JMAG-RT apply to the design quality verification of motor control ECU

Yoshinori Takeuchi
DENSO CORPORATION,Corporate ePF Division
Head Office:1-1, Showa-cho, Kariya-shi, Aichi-ken, 448-8661, Japan
TEL:+81-566-61-5112,FAX:+81-566-25-4618
YOSHINORI_TAKEUCHI@denso.co.jp

Abstract ：
DENSO is an automotive ECU supplier that has been developing ECUs for controlling traction motors for diversifying H/EVs. The algorithms of ECU must be validated from various aspects whether it fulfills customer's specifications. However, there are many conditions that cannot be tested using a real vehicle. In such cases we use HILS (Hardware-In-the-Loop Simulation). Conventional HILS was not suitable for the validation of algorithms since it lacked motor models that can simulate all of the necessary characteristics in real time. We found JMAG-RT as a possible candidate of model generator, but we had to have motor parameters with sufficient precision. As an ECU supplier, we cannot acquire those data. Instead, we found a method to generate motor models from control parameter maps in the specification of the customer. This idea was implemented by JSOL corporation. Some case studies using JMAG-RT are introduced here applied for the improvement of design quality.

JMAG Users Conference 2011 12/7/2011

JMAG-RT Application for Control Quality Studies of Motor Control ECUs

DENSO CORPORATION
Corporate ePF Division
Mr. Yoshinori Takeuchi

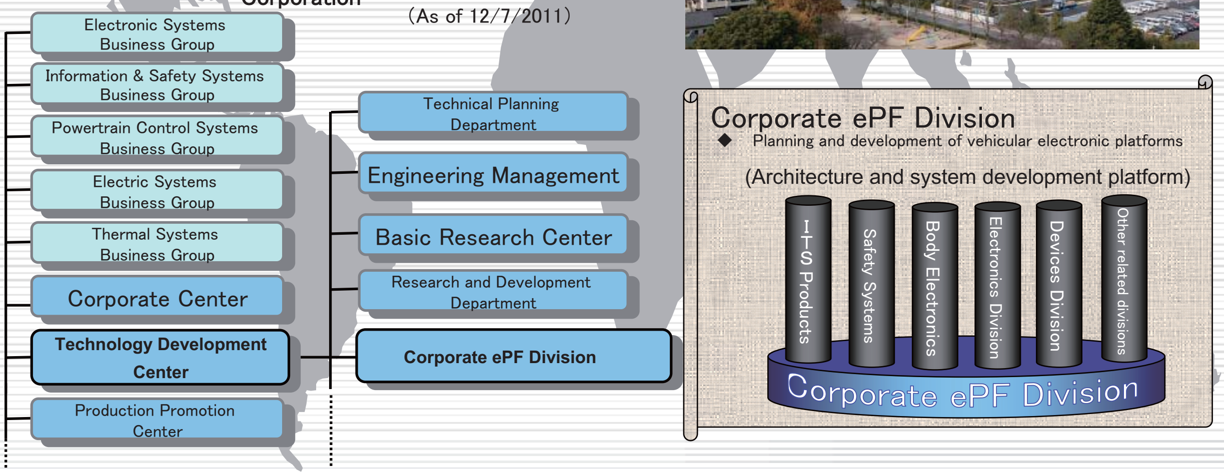
DENSO

Company Introduction

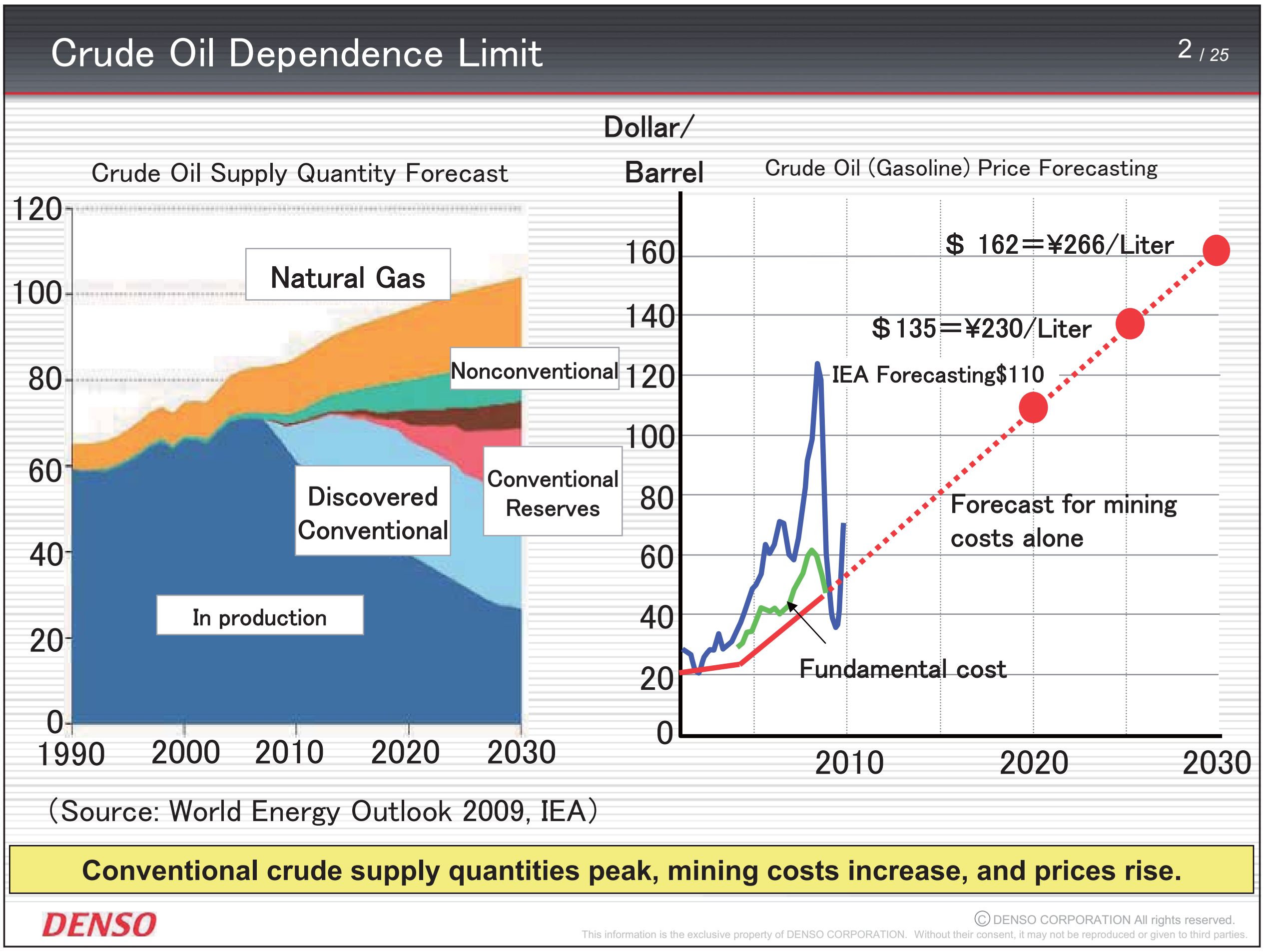
1 / 25

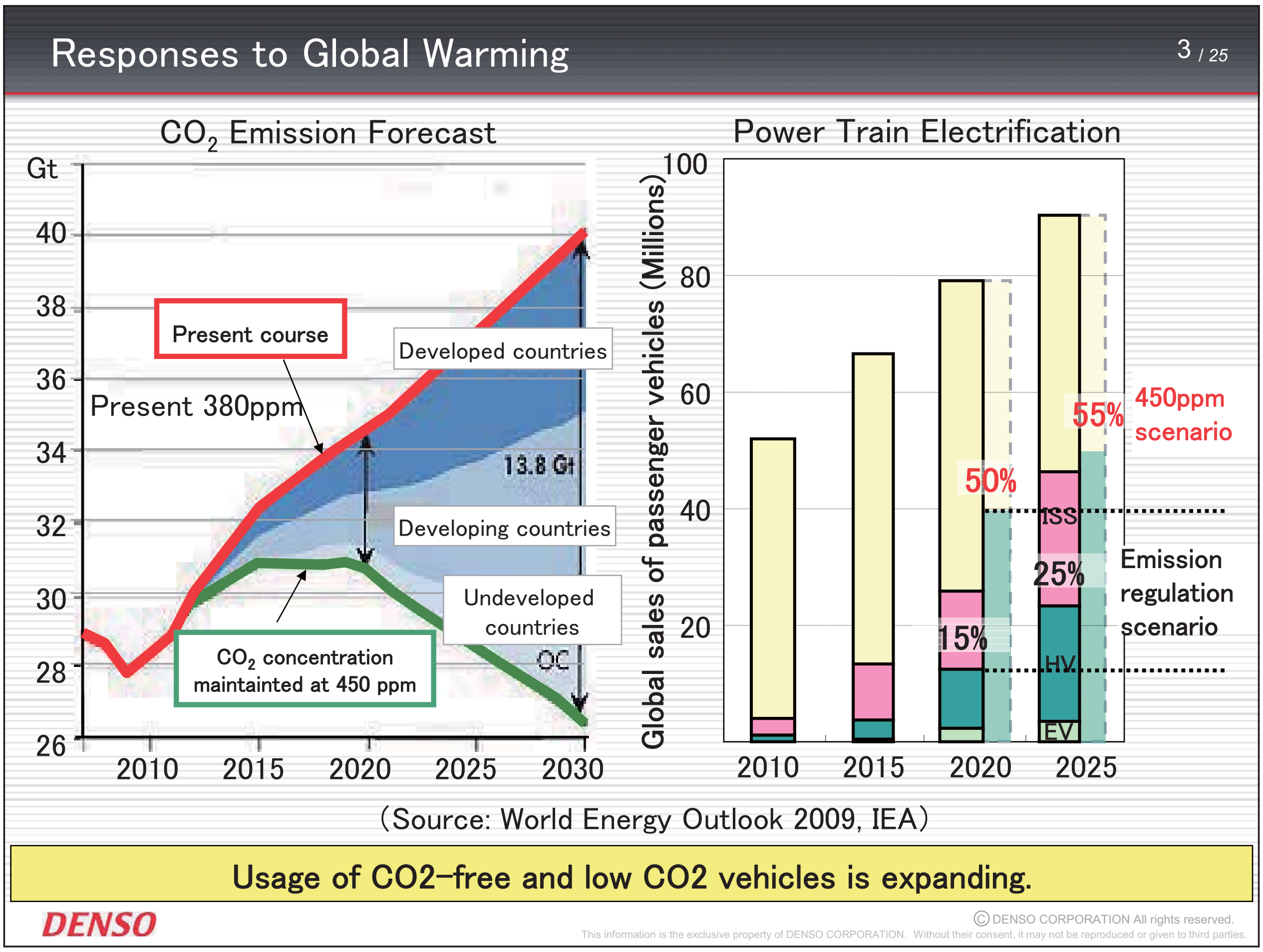
Company name	DENSO CORPORATION	
Established	December, 1949	
Headquarters	Kariya City, Aichi Prefecture	
Capital	¥187.4 billion (U.S. $2.3 billion)	
	〈Non-consolidated〉	〈Consolidated〉
Net sales	¥1,945.7 billion	¥3,131.5 billion
Employees	38,318	123,165
Main customers	Domestic and international automotive manufacturers,including Toyota Motor Corporation	

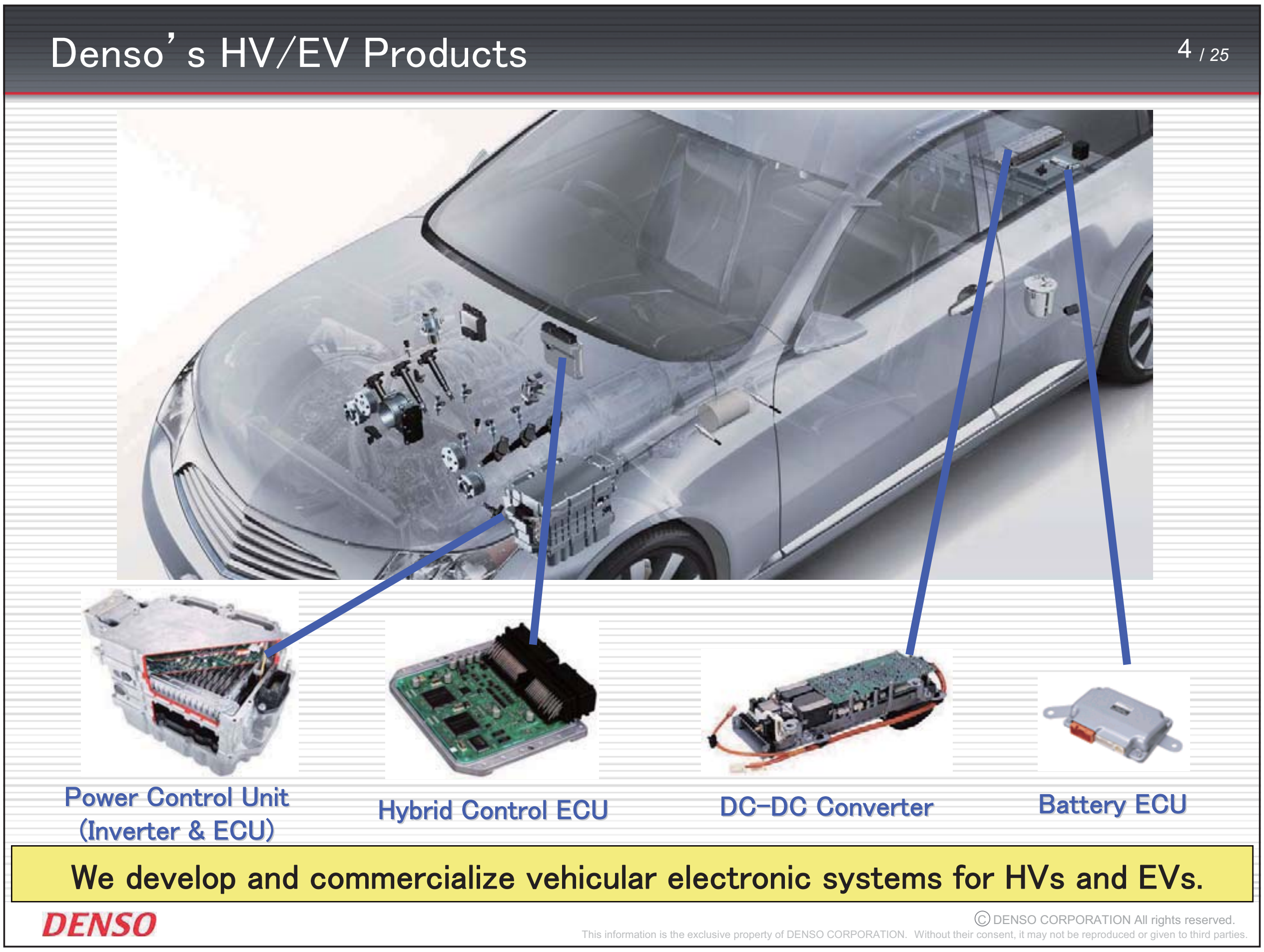
(As of 12/7/2011)

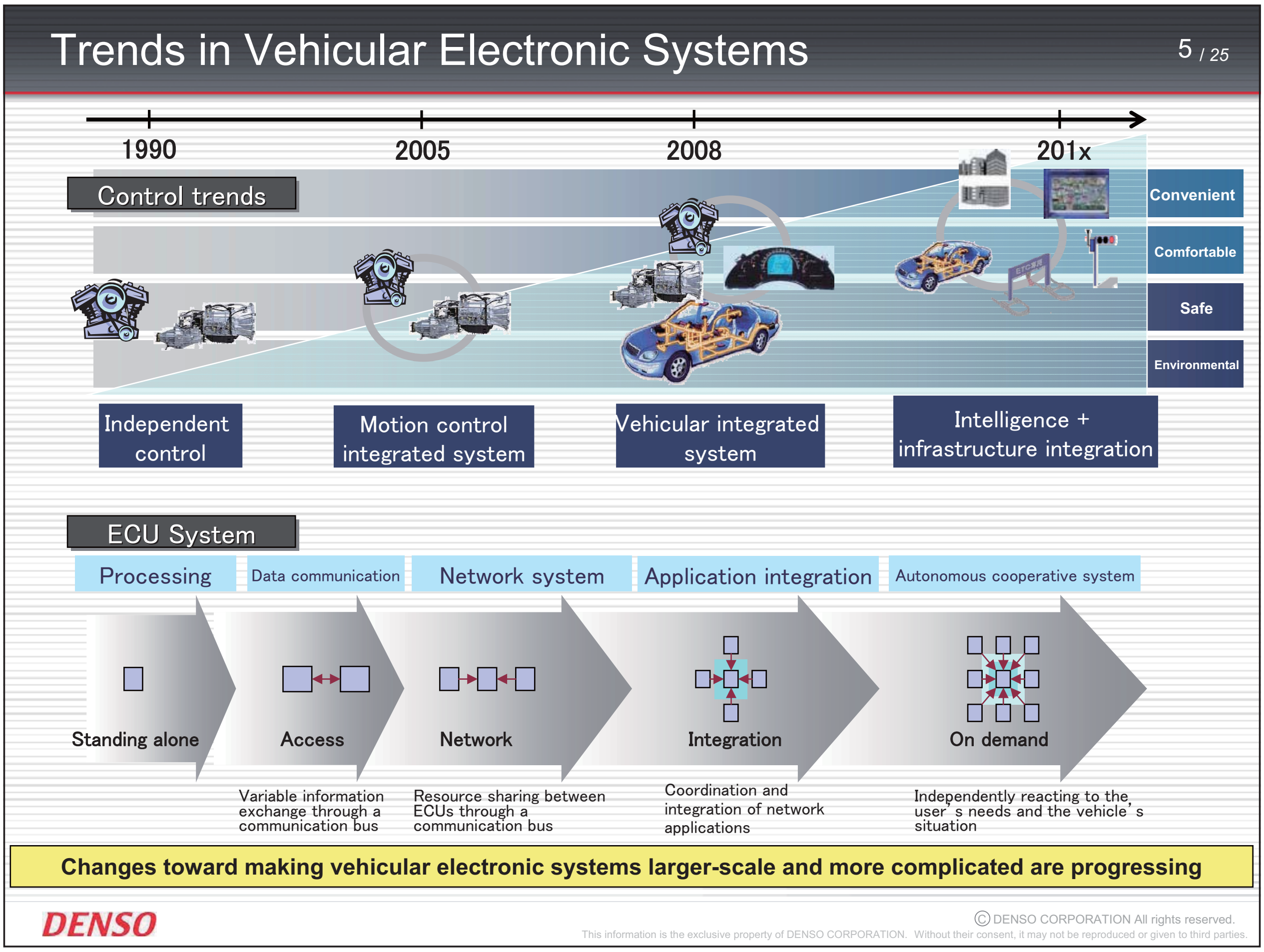


DENSO

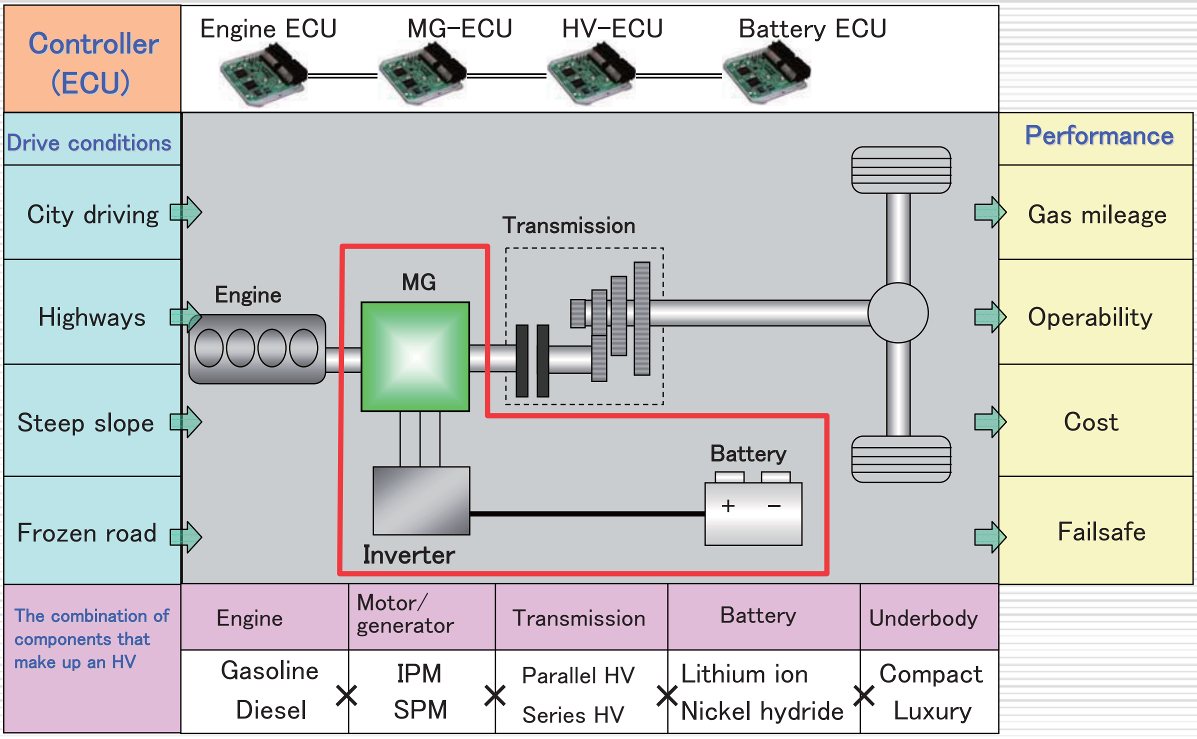

Crude Oil Dependence Limit
2 / 25
Crude Oil Supply Quantity Forecast
Natural Gas
Nonconventional
Discovered Conventional
Conventional Reserves
In production
120
100
80
60
40
20
0
1990
2000
2010
2020
2030
Dollar/ Barrel
Crude Oil (Gasoline) Price Forecasting
$ 162=¥266/Liter
$135=¥230/Liter
IEA Forecasting$110
Forecast for mining costs alone
Fundamental cost
160
140
120
100
80
60
40
20
0
2010
2020
2030
(Source: World Energy Outlook 2009, IEA)
Conventional crude supply quantities peak, mining costs increase, and prices rise.
DENSO
©DENSO CORPORATION All rights reserved.
This information is the exclusive property of DENSO CORPORATION. Without their consent, it may not be reproduced or given to third parties.


Responses to Global Warming
3 / 25
CO2 Emission Forecast
Gt
40
38
36
34
32
30
28
26
Present course
Present 380ppm
Developed countries
13.8 Gt
Developing countries
Undeveloped countries
OC
CO2 concentration maintainted at 450 ppm
2010
2015
2020
2025
2030
Power Train Electrification
Global sales of passenger vehicles (Millions)
100
80
60
40
20
50%
55%
450ppm scenario
ISS
25%
15%
HV
EV
Emission regulation scenario
2010
2015
2020
2025
(Source: World Energy Outlook 2009, IEA)
Usage of CO2-free and low CO2 vehicles is expanding.
DENSO
©DENSO CORPORATION All rights reserved.
This information is the exclusive property of DENSO CORPORATION. Without their consent, it may not be reproduced or given to third parties.


Denso's HV/EV Products
4 / 25
Power Control Unit
(Inverter & ECU)
Hybrid Control ECU
DC-DC Converter
Battery ECU
We develop and commercialize vehicular electronic systems for HVs and EVs.
DENSO
© DENSO CORPORATION All rights reserved.
This information is the exclusive property of DENSO CORPORATION. Without their consent, it may not be reproduced or given to third parties.

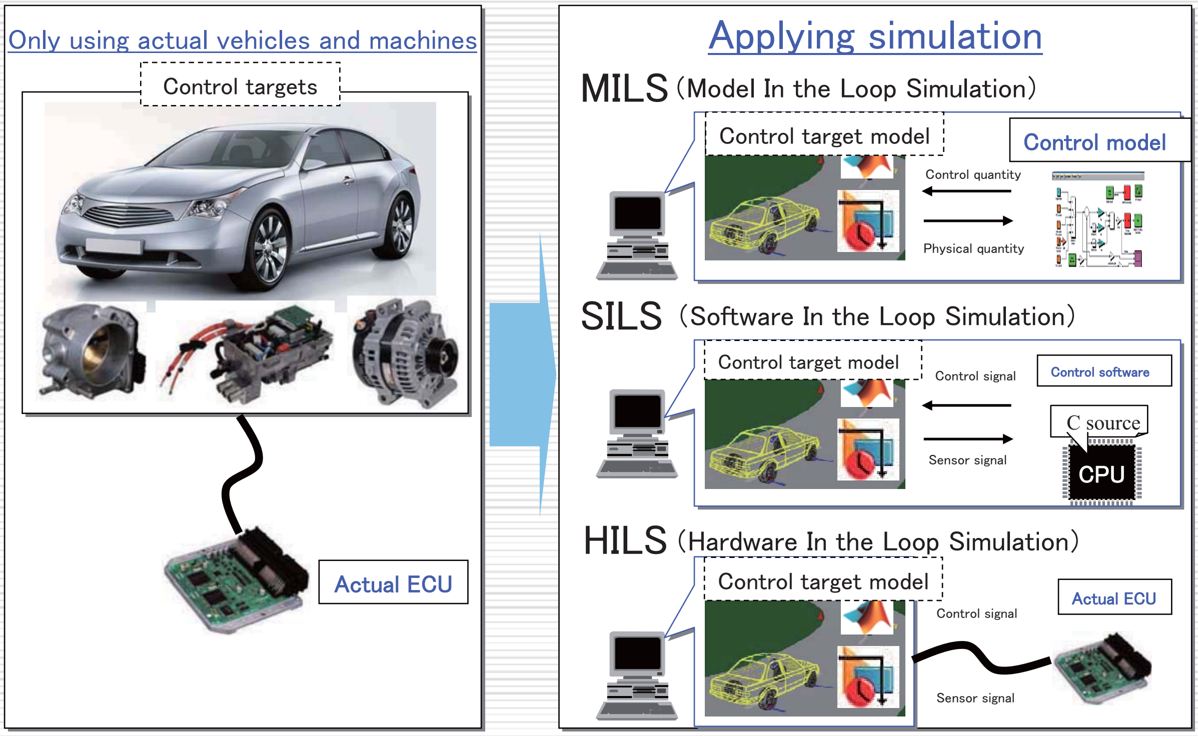

Trends in Vehicular Electronic Systems
5 / 25
1990
2005
2008
201x
Control trends
Convenient
Comfortable
Safe
Environmental
Independent control
Motion control integrated system
Vehicular integrated system
Intelligence + infrastructure integration
ECU System
Processing
Data communication
Network system
Application integration
Autonomous cooperative system
Standing alone
Access
Network
Integration
On demand
Variable information exchange through a communication bus
Resource sharing between ECUs through a communication bus
Coordination and integration of network applications
Independently reacting to the user's needs and the vehicle's situation
Changes toward making vehicular electronic systems larger-scale and more complicated are progressing
DENSO
© DENSO CORPORATION All rights reserved.
This information is the exclusive property of DENSO CORPORATION. Without their consent, it may not be reproduced or given to third parties.

Electronic Control Systems for HVs



The supplier's mission is to provide the most suitable electronic control system for the various compositions of HVs.

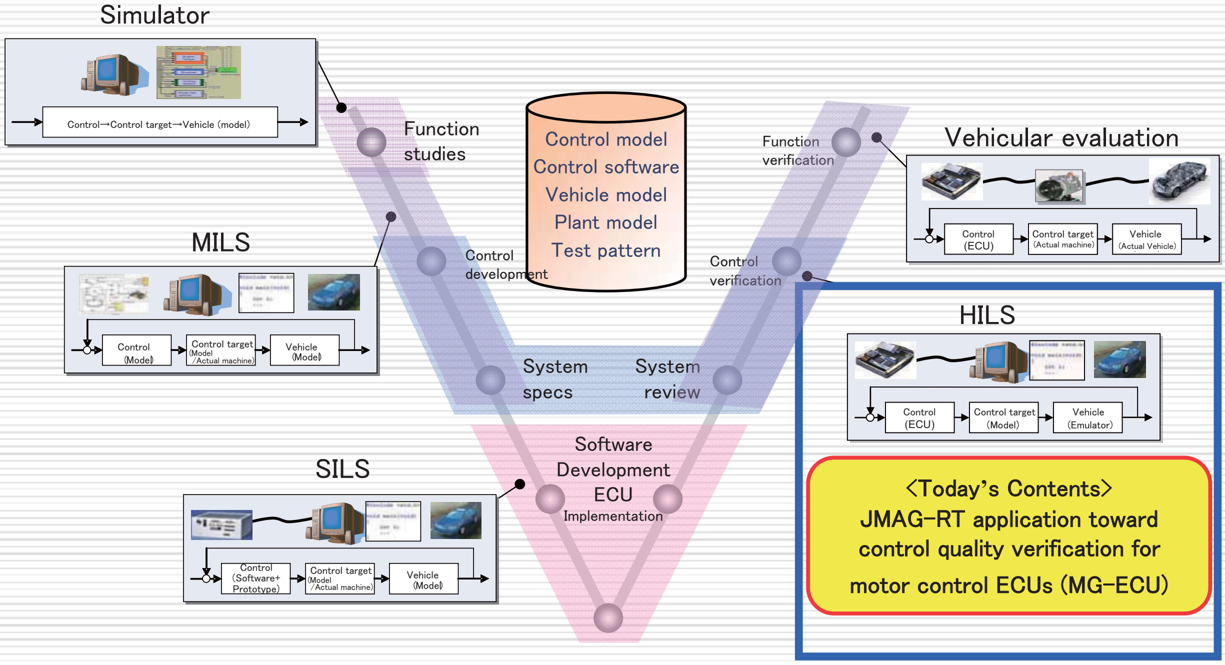
Changes in the Development Environments for Electronic Control Systems



The development environment is changing from one that is based on actual machines and vehicles are used to one which applies simulation.

Denso's Electronic Control System Development Model

8 / 25



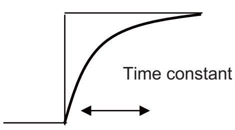
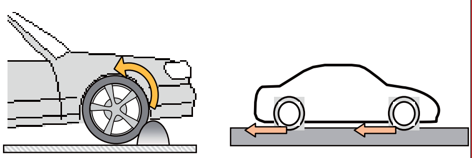
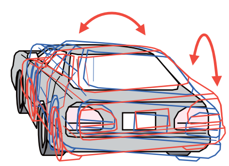
We apply it to simulations in every development phase.

DENSO

Control Quality Verification for Motor Control ECUs

9 / 25

■Items for motor control quality verification

Range	Function	Robustness	Functionality
Environment	Motor-bench	HILS	Actual vehicle
Viewpoint	Torque accuracy, Responsiveness	Environmental leeway, Stability	Ride quality, operability
Contents	･The motor torque accuracy against the designated torque ･The motor torque's response time constant  Fulfilling the value required from the vehicle manufacturer.	･From deserts to ice fields ･Product variation (motors, sensors, etc.) ･Slip and grip between the road surface and the tires  Stable operation without control breakdowns.	･Various driving patterns  No feeling of discomfort

We carry out verifications of motor control robustness in limit conditions.

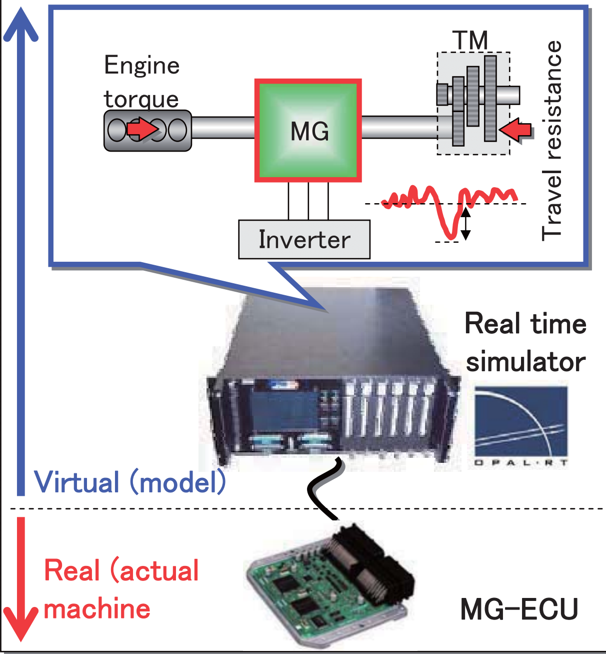
DENSO

Robustness Verification Environment for MG-ECU Controls

10 / 25

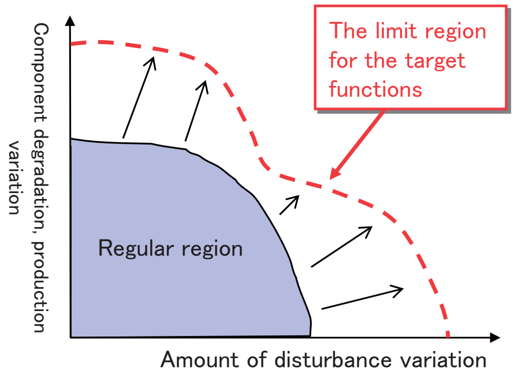
■The composition of MG-HILS

Replicating torque fluctuations from disturbance



■Range of application

Verifying the robustness of MG-ECU controls



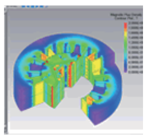
We carry out robustness verification, which is hard with an actual machine, with an HILS environment.

DENSO

Problems with Motor Model Accuracy

11 / 25

■Types and accuracy of motor models

		dq (Fixed parameters)	JMAG-RT (FEA)
Parameter		O: Available Inductance, resistance, flux	×: Unavailable  The motor's design information Dimensions, materials
Accuracy		Low	High
	Magnetic saturation	×: Currently unavailable	O: Currently available
	Back EMF	×: Sine wave	O: Nonlinear
	Cogging	×: Currently unavailable	O: Currently available
Real time		O: 50nsec	O: 200nsec

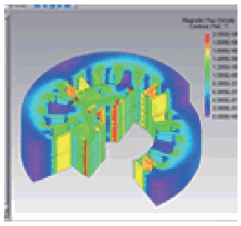
The accuracy is equivalent with an actual motor, and it is necessary to have a motor model that can be constructed easily.

DENSO

Analysis of Nonlinear Map Generation Methods Using Design Information

■Nonlinear Map Generation Methods From Design Information (JMAG-RT)

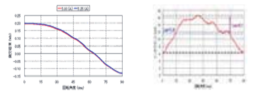
Motor design information



Geometry, dimensions, material quality

JMAG-RT

We use FEM to divide the mesh, calculate the flux, and generate a nonlinear map from changes in the flux.



Nonlinear map generation (multiple)

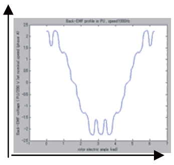
Angle phase [rad]

Amplitude [A]

Ld、Lq

130,000 points

Voltage [V]



Rotation angle [rad]

Inductance map

Back EMF map

■Nonlinear maps necessary for a motor model

① Resistance map ② Inductance map ③ Back EMF map

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} r_a & 0 & 0 \\ 0 & r_b & 0 \\ 0 & 0 & r_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \omega_e \left\{ \frac{d}{d\theta_e} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \right\} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

ω_e :Electric angular velocity [rad/s] θ_e :Electric degree [rad]

If we can generate a nonlinear map, then we can construct a motor model that provides the necessary accuracy.

DENSO

Inductance Map Generation Using the Control Map Within the ECU

■Torque estimation map within the MG-ECU

Torque estimation map

Amplitude [A]

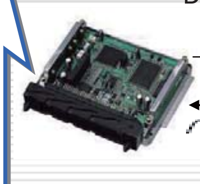
Angle phase [rad]

	0	30	600
0			
10			
360			

Torque [Nm]

20 × 10 × 2 = 400 points

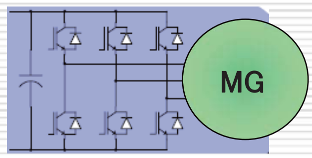
MG-ECU



Drive PWM

Current

Motor, inverter



■From torque estimation maps to inductance nonlinear map generation

Amplitude [A]

Angle phase [rad]

	0	30	600
0			
10			

Torque [Nm]

20 × 10 × 2 = 400 points

A map for torque estimation provided by a vehicle manufacturer

$$\tau = \phi i_q + (L_d - L_q) i_d i_q$$

τ : Torque Φ: Flux

Calculating the inductance LdLq from the torque formula

Id [A]

Iq [A]

-500	-100	0

130,000 points

Creating Ld and Lq nonlinear maps with linear interpolation

We calculate inductance maps (Ld and Lq) from torque estimation maps in the ECU.

DENSO

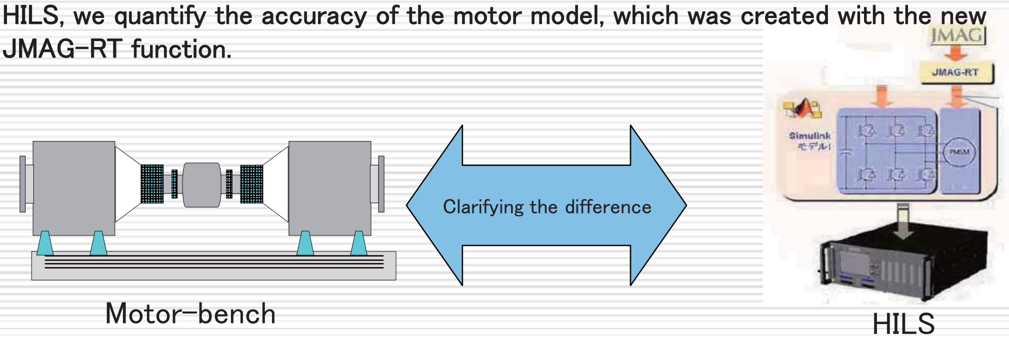
Proposed Calculation Methods

A new function has been proposed that generates a JMAG-RT file (rtt) from various types of data.

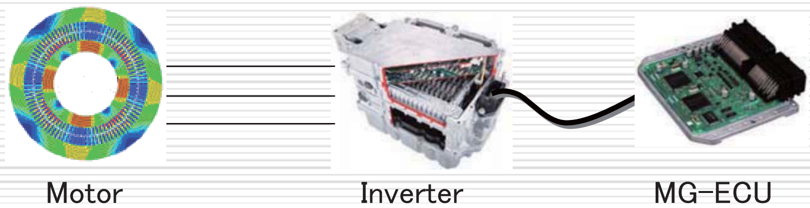
This mechanism makes it possible to generate a motor model from an inductance map.

The Evaluation Policy for Motor Models Constructed in JMAG-RT

By assuming that the motor-bench values are correct and clarifying the difference with HILS, we quantify the accuracy of the motor model, which was created with the new JMAG-RT function.



Instead of an evaluation of just the motor, it is an evaluation of the combination of the motor, the inverter, and the MG-ECU.

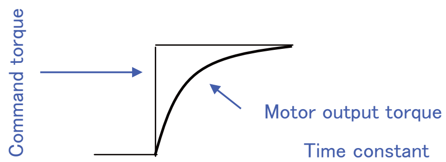


We quantify the accuracy by taking the motor-bench calculation data to be true and clarifying the difference.

Evaluation Standpoints

16 / 25

■Evaluation standpoints

Standpoint	Contents	Judgment method	Required value
Torque accuracy	Fixing the motor rotation speed and the command torque, and measuring the steady state torque.	Difference in torque accuracy	Within ±5%
Phase current frequency characteristics	Fixing the motor rotation speed and the command torque, and measuring the steady state current phase.	Difference in the intensity of harmonic components	Within ±5%
Responsiveness	Performing step input for command torque and measuring the output torque. 	Difference in the time constant of the torque response waveform	Within ±5%

We evaluate the motor model's accuracy from these three standpoints.

DENSO

Evaluation results

17 / 25

■A list of the evaluation results

Standpoint	Points	Result	
Torque accuracy	199	OK	Accuracy: Confirmed at within ±5%
Phase current frequency characteristics	16	Borderline	There were deviations of over 200% in the frequency intensity of the harmonic components (Resulting from the fact that the harmonic components were not included in the measurement data during the model's creation).
Responsiveness	18	OK	Time constant: Confirmed at within ±5%

We were able to confirm that the accuracy of the motor model fulfills the required values (Application to quality verification is possible).

DENSO

Evaluation Result 1: Torque Accuracy (Display of the Difference with an Actual Motor-bench) 18 / 25

■Difference in torque accuracy

We confirmed that the difference in torque accuracy fulfills the required value.

DENSO

Evaluation Result 2: Frequency Characteristics (Display of the Difference with an Actual Motor-bench) 19 / 25

DENSO

Evaluation Result 3: Responsiveness (Display of the Difference with an Actual Motor-bench) 20 / 25

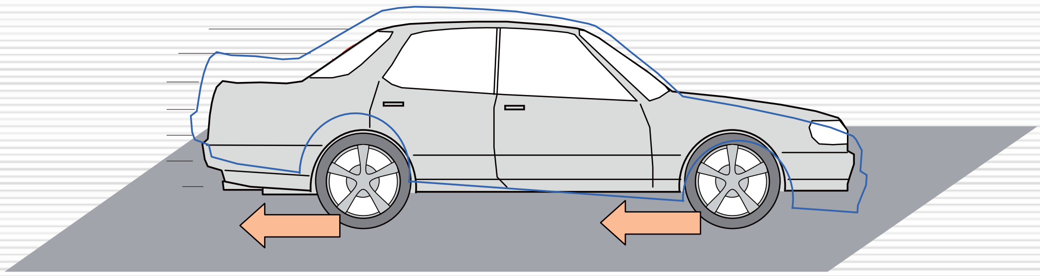
■Response waveform of the motor output torque

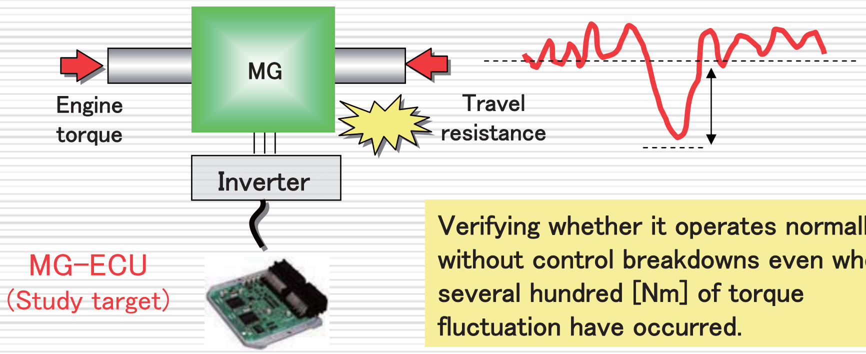
We confirmed that the time constant difference fulfills the required value.

DENSO

An Example of MG-ECU Control Robustness Verification 21 / 25

(Ex.) When you have suddenly slipped and hit the brakes while driving





Verifying whether it operates normally without control breakdowns even when several hundred [Nm] of torque fluctuation have occurred.

We applied it to conditions that are difficult to verify with an actual machine (motor-bench) or vehicle.

DENSO

The Condition Settings for Verifying Robustness

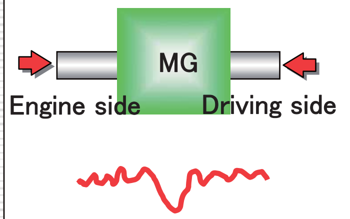
22 / 25

■Combined conditions

Load torque

−Driving load torque

−Engine torque



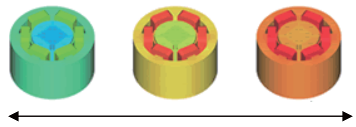
Minus several hundred [Nm]

×

Temperature characteristic fluctuations

−Magnetic flux of the magnet

−Resistance



×

Production variation

Motor

−Inductance

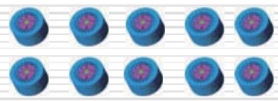
−Resistance

Sensor

−Voltage

−Current

−Angle



Dozens of rtt files

By applying JMAG-RT it became possible to set all of the verification conditions.

DENSO

Robustness Verification When the Rotation Speed Suddenly Changes

23 / 25

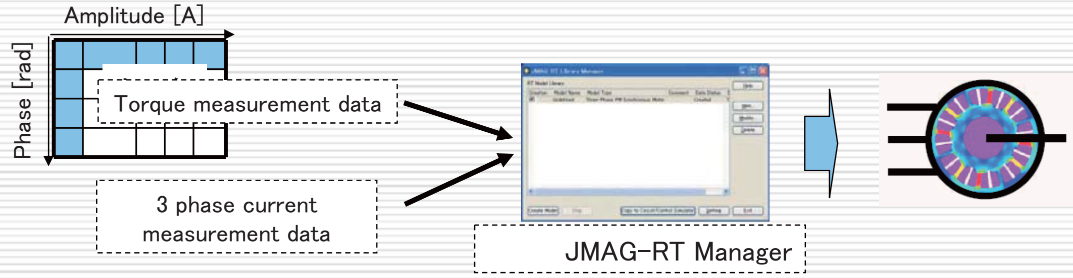
We were able to verify that the motor controls operate normally without any breakdowns even under the most difficult conditions.

DENSO

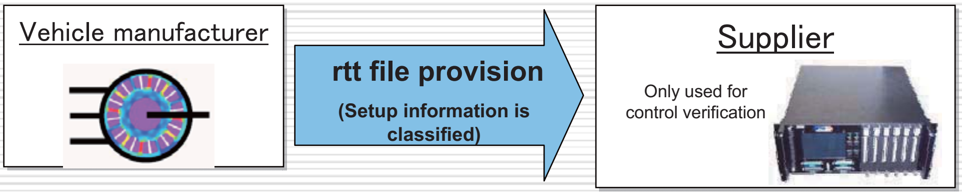
Hopes and Expectations for JMAG-RT in the Future

24 / 25

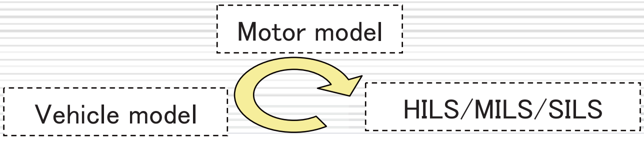
(1) Supporting multiple data



(2) Support for classifying JMAG-RT (.rtt) files



(3) Further coupling with a variety of tools



DENSO

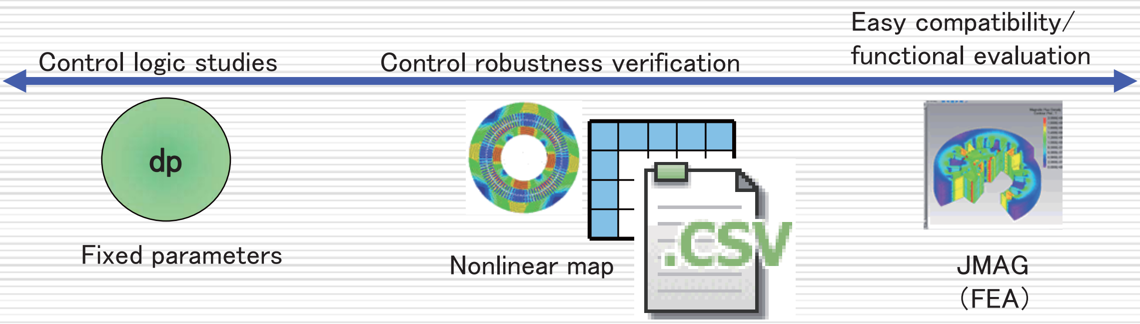
In Conclusion

25 / 25

Thanks to JSOL's cooperation we were able to get a mechanism that easily creates motor models and provides nonlinear characteristics equivalent with an actual motor.

The accuracy of the motor model was within ± 5% when compared with an actual motor.

By applying JMAG-RT, it became possible to verify motor control robustness.



Thank you for your attention

DENSO