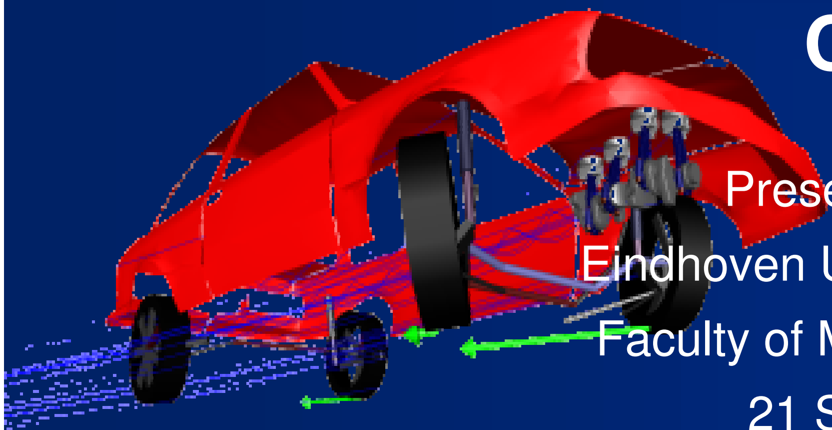
Ford Motor Company

VOLVO · mazda · LINCOLN · Ford · Mercury · JAGUAR · ASTON MARTIN · LAND ROVER

Physical Plant Modeling with Modelica - An Investigation of Improved Engine Cranking



Presentation given for:

Eindhoven University of Technology

Faculty of Mechanical Engineering

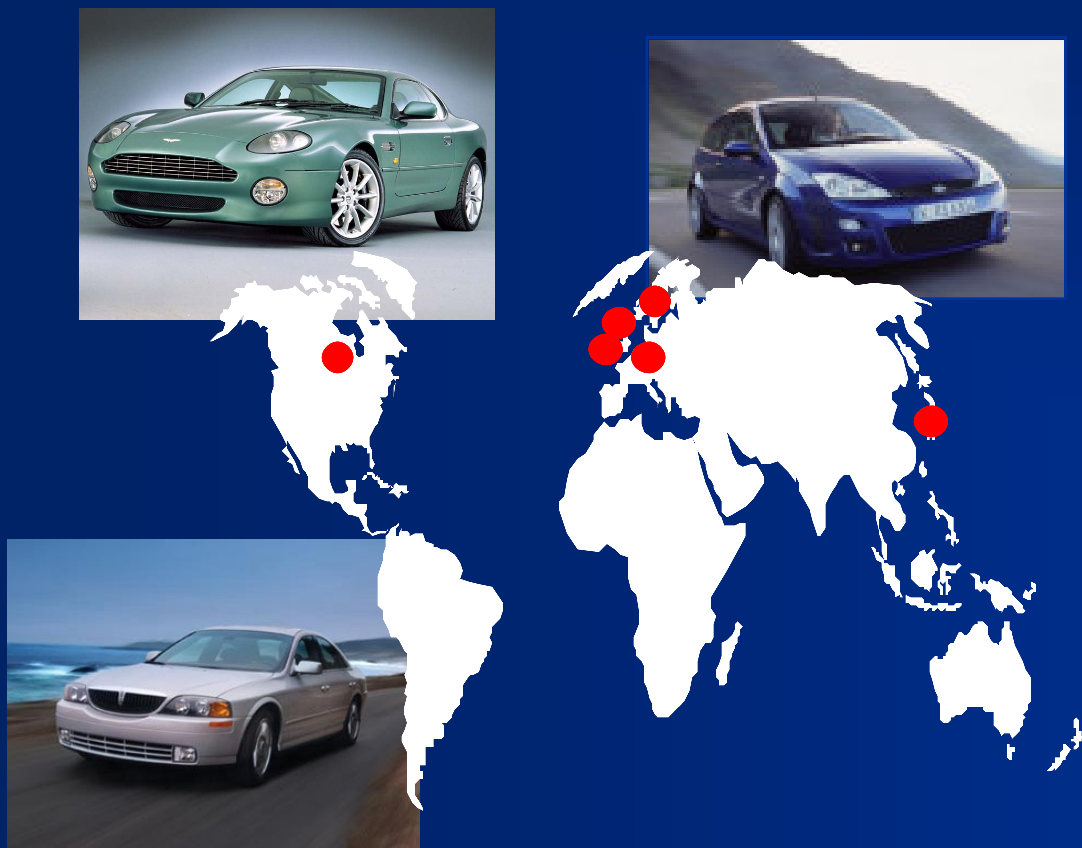
21 September, 2004

Erik Surewaard

✉ esurewa1@ford.com ☎ +49 (0) 241 9421120

Ford Forschungszentrum Aachen, Germany

Company Overview



Overall

- 111 plants in 25 countries
- Over 300.000 employees
- $164 billion revenues
- 6.7 million vehicle units

R&A (Research)

- United States
    - FRL - 900 employees
- Ford of Europe - 290 emp.
    - FFA -160 employees

● R&A location

Erik Surewaard
esurewa1@ford.com

Ford Forschungszentrum Aachen (FFA)

Research Topics

- Clean Diesel Engines
- Environmental Science
- Advanced Material Technologies
- Alternative Powertrains
  - Fuel Cells
  - Energy Management
  - Vehicle Electronics and Controls
- Vehicle Dynamics
- Telematics
- Vehicle Interior Technology

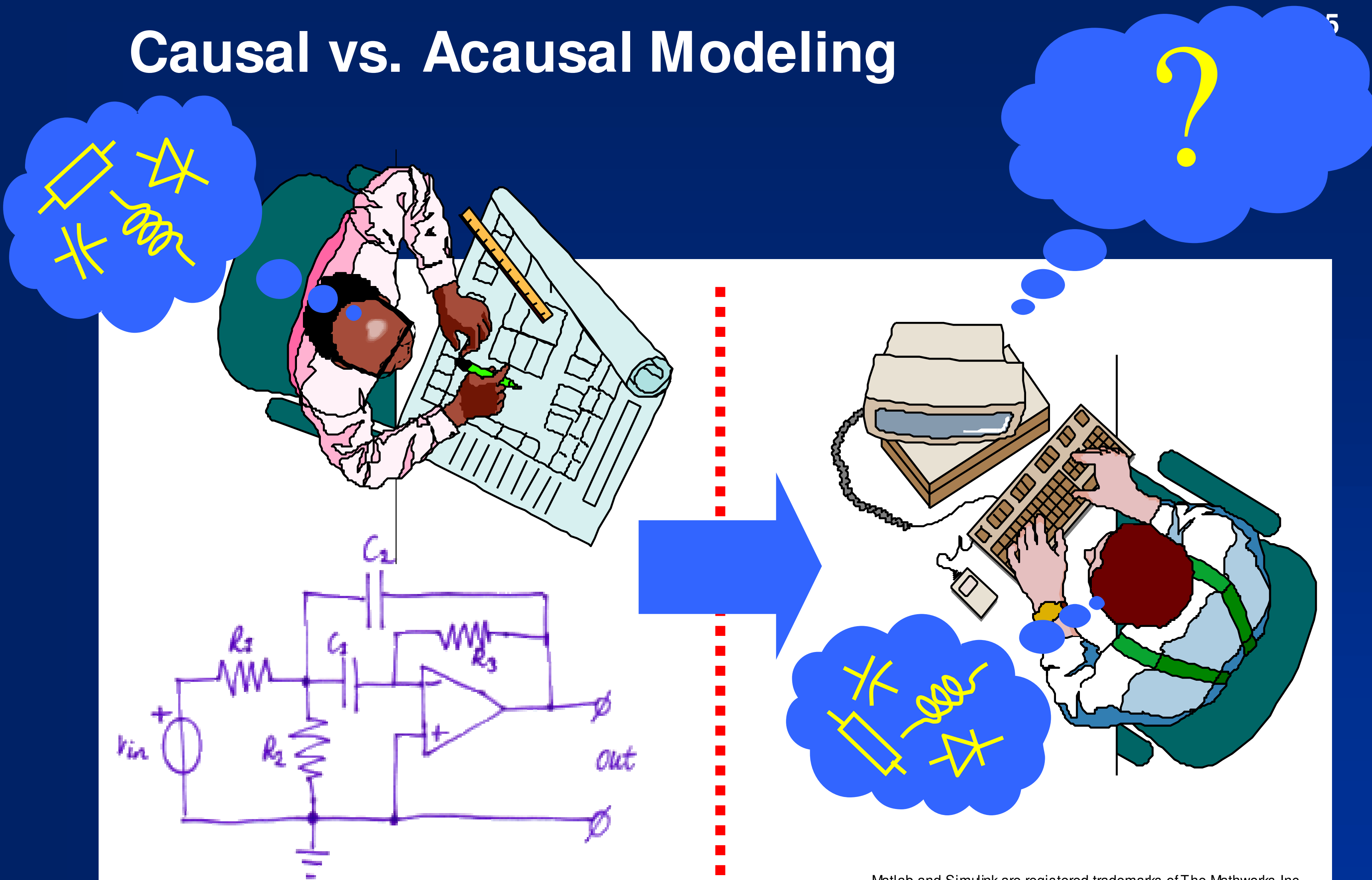
Dr.ir. Daniël Kok
Dr.ir. Engbert Spijker
Dr. Thomas Hochkirchen
Dipl.ing. Mark Eifert
Dipl.ing. Servé Ploumen
ir. Maurice Rienks
Dr. Eckhard Karden
Dr. Lutz Gaedt
ing. Max Leyten MSc.
Dipl.ing Holger Jung
ir. Erik Surewaard

Erik Surewaard
esurewa1@ford.com

Contents

Erik Surewaard
esurewa1@ford.com

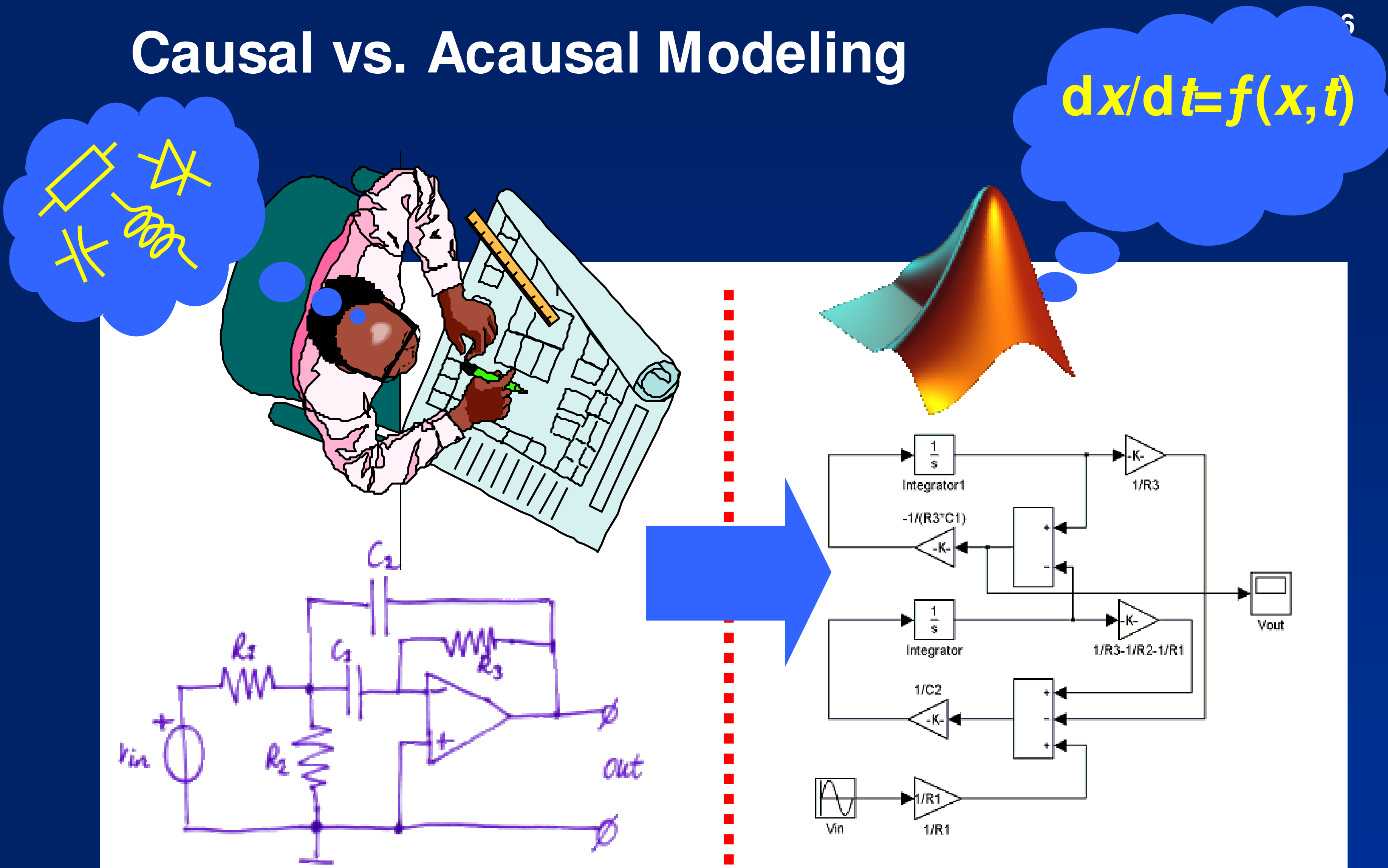
Causal vs. Acausal Modeling



Matlab and Simulink are registered trademarks of The Mathworks Inc.
The Modelica logo is property of the Modelica Association (www.modelica.org)

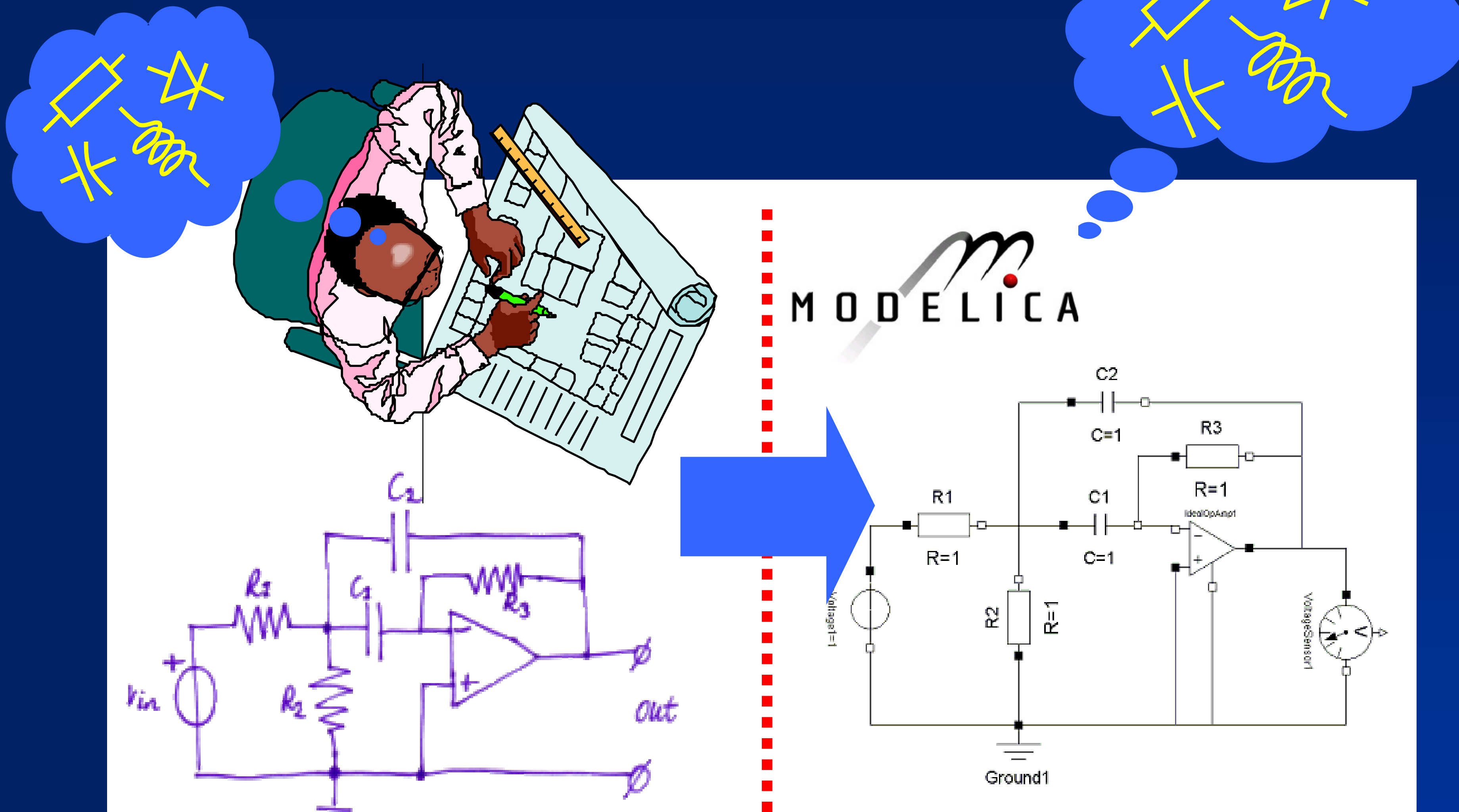
Erik Surewaard
esurewa1@ford.com

Causal vs. Acausal Modeling



Erik Surewaard
esurewa1@ford.com

Causal vs. Acausal Modeling

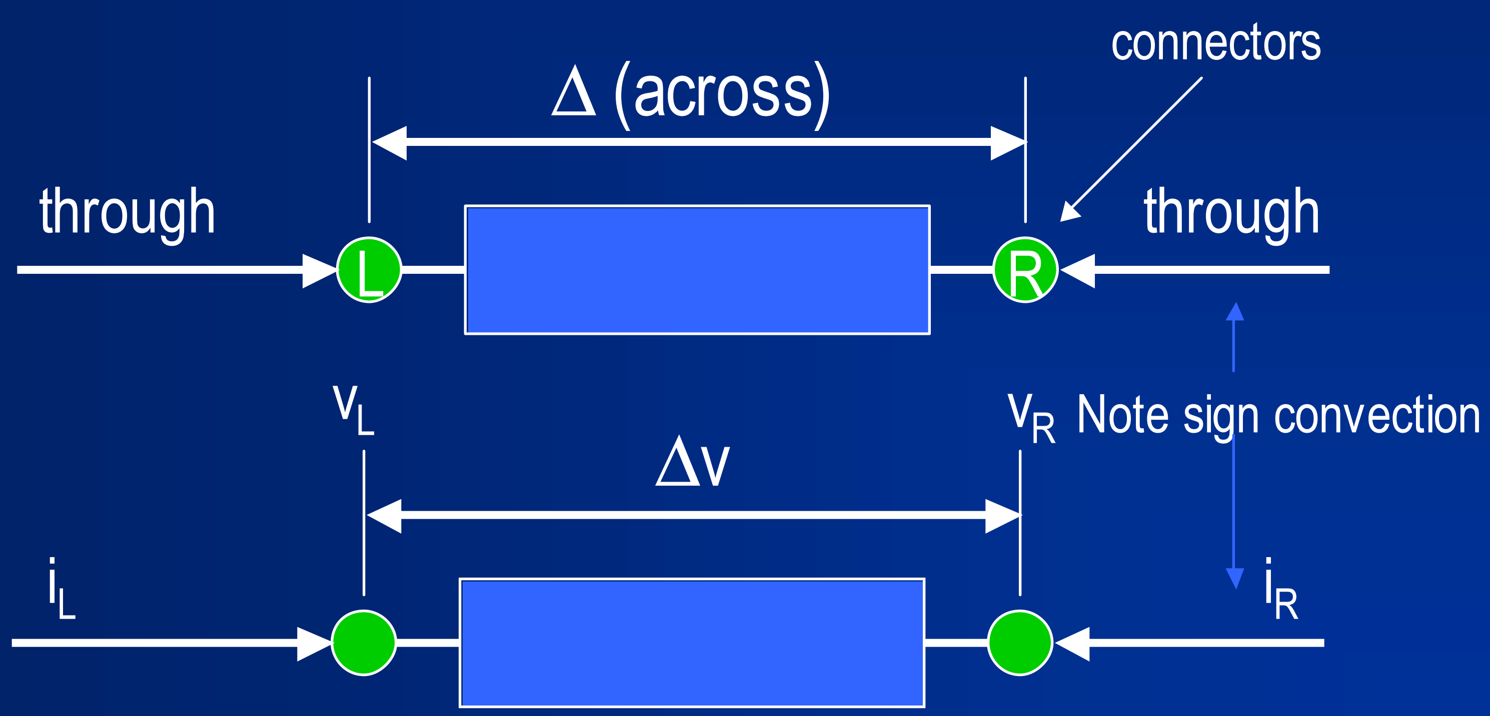


Erik Surewaard
esurewa1@ford.com

Causal vs. Acausal Modeling

Acausal component model

- Acausal since for instance voltage is not the response of current and vice versa
- Conservation laws: sum of all currents / torques / heat flow / etc… = zero in each connection point



Erik Surewaard
esurewa1@ford.com

Modelica - Fundamentals

MODELICA

www.modelica.org

- Modelica Association: a non-profit organization
- Multi-domain
  - Complex connector definitions
  - Expressive enough to handle domain-specific behavior
- Additional benefits
  - Non-proprietary
  - Causal AND acausal
  - Continuous and discrete
  - Object-oriented
  - Modeling by putting down text-book equations
  - Configuration management
  - Many free libraries already available (*e.g.* electrical, mechanical, multi-body, thermal, vehicle dynamics, SPICElib, thermofluid, fuzzycontrol, etc…)

Erik Surewaard
esurewa1@ford.com

Modelica - Fundamentals

- Connector definition

```
connector Pin "Electrical Pin"
  Voltage v "Voltage at the pin";
  flow Current i "Voltage into the pin";
end Pin;
```

- Component definition

```
model Resistor "Electrical Pin"
  Pin p, n "two pins";
  parameter Resistance R "Resistance";
equation
  p.i = (p.v-n.v)/R "Ohm's Law";
  n.i + p.i = 0;
end Pin;
```

Erik Sureward
esurewa1@ford.com

Modelica - Fundamentals

- Different physical domains

```
connector Flange "Mechanical connection"
  Position x "Location of the flange";
  flow Force F "Momentum entering at flange";
end Flange;
```

```
connector Port "Hydraulic port"
  Pressure P "Pressure at this port";
  flow MassFlowRate m_dot "Inward mass flow";
end Port;
```

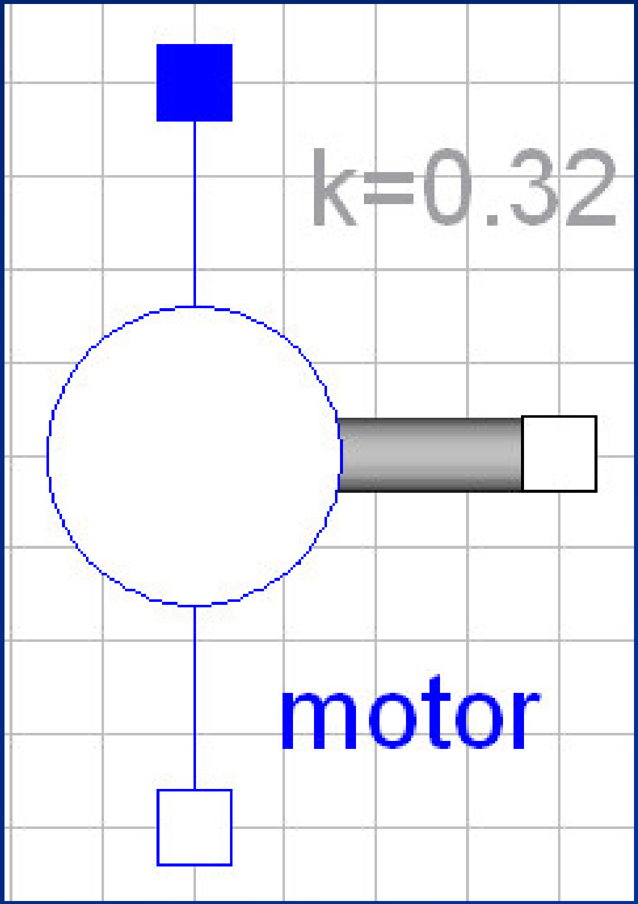
```
connector Thermal "Thermal node"
  Temperature T "Temperature at this node";
  flow HeatFlowRate q "Inward heat flow";
end Pin;
```


Erik Surewaard
esurewa1@ford.com

Modelica - Fundamentals

Mixing different domains

```
model EMF
  parameter Real k;
  Voltage v, i;
  AngularVelocity w;
  PositivePin p;
  NegativePin n;
  Flange_b flange_b;
equation
  v = p.v - n.v;
  p.i + n.i = 0;
  i = p.i;
  w = der(flange_b.phi);
  k*w = v;
  flange_b.tau = -k*i;
end EMF;
```

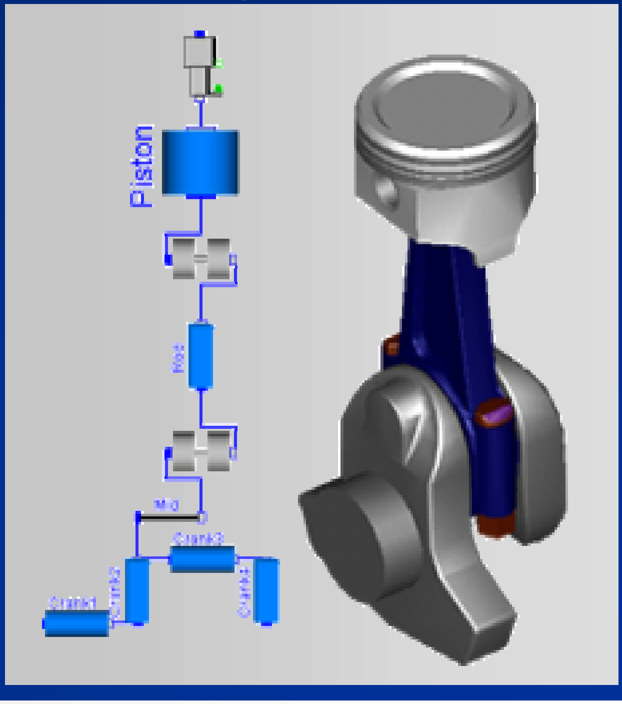


Erik Surewaard
esurewa1@ford.com

Modelica - Dymola

Dymola is a commercial tool of Dynasim AB

- Makes use of the Modelica language
- Hardware-in-the-loop simulations (dSpace, xPC, RT-LAB)
- Interface to Simulink (NO co-simulation but based on S-functions)
- C-export (import models in other simulation packages *e.g.* AnSoft Simplorer etc.)
- 3D tool (for multibody modeling)
- Pre- and postprocessing
- Programming and ‘drag and drop’-modeling

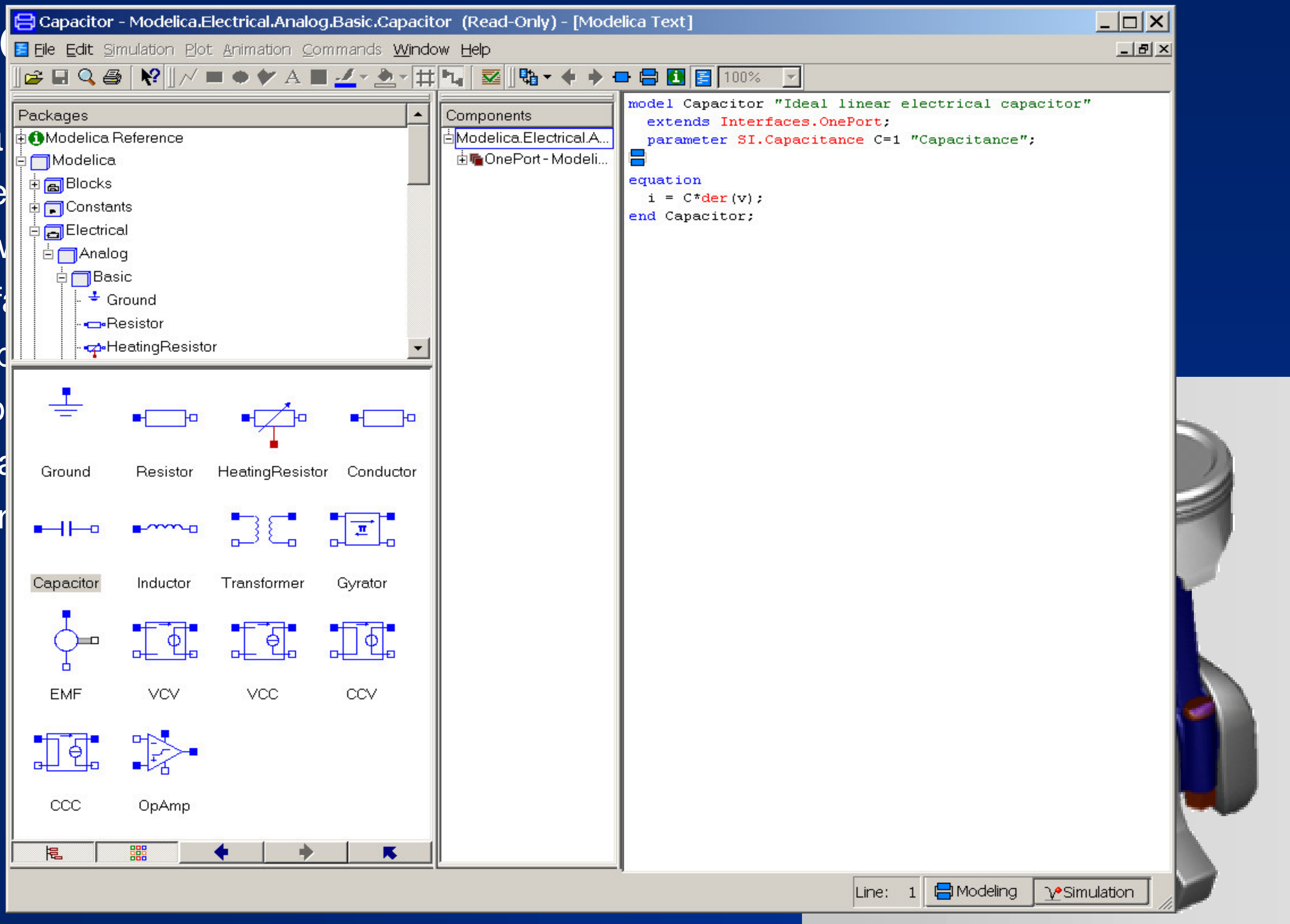


Erik Surewaard
esurewa1@ford.com

Mod

Dymola

- Make
- Hardv
- Interf
- C-exp
- 3D to
- Pre- a
- Progr

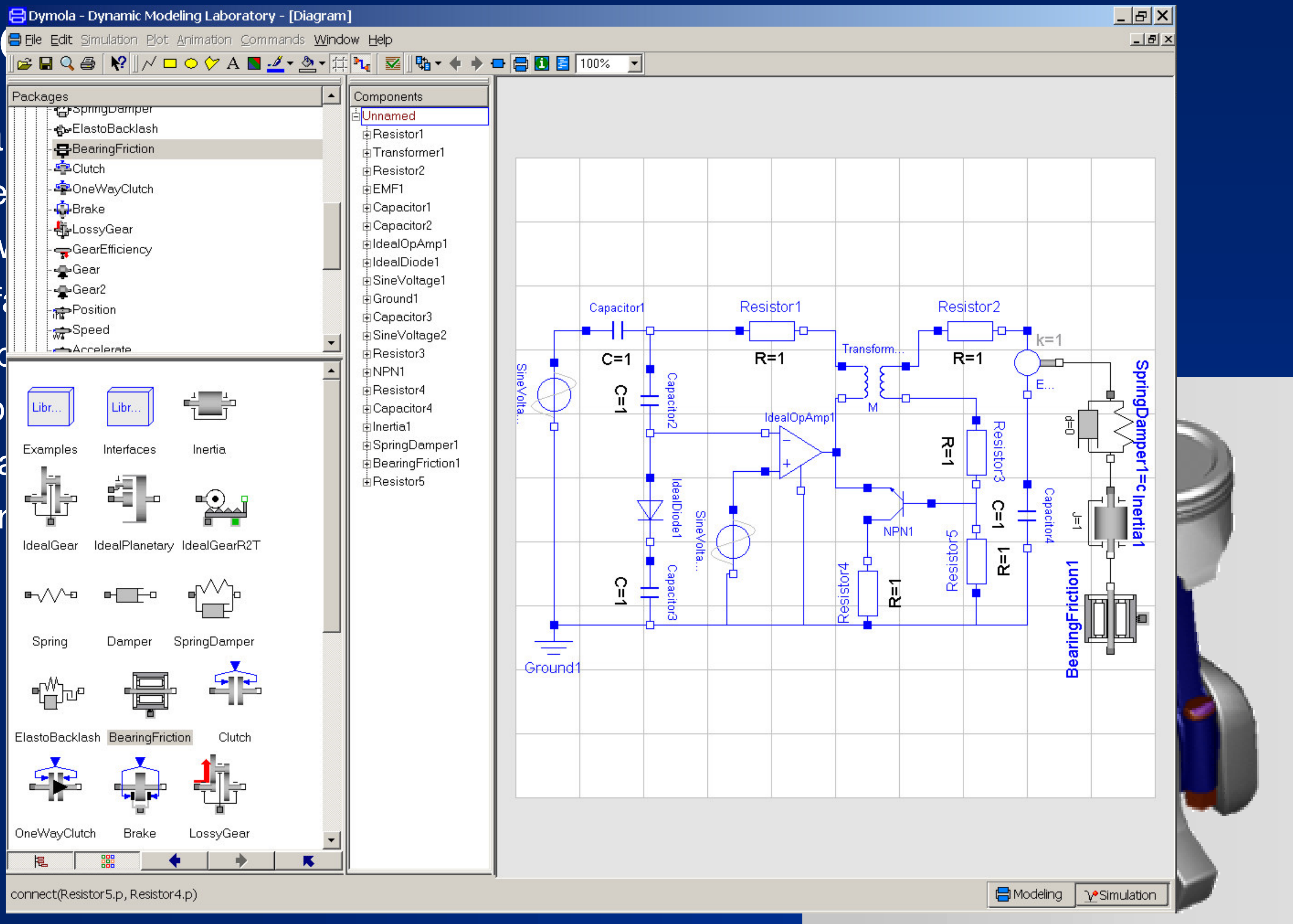


Erik Surewaard
esurewa1@ford.com

Mod

Dymola

- Make
- Hardv
- Interf
- C-exp
- 3D to
- Pre- a
- Progr



Erik Surewaard
esurewa1@ford.com

Contents

- Ford Forschungszentrum Aachen – Energy Management Group

Modeling

- Causal vs. Acausal Modeling
- Modelica
  - Fundamentals
  - Dymola

Example

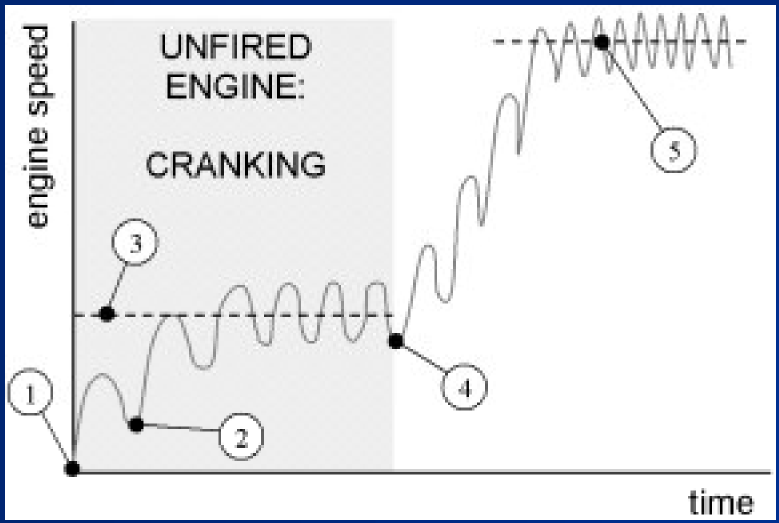
- Engine Cranking Modeling
  - “What happens during engine cranking?”
  - ISG and Dual Storage System
  - Component Modeling (Battery, Supercap, Engine, Engine Losses)
  - Cranking Simulation Model
  - Simulation Results

- Summary
- Acknowledgement and References

Erik Surewaard
esurewa1@ford.com

"What happens during engine cranking?"

- Cranking is defined by the motored state of the engine (no firing)
- Critical for the cranking device (startermotor) are:
  - (1) Engine break-away (static friction torque)
  - (2) Get the engine succesfully through the 1st /2nd compression
  - (3) Reach a motored speed from which the engine can start firing



- Lower temperature means higher friction (lower tolerances and higher viscosity) and therefore more difficulties with cranking the engine.

Erik Sureward
esurewa1@ford.com

ISG and Dual Storage System

Conventional situation

- Separate starter motor and alternator
- Starter motor geared to engine flywheel
- Alternator in FEAD (belt)

Proposal

- Alternator is enhanced (higher efficiency) and given motoring capability
- Integrated functionality of both starter motor and alternator (ISG)
- Connected in belt: belt-ISG

Erik Sureward
esurewa1@ford.com

ISG and Dual Storage System

lternator

he flywheel

er efficiency)

y

th starter

- Connected in belt: belt-ISG

!!! CAUTION !!!

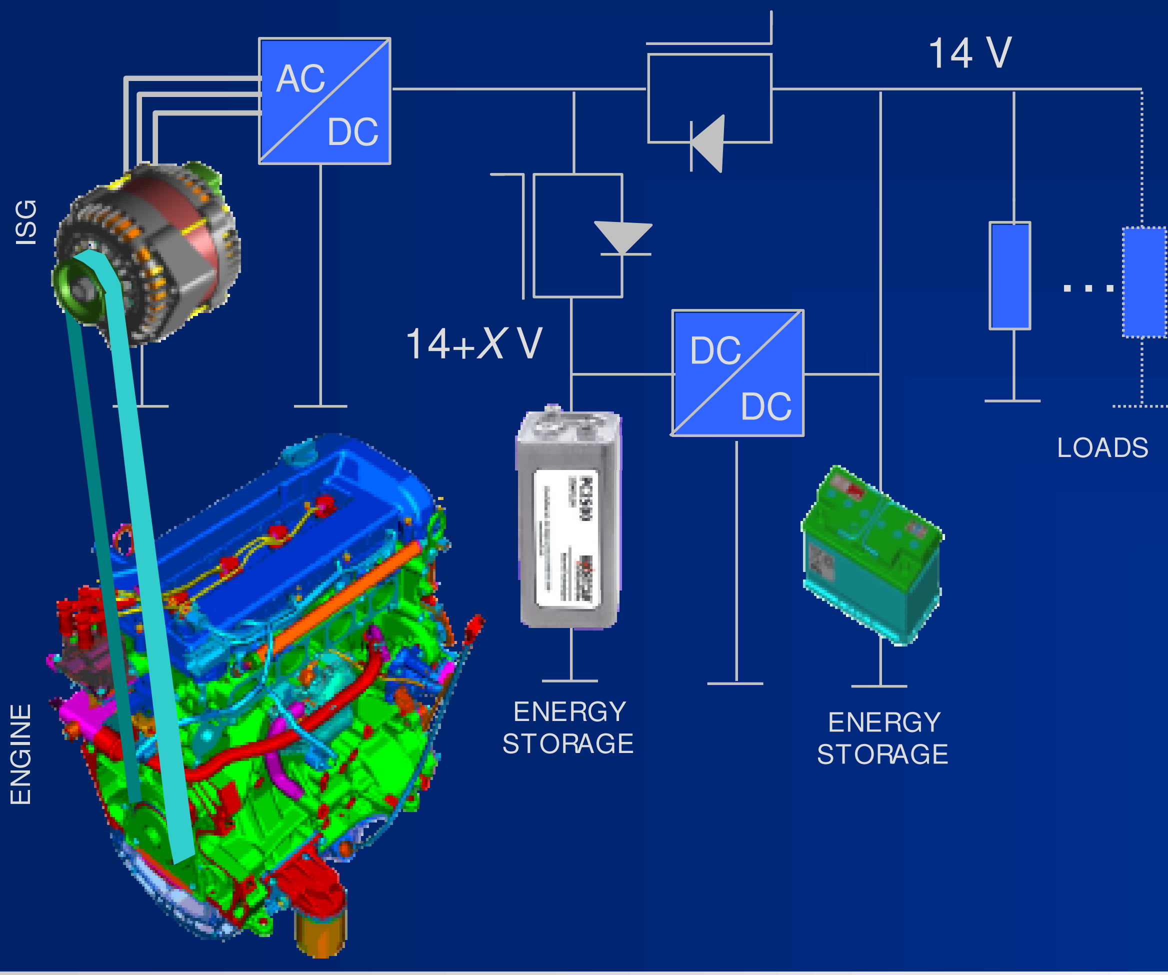
Due to the ratio difference…

1. A different device inertia when lumped on the crankshaft:
   startermotor approx. 0.39 $kg \cdot m^2$
   B-ISG approx. 0.0054 $kg \cdot m^2$
2. The B-ISG needs to deliver a much higher torque than the startermotor. This is especially difficult for Diesel engines (high compression ratio): Dual Storage System.

Erik Surewaard
esurewa1@ford.com

ISG and Dual Storage System

Operation principle

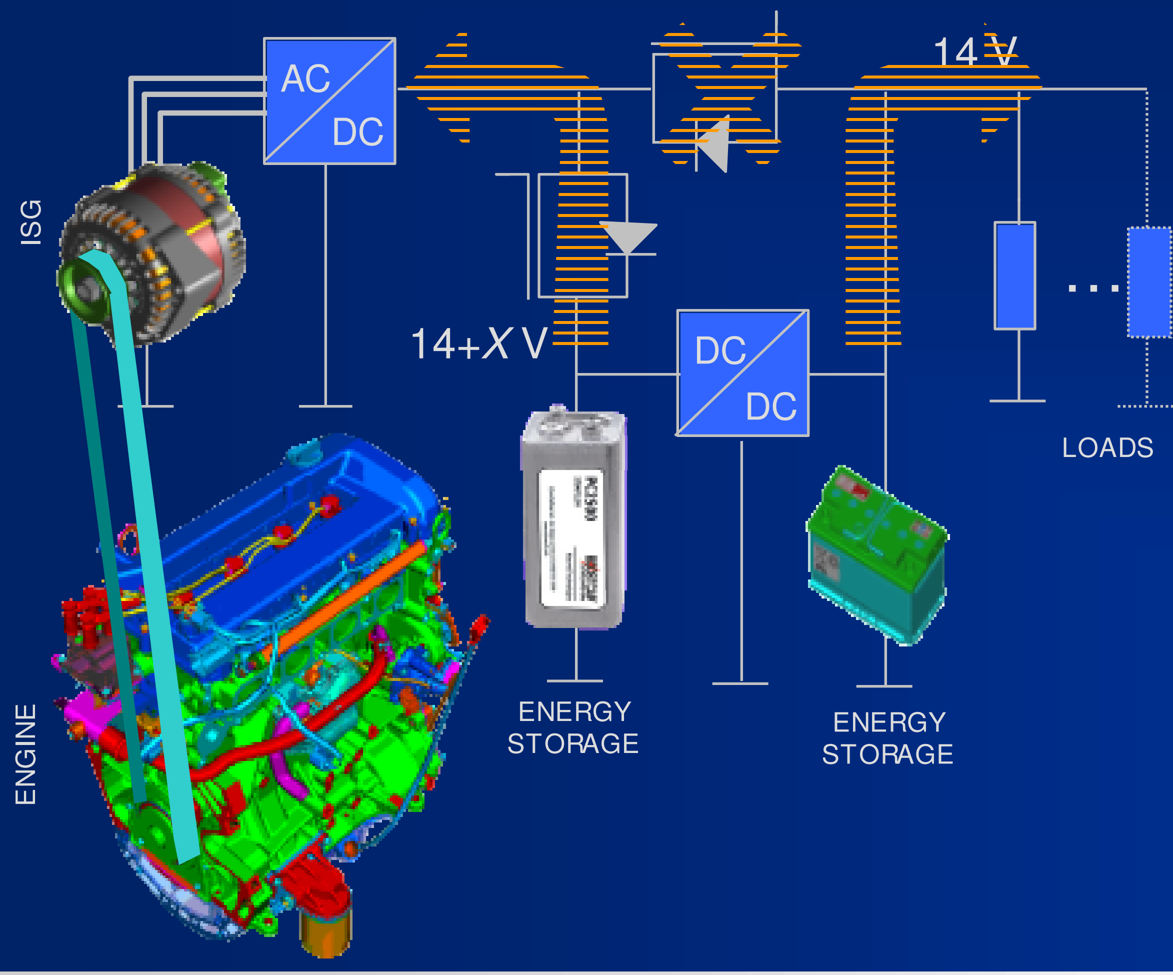


Operating modes:
- 14+X V Cranking
- 14+X V (Re-)generation
- 14 V generation

Erik Sureward
esurewa1@ford.com

ISG and Dual Storage System

Operation principle



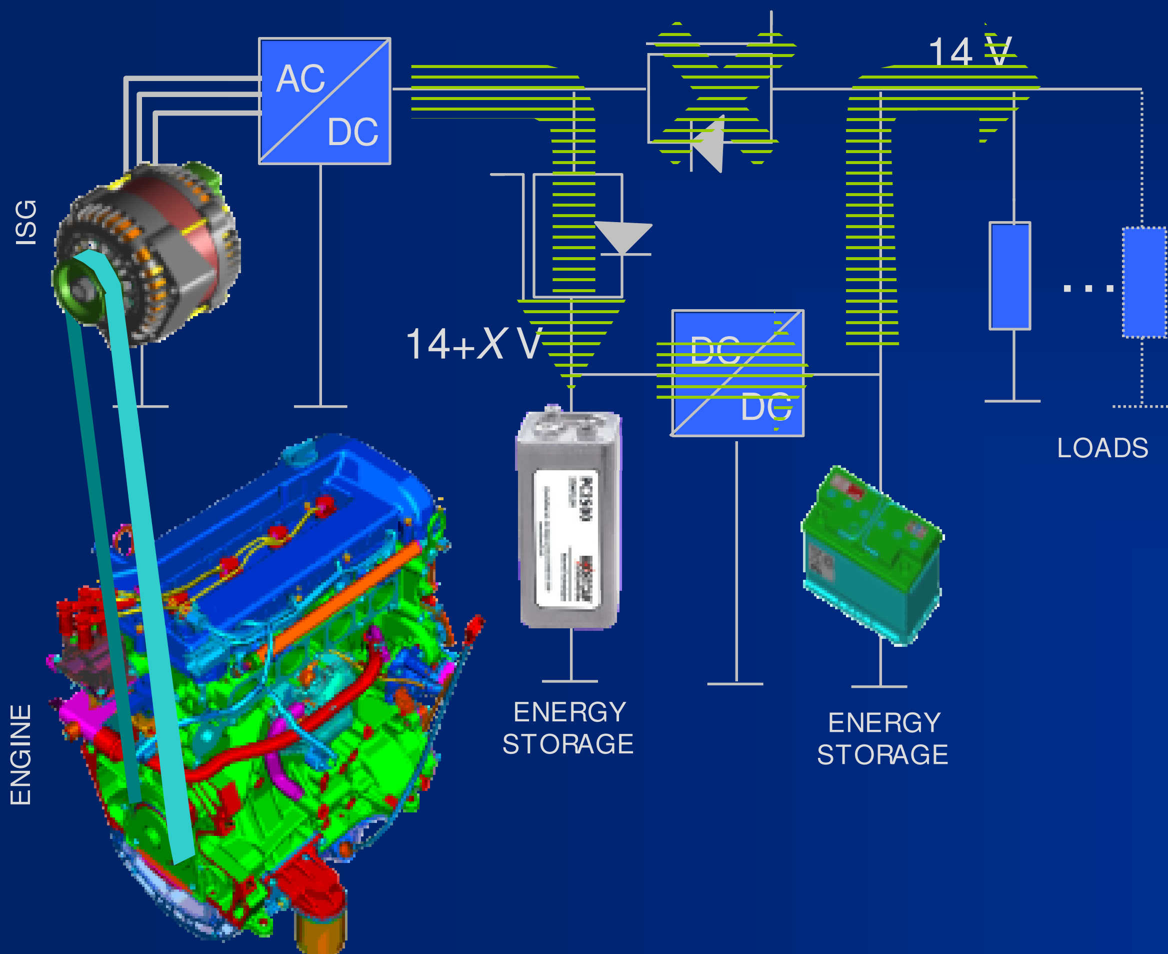
Operating modes:

- 14+X V Cranking
- 14+X V (Re-)generation
- 14 V generation

Erik Surewaard
esurewa1@ford.com

ISG and Dual Storage System

Operation principle



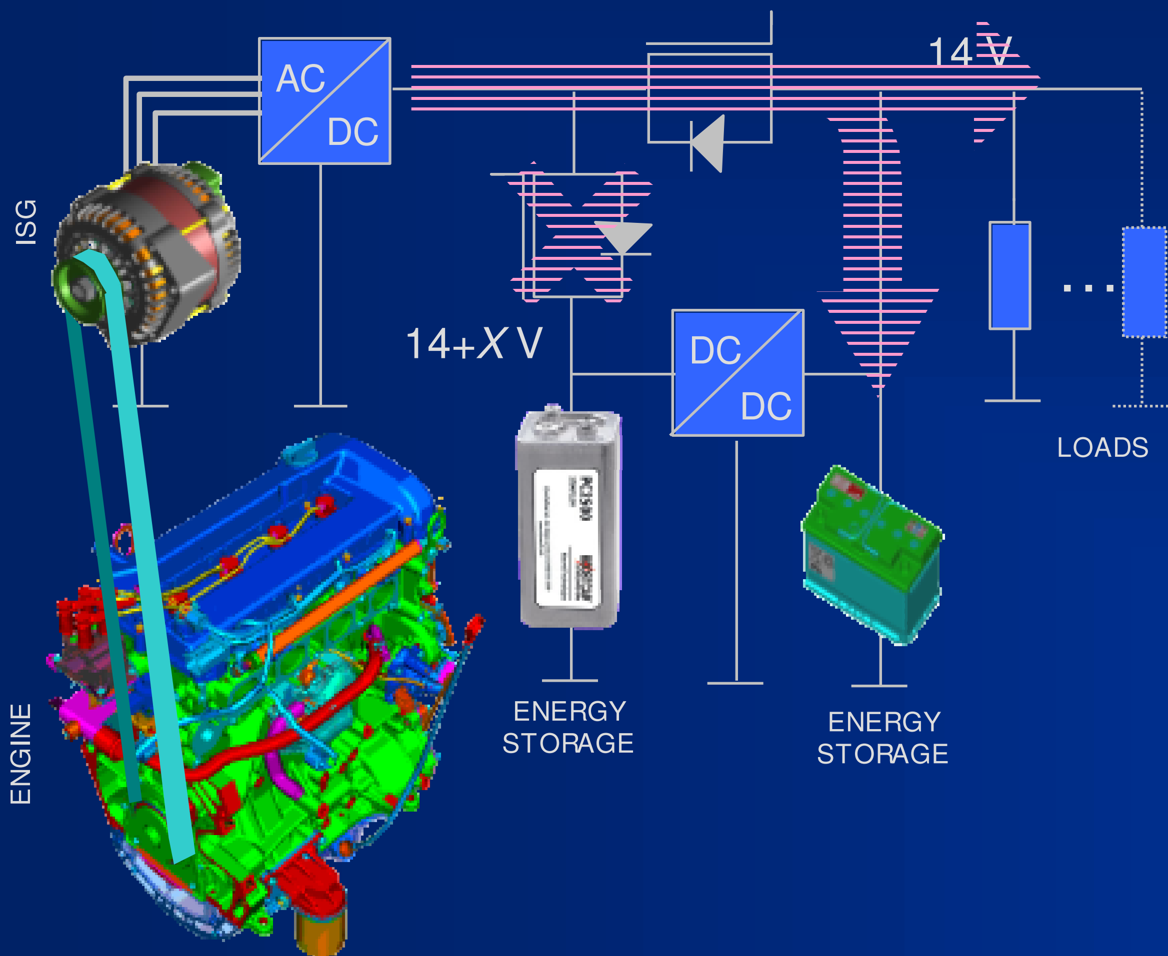
Operating modes:

- 14+X V Cranking
- 14+X V (Re-)generation
- 14 V generation

Erik Sureward
esurewa1@ford.com

ISG and Dual Storage System

Operation principle

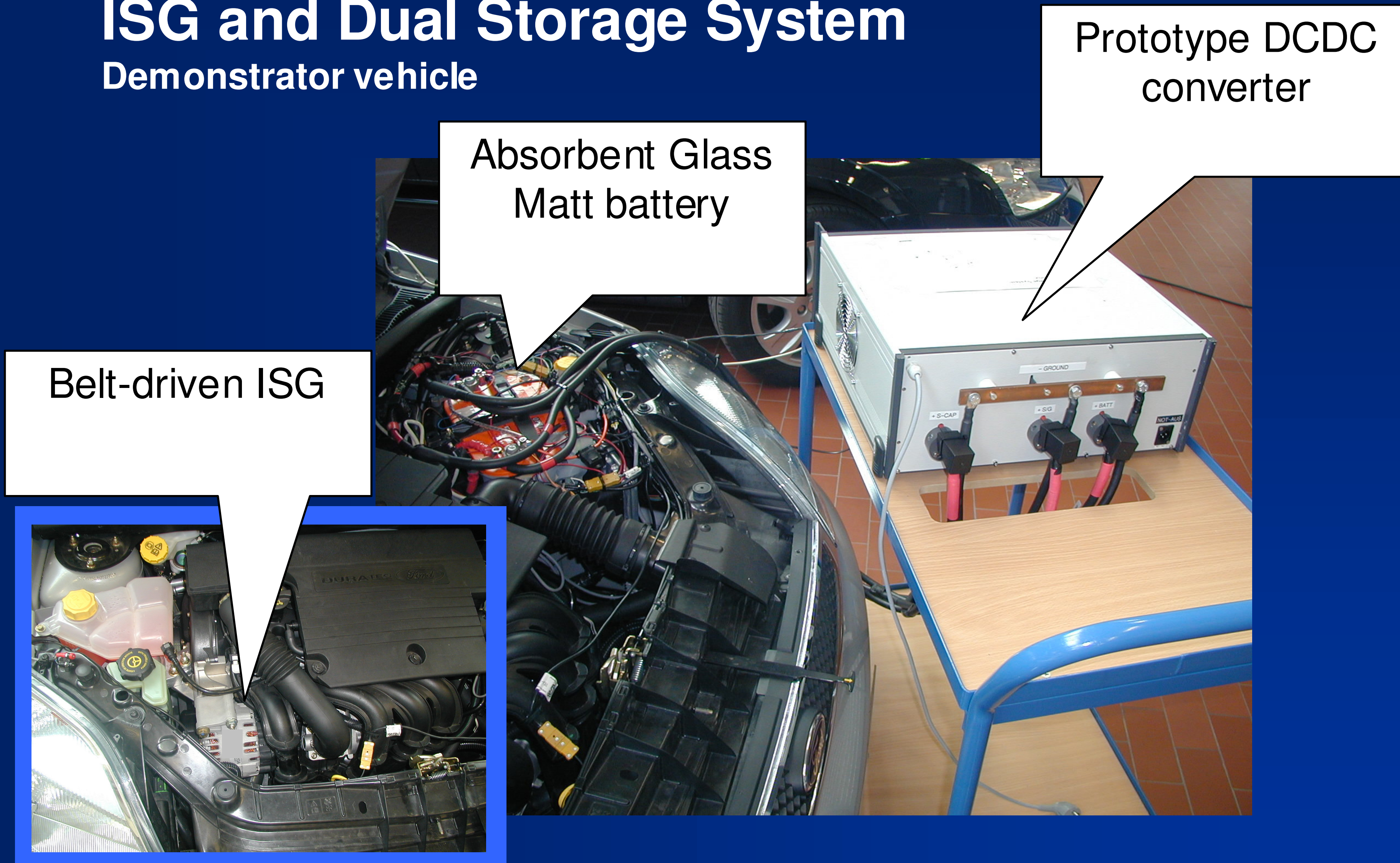


Operating modes:
- 14+X V Cranking
- 14+X V (Re-)generation
- 14 V generation

Erik Surewaard
esurewa1@ford.com

ISG and Dual Storage System

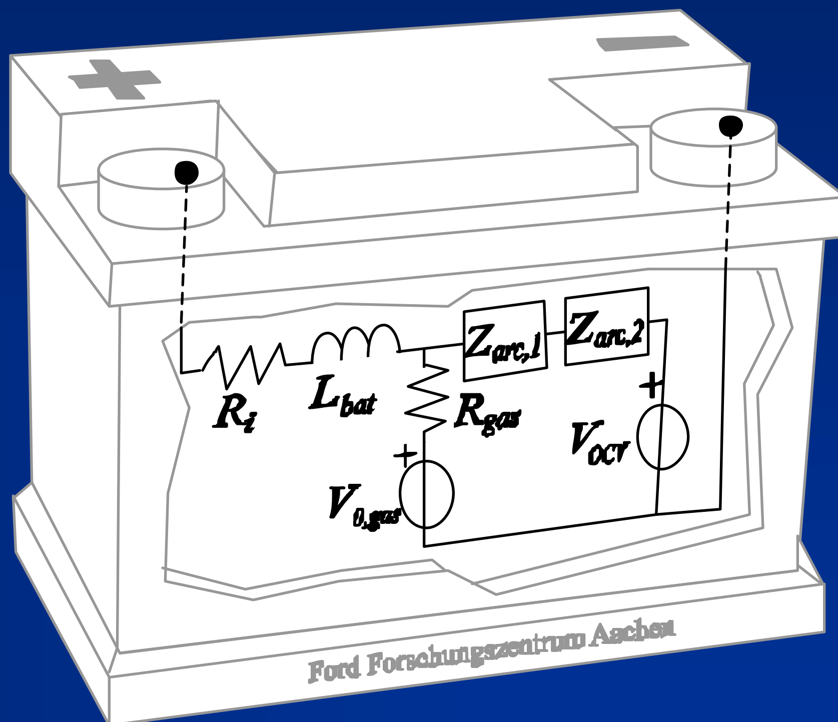
Demonstrator vehicle



Erik Surewaard
esurewa1@ford.com

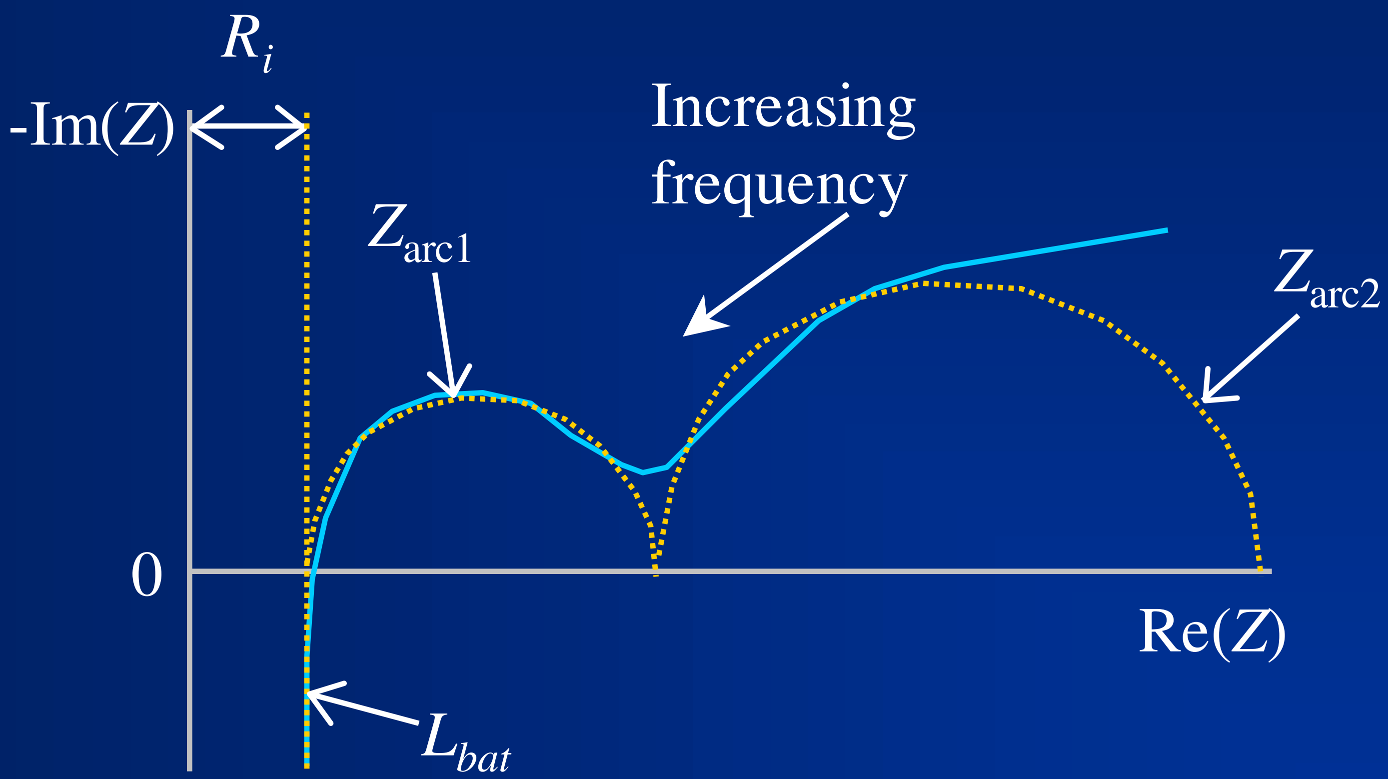
Component Modeling - Battery
Model background

- Theory and parameterization: Aachen University of Technology
- Based on impedance spectroscopy measurements
    - Battery is excitated with AC currents
    - Different operating points are taken: State of Charge (SOC) and temperature
    - Usable for different battery technologies: lead-acid flooded / AGM



Erik Surewaard
esurewa1@ford.com

Component Modeling - Battery
Model Background

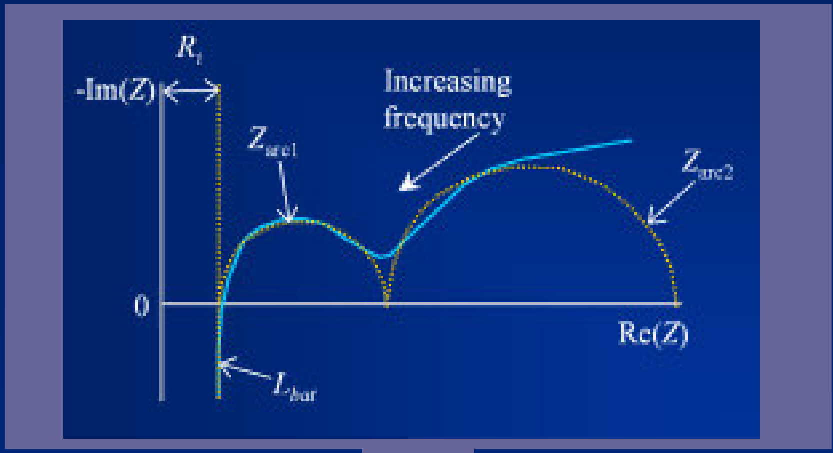


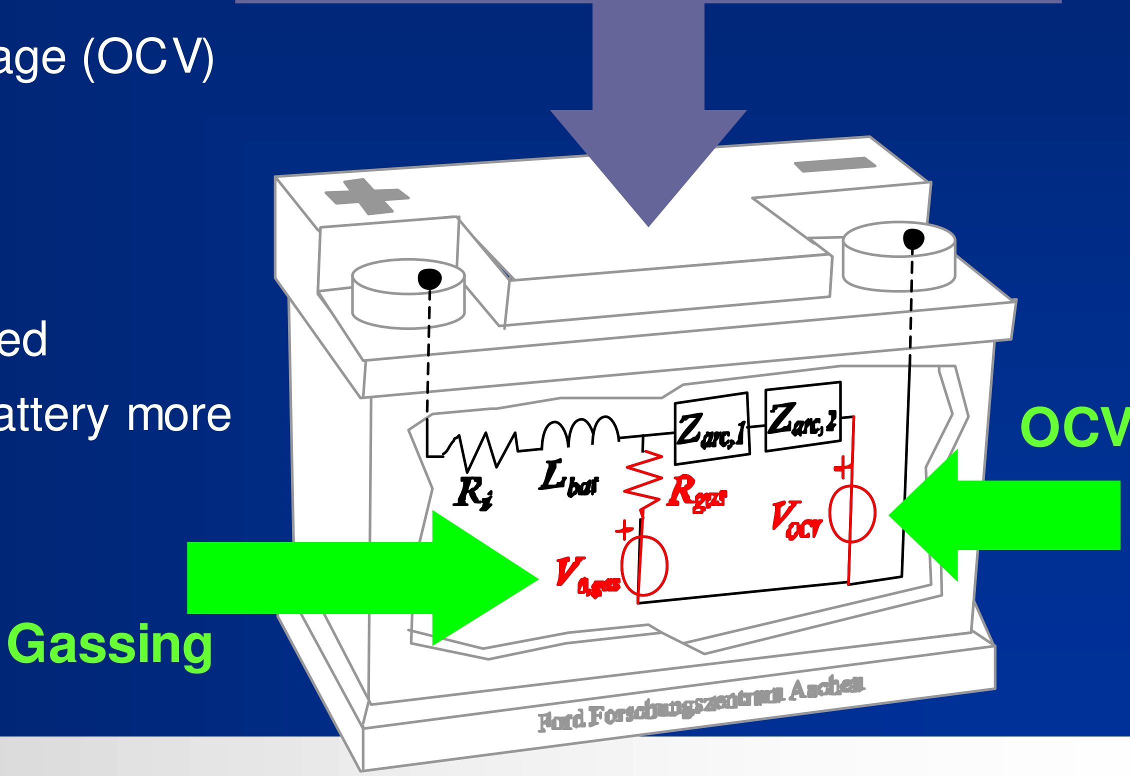
Erik Surewaard
esurewa1@ford.com

Component Modeling
Model implementation

- Impedance spectrum is approximated with electric circuit representation. Additional are:
  - Open Circuit Voltage (OCV)
  - Gassing reaction (overcharging)

- Inductance can be omitted
  - Cabling to/from battery more dominant

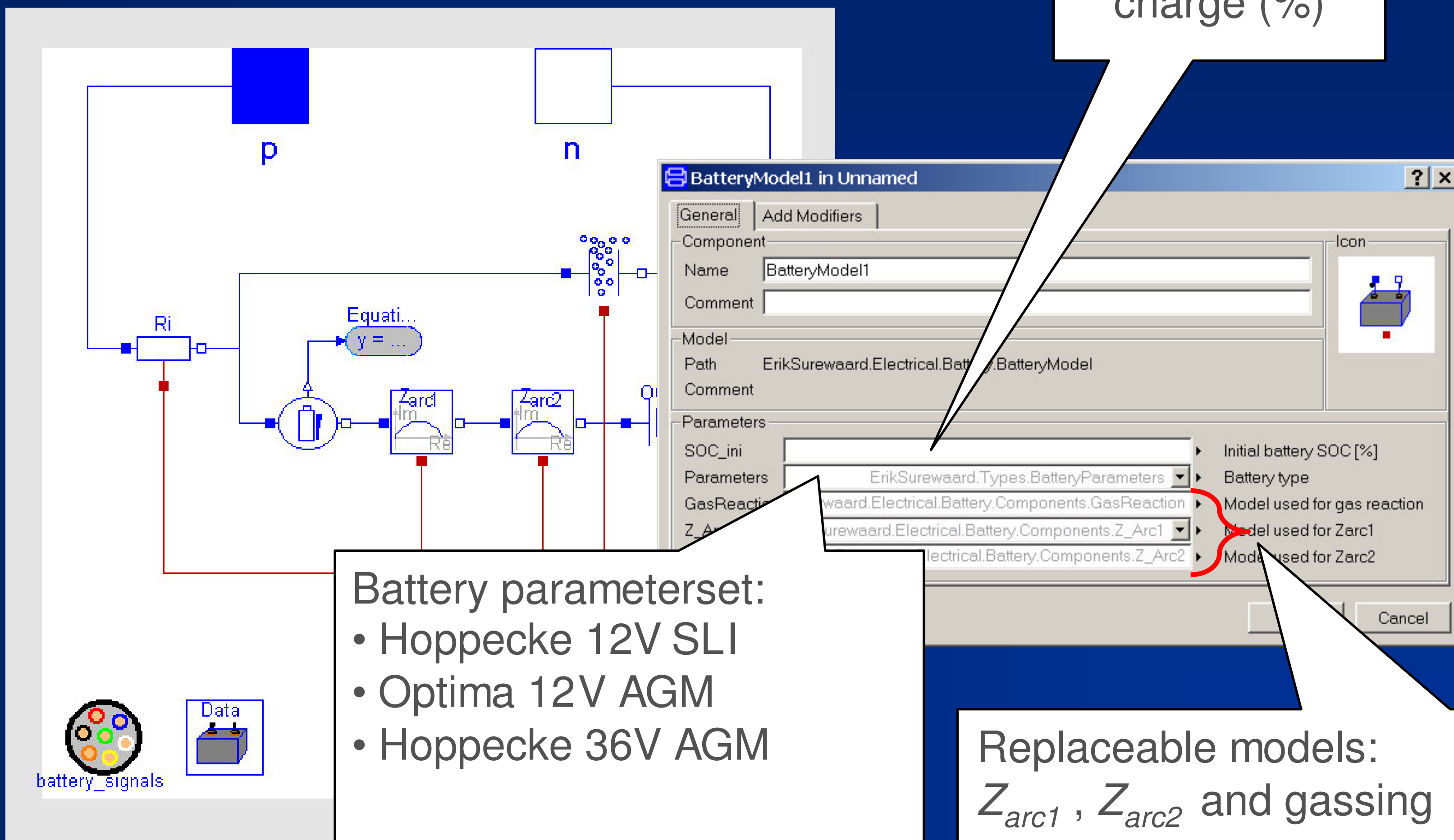




Erik Surewaard
esurewa1@ford.com

Component Modeling - Battery

Model Implementation



Initial state of charge (%)

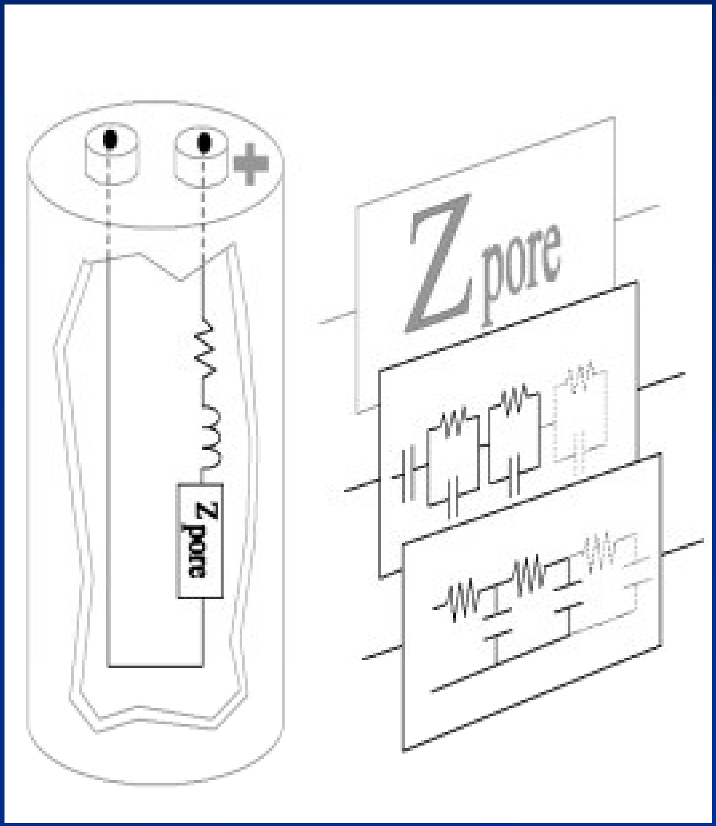
Battery parameterset:
- Hoppecke 12V SLI
- Optima 12V AGM
- Hoppecke 36V AGM

Replaceable models: Z_{arc1} , Z_{arc2} and gassing

Erik Surewaard
esurewa1@ford.com

Component Modeling - Supercapacitor
Model Background

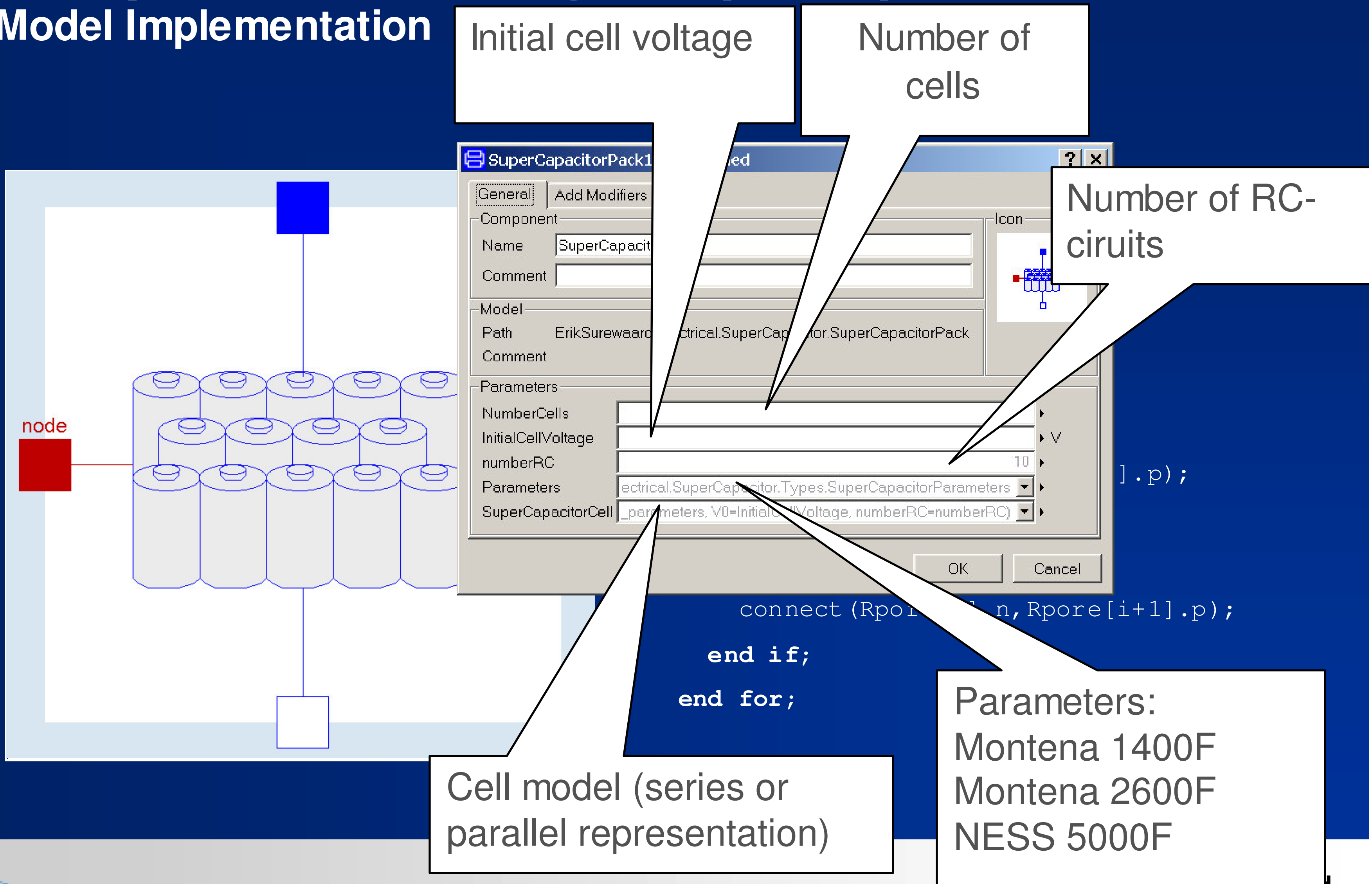
- Theory and parameterization: Aachen University of Technology
- Based on impedance spectroscopy measurements
    - Less complex as batteries
- Different implementation forms:
    - RC series / RC ladder
- Parameterized as function of
    - Temperature
    - Voltage



Erik Surewaard
esurewa1@ford.com

Component Modeling - Supercapacitor

Model Implementation



Erik Surewaard
esurewa1@ford.com

Component Modeling - Engine
Model Implementation

- Based on models developed by John Batteh, Michael Tiller, Charles Newman and Paul Bowles (all Ford Motor Company).
- Literature:
  Batteh, J., Tiller, M. and **Newman, C.,** "Simulation of Engine Systems in Modelica", pp. 139-148, 3rd Modelica Conference, 2003

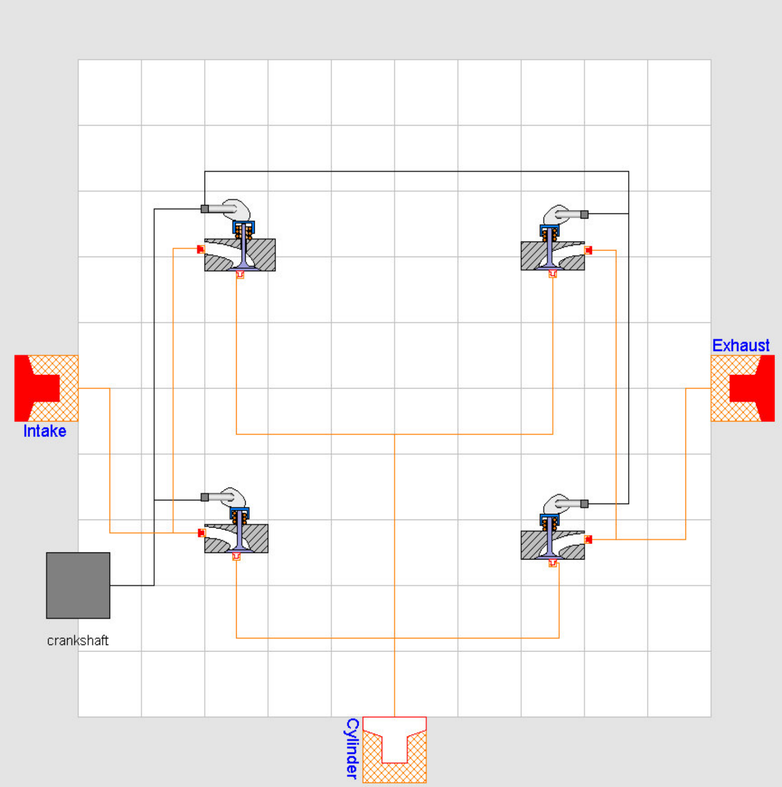
  Bowles, P. and **Batteh, J.**, "A Transient Multi-Cylinder Engine Model using Modelica", SAE paper 2003-01-3127, 2003

Erik Surewaard
esurewa1@ford.com

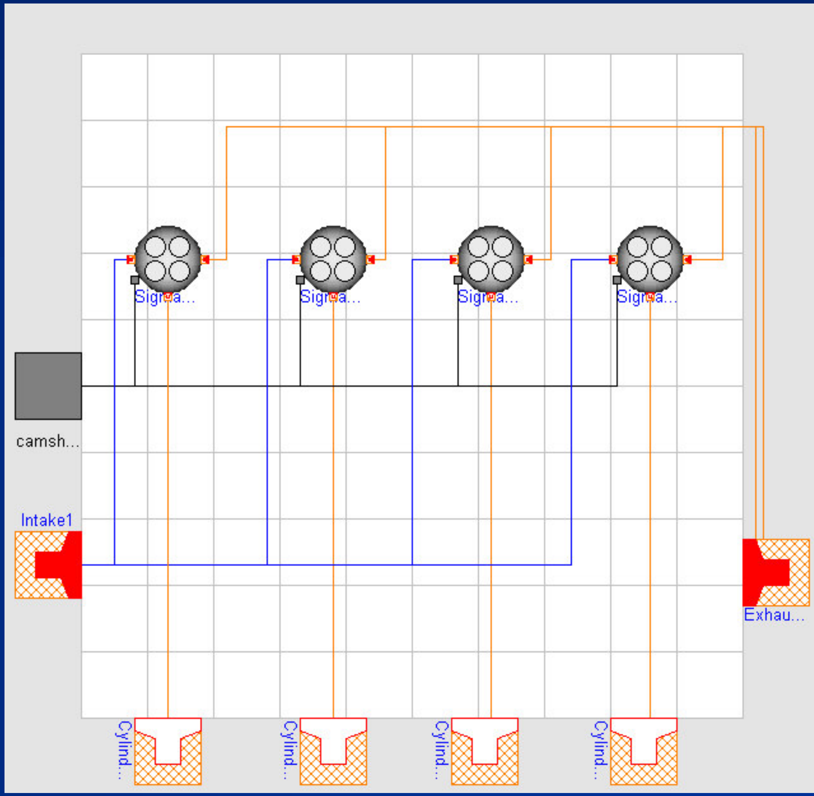
Component Modeling - Engine

Model Implementation

Valvetrain Model



Engine Head

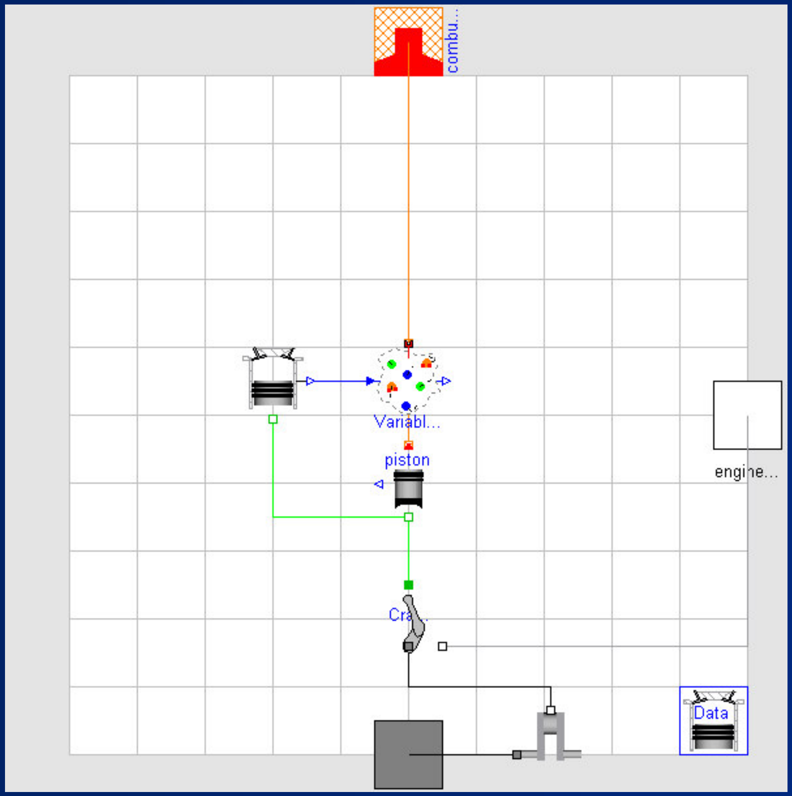


Erik Surewaard
esurewa1@ford.com

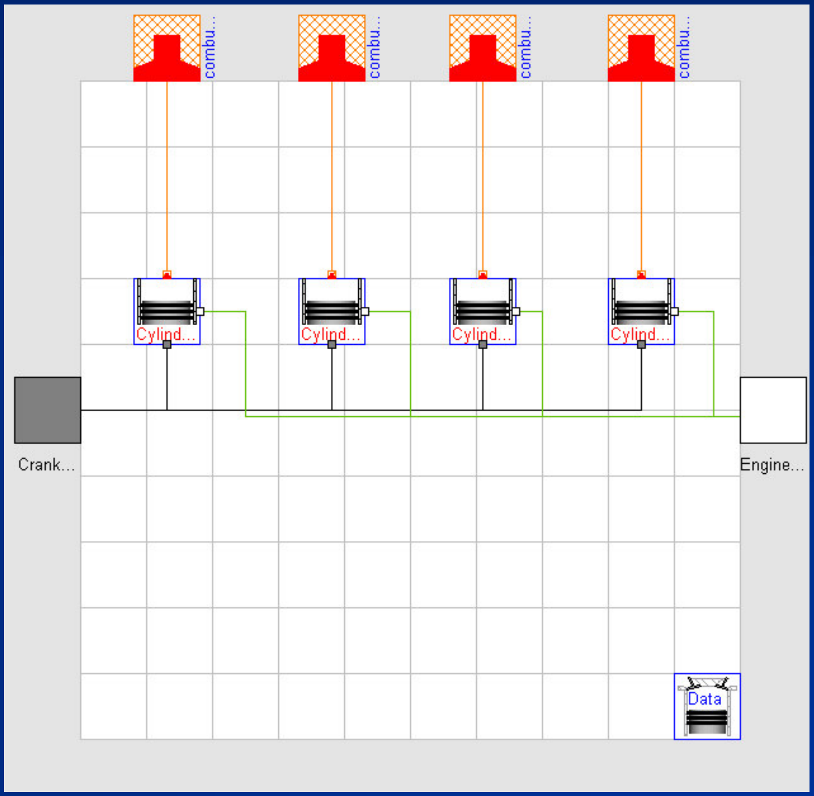
Component Modeling - Engine

Model Implementation

Motored Cylinder Model



4-Cylinder Engine



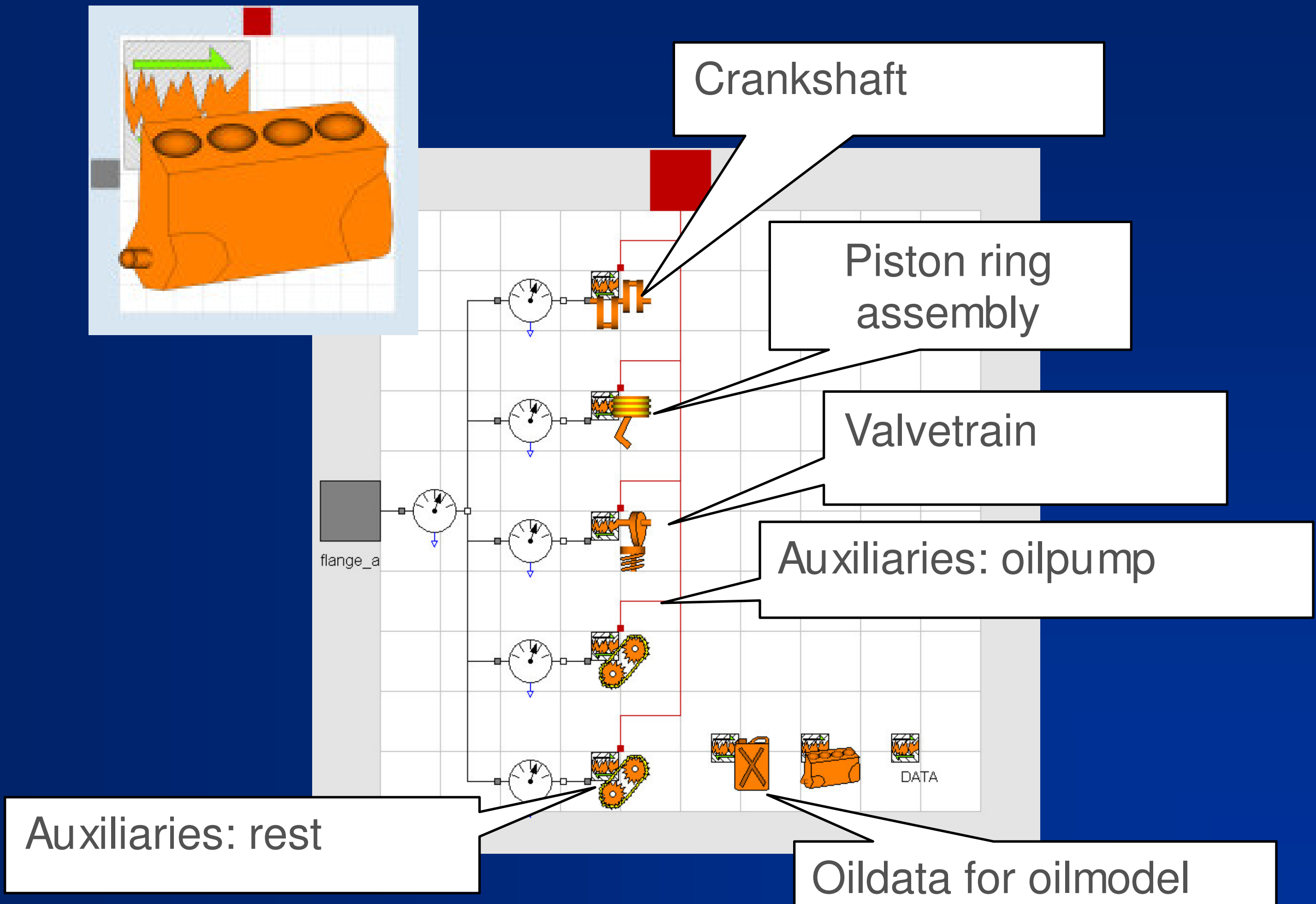
Erik Surewaard
esurewa1@ford.com

Component Modeling - Engine Losses
Model Implementation

- Based on: **Shayler, P., Leong, D.K.W. and Murphy, M.,** “Friction Teardown Data from Motored Engine Tests on Light Duty Automotive Diesel Engines at Low Temperatures and Speeds”, ASME paper, ICEF2003-745, 2003
- Correction of the “Patton, Nitschke, Heywood”-engine losses model to make it suitable for low speeds and low temperatures
- Separate functions for losses of (i) crankshaft, (ii) piston ring assembly, (iii) valvetrain and (iv) auxiliary components
- Function have fitting parameters to fit them to measured engine data
- Shayler-paper describes loss data of a 1.8L Ford Diesel engine and the fitting parameters for low enginespeeds and low temperature.

Erik Surewaard
esurewa1@ford.com

Component Modeling - Engine Losses
Model Implementation



Erik Surewaard
esurewa1@ford.com

Contents

- Ford Forschungszentrum Aachen – Energy Management Group

Modeling

- Causal vs. Acausal Modeling
- Modelica
  - Fundamentals
  - Dymola

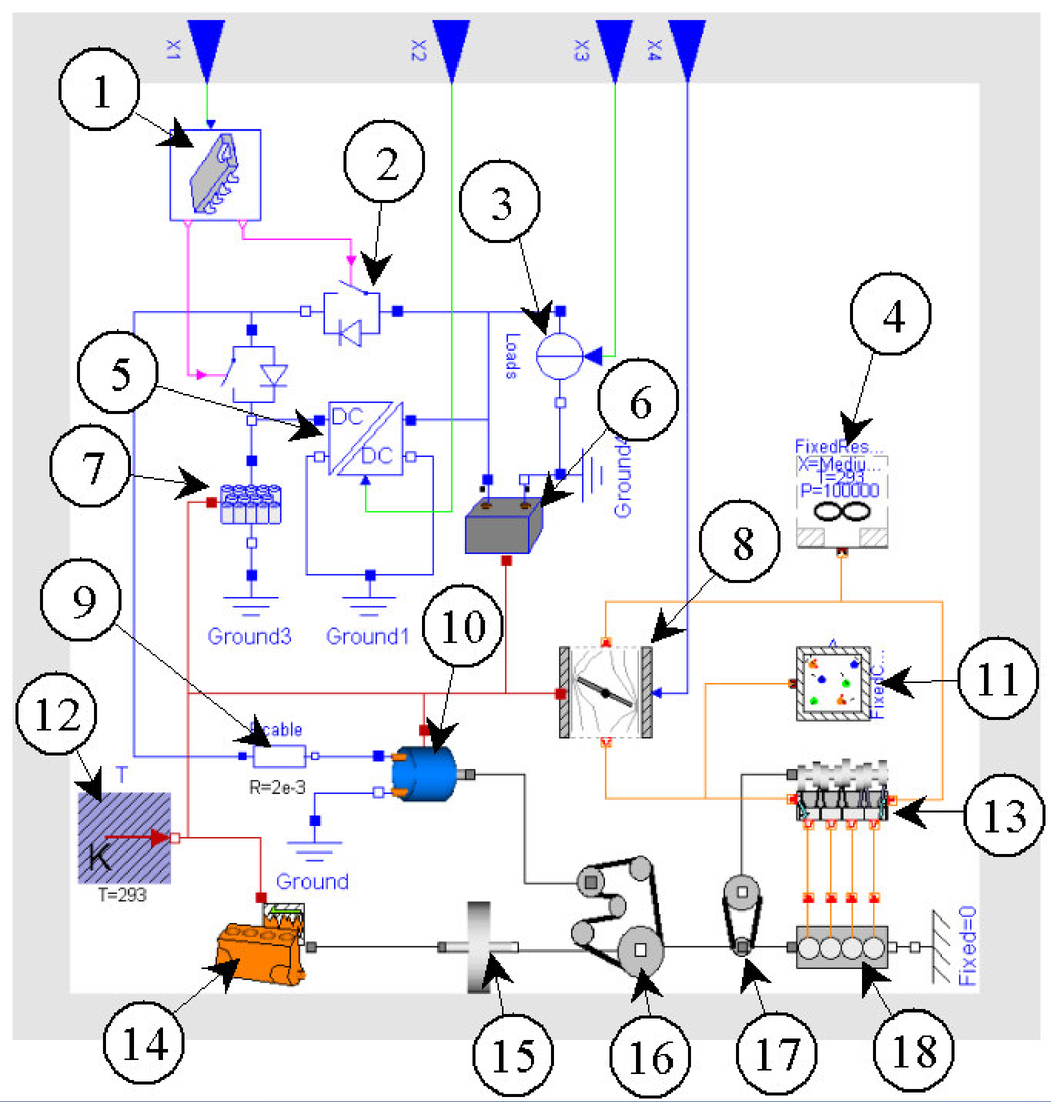
Example

- Engine Cranking Modeling
  - “What happens during engine cranking?”
  - ISG and Dual Storage System
  - Component Modeling (Battery, Supercap, Engine, Engine Losses)
  - Cranking Simulation Model
  - Simulation Results

- Summary
- Acknowledgement and References

Erik Surewaard
esurewa1@ford.com

Cranking Simulation Model

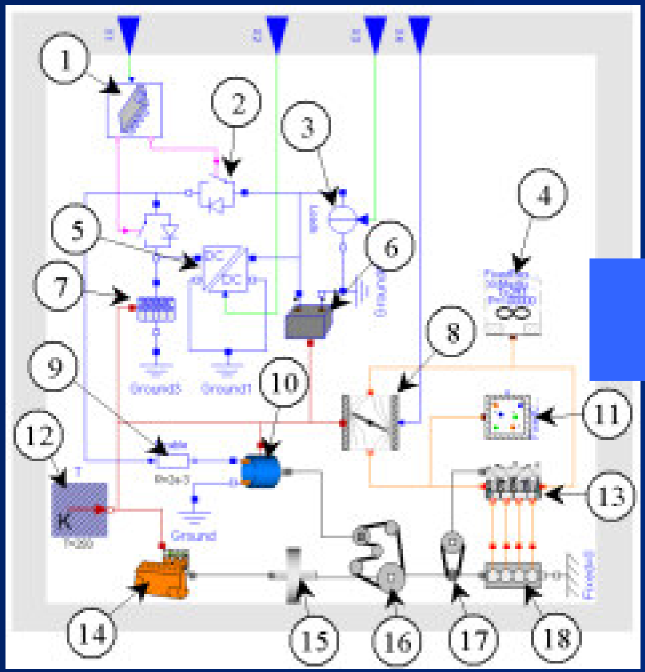


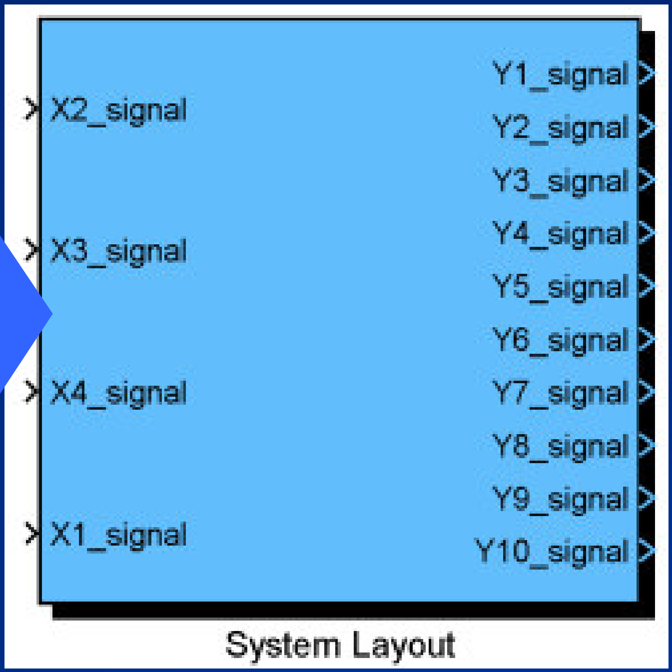
1. Controller
2. MOSFET switch
3. Current drain
4. Environment
5. DCDC converter
6. Battery (12V,70Ah,flooded)
7. Supercapacitor (9x4000F,2.7V)
8. Throttle
9. Cable resistance
10. ISG
11. Intake manifold
12. Temperature input
13. Engine head (1.8L Diesel)
14. Engine losses (1.8L Diesel)
15. Flywheel
16. Front End Accessory Drive
17. Chain drive
18. Engine Block (1.8L Diesel)

Erik Surewaard
esurewa1@ford.com

Cranking Simulation Model

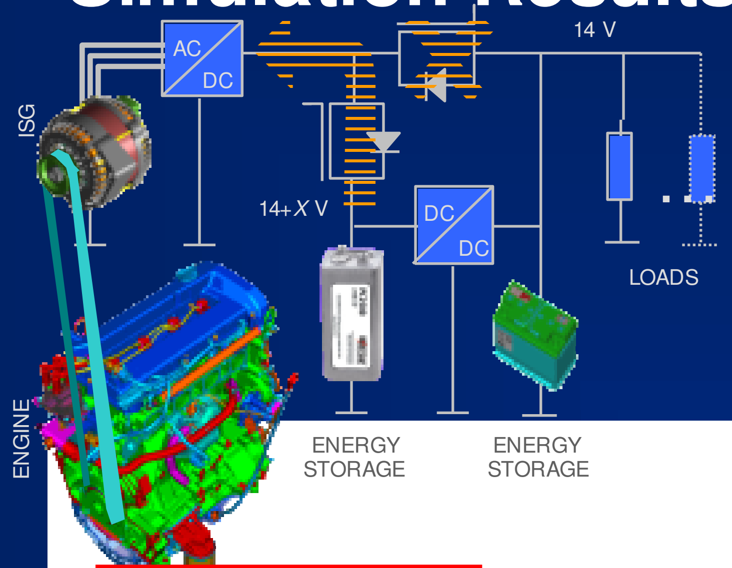
- Compilation of Modelica model to Simulink:
  either by (i) C-function export or (ii) Simulink native S-function
- In either case NO co-simulation! Only Simulink integration algorithms are used to solve the system in that case!



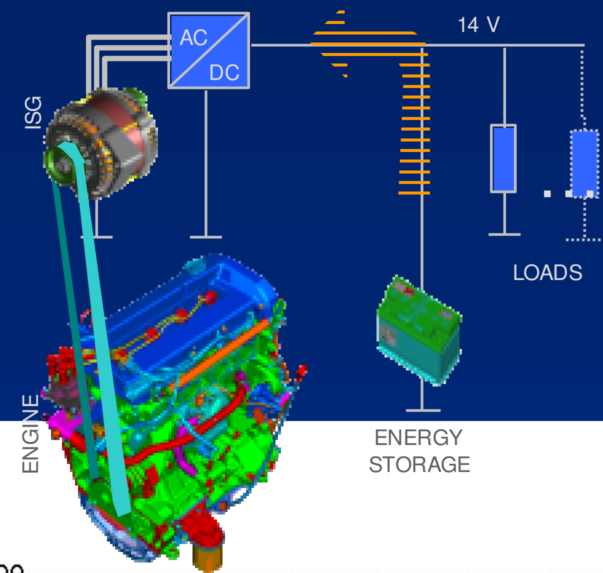


Erik Surewaard
esurewa1@ford.com

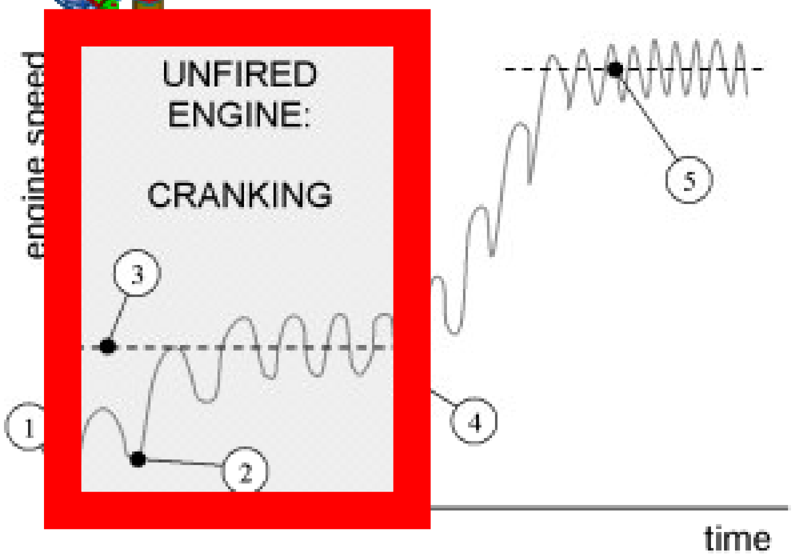
Simulation Results

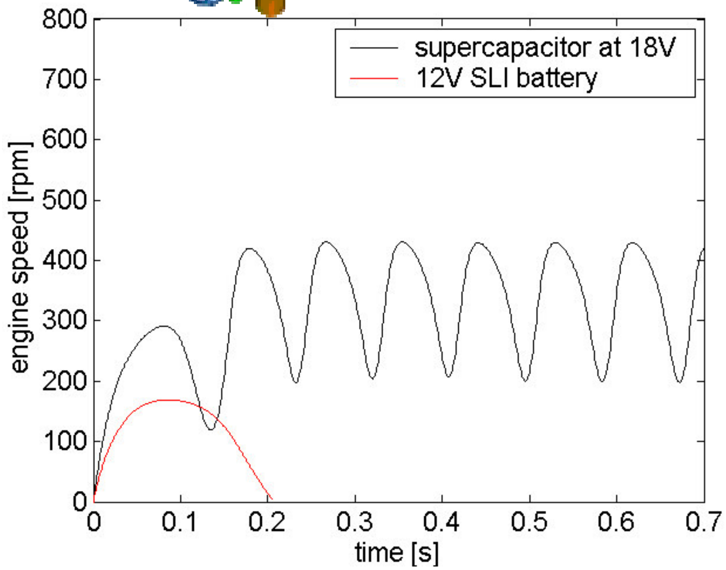


OR



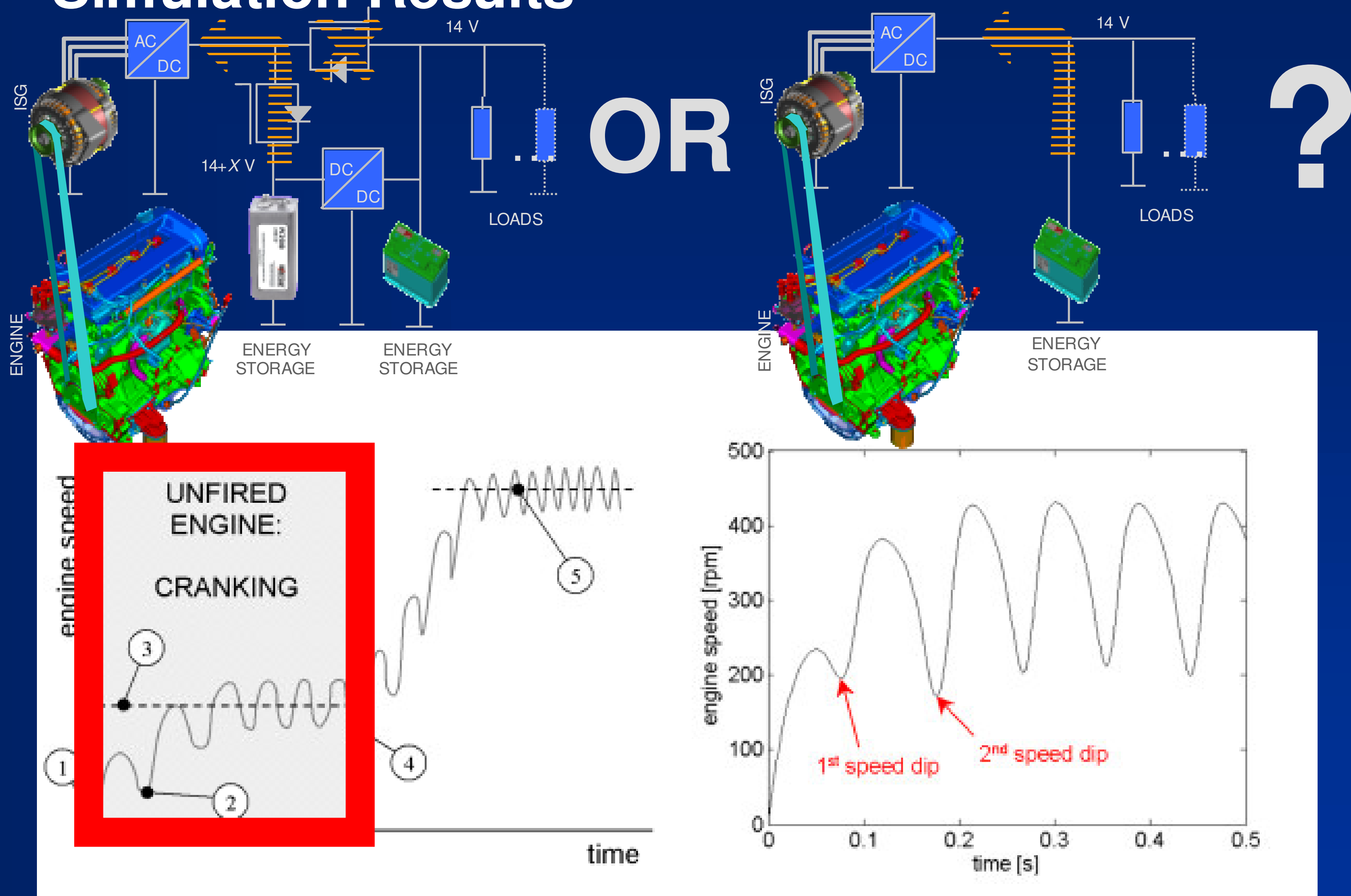
?





Erik Surewaard
esurewa1@ford.com

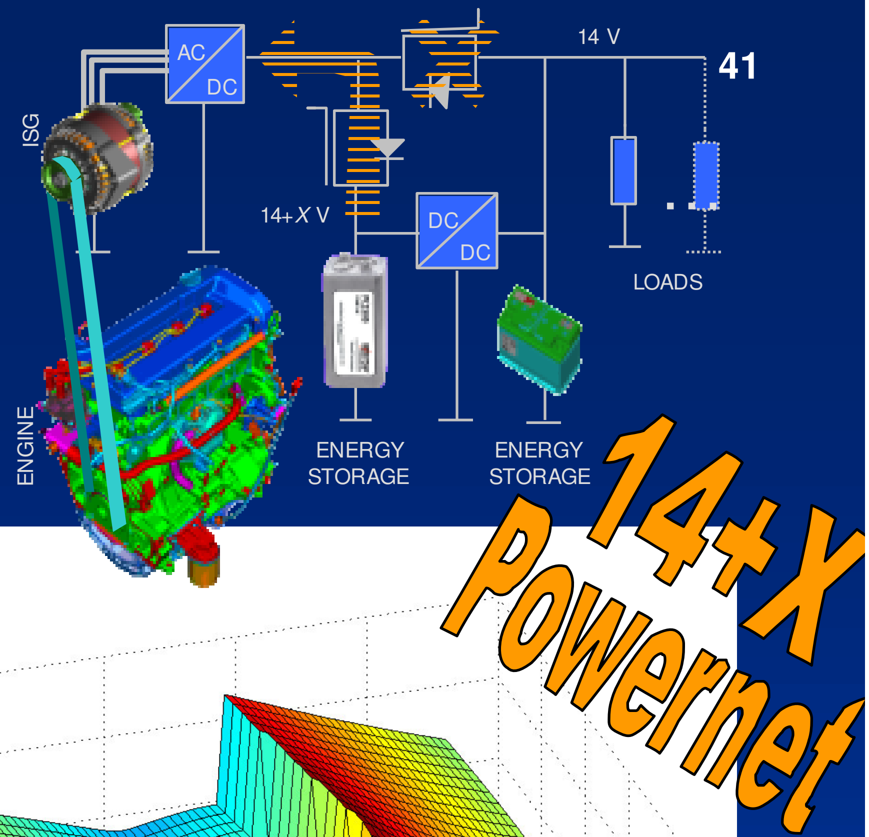
Simulation Results

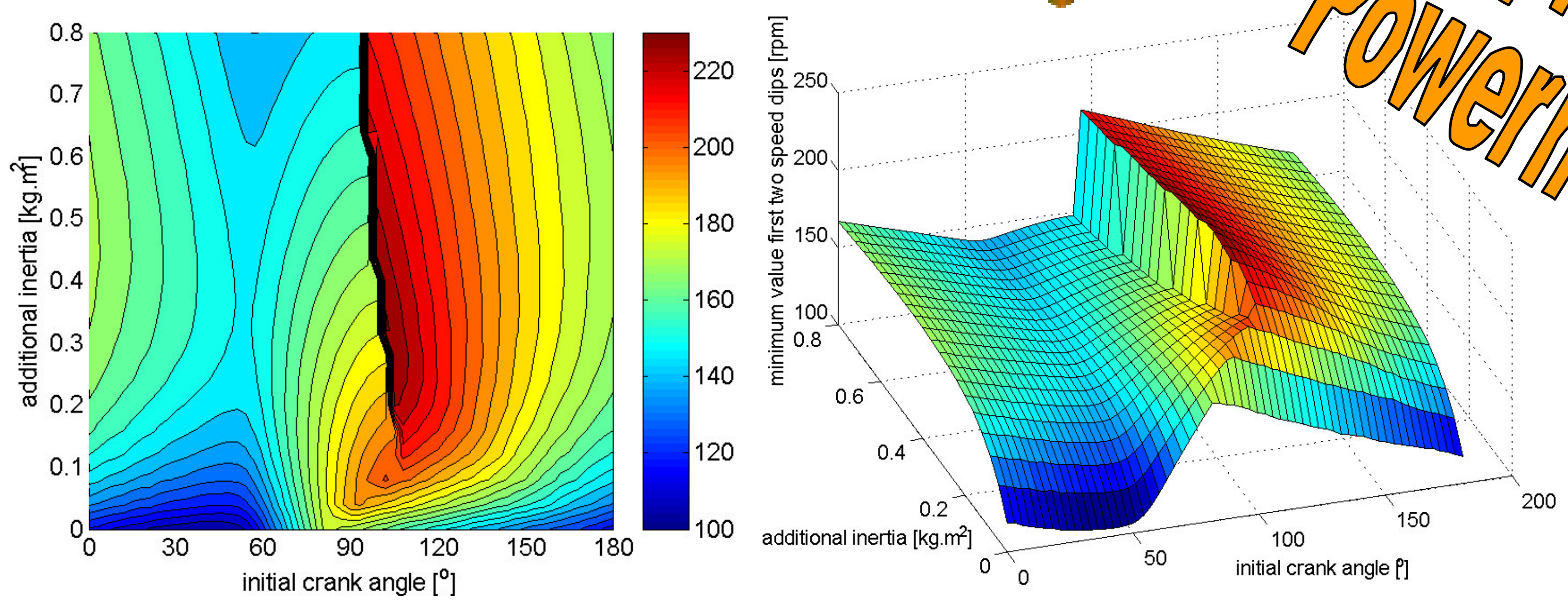


Erik Surewaard
esurewa1@ford.com

Simulation Results

- Initial supercap voltage of 18V, temperature = - 30^{0}C !!!
- Influence of add. inertia and initial crankangle
- Engine cranks always

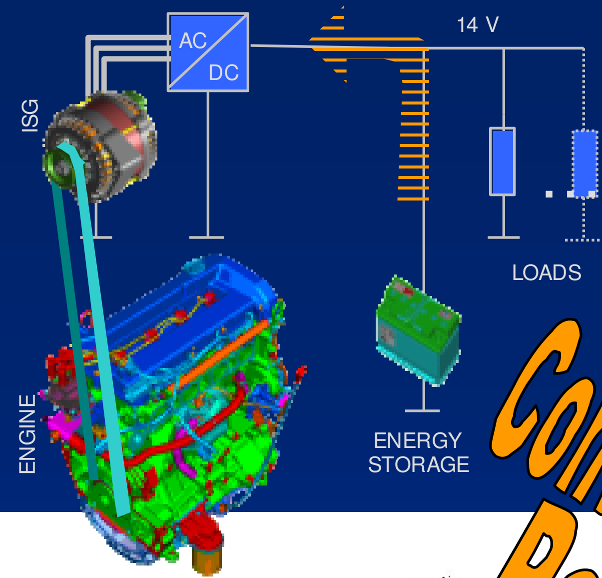


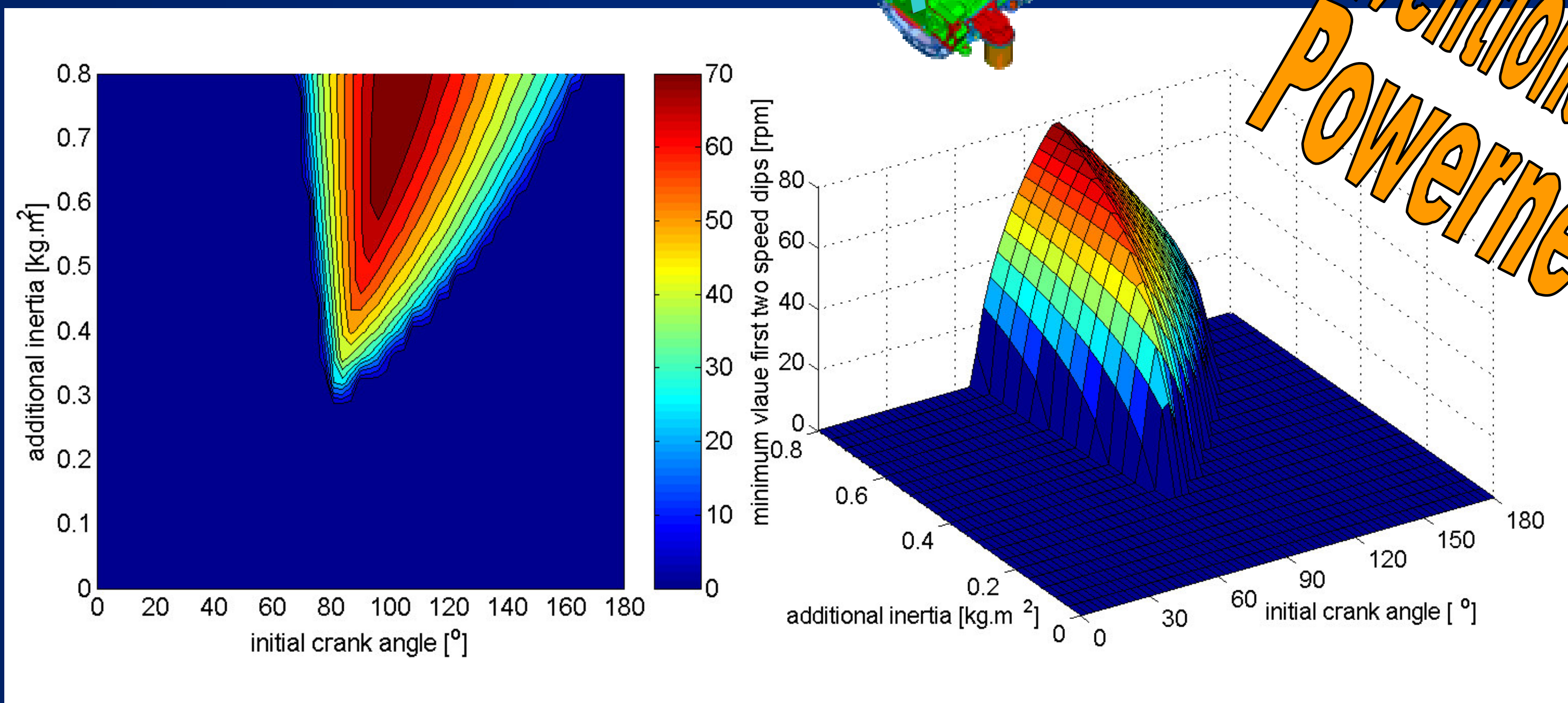


Erik Sureward
esurewa1@ford.com

Simulation Results

- 12V flooded 70 Ah battery, temperature = - 30^{0}C !!!
- Initial battery SOC = 70% !
- Not always succesfull: add. inertia needed! But no SCAP or DCDC!!!

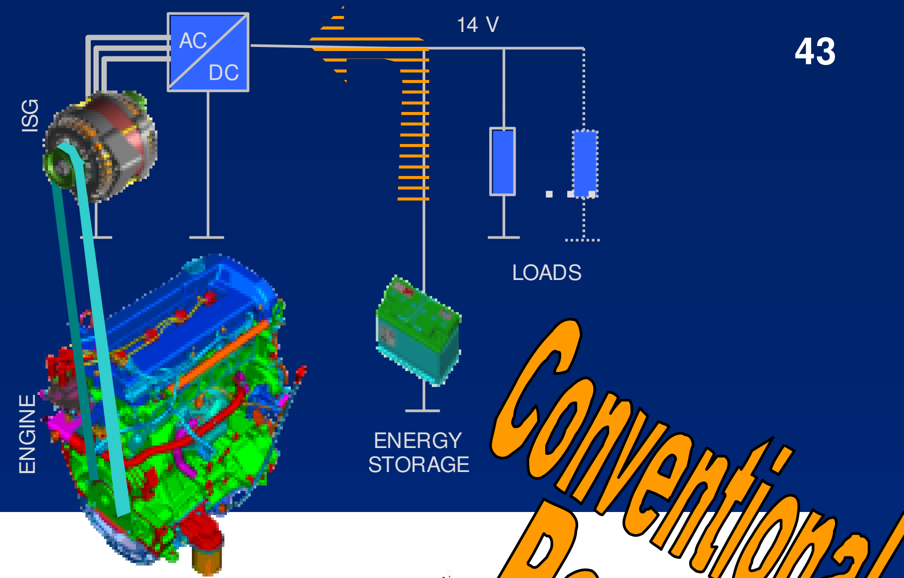


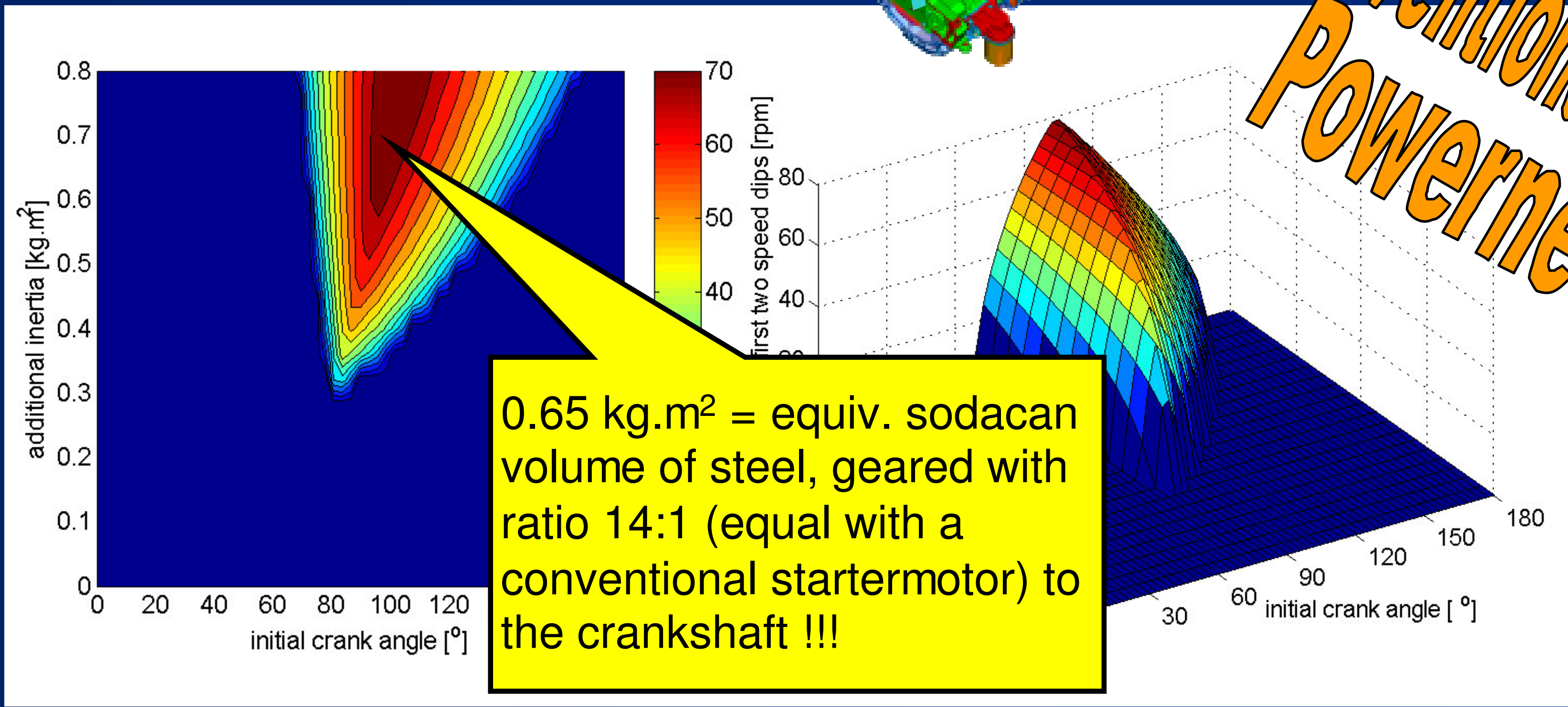


Erik Surewaard
esurewa1@ford.com

Simulation Results

- 12V flooded 70 Ah battery, temperature = - 30^{0}C !!!
- Initial battery SOC = 70% !
- Not always succesfull: add. inertia needed! But no SCAP or DCDC!!!





Erik Surewaard
esurewa1@ford.com

Summary

- Modelica is a great tool for both (a)causal modeling! It can not only be used as a standalone tool but also complementary with Simulink! This will have great benefits compared with a 'Simulink only' modeling environment.

- There is no need to use a Dual Storage System (with a supercapacitor, DCDC converter and a battery) to guarantee succesfull cranking a 1.8L Diesel engine with a belt-driven ISG at –30^{0}C!
  By using a small additional inertial mass and initial crankangle positioning next to a conventional powernet (12V flooded battery), succesfull cranking can 1.8L Diesel engine with a belt-driven ISG at –30^{0}C be guaranteed! And the conventional startermotor can be omitted in this case!

Erik Sureward
esurewa1@ford.com

Acknowledgement

- **Daniël Kok**, Team leader of the Energy Management Group, Ford Forschungszentrum Aachen, Germany
- **Michael Tiller**, Technical Specialist of the Powertrain Research Department, Scientific Research Laboratories, Dearborn, USA

References

- **Tiller, M.**, “Introduction to Physical Modeling with Modelica”, Kluwer Academic Publishers, Boston, 2001
- **Surewaard, E., Tiller, M.** and **Linzen, D.**, “A Comparison of Different Methods for Battery and Supercapacitor Modeling”, SAE paper 2003-01-2290, 2003
- **Surewaard, E., Tiller, M.** and **Karden. E.**, “Advanced Electric Storage System Modeling in Modelica”, Proc. of the 3rd Int. Modelica Conference, Sweden, 2004
- **Surewaard, E., Kok, D.** and **Tiller, M.**, “Engine Cranking: Advanced Modeling and an Investigation of the Initial Crank Angle and Inertia, SAE paper 2004-01-1875, 2004

Erik Surewaard
esurewa1@ford.com