SAFETY SIMULATION IN THE CONCEPT PHASE: ADVANCED CO-SIMULATION TOOLCHAIN FOR CONVENTIONAL, HYBRID & FULLY ELECTRIC VEHICLES

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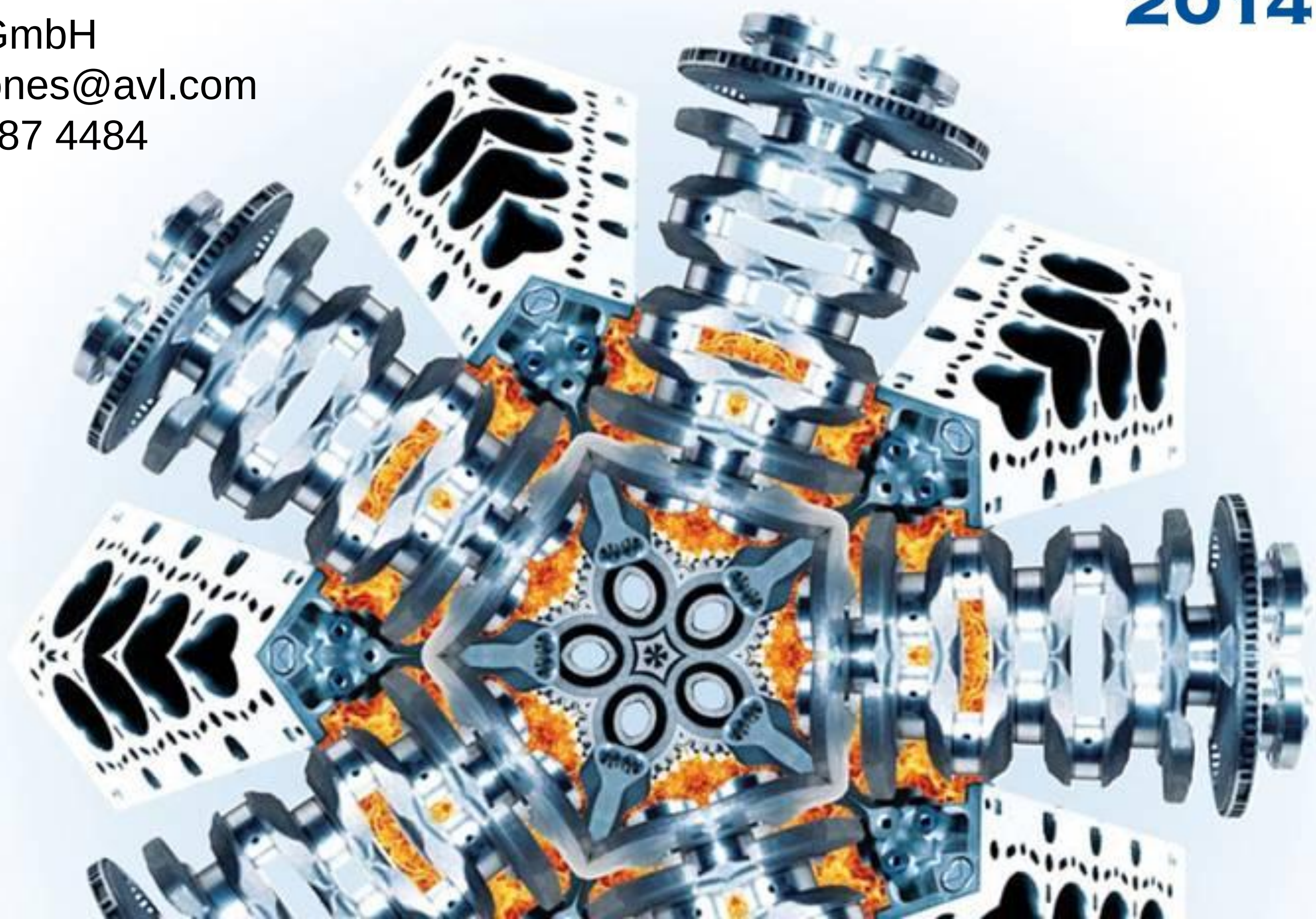

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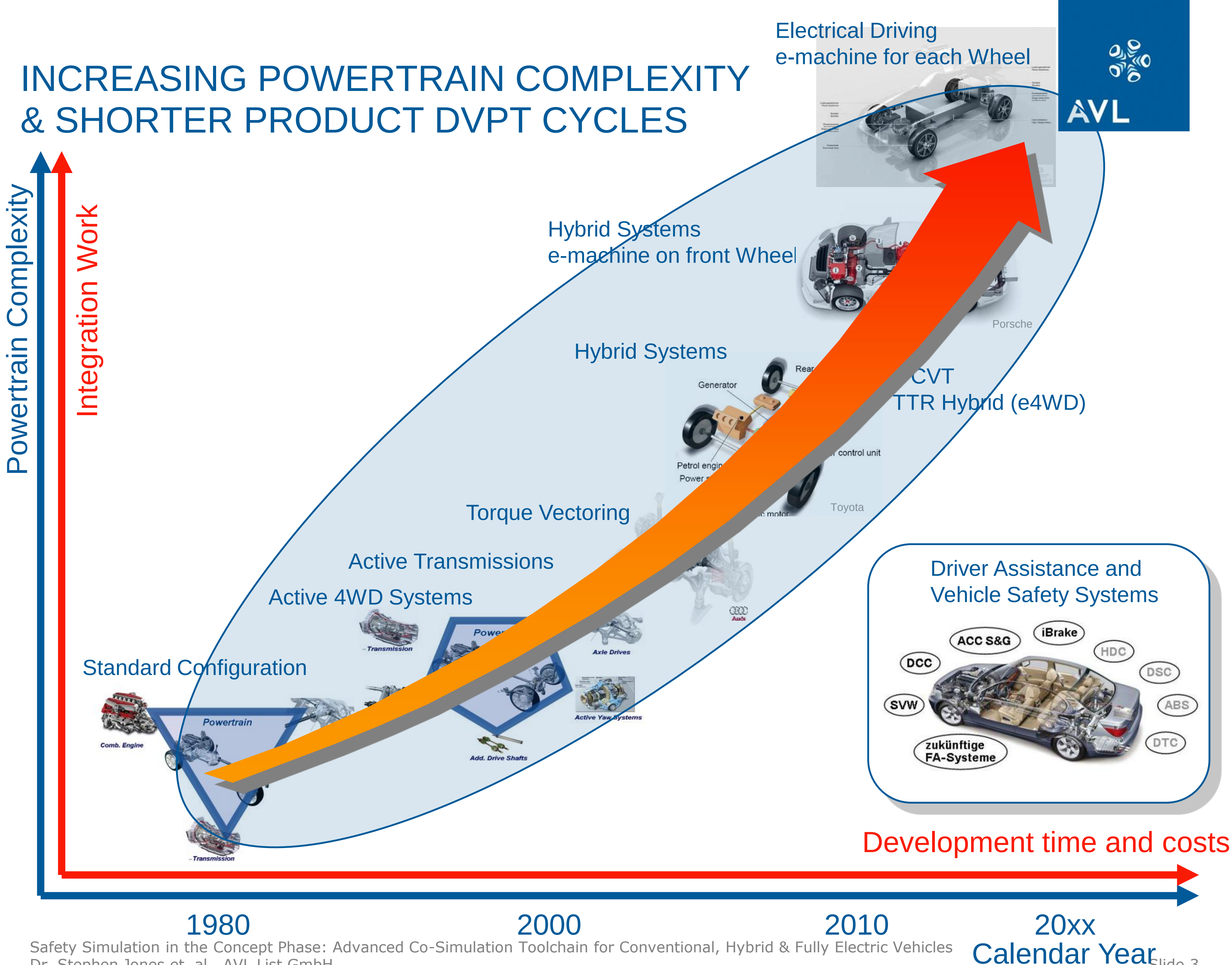
INCREASING POWERTRAIN COMPLEXITY & SHORTER PRODUCT DVPT CYCLES



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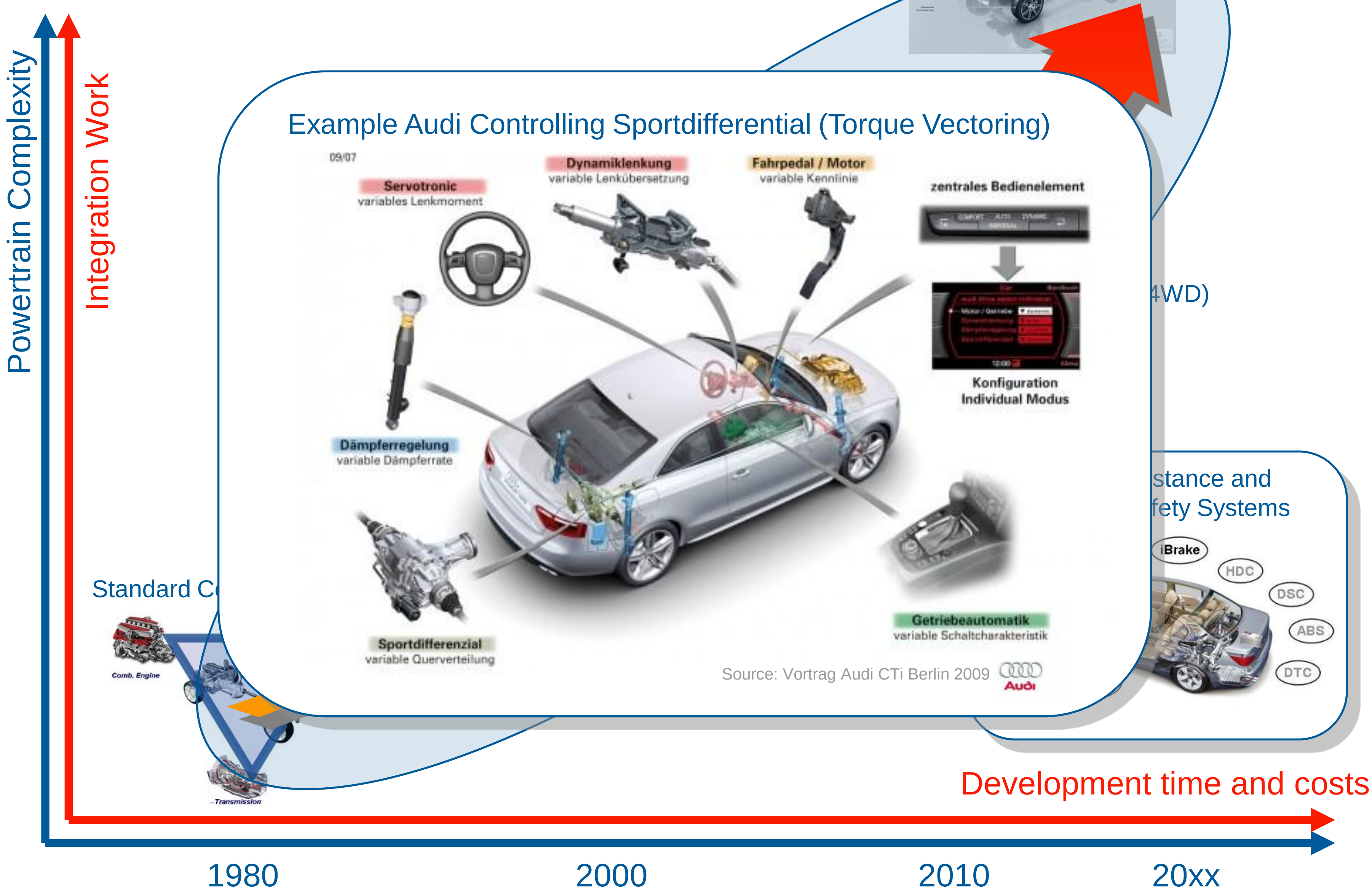
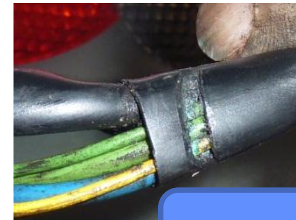


FUNCTIONAL SAFETY ANALYSIS VIA SYSTEM CO-SIMULATION

- ISO 26262, a Functional Safety standard of “Road vehicles -- Functional Safety”, published in November 2011.
- Aims to address possible hazards caused by the malfunctioning behaviour of electronic and electrical systems, with a max. gross weight of 3500kg.
- Extension is planned to include heavy duty trucks (>3500kg).
- In AVL, virtual reality simulation is built up for safety simulation for ISO 26262 and hazard severity rating in early concept phase.
- With such co-simulation techniques, incident severity & vehicle controllability following defined system failures can be virtually determined and *Automotive Safety Integrity Level* (ASIL) may be defined.

ISO 26262

SAFETY - PROBLEM STATEMENT
ISO 26262 – ASIL OVERVIEW



Severity class	Probability class	Controllability class		
		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	[illegible]
	E3	QM	QM	[illegible]
	E4	QM	A	[illegible]
S2	E1	QM	QM	[illegible]
	E2	QM	QM	[illegible]
	E3	QM	A	[illegible]
	E4	A	B	[illegible]
S3	E1	QM	QM	[illegible]
	E2	QM	A	[illegible]
	E3	A	B	[illegible]
	E4	B	C	[illegible]

Event

Exposure

Severity

Controllability

3 aspects in ASIL

Residual Risk

Tolerable Risk

Inherent Risk

Necessary risk reduction

Actual risk reduction

SAFETY - PROBLEM STATEMENT
ISO 26262 – ASIL – EXPOSURE & SEVERITY

- For **Exposure** and **Severity** there are, to some extent, clear guidelines on how they can be evaluated:

Exposure

		Class of probability of exposure in operational situations (see Table 2)			
		E1	E2	E3	E4
Frequency of situation		Occurs less often than once a year for the great majority of drivers	Occurs a few times a year for the great majority of drivers	Occurs once a month or more often for an average driver	Occurs during almost every drive on average
Examples	Road layout	—	— Mountain pass with unsecured steep slope	—	—
	Road surface	—	— Snow and ice on road	— Wet road	—
	Nearby elements	—	—	— In tunnel — In car wash — Traffic congestion	—
	Vehicle stationary state	— Stopped, requiring engine restart (at railway crossing) — Vehicle being towed — Vehicle during jump start	— Trailer attached — Roof rack attached	— Vehicle being refuelled — Vehicle on a hill (hill hold)	—
	Manoeuvre	—	— Evasive manoeuvre, deviating from desired path	— Overtaking	— Starting from standstill — Shifting transmission gears — Accelerating — Braking — Executing a turn (steering) — Using indicators — Manoeuvring vehicle into parking position — Driving in reverse

Severity

	Class of severity (see Table 1)			
	S0	S1	S2	S3
Reference for single injuries (from AIS scale)	— AIS 0 and less than 10 % probability of AIS 1-6 — Damage that cannot be classified safety-related	More than 10 % probability of AIS 1-6 (and not S2 or S3)	More than 10 % probability of AIS 3-6 (and not S3)	More than 10 % probability of AIS 5-6
Examples	— Bumps with roadside infrastructure — Pushing over roadside post, fence, etc. — Light collision — Light grazing damage — Damage entering/ exiting parking space — Leaving the road without collision or rollover	— Side impact with a narrow stationary object, e.g. crashing into a tree (impact to passenger cell) with very low speed — Side collision with a passenger car (e.g. intrudes upon passenger compartment) with very low speed — Rear/front collision with another passenger car with very low speed — Collision with minimal vehicle overlap (10 % to 20 %) — Front collision (e.g. rear-ending another vehicle, semi-truck, etc.) without passenger compartment deformation	— Side impact with a narrow stationary object, e.g. crashing into a tree (impact to passenger cell) with low speed — Side collision with a passenger car (e.g. intrudes upon passenger compartment) with low speed — Rear/front collision with another passenger car with low speed — Pedestrian/bicycle accident while turning (city intersection and streets)	— Side impact with a narrow stationary object, e.g. crashing into a tree (impact to passenger cell) with medium speed — Side collision with a passenger car (e.g. intrudes upon passenger compartment) with medium speed — Rear/front collision with another passenger car with medium speed — Pedestrian/bicycle accident (e.g. 2-lane road) — Front collision (e.g. rear-ending another vehicle, semi-truck, etc.) with passenger compartment deformation

SAFETY - PROBLEM STATEMENT
ISO 26262 – ASIL – CONTROLLABILITY (1/2)

Controllability in ASIL:

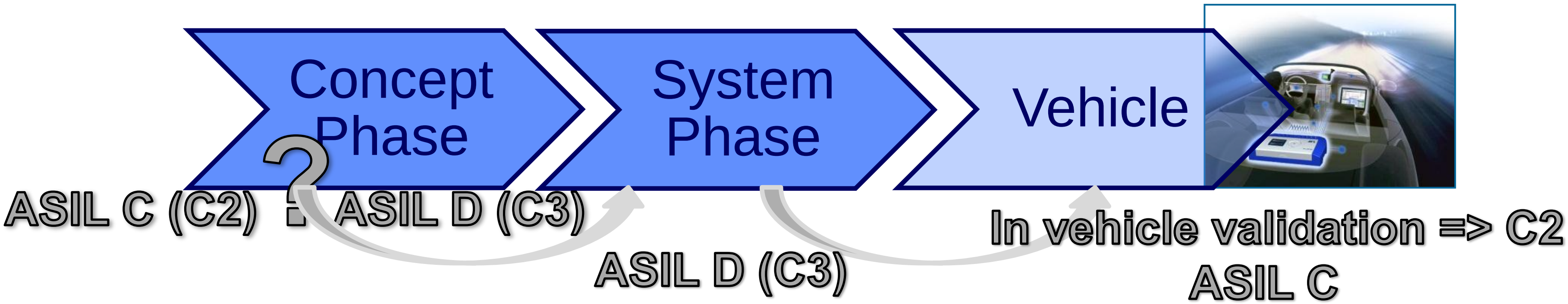
- Controllability **harder to assess**. Especially with **novel powertrains!**
- For **heavy duty vehicles**, due to large architectural differences, controllability estimation becomes **even more challenging**.
- ISO 26262: “*Controllability estimations can be influenced by a number of factors including the cultural background of the analyst, the target market for the vehicle, or driver profiles for the target market*.”
- Moreover: “*As no controllability is assumed for category C3, it is not relevant to have appropriate evidence of the rationale for such a classification*” => **Everything that is not C3 must be justified …**

SAFETY - PROBLEM STATEMENT
ISO 26262 – ASIL – CONTROLLABILITY (2/2)

Four Classes of Controllability

C0	C1	C2	C3
Controllable in general	Simply controllable	Normally controllable	Difficult to control or uncontrollable

Most of the controllability assumptions can only be proven at the end of development cycle, on test track with a comprehensive measurement plan:



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INTRODUCTION OF METHODOLOGY

We propose a methodology for **estimation of controllability** to support the argumentation in HRA based on:

- Simulate vehicle lateral and longitudinal dynamics for various driving conditions (wet road, icy road, high speed, curves, etc.).
- Induce different faults with respect to analyzed item (e.g. E-machine failure on electric vehicle).
- Model human driver category for simulation.
- Based on simulation results we observe human driver's ability to react when each hazardous situation occurs.

SYSTEM CO-SIMULATION TOOLCHAIN
1D POWERTRAIN & 3D VEHICLE DYNAMICS & CONTROL

AVL

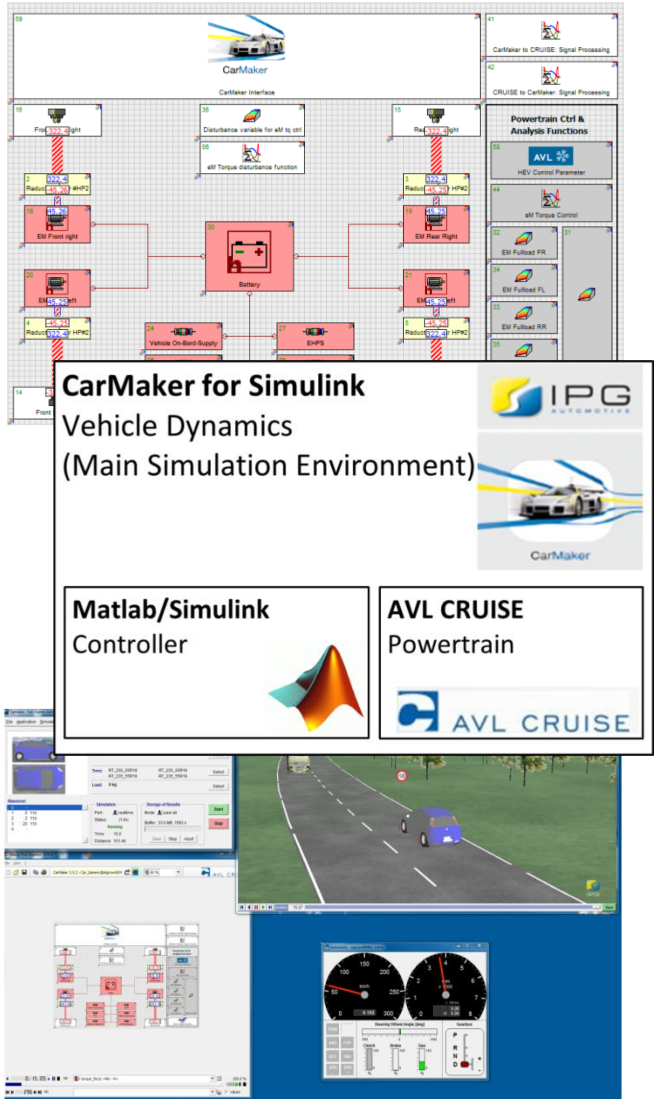
Simulation Toolchain:

- ❑ 1D Powertrain Model
- ❑ Vehicle Dynamics – 3D Road & Driver
- ❑ Control System & Simulation Integration

Supporting Simulation Tools:

- ❑ DoE – Optimization
- ❑ Road Data Handling
- ❑ Navigation Data
- ❑ E/E Architecture representation

CONCEPT SAFETY SIMULATION
CO-SIMULATION TOOLCHAIN FOR LIGHT VEHICLES



Co-Simulation with AVL CRUISE, IPG CarMaker & Matlab Simulink

- CRUISE Powertrain
  - Powertrain model, conventional & electrified
  - Energy Management System
  - Energy Flow Diagrams
- CarMaker Vehicle Dynamics
  - 3D vehicle dynamics
  - 3D track model
  - Traffic scenario
  - Ability to design complex driving manoeuvres in traffic scenarios
  - Interaction with traffic signs and other vehicles
  - Direct access to internal Cruise Data through CarMaker
- Matlab Simulink
  - Main simulation environment
  - Controller development
  - Post-processing environment

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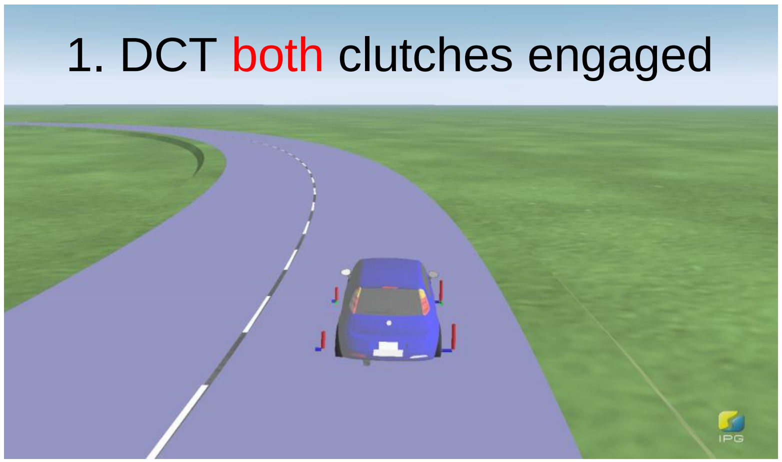
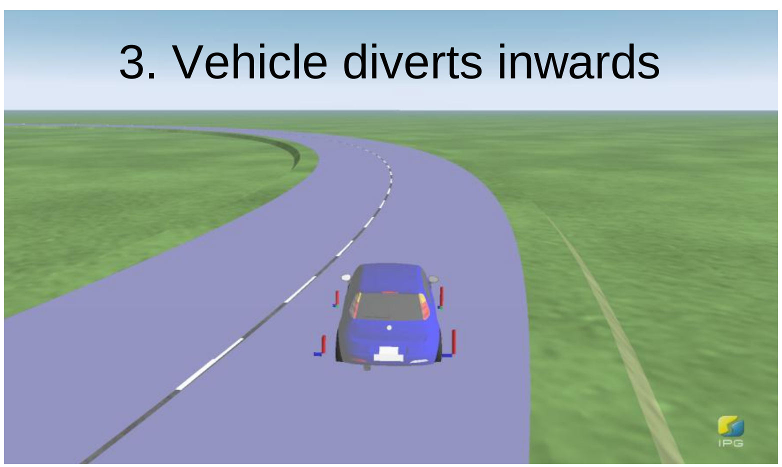
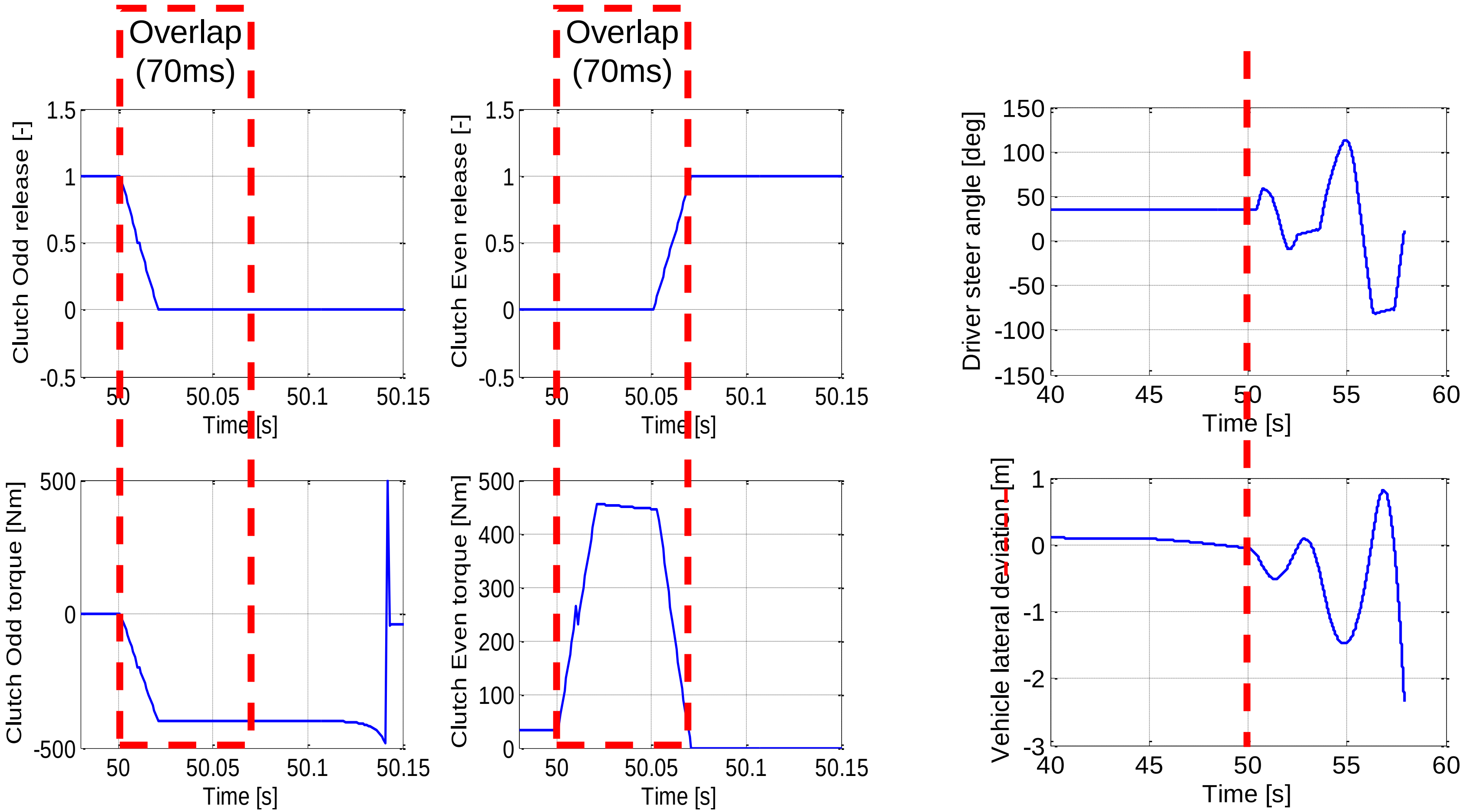
DCT – SIMULTANEOUS CLUTCH CLOSURE ON WET ROAD PASSENGER CAR MOTION SNAPSHOTS

- Vehicle runs at speed of 70 km/h in a circle with radius of 100m
- Wet road surface with friction μ=0.4



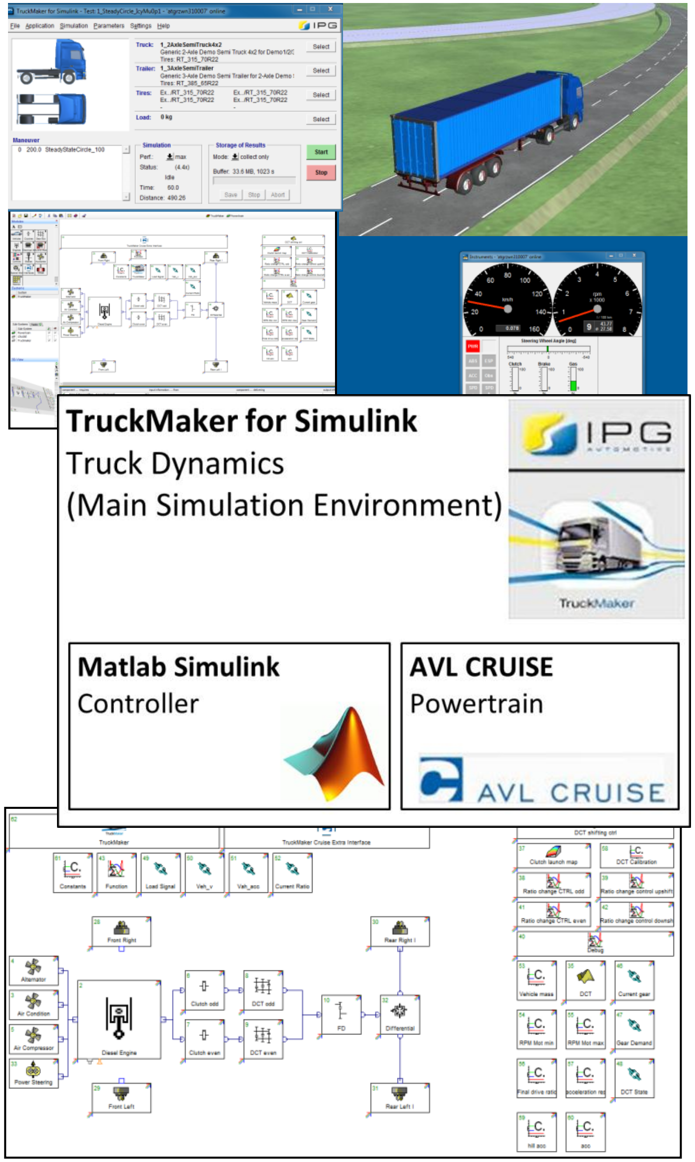


DCT – SIMULTANEOUS CLUTCH CLOSURE ON WET ROAD CRUISE POWERTRAIN CLUTCH SIGNALS



- Double clutch engagement of 70 ms overlap causes vehicle to laterally divert more than 2 m, and therefore could run into the path of an oncoming vehicle, or a road side obstacle → ISO26262 Hazard
- Human driver model tries to correct with large steering effort, without success

CO-SIMULATION TOOLCHAIN FOR HEAVY DUTY VEHICLES



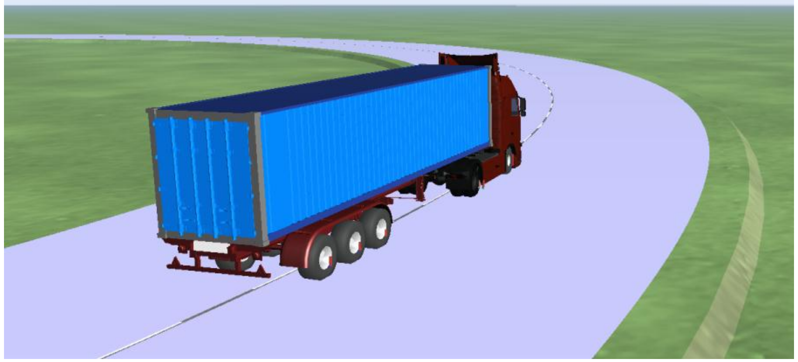
Co-Simulation with AVL Cruise, TruckMaker & Matlab

- **Cruise Powertrain**
  - Powertrain model with DCT
  - DCT controller embedded in Cruise as Matlab DLL
  - Energy Flow Diagrams
- **TruckMaker for HD Vehicle Dynamics**
  - 3D truck dynamics
  - 3D track model
  - Traffic scenario
  - Ability to design complex driving manoeuvres in traffic scenarios
  - Interaction with traffic signs and other vehicles
  - Direct access to internal Cruise Data through TruckMaker
- **Matlab Simulink**
  - Controller development
  - Post-processing environment

DCT – SIMULTANEOUS CLUTCH CLOSURE ON ICY ROAD HEAVY DUTY TRUCK MOTION SNAPSHOTS

- Vehicle runs at speed of 32 km/h in a circle with radius of 100m
- Icy road surface with low friction μ=0.1

1. DCT both clutches engaged



2. Vehicle starts to divert

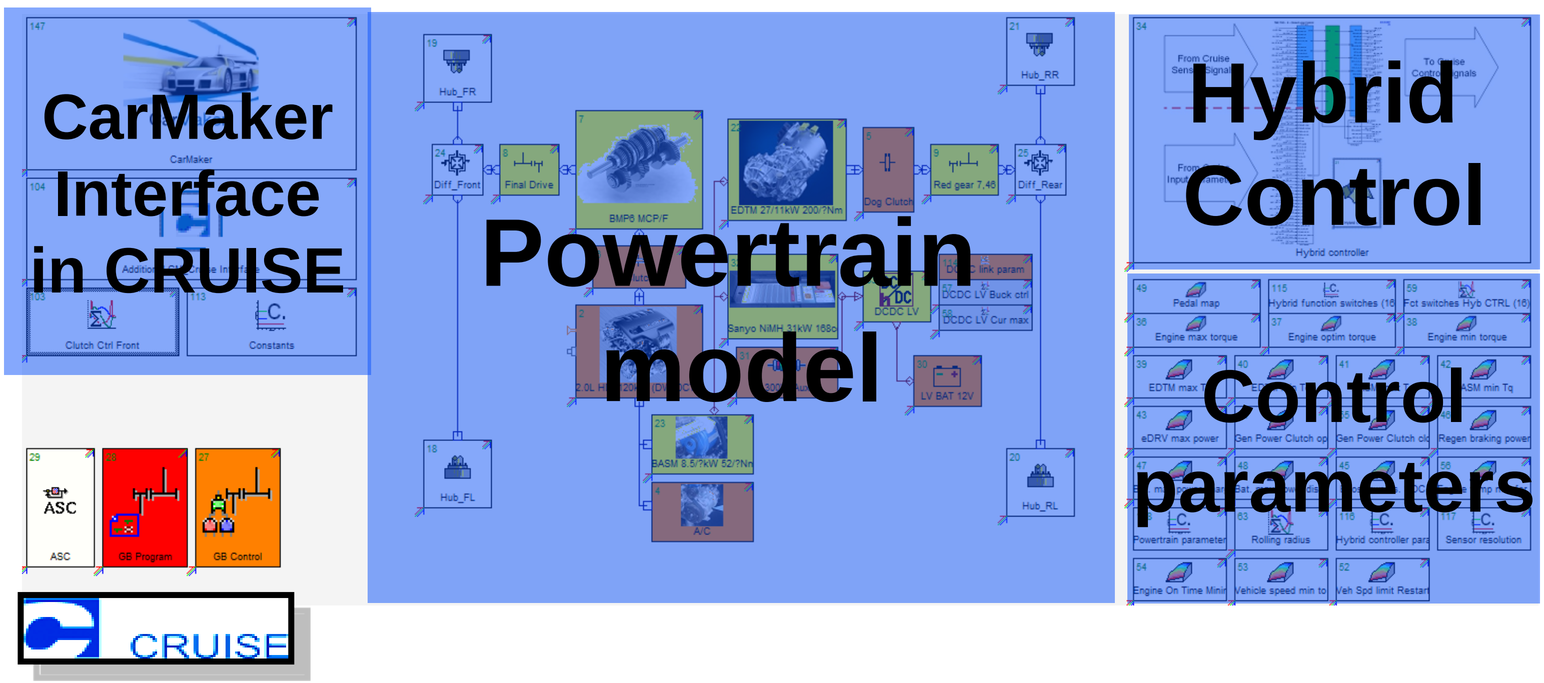
3. Vehicle diverts outwards

4. Vehicle runs out of track

SAFETY SIMULATION:
4WD DIESEL HYBRID ELECTRIC PASSENGER CAR

CRUISE model for CarMaker-CRUISE Co-Simulation:

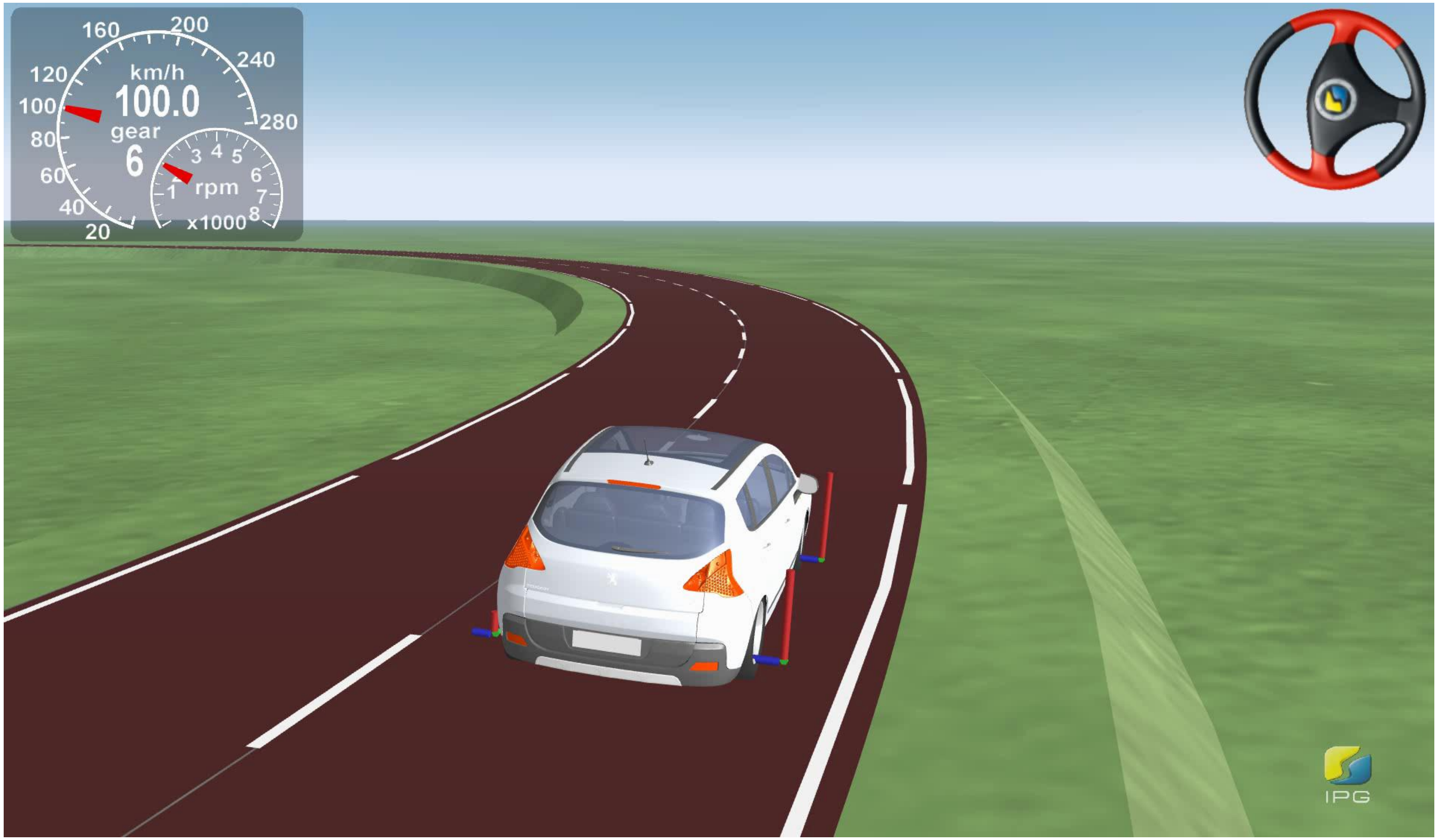
- Front axle driven by ICE, while rear axle driven by electric machine.
- CRUISE model with Hybrid Controller is validated against measurements.
- CRUISE model adapted for co-simulation: CarMaker, CRUIS, Matlab Simulink.



SAFETY SIMULATION:
4WD DIESEL HYBRID ELECTRIC PASSENGER CAR

Dry road, Unintended full positive EM torque, Gentle driver braking

- Two vehicles in video: **Grey** (normal, no failure), **White** (with failure)



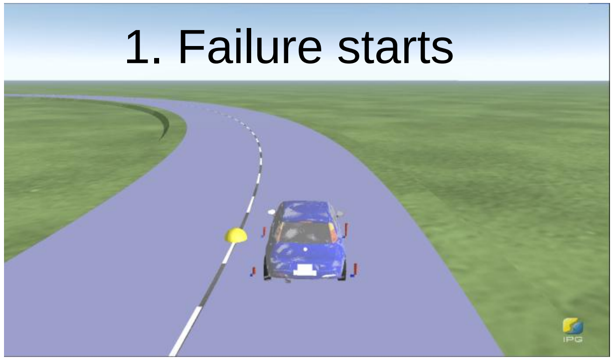
SAFETY SIMULATION:
4WD DIESEL HYBRID ELECTRIC PASSENGER CAR

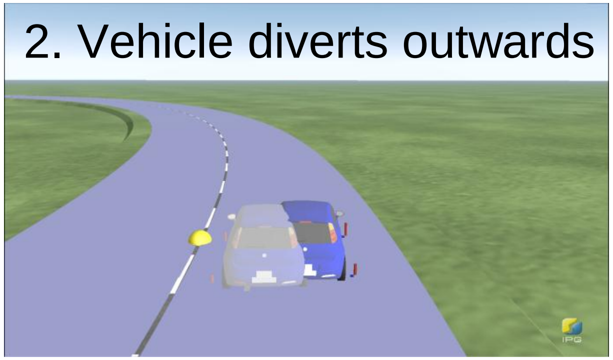
Wet road, Unintended full negative EM torque, Harsh driver braking

- Two vehicles in video: **Grey** (normal, no failure), **White** (with failure)

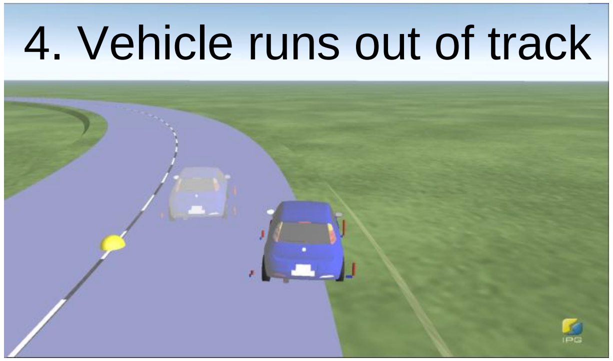
EV WITH FOUR E-MACHINES
E-MACHINE FAILURE & SAFETY
PASSENGER CAR MOTION SNAPSHOTS

- EV, 800 kg, 4 e-machines with 12.5 kW each
- Single e-machine (front left) fails with full positive torque while running in a circle, speed=70 km/h, radius=110 m, wet asphalt road μ=0.4
- Two vehicles in snapshots:
  - Grey colour car: Reference without EM failure
  - Blue colour car: With single EM failure

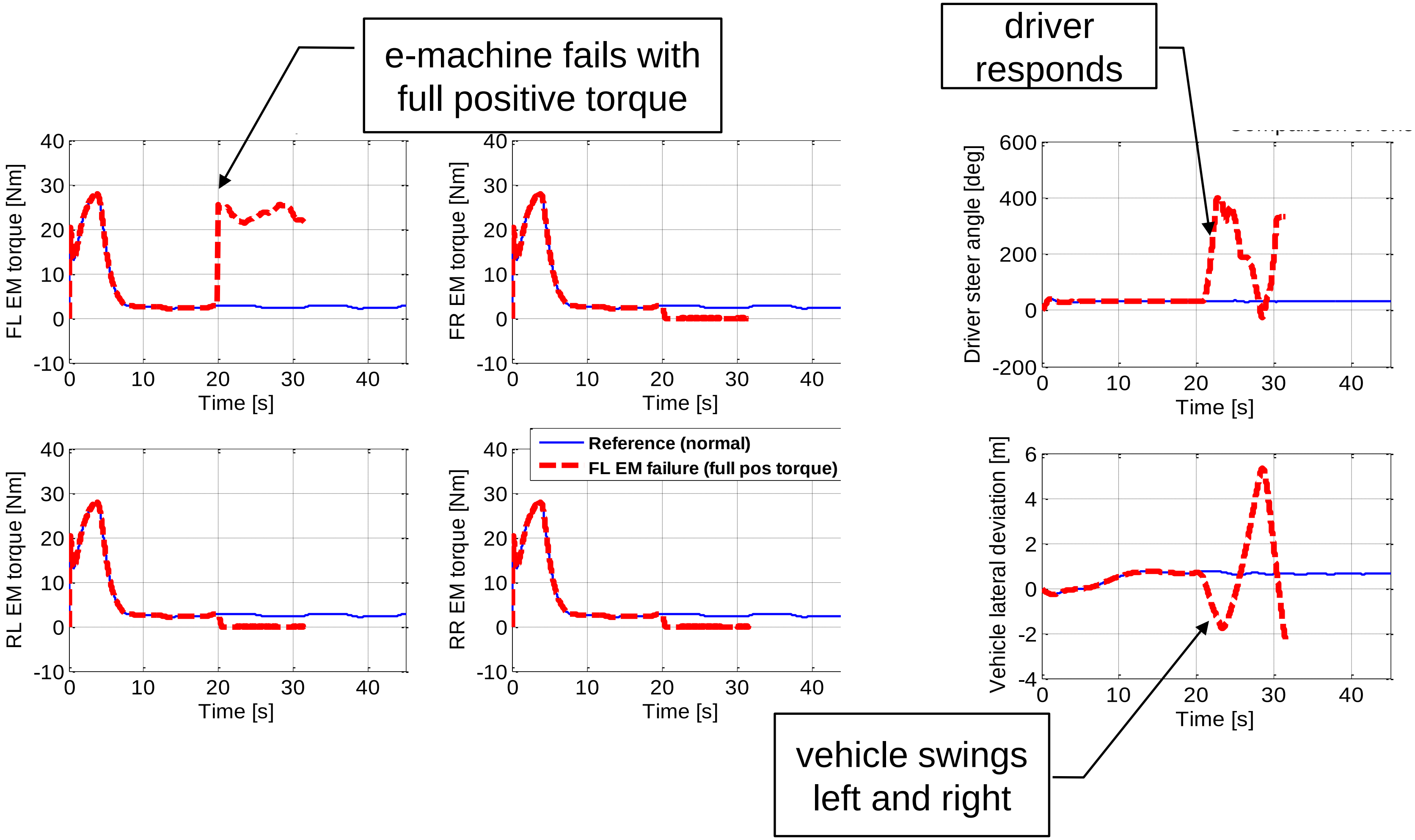

1. Failure starts


2. Vehicle diverts outwards


3. Vehicle diverts inwards


4. Vehicle runs out of track

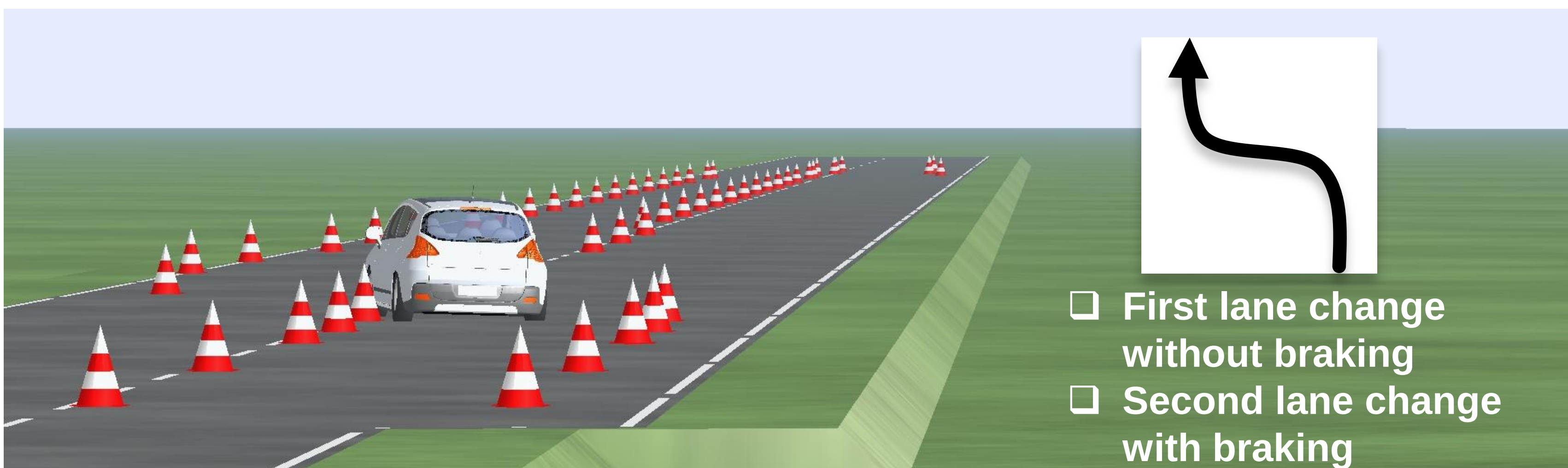
EV WITH MULTIPLE E-MACHINES
E-MACHINE FAILURE & SAFETY
PASSENGER CAR MOTION SIGNALS



EV WITH TWO E-MACHINES & VDC FUNCTIONS IN DOUBLE LANE CHANGE

OpEneR project: Co-Simulation Double Lane Change (DLC) Maneuver

- Double Lane Change (DLC): Standard maneuver for testing VDC, ABS & TCS.
- Main features of the ESP®*hev* system are virtually validated by the co-simulation tool-chain in a standard DLC maneuver.
- In OpEneR focus was virtual assessment interactions between electrical regeneration on both axles (efficiency) & Vehicle Dynamic Controllers (safety).
- **Easily extended to assess ASIL of system failure.**



CONTROLLABILITY OUT OF SAFETY SIMULATION: EV CONTROLLABILITY MATRIX

Driving Scenario	Road Friction	EM-Torque Failure	Controllability
Straight 100km/h	Dry (µ=0.8)	Full pos. Trq.	Controllable
		Zero Trq.	
		Full neg. Trq.	
		2 Rear EM Full neg. Trq.	
	Wet (µ=0.4)	Full pos. Trq.	
		Zero Trq.	
		Full neg. Trq.	
		2 Rear EM Full neg. Trq.	
Circling R=110m 100km/h	Dry (µ=0.8)	Full pos. Trq.	Uncontrollable
		Zero Trq.	Controllable
		Full neg. Trq.	Uncontrollable
		2 Rear EM Full neg. Trq.	
Circling R=110m, 70km/h	Wet (µ=0.4)	Full pos. Trq.	Uncontrollable
		Zero Trq.	Controllable
		Full neg. Trq.	Uncontrollable
		2 Rear EM Full neg. Trq.	
	Dry (µ=0.8)	Full pos. Trq.	Controllable
		Zero Trq.	
		Full neg. Trq.	
		2 Rear EM Full neg. Trq.	
Circling R=110m 70km/h; driver reaction time 2s	Dry (µ=0.8)	Full pos. Trq.	Uncontrollable
		Zero Trq.	Controllable
		Full neg. Trq.	Uncontrollable
		2 Rear EM Full neg. Trq.	Controllable

CONTROLLABILITY OUT OF SAFETY SIMULATION: EV CONTROLLABILITY MATRIX

Driving Scenario	Road Friction	EM-Torque Failure	Controllability
Straight 100km/h	Dry (μ=0.8)	Full pos. Trq.	Controllable
		Zero Trq.	
		Full neg. Trq.	
		2 Rear EM Full neg. Trq.	
	Wet (μ=0.4)	Full pos. Trq.	
		Zero Trq.	
		Full neg. Trq.	
		[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]
Circling R=110m, 70km/h	[illegible]	[illegible]	Uncontrollable
		2 Rear EM Full neg. Trq.	
	Dry (μ=0.8)	Full pos. Trq.	Controllable
		Zero Trq.	
		Full neg. Trq.	
		2 Rear EM Full neg. Trq.	
Circling R=110m 70km/h; driver reaction time 2s	Dry (μ=0.8)	Full pos. Trq.	Uncontrollable
		Zero Trq.	Controllable
		Full neg. Trq.	Uncontrollable
		2 Rear EM Full neg. Trq.	Controllable

Based on these results, the hazard analysis and risk assessment (HRA) can be evaluated

CONTENTS

SUMMARY & OUTLOOK

- Advanced 3D Vehicle / 1D Powertrain co-simulation toolchain proven for Conventional, Hybrid & Fully Electric Vehicles. For Cars, Heavy Duty Trucks & Buses.
- Virtual Functional Safety Analysis of vehicles in early development phase.
- Simulation supports improved Hazard Analysis & Risk Assessment by cross-functional expert system engineering team.
- Same co-simulation techniques may be used to develop & validate fault mitigation strategies e.g. failure detection functions, improved HW including sensors & communication networks.

AVL

Thank you for your kind attention!

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