History & Future Vision of CAE Utilization

Contents

1. My work experience and current
2. History of CAE utilization in engine development process
3. Present situation and problems
4. Future vision of CAE utilization

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My work experience and current

Toyota Motor Corporation (1982-2015)

1. Engineering IT division 3 years
2. Engine engineering division 30 years
   - Project(CAE) general manager
   - Main responsibility was to reduce engine development time and cost by CAE

Director of Academic Society (2007-)

1. Japan Society for Computational Engineering and Science
2. Robust Quality Engineering Society

CEO of SAWADA R&D Center (2015-)

- Engineering consulting and mediation

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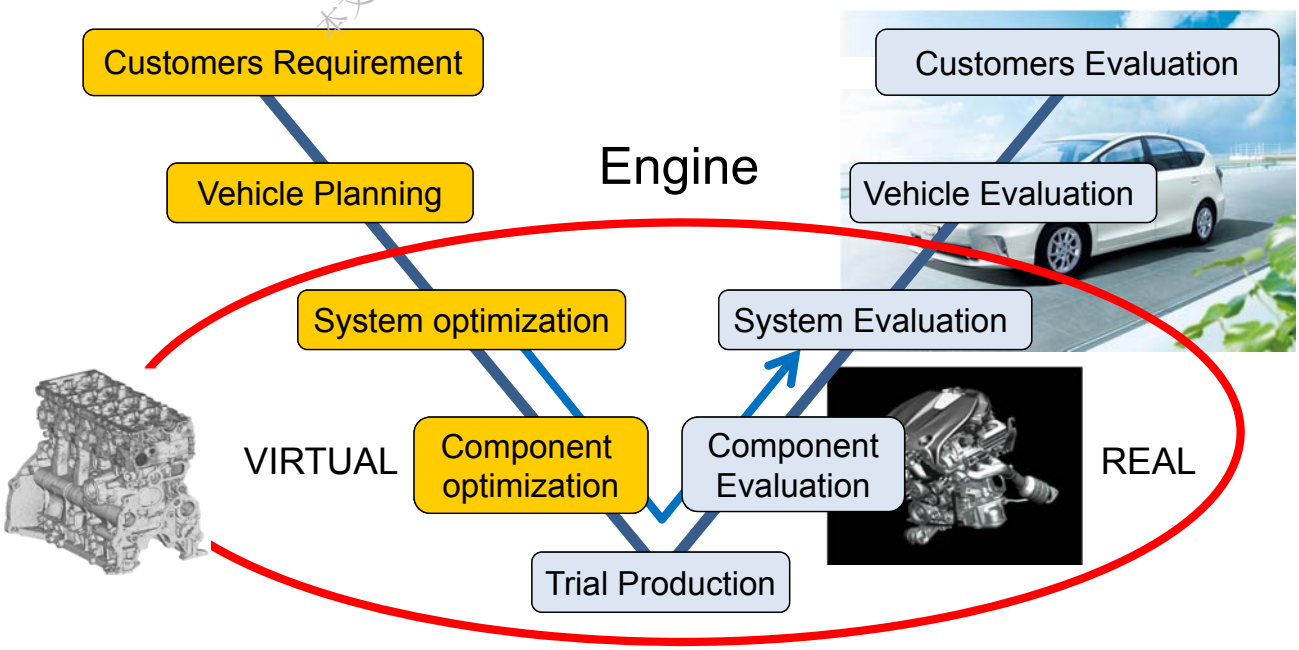
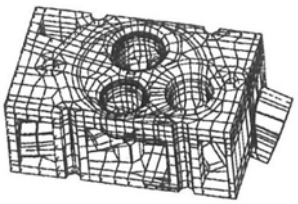
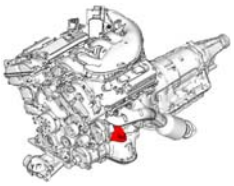
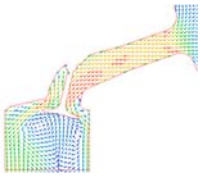
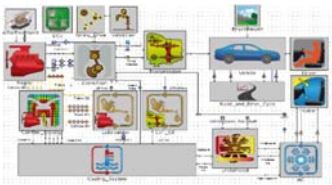
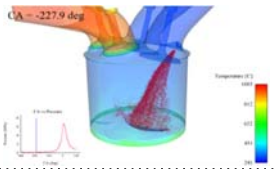
Vehicle & Engine development process

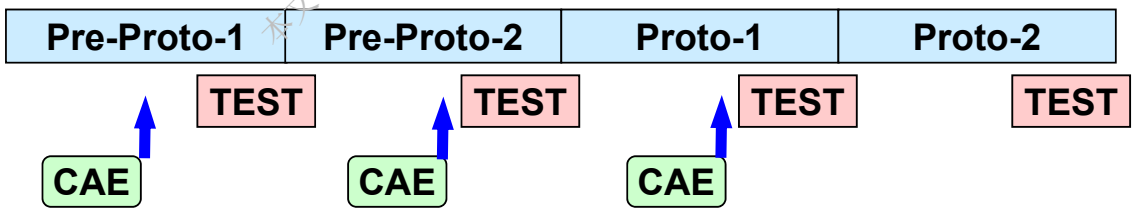


History of CAE utilization

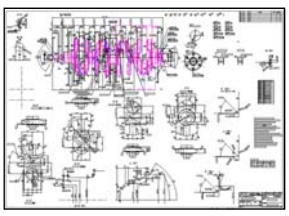
'85	'95	'05	'10	'15
1st Generation	2nd Generation	3rd Generation	Current	
CAD-less Simulation 	Wire-frame CAD CAE(FEM) 	3D-Solid CAD CAE(FEM, CFD)  	System Simulation (0D, 1D)  Cycle Simulation (3D-detail) 	
Component Design CAE	Component Trouble Shooting	Assembly Evaluation CAE	System Planning CAE	
In-design process	Off-line CAE	In-process CAE	MBD	

1st Generation :CAE

■ Utilization for component design



Drafting



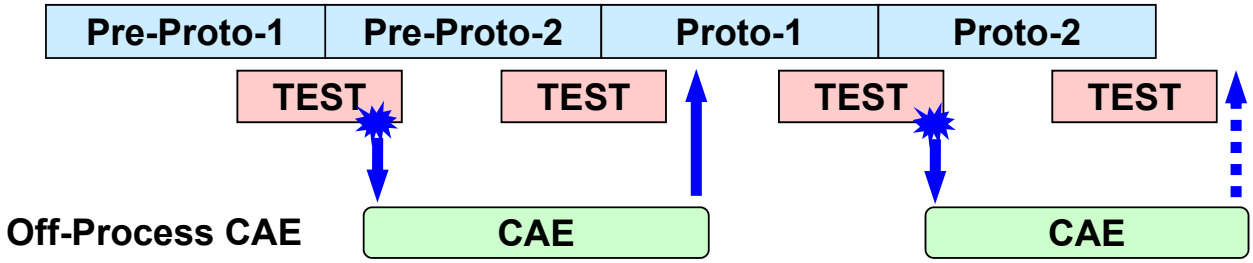
FEM modeling: a couple of days

FEM Auto Generation program

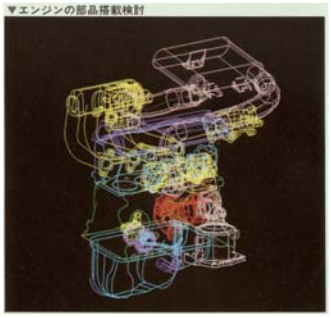
- Mesh scale
  ～1,000 nodes
- Static, Linear Analysis
- Machine
  Super Computer
  EWS for Pre, Post

2nd Generation :CAE

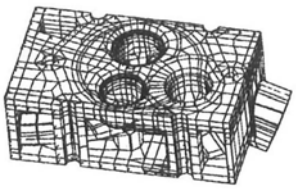
■ CAE Utilization for trouble shooting



CAD
Wire frame model



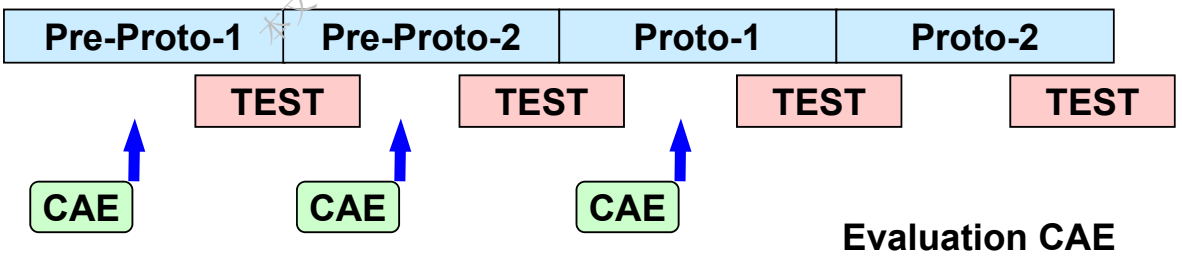
FEM modeling: 3 months



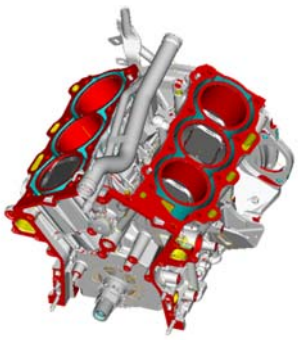
- Mesh scale
  ～10,000 nodes
- Static, Linear Analysis
- Machine
  Super Computer
  EWS for Pre, Post

3rd Generation :CAE

■ In-Process CAE: CAE utilization before prototype



3D-Solid model



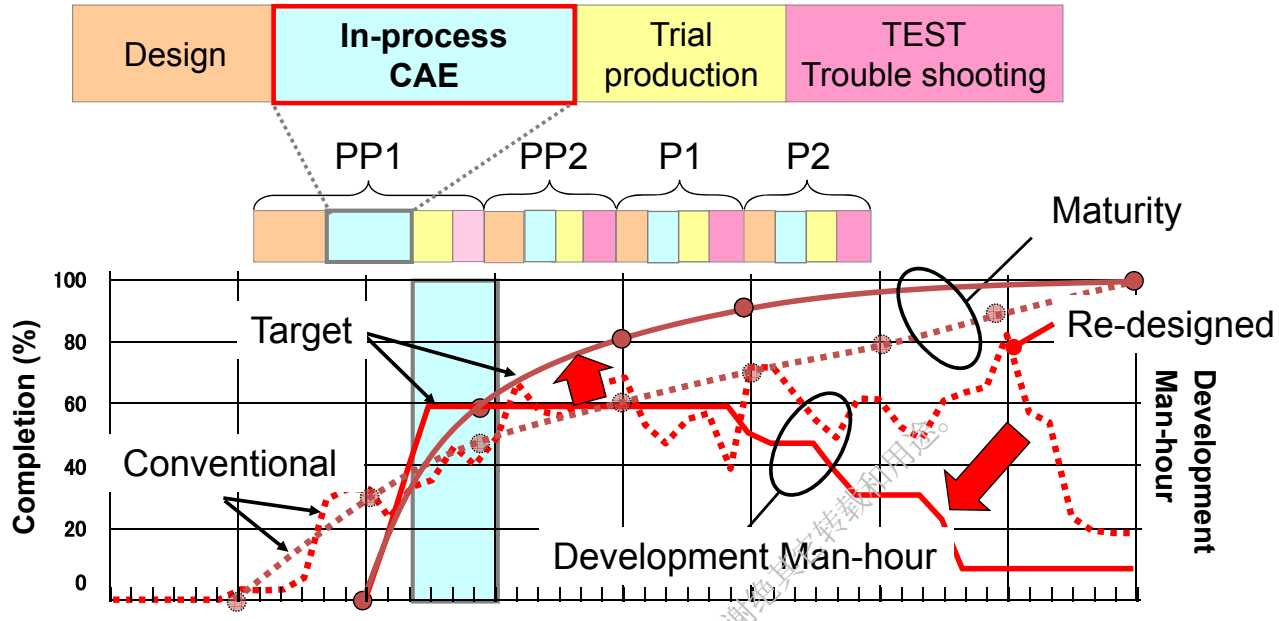
Auto mesh

FEM modeling: 1 week

- Mesh scale
  ～3,000,000 nodes
- Non-linear, Dynamic
- Machine
  Super EWS
  Windows EWS
  for Pre, Post

Challenge in 3rd Generation

From CAE utilization for trouble shooting to in-process CAE



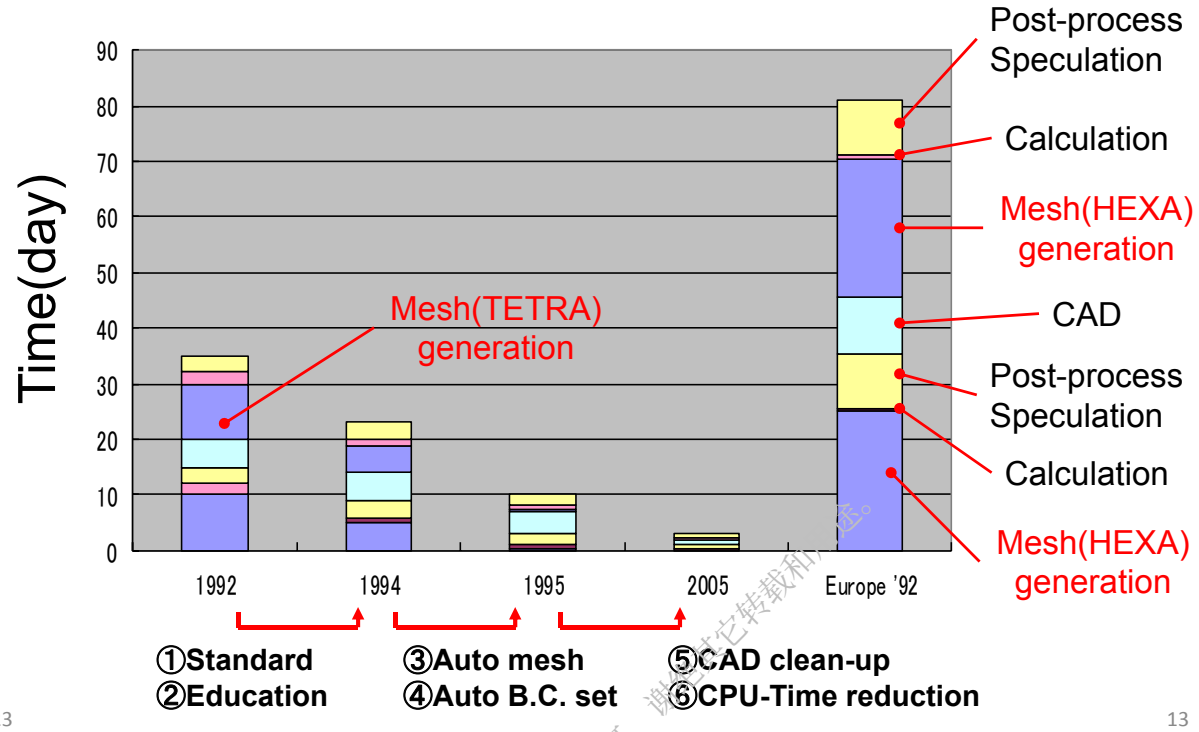
Challenge in 3rd Generation

How to realize in-process CAE

1. Reduction of CAE period of time
2. CAE accuracy improvement
3. Increment of CAE item

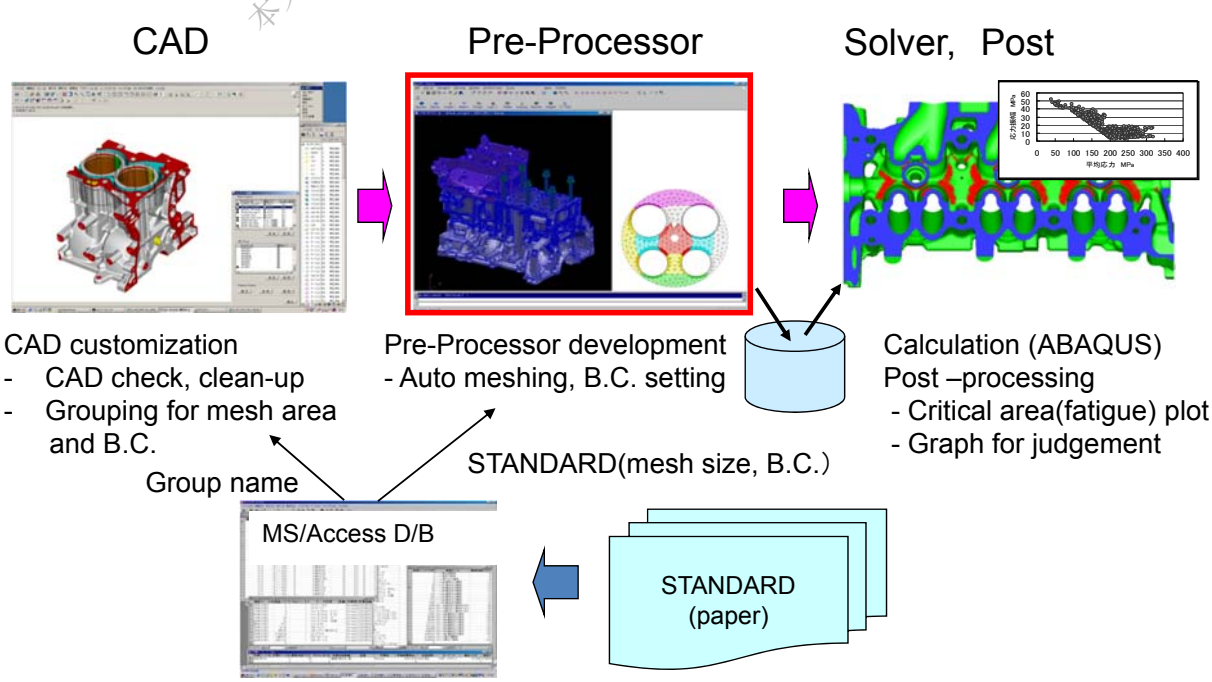
Challenge in 3rd Generation

Reduction of CAE period of time



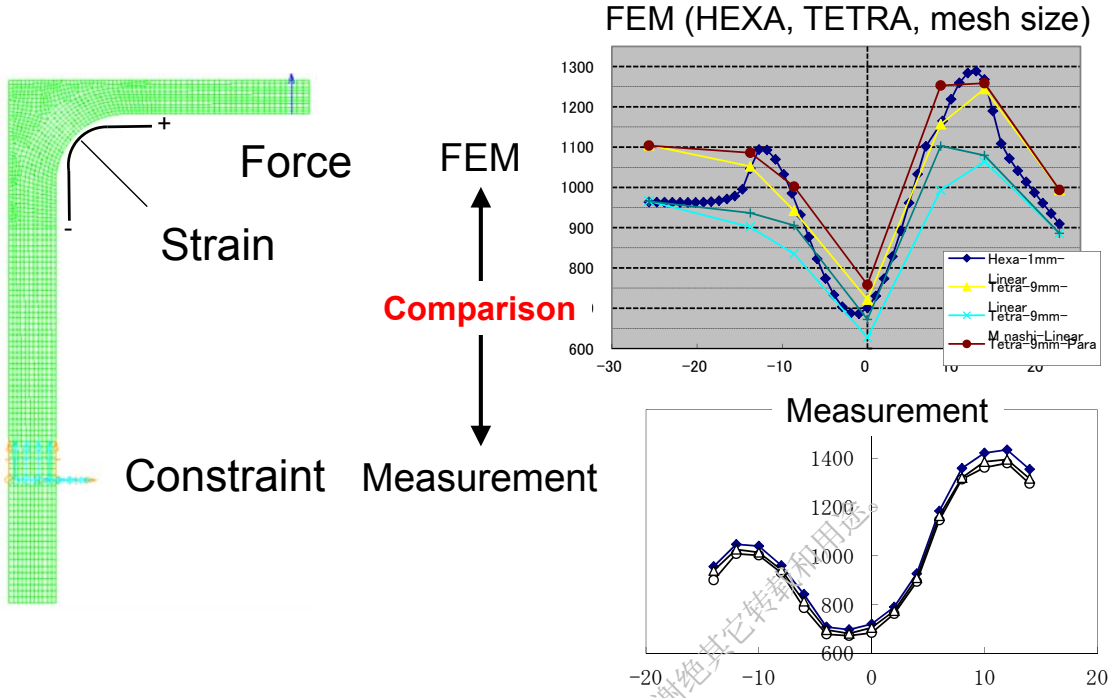
Challenge in 3rd Generation

Reduction of CAE period of time



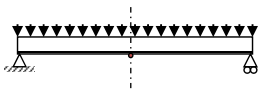
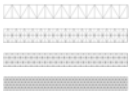
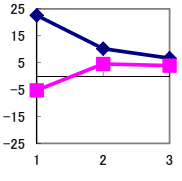
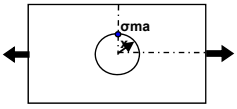
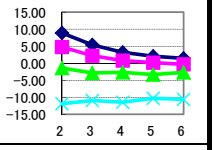
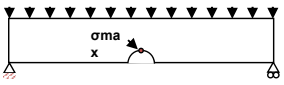
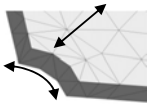
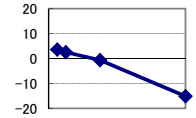
Challenge in 3rd Generation

CAE accuracy improvement (Validation)



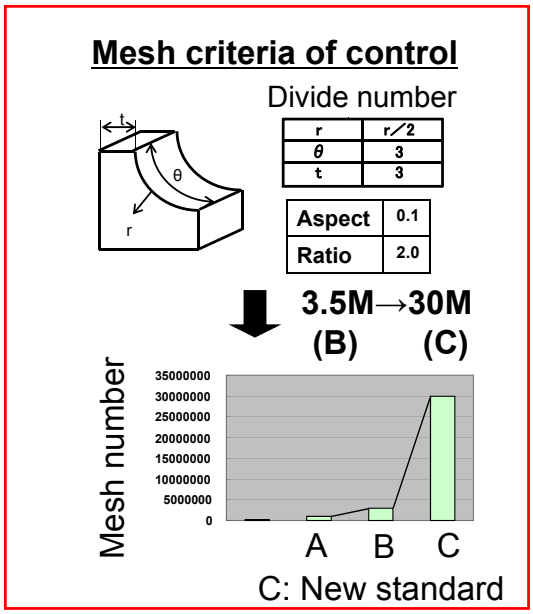
Challenge in 3rd Generation

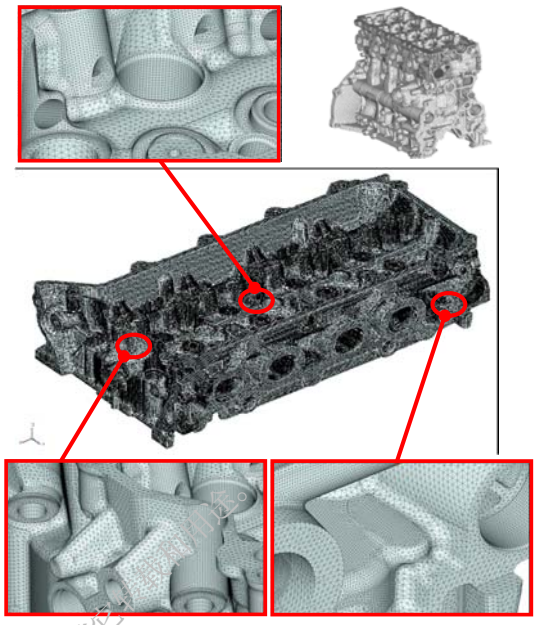
CAE accuracy improvement (Verification)

Configuration		Mesh size	Verification
A Straight beam			
B Bend			
C Shell W/hole		Variation of mesh devide	
D Shell W/notch			

Challenge in 3rd Generation

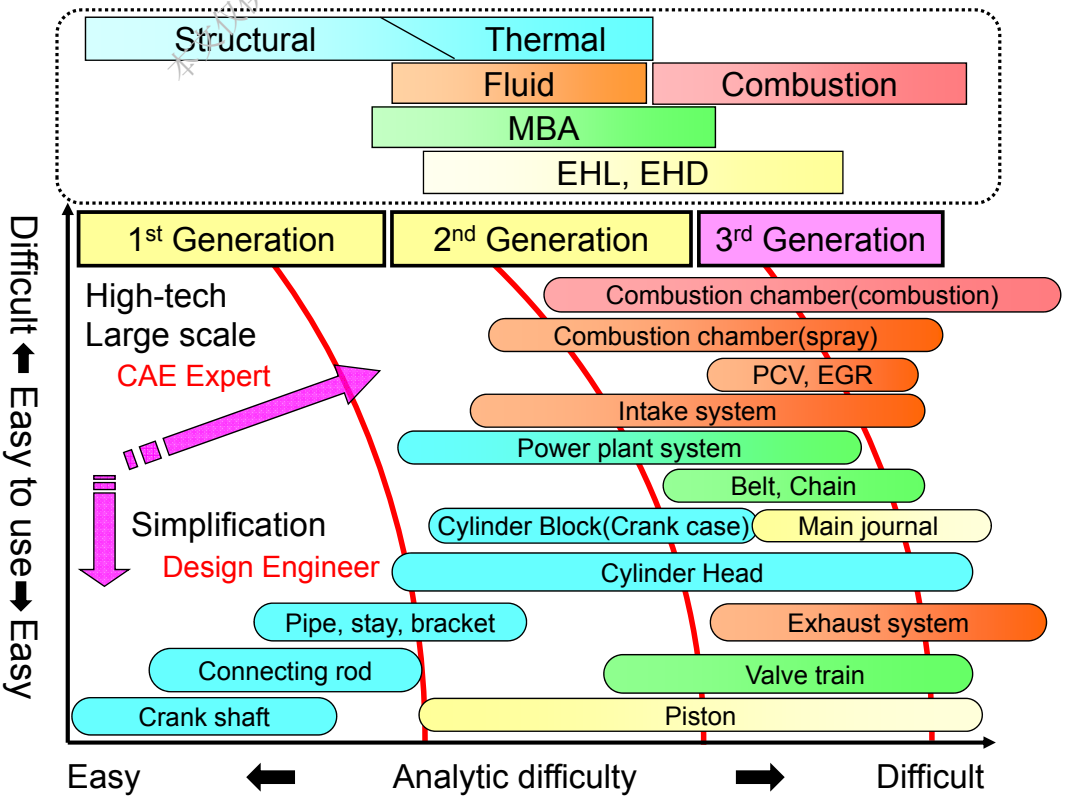
CAE accuracy improvement (Mesh control)





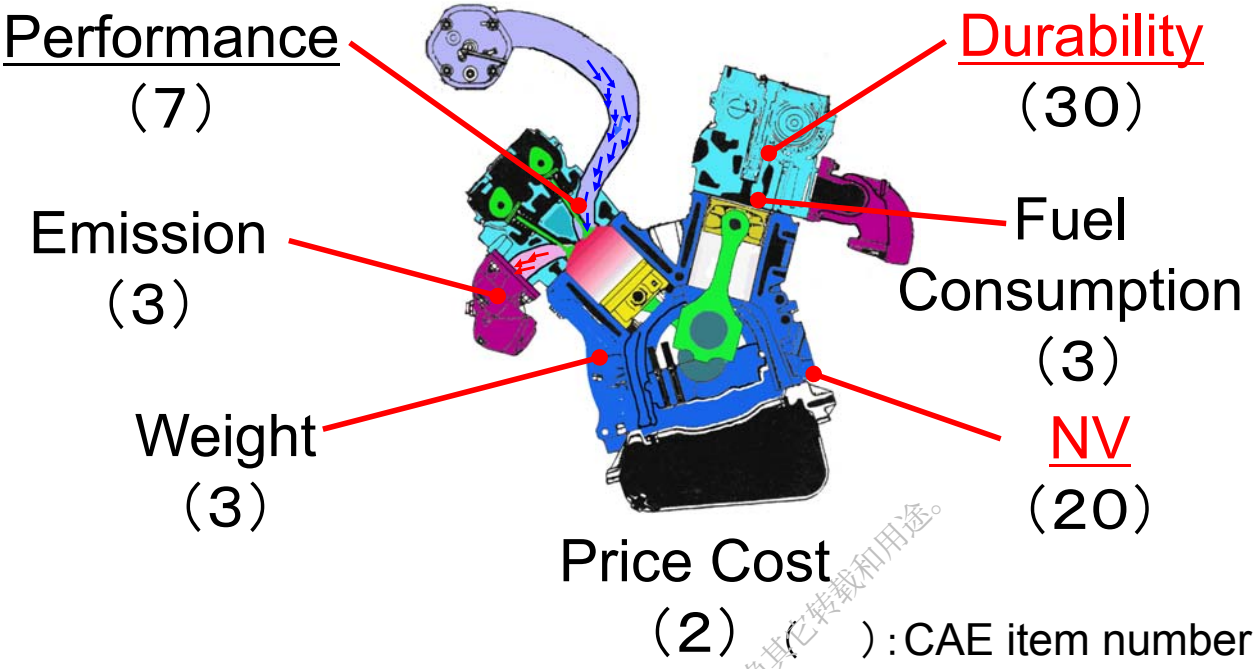
Challenge in 3rd Generation

Increment of CAE item



Challenge in 3rd Generation

Increment of CAE item



Challenge in 3rd Generation

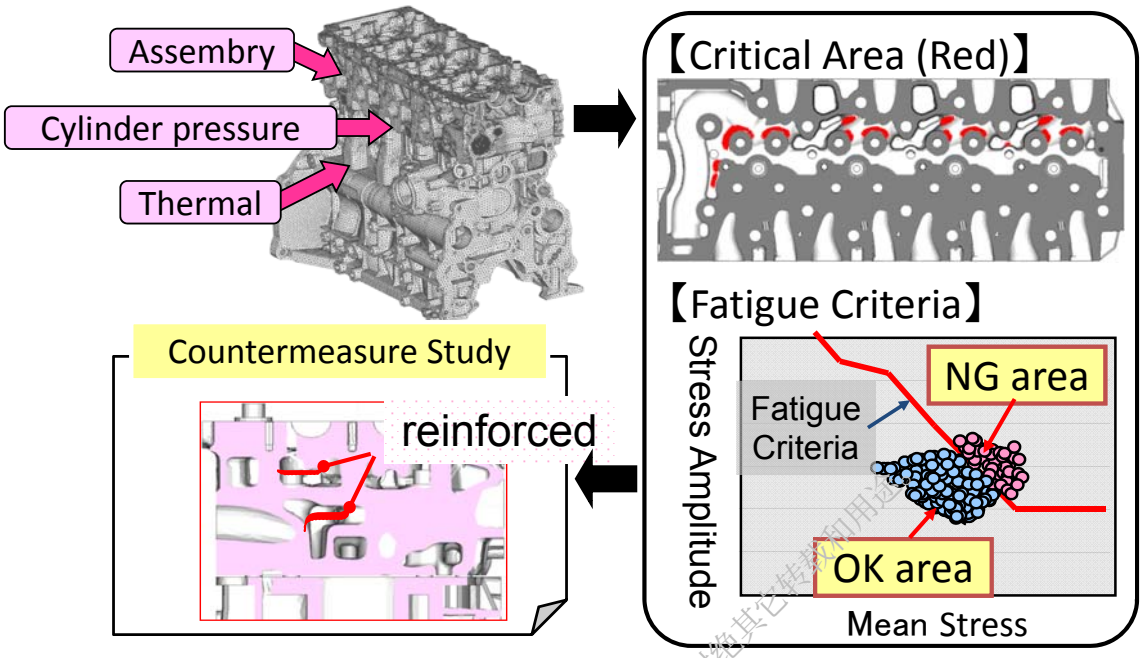
Increment of CAE item(CAE Menu example)

3: Absolute, 2: Relative(%), 1: Tendency

Area	Component	No.	Evaluation item	CAE Output	CAE level
Performance (A)	Intake, Exhaust System (1D)	A01	Torque Volumetric Efficiency Cylinder Pressure Flow Rate	Max Torque, Max Power, air flow or Intake rate	2
	Intake Manifold	A02	Intake Manifold Flow Rate Intake manifold + port flow rate	Mass flow rate; Flow Coefficient	1
	Intake Port	A03	Flow Coefficient Tumble Ratio	Flow Coefficient Tumble ratio Impeller RPM	1
	Intake System Parts	A04	Pressure Loss	Pressure loss	1
	Exhaust System	A05	Pressure Loss	Pressure loss	3
Calibration (B)	EGR	B01	EGR Cylinder Distribution	EGR variation b/w cylinders Throttle catching ratio	2

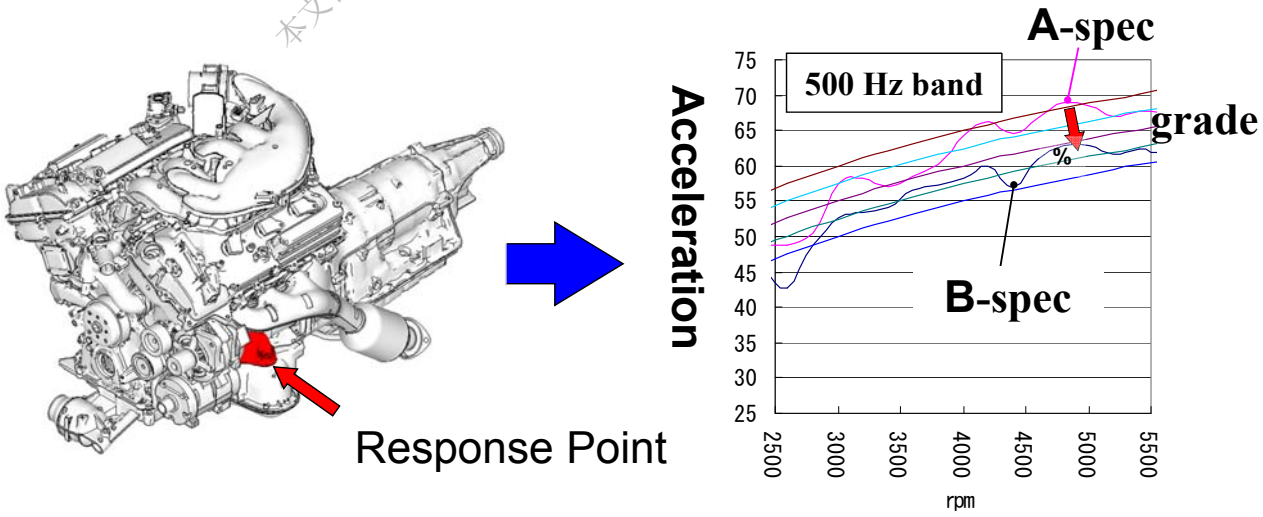
Challenge in 3rd Generation

Example of CAE level 3: Cylinder Head Durability



Challenge in 3rd Generation

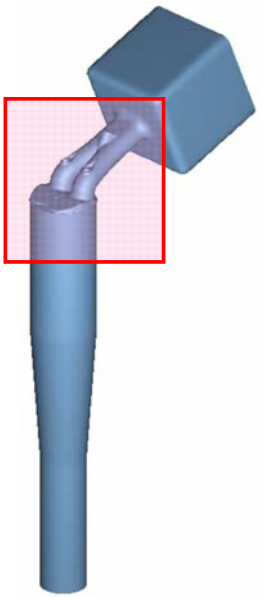
Example of CAE level 2: Mount tip vibration



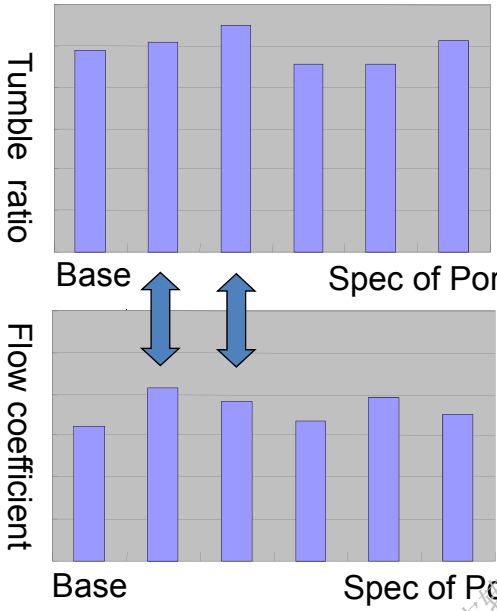
Mount tip Vibration level
(1/3octave tracking analysis)

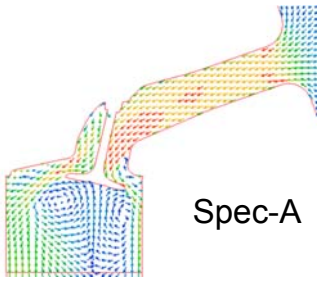
Challenge in 3rd Generation

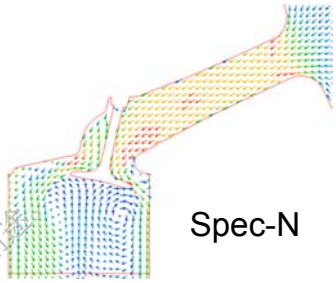
Example of CAE level 1: Intake port CFD



Intake port & Chamber



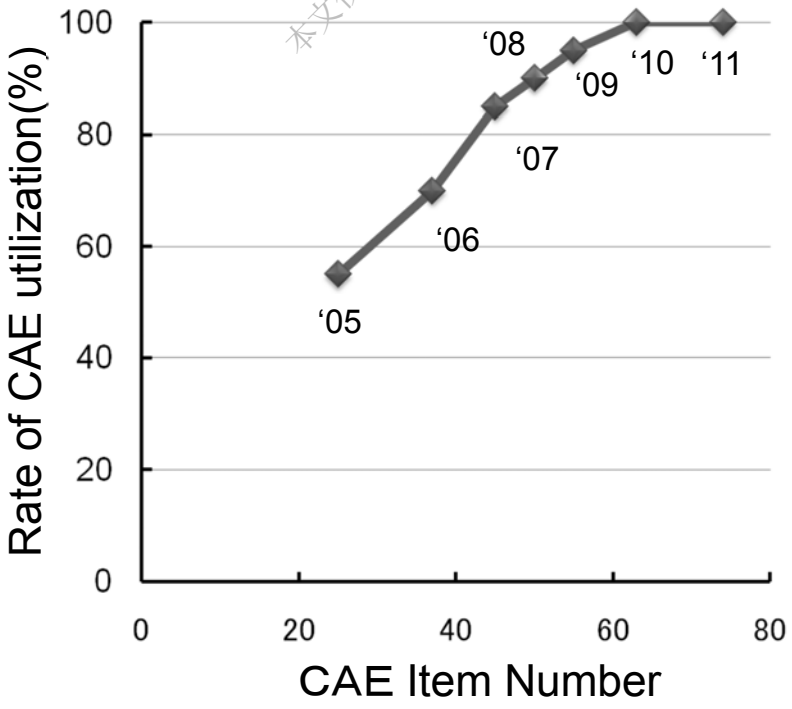


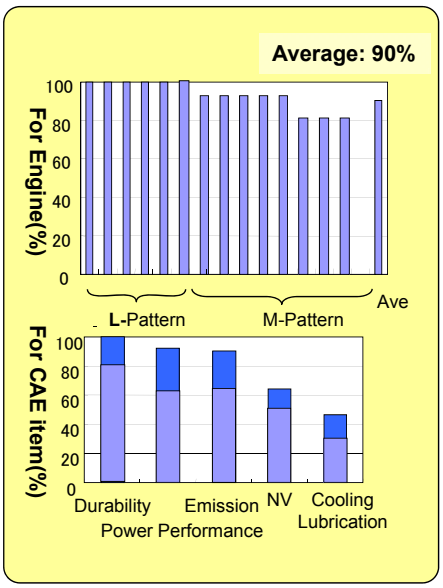


velocity [m/s]

Challenge in 3rd Generation

Increment of CAE item and rate of CAE utilization

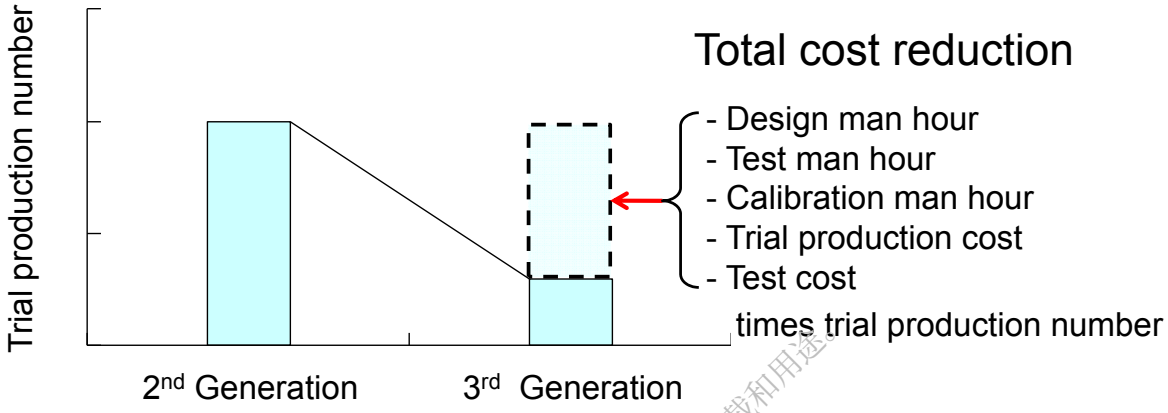




Challenge in 3rd Generation

Summary

Reduction of cost of trial production
by realization of “In-Process” CAE



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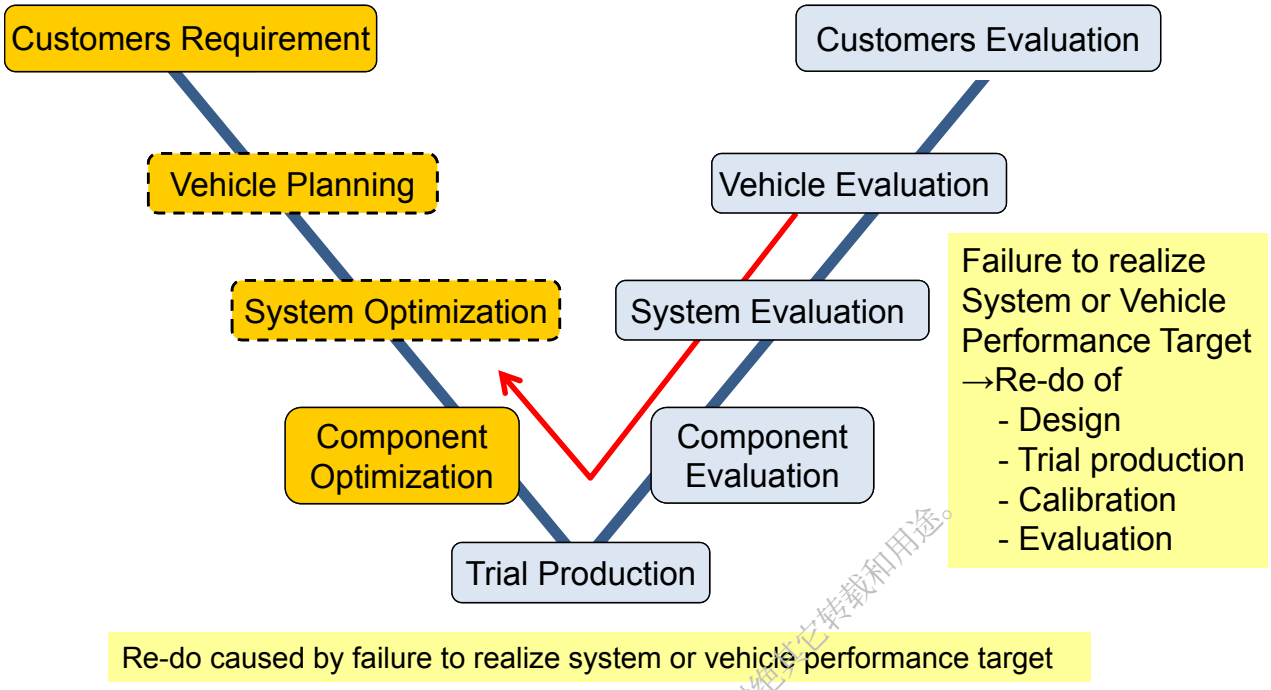
Current situation and challenge

Process and problems



Re-do caused by failure to realize system or vehicle performance target

Current situation and challenge

The reason of re-do

1. Performance target setting in virtual process is not reasonable.
2. There are few or not good **models** in virtual process for reasonable performance target setting.

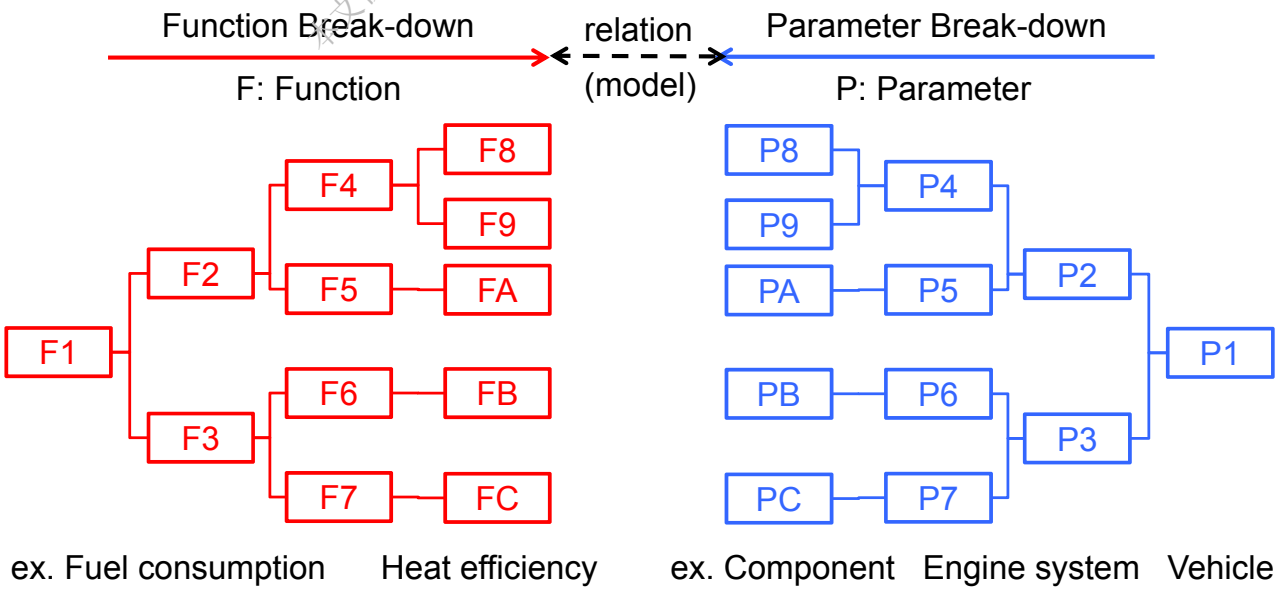
Current situation and challenge

The reason of re-do

Process	O: Objective function D: Design parameter	**Model**(function) <O = f(D)>
Customer requirement	O: Customer rating D: Vehicle performance	×
Vehicle Planning	O: Vehicle performance D: System performance	×
System Optimization	O: System performance D: Component performance	△
Component Optimization	O: Component performance D: Component design parameter	○

Current situation and challenge

Model definition



Model = Relational expression, $F_i = f(P_i)$

Current situation and challenge

Example of functional break-down

	Customer ➡	Vehicle ➡	System ➡	Components
Fuel Economy	Fuel consumption	Vehicle fuel consumption (Driving mode)	Engine fuel consumption (BSFC)	Friction Thermal efficiency
Fun to drive	Drivability, Accelerator response	Acceleration	Engine torque	Combustion pressure
	Sound quality Low noise	Sound pressure Vehicle vibration	Engine vibration (force)	Combustion Pressure Component vibration

The physical items on the list are function (performance) and these have target.

Current situation and challenge

Functional break-down and design parameter

Process	Function (performance) ex.	Design parameter
Vehicle	- Acceleration	Engine torque - Vehicle mass property
⬇ System (Engine)	-Engine torque	Combustion pressure - Engine mass property - Engine intake and exhaust system property (1D)
⬇ Component	-Combustion pressure	- Combustion chamber, intake and exhaust design parameter (3D)

Ex. Optimization of system(engine): Combustion pressure that is objective function in optimization of component is design parameter

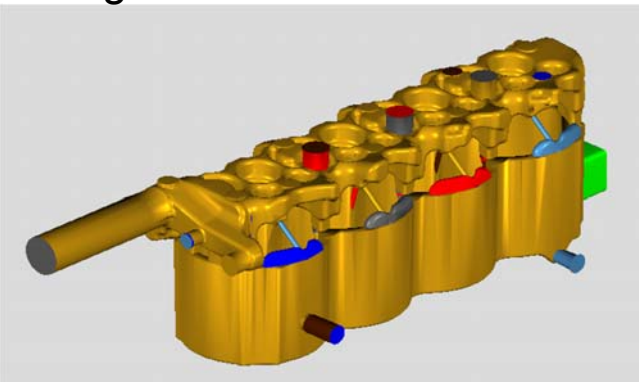
This means previous process (system optimization) define the target of next process

Current situation and challenge
Classification of models

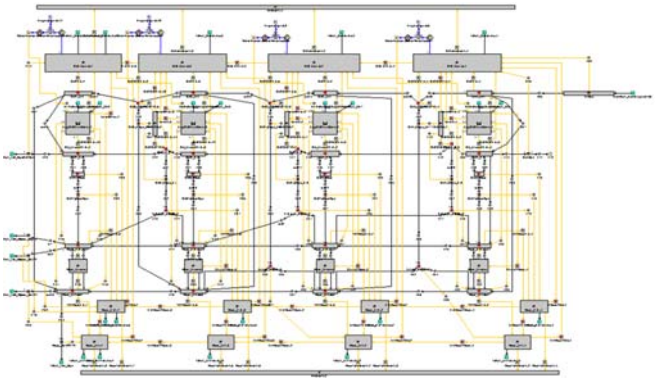
Classification	Definition	CAE tool example
Physical	- Mathematical formula based on physical law - Different from governing equation which need digitizing	- AMESim - Dymola - SimulationX - MappleSim - Matlab/Simulink
Statistical	- Mathematical formula or table based on measurement - Multiple linear regression - Combination with physical model	- Included in physical model tools
1D Digitizing	- Computational method for solving governing equation - Dynamic equation, Navier-Stokes - Discrete dimension is 1D	- GT Suite - AVL Boost, Cruise
3D Digitizing	- Same as above - Discrete dimension is 1D	- ABAQUS, NASTRAN - Converge, STAR, Fluent iconCFD

Current situation and challenge
Model examples (Water Jacket)

Engine W/J 3D Model



Equivalent 1D Model

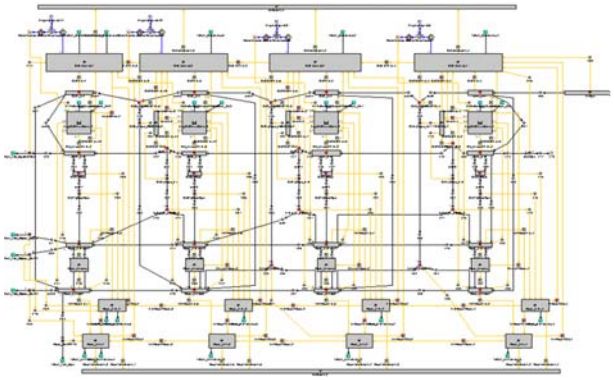


form（3D dimension）
Boundary conditions
(inlet, outlet flow rate ← pump).
The governing equations (Navier-Stokes)
→ Pressure drop, velocity, heat transfer coefficient (water - metal)

Form（1D dimension, diameter, lengths, volume)
Characteristic shape (pressure drop ← bent, orifice)
Boundary conditions (inlet, outlet flow rate ← pump).
The governing equations (Navier-Stokes)
→ Pressure drop, velocity,
heat transfer coefficient (water - metal)

Current situation and challenge
Model examples (Water Jacket)

1D Model



Form（1D dimension, diameter, lengths, volume)
Characteristic shape (pressure drop ← bent, orifice)
Boundary conditions (inlet, outlet flow rate ← pump).
The governing equations (Navier-Stokes)
→ Pressure drop, velocity,
heat transfer coefficient (water - metal)

Physical Model

$$dh2 = hmix2 \times A2 \times (Tf - T2)$$
$$dh4 = hmix4 \times A4 \times (Tf - T4)$$
$$hmix = \sqrt[3]{hconv^3 + hfree^3}$$
$$hfree = \frac{Nu(Gr,Pr) \times \lambda}{diam}$$
$$hconv = \frac{Nu(Re,Pr) \times \lambda}{diam}$$

Equation of water × metal heat transfer

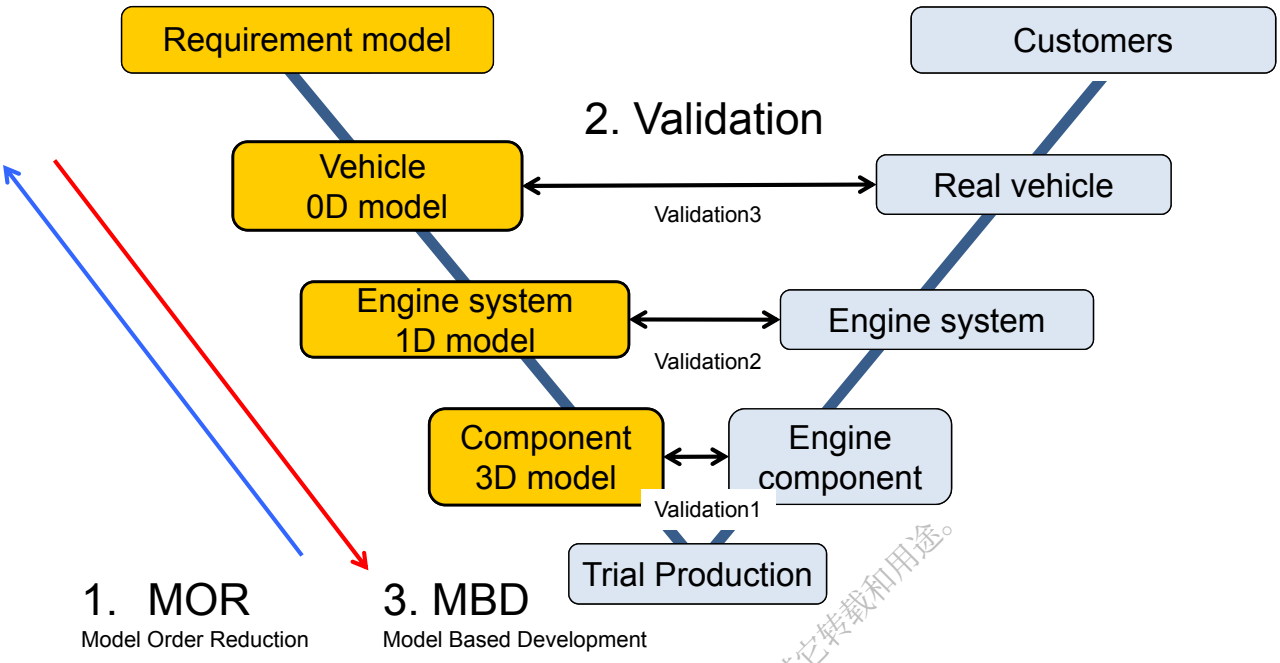
ff	friction factor
rec	critical Reynolds number
numin	constant value for laminar Nusselt
nuf	expression for free convection Nusselt number = f(gr,pr)
nul	expression for laminar Nusselt number = f(re,pr,mu,mus,ff)
nut	expression for turbulent Nusselt number = f(re,pr,mu,mus,ff)

Characteristic shape × physics
(Nusselt number)
Boundary conditions
(inlet, outlet flow rate ← pump).
The governing equations (Navier-Stokes)
→Average heat transfer coefficient
(water - metal)

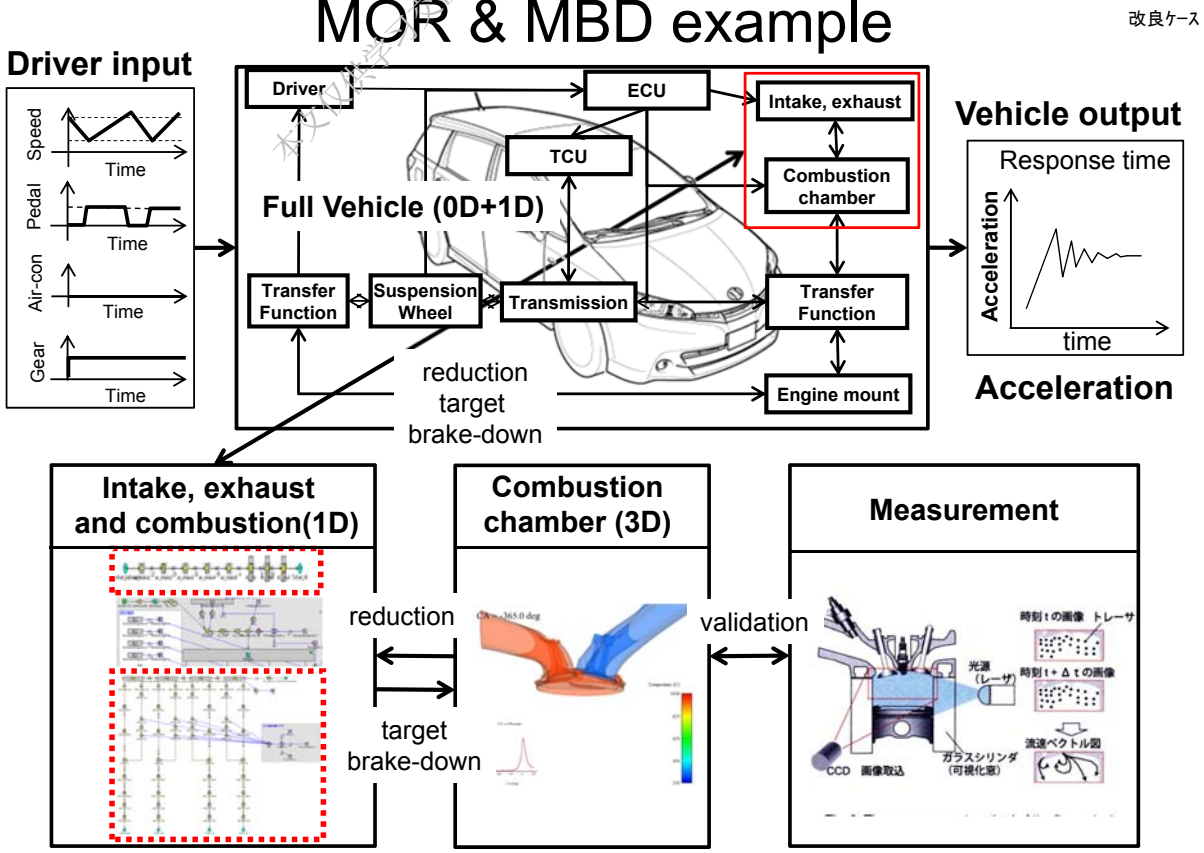
Current situation and challenge
Process and Model

Process	Model for optimization	Reason
Vehicle	Physical and Statistical 1D-digitiing	- Detail design optimization is done in later process (component). - Design parameter is value of trait and model for optimization is physical and statistical or partially 1D.
System (Engine)	1D-digitizing	- Detail design optimization is done in later process (component). - Design parameter is 1D and model for optimization is 1D-digitizing.
Component	3D-digitizing	- Design parameter is 3D. - 1D design parameters optimized in previous process are constraint in this process.

Current situation and challenge
Modeling and Development process(MBD)

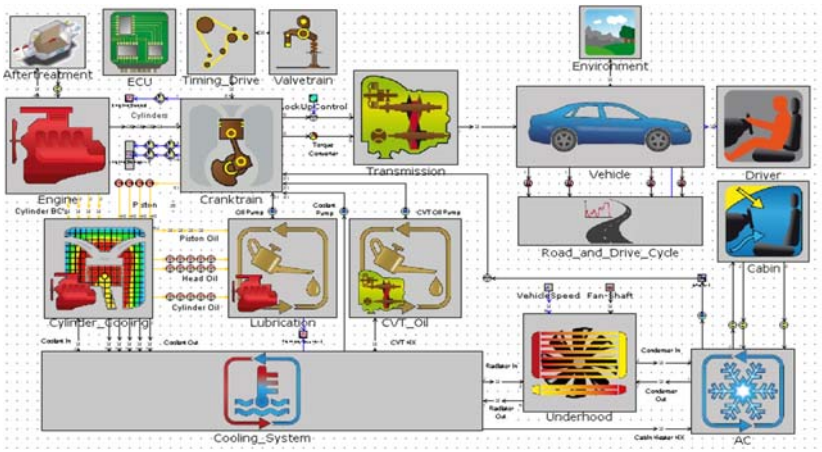


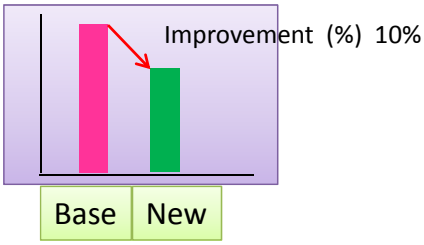
Current situation and challenge
MOR & MBD example



Current situation and challenge
MOR & MBD example
(Fuel consumption, GT/Suite application)

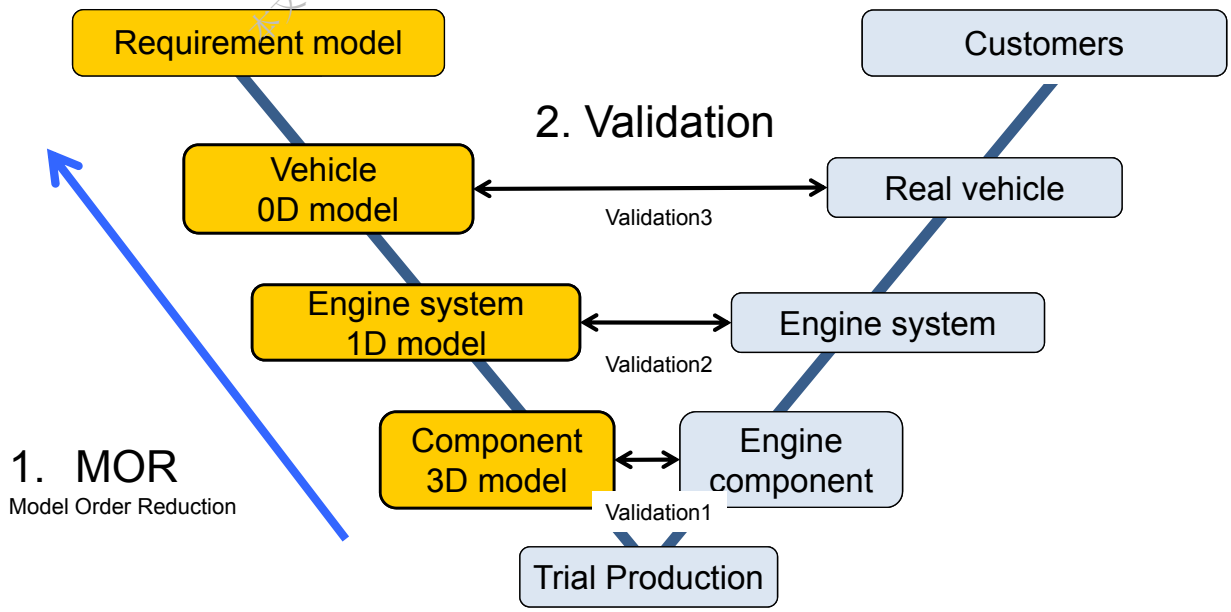
Input: Driving mode → Objective Function: Vehicle Fuel Consumption



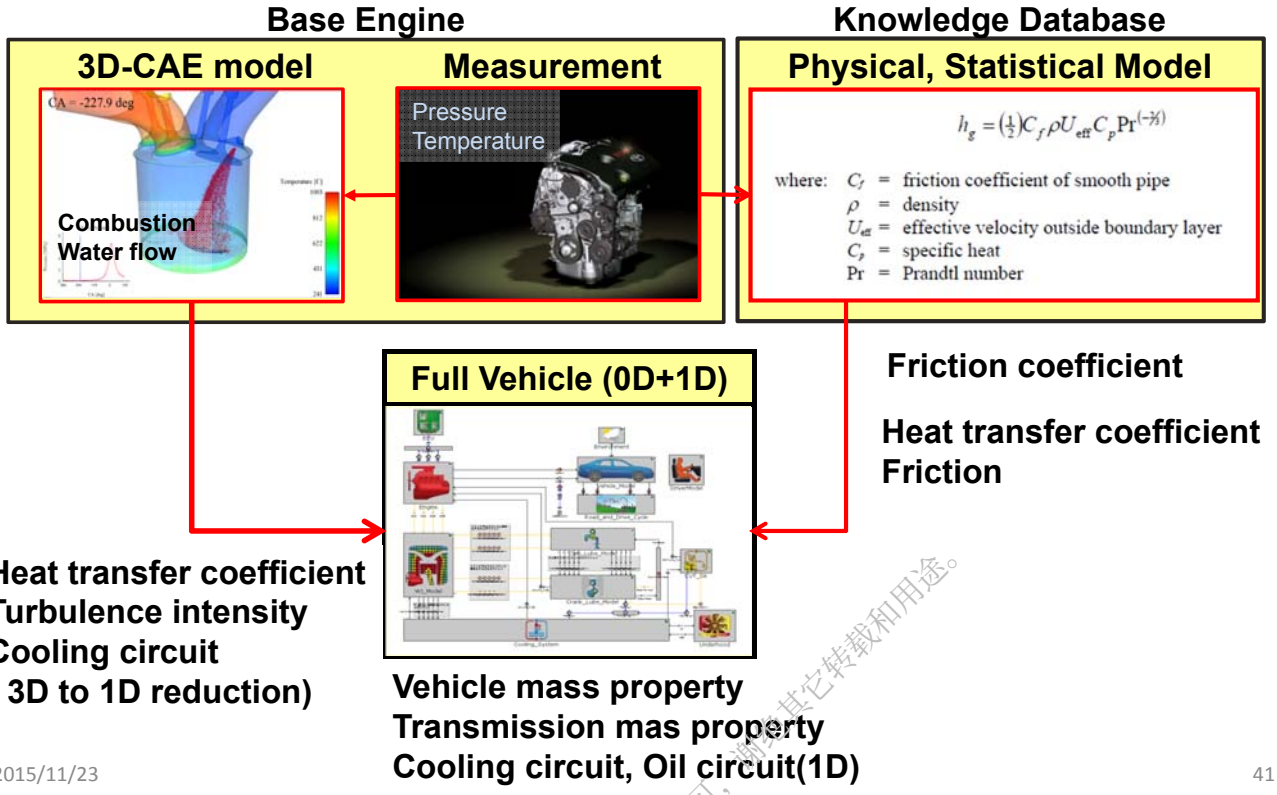


Engine Design Parameter: Base → New
Engine component (hardware)
(combustion chamber, port, piston, oil circuit, cooling circuit)

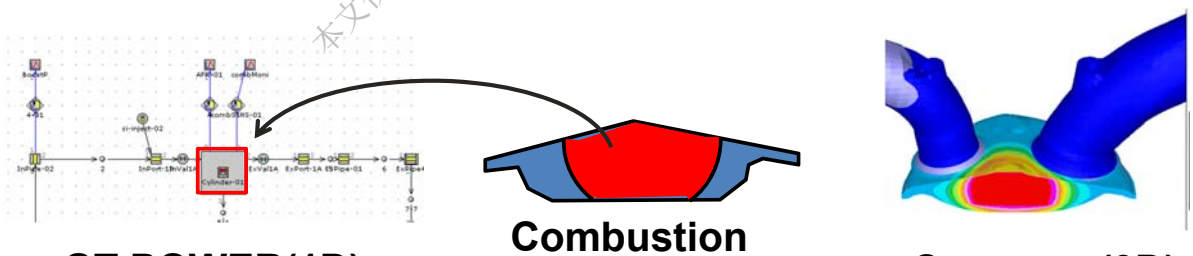
Current situation and challenge
MOR example



Current situation and challenge
Modeling example



Current situation and challenge
Modeling(engine air & combustion)



Same Physical Model Based

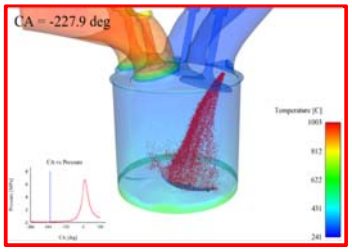
$$\frac{dQ}{dt} \propto ST \approx a \cdot u'^{a} P^{b}$$

dQ/dt: Heat release ratio
ST: Turbulence speed
u': Turbulence intensity
P: Cylinder pressure
a, b: parameter (it depends physical model)

Current situation and challenge
Modeling (Heat transfer)

<To be> **<Current>**

3D-CFD



OR

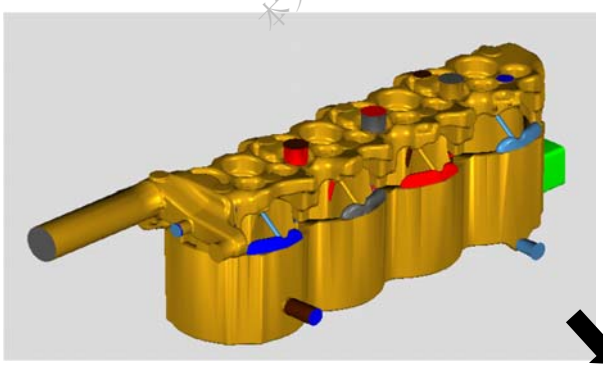
Experimental equation (Woschini)

$$\frac{dQ_{loss}}{dt} = h \cdot A_{Wg} \cdot (T_g - T_{Wg})$$

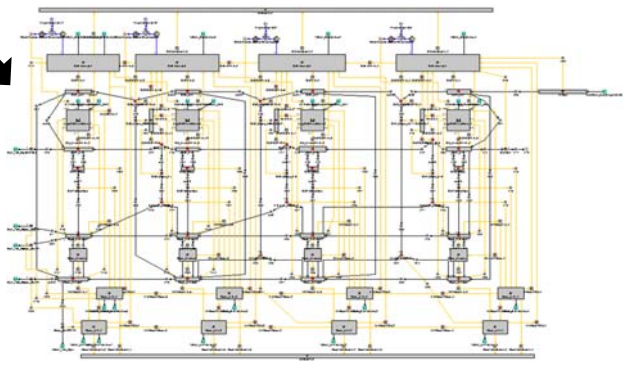
$$Where: h = \text{experimental equation}$$

$$h_{head} = a \cdot h$$
$$h_{liner} = b \cdot h$$
$$h_{piston} = c \cdot h$$

Current situation and challenge
Modeling (Cooling circuit)



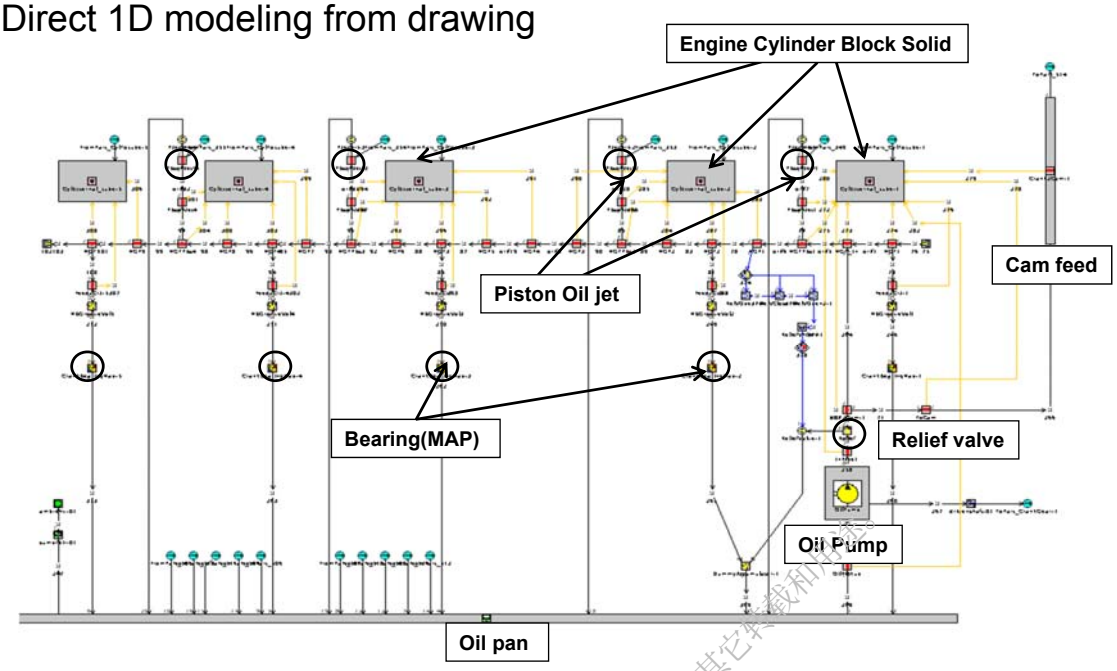
Heat transfer coefficient between water and metal is calculated by 3D-CFD



MOR(Model Order Reduction)
3D W/J model to 1D GT

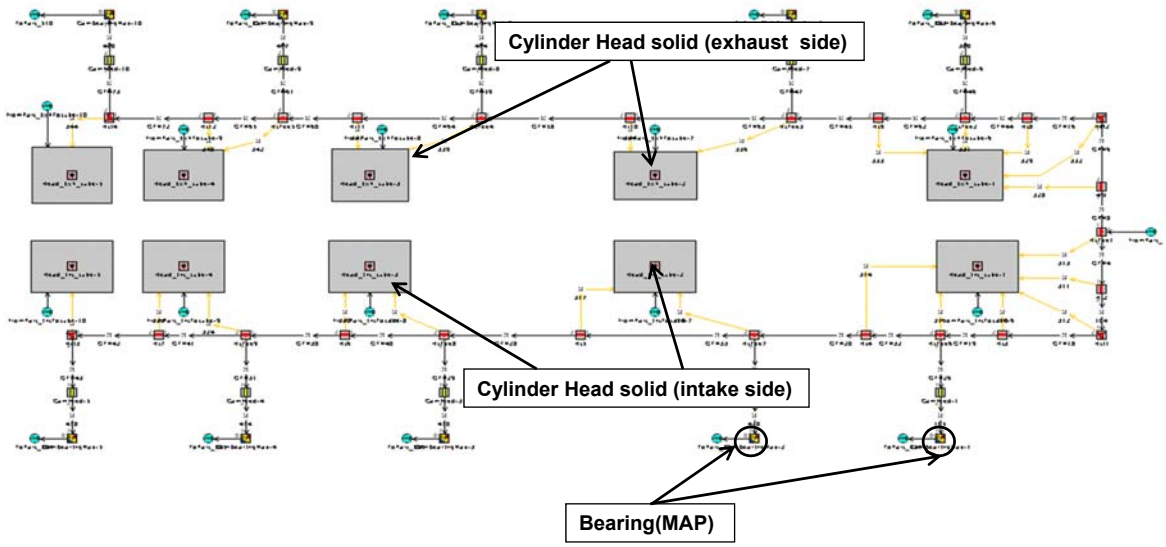
Current situation and challenge
Modeling (Oil circuit 1)

Direct 1D modeling from drawing



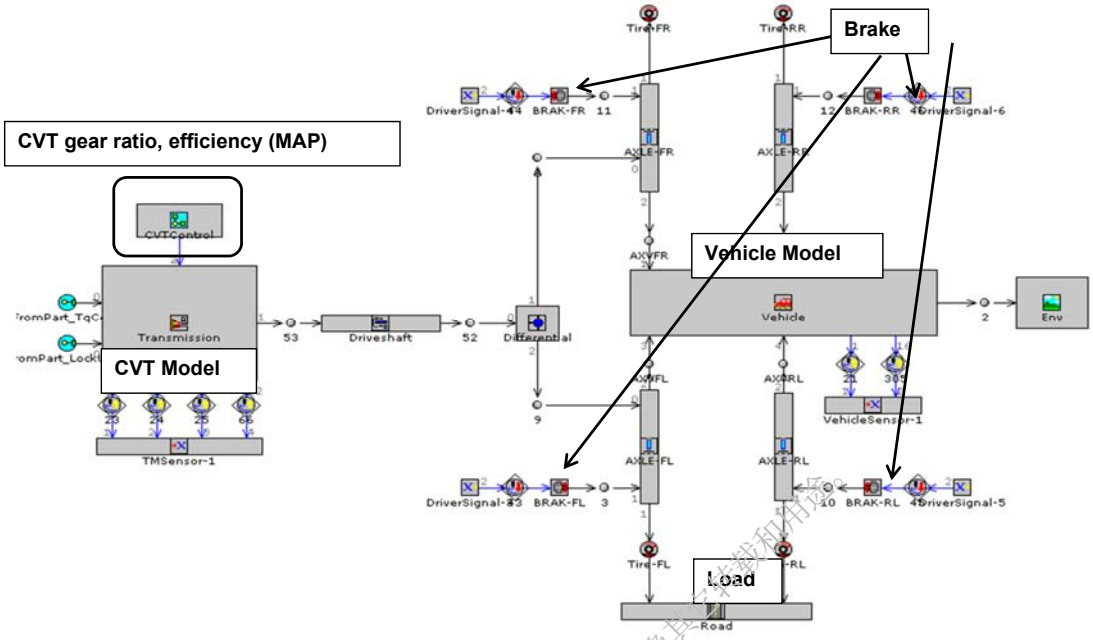
Current situation and challenge
Modeling (Oil circuit 2)

Direct 1D modeling from drawing

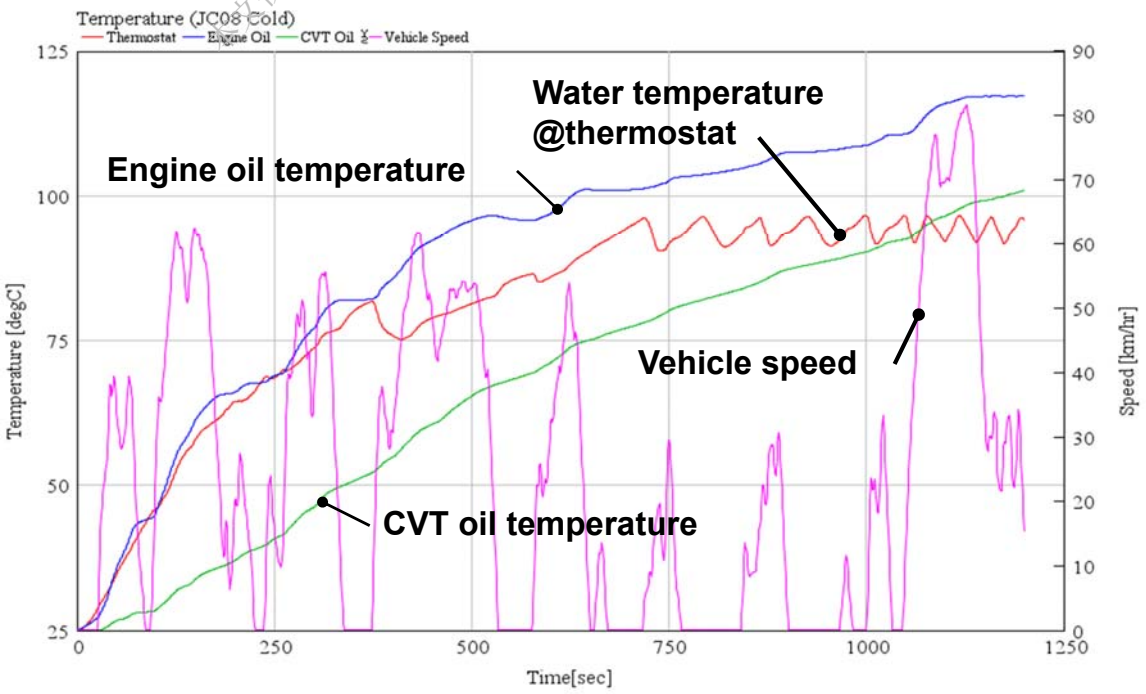


Current situation and challenge
Modeling (Vehicle & T/M)

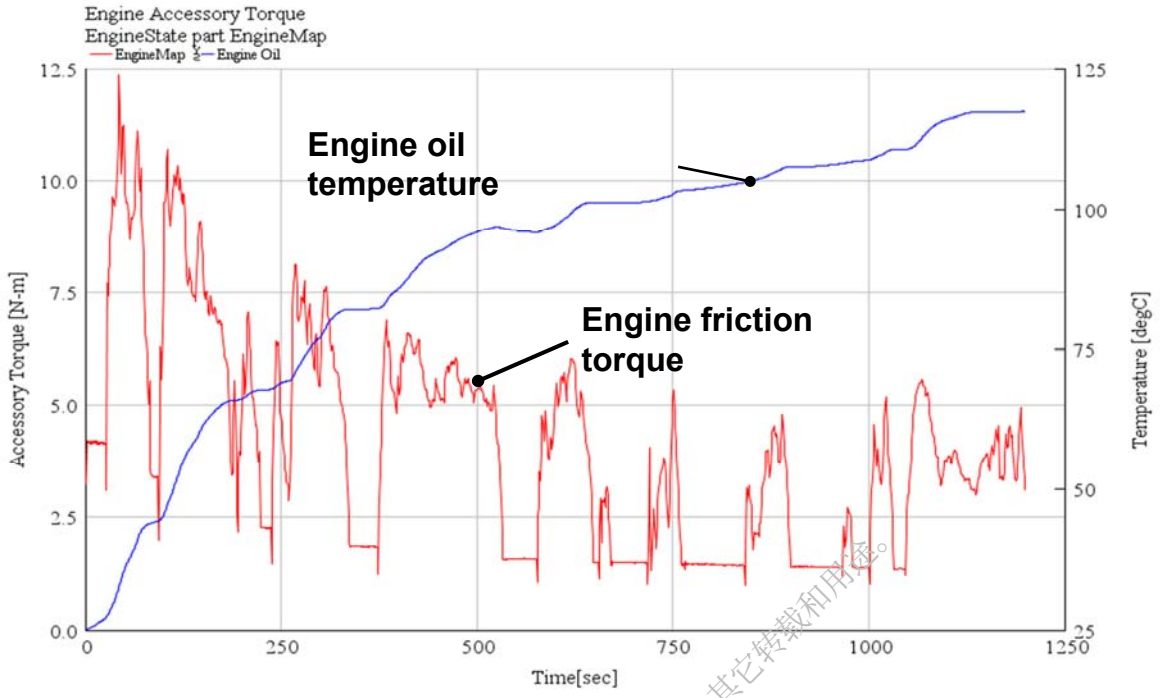
Direct 1D (0D) modeling from vehicle and T/M spec



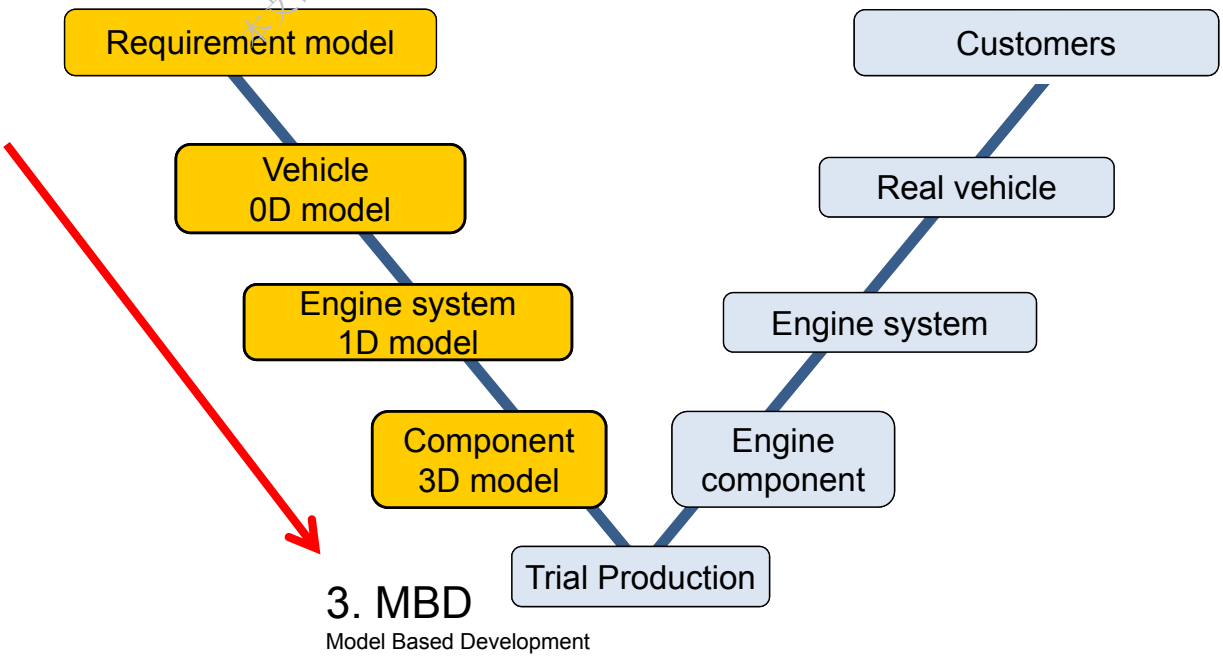
Current situation and challenge
Full vehicle 1D(0D) Simulation



Current situation and challenge
Full vehicle 1D(0D) Simulation



Current situation and challenge
MBD example



Currently MBD is still in concept phase

Current situation and challenge
MBD example (Concept)

Process	Function (performance) ex.	Design parameter
Vehicle	- Vehicle fuel consumption (Driving mode)	- Engine Fuel Consumption(BSFC) - Vehicle mass property - T/M (CVT 1D parameter)
System (Engine)	- Engine Fuel Consumption (BSFC) MAP	- Friction (FMEP) MAP - Thermal efficiency
Component	- Friction (FMEP) MAP - Thermal efficiency	- Friction (cylinder system, valve, oil, water circuit) - Combustion chamber

History & Future Vision of CAE Utilization

Contents

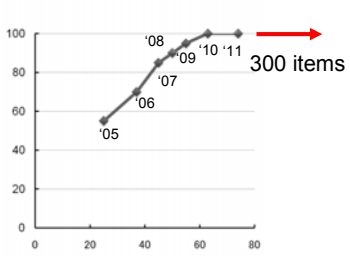
1. My work experience and current
2. History of CAE utilization in engine development process
3. Current situation and challenge
4. Future vision of CAE utilization

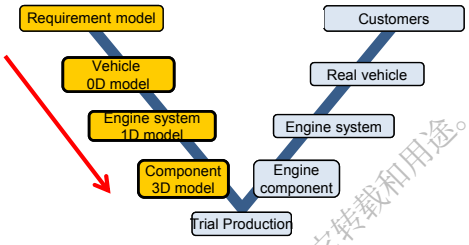
Future vision of CAE utilization
Four Directions

1. Increment of CAE items
2. MBD from concept phase to realization

} Extension of the past

3. Direct numerical Simulation for developing physical model
4. 1D(0D)+Robustness Simulation for cultivating design sense

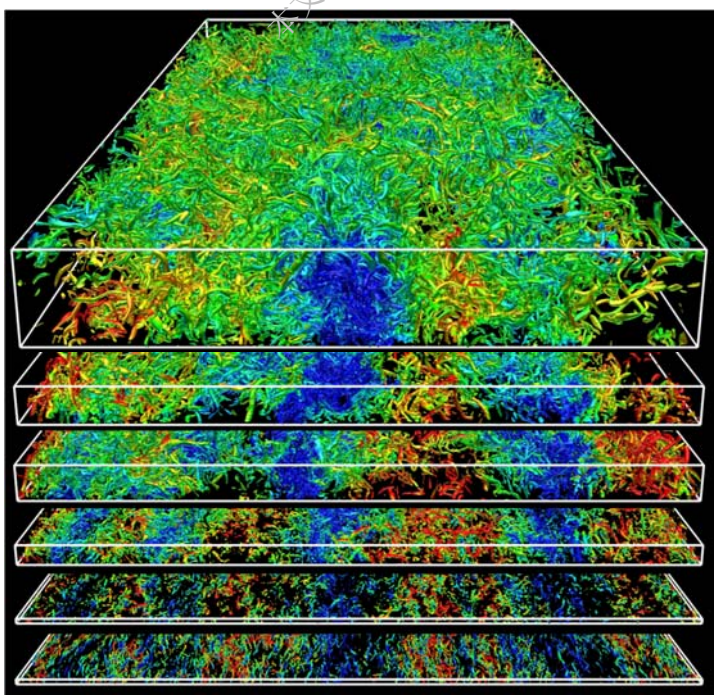


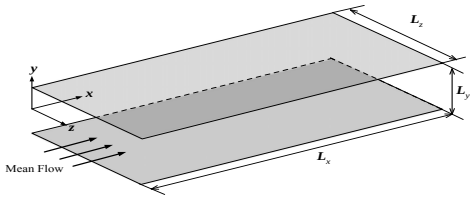


1. Increment of CAE items

2. MBD from concept phase to realization

Future vision of CAE utilization
DNS for developing physical model





DNS for channel flow
by Super parallel computer

1. Clarification of mechanism of turbulent flow generation
2. Verification of LES physical models

Future vision of CAE utilization

1D(0D)+Robustness Simulation

Shape→Function→Shape

(Base) (New)

1. Insight **function** from shape
2. Break-down **function** to riverhead } Training
3. Modeling of **function** and packaging (1D)
4. Optimization (Sensitivity and SN ratio)
5. 1D to 3D shape (parametric, topologic and finally completely new)

modeFRONTIER is very good tool for 4 and 5

History & Future Vision of CAE Utilization

感谢您的关注

Thank you for your attention

ご静聴ありがとうございました