MATLAB EXPO

FCEV용 모터 설계를 위한 차량 모델링

김동민 교수, 호남대학교

MathWorks®

Contents

1. CV

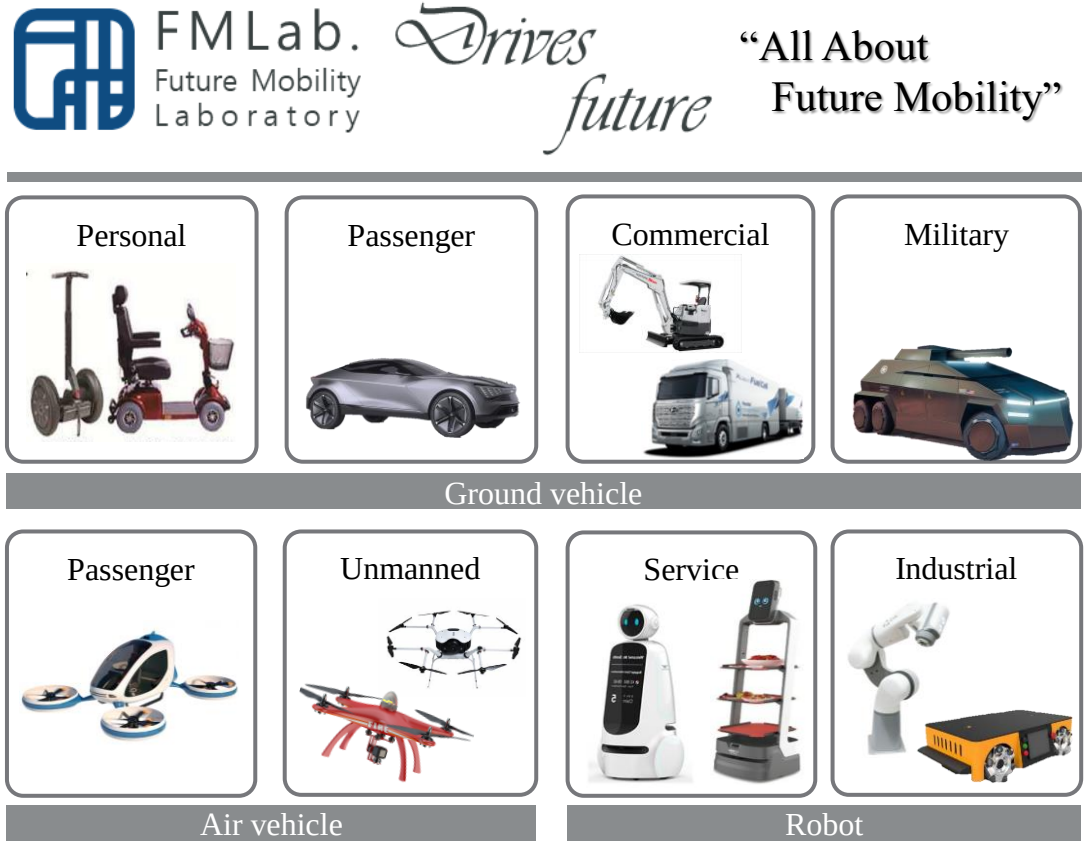
1. CV
- Prof. Dong-Min Kim, Ph.D.

- Academic Experiences
  - 2021 ~ Present Assistant Prof., Dept. of Automotive Engineering, Honam University
  - 2021 Post-Doc., Dept. of Automotive Engineering, Hanyang University
  - 2015 ~ 2016 Visiting Researcher, UC Davis
- Education
  - 2021 Ph.D. in Automotive Engineering, Hanyang University
    [Dissertation] Modeling and Optimization of Fuel Cell Electric Vehicle Considering Wide Variation of DC Link Voltage to Electric Powertrain and Air Supply System
    [Advisor] Myung-Seop Lim
  - 2013 B.S. in Electronic System Engineering, Hanyang University ERICA
- Research Achievements
  - SCI(E) Journal : 14 / Conference : 42

1. CV

- Prof. Dong-Min Kim, Ph.D.

- Laboratory : sites.google.com/view/drives-future



Research Theme

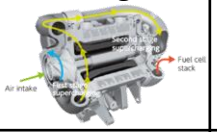
- Multi-physics design of electric machines
  - ✓ High-speed motor
  - ✓ Deep learning-based temperature estimation
- Condition monitoring of electric machines
  - ✓ Deep learning-based condition monitoring
- Future mobility powertrain design and control
  - ✓ Novel e-powertrain layout design and control
  - ✓ Fault-tolerant electric machines for autonomous vehicle and air mobility
  - ✓ Electric & hybrid electric propulsion system for air mobility
- Energy management
  - ✓ Motor-Inverter-Battery integrated control
- Optimization
  - ✓ Deep learning-based optimization

2. Research Overview

2. Research Overview

- background (1) : importance of air compressor

- Require high output power
  - about 10% of e-powertrain system output power

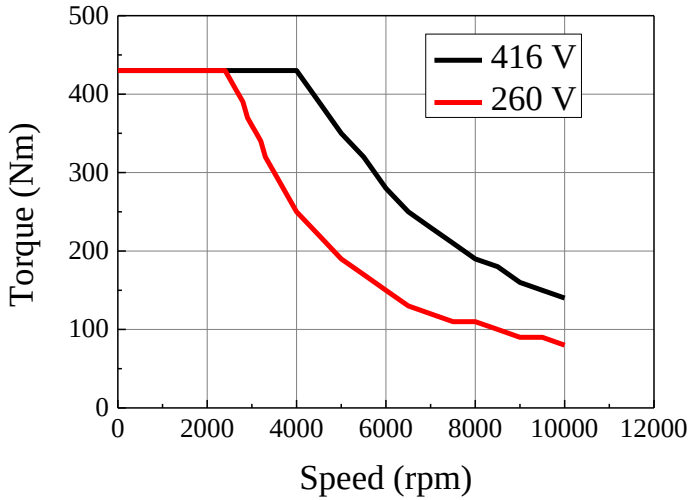
OEM			Hyundai		Toyota	Honda	GM	Daimler	VW
Vehicle			Tucson 	NEXO 	Mirai 	Clarity 	Equinox 	B-Class 	A7 H-tron 
Air Compressor	Type		Centrifugal	Centrifugal	Twin Screw	Centrifugal	Centrifugal	Centrifugal	Centrifugal
	Comp. Ratio		1.5	2.1	2.5	3.3	2.5	2.5	2.5
	Bearing		Ball	AFB	Ball	AFB	AFB	AFB	AFB
	Figure		1 stage 	1 stage 		2 stage 	1 stage 	1 stage 	1 stage 
	Motor	Speed	42 krpm →	100 krpm	12 krpm	100 krpm	85 krpm		
		Power	7.5 kW →	13.5 kW	-	20 kW	15 kW		
	Supplier		Hanon System		Toyota Ind.	Honeywell	Liebherr-Aerospace		

몇몇 모델 Update 예정

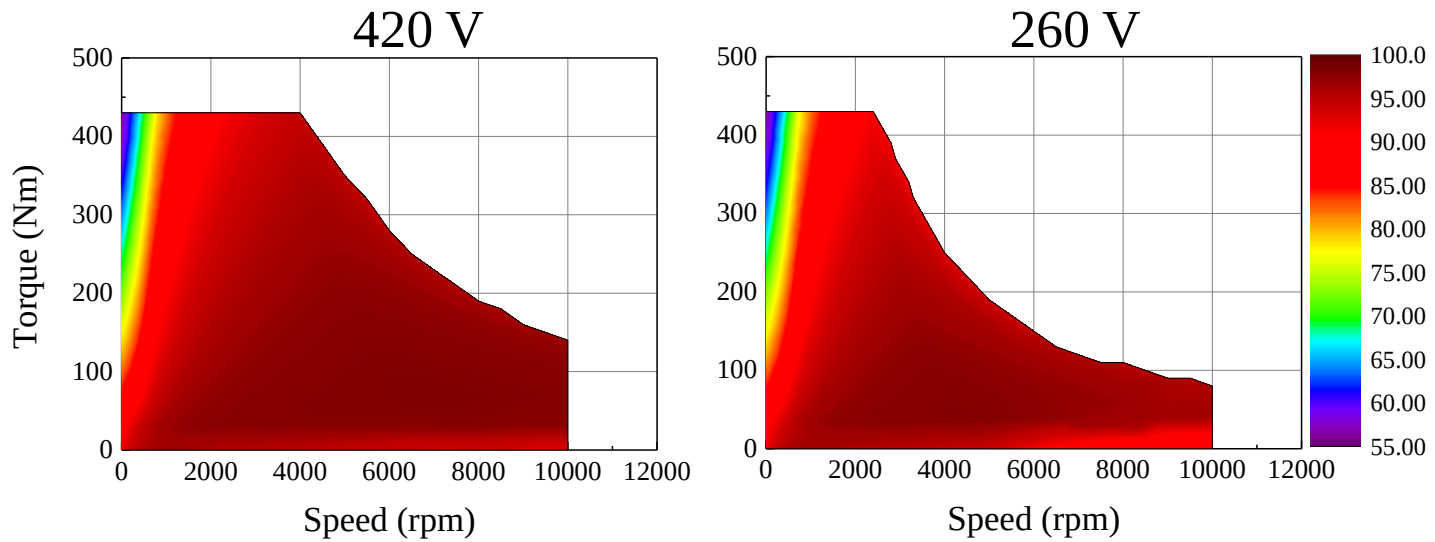
2. Research Overview

- background (2) : fuel cell output voltage characteristics

- The maximum output voltage : 420 V_{DC}
- The minimum output voltage : 260 V_{DC}



Torque-Speed curve



Efficiency map

2. Research Overview

- overview

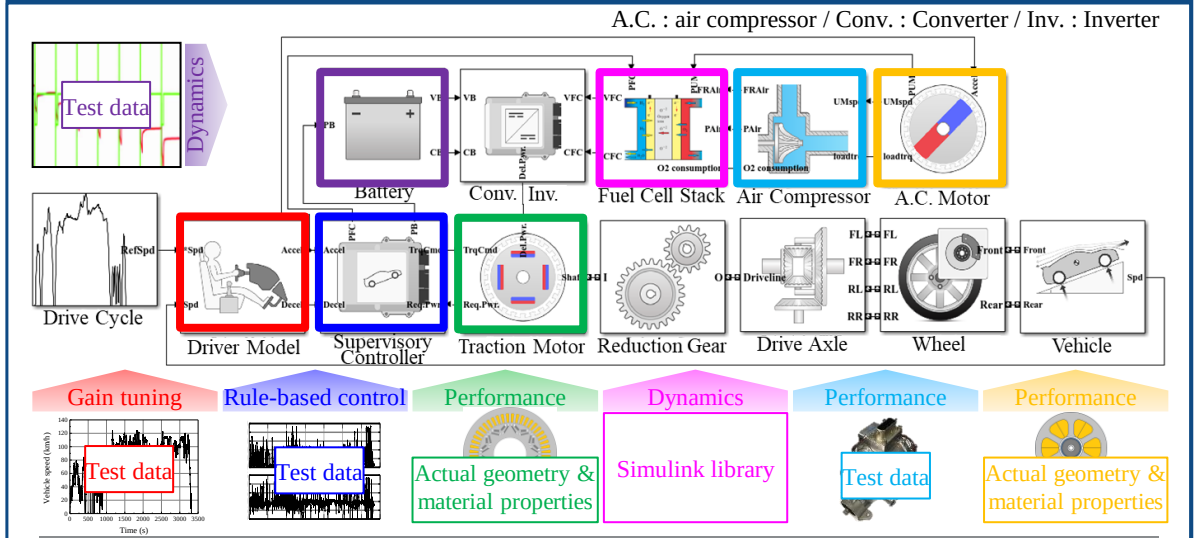
Items		Value	Unit	Note
Overall length		4670	mm	
Overall width		1860	mm	
Overall height		1630	mm	17-inch tire
Wheelbase		2790	mm	
Drag coefficient		0.329	-	
Maximum speed		177	km/h	17-inch tire
Driving system		Front-wheel driving	-	
Empty vehicle weight		1820	kg	17-inch tire
Government-certified standard fuel efficiency	Combined	2.86	km/kWh	17-inch tire
	City	2.96	km/kWh	
	Highway	2.76	km/kWh	

※ Reference : Hyundai NEXO official catalogue

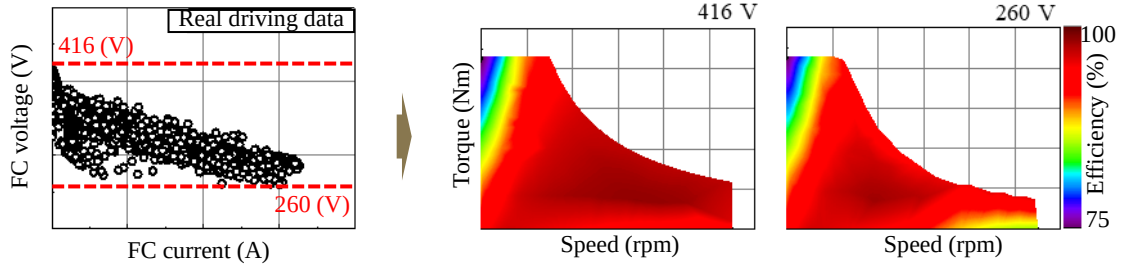
2. Research Overview

- overview

FCEV system modeling



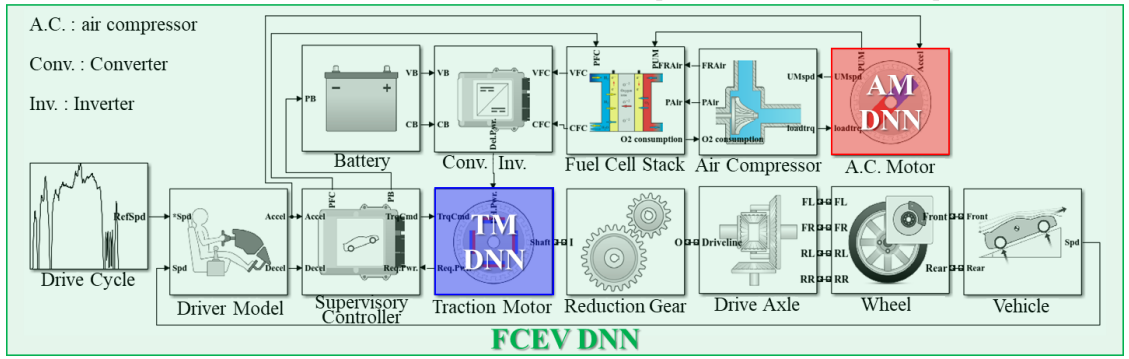
High-fidelity modeling



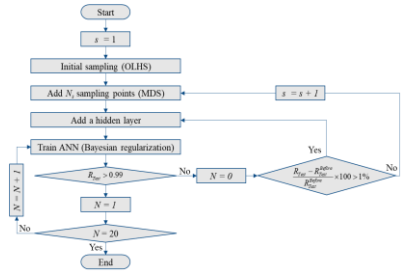
Consider fuel cell output voltage characteristics

Deep learning-based optimization

TM : traction motor / AM : air compressor motor / DNN : deep neural network



Surrogate modeling based on deep learning



Items	TM maximum torque	TM total loss	AM maximum torque	AM total loss	FCEV fuel economy	FCEV trace NRMSE
Number of hidden layers	10	18	31	5	10	11
Number of sampling points	114	258	462	60	250	255

Adaptive layering and sampling algorithm

3. Research Goals and Challenges

3. Research Goals and Challenges
- in detailed modeling

- Vehicle dynamics modeling
  - reduction gear
  - drive axle
  - wheel
  - vehicle
- Consideration of actual data
  - electric motors
  - air compressor
  - lithium-ion battery
  - fuel cell stack
  - supervisory controller
  - driver model

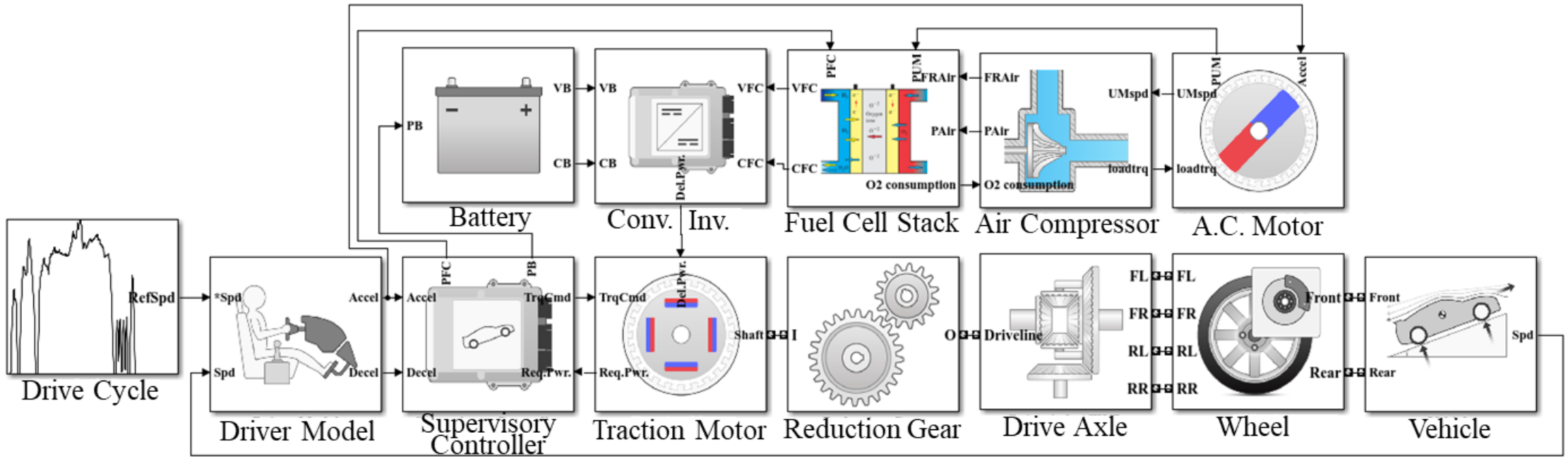
3. Research Goals and Challenges
- in surrogate modeling

- Considering fuel cell output voltage variation
  - traction motor
  - air compressor motor
- Using deep neural network (DNN)
- Developing DNN construction algorithm

4. Application of MathWorks Solutions
: in detailed modeling

4. Application of MathWorks Solutions

- in detailed modeling : developed FCEV model

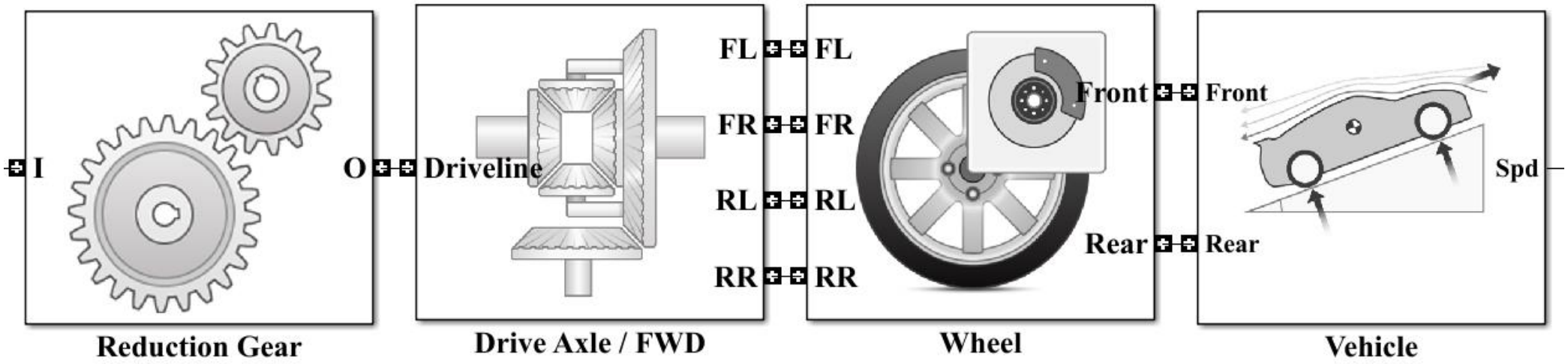


A.C. : air compressor / Conv. : Converter / Inv. : Inverter

4. Application of MathWorks Solutions

- in detailed modeling : vehicle dynamics modeling

- Driveline and vehicle body



4. Application of MathWorks Solutions

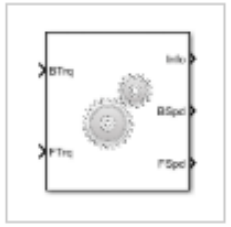
- in detailed modeling : vehicle dynamics modeling

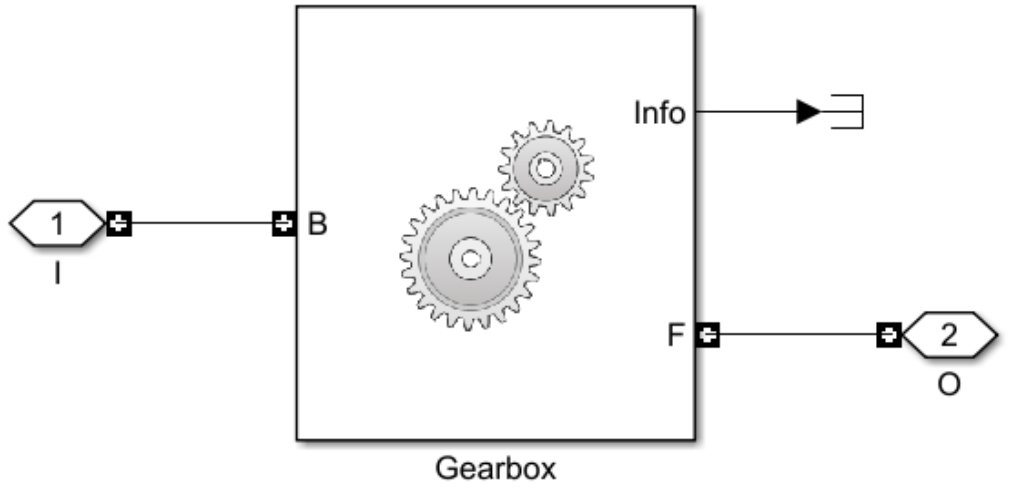
- Reduction gear
  - Simulink “Powertrain Blockset”

Gearbox

Ideal rotational gearbox

Library: Powertrain Blockset / Drivetrain / Couplings

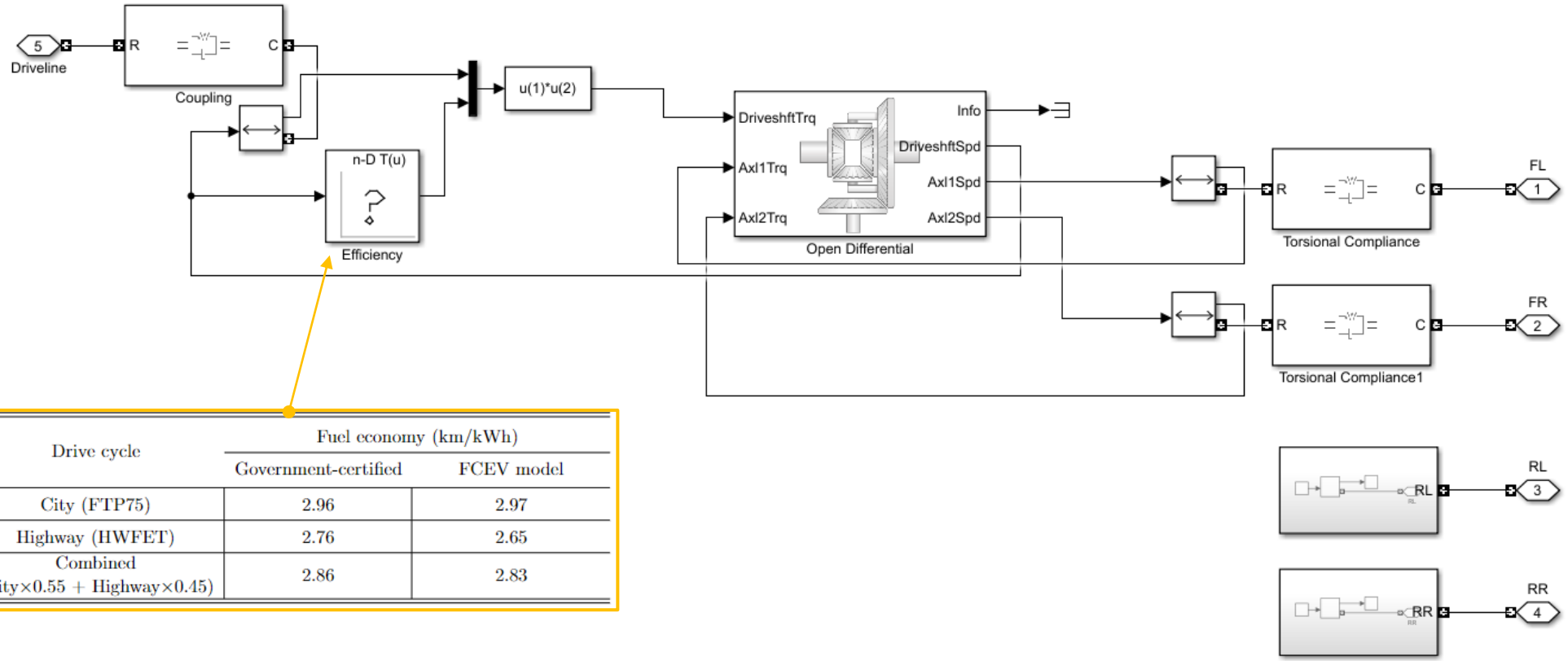




4. Application of MathWorks Solutions

- in detailed modeling : vehicle dynamics modeling

- Drive axle / FWD
  - Simulink “Powertrain Blockset”



Drive cycle	Fuel economy (km/kWh)	
	Government-certified	FCEV model
City (FTP75)	2.96	2.97
Highway (HWFET)	2.76	2.65
Combined (City×0.55 + Highway×0.45)	2.86	2.83

4. Application of MathWorks Solutions

- in detailed modeling : vehicle dynamics modeling

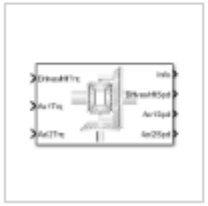
- Drive axle / FWD
  - Simulink “Powertrain Blockset”

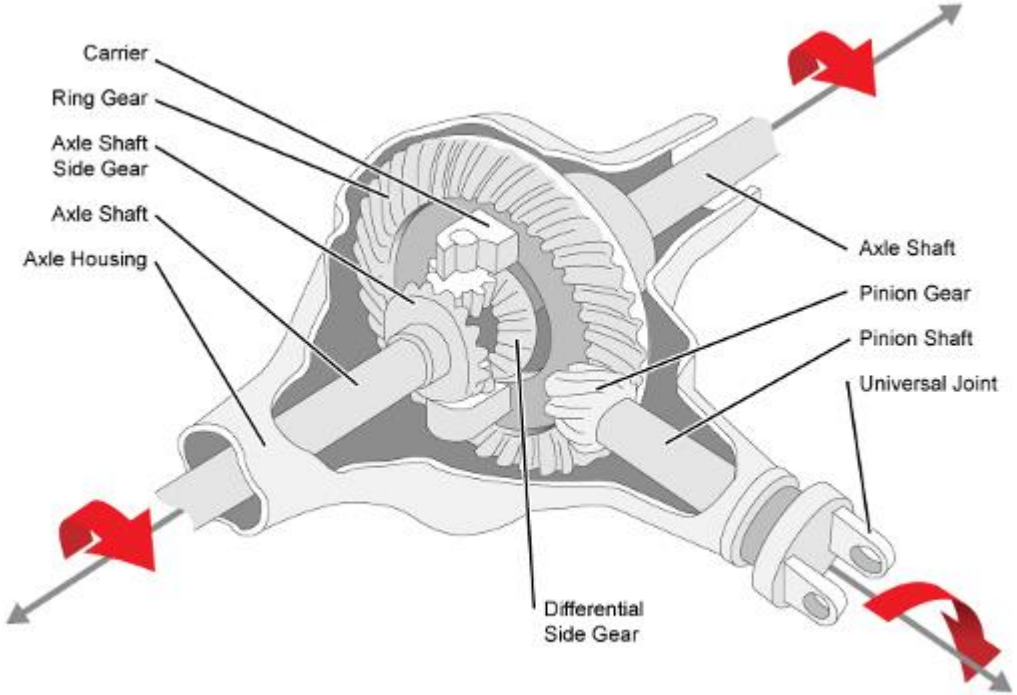
Open Differential

Differential as a planetary bevel gear

Library: Powertrain Blockset / Drivetrain / Final Drive Unit

Vehicle Dynamics Blockset / Powertrain / Drivetrain / Final Drive Unit

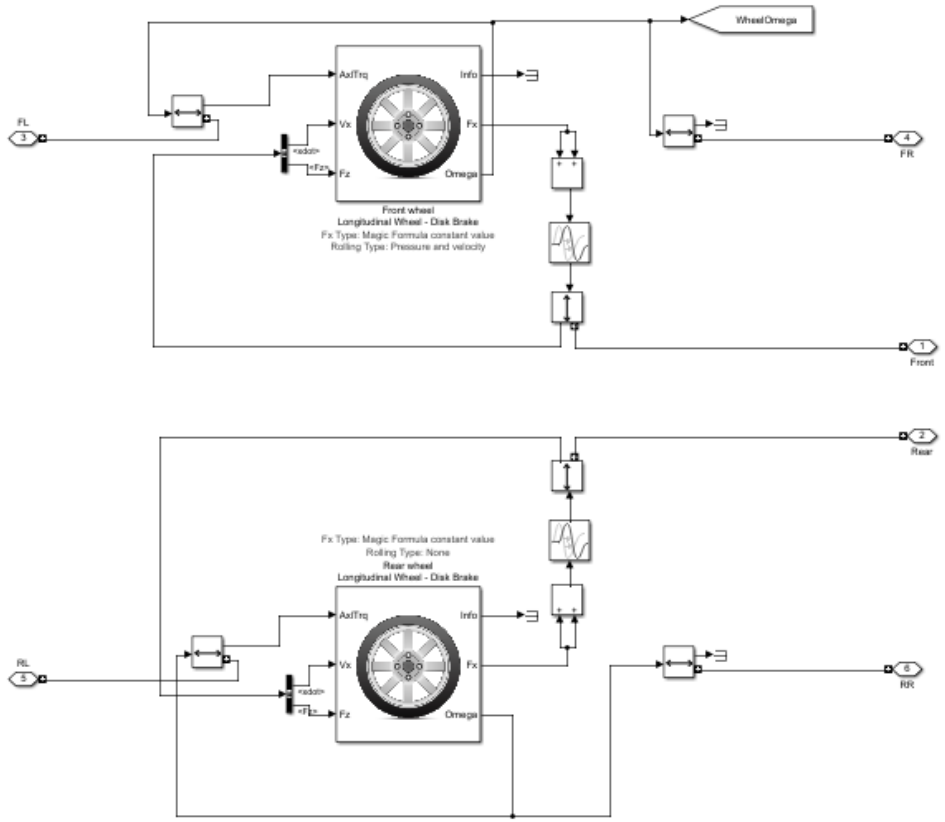




4. Application of MathWorks Solutions

- in detailed modeling : vehicle dynamics modeling

- Wheel
  - Simulink “Powertrain Blockset”



Longitudinal Wheel

Longitudinal wheel with disc, drum, or mapped brake

Library: Powertrain Blockset / Drivetrain / Wheels

Vehicle Dynamics Blockset / Wheels and Tires

Longitudinal Wheel (mask) (link)

Represents the longitudinal behavior of a tire characterized by the tire Magic Formula or mapped data. Block includes options for the rolling resistance and brakes.

Block Options

Longitudinal Force:	Magic Formula constant value
Rolling Resistance:	Pressure and velocity
Brake Type:	None
Vertical Motion:	None

4. Application of MathWorks Solutions

- in detailed modeling : vehicle dynamics modeling

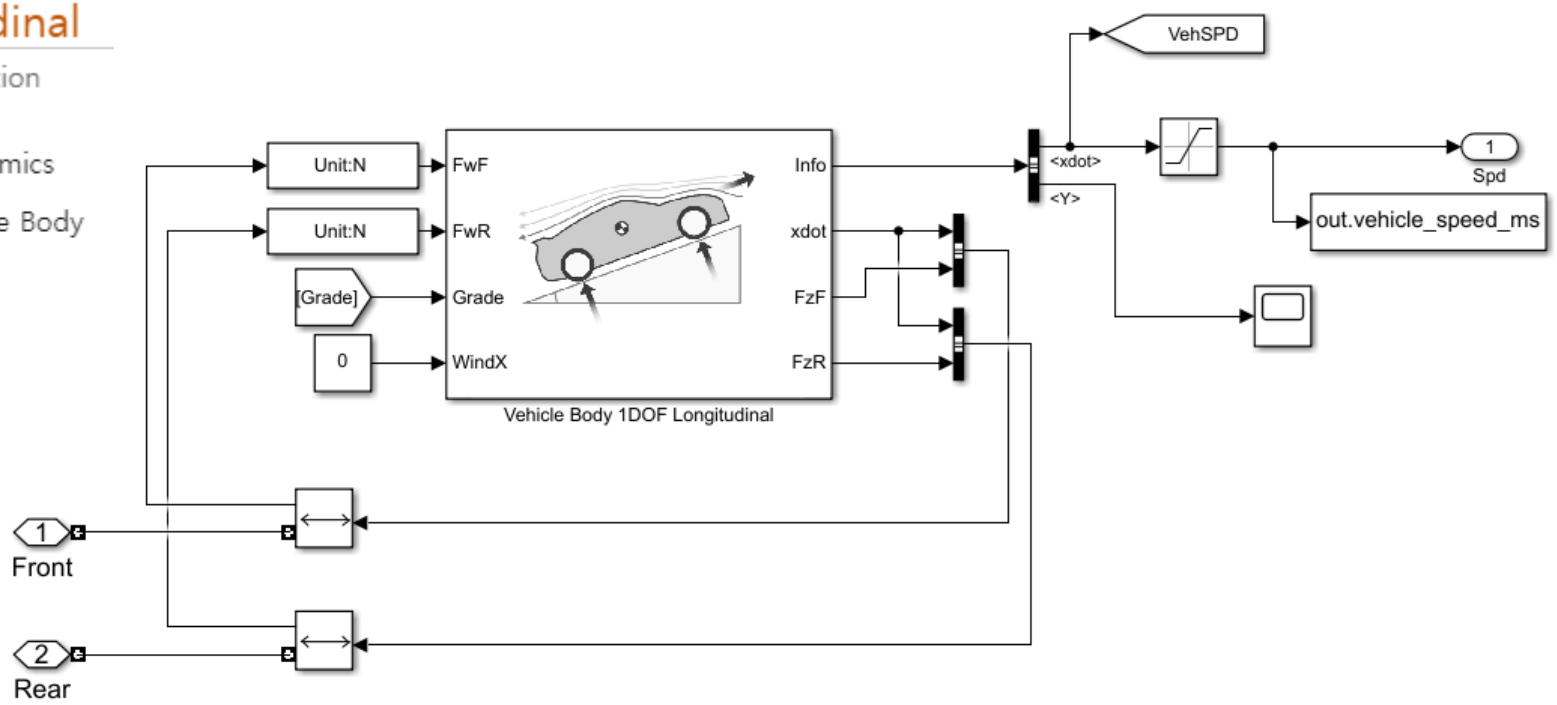
- Vehicle
  - Simulink “Powertrain Blockset”

Vehicle Body 1DOF Longitudinal

Two-axle vehicle in forward and reverse motion

Library: Powertrain Blockset / Vehicle Dynamics

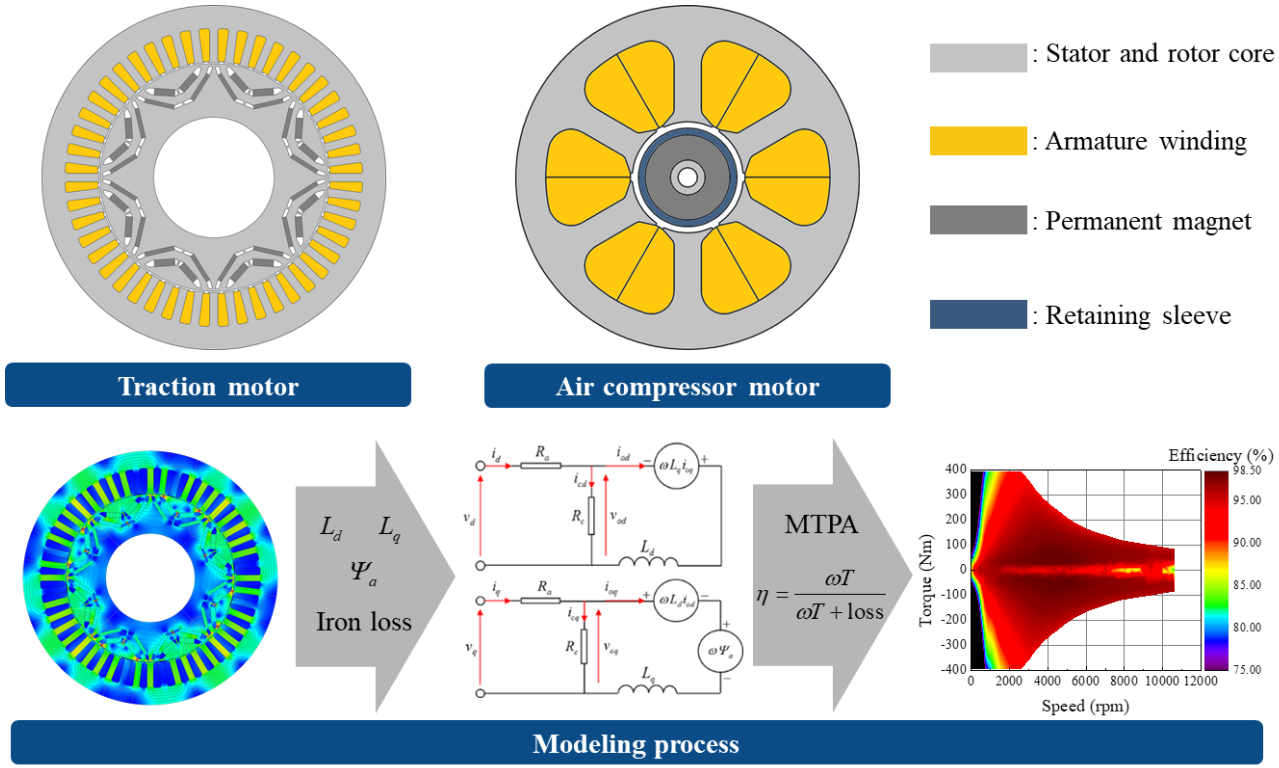
Vehicle Dynamics Blockset / Vehicle Body



4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

- Electric motors
  - Simulink + In-house PG “2D Electromagnetic FEA”



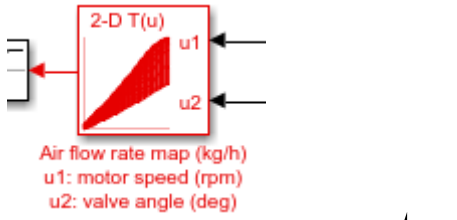
Items		Value	Unit	Note
Pole / Slot number				
Maximum output				
Maximum torque				
Maximum speed				
Nominal DC voltage				
Maximum current				
Maximum current density				
Rotor	Core material			
	PM residual induction			
	Stack length			
Stator	Core material			
	Series turns per phase			
	Stack length			

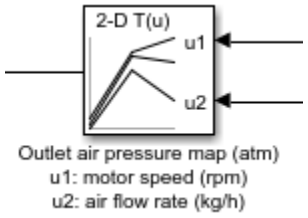
Items		Value	Unit	Note
Pole / Slot number				
Maximum output				
Maximum torque				
Maximum speed				
Nominal DC voltage				
Maximum current				
Maximum current density				
Rotor	Core material			
	PM residual induction			
	Axial length			
Stator	Core material			
	Series turns per phase			
	Stack length			

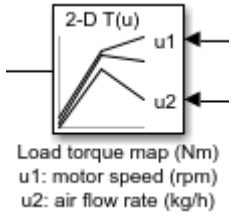
4. Application of MathWorks Solutions

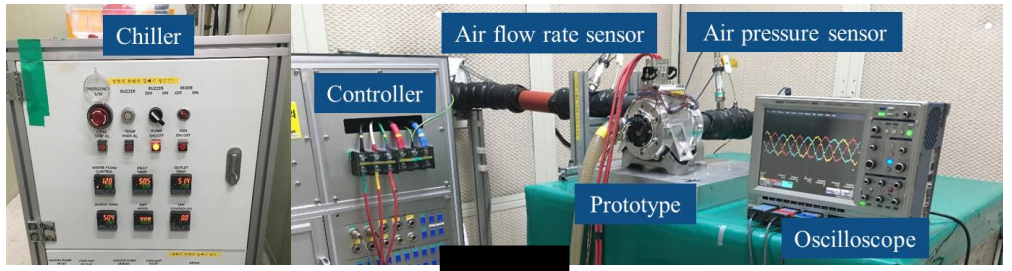
- in detailed modeling : consideration of actual data

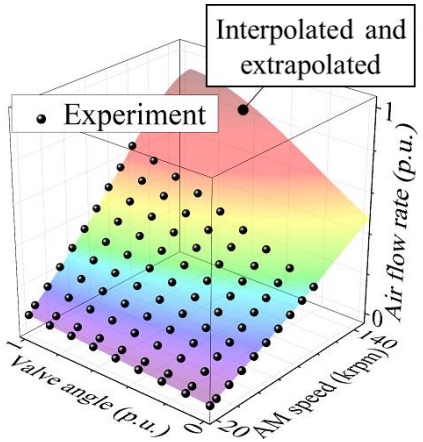
- Air compressor
  - Compression Part : Simulink + MATLAB “Curve Fitting Toolbox”

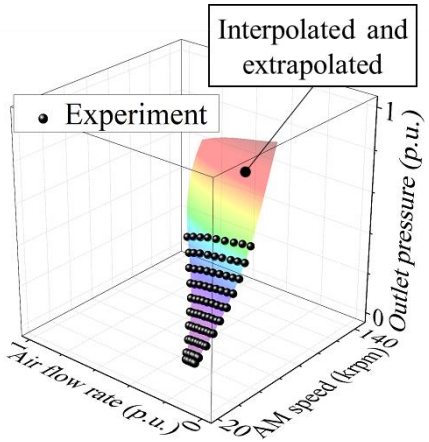


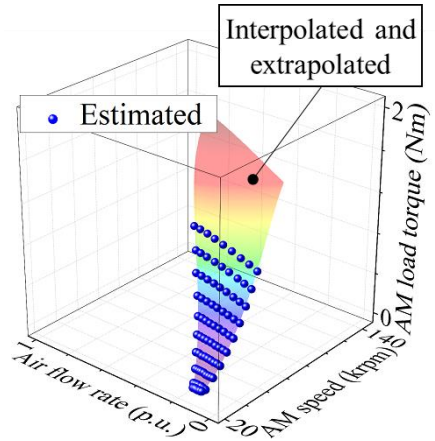












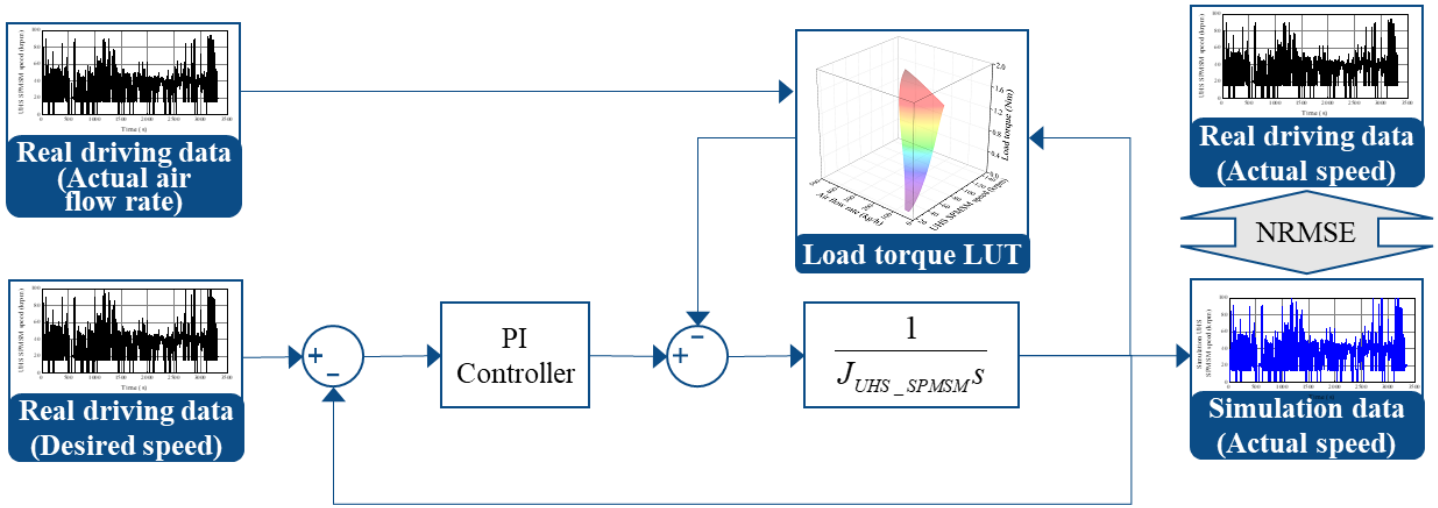
4. Application of MathWorks Solutions
- in detailed modeling : consideration of actual data

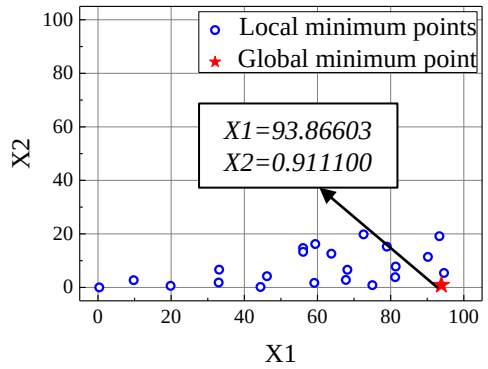
- Air compressor
  - Controller (A.C. motor speed) : Simulink + MATLAB “Optimization Toolbox”

    “fmincon SQP algorithm”
    - Objective function

      Minimize NRMSE of motor speed profile (test, simulation)
    - Find

      PI controller gain





4. Application of MathWorks Solutions
- in detailed modeling : consideration of actual data

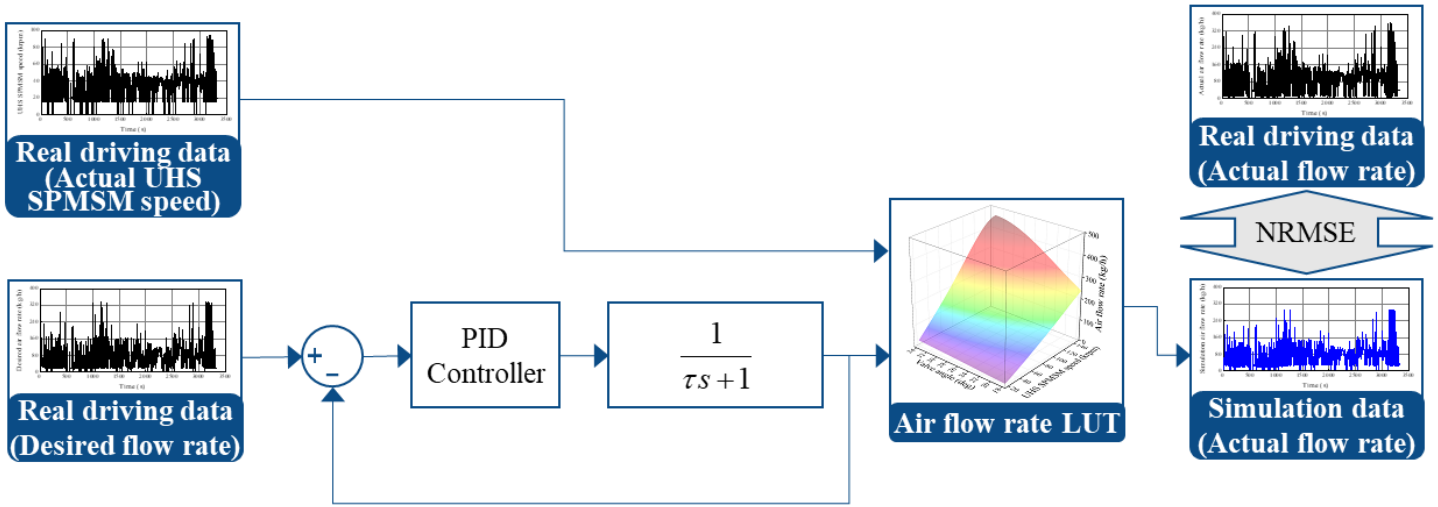
- Air compressor
  - Controller (air flow rate) : Simulink + MATLAB “Optimization Toolbox”

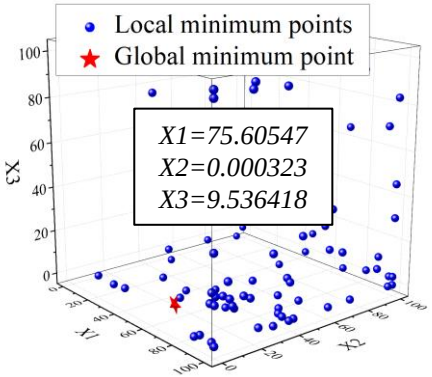
“fmincon SQP algorithm”

- Objective function

  Minimize NRMSE of air flow rate profile (test, simulation)
- Find

  PID controller gain for various initial points





4. Application of MathWorks Solutions

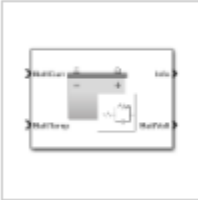
- in detailed modeling : consideration of actual data

- Lithium-ion battery
  - Powertrain Blockset

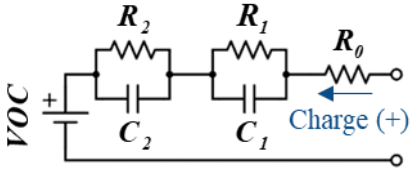
Equivalent Circuit Battery

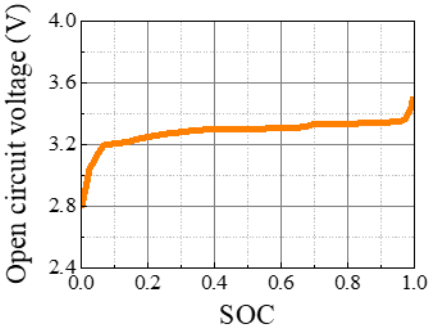
Resistor-capacitor (RC) circuit battery

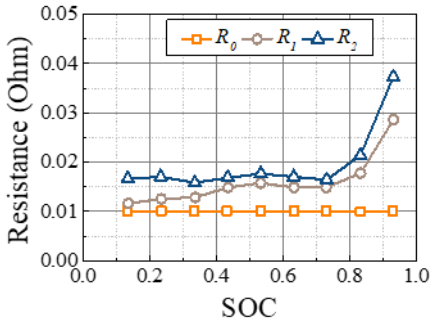
Library: Powertrain Blockset / Energy Storage and Auxiliary Drive / Network Battery

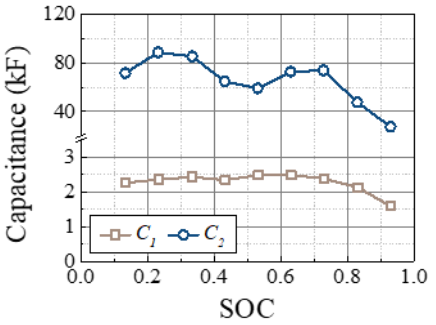


- No. of RC pair = 2









4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

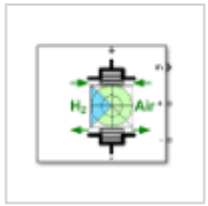
- Fuel cell stack
  - Simulink “Simscape : Fuel Cell Stack - Detailed Model”

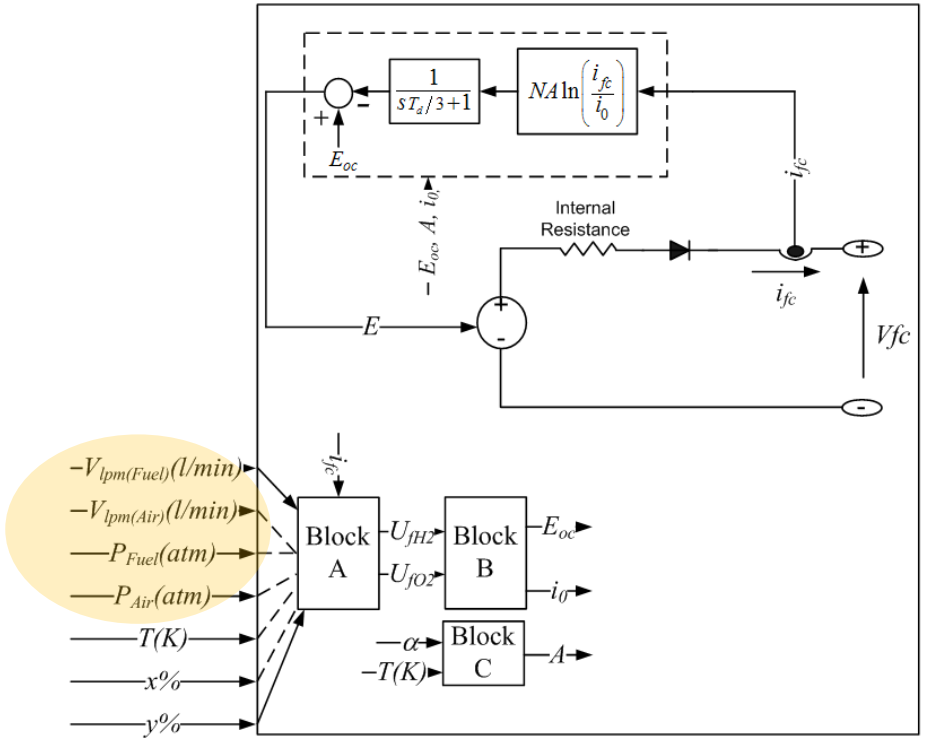
    : to consider air compressor performance

Fuel Cell Stack

Implement generic hydrogen fuel cell stack model

Library: Simscape / Electrical / Specialized Power Systems / Sources

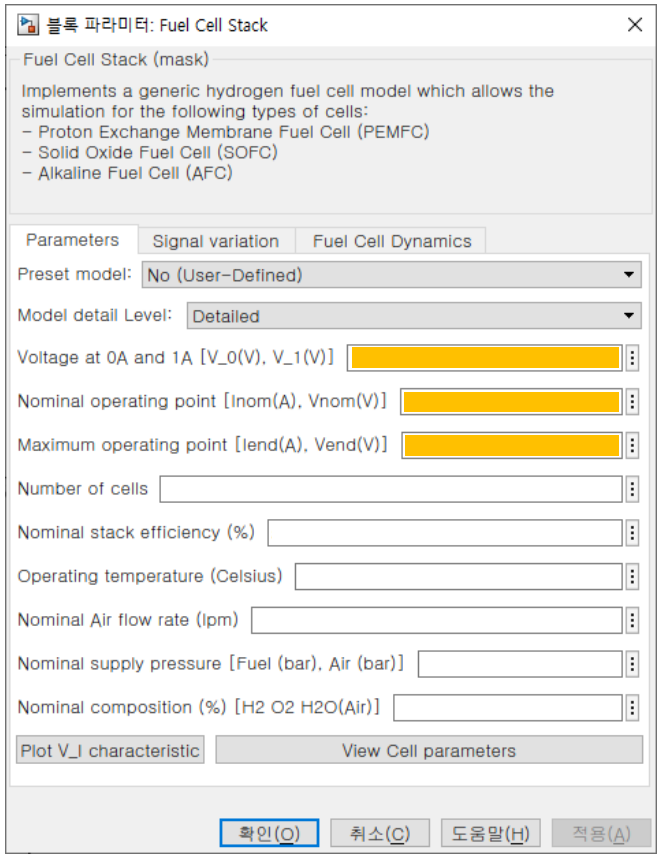


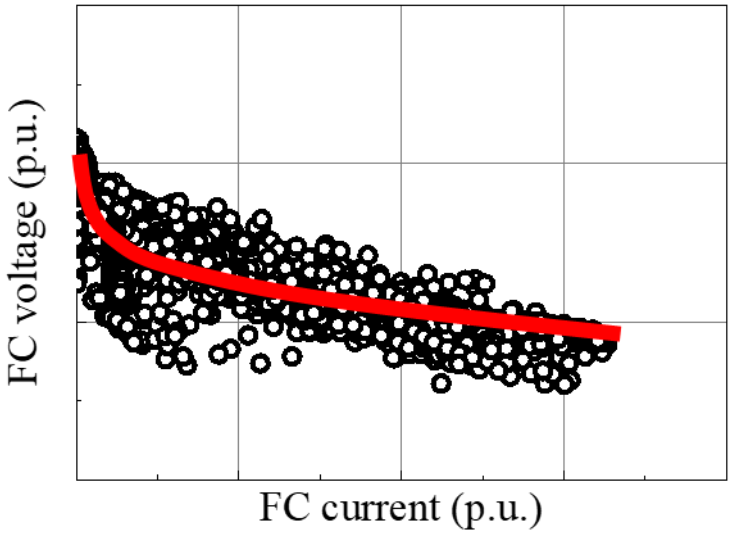


4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

- Fuel cell stack
  - Nominal V-I Curve : Simulink “Simscape” + MATLAB “Curve Fitting Toolbox”

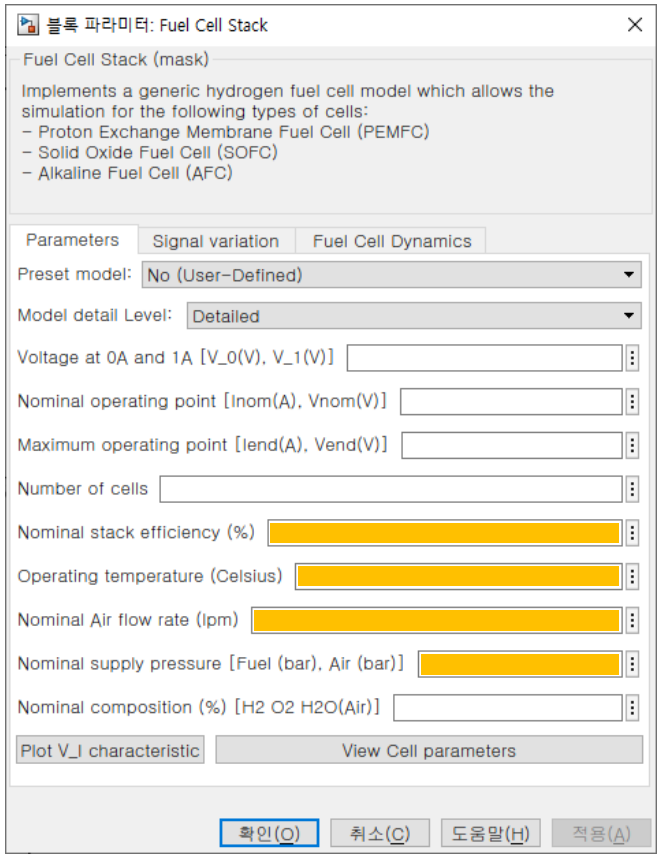




4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

- Fuel cell stack
  - Other Parameter : Simulink “Simscape” + MATLAB “Optimization Toolbox”



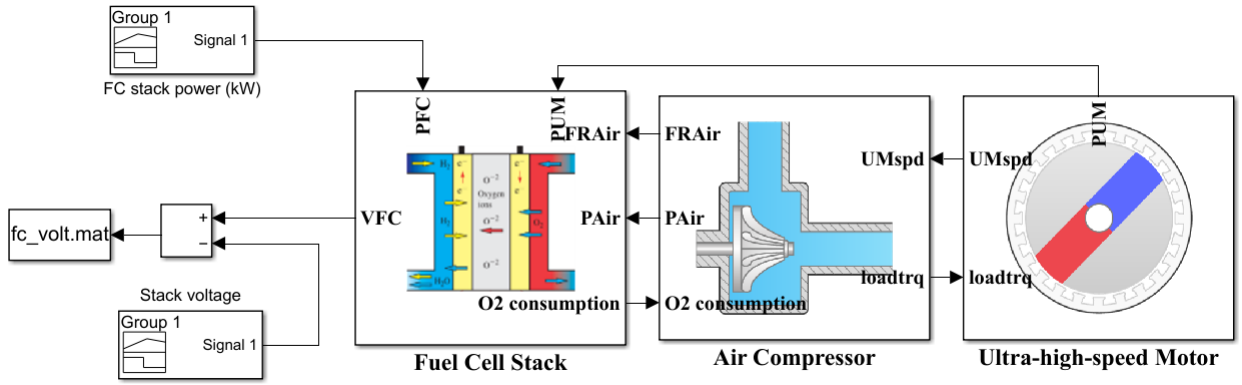
“fmincon SQP algorithm”

- Objective function

  Minimize NRMSE of FC voltage profile (test, simulation)

- Find

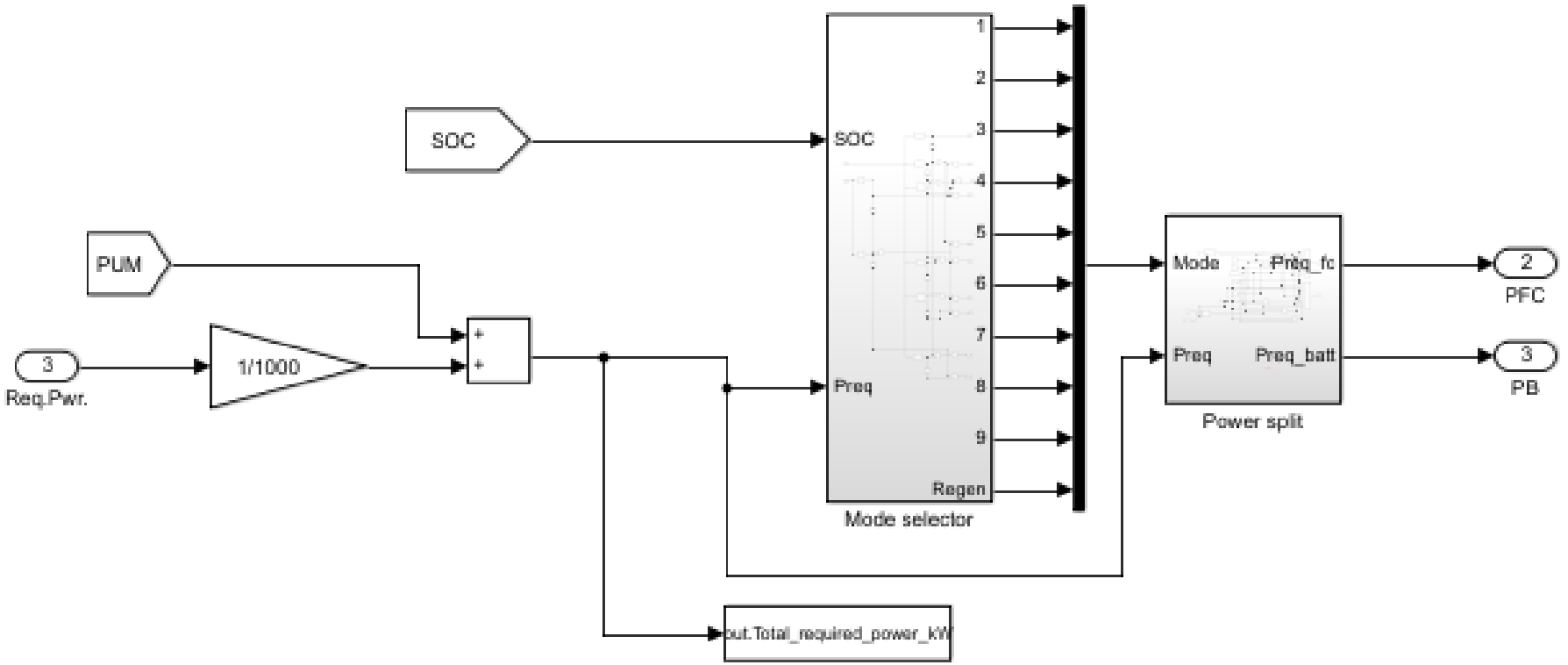
  for various initial points



4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

- Supervisory controller : power & energy management, motor control
  - Simulink + MATLAB “Optimization Toolbox”



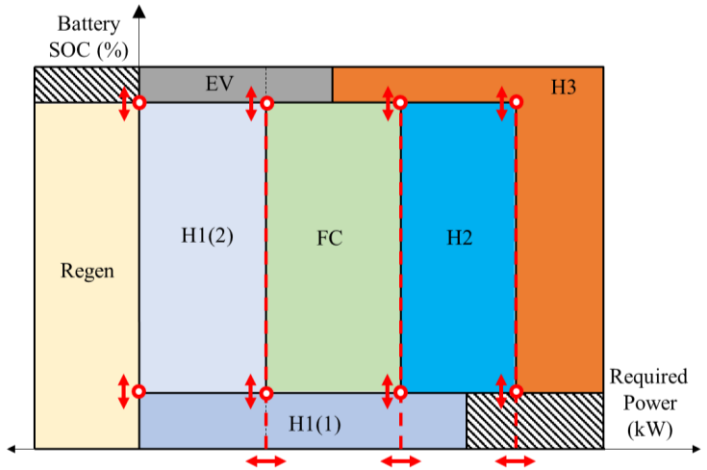
4. Application of MathWorks Solutions
- in detailed modeling : consideration of actual data

- Supervisory controller : power & energy management, motor control
  - Simulink + MATLAB “Optimization Toolbox”

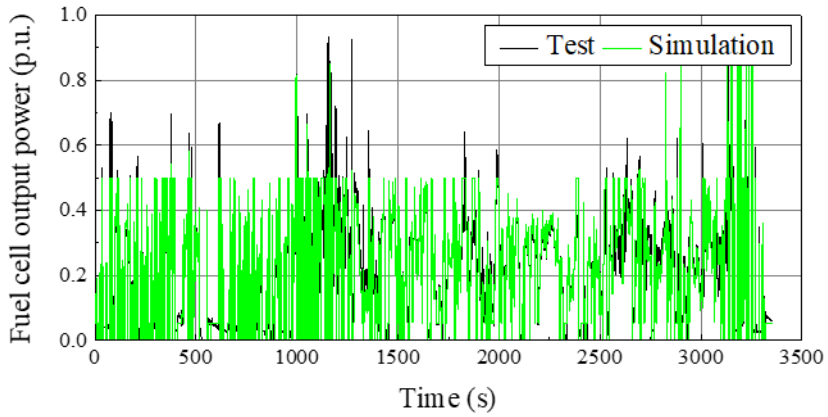
    “fmincon SQP algorithm”
    - Objective function

      Minimize NRMSE of FC power profile (test, simulation)
    - Find

      Thresholds



for various initial points



4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

- Driver model
  - Simulink “Powertrain Blockset” + MATLAB “Optimization Toolbox”

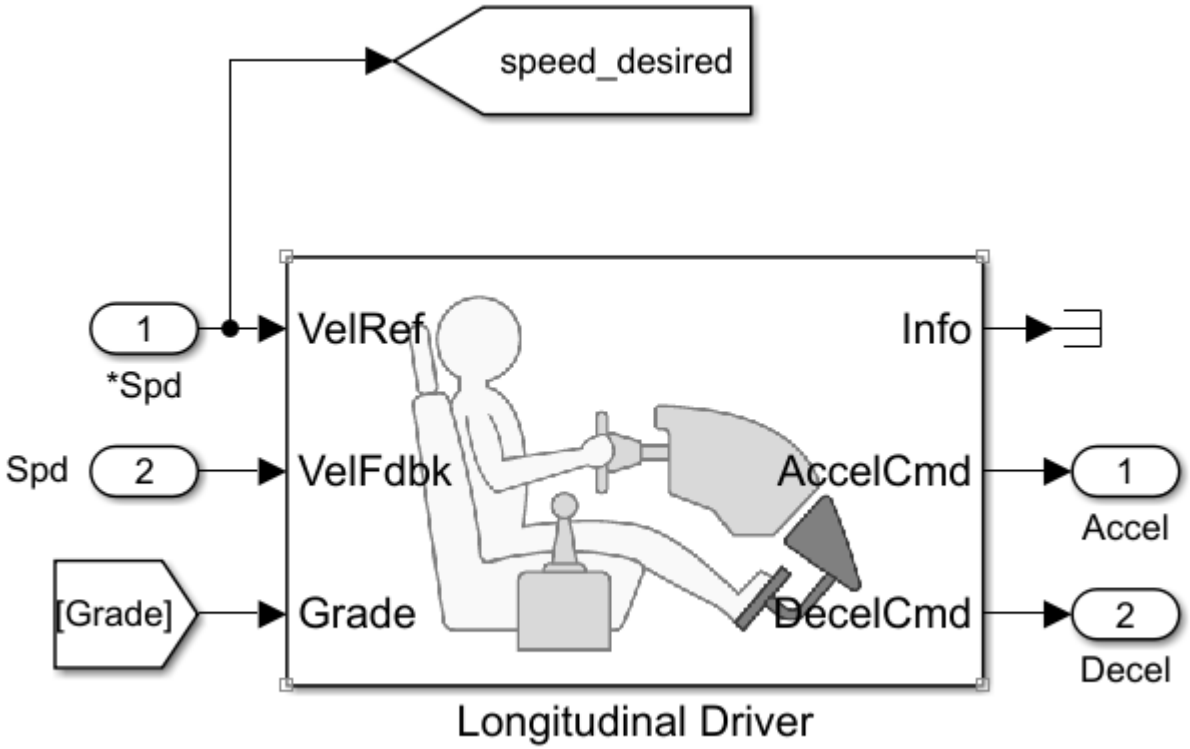
Longitudinal Driver

Longitudinal speed-tracking controller

Library: Powertrain Blockset / Vehicle Scenario Builder

Vehicle Dynamics Blockset / Vehicle Scenarios / Driver

$$y = \frac{k_P e_{ref}}{v_{nom}} + \int \left(\frac{k_I e_{ref}}{v_{nom}} + k_{AW} e_{out} \right) e_{ref}\, dt + \frac{k_{FF}}{v_{nom}} + k_G \theta$$



4. Application of MathWorks Solutions

- in detailed modeling : consideration of actual data

- Driver model
  - Simulink “Powertrain Blockset” + MATLAB “Optimization Toolbox”

    “fmincon SQP algorithm”
    - Objective function

      Minimize NRMSE of vehicle speed (test, simulation)

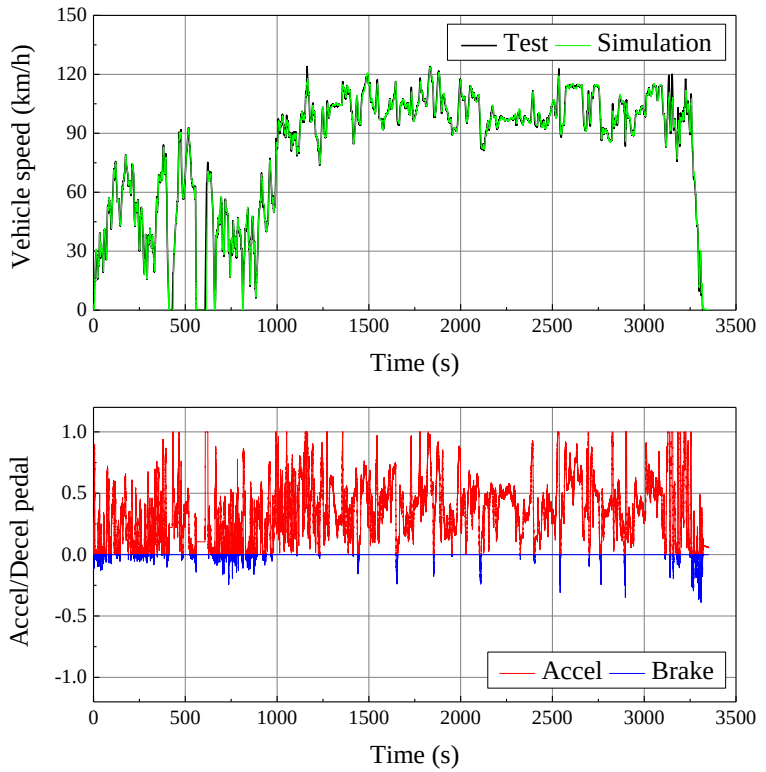
$$NRMSE = \sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}\left(\frac{Y^{Test}(t_n)-Y^{Simulation}(t_n)}{\max\{Y^{Test}(t)\}-\min\{Y^{Test}(t)\}}\right)^2}\cdot 100\%$$

    - Find

$$k_P,\ k_I,\ k_{FF},\ k_G$$

      for various initial points

$$k_P = 13.56 / k_I = 0.97 / k_{FF} = 0.048 / k_G = 0.01$$

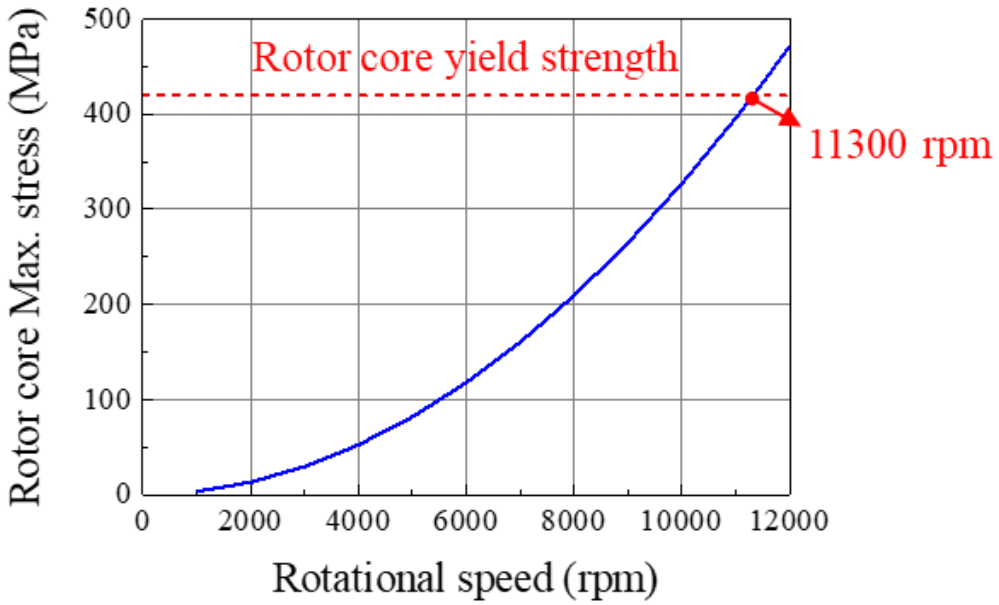


4. Application of MathWorks Solutions
: in surrogate modeling

4. Application of MathWorks Solutions

- in surrogate modeling : consideration of fuel cell voltage variation

- Traction motor
  - In-house electromagnetic FEA PG + ANSYS structural FEA PG



[Responses]
Max torque (X1, X2, DC link voltage, TM speed)
Total loss (X1, X2, DC link voltage, TM speed, TM torque)

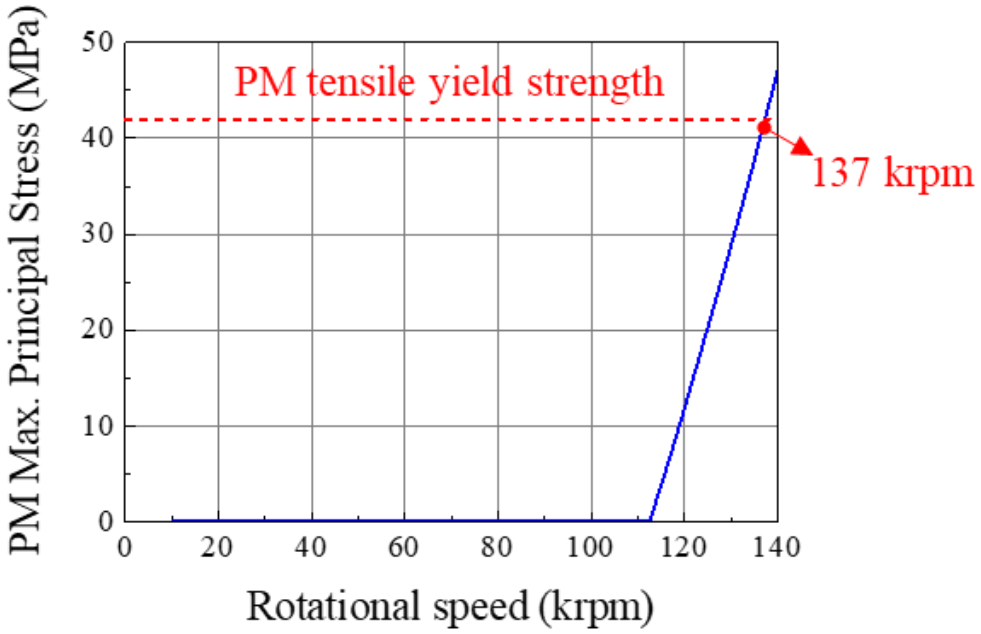
[Constraints]
$LB_1 < X1 < UB_1$, $LB_2 < X2 < UB_2$
current density : constant
slot fill factor : constant
TM speed < 11300 rpm

[Design variables]
X1: The number of turns of traction motor
X2: The stack length of traction motor

4. Application of MathWorks Solutions

- in surrogate modeling : consideration of fuel cell voltage variation

- Air compressor motor
  - In-house electromagnetic FEA PG + ANSYS structural FEA PG



[Responses]
Max torque (X4, X5, DC link voltage, AM speed)
Total loss (X4, X5, DC link voltage, AM speed, AM torque)

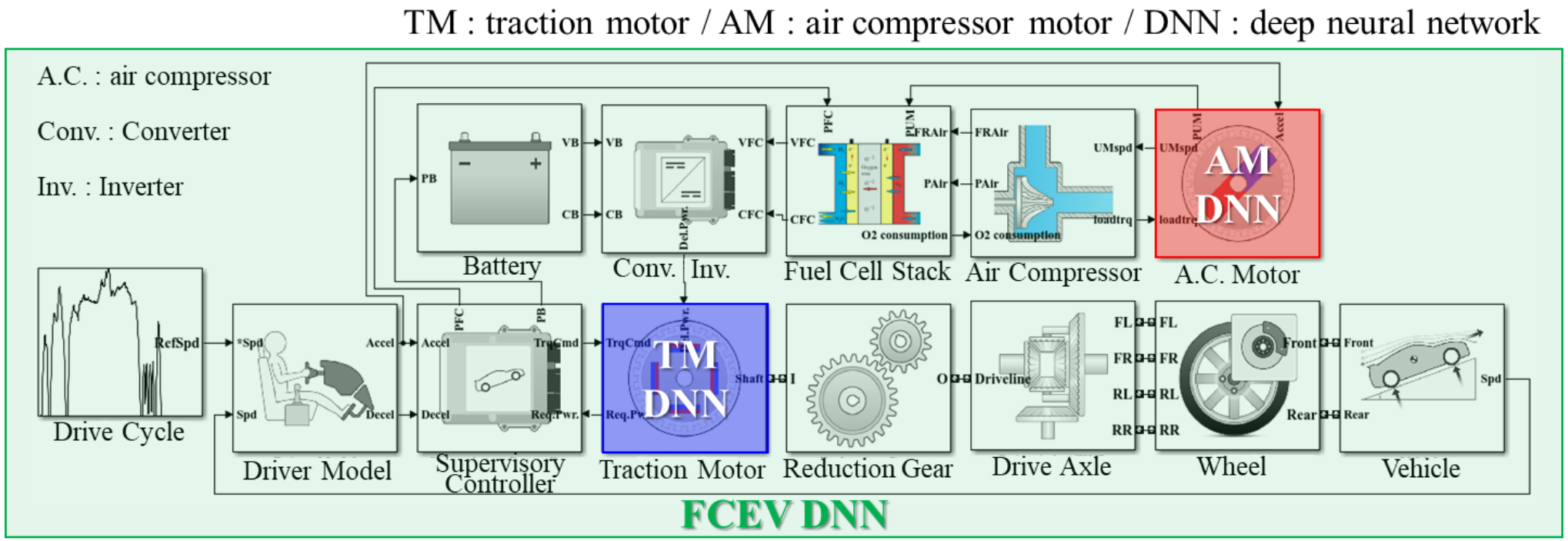
[Constraints]
$LB_4 < X4 < UB_4$, $LB_5 < X5 < UB_5$
current density : constant
slot fill factor : constant
UM speed < 137 krpm

[Design variables]
X4: The number of turns of air compressor motor
X5: The stack length of the air compressor motor

4. Application of MathWorks Solutions

- in surrogate modeling : application of deep neural network

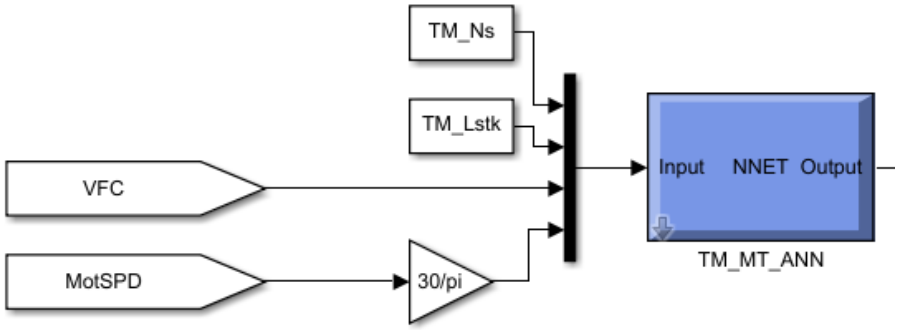
- DNN implanted DNN concept
  - overview

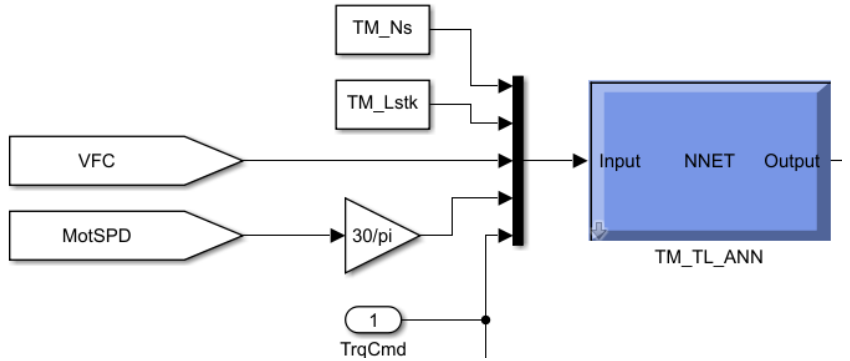


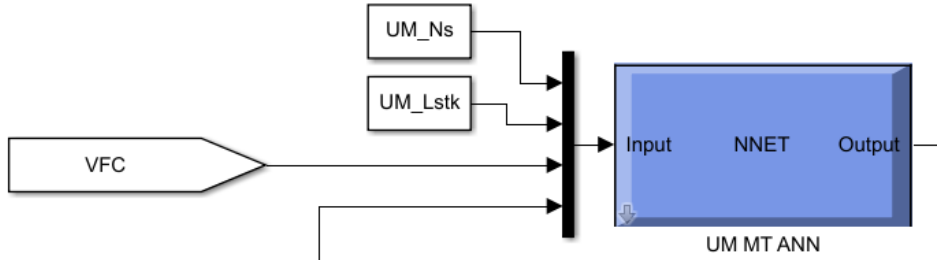
4. Application of MathWorks Solutions

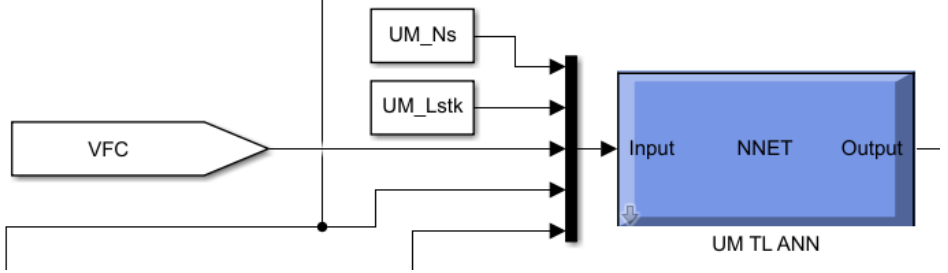
- in surrogate modeling : application of deep neural network

- TM and AM DNN construction
  - MATLAB “lhsdesign” “nntool” + Simulink “Function Fitting Neural Network”
    - Activation function : Sigmoid
    - Backpropagation : Bayesian regularization
    - Number of hidden layers : adaptive
    - Number of sampling points : adaptive









4. Application of MathWorks Solutions

- in surrogate modeling : application of deep neural network

- FCEV DNN construction
  - MATLAB “lhsdesign” “nntool” + Simulink “Function Fitting Neural Network”
    - Activation function : Sigmoid
    - Backpropagation : Bayesian regularization
    - Number of hidden layers : adaptive
    - Number of sampling points : adaptive

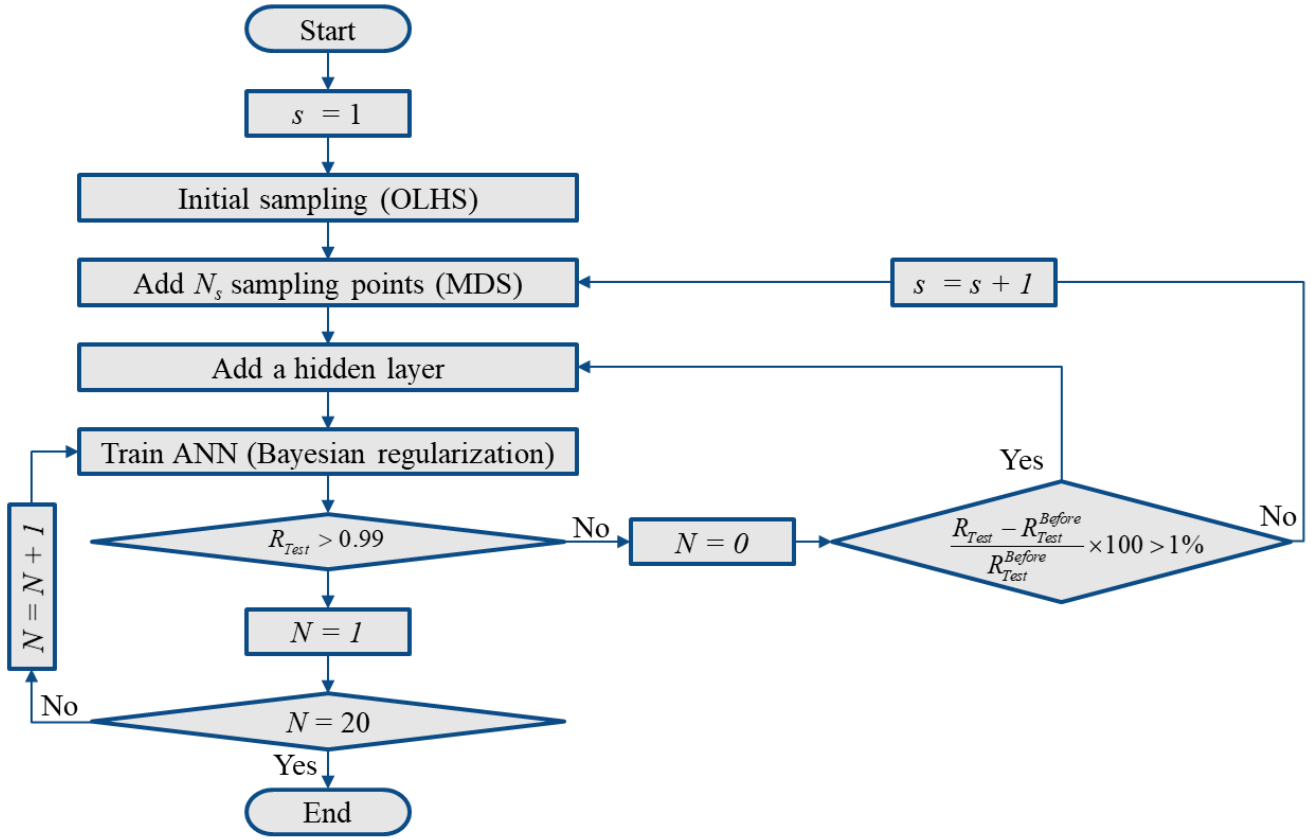
[Responses]
Energy consumption (X1, X2, X3, X4, X5)
Trace NRMSE (X1, X2, X3, X4, X5)

[Constraints]
$LB_1 < X1 < UB_1$, $LB_2 < X2 < UB_2$, $LB_3 < X10 < UB_3$,
$LB_4 < X4 < UB_4$, $LB_5 < X5 < UB_5$, Trace NRMSE < 1 %

[Design variables]
X1: The number of turns of traction motor
X2: The stack length of traction motor
X3: Gear ratio
X4: The number of turns of air compressor motor
X5: The stack length of the air compressor motor

4. Application of MathWorks Solutions
- development of DNN construction algorithm

- Adaptive layering and sampling (ALS) algorithm
  - MATLAB “nntool”



The number of initial sampling points $= 10 \times n_v$

$(n_v:$ the number of variables$)$

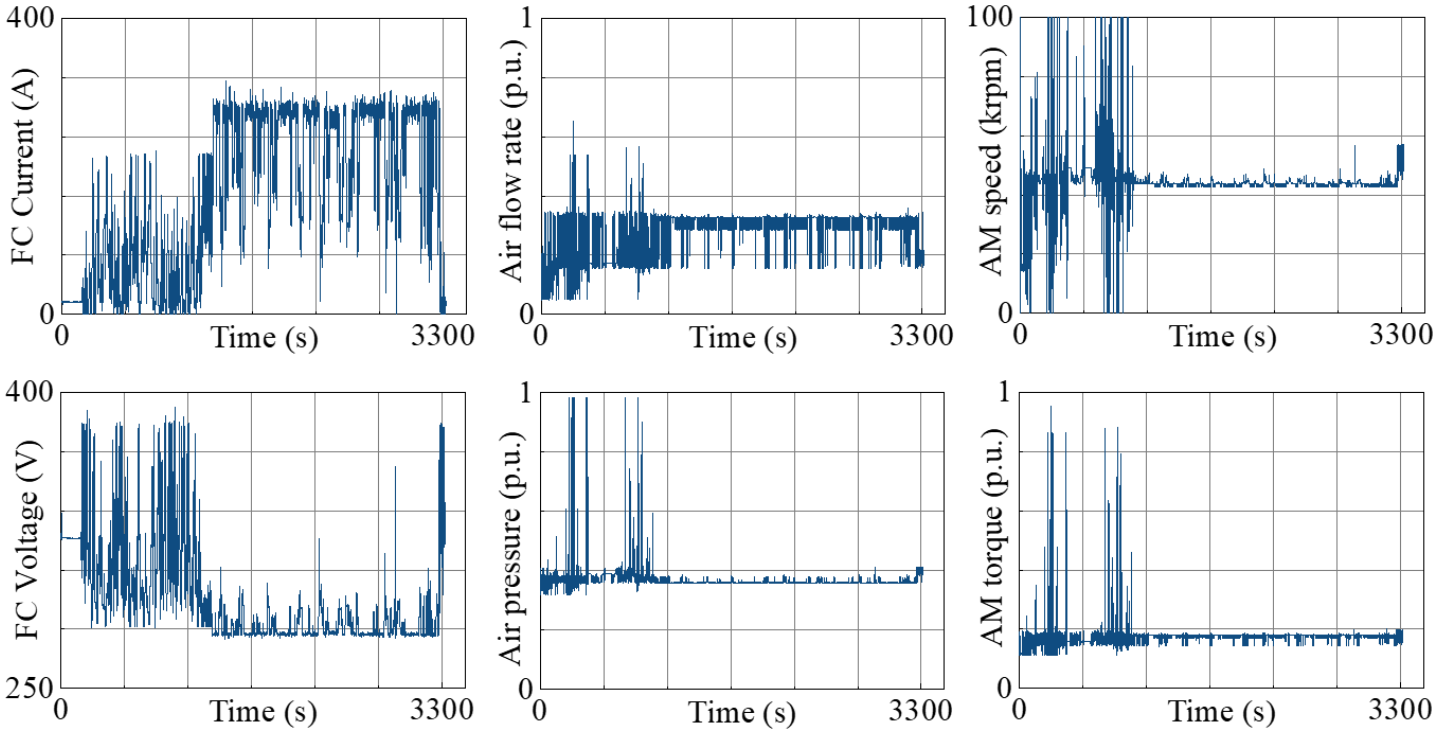
$N_s = 10 \times n_v$, when $s = 1$

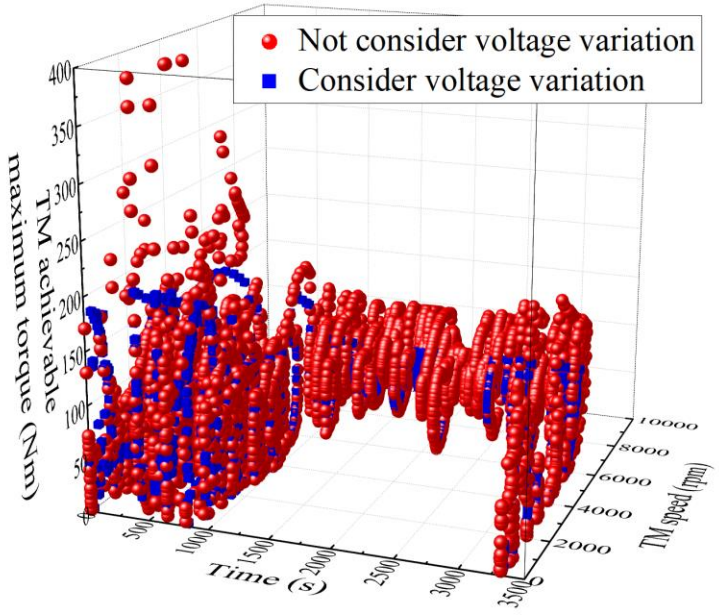
$$N_s = \left[\left(\frac{0.6}{R_{Test}}\right) \times 10\right] \times n_v, \text{when } s = 3, 4, \ldots$$

5. Achievements and Outlook

5. Achievements and Outlook
- detailed FCEV modeling

- Example of vehicle simulation based on developed model
  - operating profiles of FC stack, air supply system, and traction motor

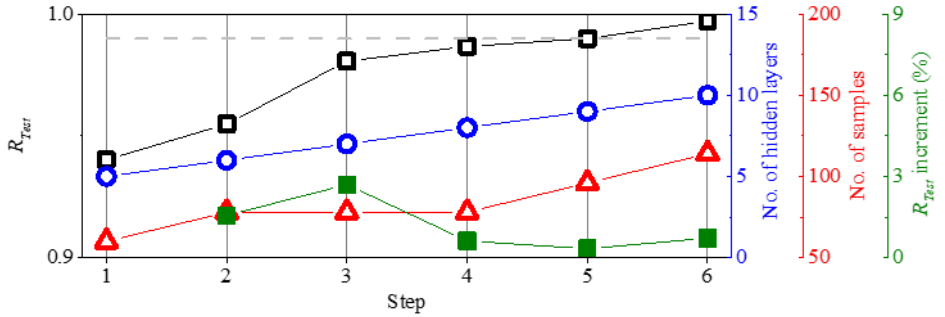




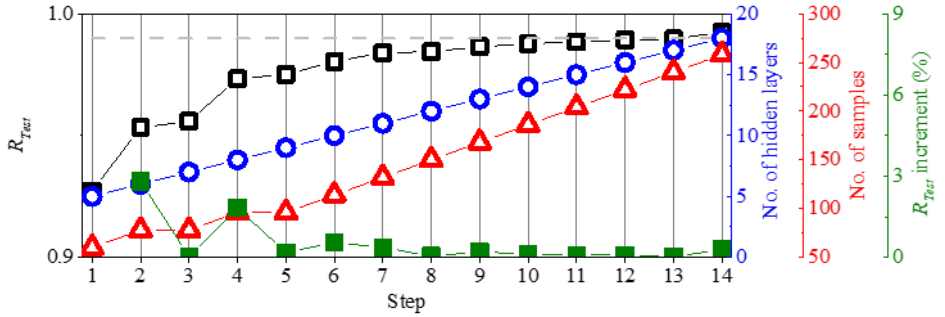
5. Achievements and Outlook

- adaptive DNN construction

- Adaptive Layering and Sampling Results and Profiles
  - traction motor maximum torque



  - traction motor total loss

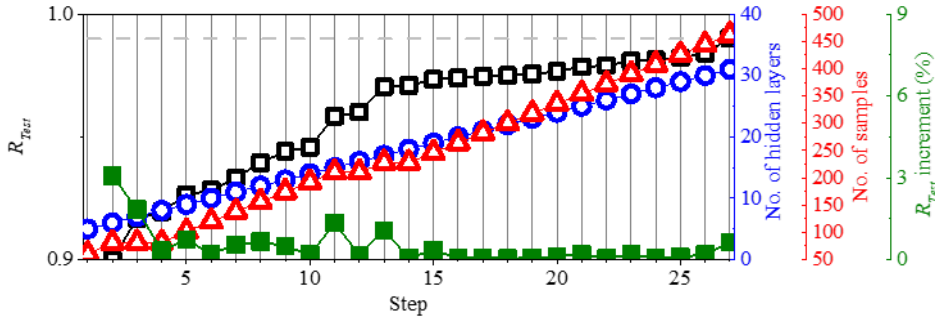


Items	The number of		
	Hidden layers	Sampling points	Data sets
Traction motor maximum torque	10	114	2166
Traction motor total loss	18	258	251136
Air compressor motor maximum torque	31	462	49564
Air compressor motor total loss	5	60	840
FCEV fuel economy	10	250	250
FCEV trace NRMSE	11	255	255

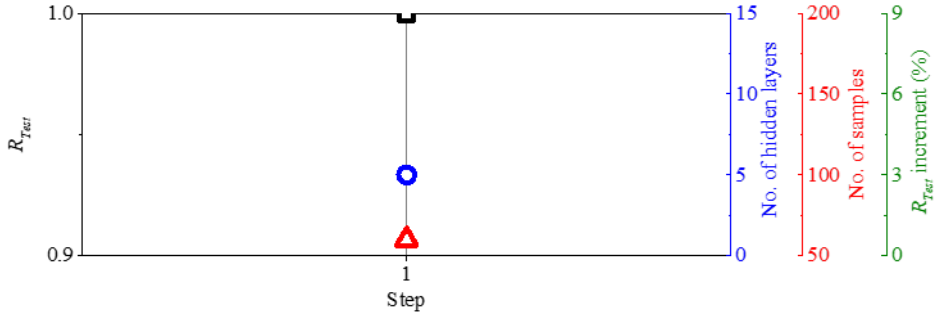
5. Achievements and Outlook

- adaptive DNN construction

- Adaptive Layering and Sampling Results and Profiles
  - air compressor motor maximum torque



  - air compressor motor total loss



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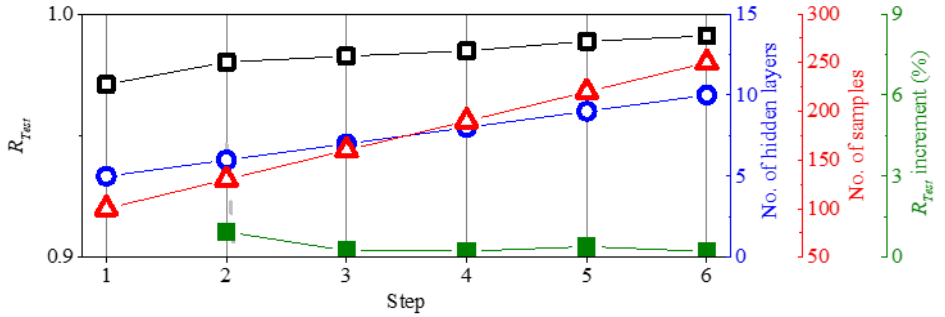
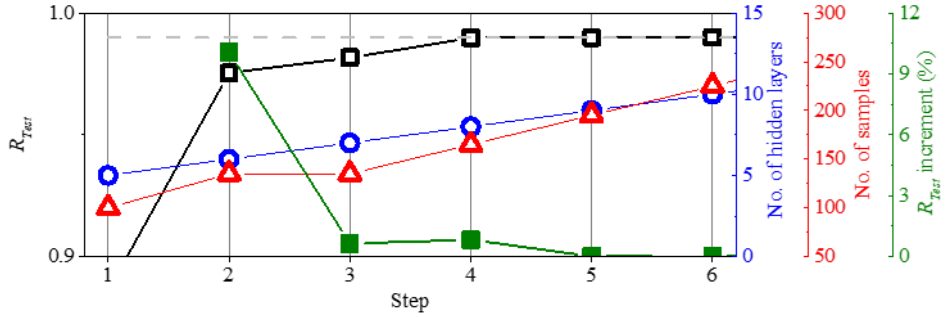
5. Achievements and Outlook

- adaptive DNN construction

- Adaptive Layering and Sampling Results and Profiles
  - FCEV fuel economy



  - FCEV trace NRMSE



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FCEV trace NRMSE	11	255	255

5. Achievements and Outlook
- electric motors optimization

- Optimization Results of Electric Motors for FCEV fuel economy
  - HWFET, FTP75, real driving test cycle

Objective function weighting			Design result					Fuel economy (km/kWh)					
FTP75	HWFET	Test	TM turns	TM stack	Gear ratio	AM turns	AM stack	FTP75		HWFET		Test cycle	
1/3	1/3	1/3	1.00	0.67	1.08	1.28	1.18	3.09	+4.4%	2.88	+4.4%	2.76	+3.0%
1	0	0	0.85	0.86	1.14	1.76	1.18	3.14	+6.1%	2.92	+5.8%	2.76	+3.0%
0	1	0	0.90	0.75	1.14	1.72	1.00	3.10	+4.7%	3.00	+8.7%	2.79	+4.1%
0	0	1	0.90	0.82	1.14	1.84	1.32	3.13	+5.7%	2.90	+5.1%	2.80	+4.5%

6. Future Works

6. Future Works

- Considering vehicle dynamics performance
  - using Simulink “Vehicle Dynamics Blockset”

- Application of other deep learning models : CNN, LSTM, GAN …
  - using MATLAB “Deep Learning Toolbox”

7. Conclusion

7. Conclusion

- Detailed fuel cell electric vehicle (FCEV) model was developed based on MATLAB and Simulink

- Deep neural network → reflect FC voltage variation to electric motors
  → high-fidelity with low time-consuming model

- Effectiveness of adaptive layering and sampling algorithm was confirmed

- MATLAB and Simulink based modeling has advantages in the easy extension of the research direction