MathWorks
AUTOMOTIVE CONFERENCE 2023
Korea

The development status of HMC vehicle dynamics model using MATLAB/Simulink

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Contents

Introduction

Vehicle model development and distribution
for System/SW verification/validation(V&V)/performance development

아키텍처	T-CAR	PROTO	PILOT	SOP
개발 단계별, 도메인별 요구 사항 (활용 목적, 시스템 모델 수준, 인터페이스 정보 등..)				

Database

SPMD TIRE WICS

Data/Model Owners (Design/CAE/Test departments)

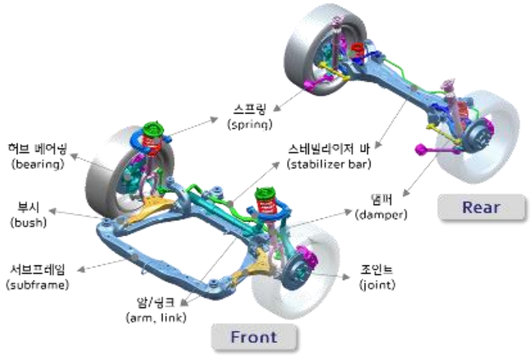
Parameterization

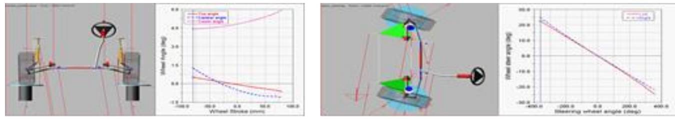
Parameter Identification

MBD
(다물체 동역학 모델)

LPM
(집중 질량 모델)

MATLAB SIMULINK





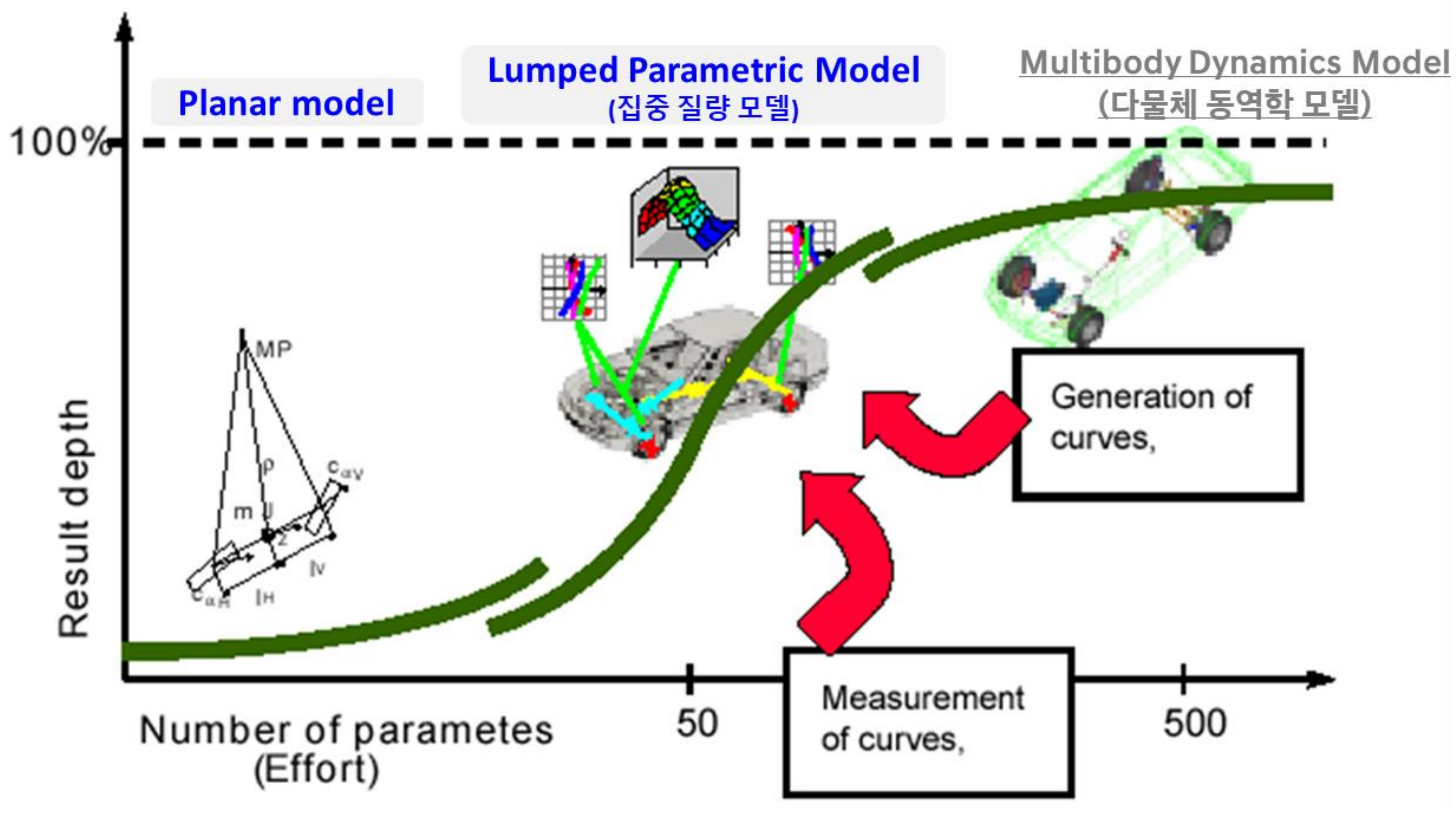
Kinematic/Compliances

MBD : Multi-Body Dynamics
LPM : Lumped Parametric Model
SPMD : Suspension Parameter Measurement Device

IPG CM
dSPACE ASM
carSIM MECHANICAL SIMULATION

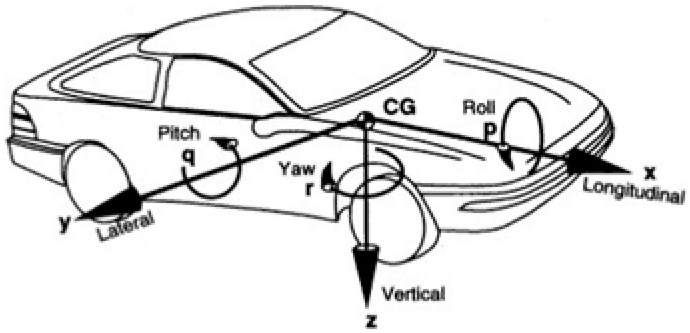
The Model and Its Understanding

<u>Reduced Order Model</u> based on CAE Model and Test Measurement

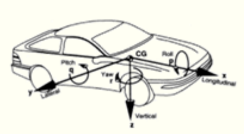
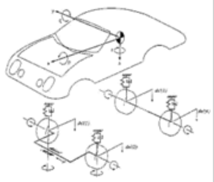
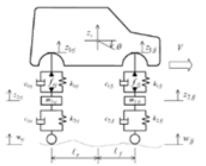
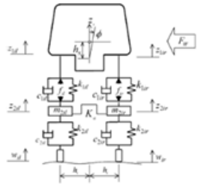
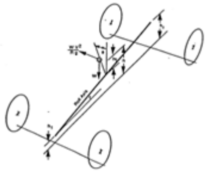
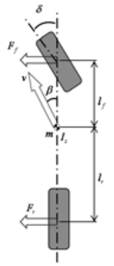
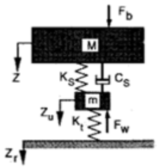
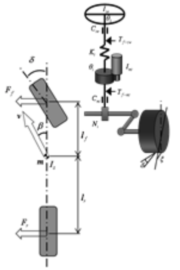


"ADAMS/Car-AT in The Chassis Development at BMW" Ewald Fischer, BMW, 14. November 2001

The Model and Its Understanding



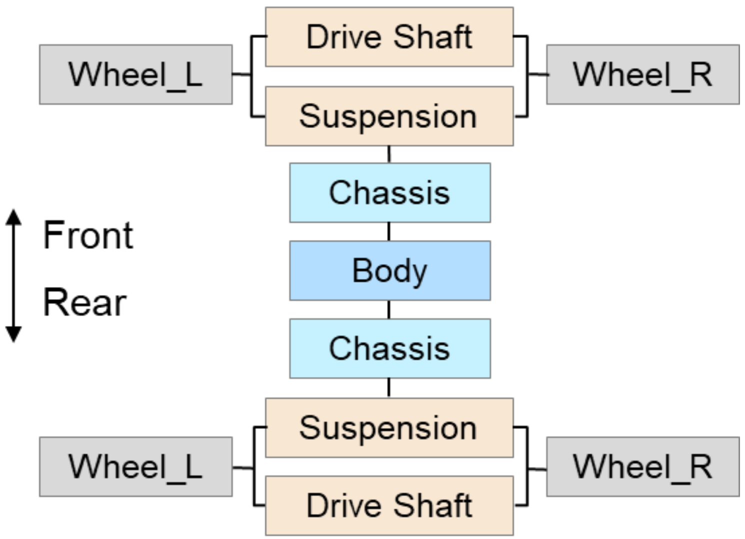
① Planar Models using MATLAB/Simulink

분류		Full vehicle	피치 모델	롤 모델	횡+요+롤	Bicycle	Quarter car	Steering
								
차량 거동	횡방향	●		●	●	●		●
	수직방향	●	●	●	●		●	
	스티어링							●
	종방향	●						
운동 자유도 (d.o.f)	Sprung	6	2	2	3	2	1	2
	Unsprung	4	2	2	-	-	1	-
	Wheel	4	-	-	-	-	-	-
	Steering	-	-	-	-	-	-	2
	Total	14	4	4	3	2	2	4

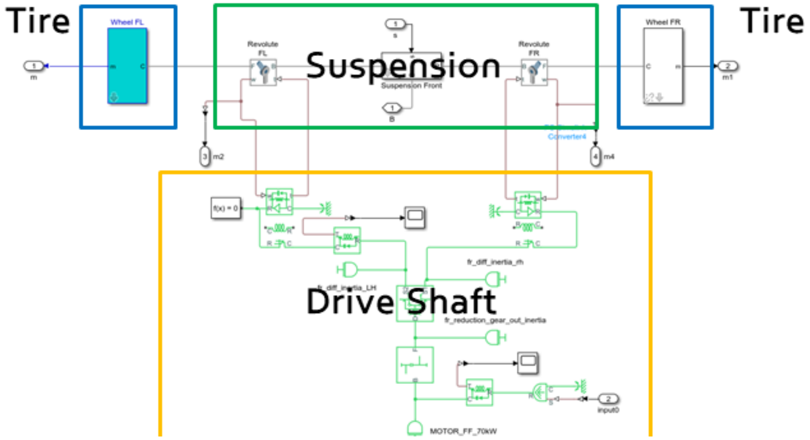
The Model and Its Understanding

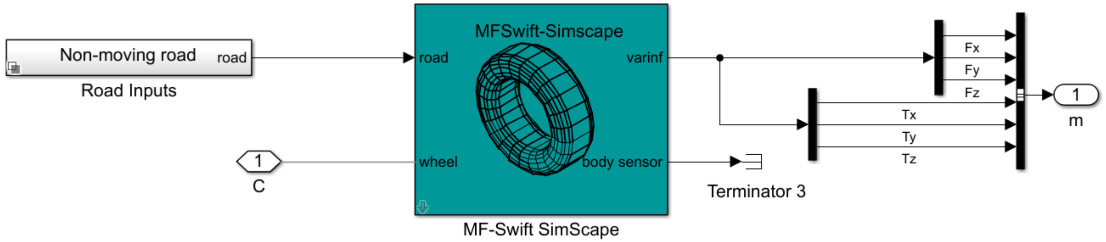
For example, 14DOF vehicle dynamics model + MF-SWIFT using Simscape

Vehicle Body(6DOF) + Wheel vertical (4DOF) + Wheel spin (4DOF)



[Chassis Simulink Model Structure]

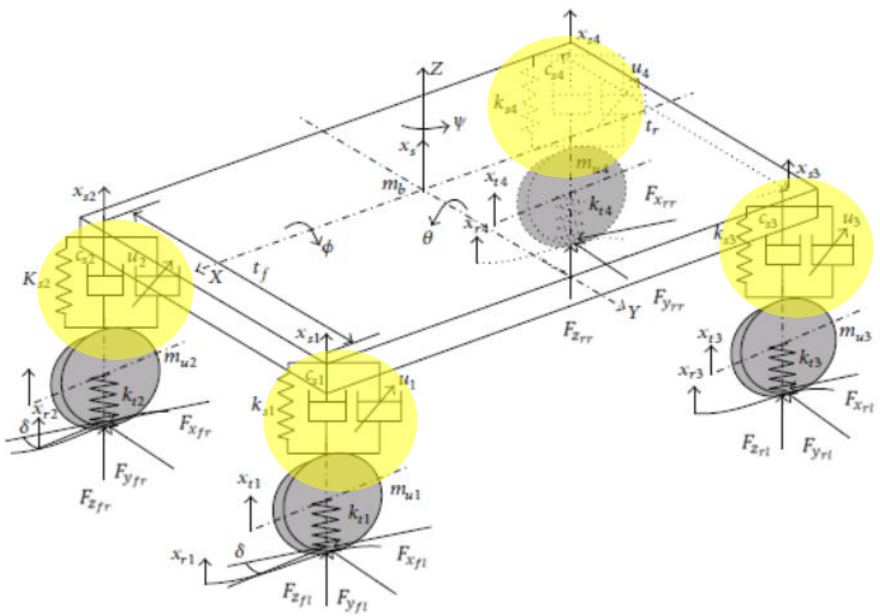




The Model and Its Understanding

② Lumped Parametric Model

A vehicle model that configures the Kinematic/Compliance characteristics of a suspension system in the form of a function through wheel relative motion (displacement, speed, acceleration) equation for a vehicle body based on 17 DOF model



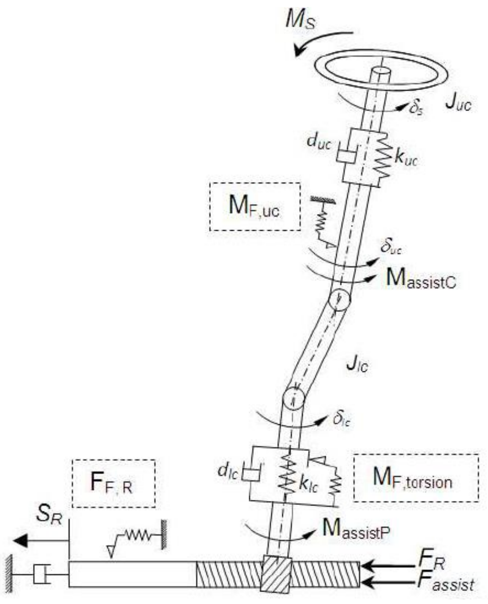
$$y'_{w/b} = f(\delta_r, \delta_l) + s'_w$$

$$y_w = y_b + A_b y'_{w/b}$$

$$\dot{y}' = \begin{bmatrix} \dot{y}'_b \\ \dot{y}'_w \end{bmatrix} = B \begin{bmatrix} \dot{y}'_b \\ \dot{\delta}_r \\ \dot{\delta}_l \end{bmatrix} = B$$

$$\ddot{y}' = \begin{bmatrix} \ddot{y}'_b \\ \ddot{y}'_w \end{bmatrix} = \dot{B} \begin{bmatrix} \dot{y}'_b \\ \delta_r \\ \delta_l \end{bmatrix} + B \begin{bmatrix} \ddot{y}'_b \\ \ddot{\delta}_r \\ \ddot{\delta}_l \end{bmatrix}$$

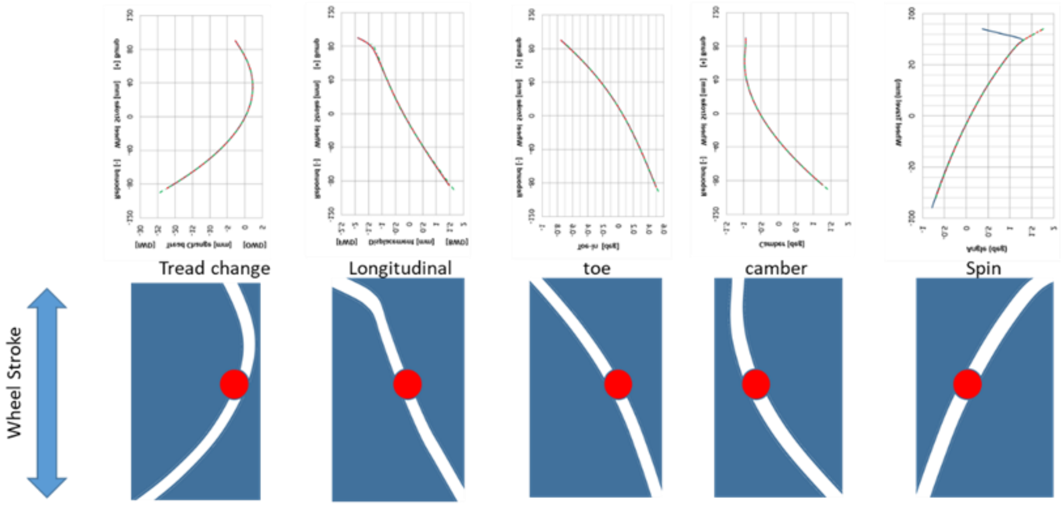
Vehicle Body 6DOF + (Wheel Vertical 1DOF + Wheel Rotation 1DOF) x 4 = 14 DOF



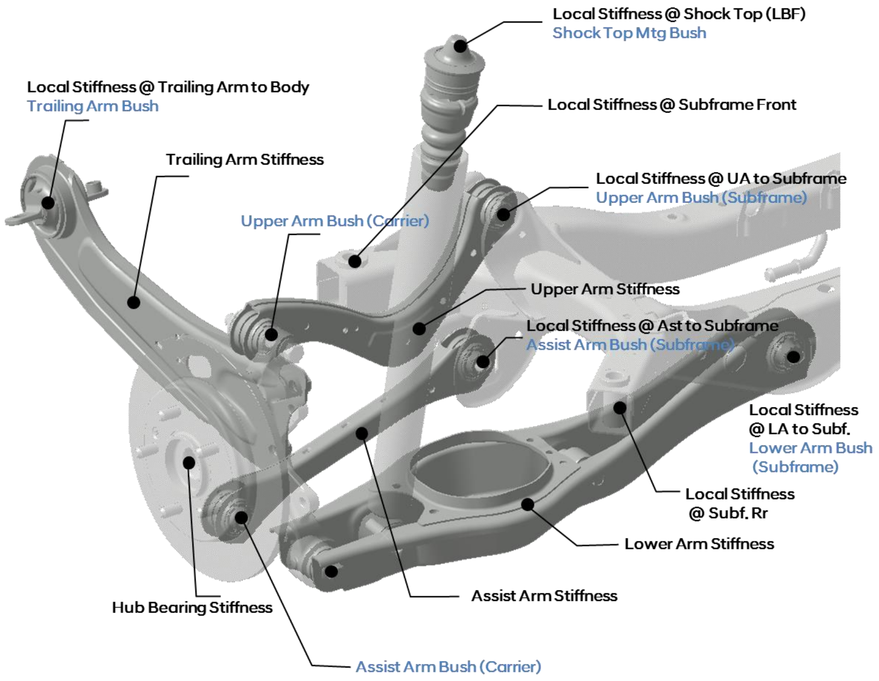
Steering system 3DOF

The Model and Its Understanding

Kinematic/Compliance Modeling from MBD simulations



2 Translations + 3 rotations : 5 variables need to be defined
Polynomial / Lookup table
(wheelbase, tread, toe, camber, caster by wheel stroke/rack stroke)



$$C = \frac{\partial q}{\partial Q} =$$

2.70E-06	-3.46E-11	-1.69E-10	-5.30E-06	-1.19E-09	-4.15E-10	2.03E-07	2.80E-07	1.25E-09	1.03E-06
-4.37E-11	1.18E-07	-7.20E-08	1.13E-10	-3.75E-07	2.02E-07	-6.15E-12	5.91E-12	-2.76E-07	-1.75E-11
-1.80E-10	-7.20E-08	1.91E-06	-1.66E-10	1.14E-06	3.09E-07	9.01E-13	9.49E-11	-7.73E-07	1.28E-09
-5.30E-06	9.24E-11	-1.87E-10	2.04E-05	-3.11E-09	1.22E-09	-3.98E-07	-2.93E-07	-1.27E-09	-3.74E-06
-1.13E-09	-3.74E-07	1.13E-06	-3.23E-09	8.41E-06	4.61E-07	-1.09E-11	1.31E-09	-4.14E-06	1.44E-08
-4.14E-10	2.02E-07	3.10E-07	1.24E-09	4.65E-07	2.70E-06	-3.34E-11	-1.67E-10	-5.04E-06	-1.19E-09
2.03E-07	-6.20E-12	-9.16E-13	-3.99E-07	-1.92E-11	-4.25E-11	8.79E-08	-2.09E-07	1.04E-10	-3.25E-07
2.79E-07	7.38E-12	9.64E-11	-2.90E-07	1.30E-09	-1.79E-10	-2.09E-07	1.95E-06	-1.91E-10	1.00E-06
1.22E-09	-2.76E-07	-7.75E-07	-1.27E-09	-4.15E-06	-5.04E-06	8.29E-11	-2.16E-10	1.89E-05	-3.14E-09
1.03E-06	-1.01E-11	1.30E-09	-3.74E-06	1.43E-08	-1.13E-09	-3.24E-07	9.94E-07	-3.25E-09	4.77E-06

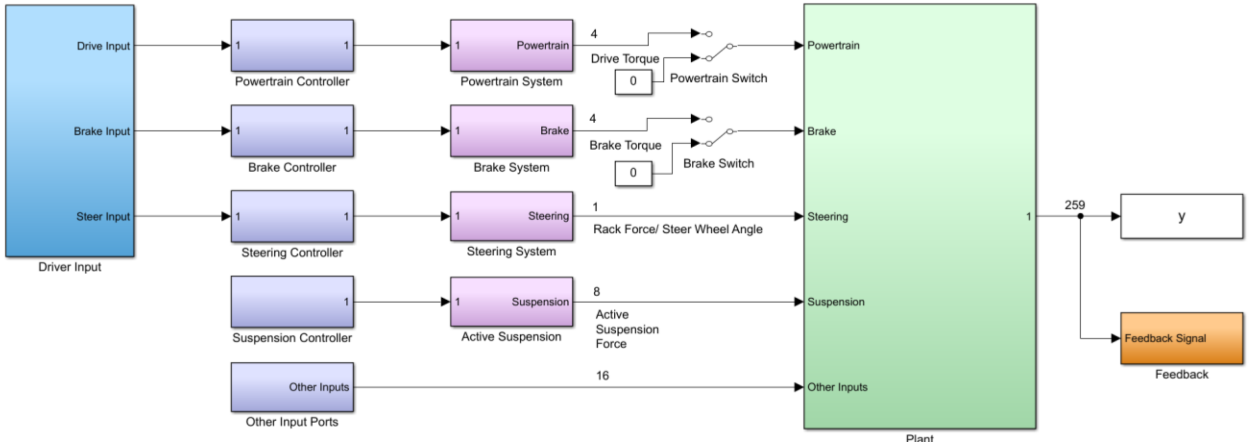
Compliance Matrices

The Model and Its Understanding

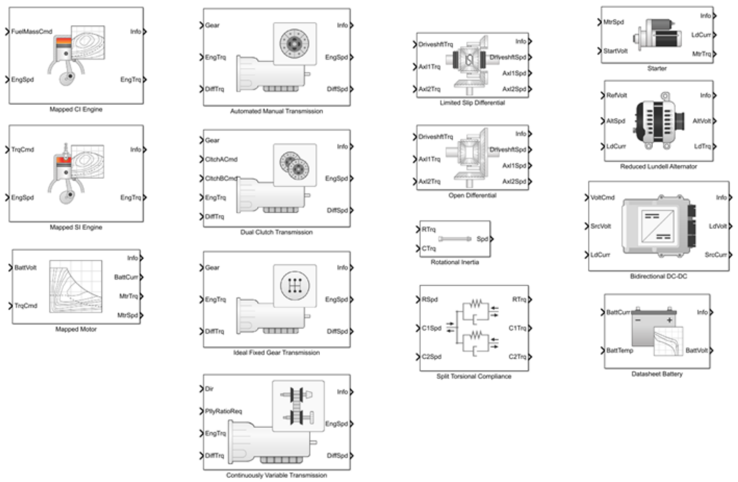
<u>Simulink based Vehicle Dynamics Model by VDL (On-going)</u> <u>*VDL(㈜브이디엘) from Kookmin Univ. Vehicle Dynamics Lab.*</u>

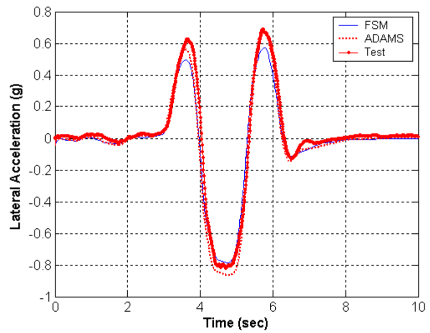
Development of a vehicle model suitable for SW Virtual Testing using Powertrain Blockset in Simulink and developed vehicle dynamics model for around 10 years with HMC

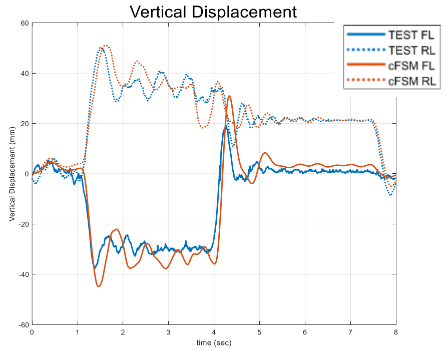
Vehicle Dynamics Model w/o Powertrain system

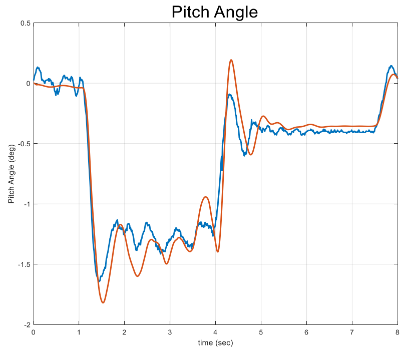


<u>Powertrain Blockset</u>









🡐 Validation with HMC chassis test teams

The Model and Its Understanding

Simulink based Vehicle Dynamics Model

This is why…

- MBD method is strongly required by SDV (Software Defined Vehicle) development strategy
- The Capabilities for integration and simulation of various controllers and development platform

Benefits

- Integration of various controllers using Native Simulink and Legacy Code and FMI
- Open environment that can be used as a common development tool for model readability and collaboration
- Applicable to optimization and controller development in connection with useful MATLAB/Simulink Toolbox
- Continuous use from MIL to HIL level through code generation support

Environment of Model Development

Modeling Automation Tool using Useful MATLAB Toolbox

MBD 해석
(ADAMS Simulation)

해석 항목
Susp. K&C / Steering
Static Vehicle Characteristic

서스펜션 모델링 (전륜 + 후륜)
1D1D + 1D (P.V, S + P.V)
2D + 1D (P.VS + P.V)
2D + 2D (P.VS + A.V)
A2D + 2D (A.VS + A.V)

차량 중량(전/후), 관성, 중심고
스태빌라이저바 강성
조향각/랙 스트로크 테이블
파라지틱 강성

① Run ADAMS Simulation

② Extract Simulation Results

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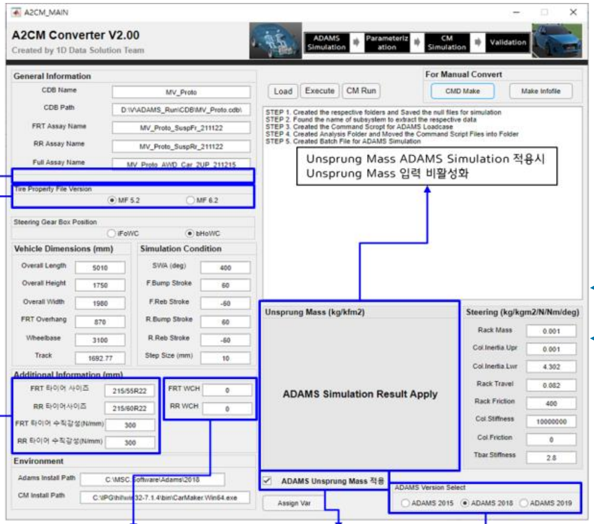
Model Converter



타이어 모델 입력 삭제

타이어 파일 버전 선택

SLR 입력 →
타이어 사이즈 / 강성 입력 변경

Unsprung Mass ADAMS Simulation 적용시
Unsprung Mass 입력 비활성화

Contact Patch 입력
→ 휠센터 높이 입력으로 변경

Unsprung Mass ADAMS Simulation 선택 가능

ADAMS 2019 선택 가능

⑦ Vehicle Model Files
And verification and validation report

⑥ Verification/Validation results

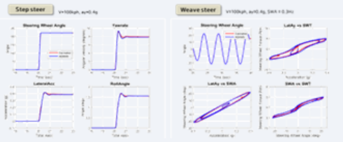
⑤ Compare Simulation and measurement results

④ Get Model Files and Simulation results

③ Create Lumped Parametric Model and Run simulations

유효성/정합성 검증
(Verification/Validation)

실시간 가상 차량 모델
유효성 검증
SPMM, 핸들링 해석 결과
요레이트, 횡가속도
롤 각, 조향 토크
타이어 슬립각, 수직 및 횡력
휠 지오메트리 정보 등



LPM 모델링
(Parameterization)

모델링 항목
Vehicle body, Bodies
스프링 상/하질량, 관성, COG

Suspension & Steering
조향 기어비 테이블
페퍼모델 파라미터
기구학 및 컴플라이언스
스태빌라이저바 및 파라지틱 강성
스프링, 댐퍼,
범프스토퍼

Tire Model
MF tire 5.2 ~ 7.0

Environment of Model Development

Tire Modeling, generally..

Test based method
: HMC, Tire Suppliers

FEM Based (just started..)
: Tire Suppliers

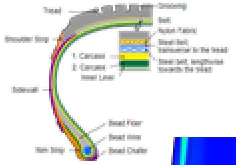
Test based

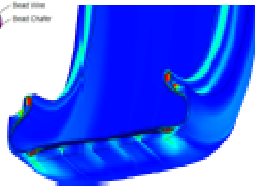
정특성

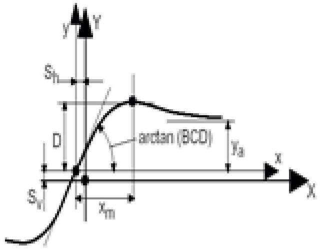
핸들링

동특성

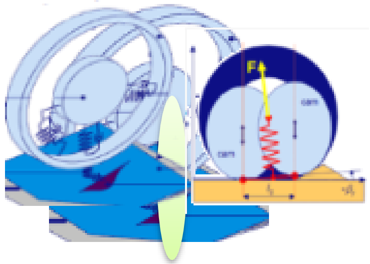
FEM Based







MF-Tyre

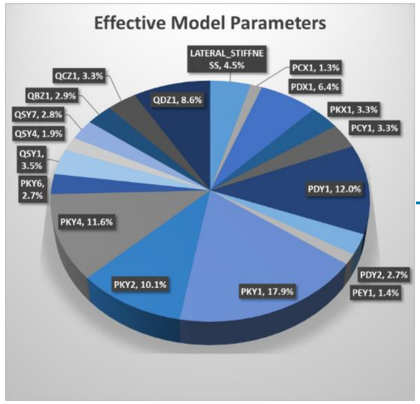


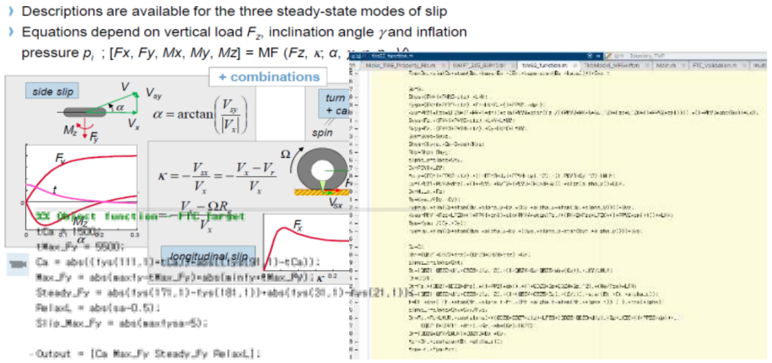
MF-SWIFT, FTire

Environment of Model Development

Tire Modeling, In case we cannot acquire tire model from previous method..

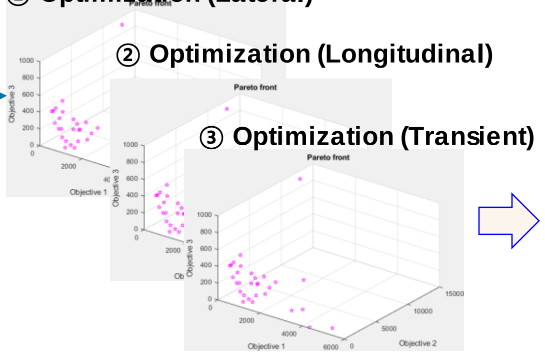
We are using design specifications/performance based tire modeling method using MATLAB Optimization Toolbox / Python(GPR ML)

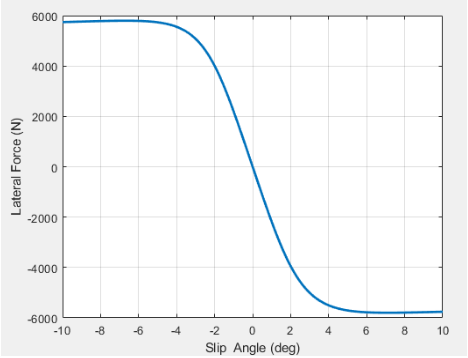


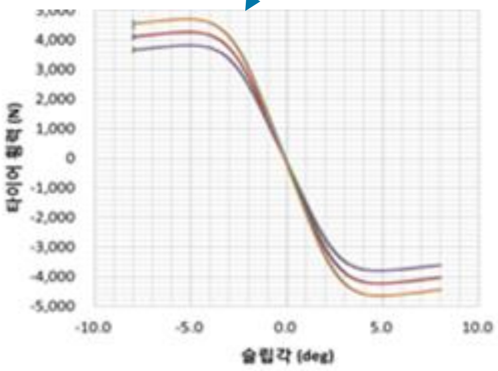


MATLAB script
based MF tire modeling

① Optimization (Lateral)
② Optimization (Longitudinal)
③ Optimization (Transient)







Comparison with
commercial Tire solver (dll)

Tire model parameter extraction to achieve functional tire characteristics using MATLAB Multi-objective genetic algorithm

Environment of Model Development

Its Front-end using
App designer

Moule 1
(7 design variables)

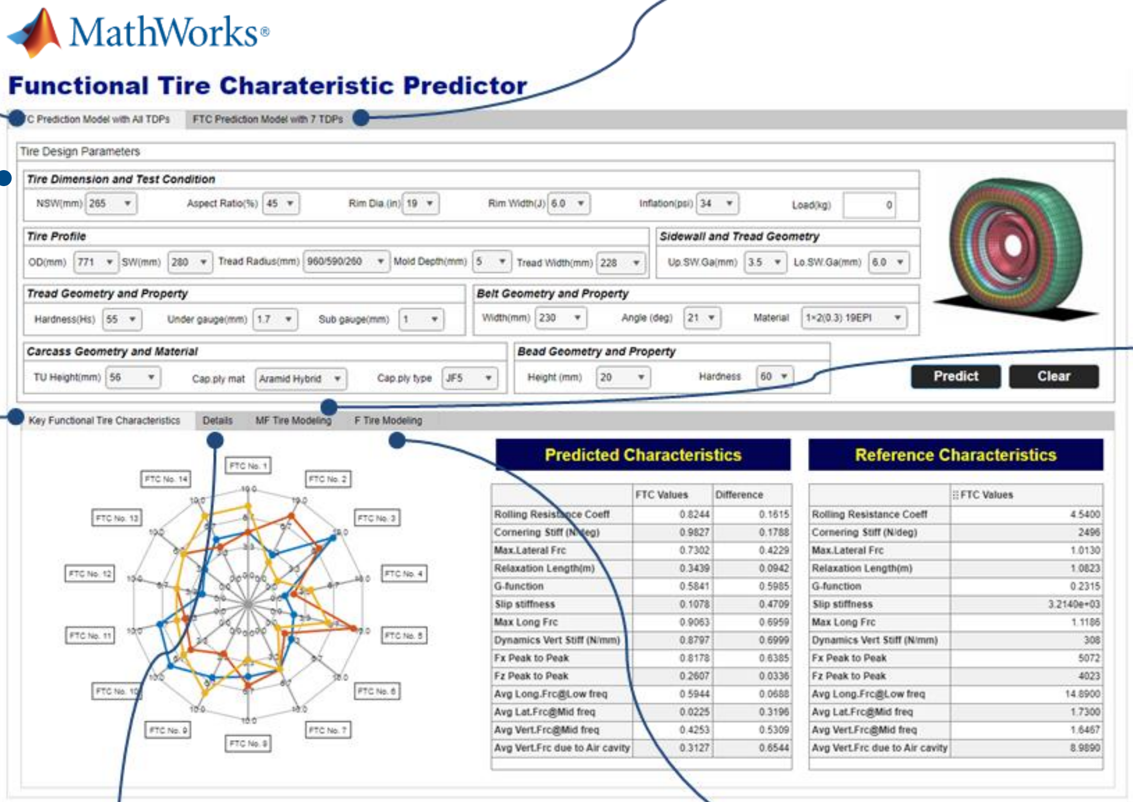
Input : 타이어 설계 변수

```
TDPs_struct_1 = struct( ...
"Mold_Tread_Depth", 7.0, ...
"Belt_Angle", 24.0, ...
"Cap_Ply_Material", 0.815, ...
"Beadfiller_Height", 35.0, ...
"Vertical_Load", 760.5, ...
"Tread_Hardness", 0.86884, ...
"Belt_Material", 1.0 ...
);
```

Module 2

Input : 타이어 설계 변수

```
TDPs_struct_2 = struct( ...
"NSW", 275.0, ...
"Series", 55.0, ...
"Rim_Diameter", 20.0, ...
"Inflation_Pressure", 36.0, ...
"Rim_Width", 8.5, ...
"Mold_Tread_Depth", 7.0, ...
"Under_Tread_Gauge", 2.2, ...
"Sub_Tread_Gauge", 1.5, ...
"Belt_Width", 240.0, ...
"Belt_Angle", 24.0, ...
"Carcass_Material", 1.0, ...
"Carcass1_Turn_Up_Height", 76.0, ...
"Cap_Ply_Material", 0.815, ...
"Cap_Ply_Type_Edge_Factor", 2.0, ...
"Cap_Ply_Type_Center_Factor",
1.0, ...
"Beadfiller_Hardness", 1.0, ...
"Beadfiller_Height", 35.0, ...
"Upper_Sidewall_Rubber_gauge", 4.5, ...
"Lower_Sidewall_Rubber_Gauge", 8.5, ...
"Tread_Width", 240.0, ...
"Tread_Radius_1", 1200.0, ...
"Tread_Radius_2", 590.0, ...
"Tread_Radius_3", 190.0, ...
"Mold_OD", 807.0, ...
"Mold_SW", 290.0, ...
"Vertical_Load", 760.5, ...
"Tread_Hardness",
0.86884, ...
"Belt_Material", 1.0, ...
"Sho_Drop", 10.81, ...
"Drop_At_TW85", 0.79 ...
);
```



Predicted Characteristics

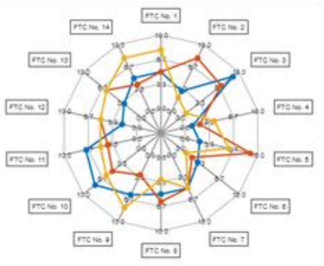
	FTC Values	Difference
Rolling Resistance Coeff	0.8244	0.1615
Cornering Stiff (N/deg)	0.9827	0.1788
Max.Lateral Frc	0.7302	0.4229
Relaxation Length(m)	0.3439	0.0942
G-function	0.5841	0.5985
Slip stiffness	0.1078	0.4709
Max Long Frc	0.9063	0.6959
Dynamics Vert Stiff (N/mm)	0.8797	0.6999
Fx Peak to Peak	0.8178	0.6385
Fz Peak to Peak	0.2607	0.0336
Avg Long.Frc@Low freq	0.5944	0.0688
Avg Lat.Frc@Mid freq	0.0225	0.3196
Avg Vert.Frc@Mid freq	0.4253	0.5309
Avg Vert.Frc due to Air cavity	0.3127	0.6544

Reference Characteristics

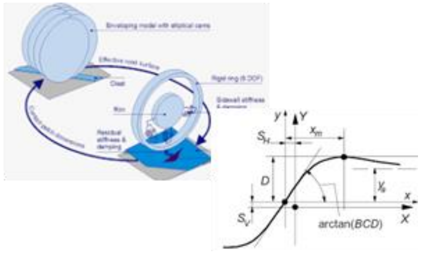
	FTC Values
Rolling Resistance Coeff	4.5400
Cornering Stiff (N/deg)	2496
Max.Lateral Frc	1.0130
Relaxation Length(m)	1.0823
G-function	0.2315
Slip stiffness	3.2140e+03
Max Long Frc	1.1186
Dynamics Vert Stiff (N/mm)	308
Fx Peak to Peak	5072
Fz Peak to Peak	4023
Avg Long.Frc@Low freq	14.8900
Avg Lat.Frc@Mid freq	1.7300
Avg Vert.Frc@Mid freq	1.6467
Avg Vert.Frc due to Air cavity	8.9890

Module 3
Direct FTC input
*** Functional Tire Characteristics**

Spider chart



To configure MF 5.2/6.2



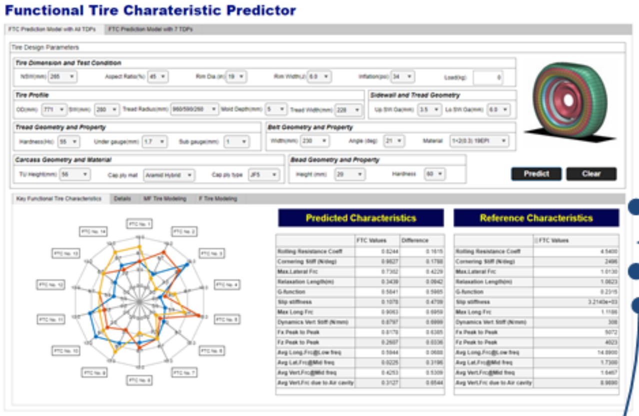
Detail Tire Performance Values

FE, Braking, Road Load	FTC Values	Handling	FTC Values	Ride	FTC Values	NVH	FTC Values
Rolling Resistance Coeff	4.5400	Rolling Resistance Coeff	4.5400	Rolling Resistance Coeff	4.5400	Rolling Resistance Coeff	4.5400
Cornering Stiff (N/deg)	2496	Cornering Stiff (N/deg)	2496	Cornering Stiff (N/deg)	2496	Cornering Stiff (N/deg)	2496
Max.Lateral Frc	1.0130	Max.Lateral Frc	1.0130	Max.Lateral Frc	1.0130	Max.Lateral Frc	1.0130
Relaxation Length(m)	1.0823	Relaxation Length(m)	1.0823	Relaxation Length(m)	1.0823	Relaxation Length(m)	1.0823
G-function	0.2315	G-function	0.2315	G-function	0.2315	G-function	0.2315
Slip stiffness	3.2140e+03	Slip stiffness	3.2140e+03	Slip stiffness	3.2140e+03	Slip stiffness	3.2140e+03
Max Long Frc	1.1186	Max Long Frc	1.1186	Max Long Frc	1.1186	Max Long Frc	1.1186
Dynamics Vert Stiff (N/mm)	308	Dynamics Vert Stiff (N/mm)	308	Dynamics Vert Stiff (N/mm)	308	Dynamics Vert Stiff (N/mm)	308
Fx Peak to Peak	5072	Fx Peak to Peak	5072	Fx Peak to Peak	5072	Fx Peak to Peak	5072
Fz Peak to Peak	4023	Fz Peak to Peak	4023	Fz Peak to Peak	4023	Fz Peak to Peak	4023
Avg Long.Frc@Low freq	14.8900	Avg Long.Frc@Low freq	14.8900	Avg Long.Frc@Low freq	14.8900	Avg Long.Frc@Low freq	14.8900
Avg Lat.Frc@Mid freq	1.7300	Avg Lat.Frc@Mid freq	1.7300	Avg Lat.Frc@Mid freq	1.7300	Avg Lat.Frc@Mid freq	1.7300
Avg Vert.Frc@Mid freq	1.6467	Avg Vert.Frc@Mid freq	1.6467	Avg Vert.Frc@Mid freq	1.6467	Avg Vert.Frc@Mid freq	1.6467
Avg Vert.Frc due to Air cavity	8.9890	Avg Vert.Frc due to Air cavity	8.9890	Avg Vert.Frc due to Air cavity	8.9890	Avg Vert.Frc due to Air cavity	8.9890

To configure F tire model

Environment of Model Development

Its Back-end using Optimization Toolbox, Curve fitting Toolbox and so on



MATLAB App-designer User Interface

Tire Design variables

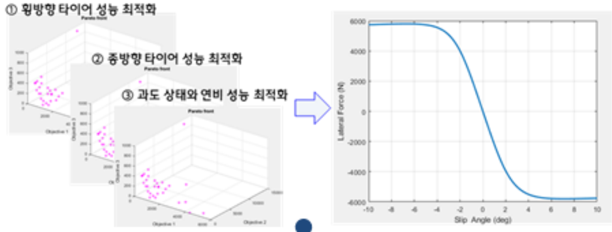
Tire Performance Values

PYTHON

Prediction Model (GPR ML)

on the way to improve accuracy
Of machine learning GPR model
with much more FEM tire simulations
(by Hankook Tire)

MATLAB Optimization function



Tire Performance Values

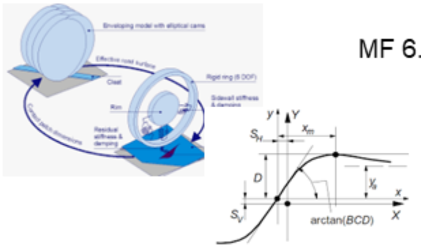
F tire model parameter

MF Tire Model Parameters

MATLAB Function to create F tire model

MATLAB Function To create MF Tire model

F 타이어 모델



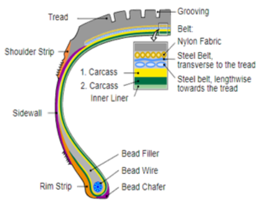
MF 6.2 타이어 모델

Environment of Model Development

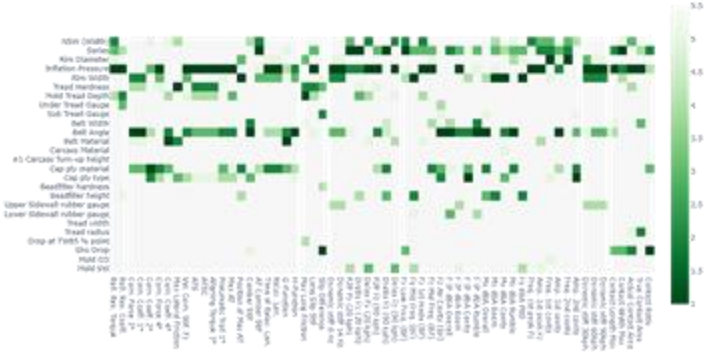
How to create prediction model for FTC (Functional Tire Characteristics)

Tire Design Variables(26)/Simulation Conditions

1. NSW (Width)
2. Series
3. Rim Diameter
4. Inflation Pressure
5. Rim Width
6. Tread Hardness
7. Mold Tread Depth
8. Under Tread Gauge
9. Sub Tread Gauge
10. Belt Width
11. Belt Angle
12. Belt Material
13. Carcass Material
14. #1 Carcass Turn-up Height
15. Cap Ply Material
16. Cap Ply Type
17. Beadfiller Hardness
18. Beadfiller Height
19. Upper Sidewall rubber gauge
20. Lower Sidewall rubber gauge
21. Tread width
22. Tread radius
23. Sho. Drop
24. Drop at TW 85 % point
25. Mold OD
26. Mold SW

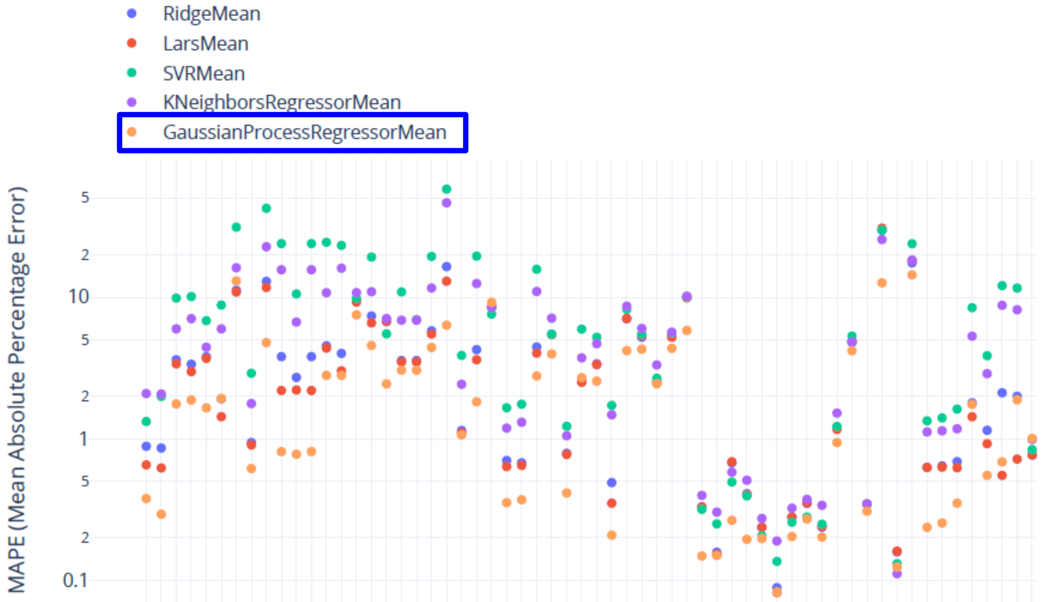


Sensitivity Analysis to select effective tire design parameters



Machine learning algorithm selection using MAPE as evaluation index

Candidates
1. Ridge Regression
2. Least-Angle Regression
3. Support Vector Regression
4. K-nearest Neighbors Regression
5. Gaussian Process Regression



Model V&V Process

VERIFICATION

유효성 검토 (Physical Plausible Check)

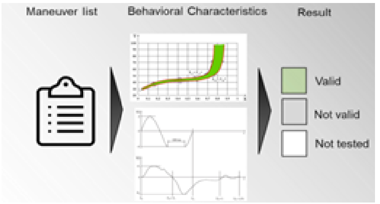
Is the model properly configured according to the vehicle specifications/design specifications?
Is it normally simulated in straight/brake/drive/steering/reverse/stop conditions?

MODEL CHECK

시스템 모델 적합성 검토 (System Model Feasibility)

- 공력 (Aero) - Drag, Lift, Side 공기 저항력
- 파워트레인 (PT) - 엔진 토크, 터보 차저, 변속 패턴(Shift/Lock up)
- 제동 (Brake) - 페달 위치, 제동 토크, 제동 압력, 마스터 실린더 압력
- 타이어 (Tire) – 타이어 F&M (Fx, Fy, Mx, My, Mz)
- 현가 힘요소 (Susp. Force) – 외력(Fspirng, Fdamp, Fstab, Fbps/rbs)
- 현가 K&C (Susp. K&C) – Toe, Camber, Caster, Wheelbase, Tread 변화량

VALIDATION



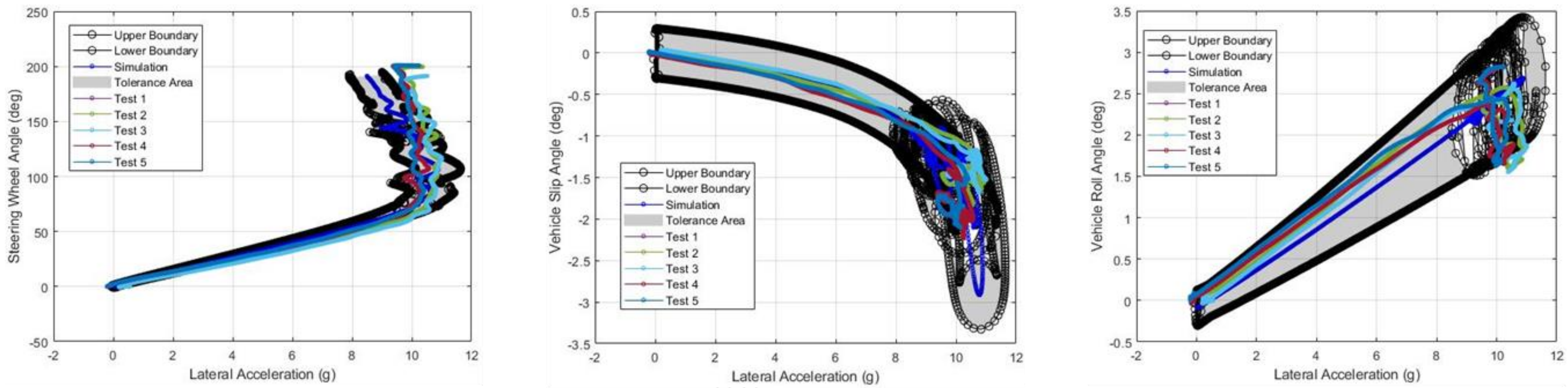
1. 해석 vs 계측간 정합성 검토 (VP Quality)

- Transient, Steady sate, Acc/Braking, Coastdown (13 maneuvers)
- ISO4138, ISO22140/7401, ISO19364, ISO 19365

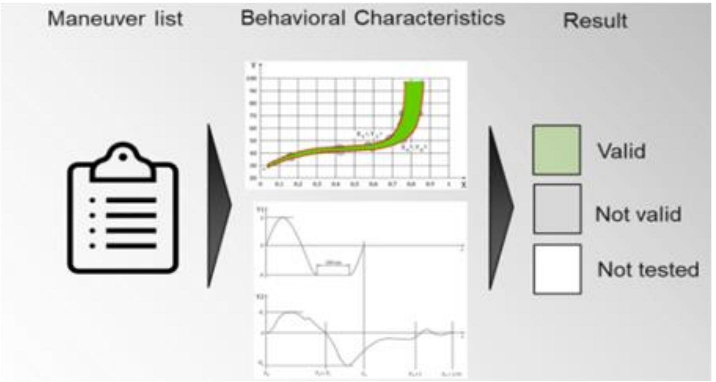
2. 해석 vs 해석(MBD) 정합성 검토 (VP Quality)

- Longitudinal / Lateral Behavior

Model V&V Process



[ISO 19364 시험 : Counter Clockwise]



$$X_T = X - \Delta Y \, \varepsilon_X^2 / D \qquad X_B = X + \Delta Y \, \varepsilon_X^2 / D$$

$$Y_T = Y + \Delta X \, \varepsilon_Y^2 / D \qquad Y_B = Y - \Delta X \, \varepsilon_Y^2 / D$$

Table 1 — Offsets and gains used to define tolerances ε_X and ε_Y for constant-radius tests

Variable on Y-axis	X offset (m/s²)	X gain	Y offset (deg)	Y gain
Steering wheel angle (deg)	0,1	0,06	1,0	0,03
Sideslip angle (deg)	0,1	0,06	0,3	0,04
Roll angle (deg)	0,1	0,06	0,2	0,2

Summary

- The demand for vehicle/system model for SW virtual verification/validation(V&V) and calibration is significantly/remarkably increased for SW development efficiency.
- MATLAB/Simulink is widely used in HMC vehicle dynamics modeling process thanks to useful and powerful toolbox and MATLAB/Simulink is very open/efficient tool to connect the different models and to operate different tool chain.
- Hyundai is on the way to develop Simulink based vehicle dynamics model including PT/PE systems in Powertrain Blockset to easily integrate control models.
- Current vehicle model quality (fidelity of system model) and qualification process need to be improved for SW virtual calibration at high long./lat. acc range. But vehicle models are widely used across many application areas for function validating, fail safe, fault diagnosis, regulation certification, virtual calibration (at low~mid acc range)
- Objective model validation index is under investigation and its criteria will be quantified in order for consistency of model quality especially for SW virtual calibration in terms of vehicle behaviors

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Thank you