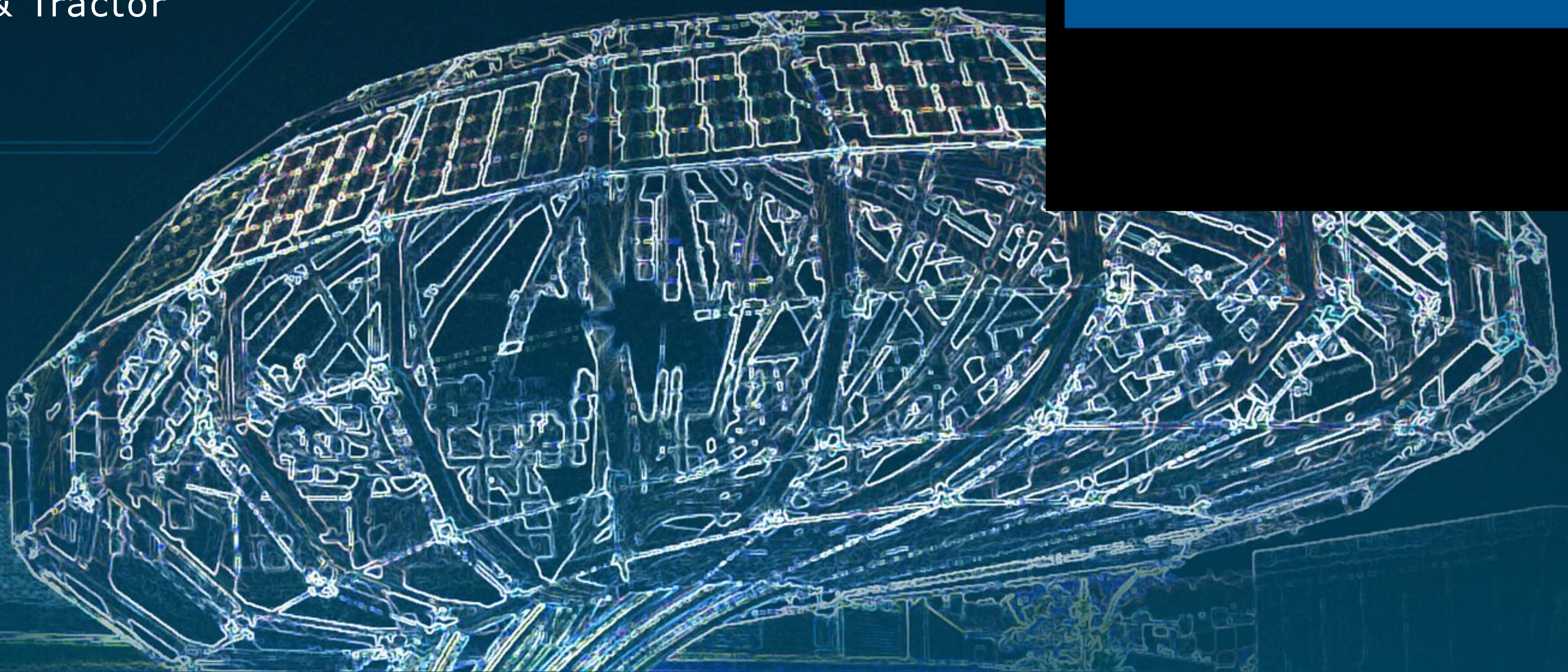
AVL Commercial Driveline & Tractor Engineering GmbH



Model-Based Systems Engineering

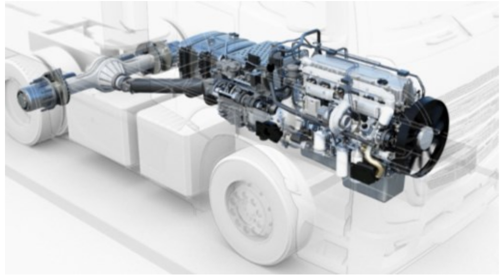
for Optimized Electrified Trucks and Buses

Martin Ackerl

What are the challenges in powertrain development?

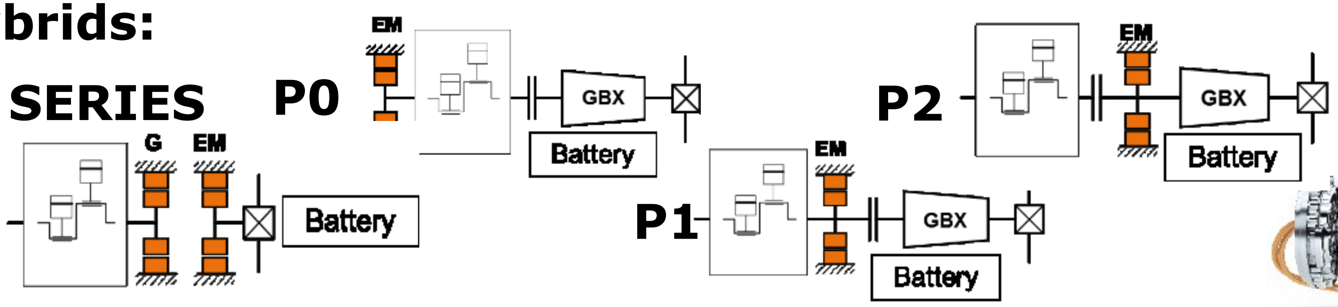
1. How to handle variant diversity of commercial vehicles in powertrain development?

2. How does the "optimal powertrain" look like?

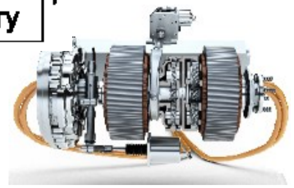


3. What are the challenges in electrified powertrain development?

Hybrids:



AVL eCVT



AVL integrated center drive

AVL integrated e-axle

Public

Agenda

1. Powertrain Systems Engineering
2. Powertrain Optimization
3. Example / Case Study with conventional powertrain

Agenda

1. Powertrain Systems Engineering

2. Powertrain Optimization

3. Example / Case Study with conventional powertrain

V-Process in Systems Engineering

Target Definition

Definition of Powertrain Architecture

Requirement Engineering

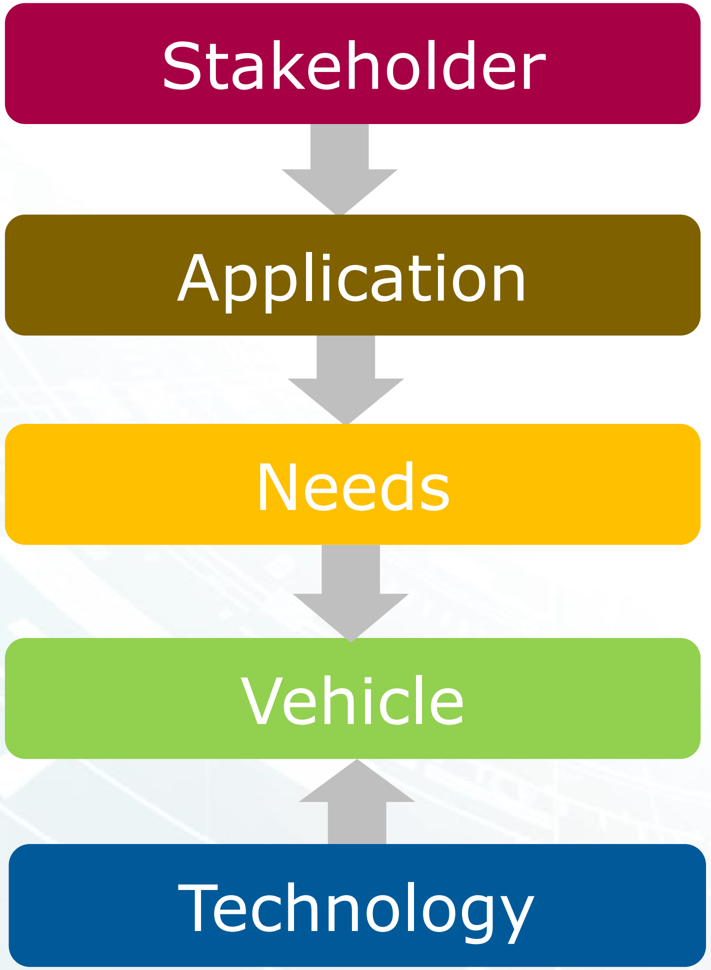
Validation

Vehicle Calibration

Verification

Integration

Target Definition → Vehicle



Stakeholder:

- Goods transportation industries, local public transport, governments, company strategy, legislation, construction industry, …

Application:

- Inner city bus line, urban bus line, intercity bus line, intercity travel, urban delivery, regional delivery, intercity delivery national deliver, international delivery, garbage collection, construction site support (tipper, concrete mixer, …), …

Needs:

- Zero Emission, daily driving range, goods loading and unloading time, acceleration demands, …

Vehicle:

- **Electric** city bus, **fuel cell** long haul truck, **diesel** intercity combination, **electric** distribution truck, …

Overview “AVL Layer Structure”

Level 0
Vehicle

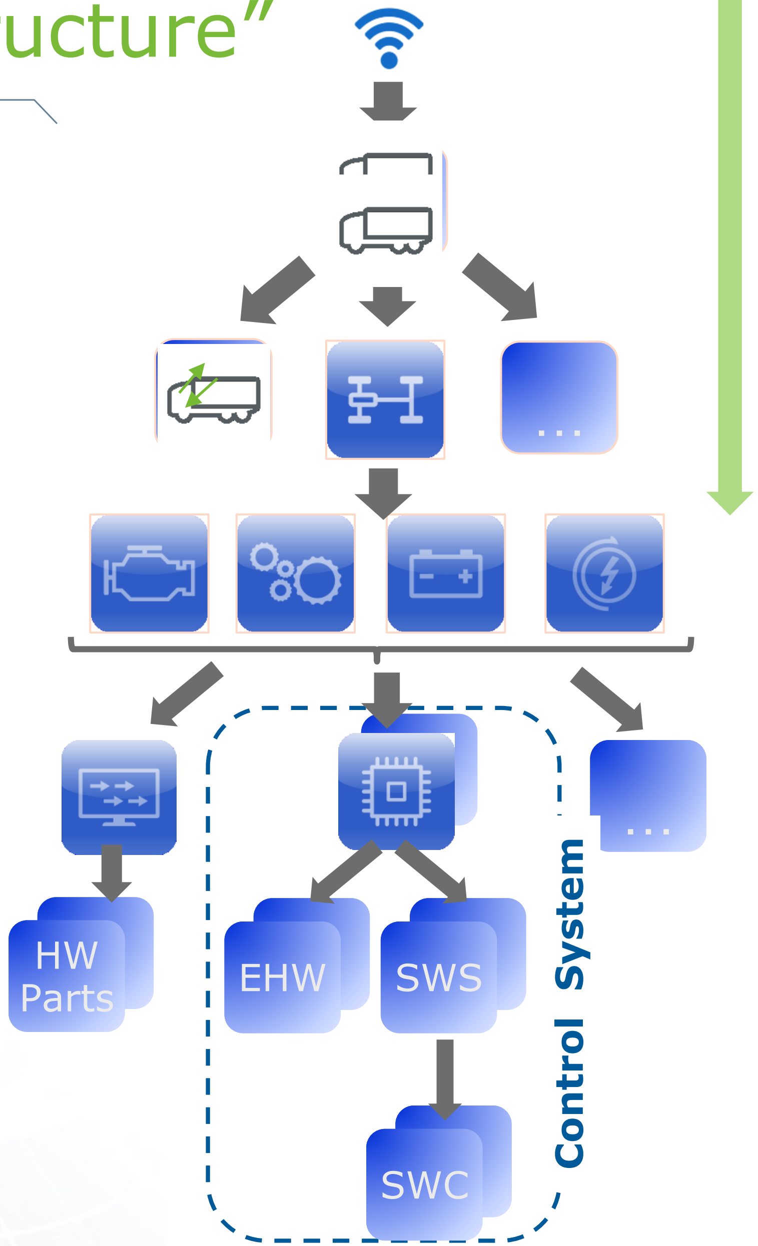
Level 1
Vehicle Sub-Systems

Level 2
Elements (i.e. Engine, Transmission,…)

Level 3
Element Sub Systems (e.g. Valve Train, Hybrid Control System)

Level 4HW Parts / SW System / EHW

Level 5
SW Components



Requirements definition and specification supported by **model based systems engineering**

E-DRIVE FAMILY INVESTIGATION TOOLKIT

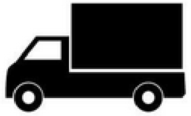
Application, Powertrain, e-Motor, Transmission, FC and Battery

Application

LCV

Truck 4x2
3,5 ton

Truck 4x2
- 8 ton



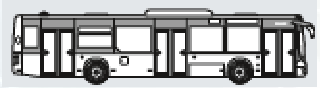
HD / MD

Truck 4x2
- 18 ton

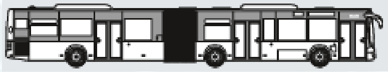
Truck 6x2
-26 ton

Truck 4x2
- 40 ton

City bus
6-12 m



City bus
- 18 m



Powertrain

Integrated E-Axle

Center drive

Wheel selective drive

Photo: Ziehl-Abegg

E-Drive

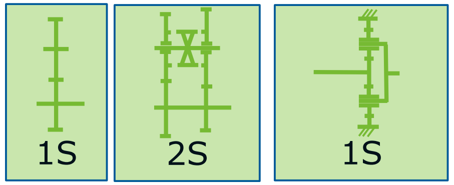
EM-S
Inv - S

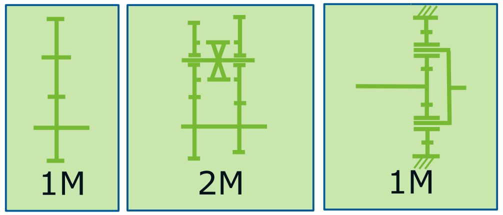
EM-M
Inv - M

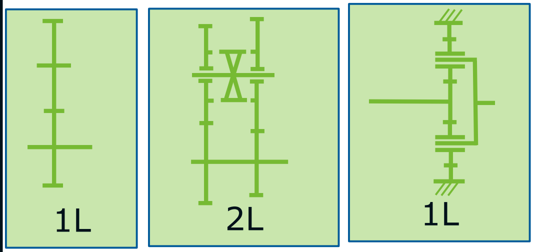
EM-L
Inv - L

EM = e-motor
Inv = Inverter
S,M,L = small, medium, large

Transmission

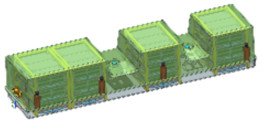


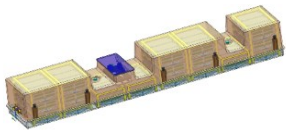




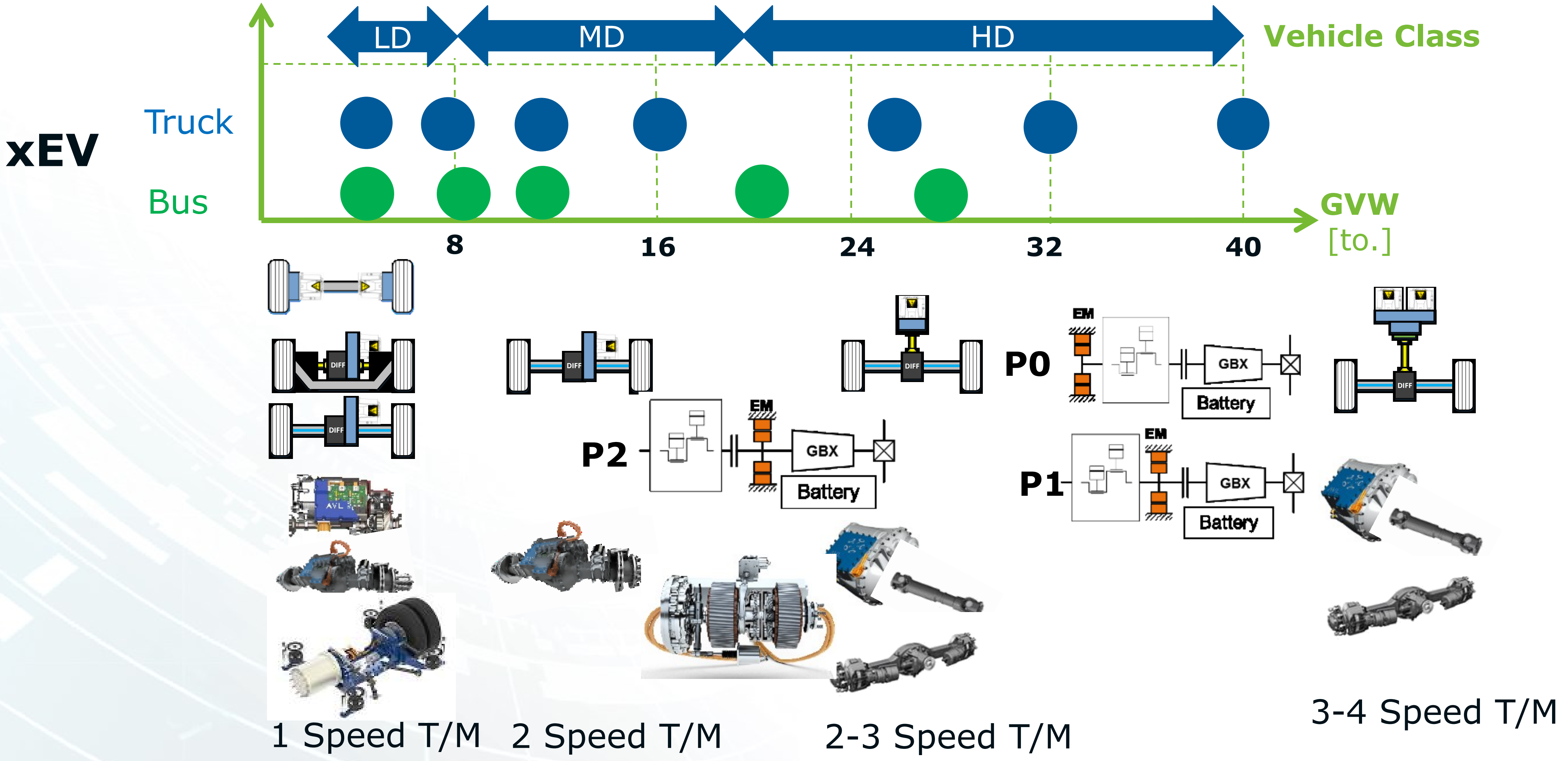
1,2= No. of speeds

FC and Bat



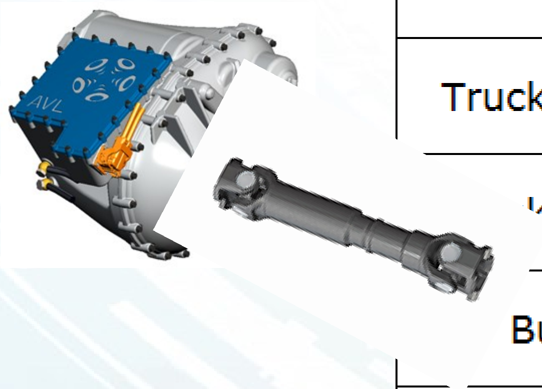


Powertrain FAMILY EXAMPLES
LD - HD



E-DRIVE FAMILIES Example

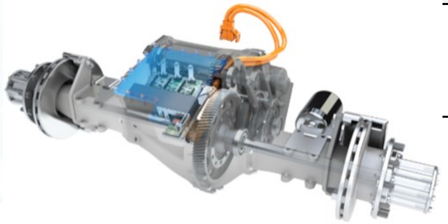
Modular Solution

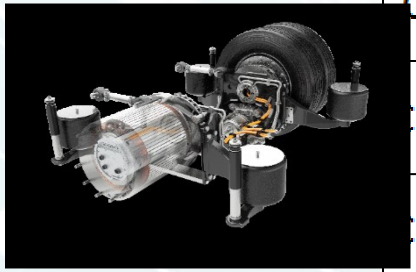


Application	*GVW [t]*	*TM Speeds*	*Cont. Power [kW]*	*Topology*	*E-Motor*	*Transmission*
Truck 4x2	8	single	110	**Center Drive**	110 kW	single-speed, 110 kW
Truck 4x2	16	multi	147	**Center Drive**	175 kW	multi-speed, 175 kW
[illegible] 6x2	26	multi	213	**Center Drive**	2 x 110 kW	Summary TM + multi-speed, 220 kW
Bus 6m	8,5	single	92	**Center Drive**	110 kW	single-speed, 110 kW
City Bus 12m	19	single	179	**Center Drive**	175 kW	single-speed, 175 kW
City Bus 18m	29	single	260	**Center Drive**	110 kW + 175 kW	Summary TM + single-speed, 285 kW

E-DRIVE FAMILIES

Specific Solution





Application	*GVW [t]*	*TM Speeds*	*Cont. Power [kW]*	*Topology*	*E-Motor*	*Transmission*
Truck 4x2	8	single	110	**integrated e-axle**	110 kW	single-speed, 110 kW
Truck 4x2	16	multi	147	**integrated e-axle**	148 kW	multi-speed, 148 kW
Truck 6x2	26	multi	213	**Center Drive**	2 x 110 kW	Summary TM + multi-speed, 220 kW
City Bus 6m	8,5	single	92	**wheel selective drive**	2 x 50 kW	2 x single-speed, 50 kW
ity Bus 12m	19	single	179	**wheel selective drive**	2 x 90 kW	2 x single-speed, 90 kW
ity Bus 18m	29	single	260	**wheel selective drive**	2 x 90 kW	2 x single-speed, 90 kW
				wheel selective drive*	2 x 50 kW	2 x single-speed, 50 kW

* Structural parts to be adapted

Agenda

1. Powertrain Systems Engineering

2. Powertrain Optimization

3. Example / Case Study with conventional powertrain

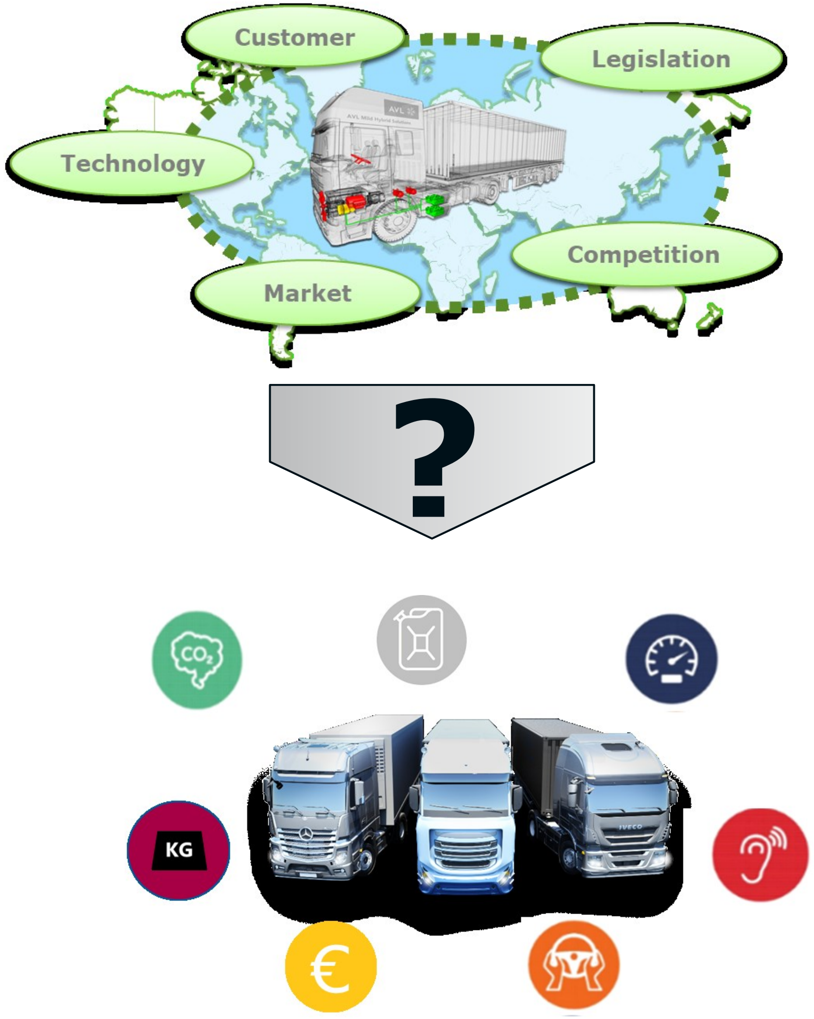
Powertrain optimization
Why?

Boundary conditions for powertrain (of defined application)

- Fuel consumption target (e.g. legislation, …)
- Product cost limit / total cost of ownership
- Vehicle requirements (performance, drivability, …)
- Target market (best in class, low cost, …)
- Zero Emission Zones (electrification/hybridization)

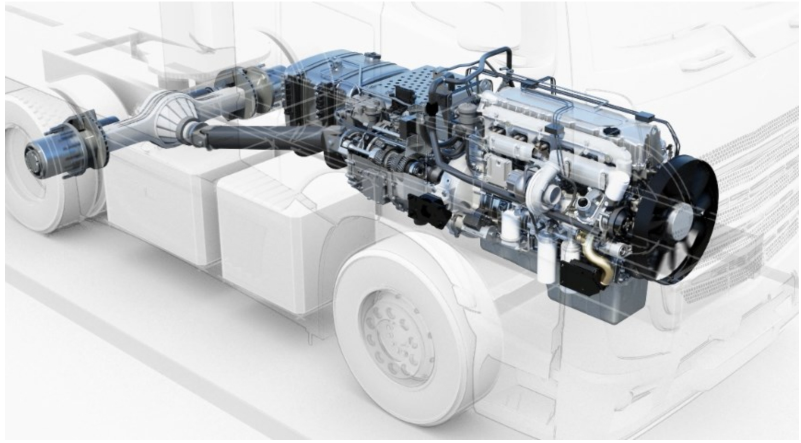
Important OEM questions to be answered (e.g. transmission):

- Which engine technology?
- Which gear ratios (transmission and axle) in combination with the engine?
- How many shift able gears?
- Gear shift strategy?
- Hybridization/Electrification concept?



Powertrain optimization
Task definition

1. Variation of powertrain parameter within simulation
   e.g.
   - Engine technology
   - Transmission gear ratios
   - Rear axle ratio
   - Powertrain calibration
2. Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.
   - Fuel consumption
   - Production costs
   - Performance
   - Drivability

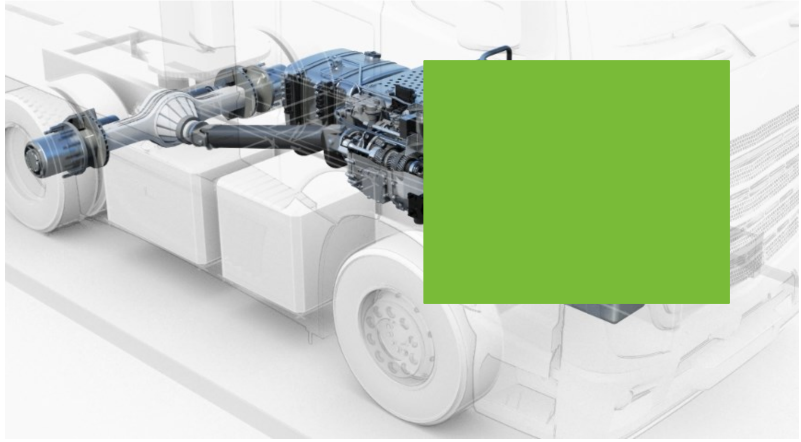


Truck powertrain incl. engine, transmission & axle

Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

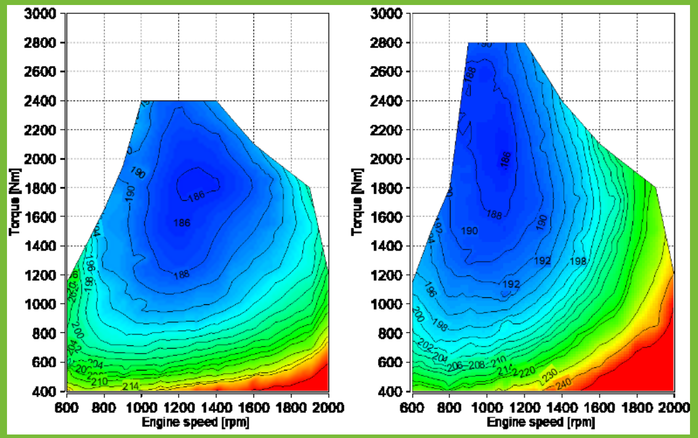
- Transmission gear ratios
- Rear axle ratio
- Powertrain calibration



Truck powertrain incl. engine, transmission & axle

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

- Fuel consumption
- Production costs
- Performance
- Drivability



Variation of engine technology

- Different full load characteristics
- Different fuel consumption maps

Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

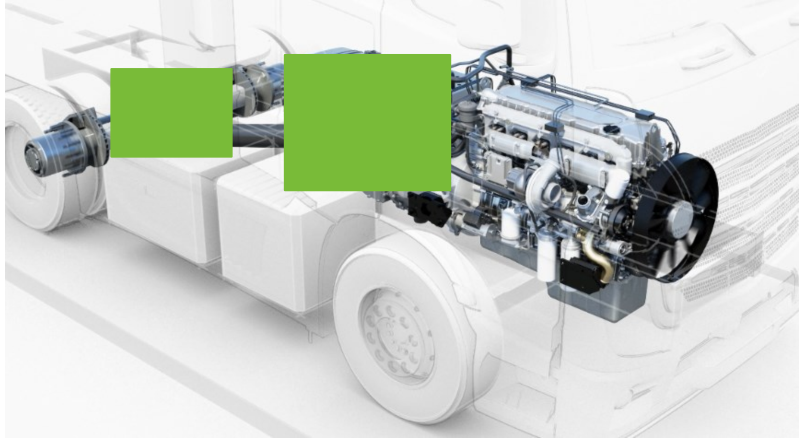
- Engine technology
- Powertrain calibration

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

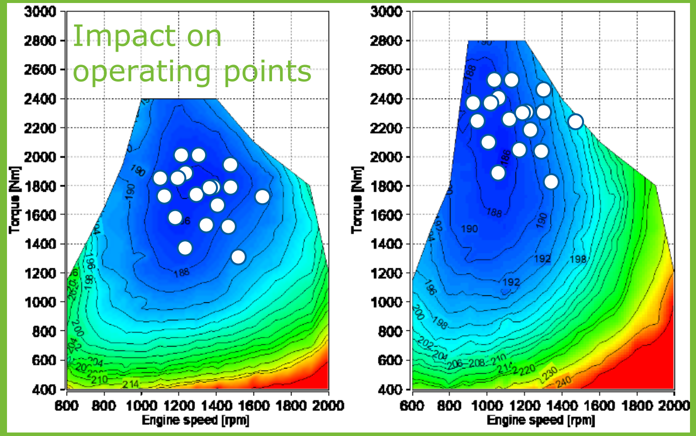
- Fuel consumption
- Production costs
- Performance
- Drivability

Variation of gear ratios

- Different transmission technologies (#gears, gear spread, OD/DD)
- Different rear axle ratios



Truck powertrain incl. engine, transmission & axle



Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

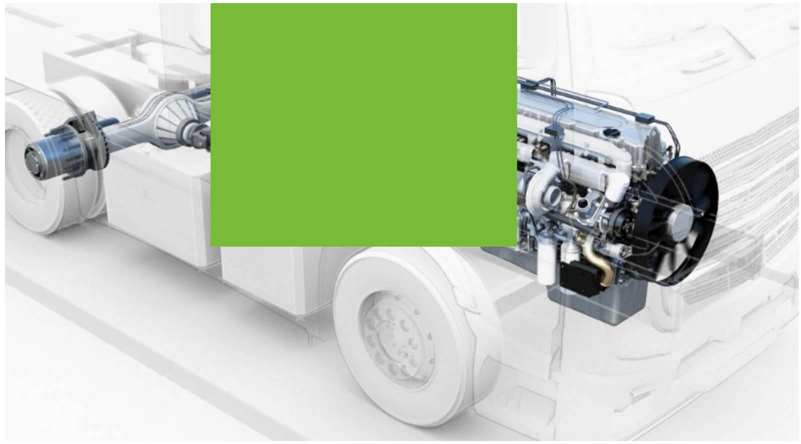
- Engine technology
- Transmission gear ratios
- Rear axle ratio

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

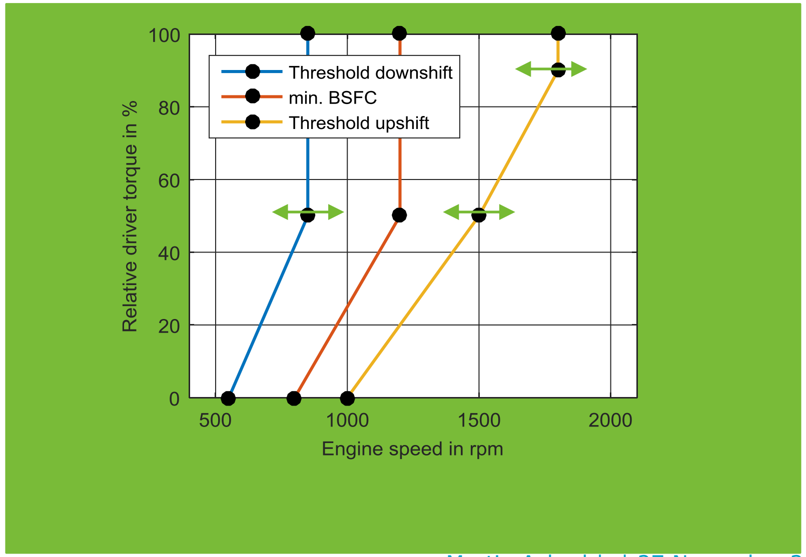
- Fuel consumption
- Production costs
- Performance
- Drivability

Variation of powertrain calibration parameter

- E.g. different upshift and downshift characteristics for gear shifting



Truck powertrain incl. engine, transmission & axle



Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

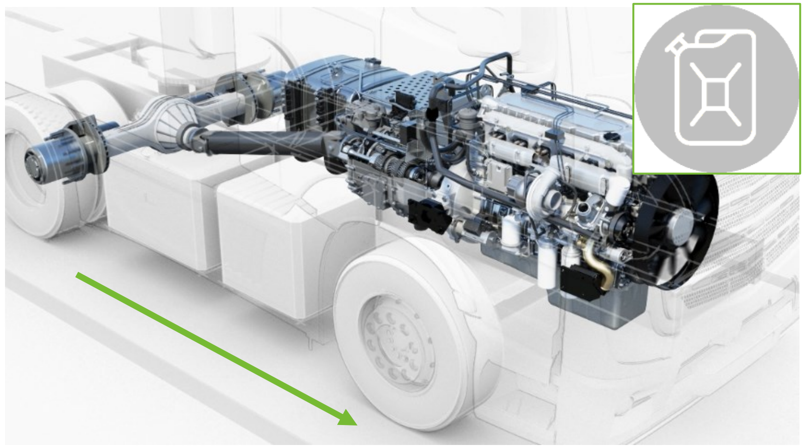
- Engine technology
- Transmission gear ratios
- Rear axle ratio
- Powertrain calibration

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

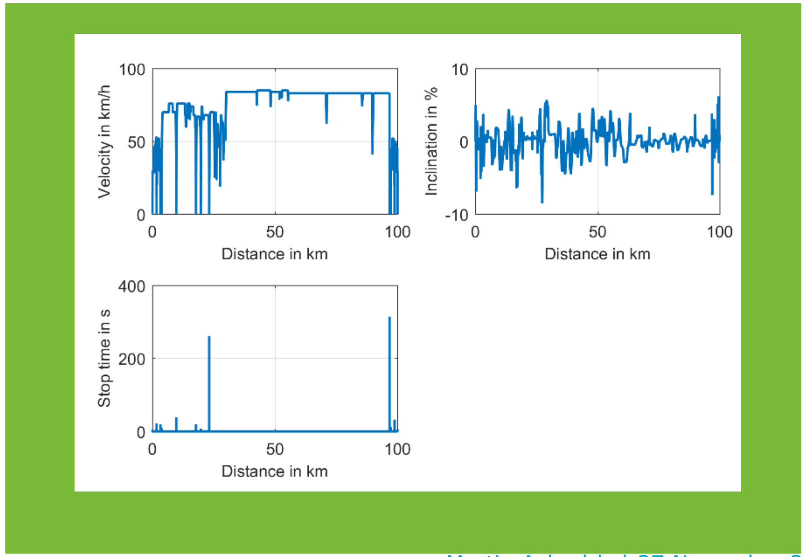
- Production costs
- Performance
- Drivability

Evaluation of fuel consumption

- Vehicle driving on defined drive cycle (**Simulation**)



Truck powertrain incl. engine, transmission & axle



Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

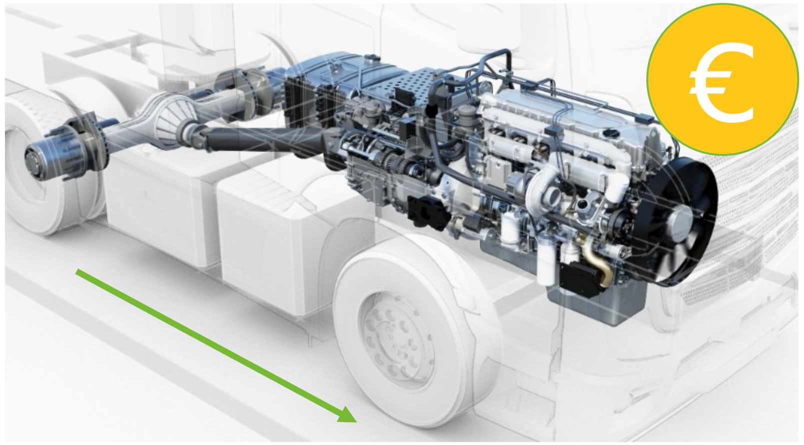
- Engine technology
- Transmission gear ratios
- Rear axle ratio
- Powertrain calibration

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

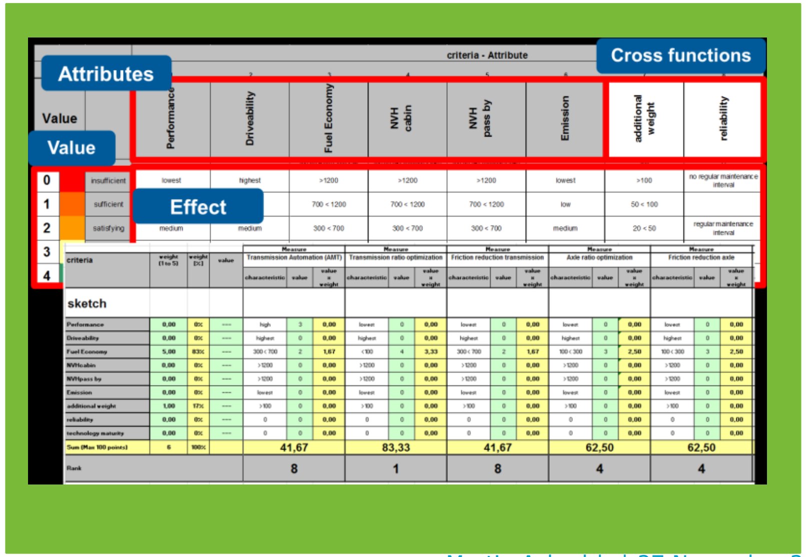
- Fuel consumption
- Performance
- Drivability

Evaluation of production cost

- **Estimation** of product cost for different technologies
- Overall cost of selected powertrain configuration



Truck powertrain incl. engine, transmission & axle



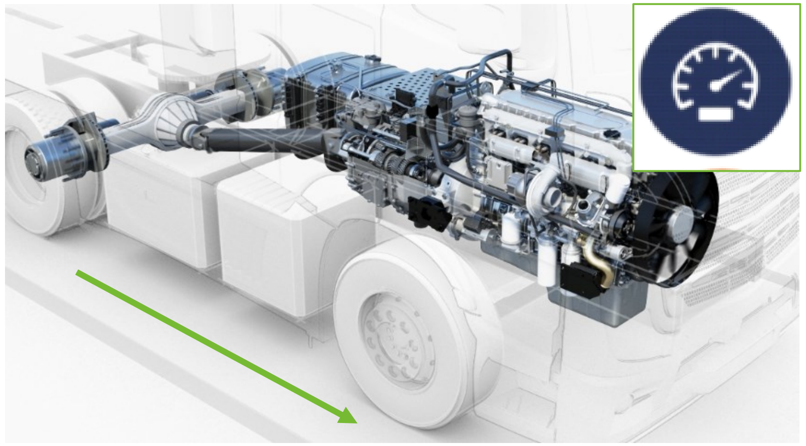
Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

- Engine technology
- Transmission gear ratios
- Rear axle ratio
- Powertrain calibration

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

- Fuel consumption
- Production costs
- Drivability



Truck powertrain incl. engine, transmission & axle

<u>Evaluation of performance</u>

- Startup gradeability (**Simulation**)
- Vehicle acceleration (**Simulation**)

Powertrain optimization
Task definition

Variation of powertrain parameter within simulation e.g.

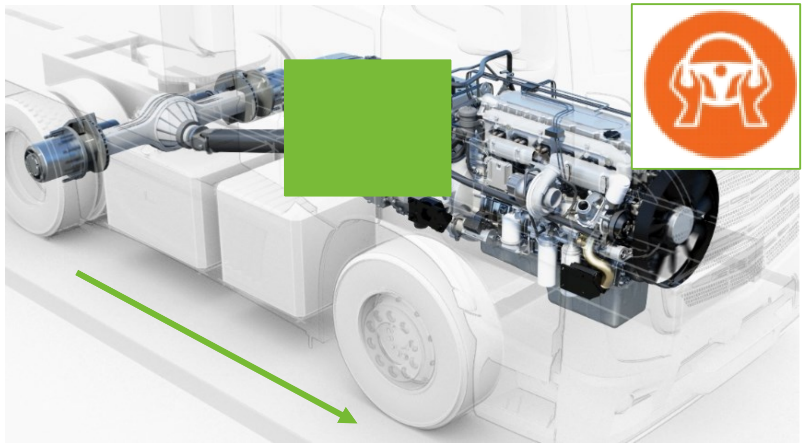
- Engine technology
- Transmission gear ratios
- Rear axle ratio
- Powertrain calibration

Optimization with respect to evaluation criteria (output of simulation or AVL knowhow) e.g.

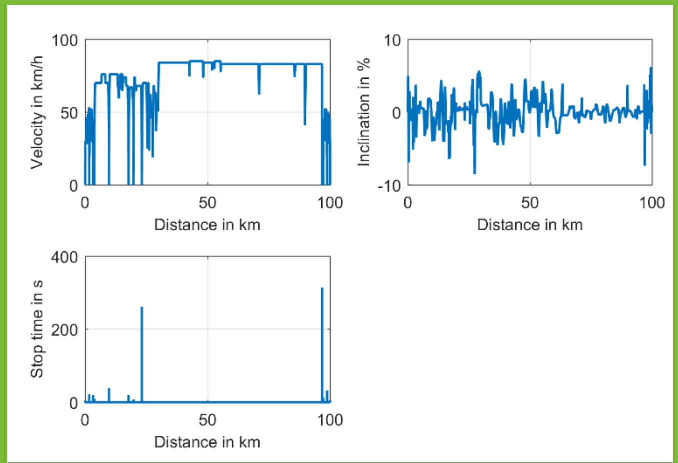
- Fuel consumption
- Production costs
- Performance

Evaluation of drivability

- E.g. number of gear shifts on defined drive cycle (**Simulation**)



Truck powertrain incl. engine, transmission & axle



Powertrain optimization
Main idea

Knowhow based

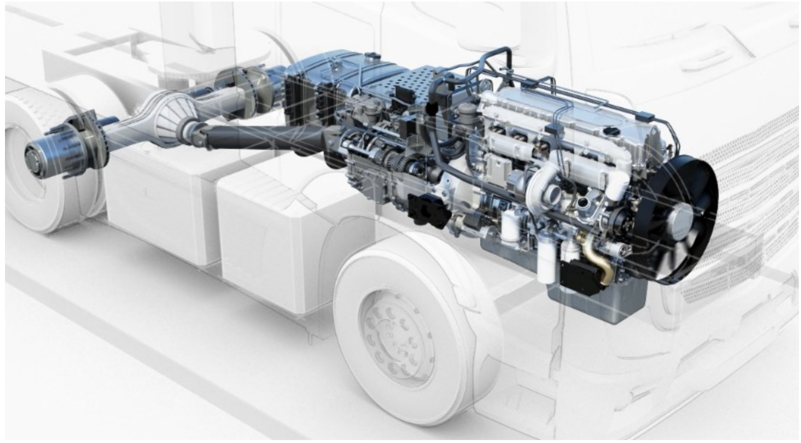
- Using expert knowledge for
  - definition of variation parameters and range
  - definition of knowhow based evaluation criteria (production costs,…)

Mathematic based (Simulation and Optimization)

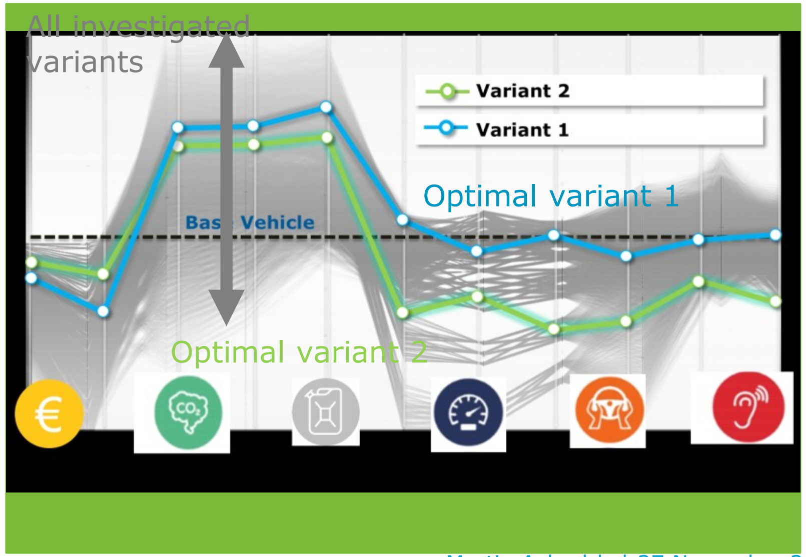
- Mathematical simulation and optimization
  - Using system **simulation** of overall vehicle and powertrain
  - Using **DoE** (Design of Experiment) approach for intelligent parameter variation
  - Using **KPI models** for optimization

Customer based

- Select optimal powertrain configuration
  - Set boundary conditions for evaluation criteria based on customer input



Truck powertrain incl. engine, transmission & axle

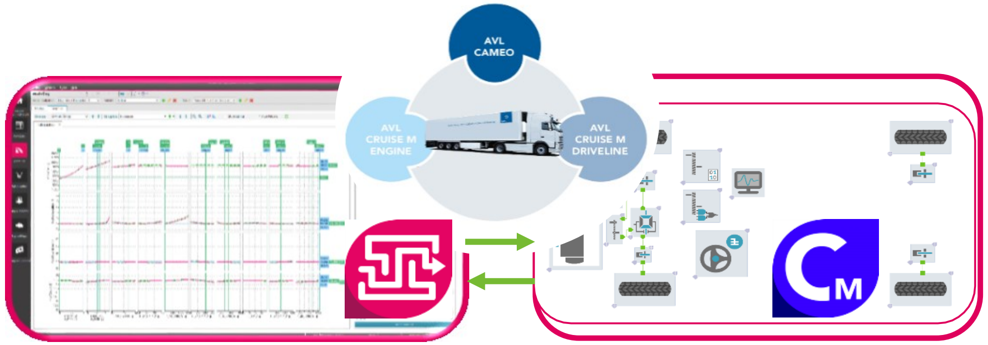


Powertrain optimization
Optimization tool

AVL Cameo

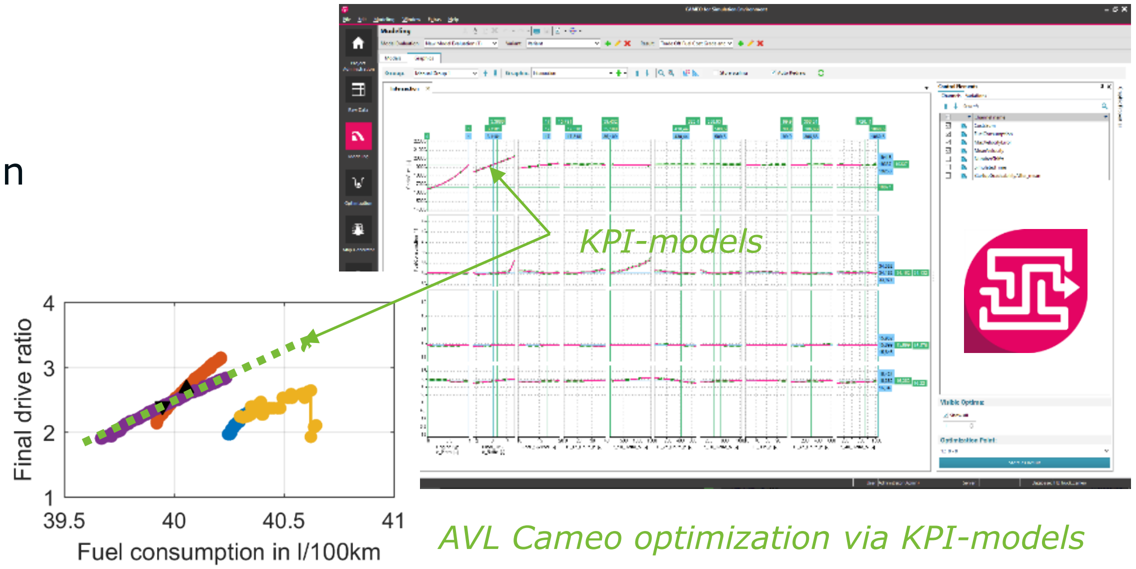
- Automation software tool
- Interface to Cruise M longitudinal vehicle simulation
  - trigger simulations
  - data exchange
- Setup and run DoE test plans
  - Different DoE approaches available (core DoE, active DoE,…)
- Generation of KPI-models
  - Multi-dimensional analytic model
  - Relation between parameters and/or evaluation criteria
  - Short calculation time

- Optimization of parameters based on KPI-models



a) Cameo *b) Cruise M*

Toolchain for powertrain optimization

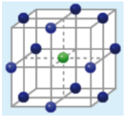


AVL Cameo optimization via KPI-models

Powertrain optimization
Methodology explanation

Preparation Phase

Set-up of DoE



Variation of vehicle parameters e.g.
- Engine technology
- Final drive
- EM power
- Battery capacity

Estimation of depending boundary conditions

e.g. Impact of
- New technologies on product cost
- Battery capacity on vehicle weight

Knowhow based

Simulation Phase

- V1 System Simulation
- V2 System Simulation
- Vn System Simulation

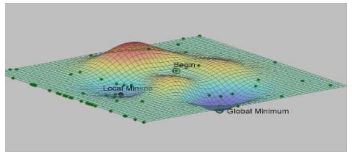
Optimization Phase

Setup of empirical KPI-models (based on simulation results)

e.g.
- Final drive → fuel consumption
- Bat. Cap → Range

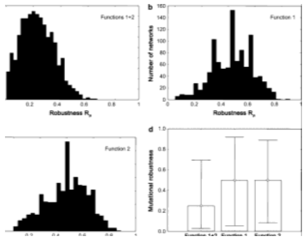
Optimization

e.g.
- Min. cost with max. performance



Verification Phase

Robustness



Definition of Worst-case Variants

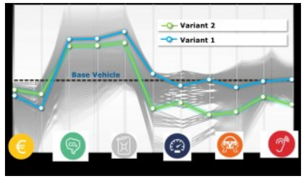
e.g. Input for DVP

Mathematic based (Simulation and Optimization)

Visualization Phase

Workshop with customer

Final definition of optimal powertrain concept



Customer based

Agenda

1. Powertrain Systems Engineering
2. Powertrain Optimization
3. **Example / Case Study with conventional powertrain**

Powertrain optimization
Example

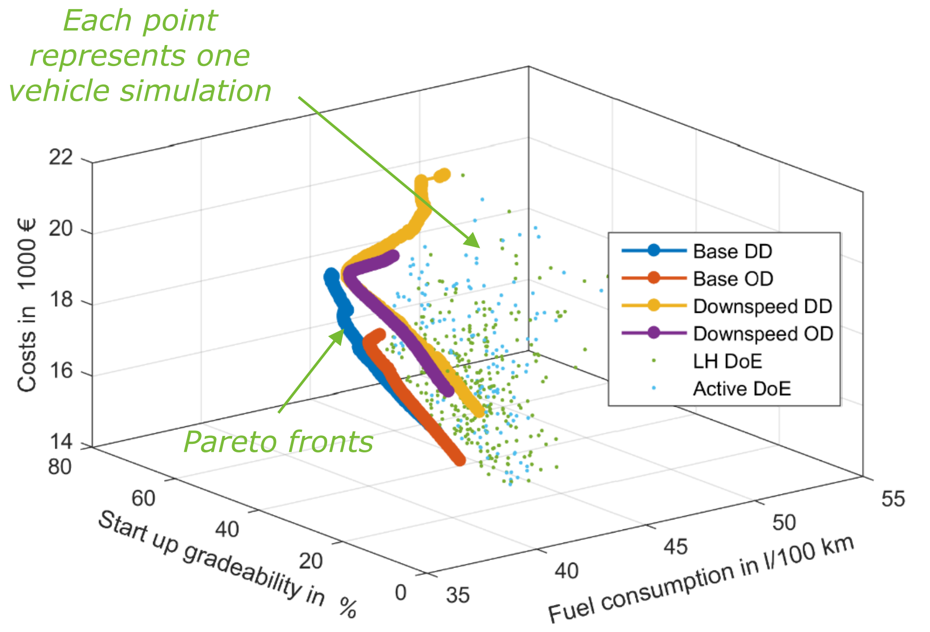
Powertrain optimization of 40t HD Truck:

- Setup vehicle model with variation parameter
- Run DoE test plan
  - Cameo triggers simulations
  - Different parameter combinations simulated
  - Pareto fronts (optimal solutions) generated
  - → **Resulting in class of optimal solutions**

- Mathematical optimization
  - Calculation of KPI-models
  - Set boundary conditions for evaluation criteria
  - Optimization of powertrain variation parameter

Powertrain parameter	Variation range
Engine type	Base vs. Downspeed
Transmission type	DirectDrive vs. Overdrive
Gear spread	10…20
Final drive ratio	1…4
Gear shift characteristics	7 variation parameter

Powertrain variation parameter



Exemplary results of Cameo DoE optimization (pareto fronts for different powertrain configurations)

Powertrain optimization
Example

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Powertrain parameter	Variation range
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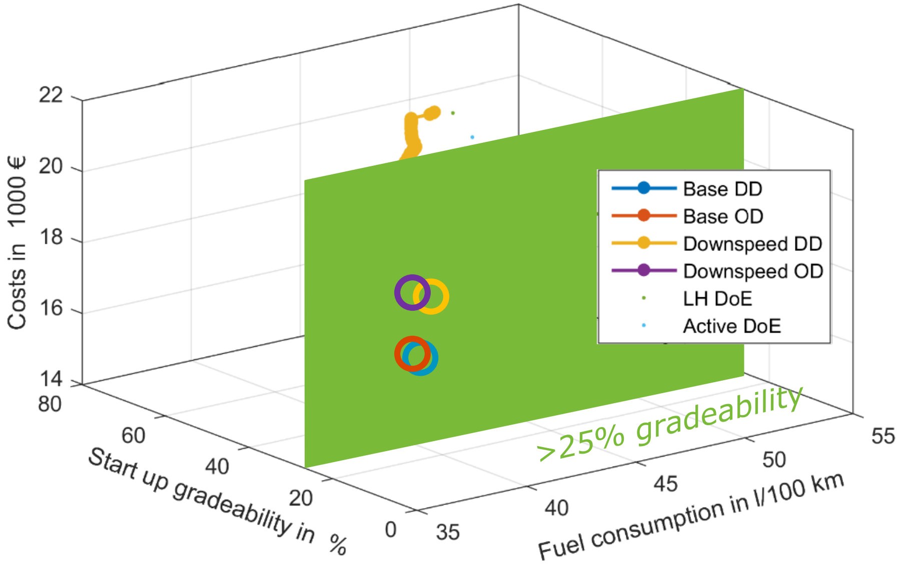
Gear shift characteristics	7 variation parameter

Powertrain variation parameter



Exemplary results of Cameo DoE optimization (pareto fronts for different powertrain configurations)

Powertrain optimization
Example

Powertrain optimization of 40t HD Truck:

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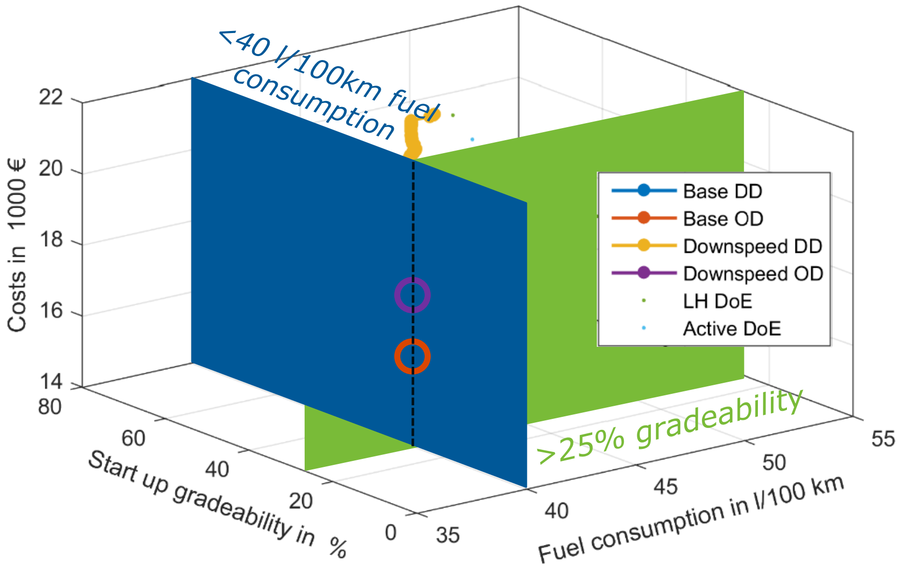
  - Cameo triggers simulations
  - Different parameter combinations simulated
  - Pareto fronts (optimal solutions) generated
  - → **Resulting in class of optimal solutions**
- Mathematical optimization
  - Calculation of KPI-models

Powertrain parameter	Variation range
Engine type	Base vs. Downspeed
Transmission type	**Overdrive**
Gear spread	**20**
Final drive ratio	**2.68**
Gear shift characteristics	**7 fixed parameter**

Powertrain variation parameter



Exemplary results of Cameo DoE optimization (pareto fronts for different powertrain configurations)

Powertrain optimization
Example

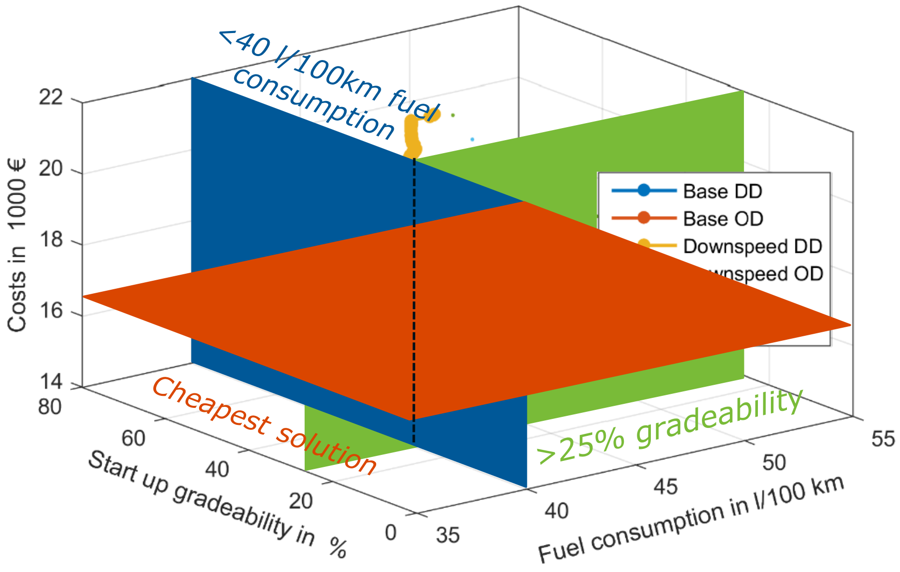
<u>Powertrain optimization of 40t HD Truck:</u>

- Setup vehicle model with variation parameter
- Run DoE test plan
  - Cameo triggers simulations
  - Different parameter combinations simulated
  - Pareto fronts (optimal solutions) generated
  - → **Resulting in class of optimal solutions**

- Mathematical optimization
  - Calculation of KPI-models

Powertrain parameter	Variation range
Engine type	**Base**
Transmission type	**Overdrive**
Gear spread	**20**
Final drive ratio	**2.68**
Gear shift characteristics	**7 fixed parameter**

Powertrain variation parameter



Exemplary results of Cameo DoE optimization (pareto fronts for different powertrain configurations)

Summary

Model based Systems Engineering for Optimized Powertrain Systems

still needs:

- Expert know-how
- Customer/Expert review of results
- → support decision making for further detailed investigations

but has the potential to:

- Handle variants diversity of vehicles and powertrains
- Find the optimal solutions for electrified powertrain variants
- Visualize the optimal solutions (Pareto Fronts) for expert decision
- → support to find a modular electrified powertrain concept for a vehicle portfolio

Thank You

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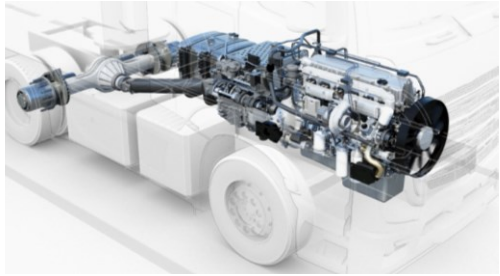
What are the challenges in powertrain development?

1. How to handle many variants of commercial vehicles in powertrain development?

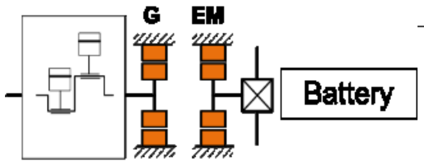
2. How does the "optimal powertrain" look like?



3. How challenges in electrified powertrain development can be look like?

Hybrids:

SERIES



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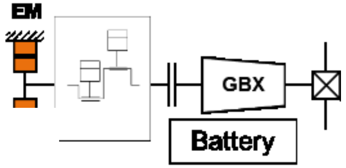

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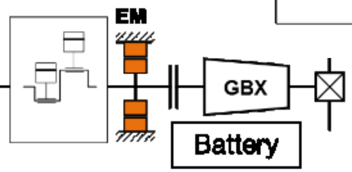

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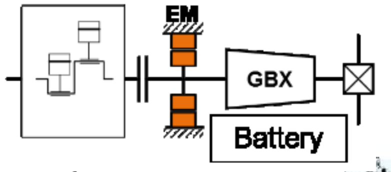

AVL eCVT

AVL integrated center drive

AVL integrated e-axle