speeds, tread temperature > road surface
- When raining tread temperature < road surface (!)
- A working road surface temperature sensor is needed to understand if above is true when running on snow or ice
- Strong wind may affect tire outer tread temperature
- Stationary rolling resistance independent of speed suggests linear heat dissipation

Thank you!

Presentation 5:

FMU-based co-simulation for autonomous vehicle dynamics control

Wenliang Zhang, KTH

FMU-based co-simulation for autonomous vehicle dynamics control

Wenliang Zhang
Postdoc Researcher
KTH Vehicle Dynamics

May 7, 2025
@SVEA Seminar 2025

Outline

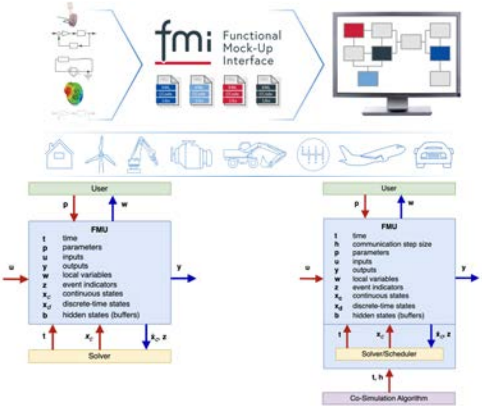
FMI & FMU

Functional Mock-up Interface (FMI)[1]

- A free standard that defines a container and an interface to exchange dynamic simulation models
- Uses a combination of XML files, binaries and C code, distributed as a ZIP file

Functional Mock-up Unit (FMU)[2]

- A file that contains a simulation model that adheres to the FMI standard



FMI & FMU illustrations. Source: FMI Standard.

[1] **https://fmi-standard.org/**.

[2] **https://modelon.com/blog/functional-mock-up-interface-fmi/**.

FMI tools

Supported by 230+ tools[1]

Vehicle	Simulation	Optimisation
CarMaker	**Simulink**	**CasADi**
CarSim	**Dymola**	OPTIMICA Compiler Toolkit
CRUISE	OpenModelica	Optimization Suite

- Maintained as a Modelica association project

[1] **https://fmi-standard.org/tools/**.

FMU-based co-simulation

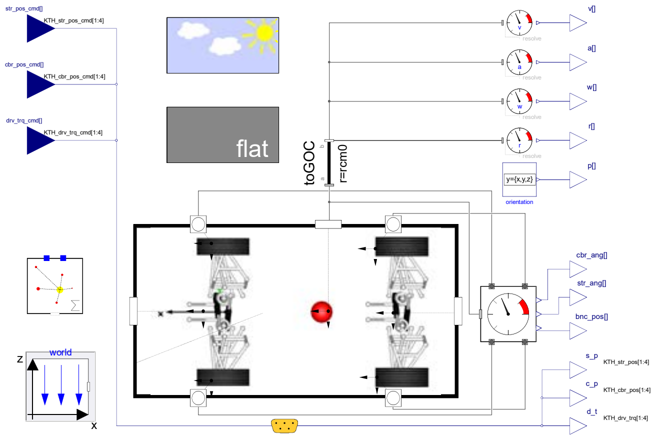
FMU-based co-simulation in vehicle domain.[1]

Advantages

- Exchange models from different tools
- Easy update and maintain components
- Improve co-simulation efficiency

[1] **https://www.mdpi.com/607960**.

FMU export – Dymola



Dymola vehicle plant model.

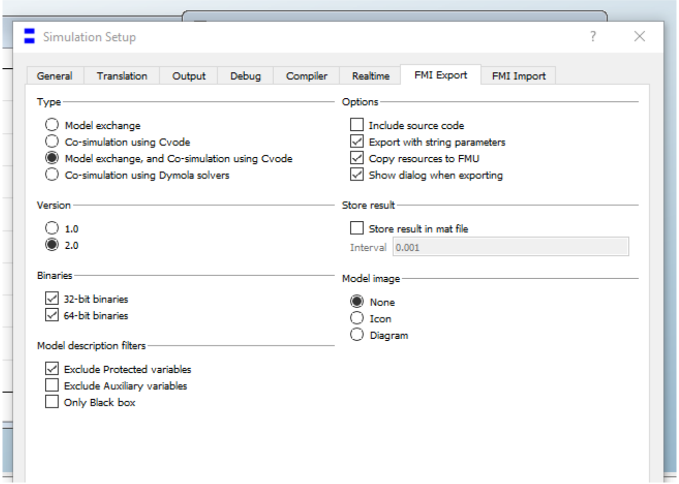
Model features

- Over-actuation
  - Four-wheel drive
  - Four-wheel steer
  - Active camber
- Major components
  - Double-wishbone suspensions
  - Pacejka tyre models
  - Aerodynamics package

FMU features

- 44 continuous states
- 57,330 variables

FMU export – Dymola

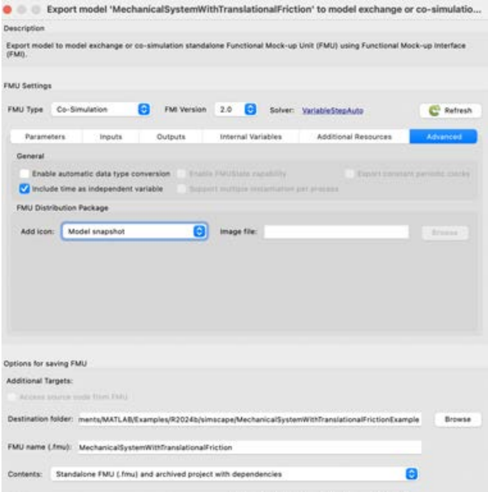


FMI export options in Dymola. Source: Claytex.

FMU export settings

- FMU type
- Version
- Binaries
- Model description filters

FMU export – Simulink



FMU export options in Simulink.

FMU import settings

- FMU type
- Version
- Solver

FMU export – Result

RCV.fmu exported from Dymola

```
binaries/
  win32/
    RCV.fmu
  win64/
    RCV.fmu
modelDescription.xml
```

modelDescription.xml

```xml
<?xml version="1.0" encoding="UTF-8"?>
<fmiModelDescription
    modelName="RCV"
    description="Research Concept Vehicle wi
    ...
    <UnitDefinitions>
        ...
    </UnitDefinitions>
    <ModelVariables>
        ...
    </ModelVariables>
    <ModelStructure>
        ...
    </ModelStructure>
    ...
</fmiModelDescription>
```

FMU export - Summary

FMU types

- Model exchange
- Co-simulation

Solver settings

- Internal solvers
  - CVODE
  - Dymola solver
  - Simulink solvers
- External solvers
  - Simulation environment dependent

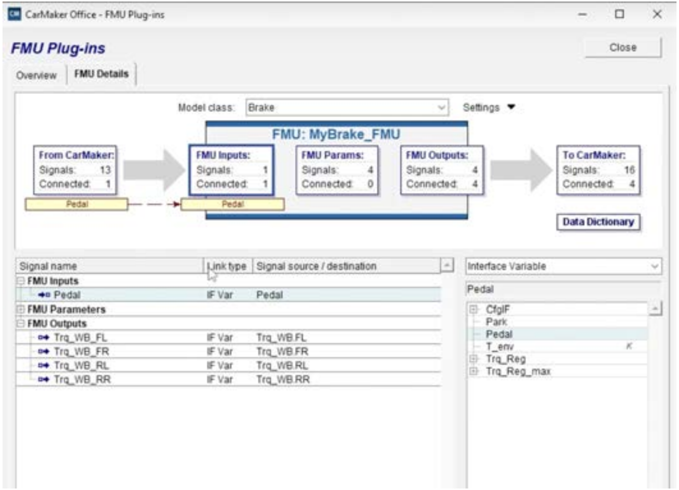
Model settings

- Configure input and output ports
- Expose signals for inspection
- Allow updating parameters

Other options

- Binaries
- Source code
- Model description filters

FMU import – CarMaker

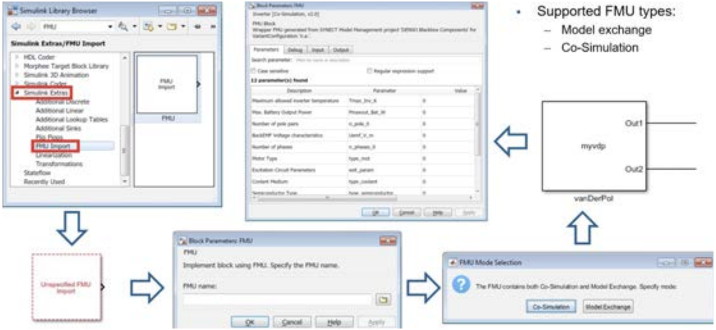


FMU details in CarMaker. Source: IPG Automotive.

FMU import signals

- Inputs
- Outputs
- Parameters

FMU import – Simulink



FMU import in Simulink. Source: MathWorks.

FMU import steps

- Add FMU block
- Load FMU file
- Select FMU type
- Configure FMU details

FMU import – FMPy

```
from fmpy import read_model_description, extract
from fmpy.fmi2 import FMU2Slave
from fmpy.simulation import apply_start_values
...
# Read model description
rcvfmu_description = read_model_description(rcvfmu_file)
# Collect variable references
rcv_variables = {}
for variable in rcvfmu_description.modelVariables:
    rcv_variables[variable.name] = variable.valueReference
...
# Extract FMU
rcvfmu_unzipdir = extract(rcvfmu_file)
...
# Initialize
rcvfmu.instantiate()
rcvfmu.setupExperiment(startTime=rcvfmu_starttime)
apply_start_values(rcvfmu, rcvfmu_description,
    start_values={'v_start': vxin0})
...
```

FMU import & setup

- Load FMU file
- Collect variables
- Initialise start time, initial states, etc.

FMU import - Summary

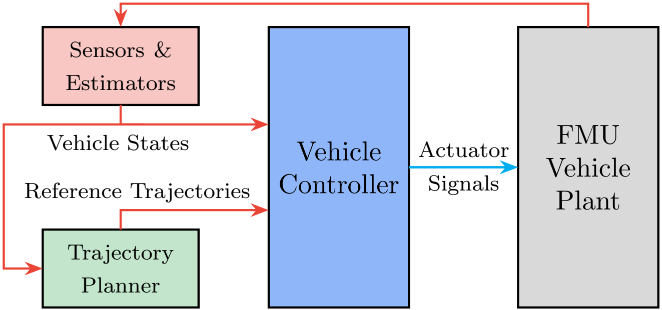
Solver settings

- Internal solvers
  - CVODE
  - Dymola solver
  - Simulink solvers
- External solvers
  - Simulation environment dependent

Model settings

- Configure input & output ports
- Extract signals for inspection
- Initialise model
  - Parameters: Road friction, sampling interval
  - States: Velocity, position

Co-simulation framework



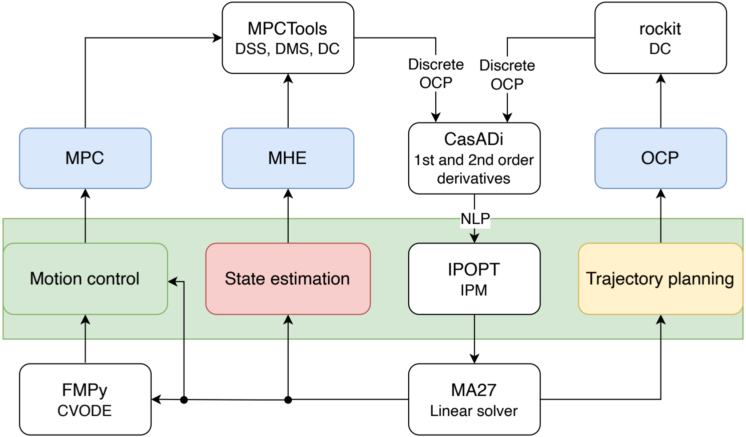
FMU-based co-simulation framework[1].

Framework components

- Autonomous driving
  - Perception
  - Planning
  - Control
- FMU vehicle

[1] W. Zhang, ‘Exploiting over-actuation for improved active safety of autonomous electric vehicles’, PhD Thesis, KTH, 2022.

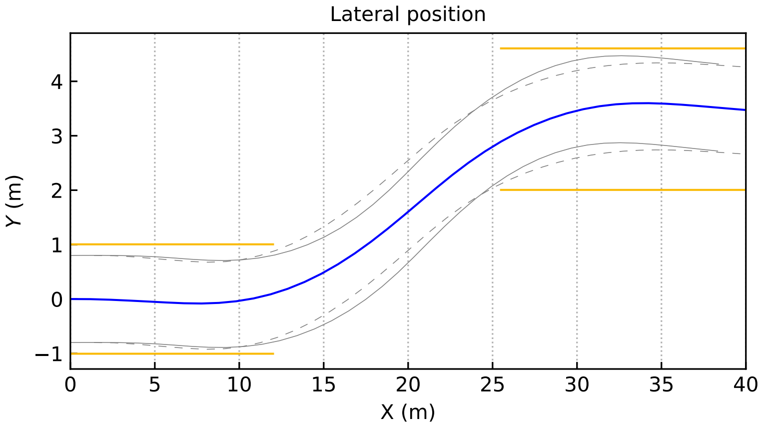
Co-simulation toolchain



FMU-based co-simulation toolchain[2].

[2] W. Zhang, 'Exploiting over-actuation for improved active safety of autonomous electric vehicles', PhD Thesis, KTH, 2022.

Control objective



Single-lane change[3].

[3]W. Zhang, L. Drugge, M. Nybacka, and J. Jerrelind, 'Integrated Control of Motion Actuators for Enhancing Path Following and Yaw Stability of Over-Actuated Autonomous Vehicles', Energies, vol. 16, no. 12, Art. no. 12, Jan. 2023, doi: 10.3390/en16124776.

MPC controller

Cost function:

$$\min_{\boldsymbol{x},\boldsymbol{x}_c,\boldsymbol{u},\Delta\boldsymbol{u},\boldsymbol{s}} \underbrace{\sum_{p=0}^{N-1} \left\| y_{k+p|k} - y^{ref}_{k+p|k} \right\|^2_{Q_y}}_{\text{tracking error}} + \underbrace{\sum_{p=0}^{N-1} \left\| u_{k+p|k} \right\|^2_{R_u}}_{\text{control action}}$$

$$+ \underbrace{\sum_{p=0}^{N-1} \left\| \Delta u_{k+p|k} \right\|^2_{R_{du}}}_{\text{change of control action}} + \underbrace{\sum_{p=0}^{N-1} \left\| s_{k+p|k} \right\|^2_{Q_s}}_{\text{slack term}}$$

$$+ \underbrace{\left\| y_{k+N|k} - y_{k+N|k} \right\|^2_{Q_{yf}}}_{\text{terminal cost of tracking error}} + \underbrace{\left\| s_{k+N|k} \right\|^2_{Q_{sf}}}_{\text{terminal cost of slack variable}}$$

Constraints:

State equation

Control constraints

State constraints

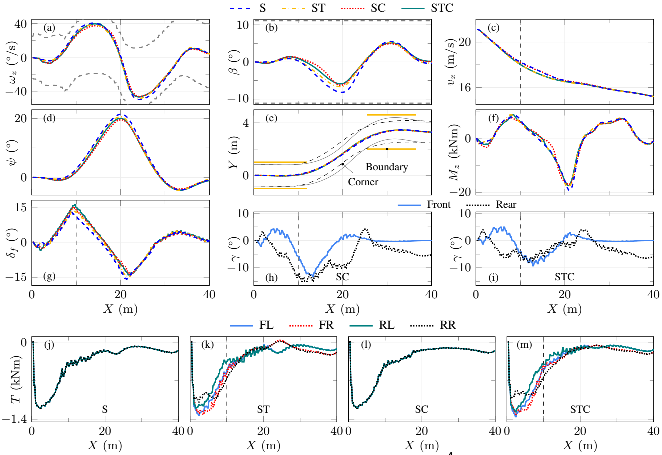
Co-simulation & Dynamics control

```
...
# Pass references
for i in range(t, t + Nt):
    i = i % Nt
    mpcsolver.par["x_sp", i] = xref[i, :]
mpcsolver.par["x_sp", Nt] = xref[Nt, :]
...
# Solve MPC
mpcsolver.solve()
uu[t, :] = np.squeeze(mpcsolver.var["u", 0])
...
# FMU model simulation
rcvfmu.setReal(rcvfmuin_steer,
    [uu[t, 0], uu[t, 0], 0, 0])
rcvfmu.setReal(rcvfmuin_torque,
    [uu[t, 1], uu[t, 2], uu[t, 3], uu[t, 4]])
rcvfmu.setReal(rcvfmuin_camber, [
    uu[t, 5], uu[t, 5], uu[t, 6], uu[t, 6]])
# Perform one step
rcvfmu.doStep(currentCommunicationPoint=time,
    communicationStepSize=rcvfmu_stepsize)
```

Co-simulation steps via FMPy

- Update reference signals to MPC
- Solve MPC and get solutions
- Pass control signals to FMU model
- Simulate FMU model by one step

Results



Trajectory tracking results[4].

[4] W. Zhang, L. Drugge, M. Nybacka, and J. Jerrelind, 'Integrated Control of Motion Actuators for Enhancing Path Following and Yaw Stability of Over-Actuated Autonomous Vehicles', Energies, vol. 16, no. 12, Art. no. 12, Jan. 2023, doi: 10.3390/en16124776.

Takeaways

- FMI & FMU $\uparrow$ Model exchange & Maintenance & Co-simulation efficiency
- FMI & FMU $\rightarrow$ Model Export & Import for various tools
  - Dymola & Simulink
  - CarMaker & CarSim
- FMI & FMU $\rightarrow$ Customised Solver & Model settings
- FMU $\rightarrow$ Co-simulation framework & Toolchain
- FMU-based co-simulation $\uparrow$ AV Dynamics control & Algorithm development

Thank you for listening!

For further questions, welcome to contact me via

wez@kth.se
https://www.researchgate.net/profile/Wenliang-Zhang-3
https://www.linkedin.com/in/wenliang-zhang-124144243

Presentation 6:

Braking Distance Minimization on Roads with Varying Friction

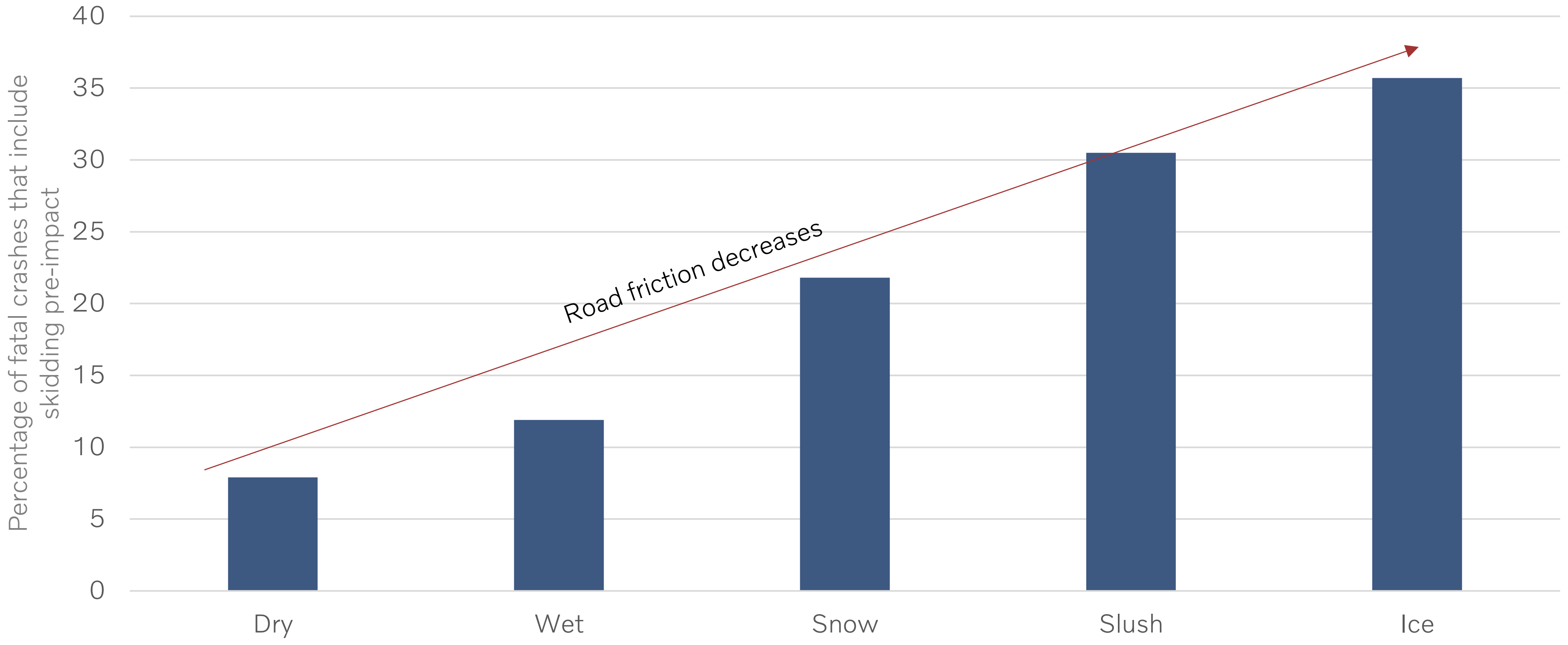
Ektor Karyotakis, Volvo Cars and Chalmers

Braking Distance Minimization on Roads with Varying Friction

Licentiate seminar, Ektor Karyotakis

2025.05.09

Loss of vehicle control (skidding) increases with bad weather/road condition (NHTSA; 2020—2022)

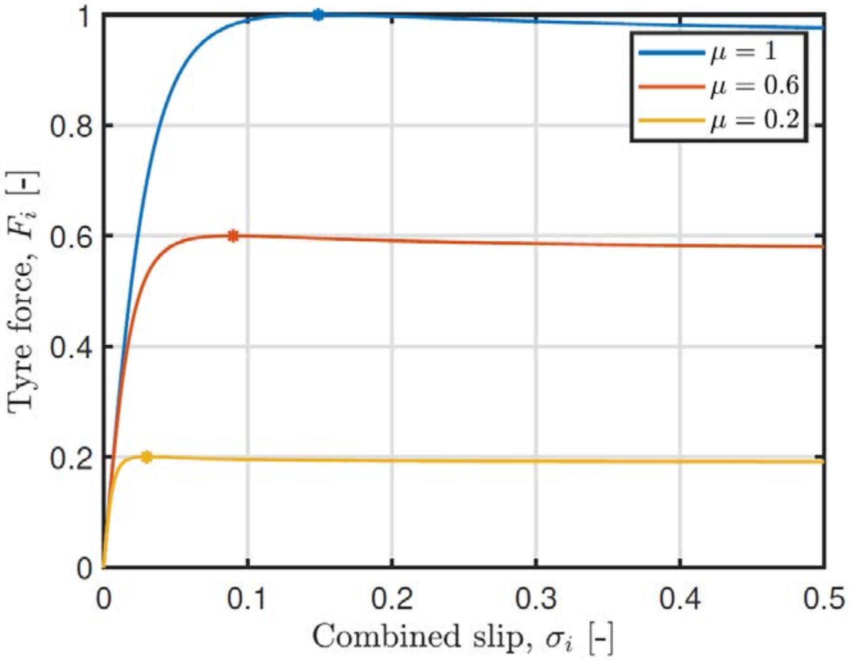


1. Better systems at low frictions
2. Current safety systems assume dry asphalt and sunny weather
3. Difficult to predict road friction

Road friction information

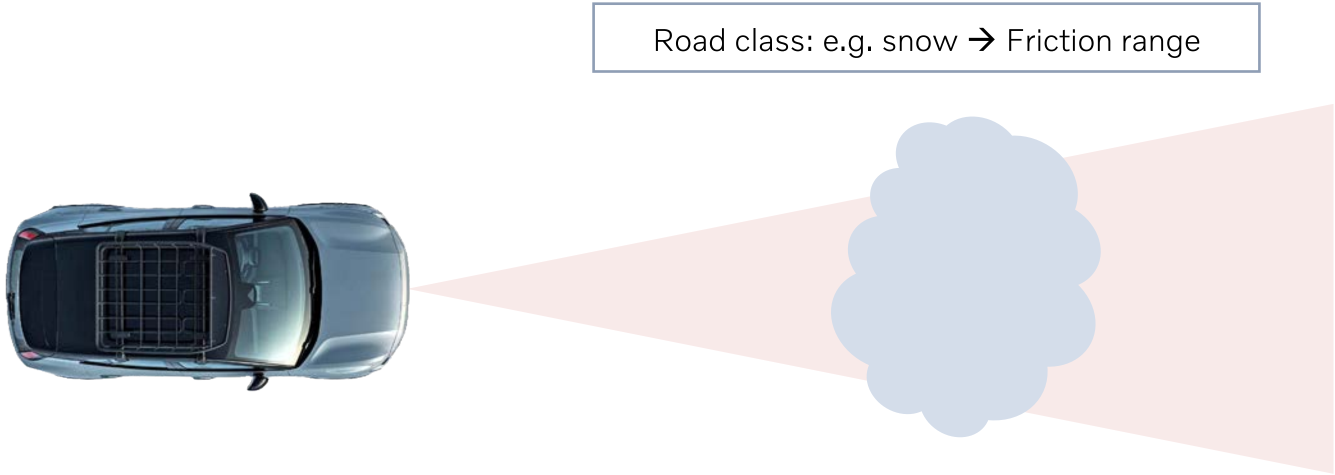
- Tyre as a sensor

Too late?



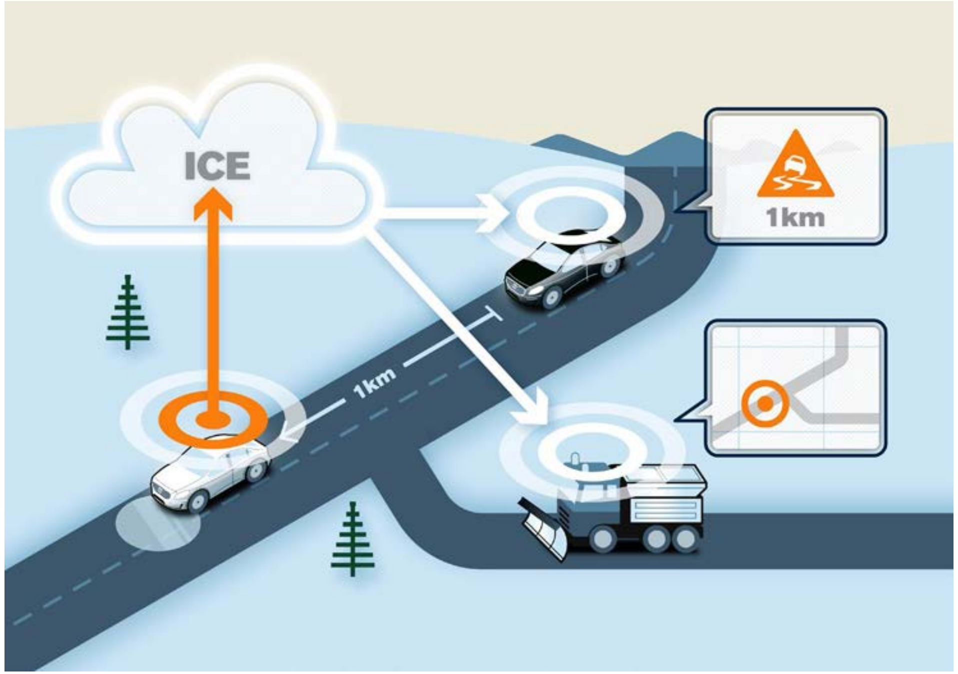
Road friction information

- Tyre as a sensor
- Camera



Road friction information

- Tyre as a sensor
- Camera
- Cloud Data

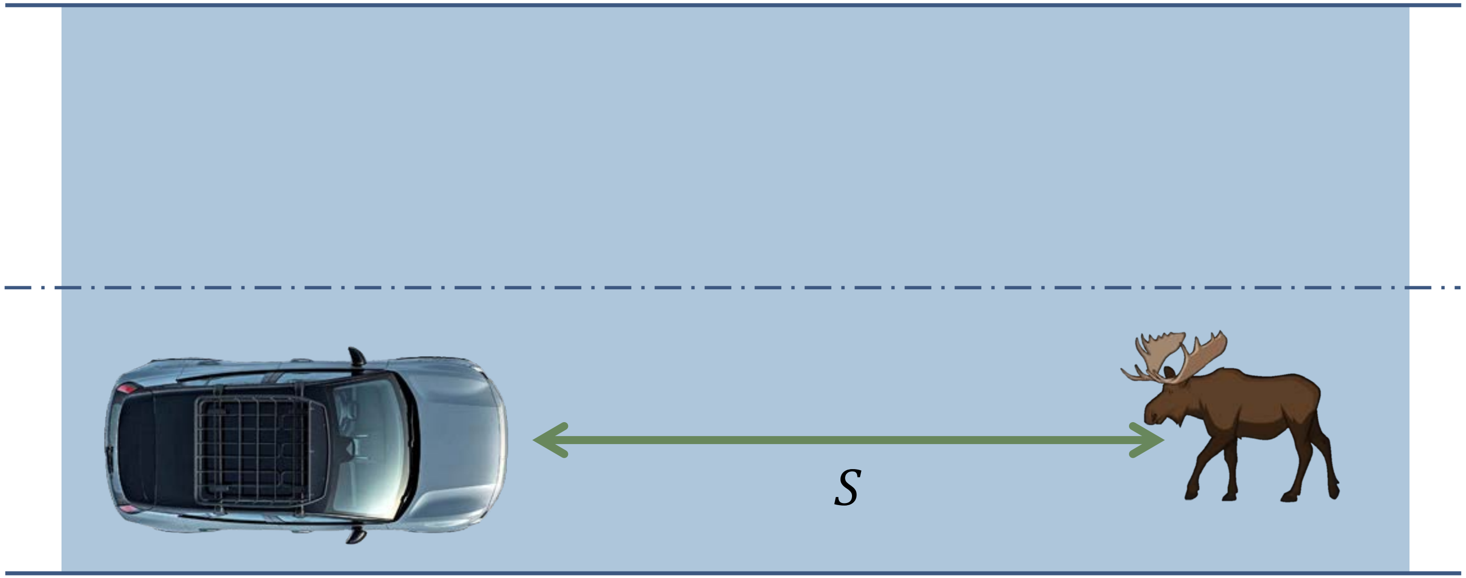


The moose and the braking distance

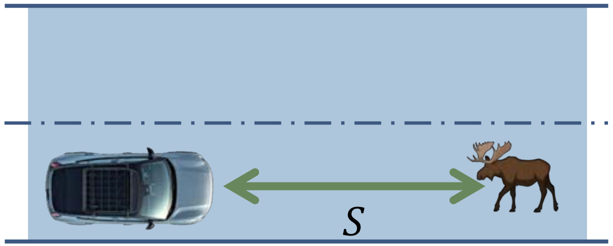
The moose and the braking distance

- Predict the shortest braking distance S?
- S depends on friction
- Pose assumptions on the road condition ahead
- Implications on path-planning & control

The moose and the braking distance: Uniform Road



Uniform Road: Braking distance equation

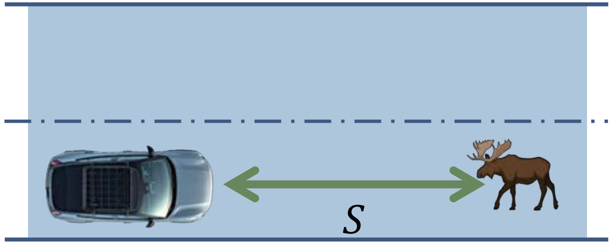


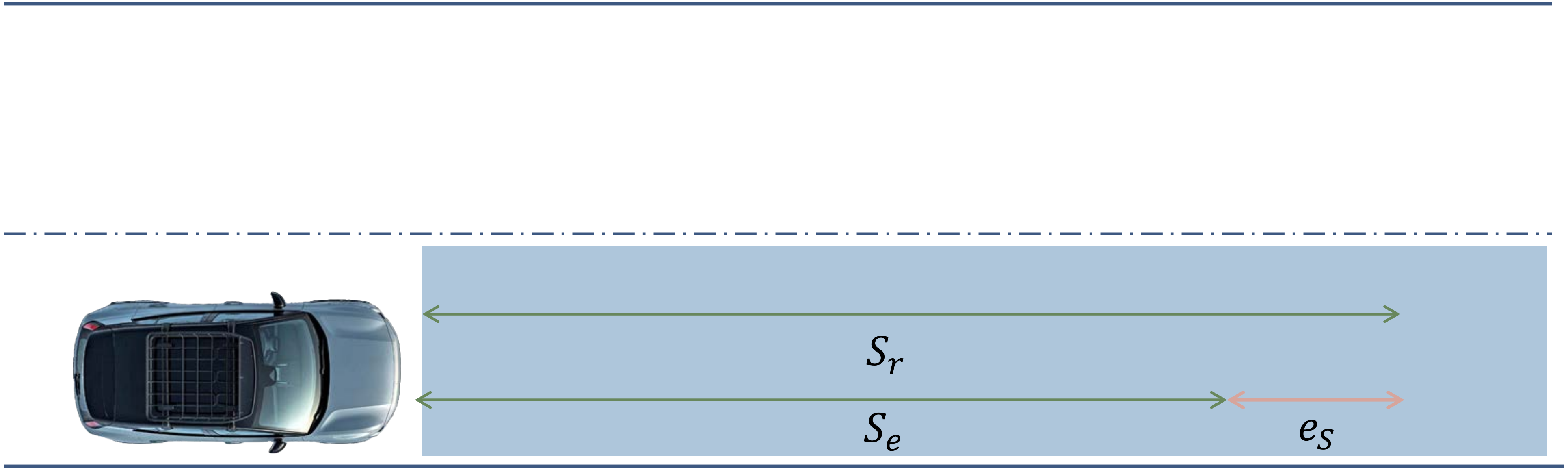
Braking distance: $$S = \frac{1}{2}\frac{V^2}{\bar{\mu} g}$$

where

- $\bar{\mu}$ is the average road friction coefficient along the path with $\mu \in [0\ 1]$,
- V the vehicle's speed,
- g is the gravity constant

Uniform Road: Friction deviation → braking distance deviation





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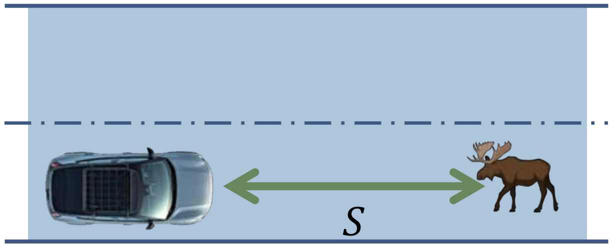
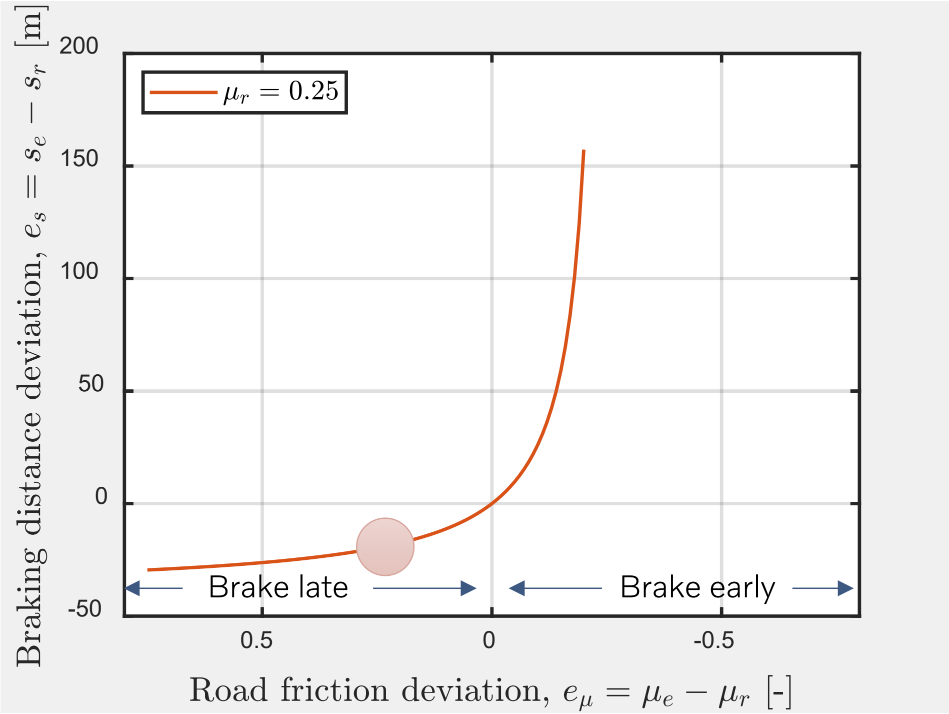
Uniform Road: Friction and distance deviations



- Deviation: estimated – real



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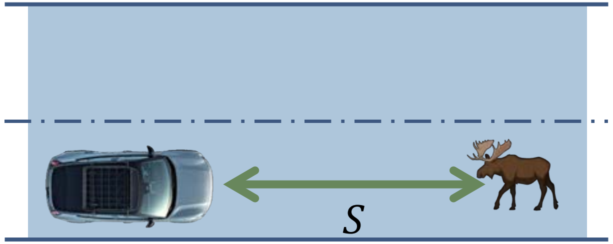
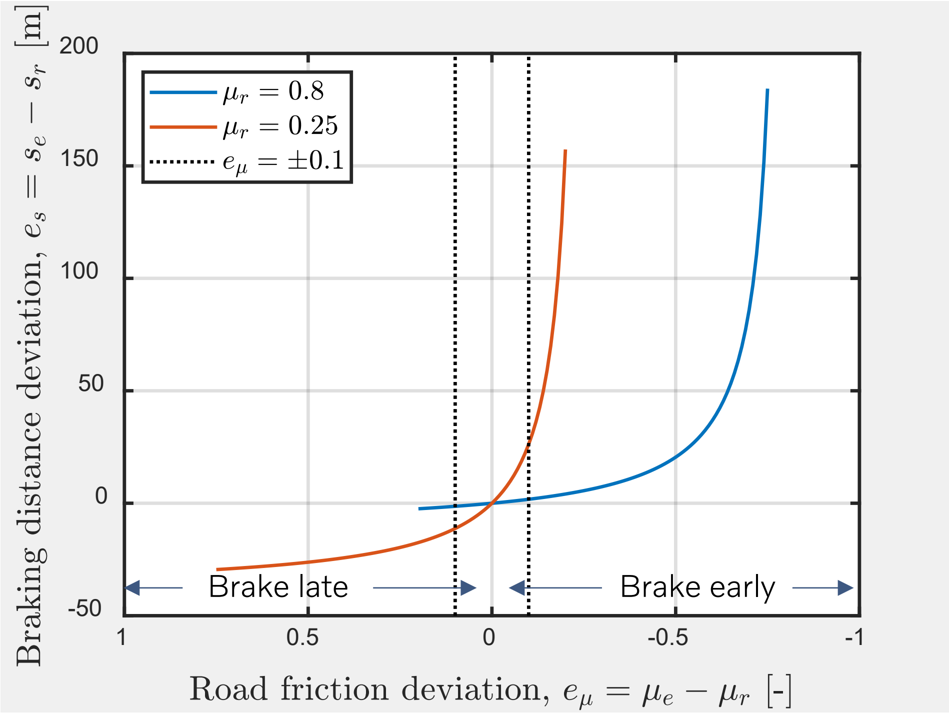


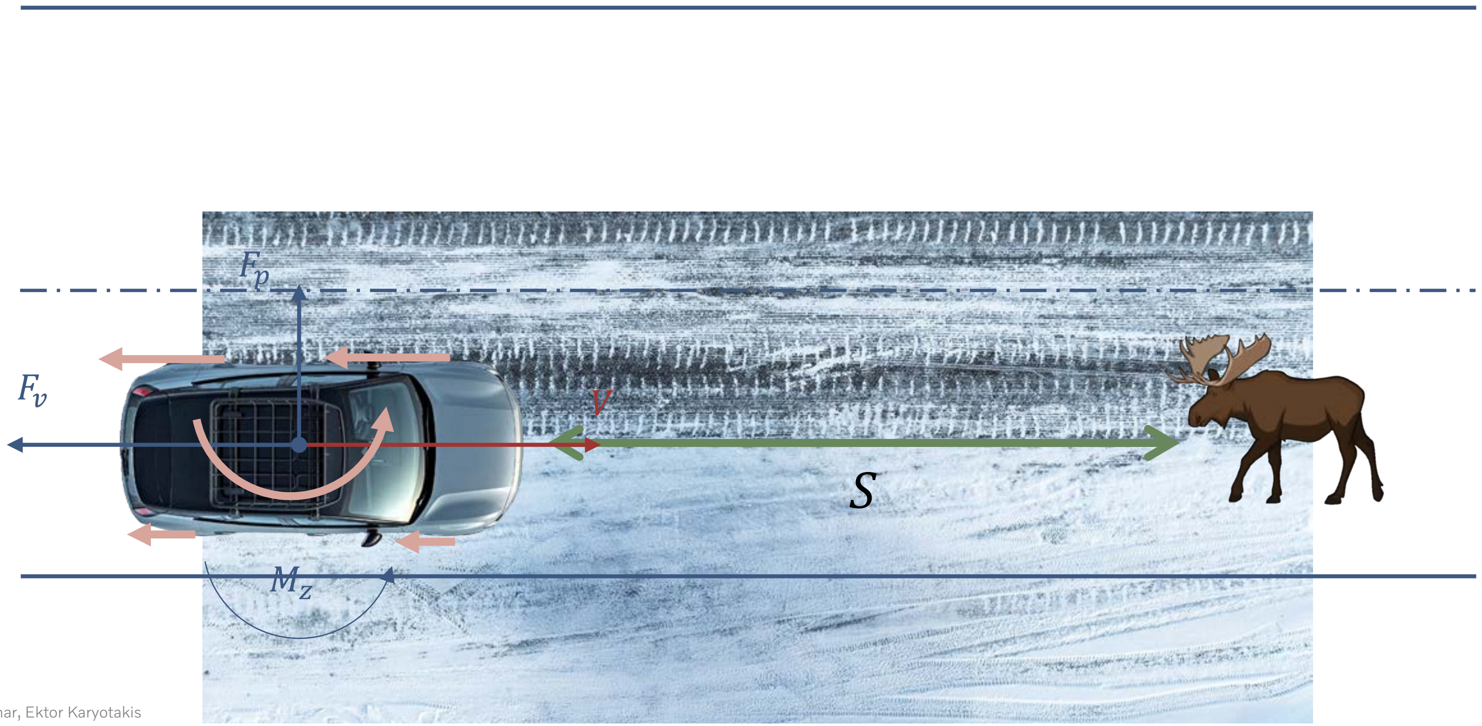
Uniform Road: Friction and distance deviations

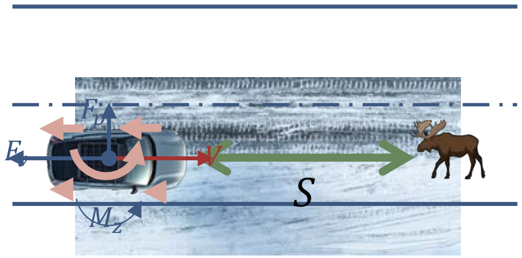
- Deviation: estimated – real
- Same friction deviation:

  Lower friction → larger br. distance deviation
- Cost of missestimating friction significant at lower frictions

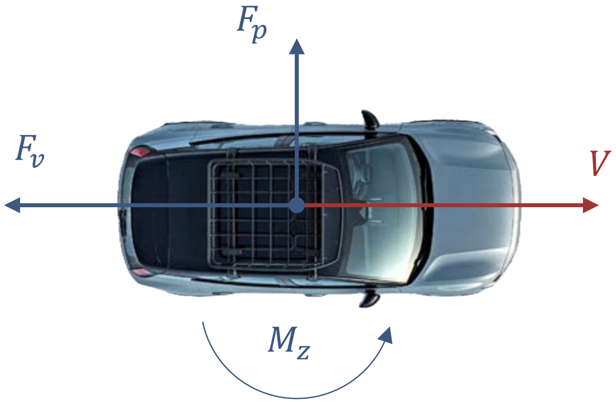


The moose and the braking distance: Split Friction Road

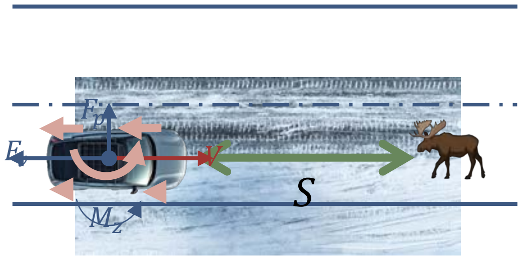


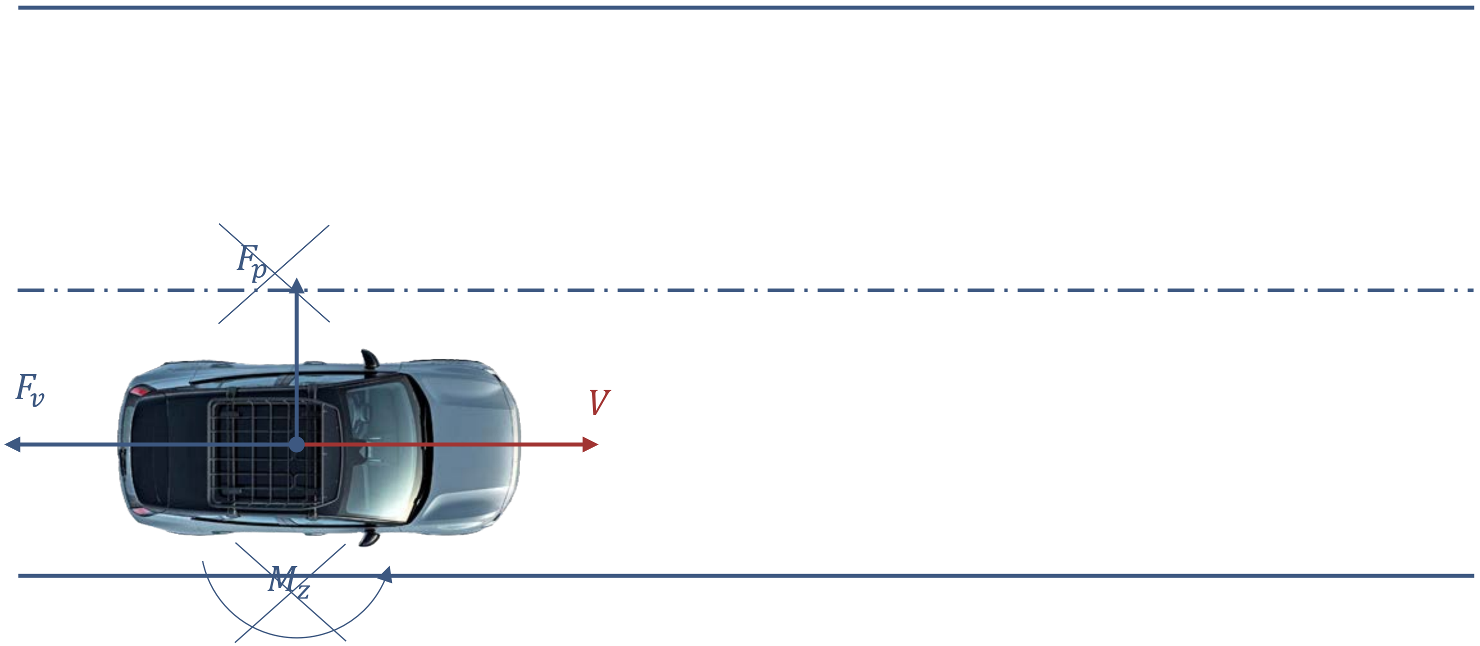


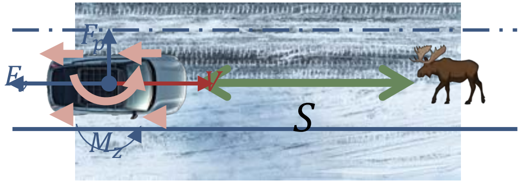
Split Friction Road: Velocity and global forces



Split Friction Road: Straight road

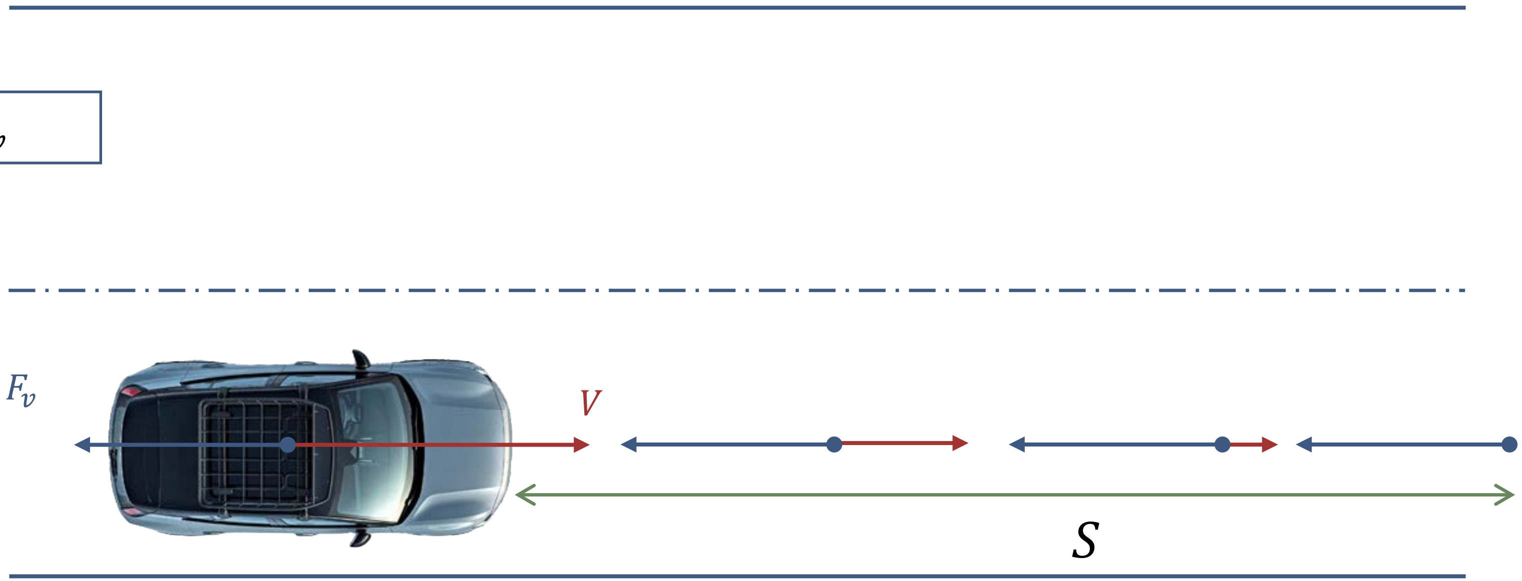


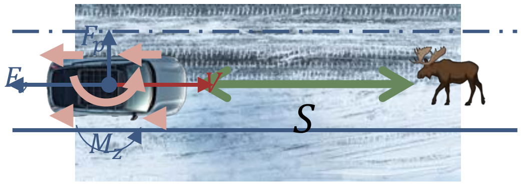




Split Friction Road: Maximum braking gives shortest distance on a straight road

$$\max \quad F_v$$

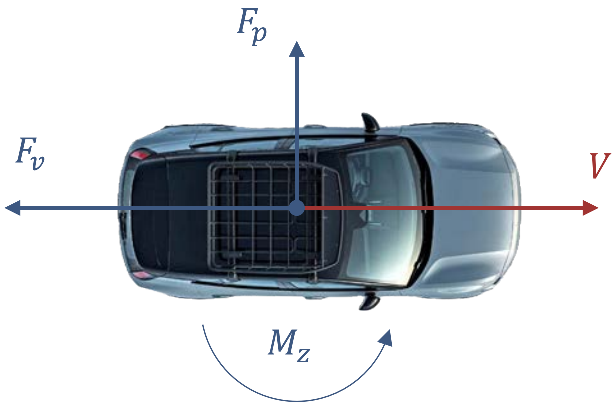


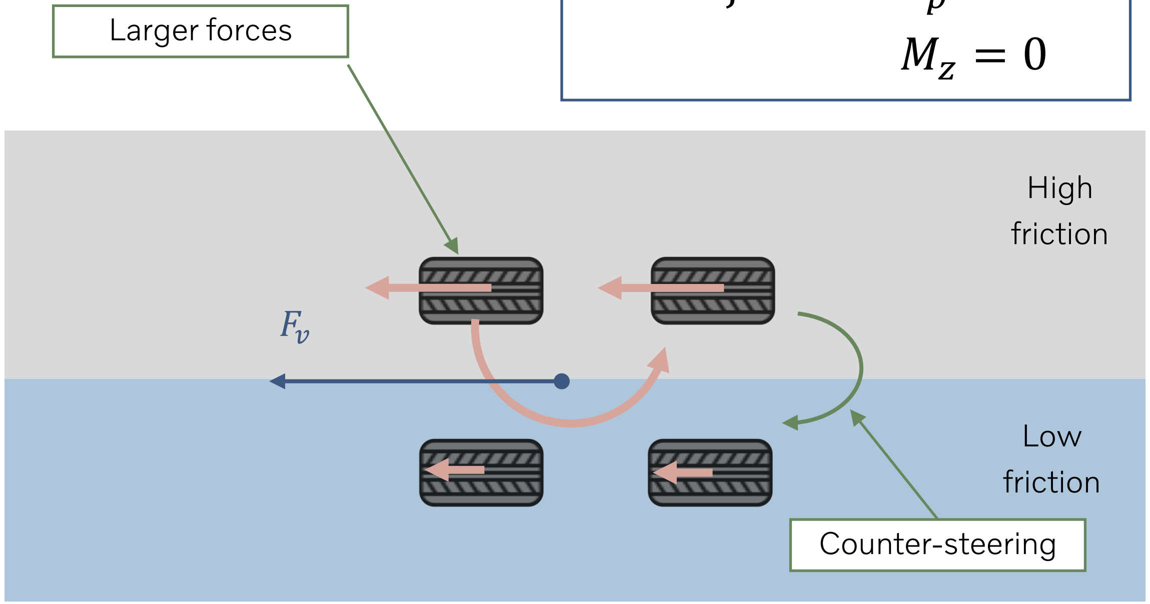


Split Friction Road: Maximum braking on straight roads

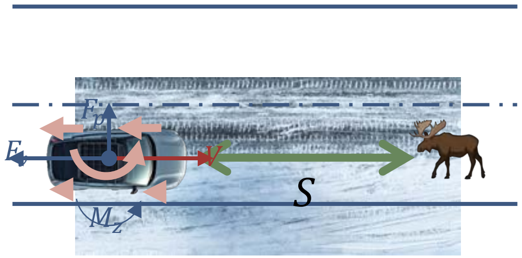
Instantaneous optimal problem

$$\begin{aligned} \max \quad & F_v \\ \text{subject to} \quad & F_p = 0 \\ & M_z = 0 \end{aligned}$$

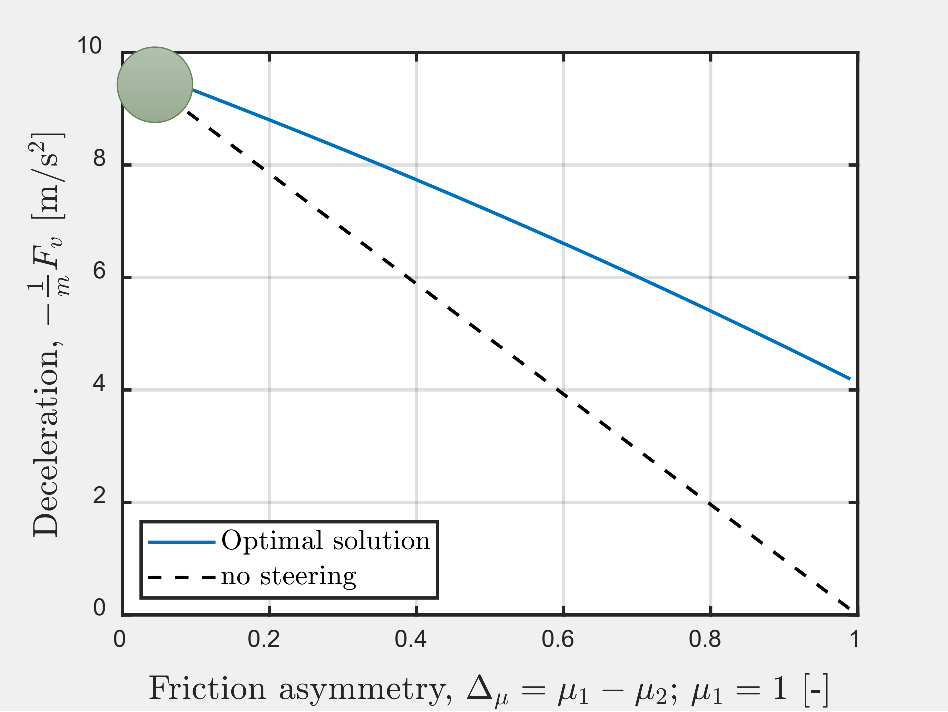


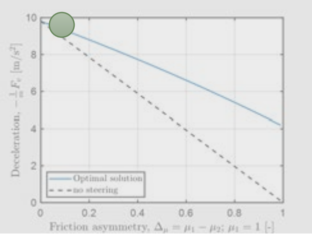


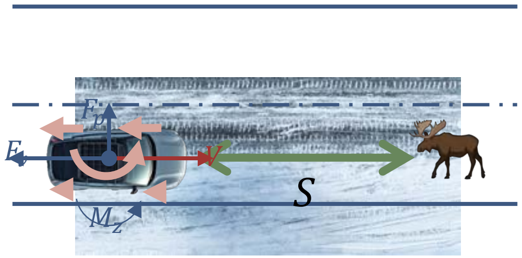
Split Friction Road: Max braking per friction asymmetry



- Counter-steering necessary for max braking

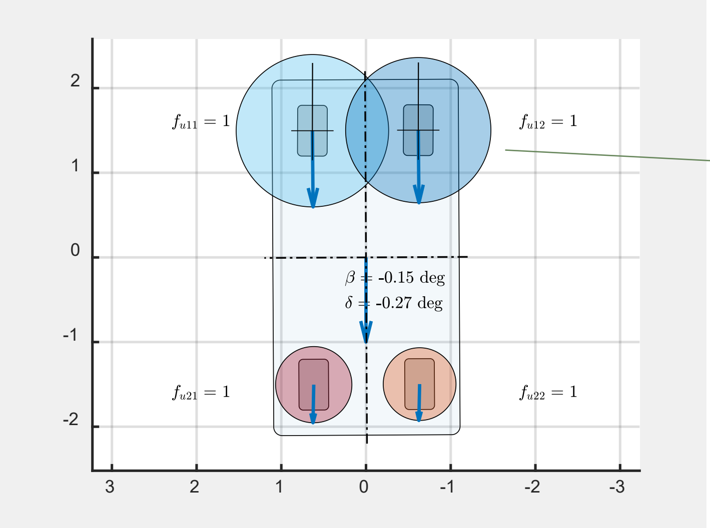


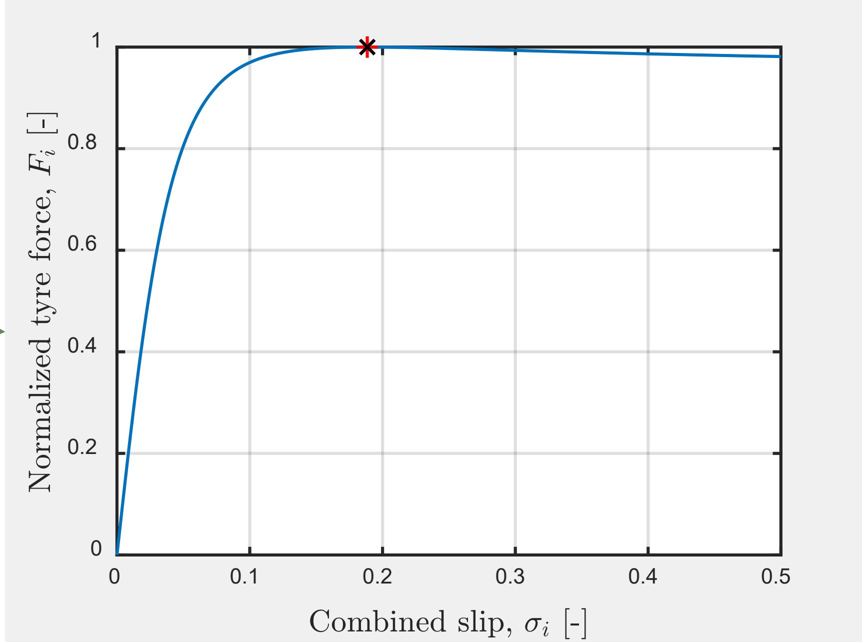




Split Friction Road: Tyre curves at zero split friction

- Maximum force at friction peak '*'
- Optimal point 'x'





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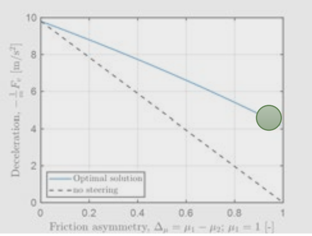
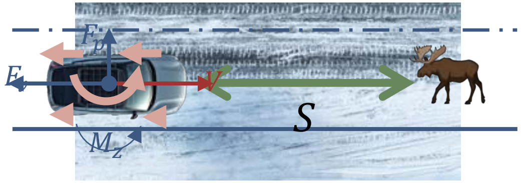
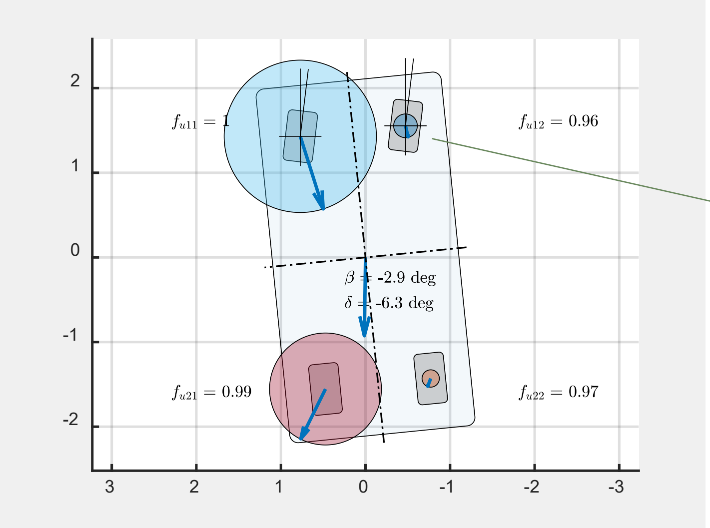
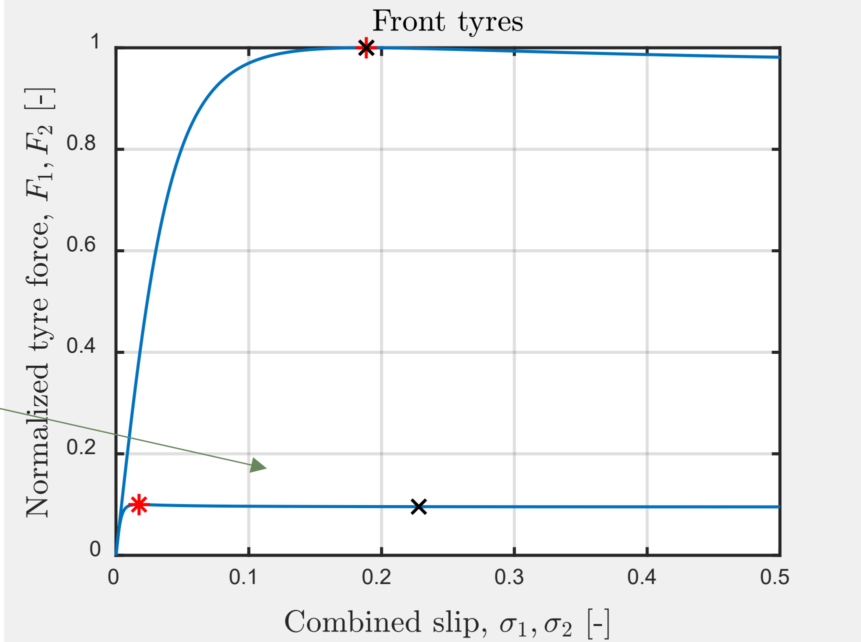




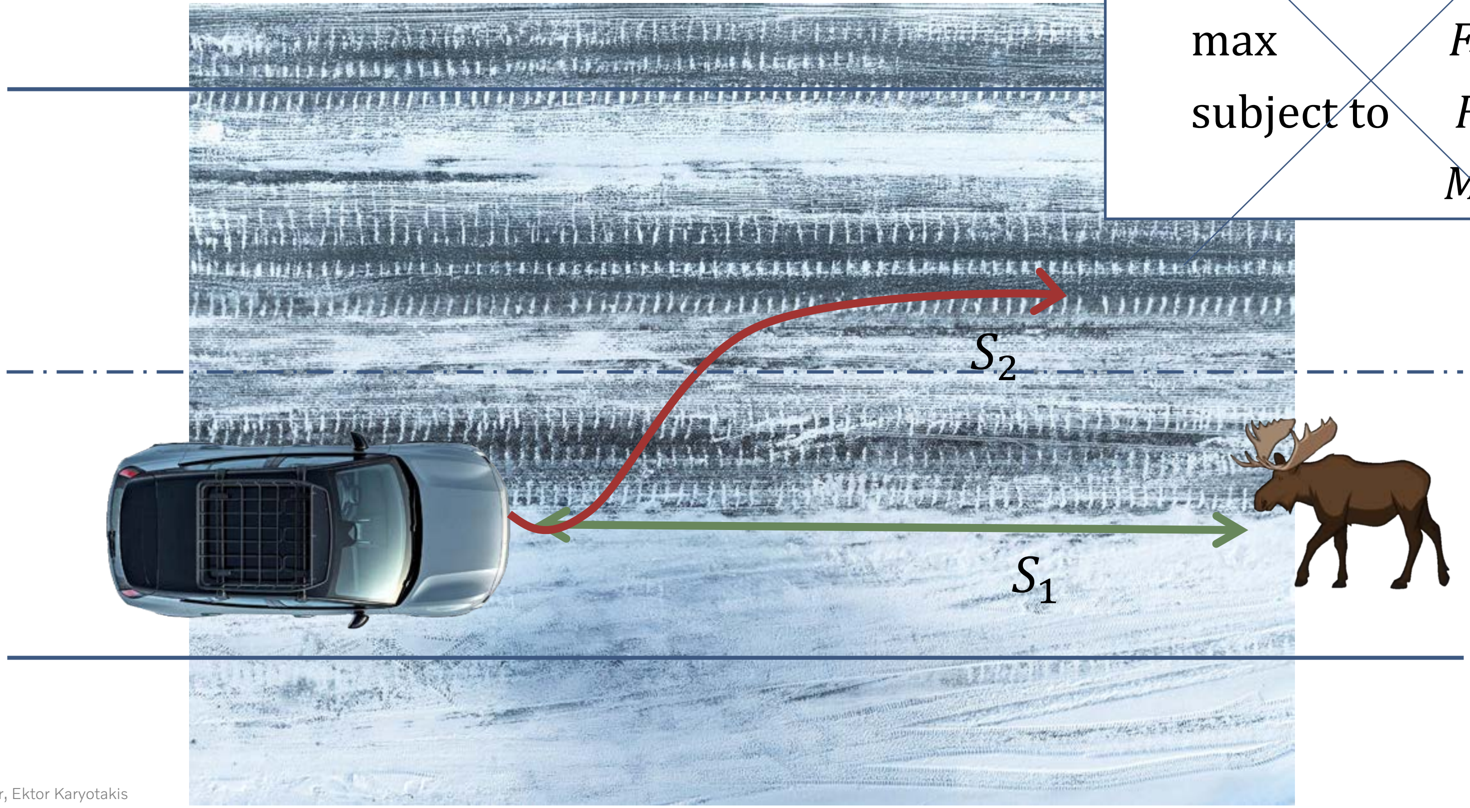
Split Friction Road: Tyre curve at extreme split friction

- Optimal point ‘x’ moves away from peak ‘*’
- Conclusion: At extreme split friction low-friction tyres at unstable tyre region





The moose and the braking distance: Optimal Path



Instantaneous problem:

$$\max \quad F_v \quad \text{subject to} \quad F_p = 0, \; M_z = 0$$

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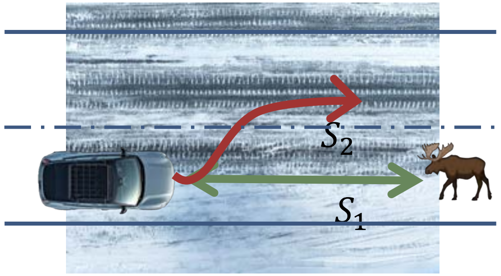
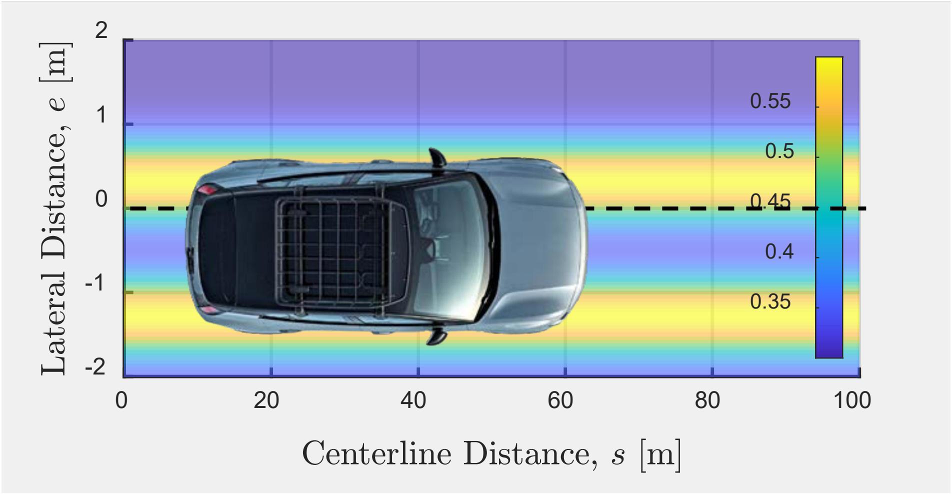
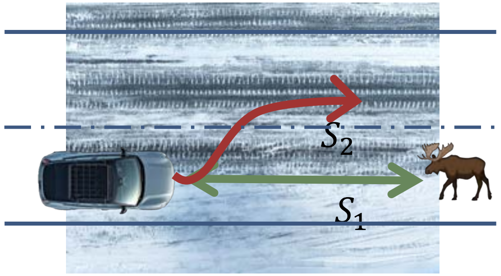
Optimal Path: Road friction profile from winter roads: Snow-tracks



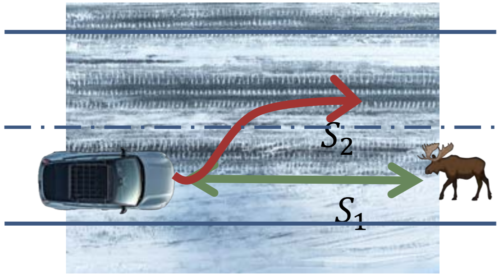


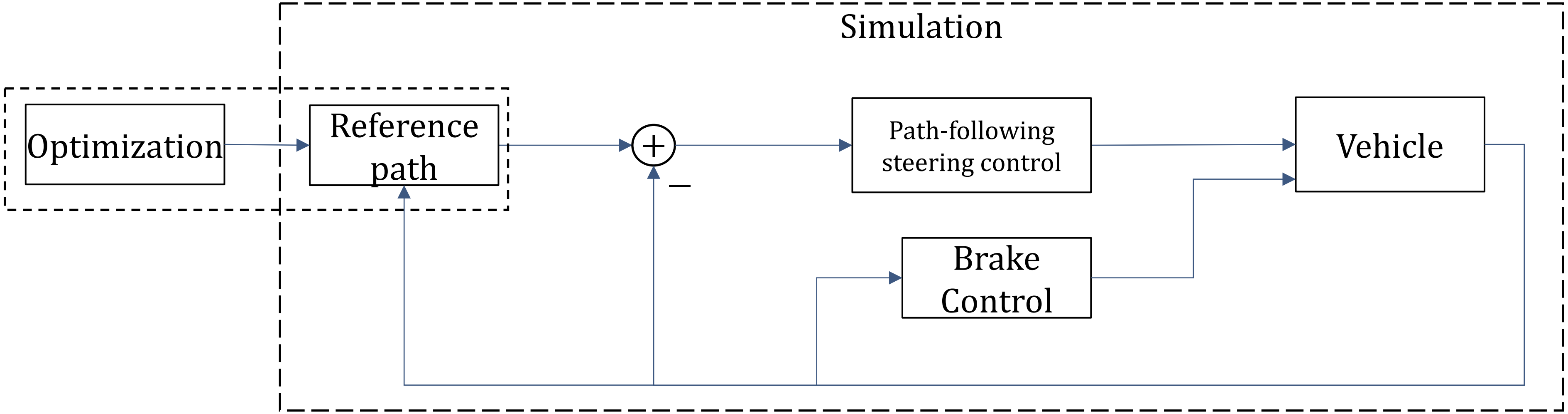


Optimal Path: Simulation & verification

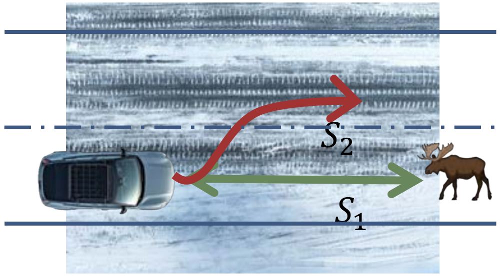
1. Full trajectory optimization with two vehicle models:
   - Particle Model (PM)
   - Single-track (ST)
2. Simulation in high-fidelity environment CarMaker™
   - Advanced tyre model
   - Verified chassis

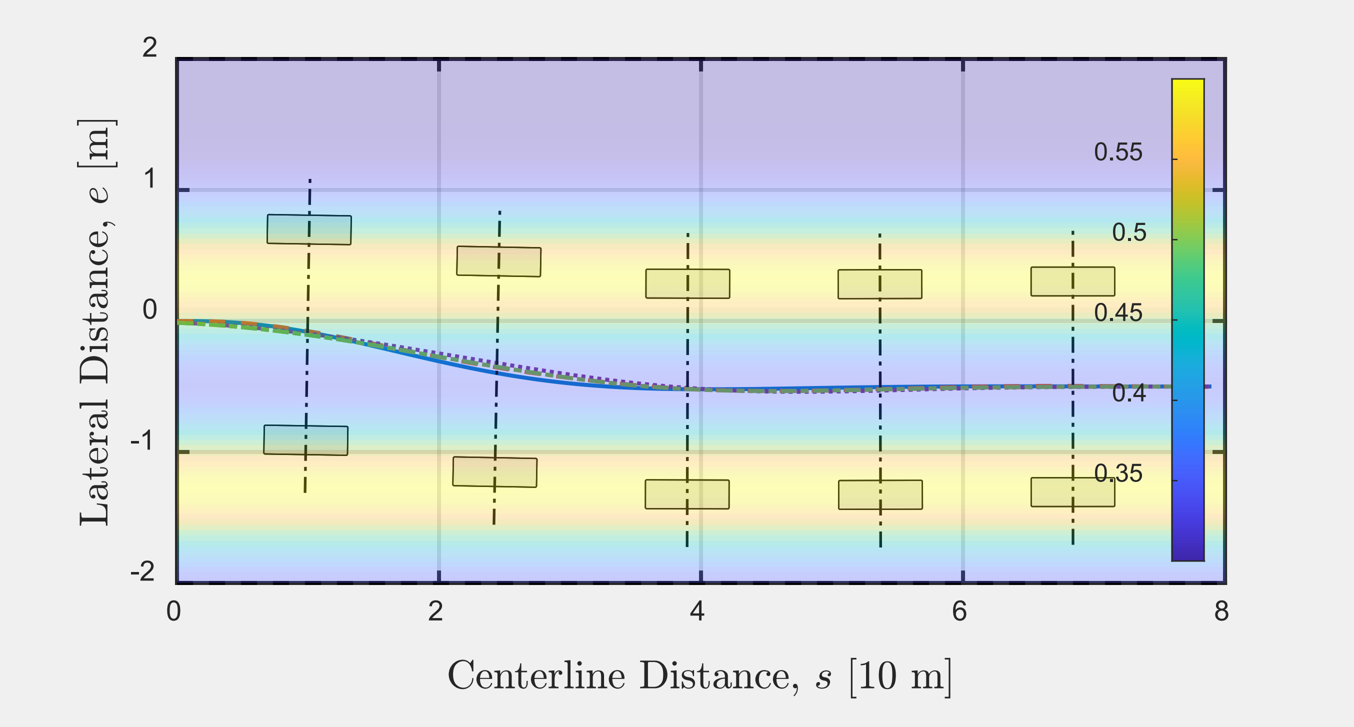
Optimal Path: CarMaker simulation structure

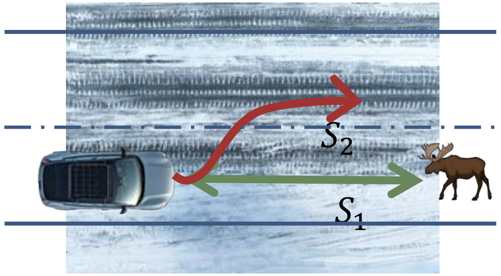




Optimal Path: Similar paths for all models







Optimal Path: Braking distance on snow-tracks

- PM model minor differences to more advanced model
- Moving to high friction can significantly reduce braking distance

		Braking distance	
Simulation	w/ PM path	78.4m	
	w/ ST path	78.8m	
	No steering	108.2m	+37%

Summary

1. Braking on uniform friction roads
   - Friction estimate deviations critical at low frictions

2. Braking on split friction
   - Extreme split friction optimal solution + control

3. Optimal path
   - Significant gains moving towards higher friction
   - Particle model sufficient for friction-aware path planning

Future work

- Adaptive speed and path framework based on predicted friction
- Addressing friction uncertainty

VOLVO

Thank you!

Presentation *7a:*

KTH, Vehicle engineering Master programme

Mikael Nybacka, KTH

Master programme in Vehicle Engineering

Mikael Nybacka

Associate Professor in Vehicle Dynamics

Programme Director for Vehicle Engineering

KTH VETENSKAP OCH KONST

Future of Vehicle Engineering – Exciting and needed transformation going on – requiring engineers!

- Flexible
- Environmental friendly
- Safe
- Cheep
- Personal
- Comfortable
- Secure
- Fast
- Integrated
- Just
- …

Master programme in Vehicle Engineering

- Some quick facts

Two-year programme (120 ECTS credits) given in English

Two tracks, **road** and **rail** vehicles

600-700 applicants and ~**300** 1st hand applicants over the last 5 years

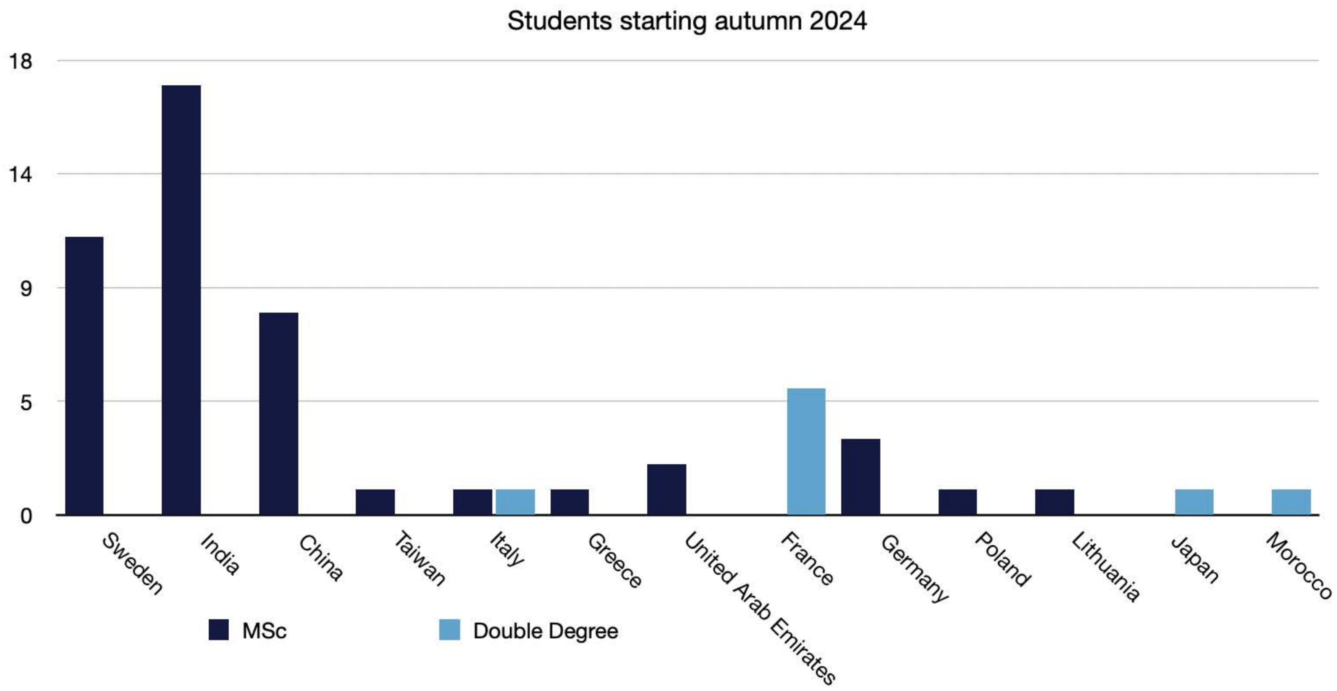
Admitted 45 students 2024 (~**15%** acceptance rate from 1st hand applicants of int. master intake)

Total amount of student / year = **45-55**

Around **1/3 Swedish** and **2/3 international** students

13 Nationalities 2024

~5 female students / year (we want more to apply!)



Entry requirements

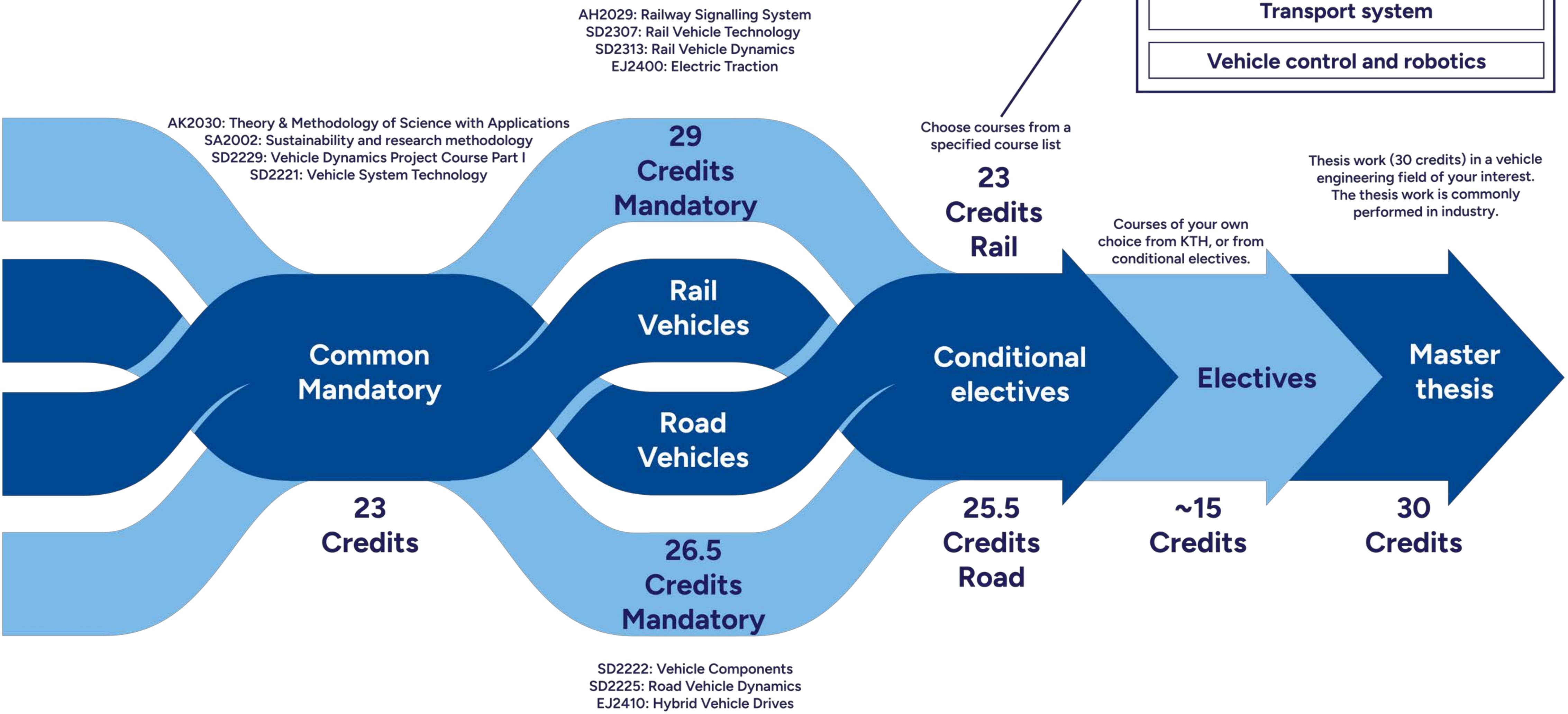
- A bachelor's degree or comparable qualification equivalent to a Swedish bachelor's degree from an internationally recognised university. 180 ECTS
- English proficiency, IELTS Academic or IELTS UKVI: An overall score of 6.5, with no selection lower than 5.5
  - Or other like TOEFL, ECPE, PTE, ESOL
- Specific documents for Vehicle Engineering
  - Summary Sheet (IMPORTANT)
- Selection criteria
  - Study results (grades, relevant subjects and English) motivation for studies (motivation letter) and prior education.
  - Prior education is evaluated based on the quality and suitability of the subjects that are relevant for the programme applied to. The merit rating is carried out on a scale of 1-75.

- Specific requirements:
- Mathematics and Programming, equivalent to approximately 25 ECTS credits in total, which must include courses or course modules in
  - 1. control theory
  - 2. programming
- Applied mechanics, equivalent to approximately 20 ECTS credits in total, which must include courses or course modules in
  - 3. solid mechanics
  - 4. fluid mechanics

Programme structure

Conditional elective courses in these topic areas

- Electric mobility
- Vehicle structures and design
- Vehicle aerodynamics and acoustics
- Transport system
- Vehicle control and robotics



Conditional elective courses in these topic areas, choose any course from any topic area

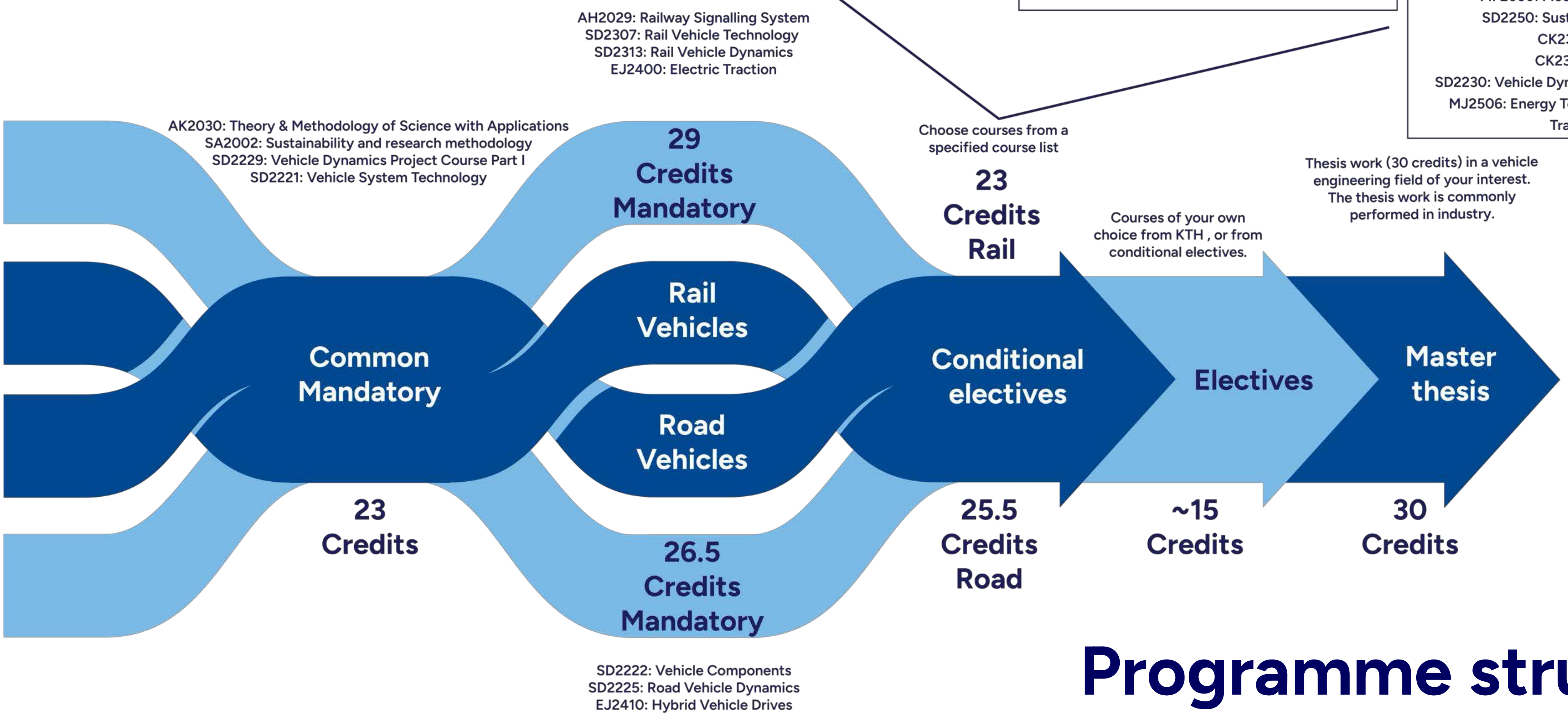
Vehicle control and robotics
MF2030: Mechatronics basic course
MF2043: Robust mechatronics
MF2007: Dynamics and Motion Control
EL2520: Control Theory and Practice, Adv.
SD2231: Applied Vehicle Dynamics Control
EL2700: Model Predictive Control
SD2230: Vehicle Dynamics Project course (Part 2)

Vehicle structures and design
SD2411: Lightweight Structures and FEM
SD2150: Experimental Structure Dynamics
SD2416: Structural Optimisation and Sandwich Design
SD2190: Vehicle Acoustics and Vibration
SD2111: Engineering acoustics
SD2250: Sustainable vehicle design
SD2230: Vehicle Dynamics Project course (Part 2)

Vehicle aerodynamics and acoustics
SD2155: Flow Acoustics
SG2211: Vehicle Aerodynamics
SD2625: Comp. Vehicle Aerodynamics
SG1217: Fluid mechanics, basic course
SG1220: Fluid mechanics for engineers
SG2214: Fluid Mechanics
SD2250: Sustainable vehicle design
SD2230: Vehicle Dynamics Project course (Part 2)

Transport system
AH2307: Urban modelling and decision
AH2171: Traffic Engineering Management
AH2170: Transport Data Collection and Analysis
AH2174: Traffic Simulation Modelling and Application
AH2173: Public transport

Electric mobility
MF2030: Mechatronics basic course
SD2250: Sustainable vehicle design
CK2300: Batteries
CK2320: Hydrogen
SD2230: Vehicle Dynamics Project course (Part 2)
MJ2506: Energy Technologies for Sustainable Transportation



Programme structure

Mandatory courses

ROAD

	Year 1				Year 2		
1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
AK2030 Theory & science 4.5 hp	EJ2410 Hybrid vehicle drives 7.5 hp				SA2002 Sustainable dev. & research methods 3.0 hp	SD221X Master thesis 30 hp	
SD2221 Vehicle system technology 8 hp	SD2222 Vehicle components 8 hp	SD2225 Road vehicle dynamics 11 hp		SD2229 Vehicle dynamic project Part I 7.5 hp			

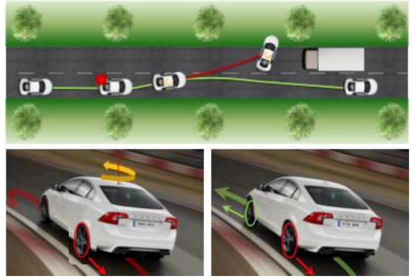
RAIL

1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
AK2030 Theory & science 4.5 hp				AH2029 Railway signalling systems 7.5 hp	SA2002 Sustainable dev. & research methods 3.0 hp	SD231X Master thesis 30 hp	
SD2221 Vehicle system technology 8 hp	SD2307 Rail vehicle technology 7.5 hp	SD2313 Rail vehicle dynamics 8 hp	EJ2400 Electric traction 6 hp	SD2229 Vehicle dynamic project Part I 7.5 hp			

- (dark blue) mandatory
- (medium blue) mandatory, but can be read during 1st or 2nd year
- (light blue) mandatory, can be read in any study period

Road - Control focus

1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
MF2030 Mechatronics Basic course 6hp	EJ2410 Hybrid Vehicle drives 7.5hp	EL2450 Hybrid and Embedded Control Systems 7.5hp	SD2231 Applied Vehicle Dynamics Control 7.5 hp	EL2700 Model Predictive Control 7.5 hp	MF2007 Dynamics and motion Control 7.5 hp	SD221X Master thesis 30 hp	
AK2030 Theory & science 4.5hp	SA2002 Sustainable dev. research methods 3hp						
SD2221 Vehicle system technology 8 hp	SD2222 Vehicle components 8 hp	SD2225 Road vehicle dynamics 11 hp		SD2229 Vehicle dynamic project Part I 7.5 hp	SD2230 Vehicle dynamic project Part 2 7.5 hp		



Conditionally electives

Free course

Road - Electric powertrain focus

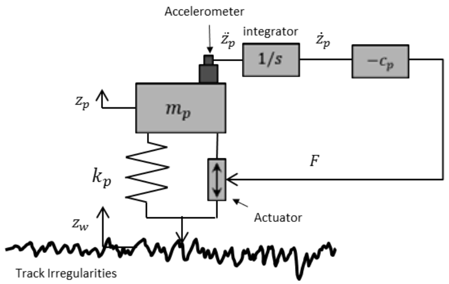
1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
MF2030 Mechatronics Basic course 6 hp	EJ2410 Hybrid Vehicle drives 7.5hp	CK2320 Hydrogen 7.5 hp	EJ2400 Electric traction 6 hp	SD2250 Sustainable vehicle design 7.5 hp	SD2230 Vehicle dynamic project Part 2 7.5 hp	SD221X Master thesis 30 hp	
AK2030 Theory & science 4.5hp	SA2002 Sustainable dev research methods 3hp						
SD2221 Vehicle system technology 8 hp	SD2222 Vehicle components 8 hp	SD2225 Road vehicle dynamics 11 hp		SD2229 Vehicle dynamic project Part I 7.5 hp	CK2300 Batteries 7.5 hp		

Road - Design focus

1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
SD2111 Engineering Acoustics 6 hp	EJ2410 Hybrid Vehicle drives 7.5hp	SD2125 Experimental structure dynamics 9 hp		SD2250 Sustainable vehicle design 7.5 hp	SD2416 Structural Optimisation and Sandwich Design 6 hp	SD221X Master thesis 30 hp	
AK2030 Theory & science 4.5hp	SA2002 Sustainable dev. research methods 3hp						
SD2221 Vehicle system technology 8 hp	SD2222 Vehicle components 8 hp	SD2225 Road vehicle dynamics 11 hp		SD2229 Vehicle dynamic project Part I 7.5 hp	SD2230 Vehicle dynamic project Part 2 7.5 hp		

Rail - Control focus

1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
MF2030 Mechatronics Basic course 6hp	SA2002 Sustainable dev. & research methods 3 hp	SD2313 Rail vehicle dynamics 8 hp	EJ2400 Electric traction 6 hp	EL2700 Model Pred. Control 7.5 hp	MF2007 Dynamics and motion Control 7.5 hp	SD231X Master thesis 30 hp	
AK2030 Theory & science 4.5hp				AH2029 Railway signalling sys. 7.5 hp			
SD2221 Vehicle system technology 8 hp	SD2307 Rail vehicle technology 7.5 hp	EL2450 Hybrid and Embedded Control Systems 7.5hp	SD2231 Applied Vehicle Dynamics Control 7.5 hp	SD2229 Vehicle dynamic project Part I 7.5 hp	SD2230 Vehicle dynamic project Part 2 7.5 hp		



Conditionally electives

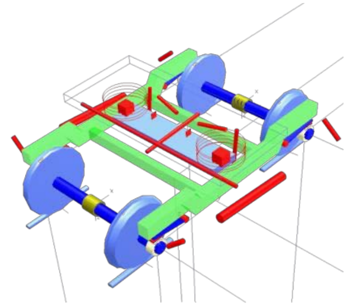
Free course

Rail - Traffic focus

1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
AH2170 Transport Data Collection and an. 7.5 hp	AF2901 Road and Rail. Track Engine. 7.5 hp	SD2313 Rail vehicle dynamics 8 hp	EJ2400 Electric traction 6 hp	AH2029 Railway signalling system 7.5 hp	AH2028 Railway traffic market and planning advanced course 7.5 hp	SD231X Master thesis 30 hp	
AK2030 Theory & science 4.5hp	SA2002 Sustainable dev. research methods 3hp						
SD2221 Vehicle system technology 8 hp	SD2307 Rail vehicle technology 7.5 hp	AH2301 Transport Policy and Evaluation 7.5 hp	AH2173 Public Transport 7.5 hp	SD2229 Vehicle dynamics project Part I 7.5 hp	AH2171 Traffic Engineering Managem. 7.5 hp		

Rail - Dynamics focus

1:1	1:2	1:3	1:4	2:1	2:2	2:3	2:4
AK2030 Theory & science 4.5 hp	SA2002 Sustainable dev. & research methods 3 hp	SD2313 Rail vehicle dynamics 8 hp	EJ2400 Electric traction 6 hp	AH2029 Railway signalling system 7.5 hp	MF2007 Dynamics and motion Control 7.5 hp	SD231X Master thesis 30 hp	
SD2221 Vehicle system technology 8 hp	SD2307 Rail vehicle technology 7.5 hp	SD2125 Experimental structure dynamics 9 hp		SD2229 Vehicle dynamics project Part I 7.5 hp	SD2230 Vehicle dynamics project Part 2 7.5 hp		



Experimental vehicles, equipment and test tracks

Volvo S90 D5 AWD Geartronic

Roller rig

Arlanda test track

Drive Lab 1 and 2

RCV-Dynamic

Research
Concept Vehicles

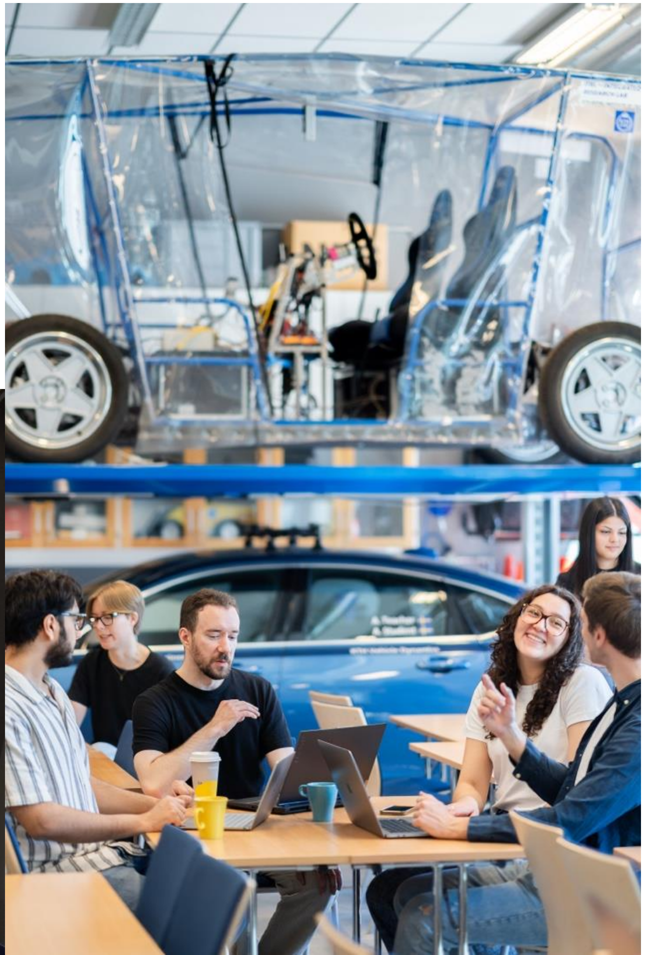
RCV-E

Driving simulators

Lunda flygfält

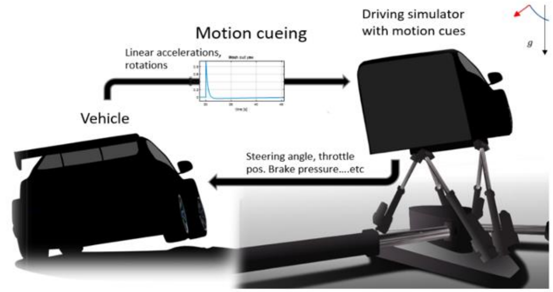
Vehicle Engineering Lab

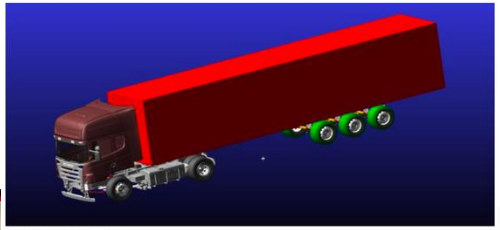
- Education
- Experiments
- Computer exercises
- Studies on your own

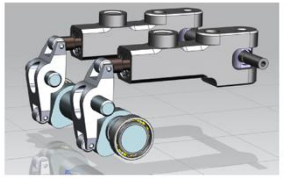


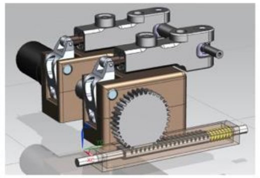
Project course final year

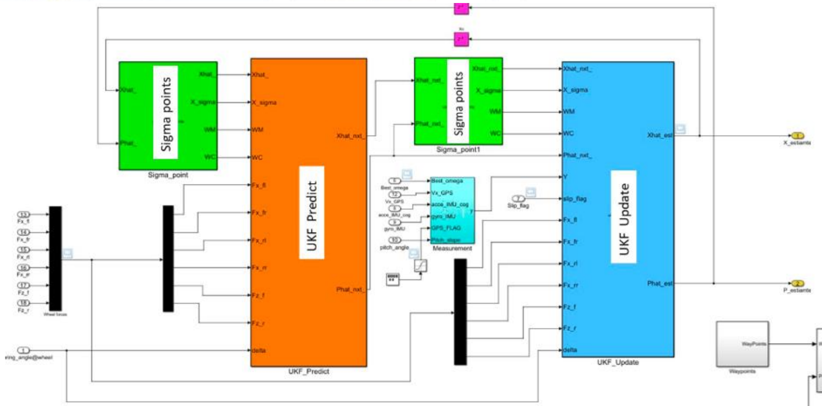
Companies send project ideas to mnybacka@kth.se in June the latest

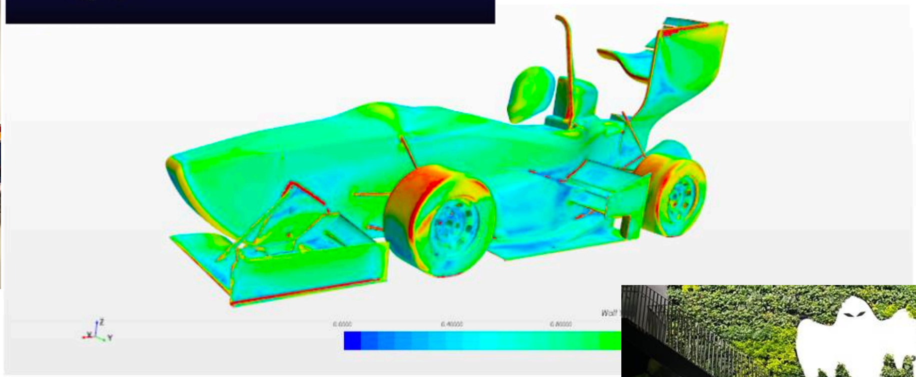


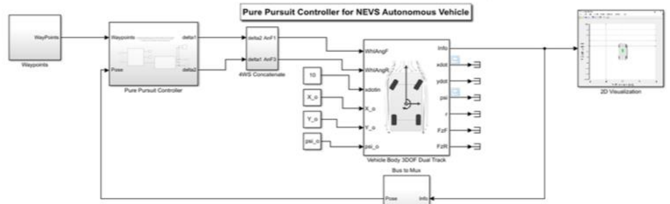


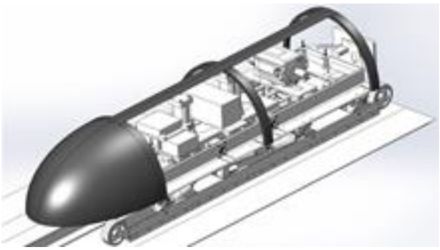












Questions?

Mikael Nybacka
Programme director

mnybacka@kth.se

Research groups ***Rail vehicles***, ***Vehicle dynamics***, ***Aero dynamics*** and ***Conceptual vehicle design***
At the division of Vehicle Engineering and Solid Mechanics

info@kth.se – accommodation, KTH user account, anything else.

master@sci.kth.se – study plans, courses, etc.

www.kth.se/en/studies/master/vehicleengineering

Presentation 7b:

Chalmers, Mobility engineering Master programme

Dag Bergsjö, Chalmers

Presentation 7c:

LiU, Vehicle engineering courses

Jan Åslund, LiU

Vehicle Engineering Courses at Linköping University

Jan Åslund

Vehicular Systems

LINKÖPING UNIVERSITY

Road Vehicle Engineering at Linköping University

Selected Courses in Vehicle Systems

TSFS02 – Vehicle Dynamics and Control

Focus on the dynamic behavior of vehicles and their control systems.

TSFS03 – Vehicle Propulsion Systems

Explores different propulsion technologies used in road vehicles.

TSFS04 – Electric Drive Systems

Covers electric systems designed for vehicle propulsion.

TSFS09 – Modeling and Control of Engines and Drivelines

Introduction to modeling and control techniques for engines and drivetrain components.

TSFS12 – Autonomous Vehicles: Planning, Control, and Learning Systems

Development of autonomous vehicle technologies through planning, control, and machine learning.

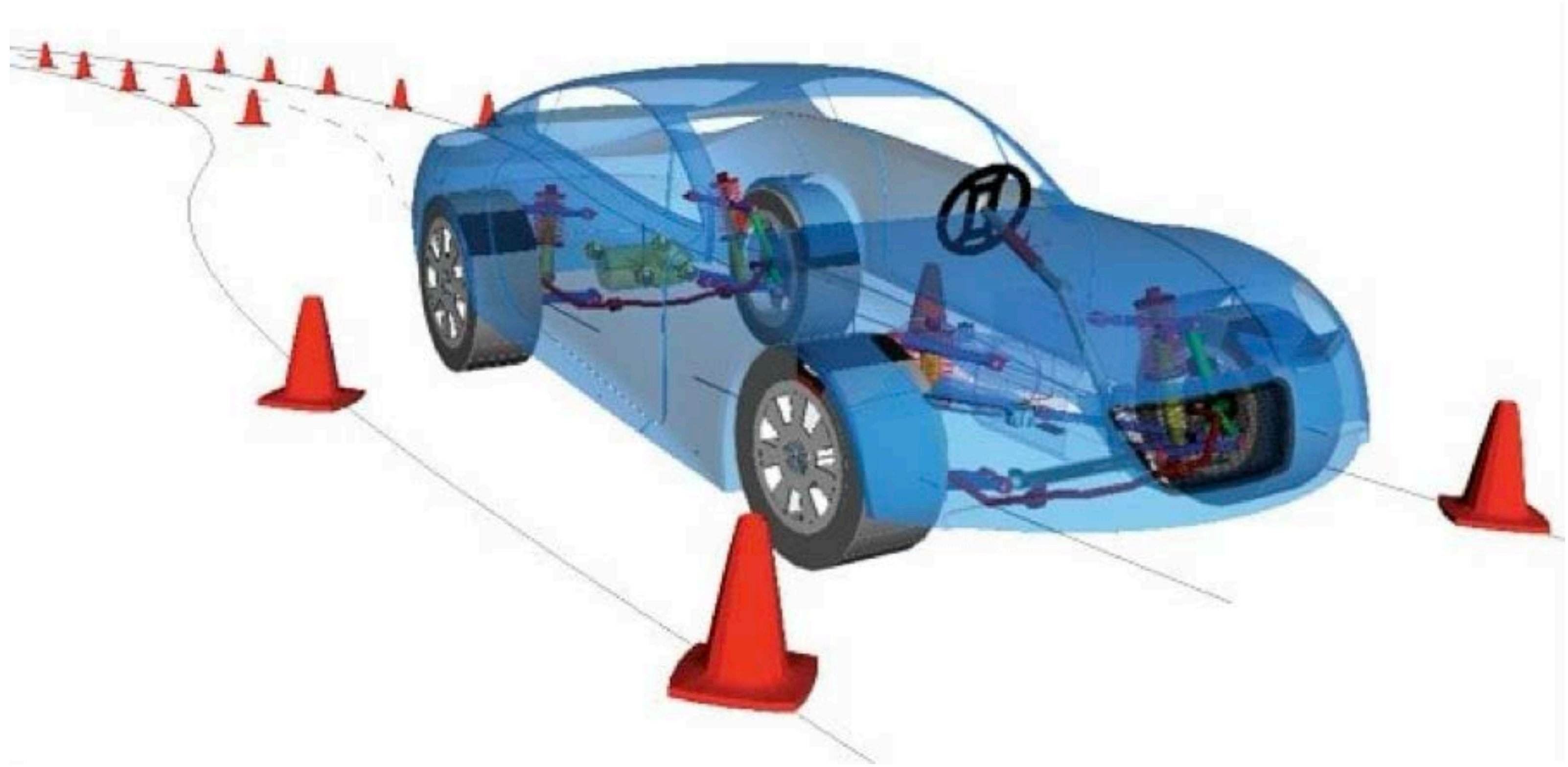
TMME11 – Road Vehicle Dynamics

Provides knowledge on chassis components and simulation of road vehicle motion.

TSFS02 Vehicle Dynamics and Control

Examiner: Jan Åslund

Modern vehicles integrate an increasing array of autonomous and semi-autonomous functions, many of which are safety-critical—such as anti-lock braking systems (ABS), traction control, and electronic stability control (ESC).



This course provides a foundational understanding of vehicle dynamics, including longitudinal, lateral, and vertical motion. Emphasis is placed on the modeling and analysis of dynamic behavior and the design principles of control systems that enhance vehicle safety, stability, and handling performance.

TSFS02 Laboratory Exercises in the Course

The course is examined through a written exam and the following five computer labs:

Brake Force Distribution & ABS

Study how brake force distribution and anti-lock braking systems affect vehicle dynamics and safety.

Cornering Dynamics

Parameterize and validate vehicle and tire models using real-world data.

Electronic Stability Control (ESC)

Develop and implement a control system to improve vehicle stability and safety.

Vertical Dynamics

Analyze how damper control influences passenger comfort and cornering performance.

Car-Trailer Stability Control

Design control strategies to ensure the stability of a car-trailer combination.

All course material is available at: https://isy.gitlab-pages.liu.se/fs/courses/TSFS02/
Don’t hesitate to contact me if you have any questions: jan.aslund@liu.se

Poster 1:

Reversing A-double using steerable axle on the last semi-trailer

Pavan Kumar Adiga Nagaraj, Niveditha Krishnakumar, Chalmers and Volvo Trucks

VOLVO

Reversing A-double using steerable axle on the last semi-trailer

SEVA presentation

Masters Student: Pavan Kumar Adiga Nagaraj, Niveditha Krishnakumar

Industrial Supervisor: Mukesh Choudhary

Academic Supervisor: Zhaohui Ge

Examiner: Bengt Jacobson

Week 19

Agenda

- Introduction
- Research questions of thesis
- Low Speed reverse assist function overview
- Modeling overview and model verification
- Controller overview and controller verification with VTM
- Test cases and controller validation in VTM
- Resuts

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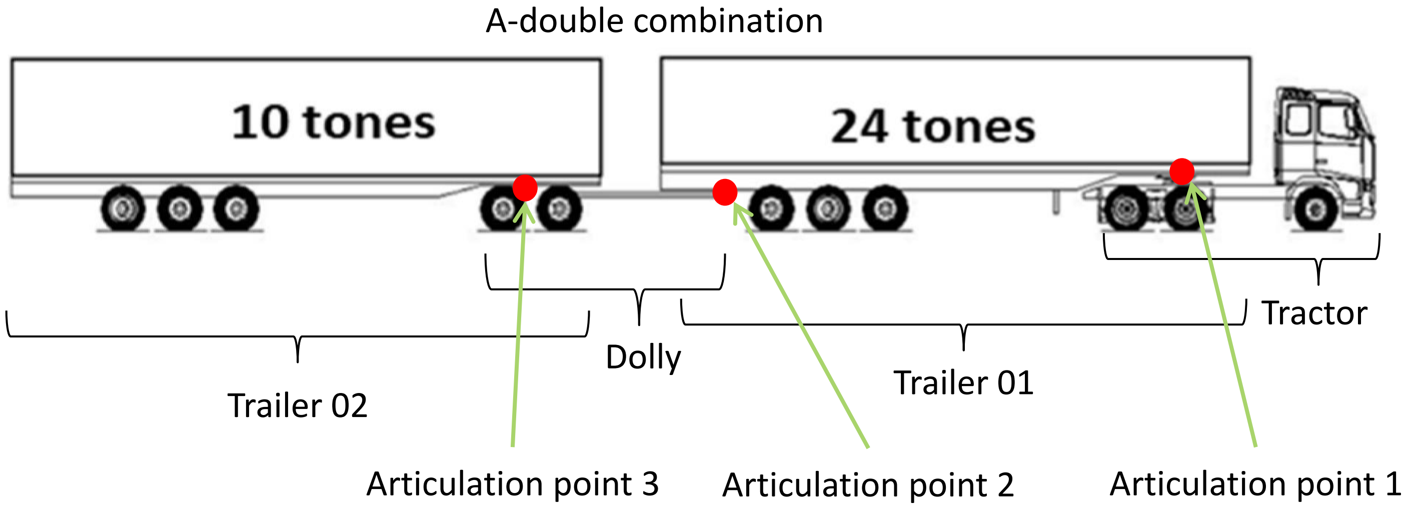
Introduction



Reversing of Long combination vehicle (LCV):-

vehicle combination : A- double combination

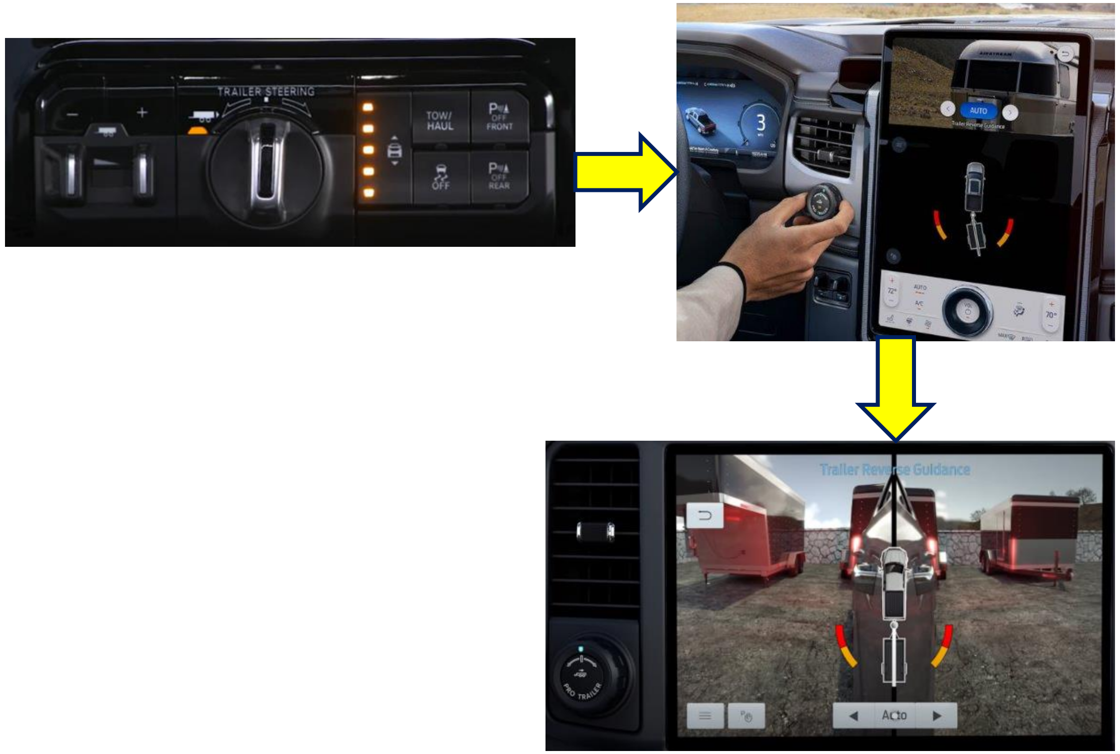
number of articulation angles: 3

reversing complixity increases as the number of articulation angles increases.

- Truck FH 4X2 are the highest sold in europe which is generally combined with just a single semi-trailer.
- Truck FH 6x4 / FH 6X2 are the next best sold truck configuration which is suitable for LC.
- In Nordic countries A-double and AB double combination was first introducced in Finland in 2019. Followed by Sweden in december 2023 officially allowing up to 34.5m.
- Intended application low speed maneuver reverse (Vx=-3.6 km/h)
- Based on the expereince, reversing an A-double for 10m straight was difficult

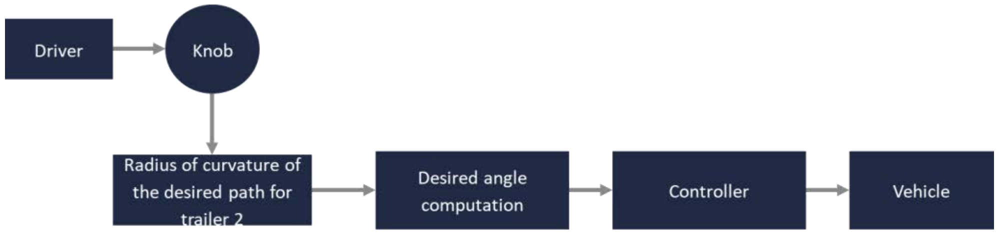
Research Questions of Thesis

1. Research A-double reversing and collect Tommi's feedback with a vehicle demo
2. Develop a control algorithm to automate steering for reversing.
3. Explore reversing using only
   - Tractor steering
   - Tractor and trailer 2 last axle steering
4. Analyze the impact of loaded vs. unloaded last trailers during reversing.
5. Test the control algorithm on a test vehicle.
6. Integrate outputs with the HMI display to provide driver feedback.

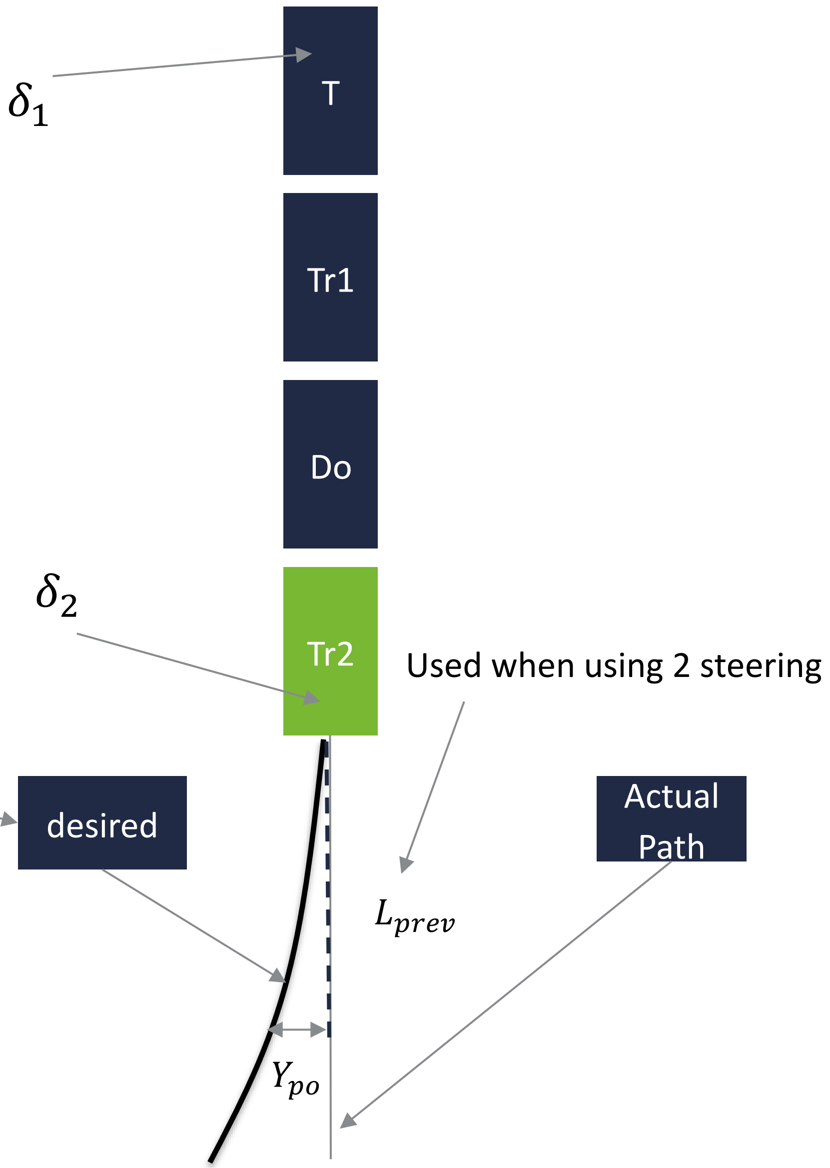


Function overview

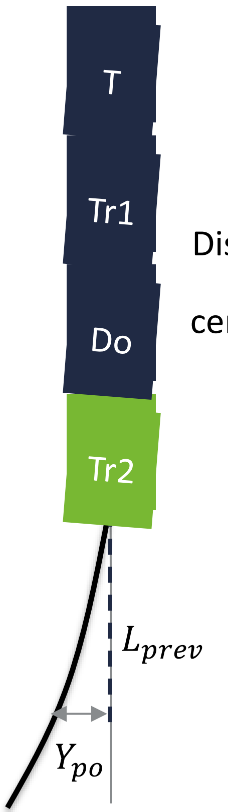
Knob to set the desired trajectory



A-Combination top view



HMI



Display warning for

certain Radius input

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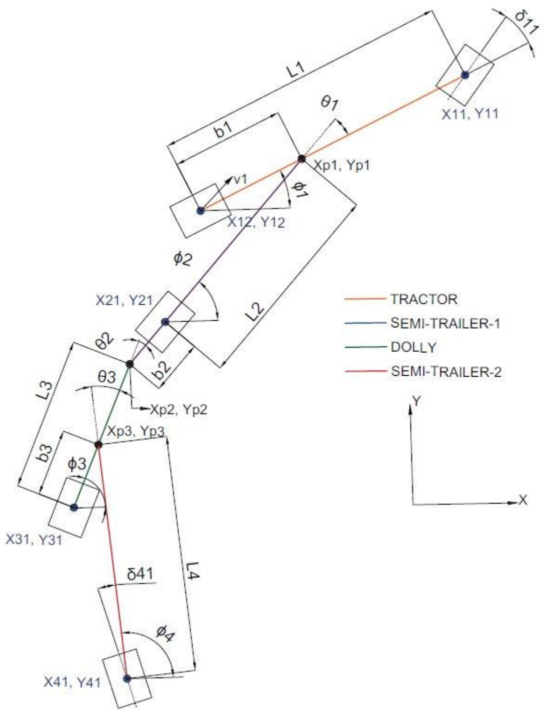
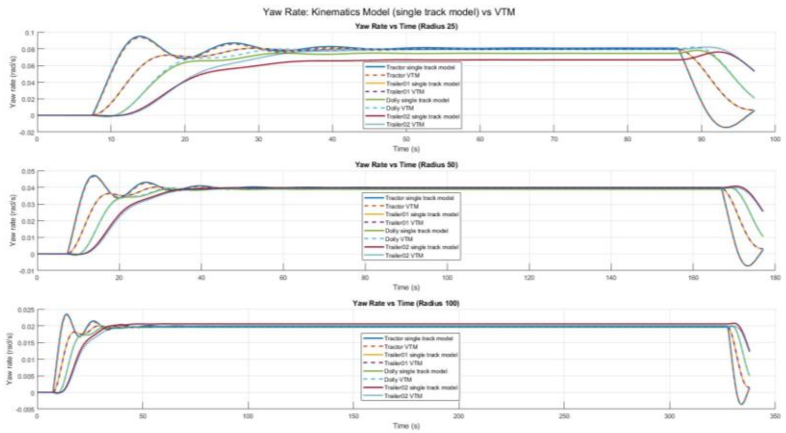
Modelling

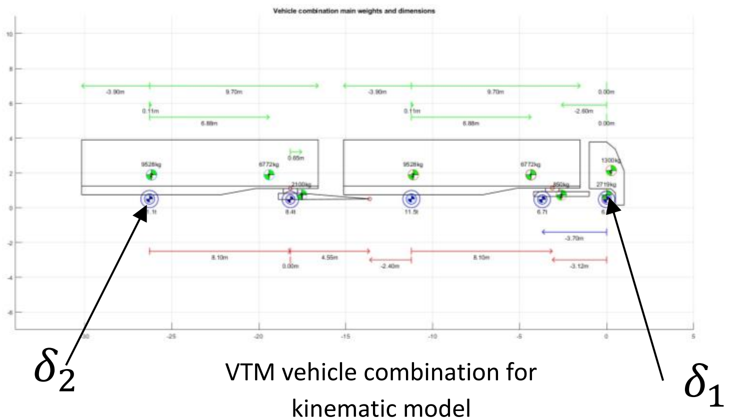


Model Verification

Results : OK

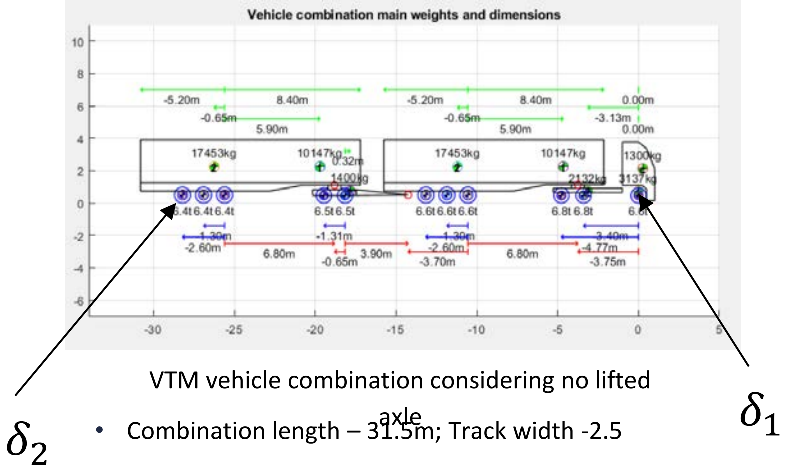


Vehicle was moving in Forward direction with the velocity of 2m/s



VTM vehicle combination for kinematic model

- Combination length – 31.5m; Track width -2.5
- Number of axles – 5 (lumped axles on all units)
- Steerable Axles: Tractor, Trailer 2
- Propelled Axles: Tractor



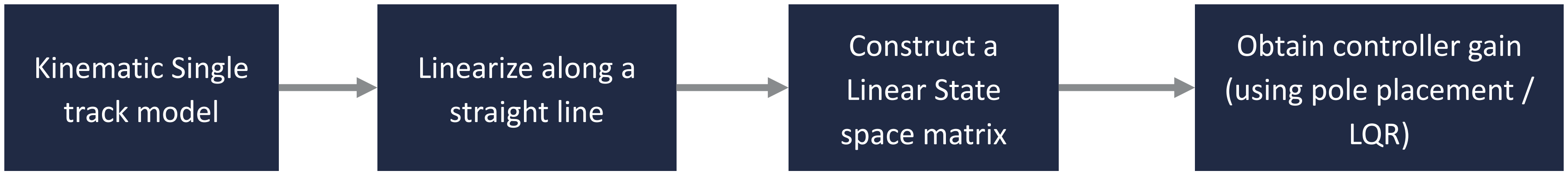
VTM vehicle combination considering no lifted axle

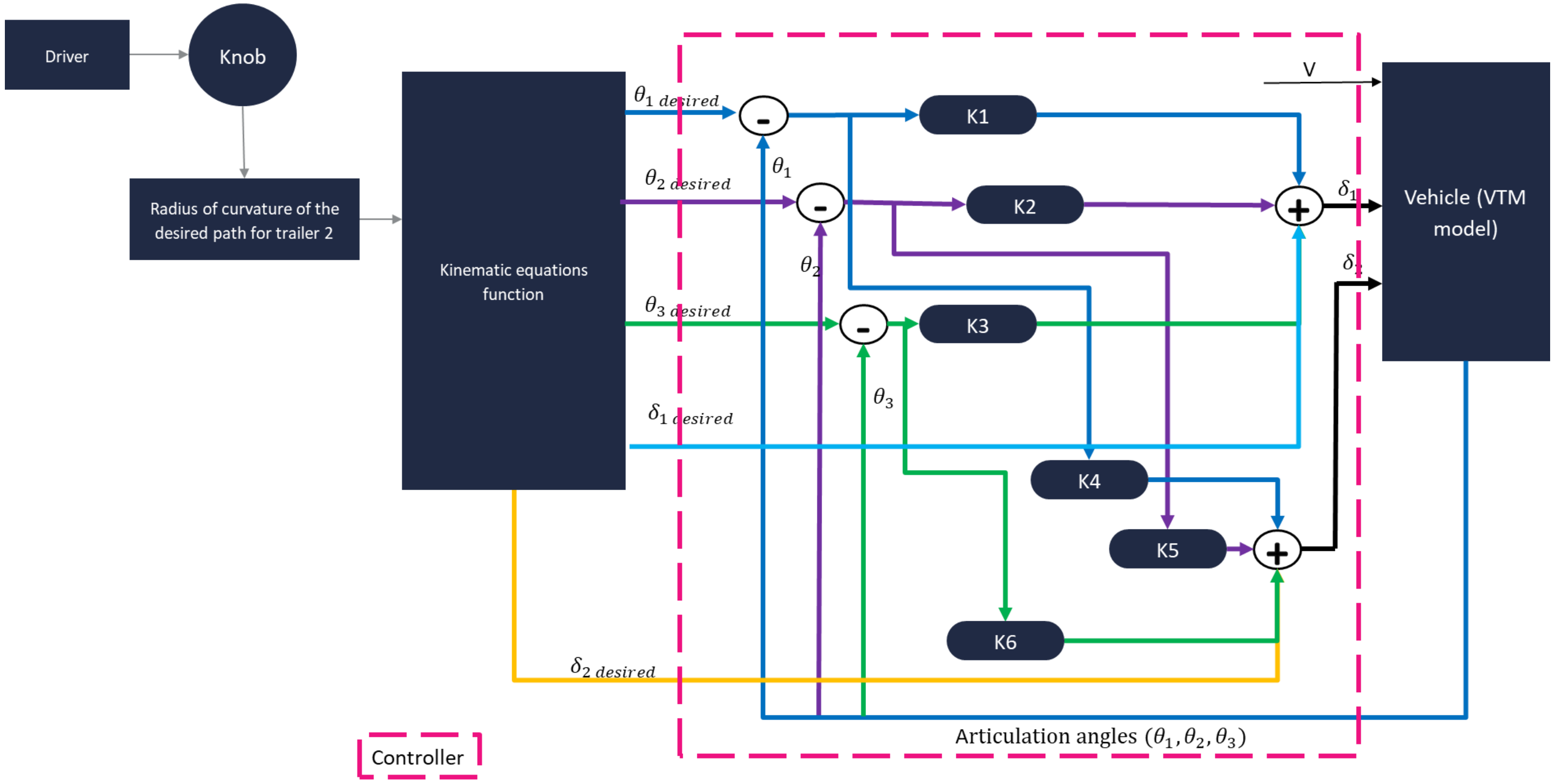
- Combination length – 31.5m; Track width -2.5
- Number of axles – 11 (no lifted axle)
- Steerable Axles: Tractor, Trailer 2
- Propelled Axles: Tractor

Define the position of each axle (X,Y) → Compute the velocity at each axle $(\dot{X}, \dot{Y})$ → Construct Non-holonomic equation → Solve for Yaw Rates

Differentiate position w.r.t time

Controller Overview



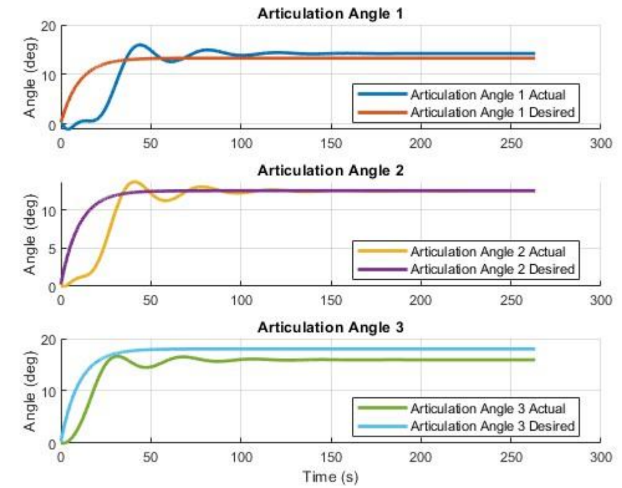


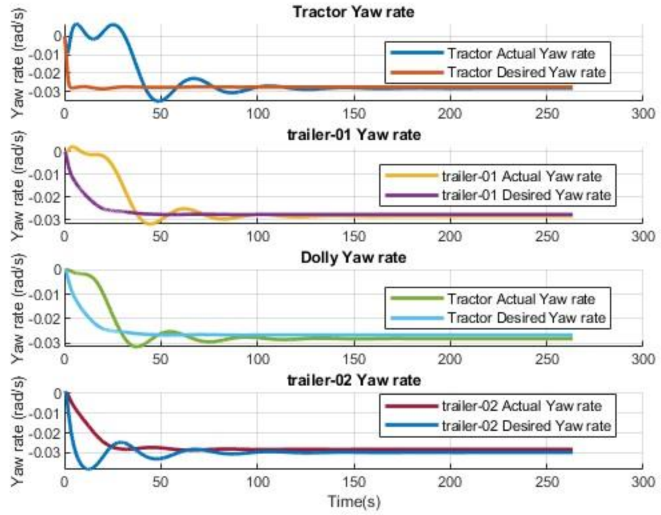
Controller Verification test case (circle radius 30 m)

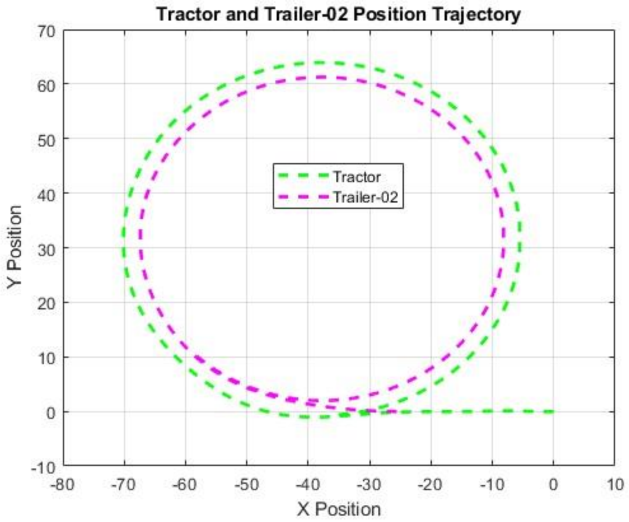
Results : OK

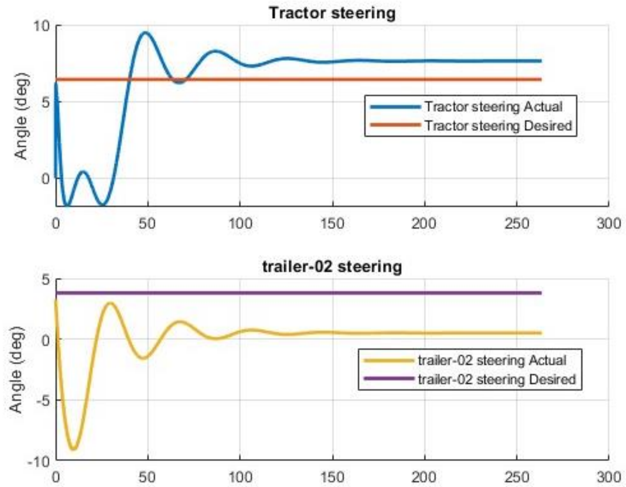
Vehicle was reversing at 1m/s

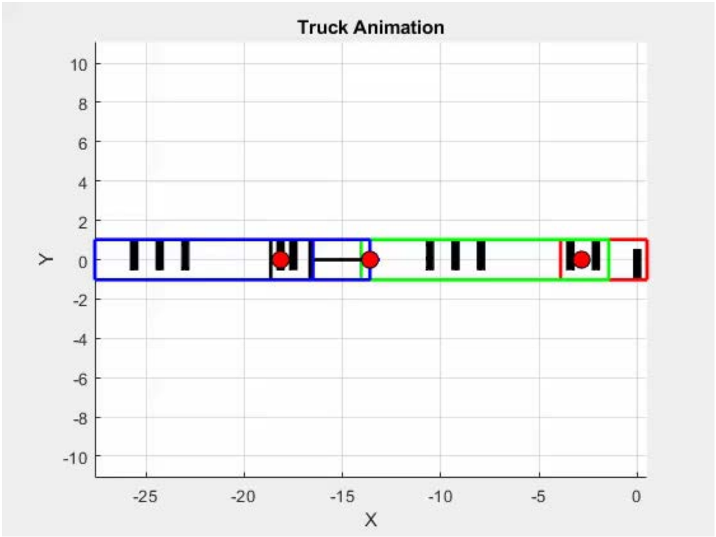
Radius 30m, all axle considered



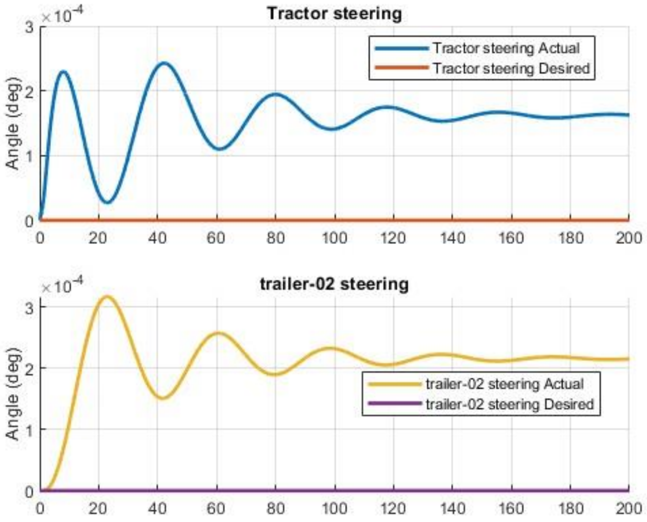


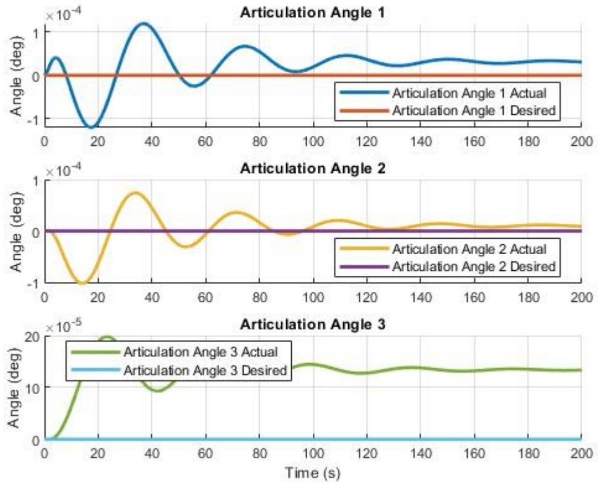


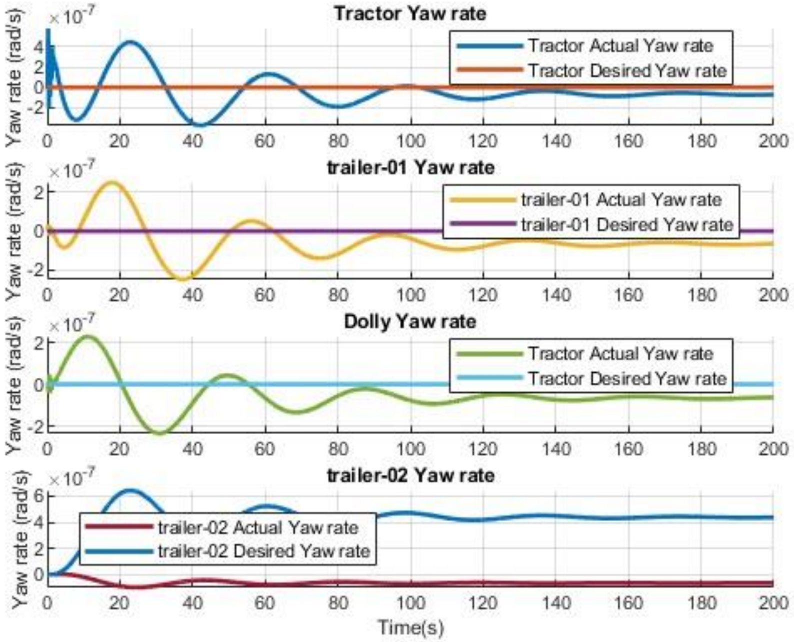




Controller Verification test case (straight line 200m)



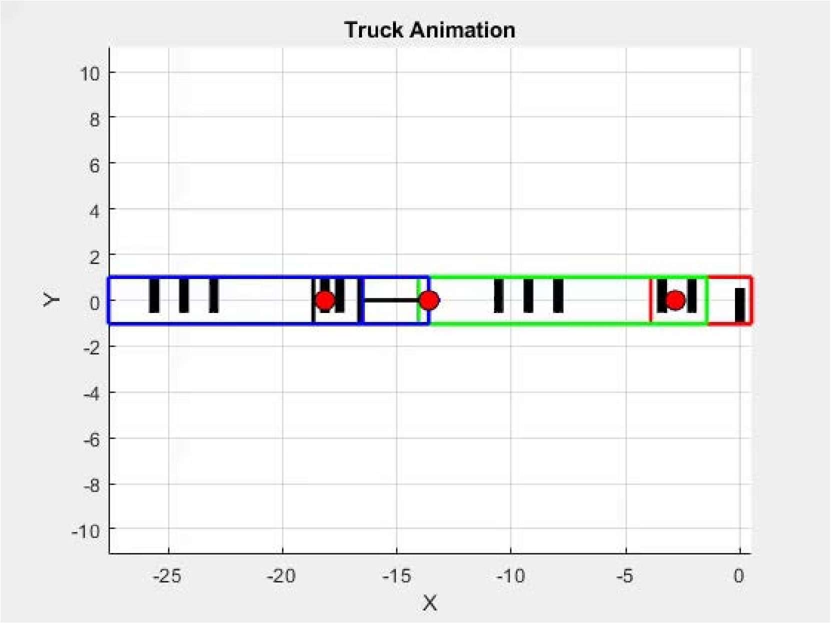




Results : OK

Vehicle was reversing at 1m/s

Straight line 200m , all axle considered



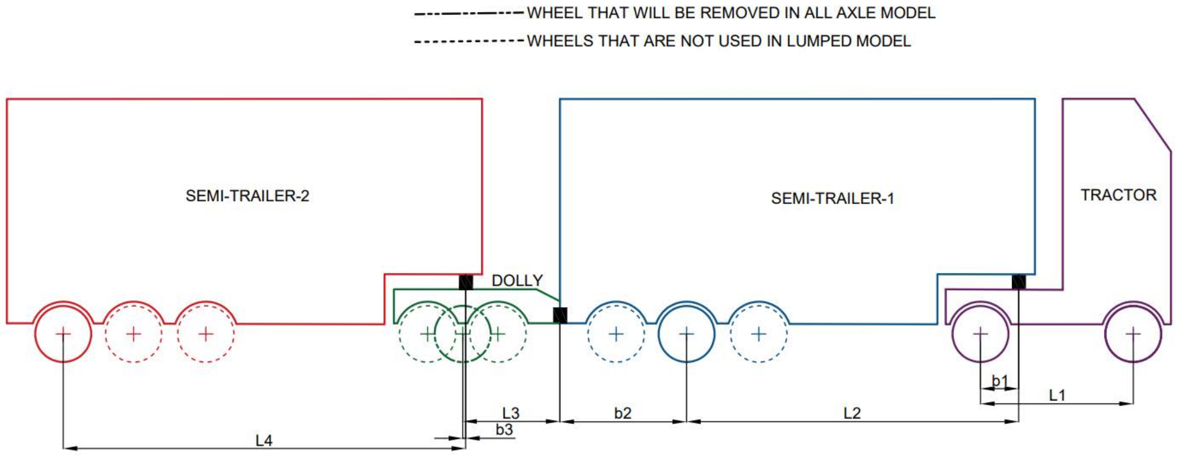
Questions and feedback

Reversing A-double using steerable axle on the last semi-trailer

Pavan Kumar Adiga, Niveditha Krishnakumar

Introduction

- Reversing of Long combination vehicle (LCV):-
  - ❑ Vehicle combination : A- double combination
  - ❑ Number of articulation angles: 3
  - ❑ Reversing complixity increases as the number of articulation angles increases.
- Intended application low speed maneuver reverse (Vx=-3.6 km/h)
- Based on the vehicle test drive it was identified that reversing an A-double for 10m straight was difficult



Research questions

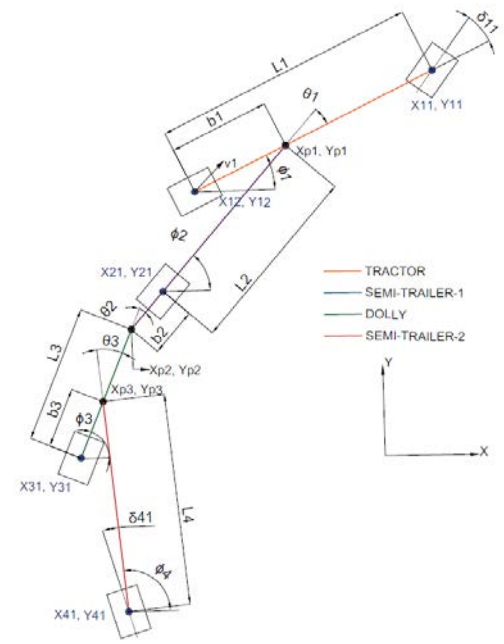
➢ Research A-double reversing and collect Tommi's feedback with a vehicle demo

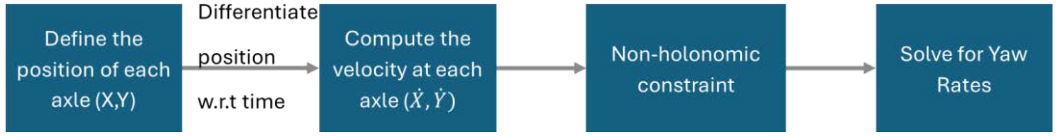
➢ Develop a control algorithm to automate steering for reversing.

➢ Explore reversing using only

1. Tractor steering
2. Tractor and trailer 2 last axle steering

Modelling approach





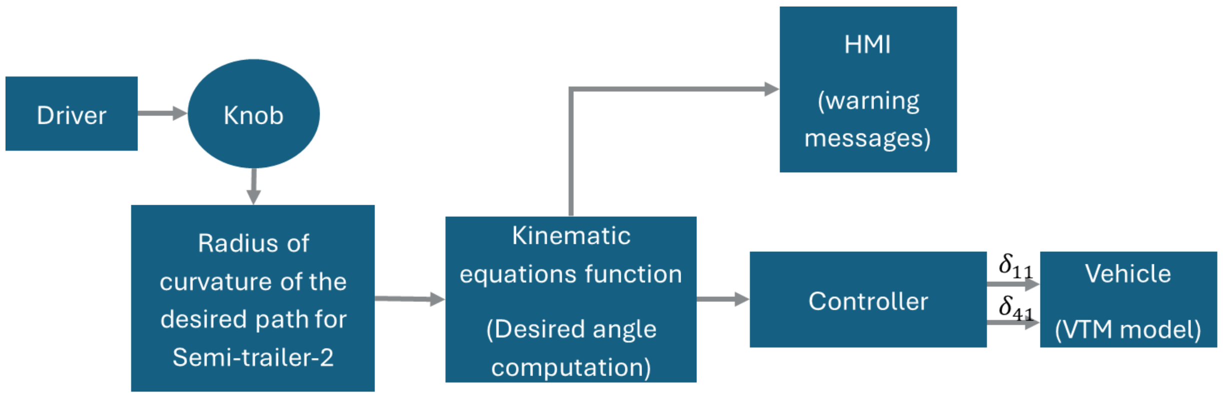
Reversing A-double using steerable axle on the last semi-trailer

Pavan Kumar Adiga, Niveditha Krishnakumar

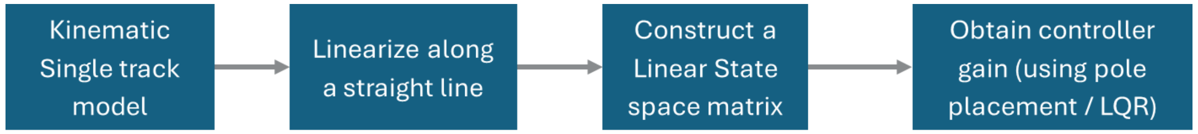
CHALMERS UNIVERSITY OF TECHNOLOGY

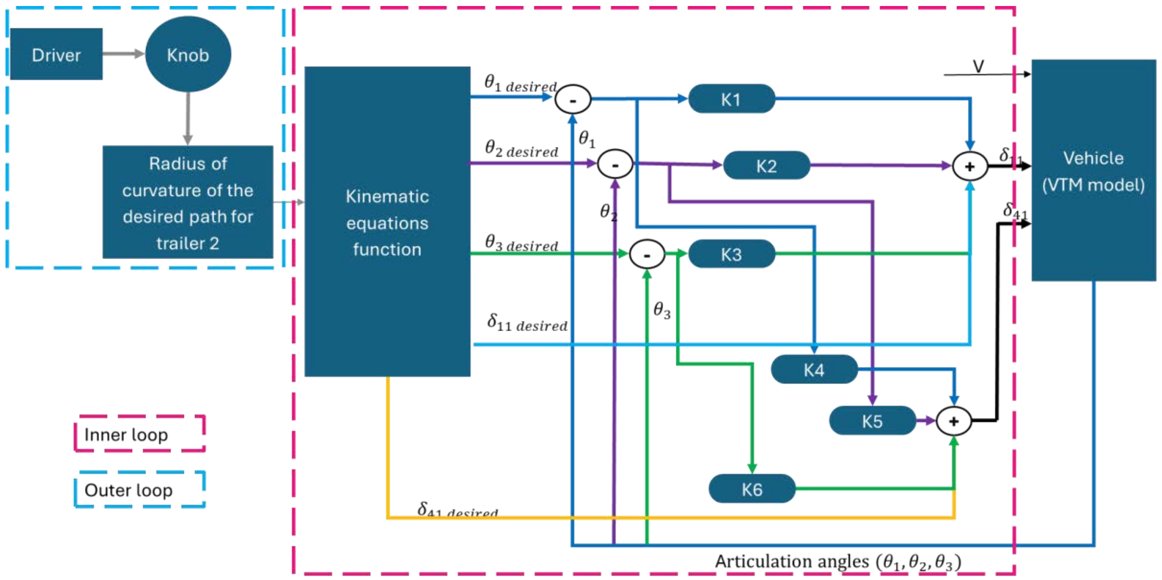
VOLVO

Function overview



Feedback Controller

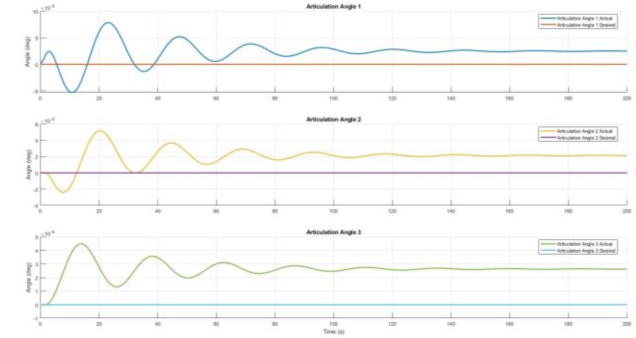




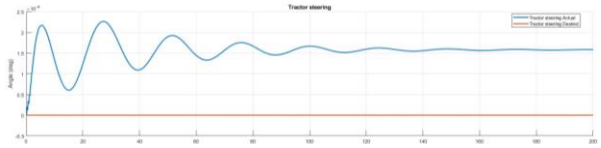
Results

Reversing of A double combination with tractor steering for a straight line

Trajectory

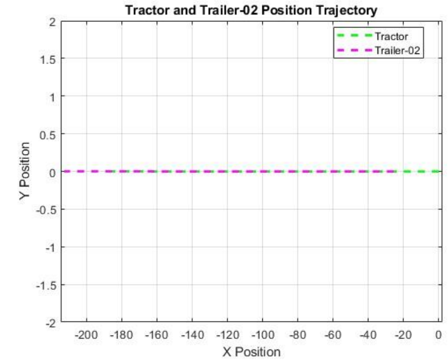


Articulation Angle

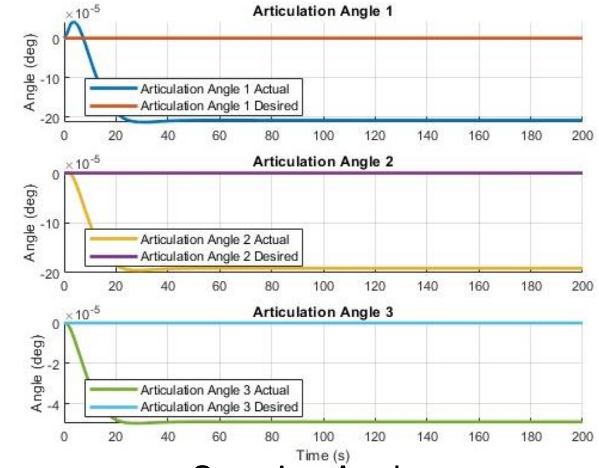


Steering Angle

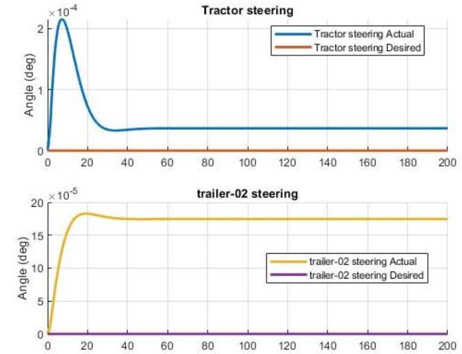
Reversing of A double combination with tractor and trailer -02 last axle steered for straight line



Trajectory



Steering Angle



Articulation Angle

Poster 2:

Onboard Estimation of Center of Gravity in Heavy Vehicles

Alfred Aronsson and Fabian Fagerlind,
Chalmers and Volvo Trucks

This poster was unfortunately cancelled

Poster 3:

Development and validation of a friction estimation model for collision avoidance maneuvers in autonomous trucks

Ganapati Girish Kamat, Chalmers and Scania

Ganapati Girish Kamat

Development and validation of a friction estimation model for collision avoidance manoeuvres in autonomous trucks

07 May 2025

About me

- Born and raised in Bangalore, India
- Education:
  - Masters in Mobility Engineering (Automotive track) @ Chalmers University
  - Bachelors in Mechanical Engineering @ BMS College of Engineering, India
- Scania Student Intro 2024
  - Summer intern @ steering design team
  - Master thesis student @ ADAS & autonomous steering functions team
- Hobbies: I enjoy playing volleyball and hiking

Introduction

- Autonomous trucks need reliable collision avoidance systems for safety

- Information on peak friction coefficient is crucial to determine braking and steering limits

- Challenge: Traditional methods assume a fixed friction coefficient, leading to suboptimal manoeuvres

Introduction

- Envisioned solution: To develop a friction estimator model based on logged signal data and use the estimated value of peak friction coefficient in a collision avoidance system

- Limitations
  - Scenario in consideration – only two road users, truck and static obstacle on a two-lane road
  - 4*2 tractor truck to be controlled
  - No vision-based or specialised direct friction sensors to be used in friction estimation
  - Testing carried out at Scania test track in dry conditions

Theory – slipslope method of friction estimation

- Longitudinal dynamics-based method
- Uses recursive least squares algorithm (RLS) to estimate the slipslope (CC_x) [1]
- Wheel speeds, axle load and longitudinal acceleration signal data extracted from log data

RLS governing equation

$$y(t) = \phi(t).\theta(t) + e(t)$$

For low slip,

$$\boldsymbol{F_x = CC_x(\alpha . F_{zf} . s_{xf} + F_{zr} . s_{xr}) - (1)}$$

$y(t)$ - F_x

$\phi(t)$ - $\alpha . F_{zf} . s_{xf} + F_{zr} . s_{xr}$ (*α = 0 for RWD and acceleration, α = 1 during braking*)

$\theta(t)$ - *estimated* CC_x

$\mu = CC_x . s_x$

For high slip,

$\boldsymbol{F_x = \mu . F_z}$ **- (2)**

$y(t)$ - F_x

$\phi(t)$ - $F_{zf} + F_{zr}$

$\theta(t)$ - *estimated* μ

RLS algorithm

$$e(t) = y(t) - \phi(t).\theta(t-1)$$

$$K(t) = \frac{P(t-1).\phi(t)}{\lambda + \phi^2(t).P(t-1)}$$

$$P(t) = \frac{1}{\lambda}\left[P(t-1) - \frac{P^2(t-1)\phi^2(t)}{\lambda + \phi^2(t).P(t-1)}\right]$$

$$\theta(t) = \theta(t-1) + K(t).e(t)$$

[1] Rajamani, Rajesh, et al. "Tire-road friction-coefficient estimation." *IEEE Control Systems Magazine* 30.4 (2010): 54-69.

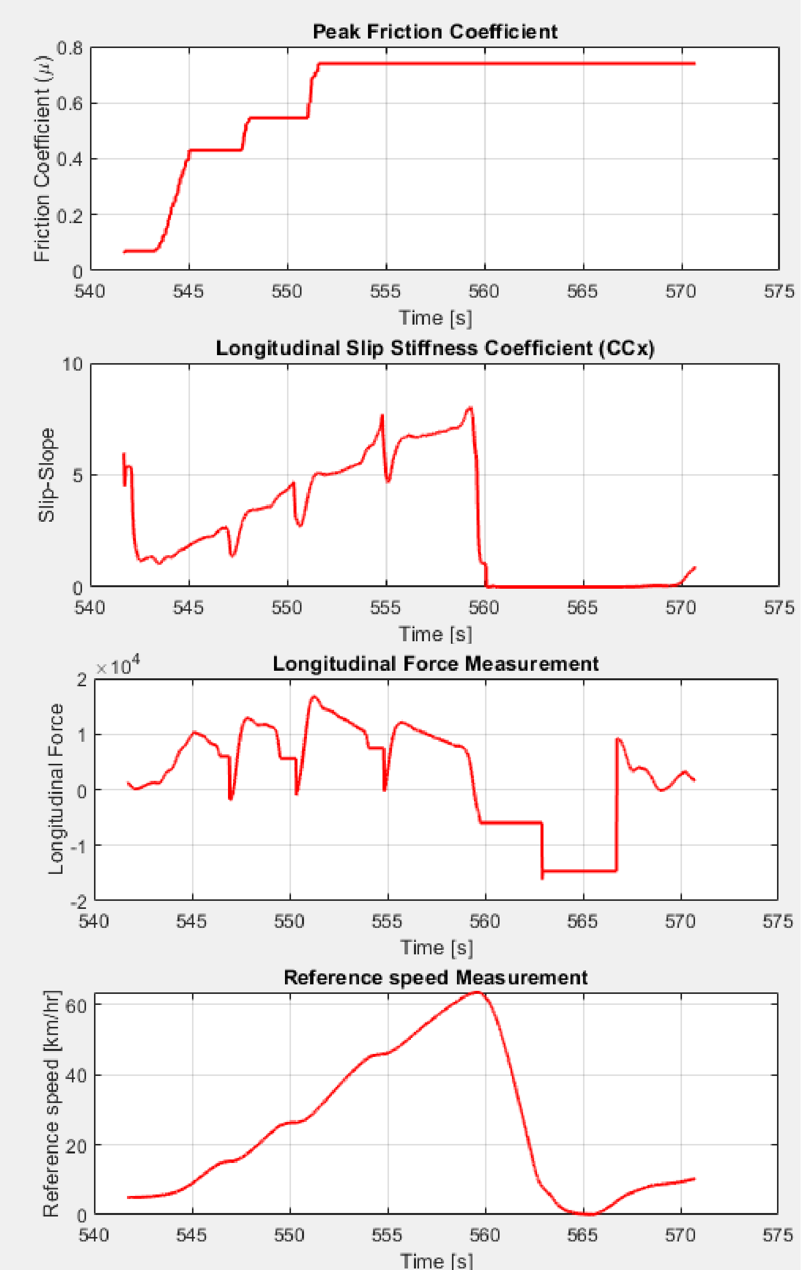
Preliminary results - friction estimator

- Truck tests conducted for logging data

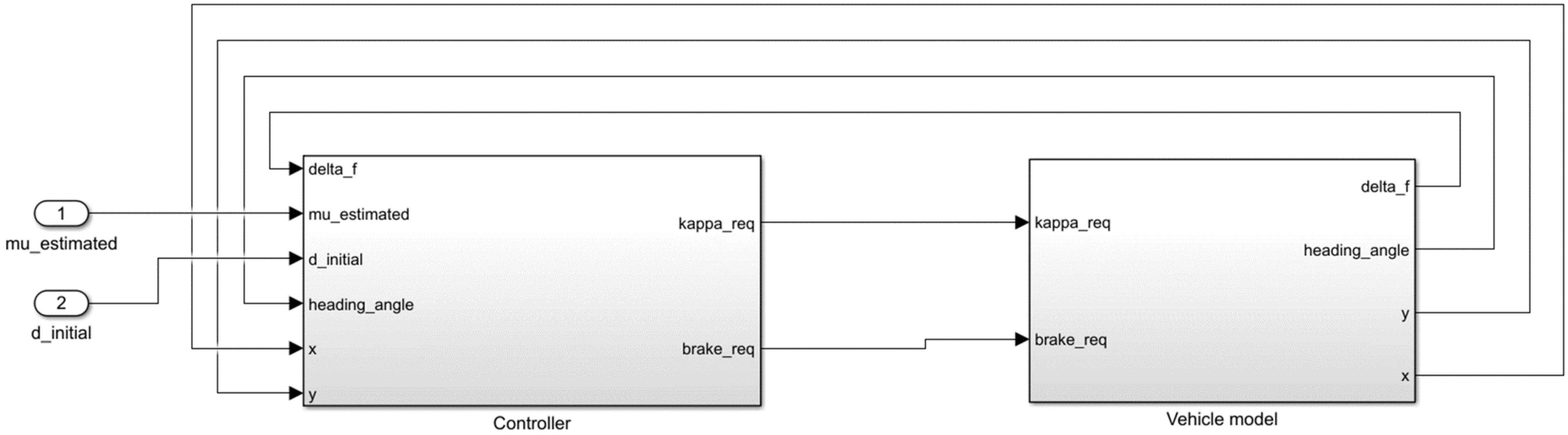
- Necessary signals extracted and filtered as required fror log data (extracted using CANalyzer)

- MATLAB code developed to estimate peak friction coefficient based on the log data sets

- Estimated peak friction coefficient converges to 0.74



Simulation setup & implementation – CA system



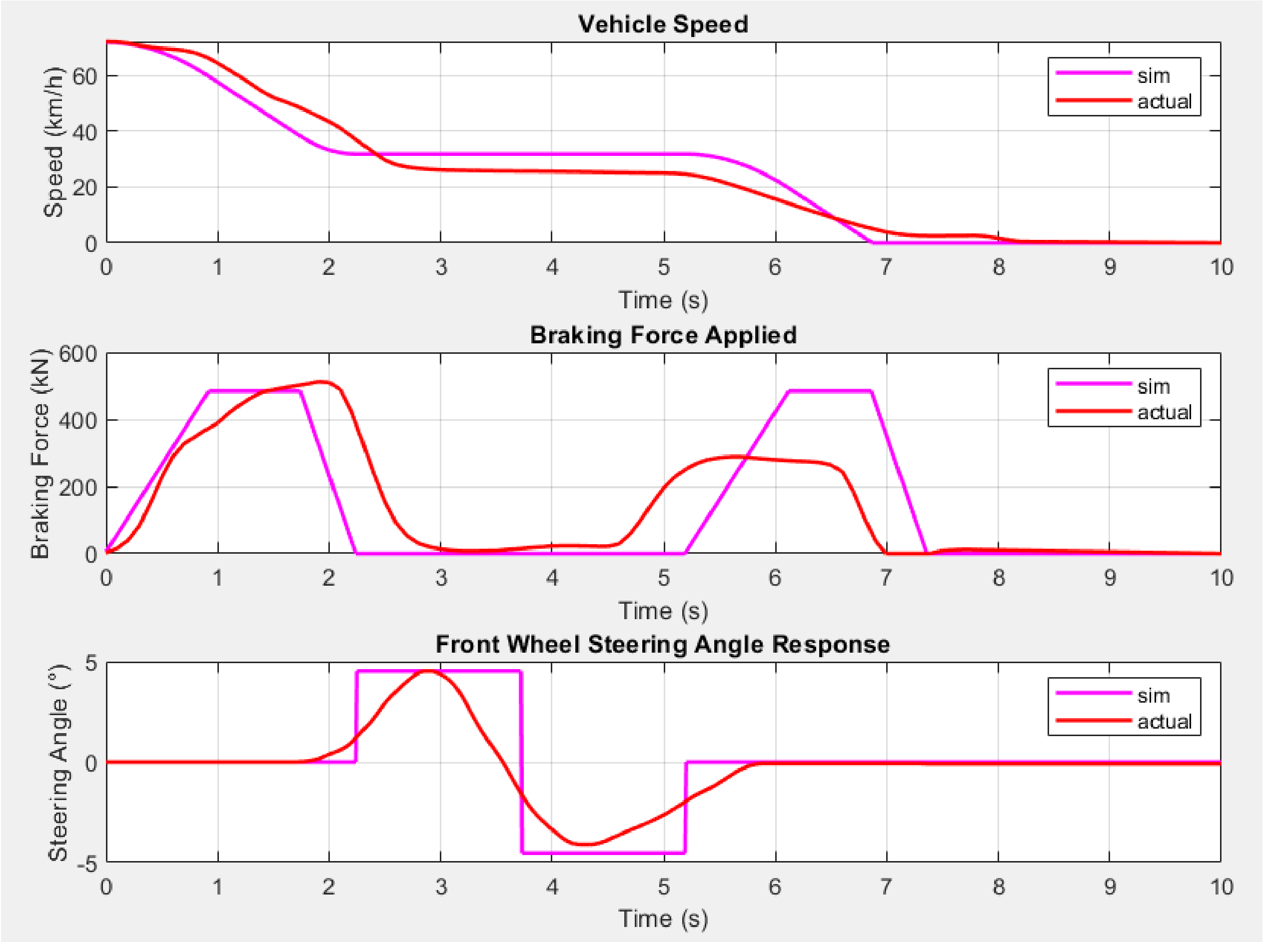
Test Plan

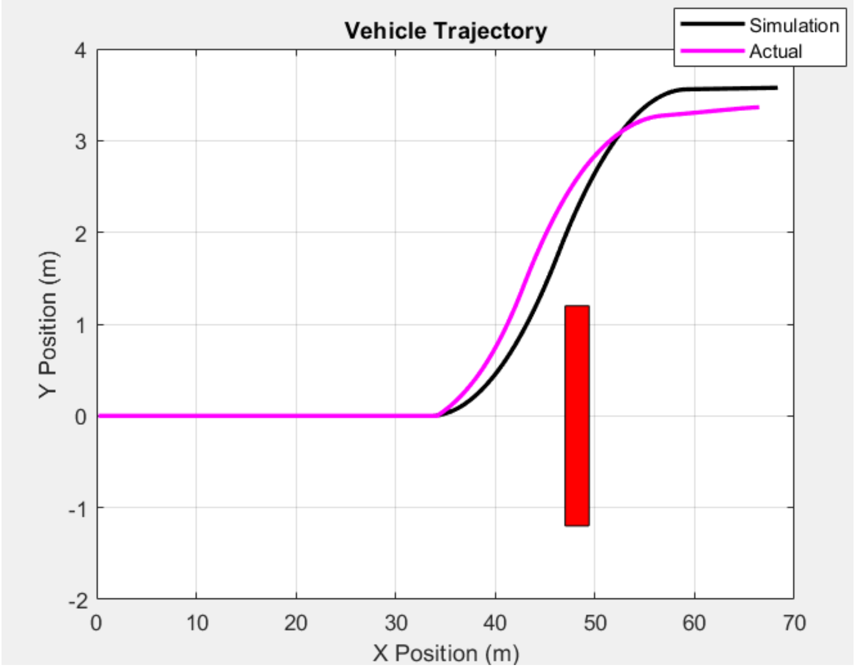
- 2 test cases to run – pure braking, brake and steer

- First reach required initial speed then perform the manoeuvre according to test case

- Data to be logged: front wheel angle, speed, lateral acceleration, trajectory of the truck

Preliminary results





Future work

- Testing with different surfaces and in different conditions

- Integrate friction estimator with the CA system to give updates on μ value in real time

- Include trailer and account for trailer dynamics

For any questions, write to me at ganapati.g.kamat@gmail.com

Thank you for listening!

Poster 4:

Physics-Informed Neural Networks for Vehicle Lateral Dynamics Modelling

Rishikesh Vishnu Sivakumar, Yuchuan Dong,
Chalmers and Zeekr

Physics-Informed Neural Networks for Vehicle Lateral Dynamics modelling

Master Student: Yuchuan Dong & Rishikesh Vishnu Sivakumar

Industry Supervisors: Utsav Khan & Karthik Prasad

Academic Supervisor: Fredrik Bruzelius

ZEEKR

Accurate real-time knowledge of a vehicle's lateral dynamics is pivotal for safe automated driving, precise motion control, energy-efficient control and robust trajectory planning.

In this study, we combined **Deep Neural Network** with **Physical Laws** to model Lateral Dynamics.

Existing approaches include:

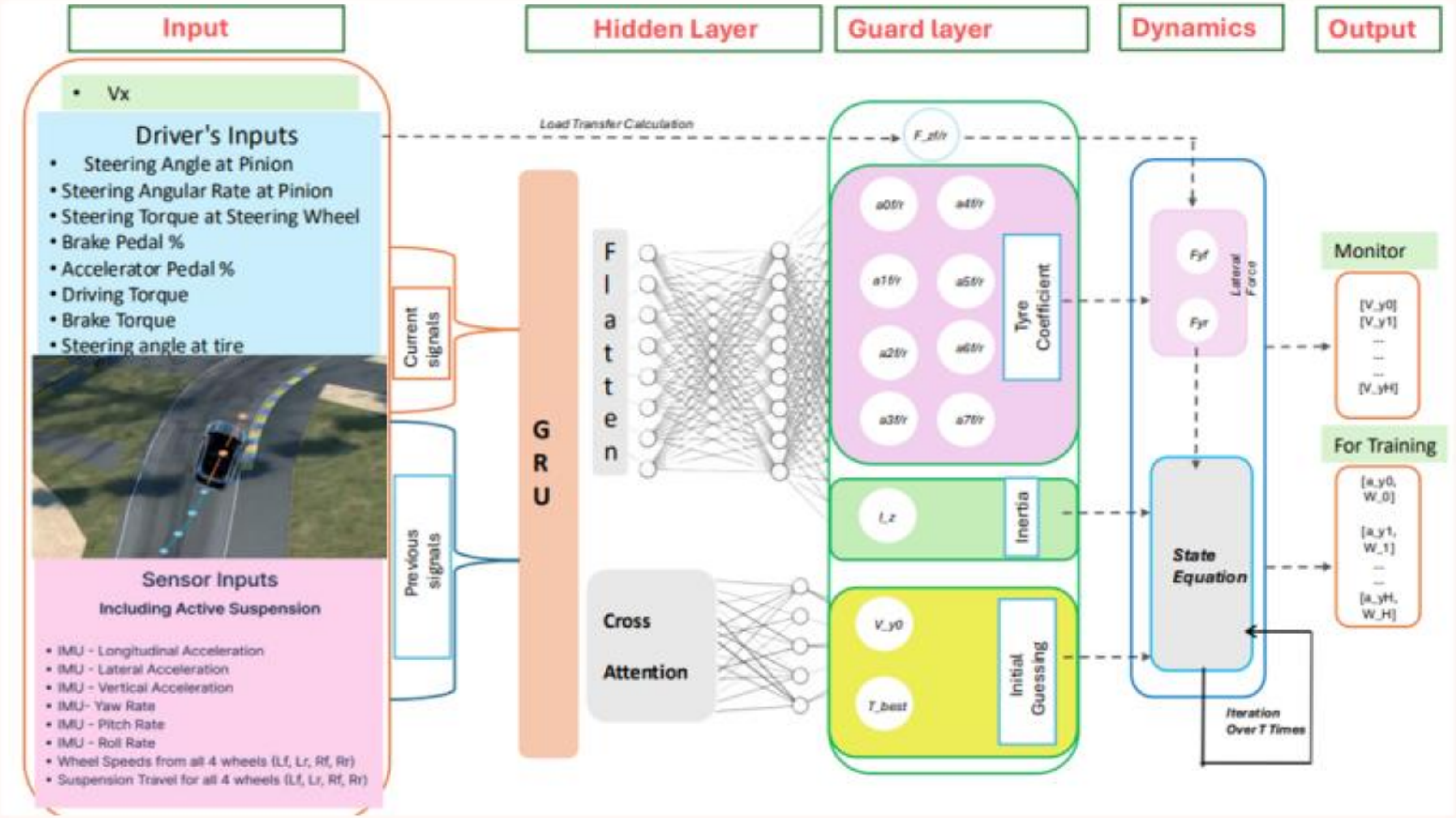
- **Physics-based methods** (e.g., Bicycle model, Pacejka tyre formula)
  - \+ Transparent and interpretable
  - − Require accurate tyre and vehicle parameters (often unknown or hard to measure)
- **Purely data-driven methods** (stacked Long Short-Term Memory/Gated Recurrent Unit)
  - \+ Learn directly from data, capturing complex dynamics
  - − Black-box models without physical insights
  - − Infering unobservable states needs expensive measurement equipments and lot of vehicle tests(e.g., lateral velocity, tyre coefficient or friction.)
- **Physics-Informed Neural Network** (e.g. Deep Dynamics)
  - \+ Combines physics and learning effectively
  - − Relies on expensive and complicated to measure inputs (e.g., lateral velocity), reducing practical utility

Our method (*PhysAttenderNet*) integrates physics information and attention-based neural networks, enabling inference of latent states and achieving accurate, physically-consistent estimations.

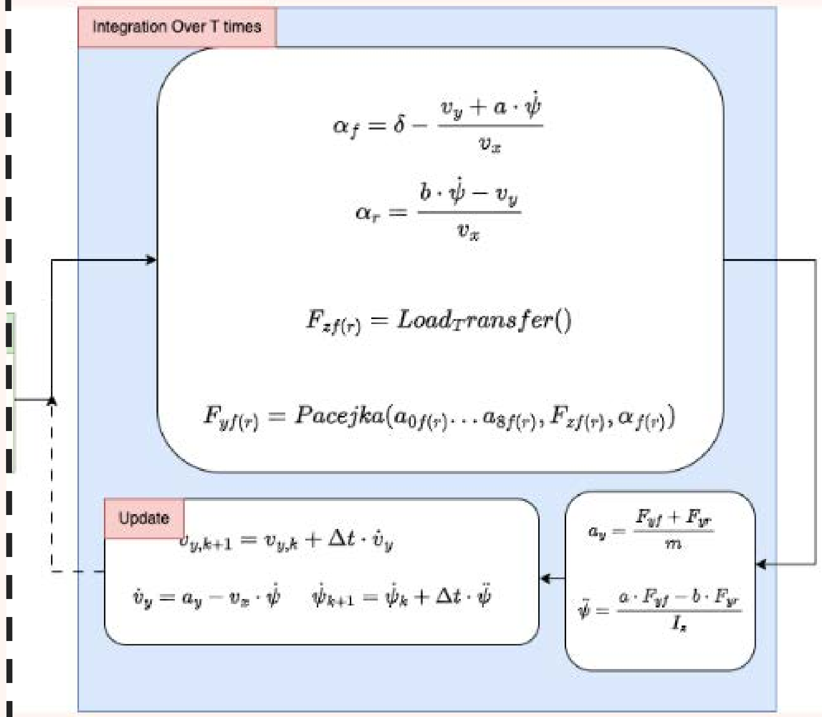
Our method accurately infers unobservable variables—including **lateral velocity** and **tyre coefficient**—and cuts state-estimation errors relative to purely data-driven method.

PhysAttenderNet

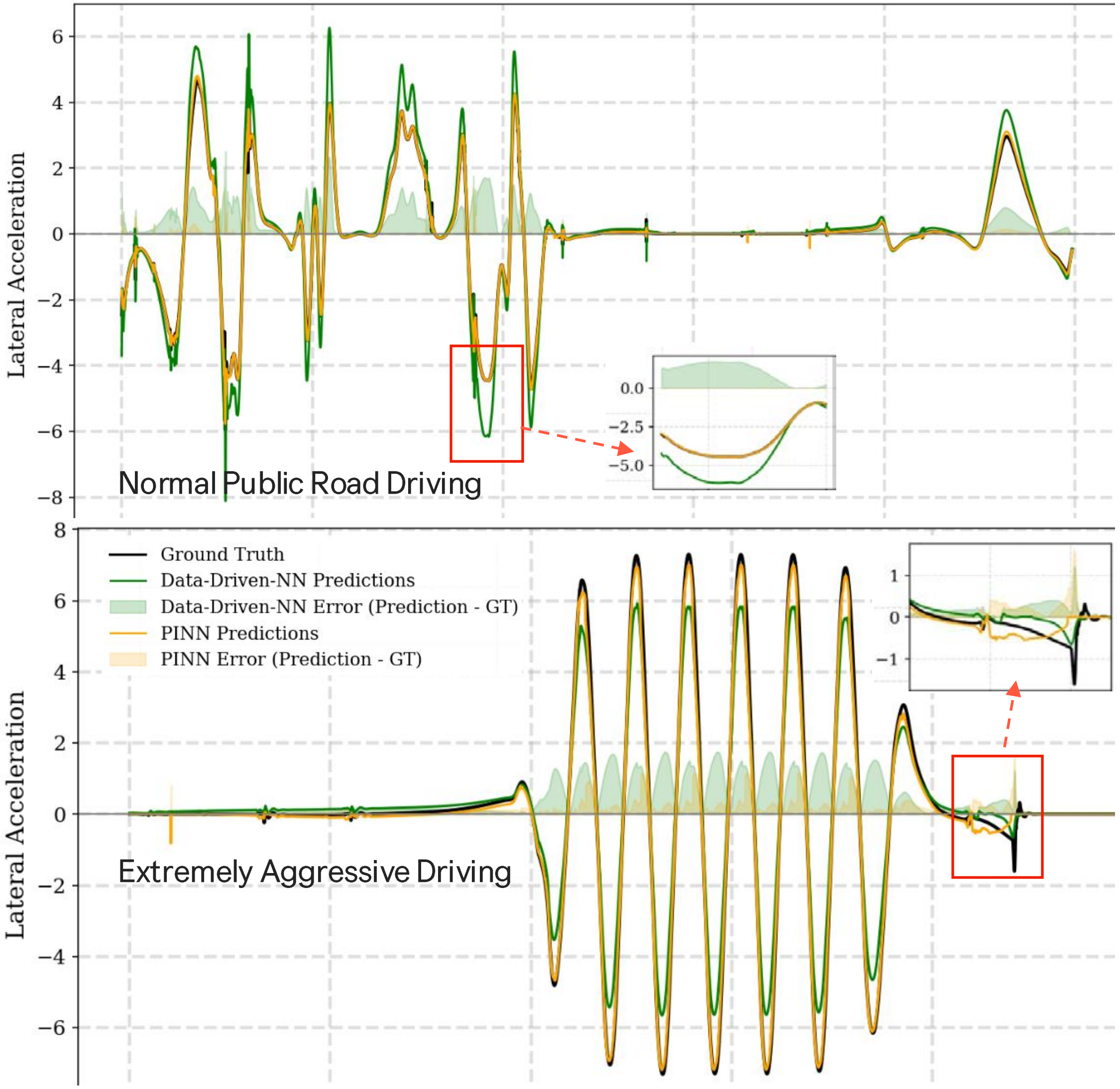
Physics and *Attention* Attend into *Network*.



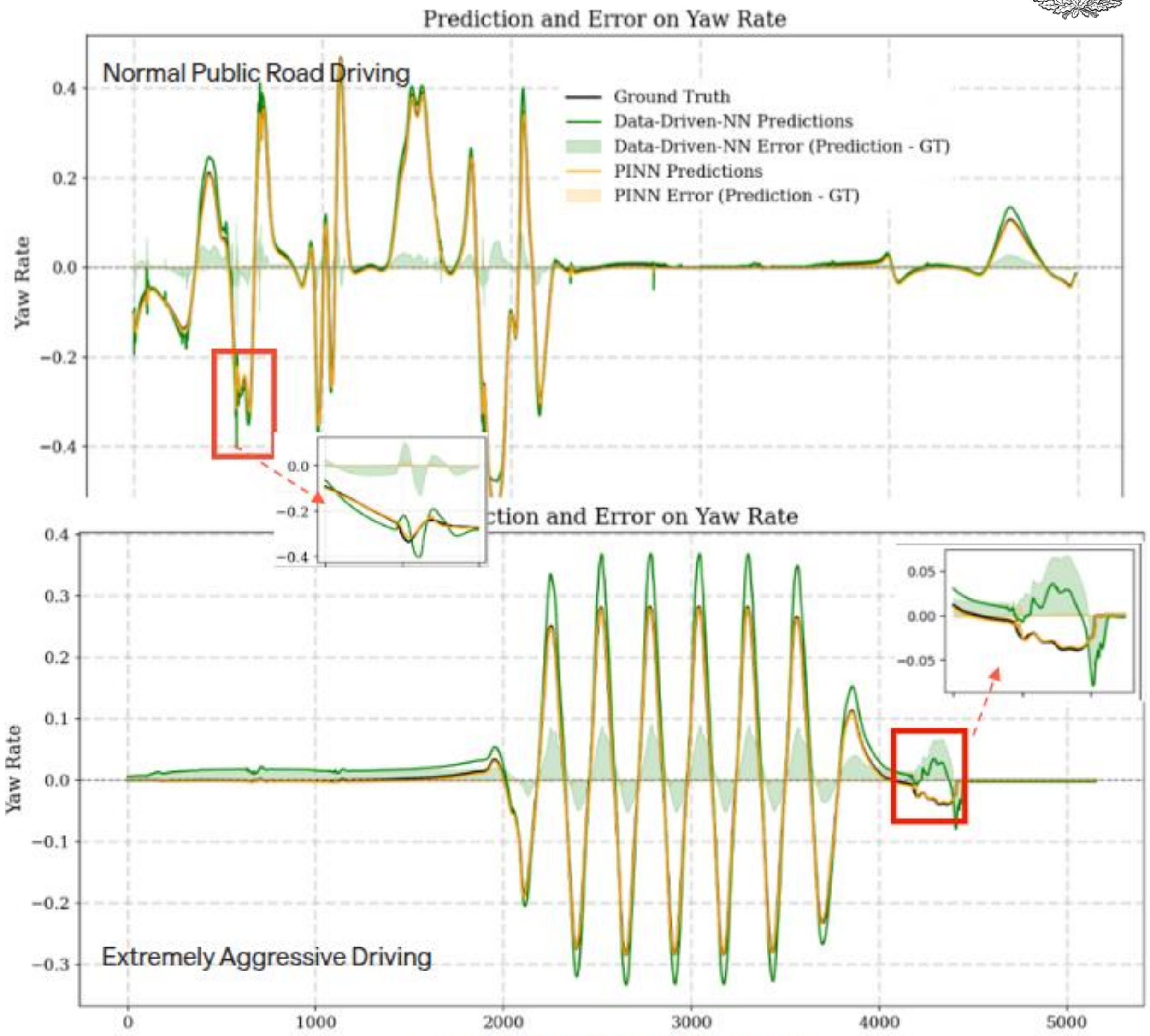
Dynamics Part in Detail



Ground truth vs. Data-Driven-NN& PhysAttenderNet predictions in **Simulation Dataset** from CarMaker



Prediction and Error on Lateral Acceleration(m/s^2)

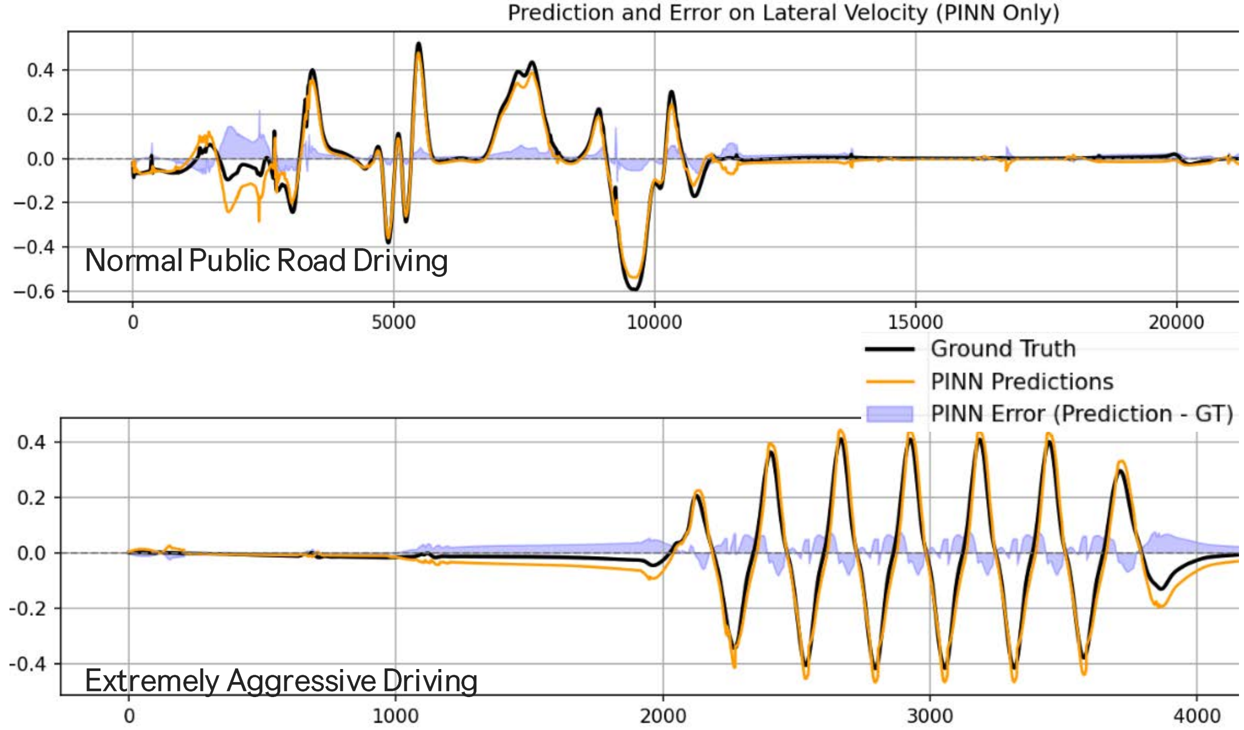


Prediction and Error on Yaw rate

Solving the 'Impossible': PhysAttenderNN Predicts **Lateral Velocity** Where Data-Driven-NN **Can't**

- PhysAttenderNN benefit from attention mechanism and embedded ODE, make it possible to estimate/predict lateral velocity.

- Only good lateral velocity estimation lead lateral acceleration and yaw rate result.



RMSE Comparison (Normal + Aggressive Driving)

Model	Lateral Acc. a_y (m/s^2)	Yaw Rate $\dot{\psi}$ (rad/s)	Lat. Vel. v_y (m/s)
Purely Data-Driven (LSTM)	0.493+0.648	0.0167+0.0303	—
PhysAttenderNet	**0.0664+0.243**	**0.00257+0.0023**	**0.0389+0.0723**

Table 1. Root Mean Square Error (RMSE) comparison. Lower is better. v_y not available from data-driven model.

*ODE: ordinary differential equation

Thanks for Listening

Physics-Informed Neural Networks for Vehicle Lateral Dynamics modelling

Yuchuan Dong Rishikesh Vishnu Sivakumar

Zeekr Tech EU Chalmers University of Technology

Overview

Accurate real-time knowledge of a vehicle's lateral dynamics is pivotal for safe automated driving, precise motion control, energy-efficient control and robust trajectory planning.

In this study, we combined **Deep Neural Network** with **Physical Laws** to model Lateral Dynamics.

Our method accurately infers unobservable variables—including **lateral velocity** and **tyre coefficient**—and cuts state-estimation errors relative to purely data-driven method.

Background:Model families

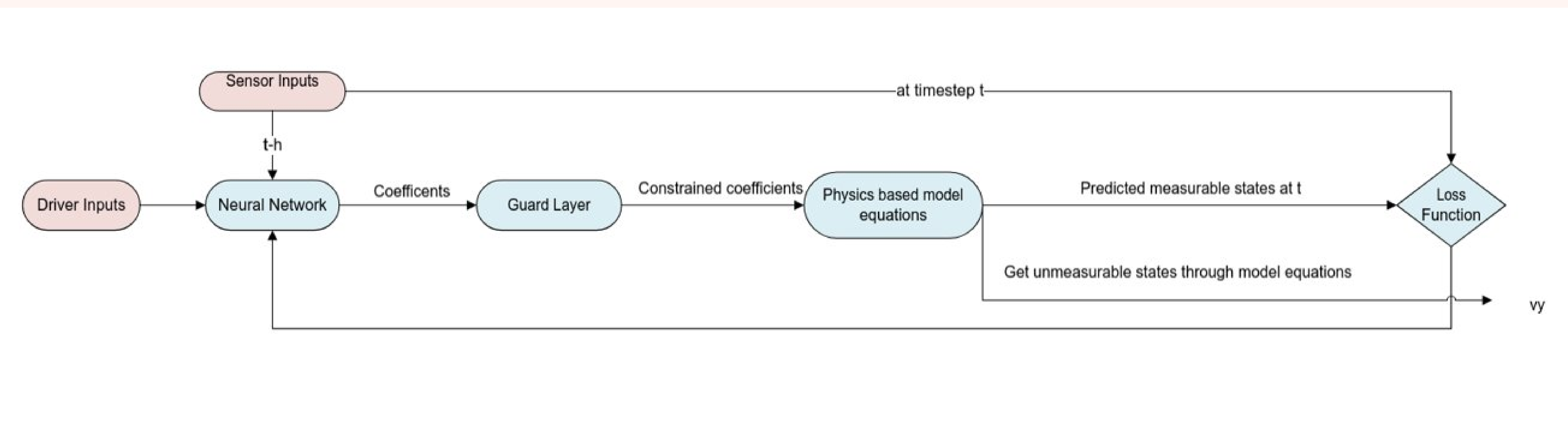
Existing approaches include:

- **Physics-based methods** (e.g., Bicycle model, Pacejka tyre formula)
  - + Transparent and interpretable
  - − Require accurate tyre and vehicle parameters (often unknown or hard to measure)
- **Purely data-driven methods** (stacked Long Short-Term Memory/Gated Recurrent Unit)
  - + Learn directly from data, capturing complex dynamics
  - − Black-box models without physical insights
  - − Infering unobservable states needs expensive measurement equipments and lot of vehicle tests(e.g., lateral velocity, tyre coefficient or friction.)
- **Physics-Informed Neural Network** (e.g. Deep Dynamics)
  - + Combines physics and learning effectively
  - − Relies on expensive and complicated to measure inputs (e.g., lateral velocity), reducing practical utility

Our method (*PhysAttenderNet*) integrates physics information and attention-based neural networks, enabling inference of latent states and achieving accurate, physically-consistent estimations.

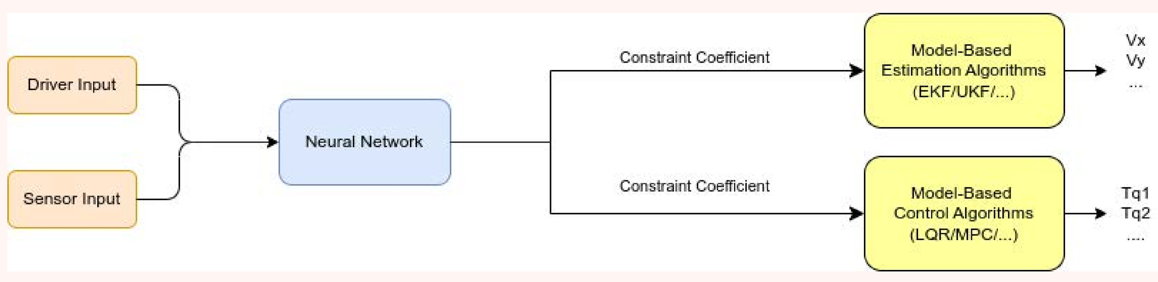
Workflow & Method

Training Pipeline



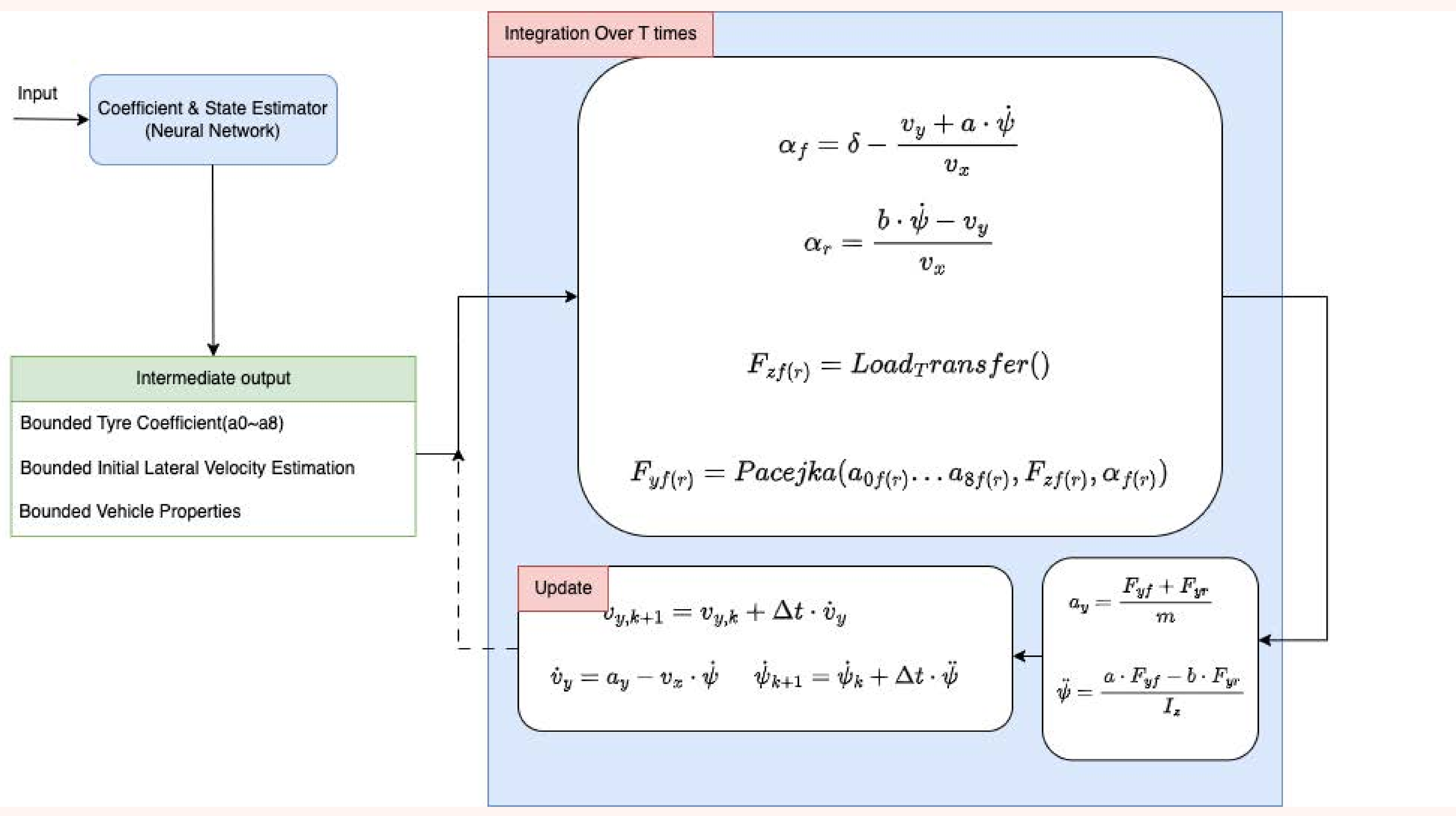
- **Sensor Measurements and Driver Commands** collected (IMU, wheel speeds, suspension travel, etc.)
- **Neural Network** predicts ODE parameters guided by domain knowledge constraints.
- **Single Track ODE Model** simulates vehicle dynamics.
- **Loss Function**: Minimizes difference between predicted and actual sensor states(Only take lateral acceleration and yaw rate).
- Outputs **unobservable states** (e.g., lateral velocity v_y), and enables estimation of model parameters.

Inference Pipeline



- **Estimate Constraint coefficient only**
- **Integration** into downstream estimators and controllers (e.g., UKF, MPC).

Method



PhysAttenderNet

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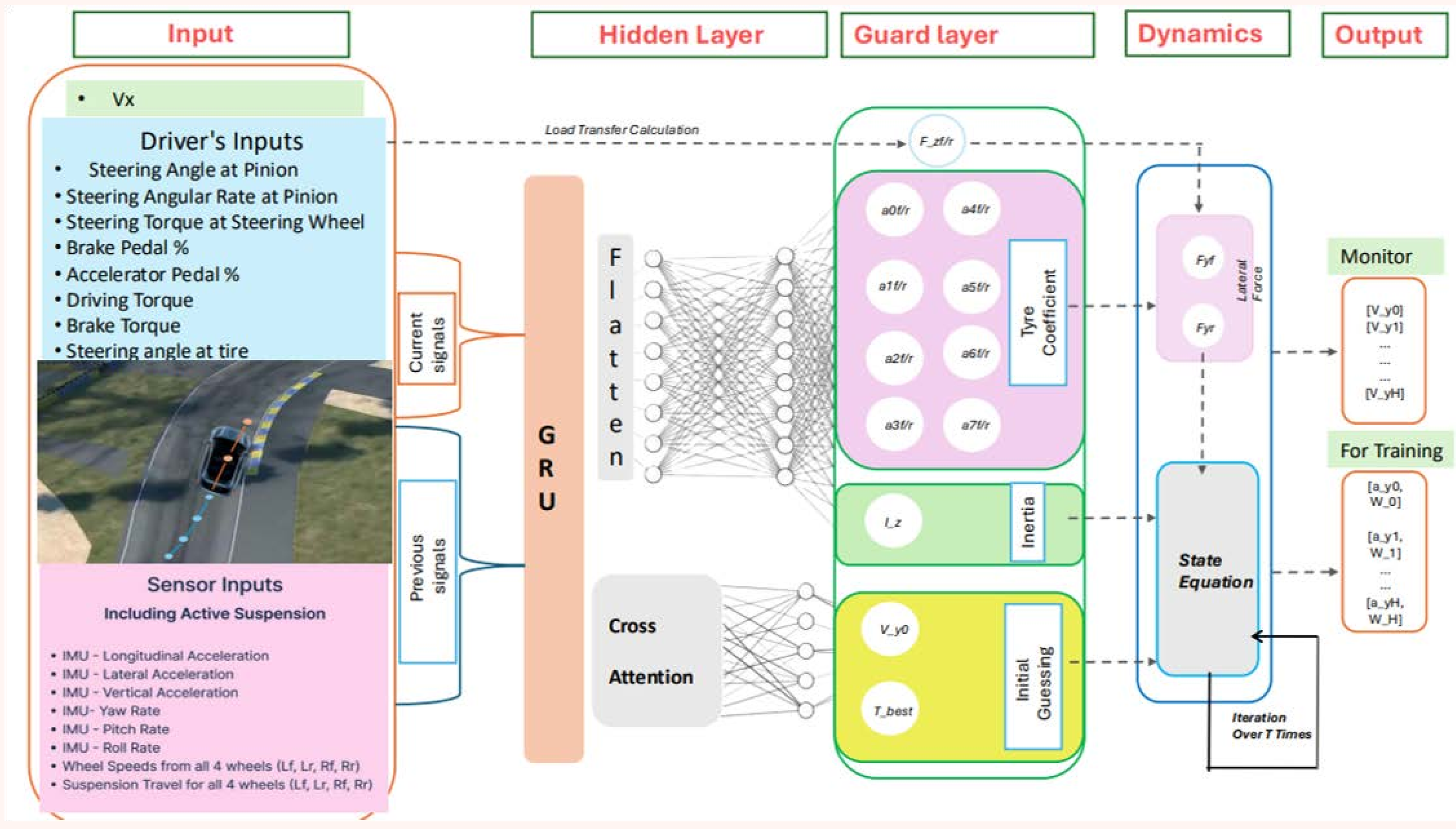

- **Input**. 50-step window of driver commands + sensor signals. *What do we feed the net?*
- **GRU Encoder**. Learns temporal patterns. *How are past moments related?*
- **Cross-Attention**. Picks the most informative instants to make estimation. *When should we focus?*
- **Guard Layer**. Clamps coefficients to physics-valid ranges. *Do the numbers make physical sense?*
- **Dynamics Layer**. 3-DOF ODE + compensation inside the NN. *Can we merge physics and learning?*
- **Training Loss**. Only a_y and $\dot\psi$ — no extra hardware needed. *Can we scale to fleet data?*
- **Outcome**. Real-time inference of v_y, tyre–road coefficient, etc. *What new states do we unlock?*

Result & Evaluation

Datasets: Public-road "normal" driving and track "extreme" manoeuvres. All data were generated from CarMaker.

Baselines: Purely data-driven LSTM (green) vs *PhysAttenderNet* (yellow); ground truth in black.

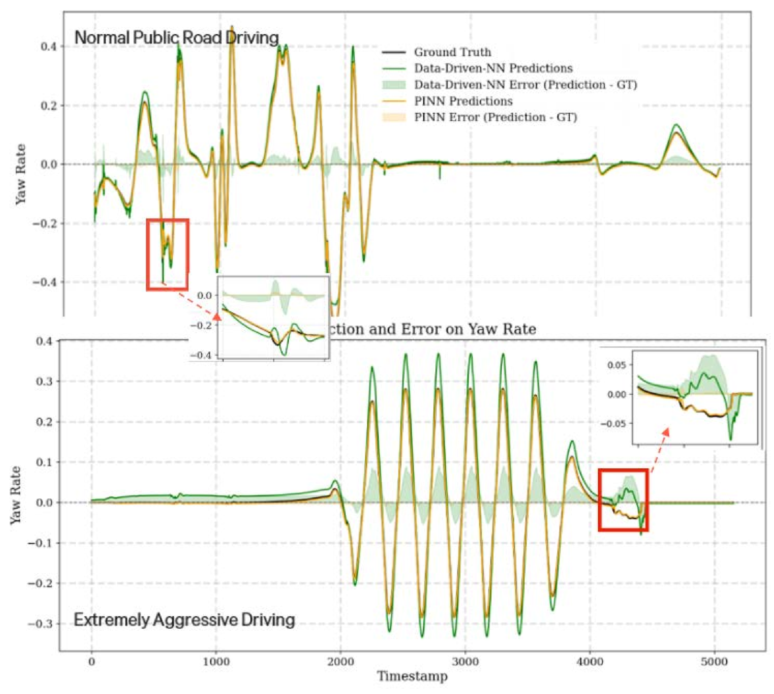

Figure 1. Result on YawRate

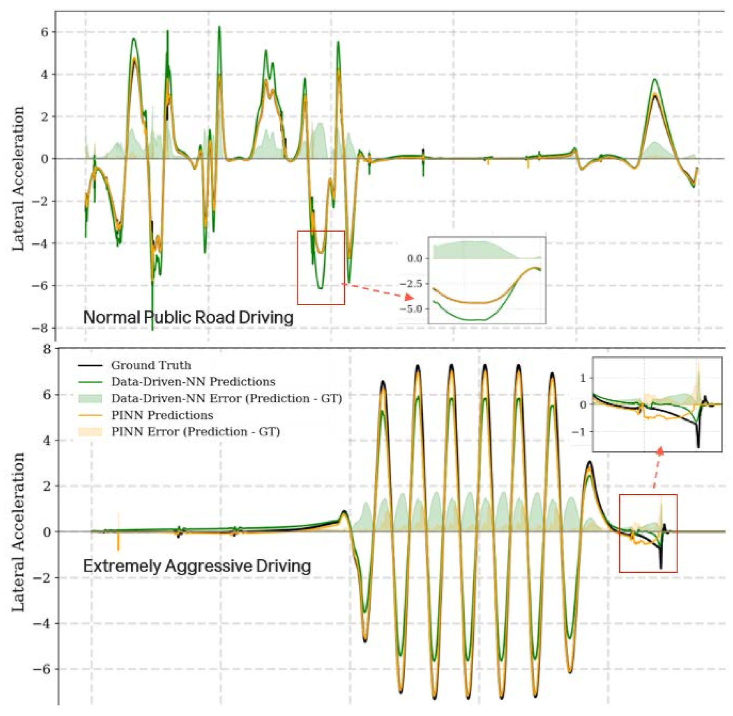

Figure 2. Result on Lateral Acceleration

- **Lateral acceleration** a_y: Lower RMSE and visibly narrower shaded error band across both datasets.
- **Yaw rate** $\dot\psi$: Comparable accuracy in normal driving; Data-driven model failed under aggressive inputs, while ours remains stable.
- **Take-away**: Physics constraints curb overfitting and deliver robust generalisation.

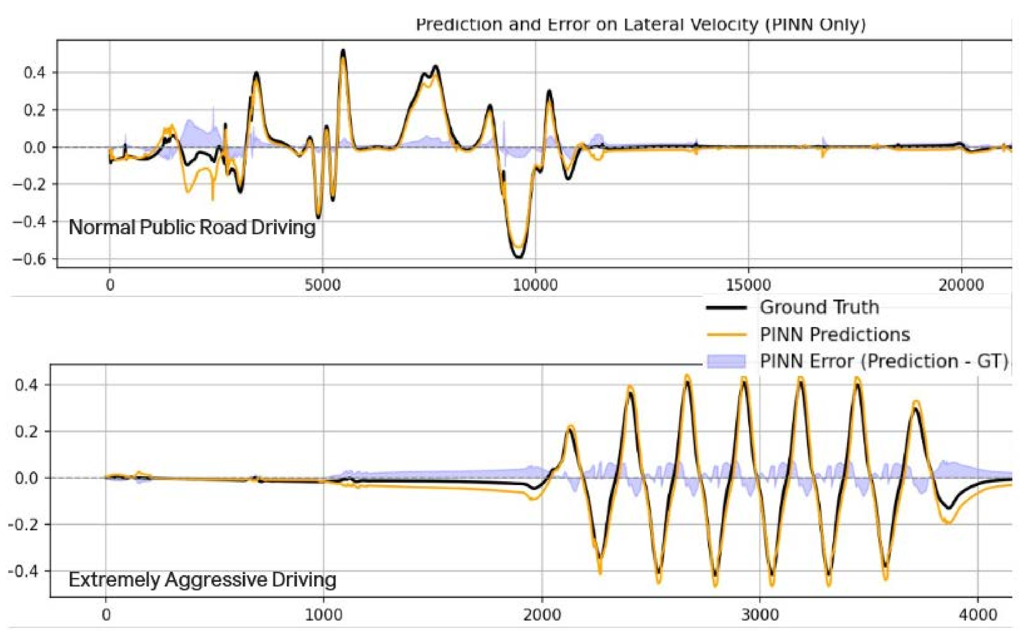

Figure 3. Result on Vy.

- **Challenge**: v_y is *unobservable* with production sensors; no ground truth is available during training.
- **Purely data-driven models**: Cannot learn or output v_y because the target signal is missing.
- **PhysAttenderNet**: Leverages physics constraints to – infer v_y online – without ever seeing its label.

RMSE Comparison (Normal + Aggressive Driving)

Model	Lateral Acc. a_y (m/s^2)	Yaw Rate $\dot\psi$ (rad/s)	Lat. Vel. v_y (m/s)
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Table 1. Root Mean Square Error (RMSE) comparison. Lower is better. v_y not available from data-driven model.

References

1. H. B. Pacejka and E. Bakker, "The Magic Formula Tyre Model", Veh. Syst. Dyn., 1992.
2. J. Chrosniak et al., "Deep Dynamics", IEEE RA-L, 2024.
3. M. Raissi et al., "Physics Informed Deep Learning", arXiv:1711.10561, 2017.

Poster 5:

Real time model for predictive axle load estimation

Ajhay Babu Jagadeesan Karthik Babu, Mayank Vijay, KTH and Scania

Master Thesis- Real time model for predictive axle load estimation

Students: Ajhay Babu Jagadeesan Karthik Babu & Mayank Vijay

SVEA Vehicle Dynamics 2025 — Model Exchange for virtual pre series

May 07, 2025

About Us

M.Sc. Vehicle engineering, KTH Royal Institute of Technology

Automotive Track in the school of Engineering Sciences

KTH Supervisor/Examiner: Lars Drugge

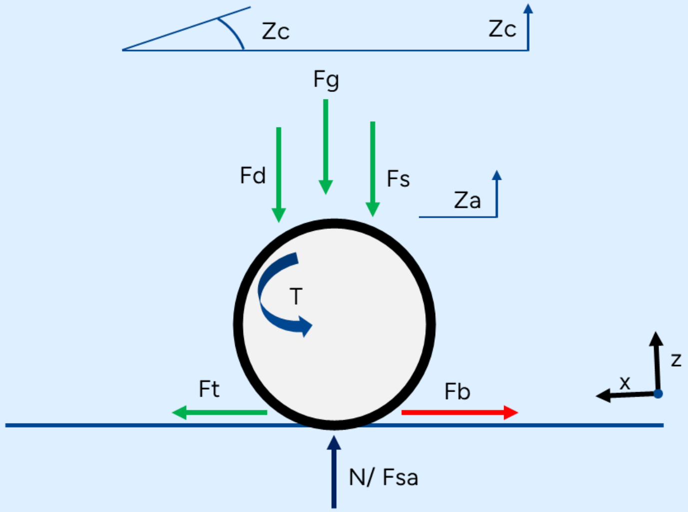
Scania CV AB TGRAMBB Brake Functions group

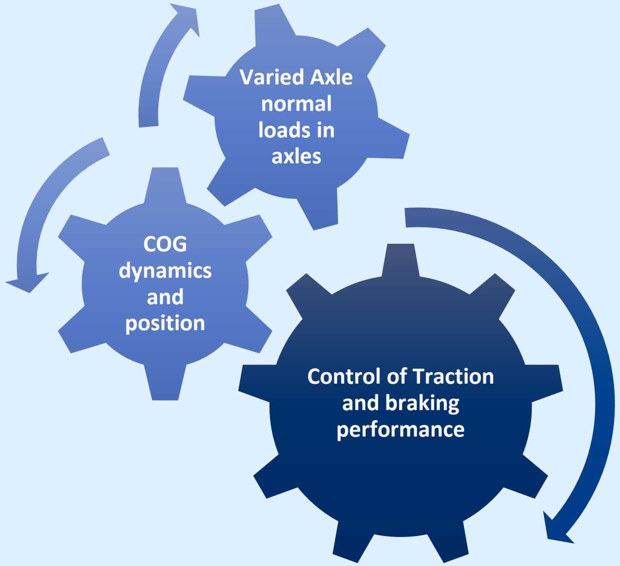
Manager: Alexander Müllersdorf

Supervisors: Henrik Johansson & Ivar Rockström

Aim of the Thesis and Outcomes

- To develop a real-time estimation framework for predicting axle loads and dynamic load transfer on a truck's driven axle, with a focus on auxiliary braking scenarios.
- This involves creating a half truck model capable of estimating axle normal loads across varying truck configurations in real time, using a recursive error-based learning algorithm for adaptive prediction.
- The thesis also aims to implement and test a vehicle-integrated prototype of this function and validate its performance against suspension bellow pressure measurements.





Half Truck model for Normal load estimation

Recursive error based learning algorithm based on adaptive parameters

Real time prototype of the functionality

Half Truck Vehicle Dynamics Model

6X2 Truck- For studying the rear bogie load transfer during longitudinal transients

3 Vehicle DOF (Longitudinal + Vertical + Pitch) XZ-Plane motions.
Computationally light with forces and mass elements

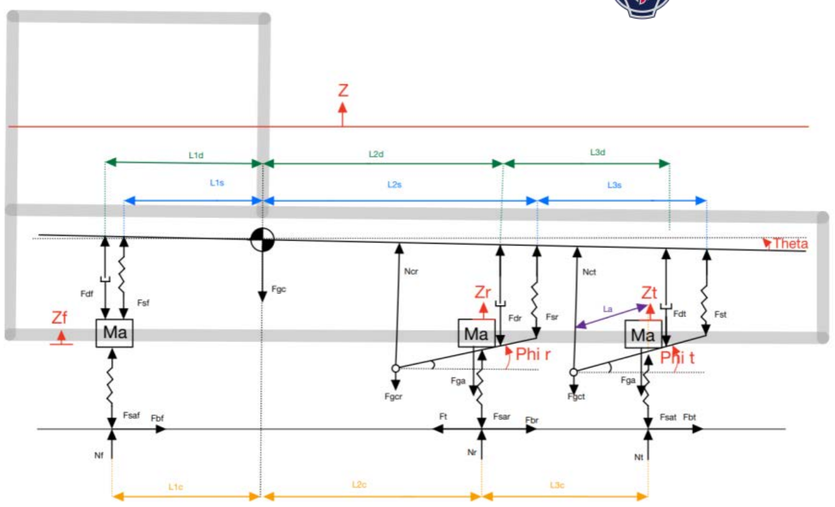
5 Coupled ODEs- $\ddot{Z}, \ddot{\theta}, \ddot{Z}_f, \ddot{\phi}_r, \ddot{\phi}_t$

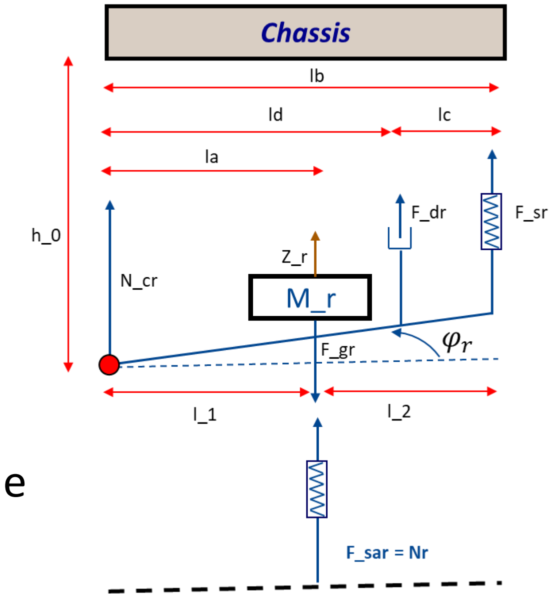
MATLAB Simulink Model-based structuring

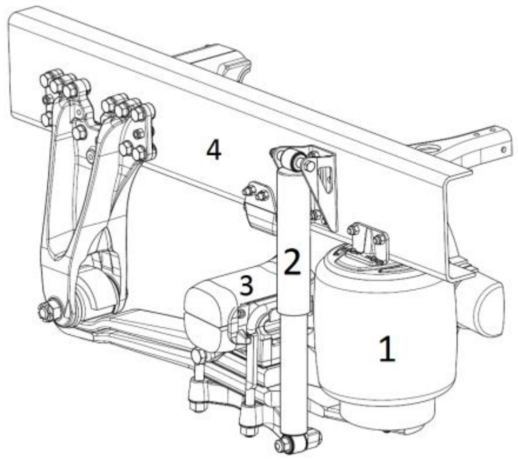
Inputs: Traction/Braking torque in the axles

Outputs: Normal force on each Axle

Validation: Suspension bellow pressure (from suspension) or Bogie displacement (relative chassis-axle)



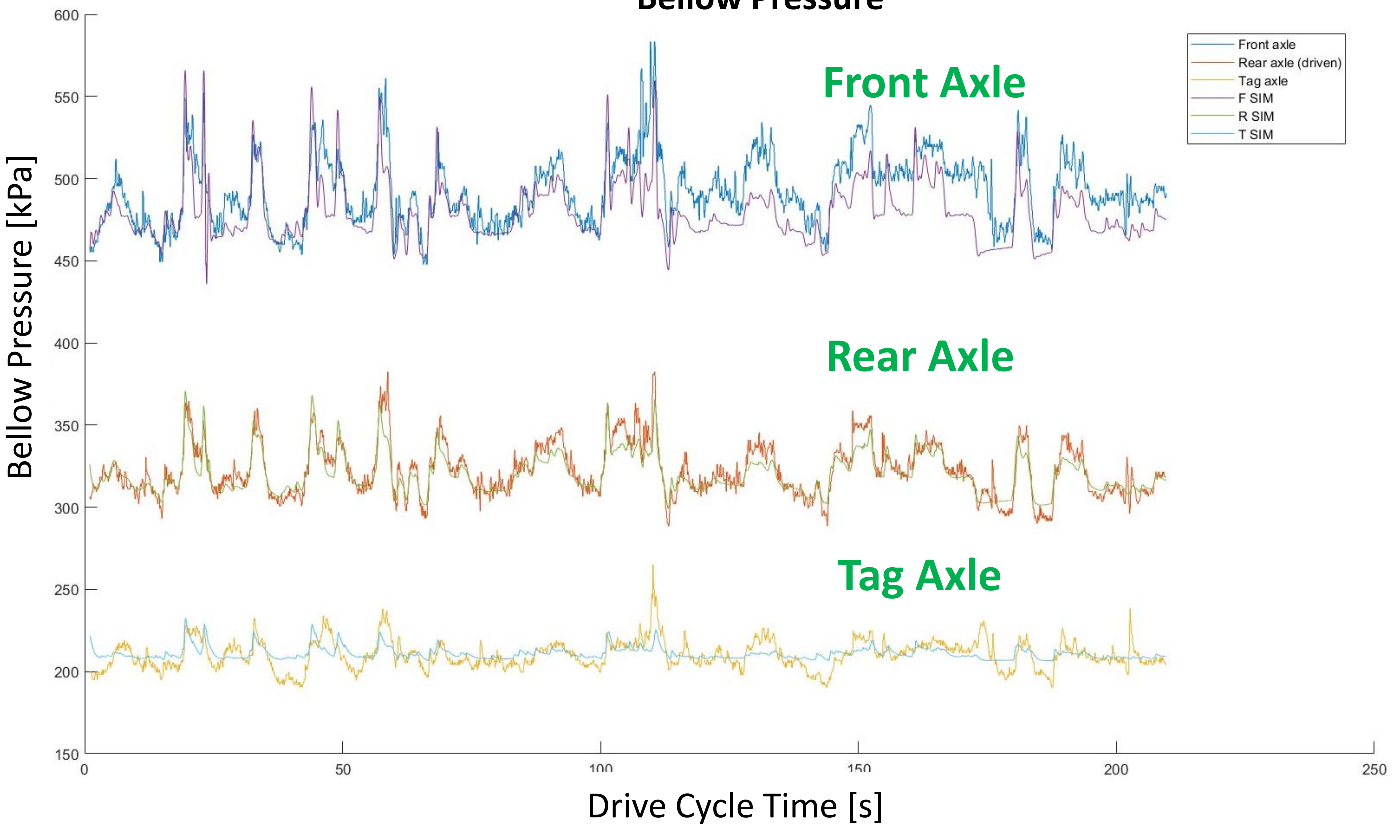




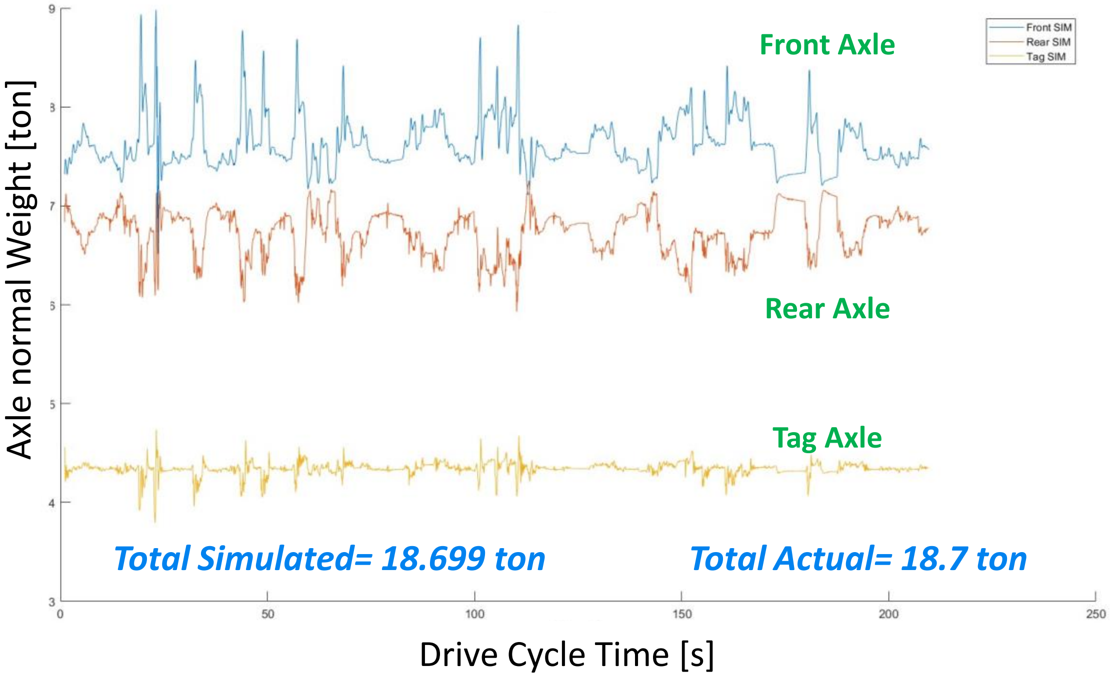
Rear & Tag Suspension kinematics

Model Simulation Results

Bellow Pressure



Axle Normal Load



Front Axle Error--- 19.3%--- 18.66 kPa--- 131.23 kg

Rear Axle Error--- 3.573%--- 7.154 kPa--- 35.73 kg

Tag Axle Error--- 4.82%--- 7.09 kPa--- 36.14 kg

Parametric Study

- Spring Stiffness Variation (K)
- Damper coeff. variation (C)
- Air bellow Area (bellow_area)
- Distance Between Rear And Tag Axle (l3c)

Real Time Learning Algorithm for Parameter Estimation

Why need a learning algorithm even when there is a defined model? --- Unmodelled, adaptive for configurations, real time

Online parameter estimator Goal → minimizes error between bellow sim_pressure & measured_pressure

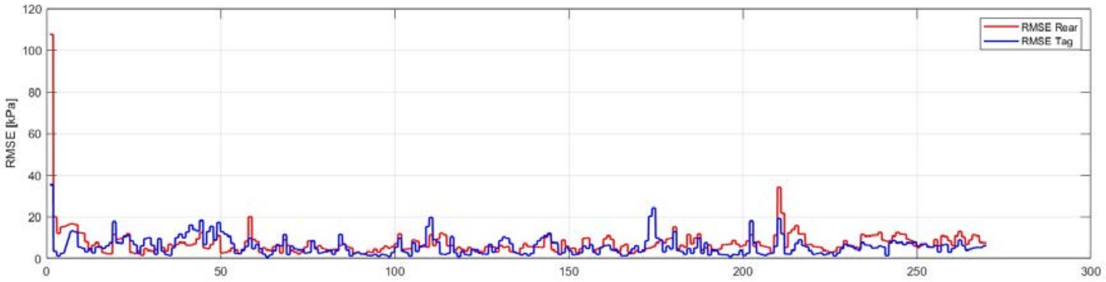
”Not all non-linearities are a trouble in modelling, some can be leveraged ”

<u>Non Linear adaptations:</u> Air spring stiffness & bellow area

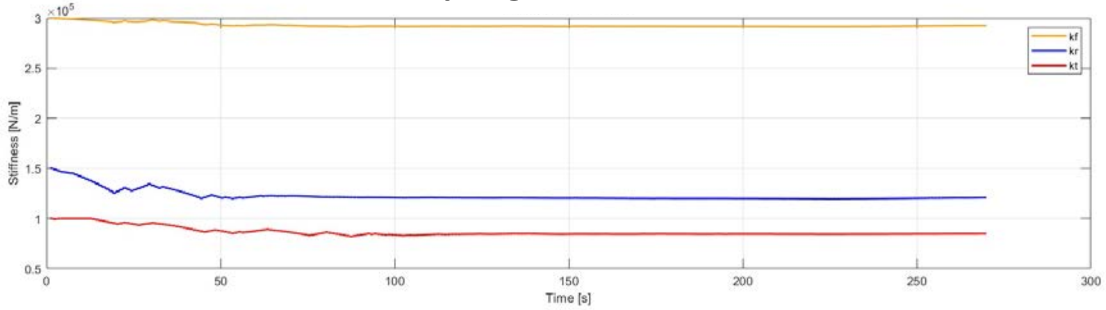
Heuristic Learning on the move:
Dynamic state-dependent Suspension Parameter Adaptation for Accurate Axle Load Estimation Based on Error Magnitude and Directionality with state dependency

Adaptive prediction with UKF:
State-Sensitive Stiffness adaptation with UKF and Simulink based pressure feedback

RMSE Evolution



Air spring stiffness Evolution

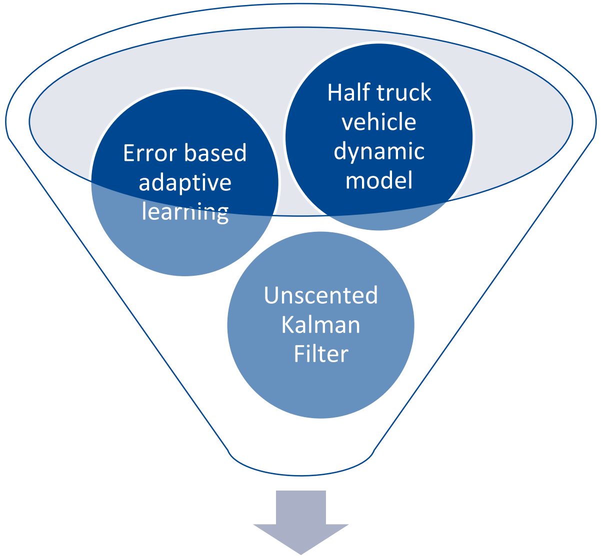


Rear Axle Error--- 7.88 kPa--- 39.92 kg--- 3.99%

Tag Axle Error--- 7.01 kPa--- 36.23 kg--- 4.83%

Vehicle Integrated Testing and Steps

- Simulink model discretized and compiled via Vector CANape for embedded deployment.
- Real-time integrated test cases framed for model validation.
- Outcomes establish a foundation for onboard axle load functionalities.



Onboard Axle Load Predictions

Thank You!

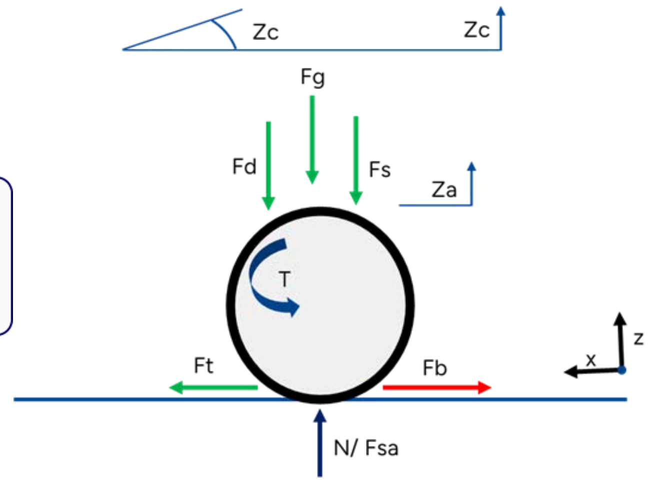
Master Thesis- Real time model for predictive axle load estimation

Ajhay Babu Jagadeesan Karthik Babu (abjkb@kth.se)
Mayank Vijay (mayankv@kth.se)

M.Sc. Vehicle Engineering, KTH Royal Institute of Technology
Scania CV AB, TGRAMBB Brake Functions Team

Aim: To develop a real-time estimation framework for predicting axle loads and dynamic load transfer on a truck's driven axle, with a focus on auxiliary braking scenarios. This involves creating a half truck model capable of estimating axle normal loads across varying truck configurations in real time, using a recursive error-based learning algorithm for adaptive prediction. The thesis also aims to implement and test a vehicle-integrated prototype of this function and validate its performance against suspension bellow pressure measurements.

- Half Truck model for Normal load estimation
- Recursive error based learning algorithm based on adaptive parameters
- Real time prototype of the functionality



Scania's tests observation

"Achieving a specified slip ratio in a braking state requires a lower auxiliary braking torque compared to the torque needed in an acceleration state"

(a) Acceleration state (b) Auxiliary braking state

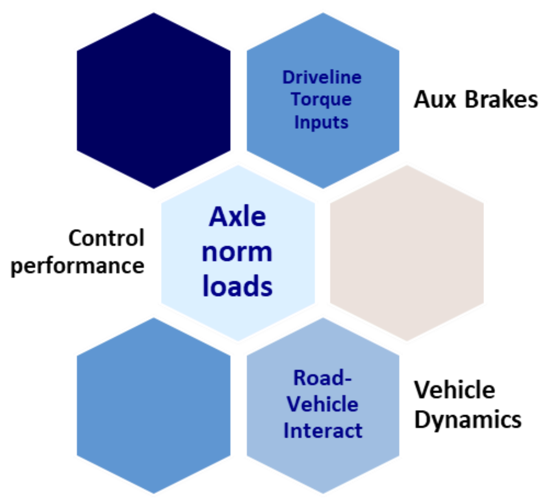
Due to Load Transfer

In acceleration: More grip on R → needs **more torque** for same slip.

In braking: Less grip on R → needs **less torque** for same slip.

Pros of estimating Normal loads in each axle

- Optimal tyre slip control
- Improved braking control (ABS, ESP)
- Avoids overloading axles and more tire life
- Axle load management leads to improved stability, traction performance and minimzed impacts on infrastructure
- Prevents suspension failure and pavement damage



Modelling Phase

Pre-Study and Literature survey for vehicle dynamics model → Development of Half truck model for normal load → Simulation and validation of model using driving data sets → Parametric study of model behaviour

Literature and algorithms for recursive error based learning → Planning of driving scenarios and real time data collection (respect to model) → Development of prediction logic using error based adaptive learning → Compilation of the prediction-vehicle dynamic model for Embedded hardware → Vehicle Integrated testing and validation → Post processing and documentation

Prediction Phase

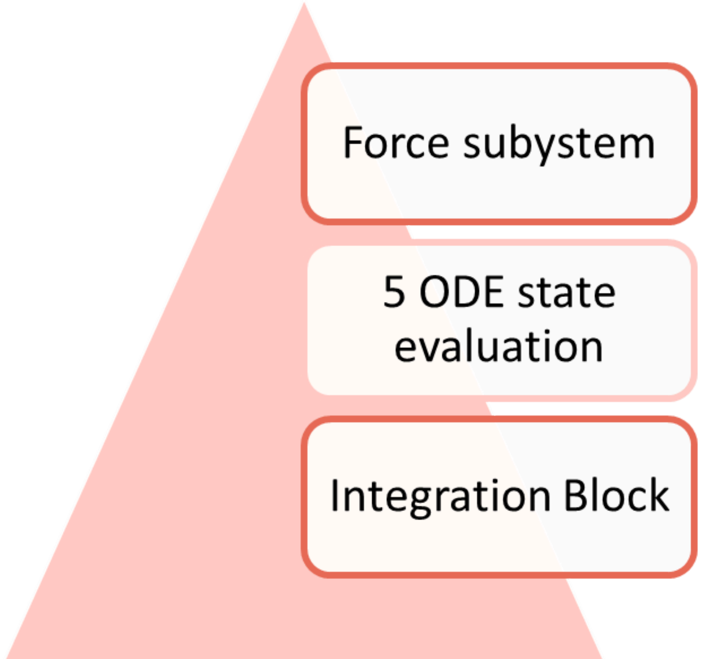
Master Thesis- Real time model for predictive axle load estimation

Ajhay Babu Jagadeesan Karthik Babu (abjkb@kth.se)
Mayank Vijay (mayankv@kth.se)

M.Sc. Vehicle Engineering, KTH Royal Institute of Technology
Scania CV AB, TGRAMBB Brake Functions Team

Half Truck Vehicle Dynamics Model

- Model formed by combining quarter car and bounce pitch modelling approaches
- 6X2 Truck- For studying the rear bogie load transfer during longitudinal transients
- 3 Vehicle DOF (Longitudinal + Vertical + Pitch) XZ-Plane motions. Computationally light with forces and mass elements
- 5 Coupled ODEs
- MATLAB Simulink Model-based structuring

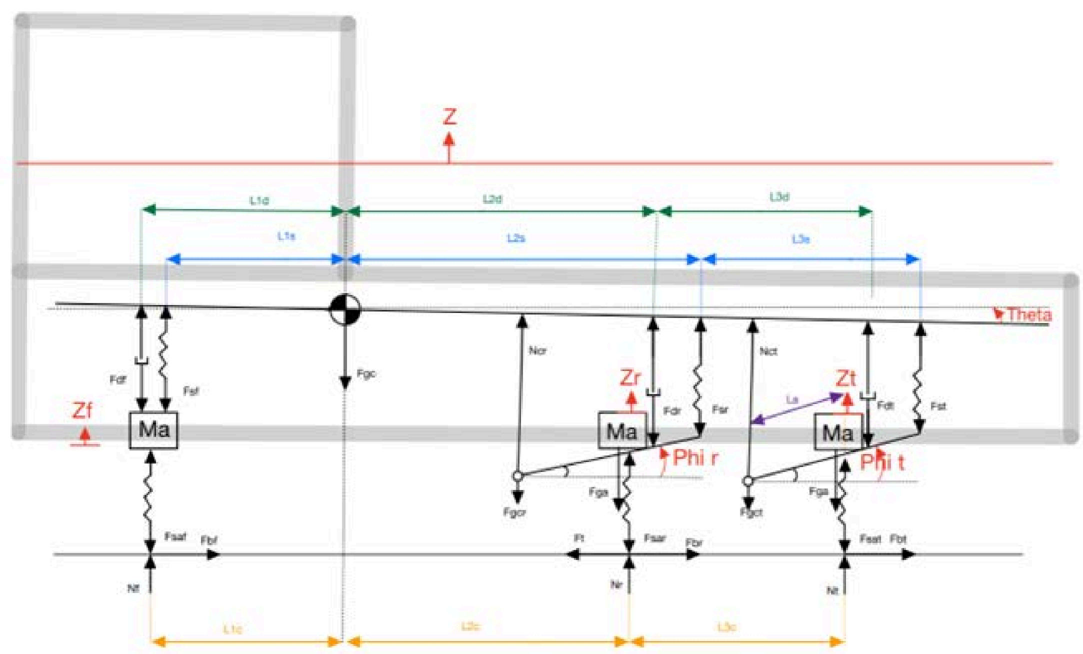


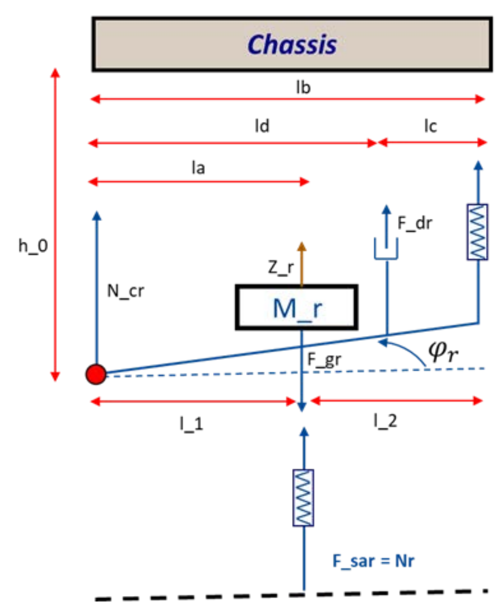
Inputs: Traction/Braking torque in the axles

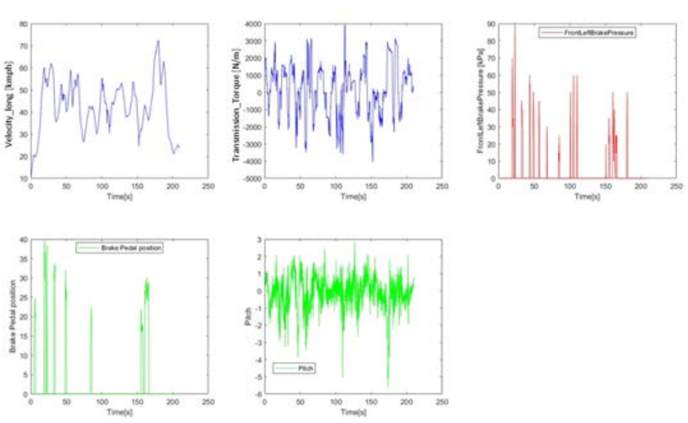
Outputs: Normal force on each Axle

Validation: Suspension bellow pressure (from suspension) and Bogie displacement (relative chassis-axle)

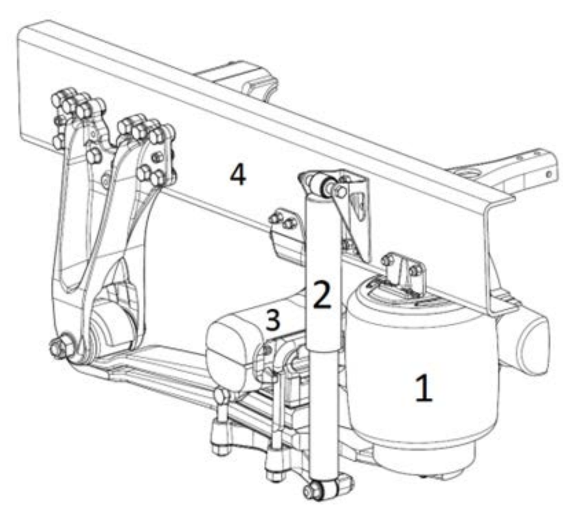
1. Chassis vertical acceleration- $\ddot{Z}$
2. Chassis rotational acceleration- $\ddot{\theta}$
3. Front axle vertical acceleration- $\ddot{Z_f}$
4. Rear axle rotational acceleration- $\ddot{\phi_r}$
5. Tag axle rotational acceleration- $\ddot{\phi_t}$







15 Data sets with different driving scenarios for model validation



Master Thesis- Real time model for predictive axle load estimation

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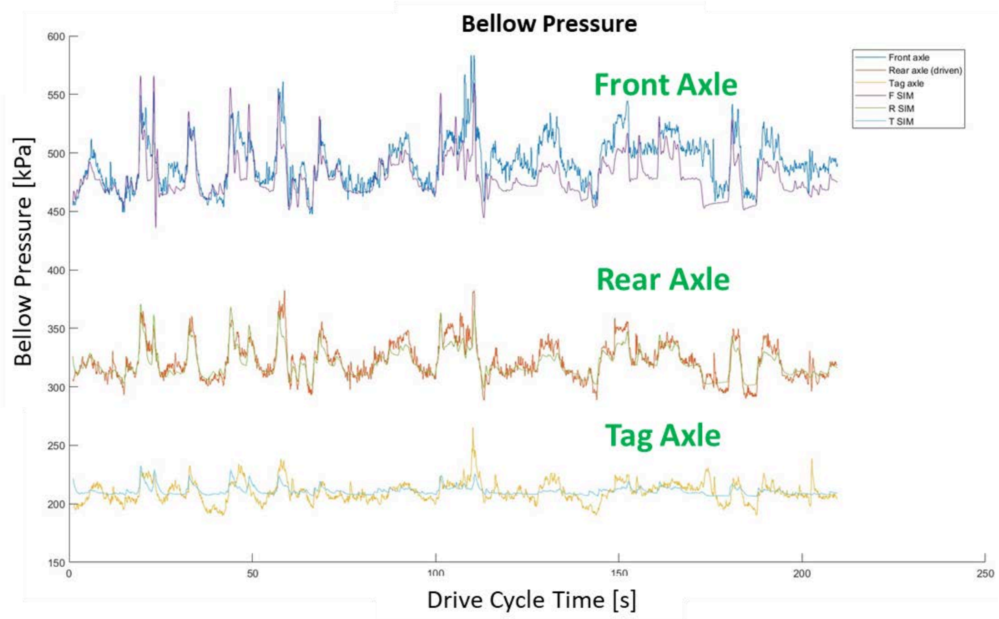
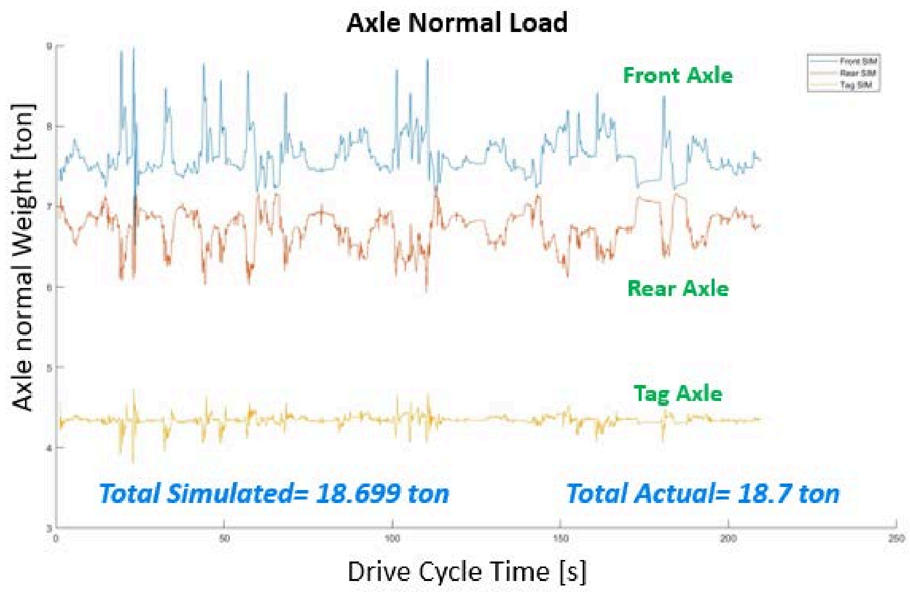
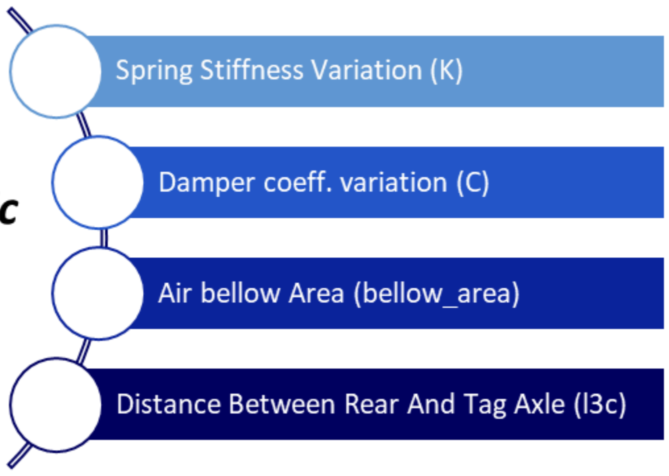
Simulation results





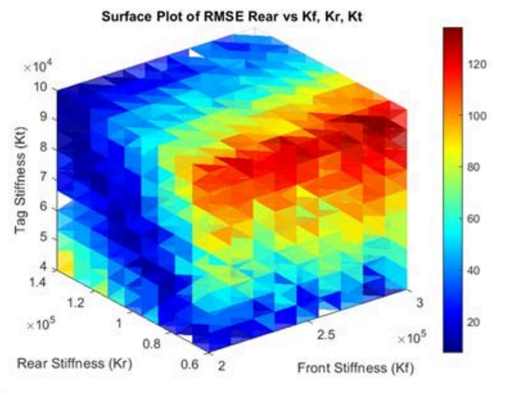
Parametric Study



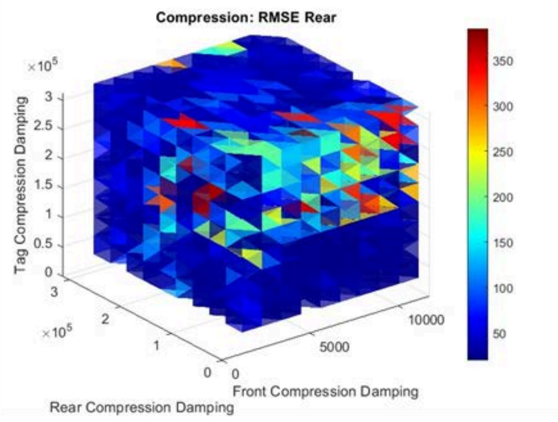
Front Axle Error--- 19.3%--- 18.66 kPa--- 131.23 kg

Rear Axle Error--- 3.573%--- 7.154 kPa--- 35.73 kg

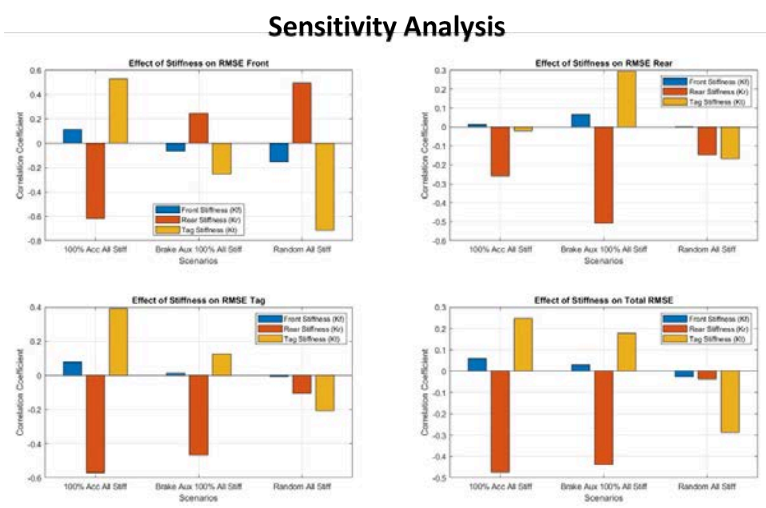
Tag Axle Error--- 4.82%--- 7.154 kPa--- 36.14 kg



RMSE Vs. Kf, Kr, Kt (3K)



RMSE Vs. Cf, Cr, Ct (3C)



Random Driving scenario- Pressure validation results

Axle	RMSE_kPa	Percent_Error	Detrended_R2	Residual_Mean_kPa	Residual_Std_kPa	Bias
	kPa	%	No unit	kPa	kPa	No unit
Front	18,667	2,712	0,614	13,369	13,029	Underprediction
Rear	7,154	0,719	0,82	2,32	6,767	Underprediction
Tag	7,289	0,303	0,31	-0,637	7,261	Overprediction
Jan 25 Random driving -----**Total Axle Load- 18.69934 tons**						

Master Thesis- Real time model for predictive axle load estimation

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Learning Algorithm

Why need a learning algorithm even when there is a defined model?

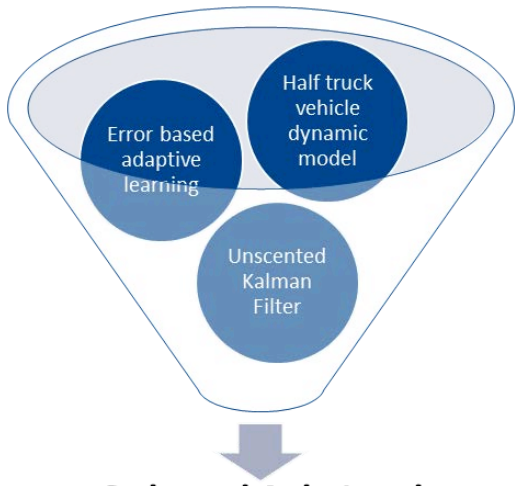
- Real systems have noise, disturbances, and unmodeled dynamics
- Estimators help correct for these using real-time data
- Combine real sensor data with model outputs to have an accurate axle load estimation

Online parameter estimator Goal → minimizes error between bellow sim_pressure & measured_pressure

Non Linear adaptations: Air spring stiffness & bellow area

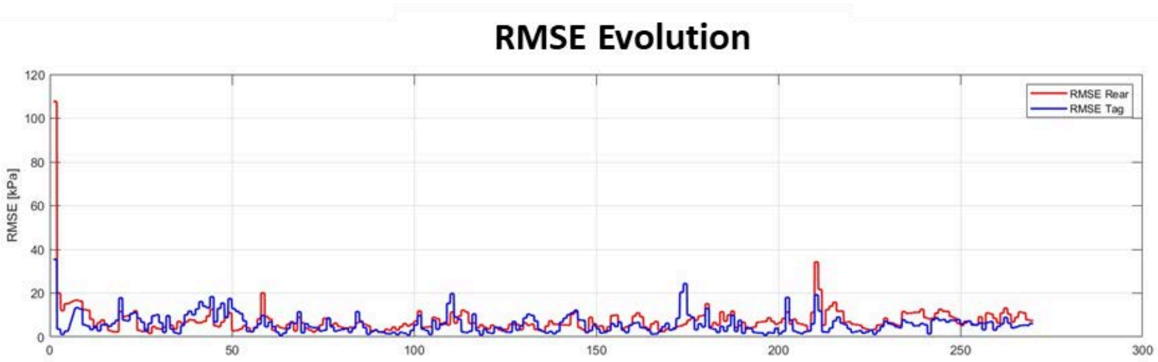
"Not all non-linearities are a trouble in modelling, some can be leveraged"

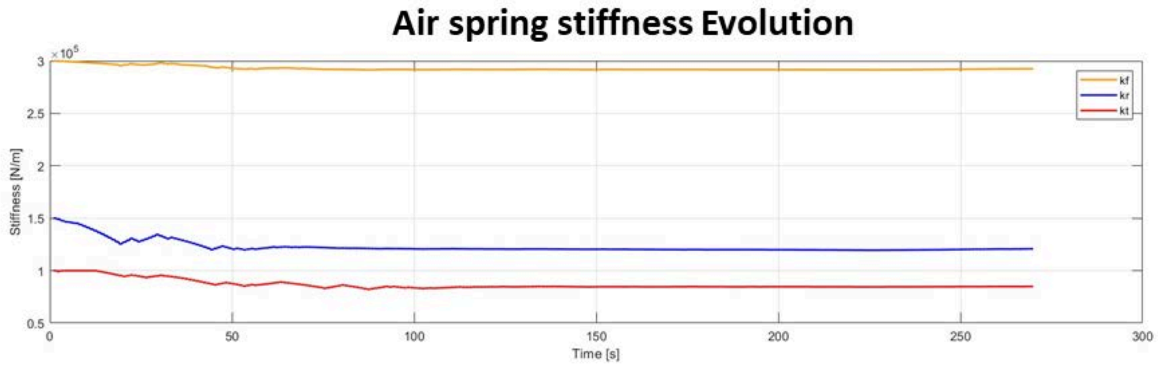
Heuristic Learning on the move:
Dynamic state-dependent Suspension Parameter Adaptation for Accurate Axle Load Estimation Based on Error Magnitude and Directionality with state dependency



Onboard Axle Load Predictions

Adaptive prediction with UKF:
State-Sensitive Stiffness adaptation with UKF and Simulink based pressure feedback





Rear Axle Error--- 7.88 kPa--- 39.92 kg--- 3.99%

Tag Axle Error--- 7.01 kPa--- 36.23 kg--- 4.83%