Development of a Multi-Physical Simulation Platform for Durability Prediction for Hyundai & Kia Electric Vehicles

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Abstract

One of the most popular ways of measuring signals for various components in vehicle on durability tracks will be Road Load Data Acquisition (RLDA) which gains load data through accelerated customer usages tests on either proving ground or field, using an instrumented vehicle. However, under the current circumstances, not only does a vehicle development cycle get shorter but also new mobility concepts keep being developed, a methodology is needed to cope with overall durability assessment in advance of a physical prototype being made for testing. In this study, this virtual testing methodology will be called Virtual RLDA.

Keywords: Durability, Multi-Physics, Vehicle Simulation

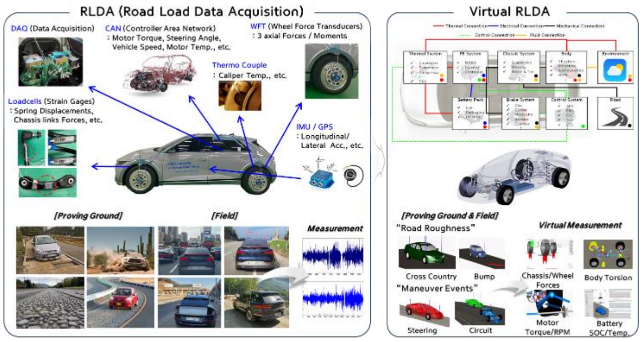

Figure 1. Idea of Virtual RLDA from Conventional Measurement Campaign

In this study, one of the most well-known electric vehicles in market is from Hyundai, with 2 in-wheel motors in rear which was chosen as the target vehicle. First, 6 major sub-systems such as vehicle controller, suspension, hydraulic brake, motor, battery and thermal management are modelled and validated separately, then they are integrated into one large vehicle model as a part of establishing the Virtual RLDA Platform which will be used for overall vehicle level durability development in early stage in Hyundai Kia Motor Company (HKMC).

1 Introduction

1.1 Background of the project

From the overall durability point of view, an electric vehicle still requires a number of studies to figure out unknown failures and degradation mechanisms especially on the motor, inverter and battery which has different failure mechanisms from conventional ICE vehicle. If the durability failures are divided into two large aspects, one aspect will be structural failure and the other will be powertrain related failure. The objective of this study is to develop the vehicle model that can cover both structural and powertrain related failures depending on the choice of the level of fidelity.

First, when it comes to structural durability of an EV, a high voltage battery system weighs about 300kg more than a fuel tank in ICE vehicle. Also, with regards to in-wheel motor systems, the motor system is integrated in each wheel assembly which have much heavier unsprung mass than conventional wheel. This weight increase has a significant influence on the amount of damage to the suspension system and each body mountings due to the increased reaction forces.

Moreover, powertrain coupled components such as subframes, motor mountings and driveshafts are also expected to have more damage due to the reaction torque from a motor as an electric motor can theoretically generate maximum torque at low speed. For this reason, a multi-physics model which can efficiently simulate a motor's movement aligned with powertrain coupled suspension is essential to replicate the coupled reaction using both table-based electrical motor model and powertrain dynamics-based suspension in a single simulation environment.

As for powertrain durability, the heat generated from motor during driving is the key factor for the degradation of powertrain systems. Also, since the hydraulic brake assembly is integrated within the in-wheel motor system, most of the brake heat during braking is directly radiated to the motor system. For this reason, there should be a realistic method to simulate the thermal interface between hydraulic brake and motor system. In order to simulate the above phenomenon in the model, the first thing we need is thermal management system, modelled with TiL Library, which controls temperatures for both coolant and refrigerant to be maintained in a proper level for most driving scenarios. The second thing we need is the vehicle controller model which simulates pure hydraulic brake pressure that is used as an input signal from thermal brake model by subtracting regenerative motor torque from the total required brake torque in a vehicle. This is one of the reasons why the vehicle controller is required in the vehicle model.

The virtual RLDA platform which is developed in this study to simulate various perspectives of durability influences in vehicle level consists of the following systems below:

- Vehicle Controller.
- Hydraulic Brake (Mechanical / Thermal)
- Vehicle Dynamics (Ideal & Bushed Suspension)
- Motor (Electrical / Thermal for Standard & IWM)
- Battery (ECM / Thermal Cell & Pack)
- Thermal Management (Entire Vehicle Circuit)
- Integrated Vehicle Model (Assembly)
- Durability Scenarios (Tire / Driver / Road Models)

1.2 Motivation of Using Modelica

The vehicle level durability simulation environment based on Modelica libraries has distinctive advantages as follows.

First, each system in a vehicle behaves based on their own physics. It would take numerous efforts to model each different domain systems from scratch as it requires each domain-specific expertise for the modelling. However, the eco-system of, Modelica provides each system domain-specific libraries which gives a lot of potential and flexibility to modelling engineers.

Also, the whole vehicle level simulation which exchanges multi-physical signals between different systems in one single simulation environment is possible in Modelica. In this study, 3 different libraries from Dassault Systèmes (battery, motor), VeSyMA (vehicle template, suspension, brake, driver, road, etc.), TiL (thermal management) are integrated to simulate one large vehicle which is the most efficient way for multi-physical simulation.

Lastly, it provides very efficient way of replacing one model to another from component to large-scale level. From the perspective of managing models in different fidelity and types, this makes the modelling process even more scalable and efficient.

The figure below is the model management strategy of the developed models in this study depending on purpose of durability scenarios.

Fidelity Level: Basic Fidelity / High Fidelity — Simulation Output: Category 1 + 2 / Category 2 Only

No.	System Models		Category 1 Proving Ground (Suspension) Road Roughness	Category 1 Proving Ground (Suspension) Maneuvering	Category 2 Proving Ground (Powertrain)	Category 2 Field	Category 2 Circuit	Simulation Outputs
1	Suspension		Bushed or Bushed Subframe		Table-based or Ideal			[Spring/Links/Bush] Force / Displacement
2	Brake		Mechanical		Thermal			[Brake] Torque, Disc Temp.
3	Driveline		Base or Joint type (Drive Shaft & Differential)					[Drive Shaft] Torque
4	Powertrain (Motor)		Electric		Electric + Thermal			[Motor] Torque / RPM [Coil & Magnet] Temp., Heat Loss
5	Battery	Cell	None or Electric		Electric + Thermal			[Cell] Voltage, SOC, Temp.
		Pack			Scaled			[Cell] Temp. in the Pack
6	Cooling				PE + Battery + Heat Pump Loop			[Coolant (PE/Battery)] Temperature
7	Tire		FTire		Pacejka			[Wheel Center] Forces / Moments
8	Driver		Longitudinal	Longitudinal + Lateral	Longitudinal	Longitudinal + Lateral		-
9	Vehicle Controller		2WD or AWD					Motor Torques, Brake Pressures
10	Simulation		Rig (Half / Full-car) or Closed-Loop		Closed-Loop			-
Representative Events			Pothole	Steering, Go & Stop	UDDS, ColdFTP	Ex) City road in Seoul	Nurbergring	-

Figure 2. Overall Vehicle Model Fidelities for Different Durability Scenarios

2 System Modelling

2.1 Vehicle Controller

The main function of the vehicle controller in the model is to decide driving torque, regenerative torque, and Hydraulic brake torque relative to the driving conditions. It also decides the clutch engagement and disengagement timing between front and rear motor of all-wheel drive (AWD) vehicle models. Figure 3 shows the vehicle controller model built with Dymola for HMC's AWD electric vehicle.

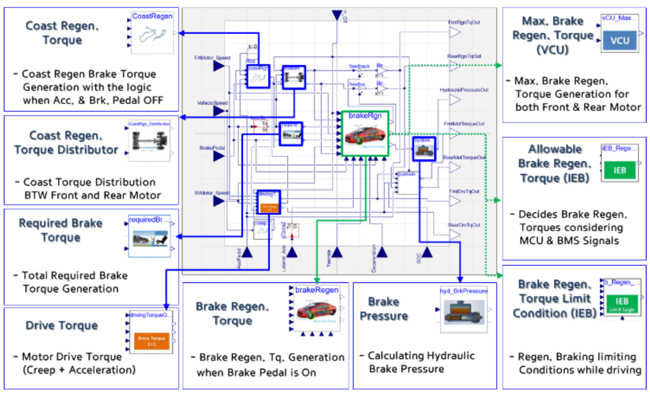

Figure 3. Vehicle Controller Model built for Electric AWD Durability Scenarios

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One of the main roles of the vehicle controller is to generate drive torque using both maximum torque map relative to motor speed and tuned torque map in the development stage which has different torque levels in different driving modes and regenerative brake levels dependant on accelerator pedal stroke. For this reason, vehicles can generate different levels of driving torque even with the same vehicle speed and accelerator pedal stroke dependent on different driving modes. The model also generates creep torque while driving using a tuned map when the accelerator pedal is not pressed.

The total brake torque can be divided into regenerative brake torque and hydraulic brake torque. The total brake torque is decided by the table-based tuned map relative to vehicle speed and brake pedal stroke. When regenerative brake torque is calculated considering the status of clutch engagement between front and rear motor based on the logic, the pure hydraulic brake torque can be lastly calculated.

Regenerative brake torque of a motor can be also divided into brake regenerative torque, which occurs when brake pedal is pressed, and coast regenerative torque, which is generated when normally brake pedal is off. Especially for brake regenerative torque, it is mainly decided by the coordinated control between vehicle controller unit (VCU) and integrated electronic brake (IEB). Therefore, the model includes the logics of interaction between different Electronic Control Units (ECUs) to decide the brake regenerative torque in sequence as it happens in real vehicle.

Hydraulic brake torque is obtained from the remaining torque between total brake torque and regenerative brake torque. The hydraulic brake model that will be discussed in the section 2.2 takes hydraulic master cylinder pressure as an input to calculate brake torque which generates disc temperatures. For this reason, additional converter which converts brake torque to pressure is also added to the model.

To validate the developed vehicle controller model, the data measured in one of the highest mountains in Korea, considered as the most severe driving conditions with frequent braking and steep steering, is used for the controller validation in Figure 4.

As it can be seen in the data, the vehicle controller generates driving torques, regenerative torques and hydraulic pressure quite accurately compared to the measurement even with the severe driving condition. There is a bit of inaccuracy in brake pressure around 850s, it is due to in accurate total brake torque from the tuned map as the measurement kept changing its driving and regenerative mode.

Comparing several values with measurement, this vehicle controller model still needs some improvements, primarily the clutch logic between front and rear motor and also for the regenerative brake logic. For this reason, the vehicle controller model will be updated. However, it still shows good prediction if it is not a very special driving case.

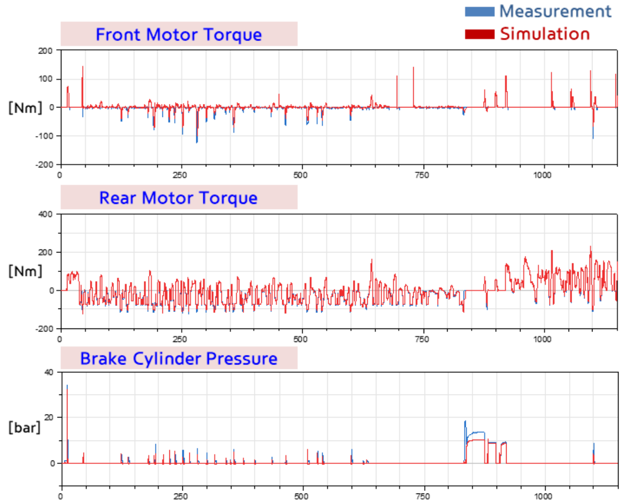

Figure 4. Validation of Motor Torque and Brake Pressure with measurement

2.2 Hydraulic Brake

The Hydraulic brake system has been modelled using Dymola and the VeSyMA library.

During the braking, the vehicle's kinetic energy, which comes from its motion, is converted into brake power through the braking system. This brake power is then transformed into thermal energy (heat) due to friction between the brake pads and the disc. As a result, the brake disc heats up, and the temperature of the disc rises, which is a key factor in brake performance and safety. The brake system modelling is divided into two key sections: hydraulic and mechanical system and the thermal system.

The mechanical brake model generates braking force relative to the driver's pedal stroke to meet the required vehicle deceleration. In high ambient temperatures or during frequent braking, heated brake discs can lead to reduced brake torque, which poses a significant safety issue. Accurate prediction of brake disc temperature is essential for both durability and vehicle safety.

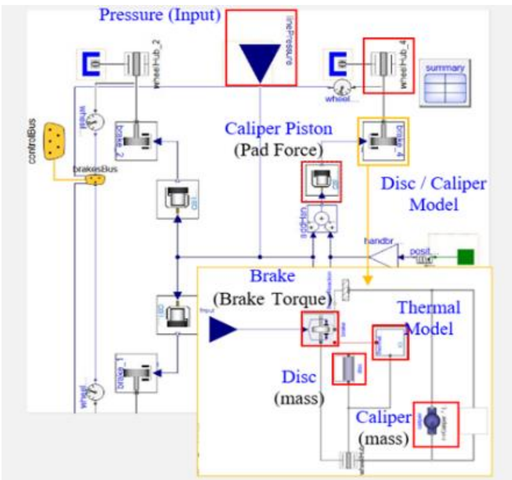

Figure 5. Mechanical brake model

Figure 5 shows the mechanical brake model, with hydraulic pressure coming from controller model, which is equally distributed to the front and rear calliper pistons. Brake Torque in the model is calculated based on pressure, piston area, disc radius, and pad mu.

$$Brake\ Torque = 2 \times \mu\_pad \times A_{Piston} + R_{Eff.} \qquad (1)$$

The thermal model, shown in Figure 6, captures key heat transfer mechanisms conduction, convection, and radiation across components like the brake pad, inner/outer disc plates, vane, and disc hub thermal mass, allowing accurate prediction of brake disc temperature during operation.

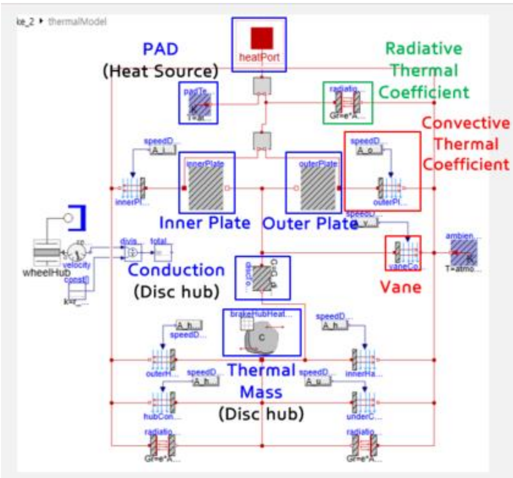

Figure 6. Thermal Brake Model

Figure 7 shows a comparison between the measured and simulated brake disc temperatures for the front left and front right wheels. The close match between the two lines means that the simulation is working well and can predict how the brake disc temperature changes during braking. This confirms that the thermal model is reliable and can be used to study how heat builds up and spreads in the brake system.

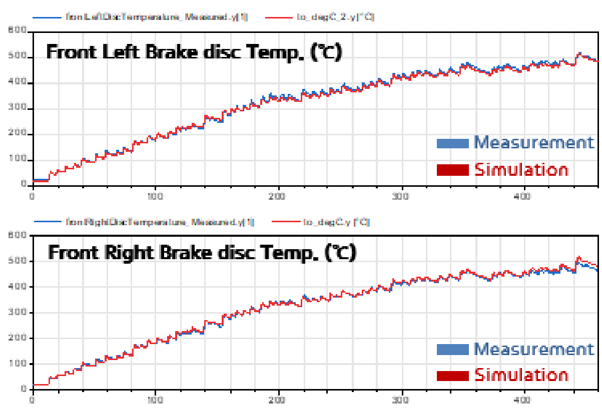

Figure 7. Comparison of the brake thermal model with experimental results

2.3 Suspension and Vehicle Dynamics

The multibody suspension systems are extended and modified from VeSyMA – Suspensions templates and models. The front and rear suspensions are variants of the MacPherson strut and Multilink linkages respectively. With examples of these existing in the VeSyMA - Suspensions library, the principal work was to parameterise them to create variants specific to the Ioniq 5 and validate them against test data.

While the initial aim was to create and validate the Ioniq 5 suspension, the long-term goal was to ensure easy future development, and ability to introduce future linkages and variants for other HKMC models.

There were three levels of fidelity used within the suspension models:

- No Bushed: Joints have no flexibility.
- Bushed: Bushes applied to appropriate linkage joints to match reality.
- Bushed Subframe: Adding bushes to the subframe, in addition to bushed linkage joints.

In all the fidelities, there was no flexibility of any of the components, just the joints, this was to both simplify, optimise but principally because adding component flexibility would add little benefit in terms of accuracy for the additional data and time requirement.

The data required to create each linkage matches the fidelity of the system, but in all cases the following data was required:

- Hardpoint locations (stated in and relative to HMC chosen orientation and origin).
- Component mass and inertia properties.
- Spring stiffness.
- Damper force curve.
- Bump stop force curve and clearance.
- Anti-Roll bar (ARB) stiffness.

In addition to all the above data, when adding bushes to either the linkage or the subframe, each bush needs the following data:

- Force, torque curve and damping constant in each axis.
- Bush orientation relative to the suspension.

When adding bushes to the subframe mass and inertia data is required for the subframe and all attached components as a lumped mass model. One key method to ensure that any future linkage can be easily created, developed and tested, mechanisms were implemented that

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reads all required data is read from external files using the open source ExternData Modelica Library[1].

Within ExternData there is a model that reads .xlxs files. Force suspension linkages there is a fixed format file for each linkage, created and used primarily by the HKMC CAE team.

Using this file as a source of all data means that both there was little chance of human error when copying data, but also that any further MacPherson or Multilink suspension from any future model can be created instantly by just changing the file that is being read.

To set this up, there was a parameter that stated the location of each item of data, both in terms of sheet (one parameter used for each group of data) and cell location (specific to each parameter). For the tables of data, such as damper and force curves, sizes of tables also needed stating. Doing this rather than hard coding locations allow any future changes to the .xlsx file format can be easily implemented without requiring version specific variants to be maintained.

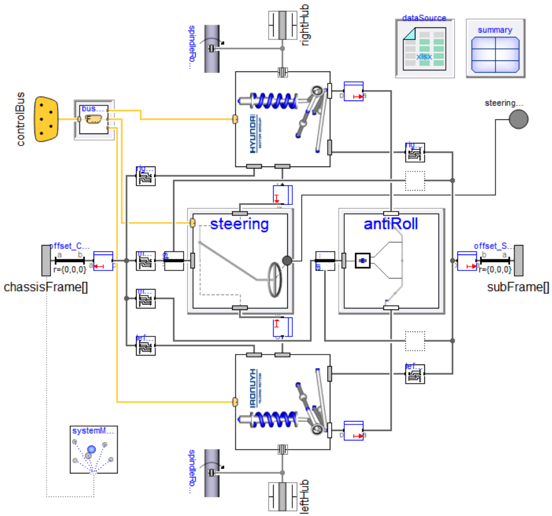

Figure 8. Front Suspension Model built based on HKMC's Standard excel template

One tedious, and repeating task of using any linkage in a vehicle is to ensure that the vehicle and suspension initialises correctly. This is important for 2 key benefits, because the hardpoints stated are for when the vehicle is resting on flat ground at curb weight; therefore, to ensure that when the vehicle settles the bushes and springs have the appropriate preload to ensure that the linkages, and by extension the geometry is in the correct positions. Secondly it ensures that simulations are more efficient because the initialisation of each vehicle is steady-state requiring no settling time at the start of each simulation and improving robustness of simulations by eliminating unstable initial conditions.

Whenever a new linkage, mass distribution, vehicle or bush parameterisation new initial settings need to be evaluated and implemented. But with each vehicle there are several load conditions that each need unique initial settings. Therefore, a series of initial functions were created to automate these tasks, performing the following functions:

- Curb weight Mass: Set the appropriate mass and inertia value in the body to ensure that the mass and inertia of the full vehicle is correct regardless of what components are used.

- Spring preload and initial attitude: find the preload in each spring and vehicle height, roll and pitch appropriate to keep the suspension in the correct position in curb weight condition.

- Bush preloads: Tune and store the preloads in each bush to ensure that the initial offset of each bush is zero when at curb weight.

- Load condition initialisation: Evaluate the body attitude, suspension positions and bush offsets (if included) for each load condition.

For each of the functions above, each value was calculated then the setting applied in the vehicle, half car and/or quarter car models, ensuring that any test at any level is using the linkages with the correct initial settings.

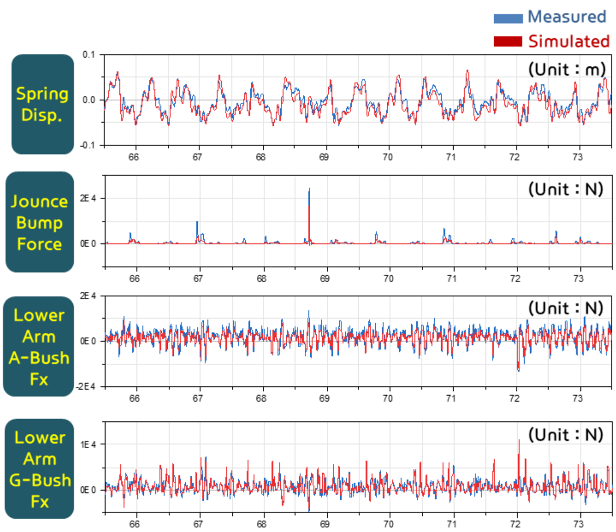

Figure 9. Validation of front left suspension from Half-car rig simulation on Belgian Pave

The first test the suspension models was to validate the dynamic spring length against measured data when a measured set of wheel forces and torques was applied to each wheel hub, comparing to a test that was driving over cobblestones in a 2up load condition. The test consisted of either the half car or full vehicle tests where the body was fixed in place and forces and torques applied to the wheel hubs. The forces and torques time traces were applied with the measured data being read in from the .mat file format they were stored in. The correlation, shown in **Figure 9**.

2.4 Electrical Motor

The investigated electric vehicle architecture combines conventional and in-wheel electric motor designs. At the front axle a conventional synchronous motor with permanent magnet (PSM). In addition, two In-Wheel Motors (IWMs) are installed at the left and right rear wheels. The durability analysis pays particular attention to the temperature development within the individual electric motors.

For building models of front motor and IWMs, the Electrified Powertrains Library developed by Dassault Systèmes is used [2]. Both types of motors are implemented based on table-based machine models from the library. The model computes the required electrical power according to the requested mechanical power with considering machine losses. The different types of machine losses are specified in form of multi-dimensional characteristic maps that typically depend on speed and torque. **Figure 10** shows the top-level structure of the table-based machine model.

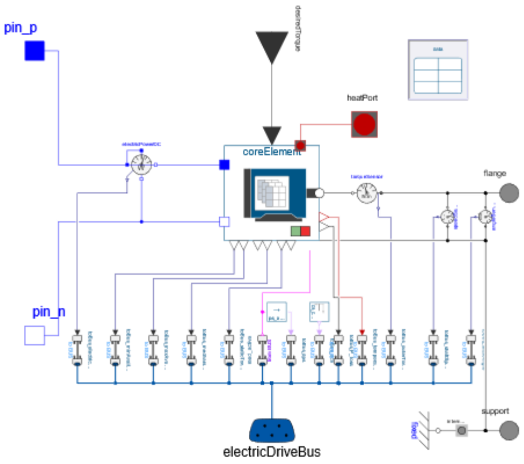

Figure 10. Top-Level structure of electric machine models

The thermal behaviours of the electric machines are modelled by lumped parameter thermal networks (LPTN). Specifically, for the IWMs that are equipped with an inner cooling channel, custom-developed thermal models are created. Heat transfer throughout the different layers of the IWM (housing to shaft and vice versa) is mainly considered in radial direction. The layers of the IWM are represented by thermal capacities in the core. During simulation, the individually computed losses by the electric machine models are injected into the respective thermal capacities. Heat exchange between the different layers is implemented via lumped thermal elements for modelling heat transfer mechanisms of conduction, convection and radiation. The cooling channel is modelled by means of components from the TIL-Library developed by TLK-thermo [3]. Behaviours of the brakes within the IWMs are modelled separately (see section 2.2).

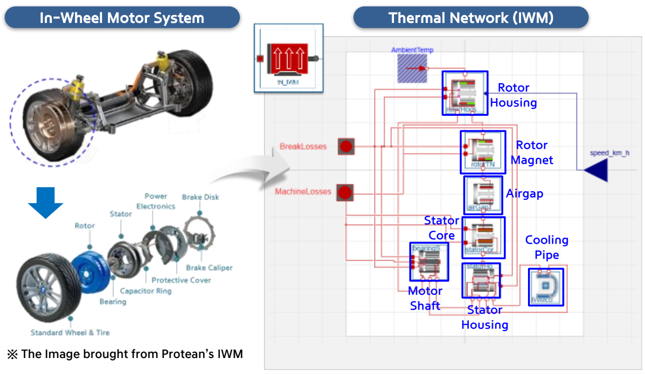

Figure 11. IWM Thermal Network Model

The electrical machine models are parameterised by provided characteristic power loss-maps extracted from test rig measurements. The maps are split into winding, core, magnet and friction losses. The thermal networks are parameterised by motor geometries and material specific properties like thermal conductivities, material densities and specific heat values.

The developed electrical and thermal motor models are validated by means of reference signals extracted from real-world driving scenarios. These reference data include, among other things, winding temperatures, speed and torque profiles at the machine flange, as well as the vehicle's velocity. **Figure 11** shows the validation results of two different compared driving scenarios focusing on the temperature development within the motor windings. The maximum deviation in temperature comparing both results is around 8.4 °C. In the current implementation a simplified setup and control strategy for the cooling channel is used. As a next step the cooling system is adapted to better fit with the real-world implementation.

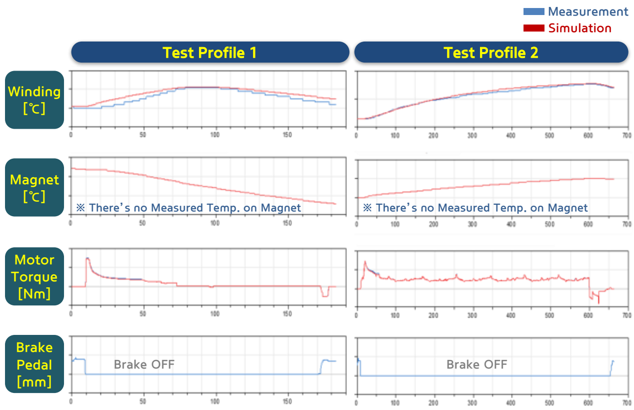

Figure 12. Validation results of the In-Wheel motor models

2.5 Battery Cell / Pack

The battery system implemented in this project is aligned to the battery pack of the Ioniq5 using an 800-Volt technology with a total capacity of up to 84 kWh. The battery pack comprises a variety of interconnected NMC-type lithium-ion pouch cells at the basis. The durability analysis pays particular attention to the temperature development within the individual battery cells of the pack when applying varying operational and environmental conditions.

Battery cell and pack models are developed based on equivalent circuit models (ECM) from the Dassault Systèmes Battery Library [4]. At the current phase of the project the focus is mainly set on the electro-thermal behaviour of cells (including aging characteristics is planned in a next step). **Figure 12** shows the structure of the used ECM cell model on the left-hand side (“Cell-Level”). The ECM cell is split into three sub-components to model electrical, thermal and aging behaviours separately. All three sub-components are continuously exchanging information via a bus connector during simulation. This approach offers a high degree of flexibility to replace individual sub-components. The selected thermal cell model can be discretised along the height-direction of the cell with additional thermal connectors at the surface sides for modelling heat exchange with the environment.

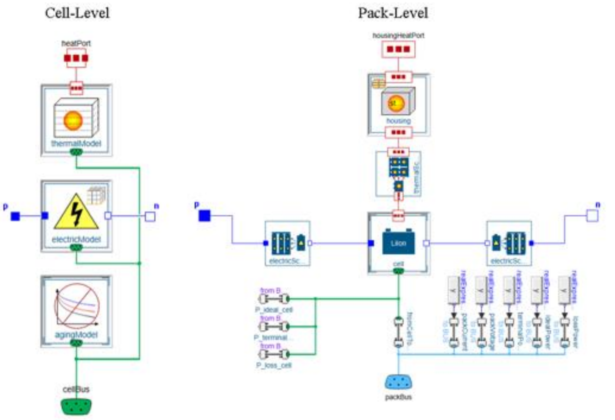

Figure 13. ECM Cell and Pack model concepts

The battery pack is modelled by means of scaled pack templates from the Battery library. Its structure is shown on the right-hand side of **Figure 13** (“Pack-Level”). Using this type of model, the behaviour of one cell instance is computed and scaled up according to the overall selected number of cells in series and parallel. The scaled model implementation is comparable to a pack setup in which all cells behave identically without deviations. This type of pack model is particularly suitable for analyses that focus on the battery pack as a complete system, such as long-term energy or aging studies. In contrast to the scaled packs, the Battery library also supports discretised pack models that calculate the behaviour of each cell individually. Thus, cell-to-cell interactions are also considered during simulation.

The ECM cell model is parameterised based on RC-data tables tested and 3D simulation. RC-data tables are used to compute the inner resistance and open-circuit-voltage of the battery cell depending on its states during simulation with respect to the cell temperature, State-of-Charge (SoC) and applied current loads at the terminal pins. The provided 3D simulation results are reused as reference temperatures within an automated data-correlation workflow for parameterising the thermal cell model.

The developed battery cell and pack models are validated by means of reference signals extracted from real-world test scenarios which consists of 7 laps in the circuit. This reference data includes, among others, captured temperatures, voltage responds and applied load profiles at cell and pack level. In **Figure 14**, the simulation results with focus on the computed temperatures within battery cells for an applied dynamic current load profile are plotted. Input current load profile as well as reference signals for the validation are provided by sensor data that are captured during running vehicle driving scenarios.

In the validation model, a simplified cooling system is implemented for pack cooling at the bottom side. The shown signals *Tmin_Pack* and *Tmax_Pack* in the diagram are the measured min./max. cell temperatures that appear inside the battery pack of the electric vehicle during operation. Signal *Tmean_Cell* in the diagram shows the computed mean core cell temperature of the scaled battery pack model (assuming that all cells behave identically).

The validation results show that computed cell temperatures are kept inside the min./max. reference data boundaries with a slight trend towards *Tmax_Pack*. By means of the scaled model simulations first initial insights into rough pack designs at early development phases are given and worst-case scenarios can be further analysed. As next steps, the use of discretised pack in combination of modified cooling system models are planned.

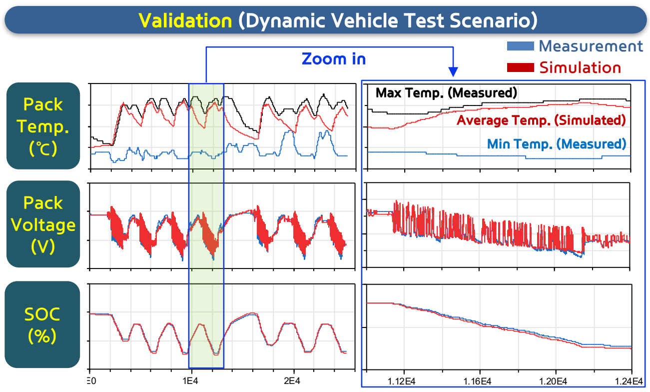

Figure 14. Pack-Level Temperature Validation

2.6 Thermal Management System

Effective thermal management is crucial for maintaining the efficiency, reliability, and longevity of EVs: the main parts (battery, inverts, electrical drive) need to work in specific temperature range for maximum efficiency and the comfort that has to be maintained in the passenger compartment. To be highly efficient and minimise its impact on the vehicle range, thermal management of EVs tries to dispatch and re-use dissipated heat as much as possible, making the circuitry and control logic associated very complex.

To evaluate properly the durability of the vehicle, the thermal management of the car needs to be modelled completely. It consists of:

- Battery Cooling System: Ensures the battery operates within safe temperature ranges to prevent degradation and maintain performance.
- Electric Motor Cooling: Manages the heat generated by the electric motor to enhance efficiency and prevent overheating, though a secondary lubrification loop.
- Power Electronics Cooling: Protects the power inverter and other electronic components from thermal stress.
- Cabin Heating and Cooling: Maintains passenger comfort while optimising energy usage.
- Heat Exchangers and Coolant Loops: Facilitate heat transfer between different components and the external environment.

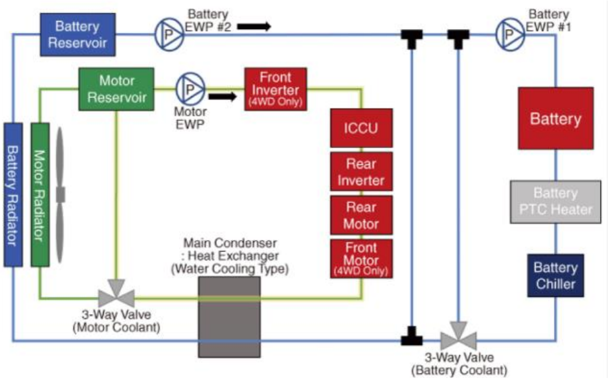

Figure 15. Overview of the thermal management system (Heat Pump is not represented in the figure here)

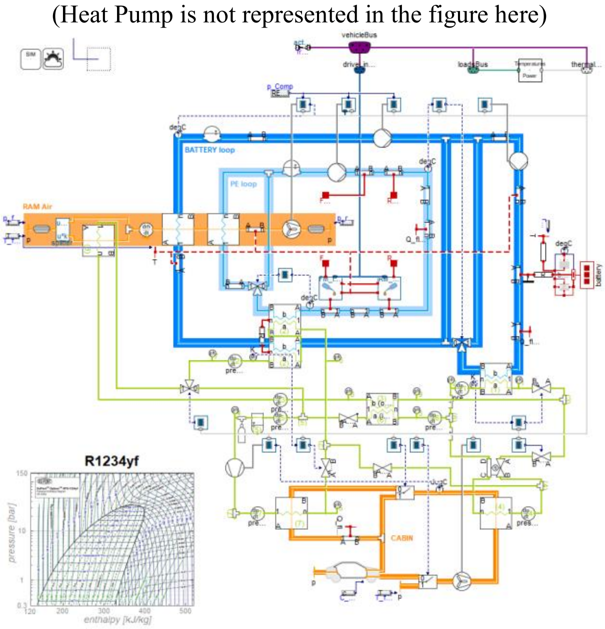

Figure 16. Thermal management system

The complete thermal management of the Ioniq5 has been built within Dymola, using the TIL library and its automotive add-on (pump, fan, compressor, TXV, valve, heat exchangers (plate & MPET), reservoir, cold plate…). It consists of five main paths or loops:

- the ram air for under the hood exchanges,
- the battery loop (glysantin 50%, dark blue),
- the e-drive and inverter loop (glysantin 50%, light blue)
- the cabin cooling path (orange)
- the reversible heat pump (R1234yf, green)

The work has been very meticulous, calibrating each component individually before building the system loop by loop. As much as possible, the model has been validated locally, using three different sets of measurement data: a partial model without the heat pump (replaced with imposed outlet temperature of coolant or air heat exchangers with the refrigerant) has been set-up for calibration.

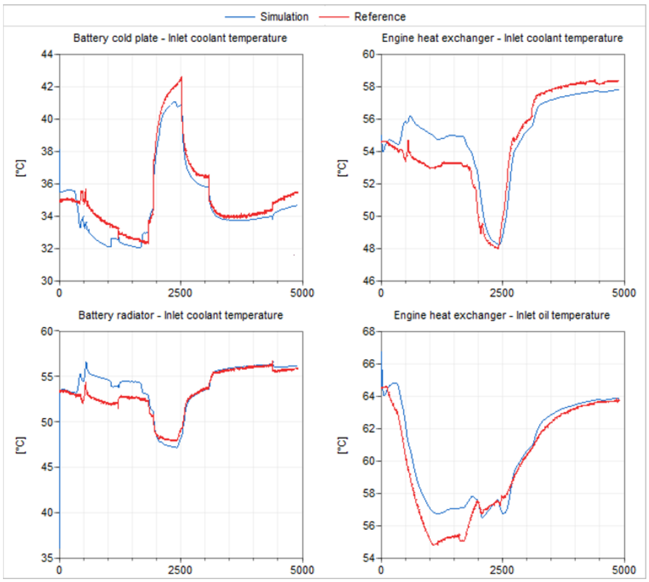

Figure 17. Calibration results for the Coolant loop

Once the loop is calibrated, the complete thermal management model has been assembled, and the control logic has been set-up.

The next step is to validate the complete model at vehicle level. The next step is to validate the complete model at vehicle level using the linkages with the correct initial settings.

3 Vehicle Modelling and Integration

By integrating all system models detailed above, the Ioniq5 electric vehicle model has been built as shown in **Figure 18**.

Since the vehicle model template is based on the VeSyMA library [5], there needs specific interfacing models for motor, battery and thermal management system models to exchange electrical and thermal signals with VeSyMA vehicle. The interfacing models make multi-physical system from different libraries to be simulated in one large vehicle environment.

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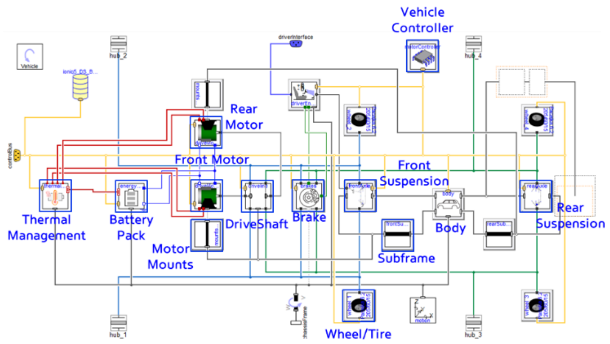

Figure 18. Integrated Electric Vehicle Model

Once the vehicle model is integrated, three representative durability scenarios previously defined in **Figure** 2 are utilised for the validation.

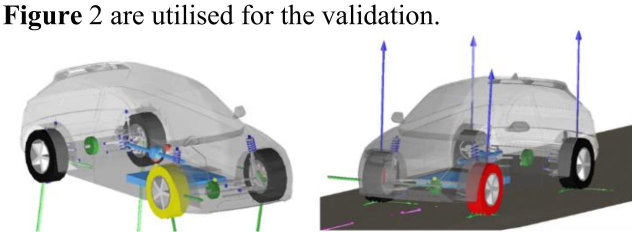

Figure 19. 2 ways of Simulation on Rough Roads

The first scenario for the validation is driving on a rough road which causes mainly longitudinal and vertical damage on suspension linkages and bush mountings. As a representative road roughness scenario, the event of consecutive potholes is chosen. For vehicle simulation, two different approaches are executed to check the availability for both options in the development stage depending on whether the pre-measured wheel forces exist or not. In **Figure 19**, the left case is replaying measured wheel forces directly on each wheel centres of the fixed-body vehicle model just to replicate the physical vehicle-level 24 channel road simulator. The right case is closed-loop simulation which the vehicle model runs on open CRG surface with grid Pacejka tire models simulating multi-contact points using the profile of measured time dependant velocity. **Figure 20** shows the spring displacement both measured and simulated as a representative validation signal for suspension model. Even though simple tire models are used for the simulation on rough road surface, the amplitude and trend are quite good matched to the measurement.

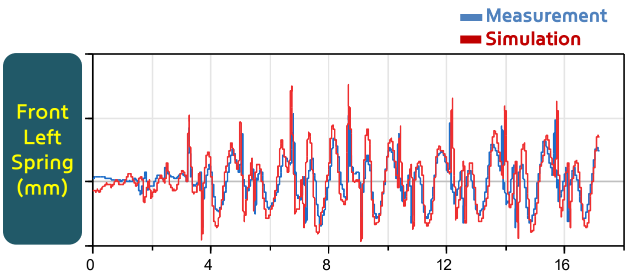

Figure 20. Spring displacement comparison between measurement and closed-loop simulation on CRG surface

The second scenario for validation is harsh acceleration and braking event which causes not only mechanical damage on brake and suspension components in longitudinal direction but also, electrical and thermal damage on the powertrain system.

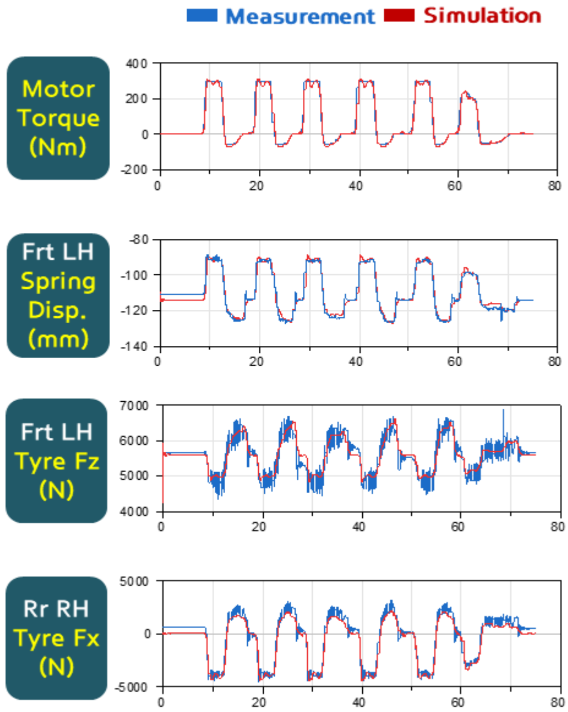

Figure 21. Suspension, Motor and Brake Validation for harsh acceleration and braking Scenario

The simulation is conducted using a closed-loop driver, by imposing measured vehicle speed as a target to drive the simulated vehicle to meet. As a result of the validation, it is due to the non-perfect logic in the vehicle controller, for the harsh braking condition, regenerative torques are not very accurate which also results in inaccuracies on brake pressure. With regards to the vehicle controller, a more accurate way of implementing the controller logic will be required in the future.

The last scenario for the validation is real-world driving scenario which is one of the mountain roads in Korea. First, road model was generated using latitude, longitude, altitude and measured velocity from GPS measurement. The road model defines the velocity target relative to distance which the driver model tries to achieve. In this scenario, powertrain dependant signals such as thermal and electrical behaviours on motor and battery are more taken into account for the durability. As shown in **Figure 23**, both front and rear motor speed are good matched to the measurement. With regards to the temperature on motor and brake, it's because there's no reference signals to be compared with, only simulated signals from the model are shown here but, they show reasonable behaviours relative to measured motor's behaviour which the vehicle model to be believed that it's quite robust even in the real world scenario.

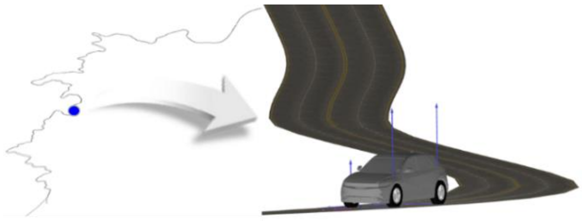

Figure 22. Road Model for field road in Korea

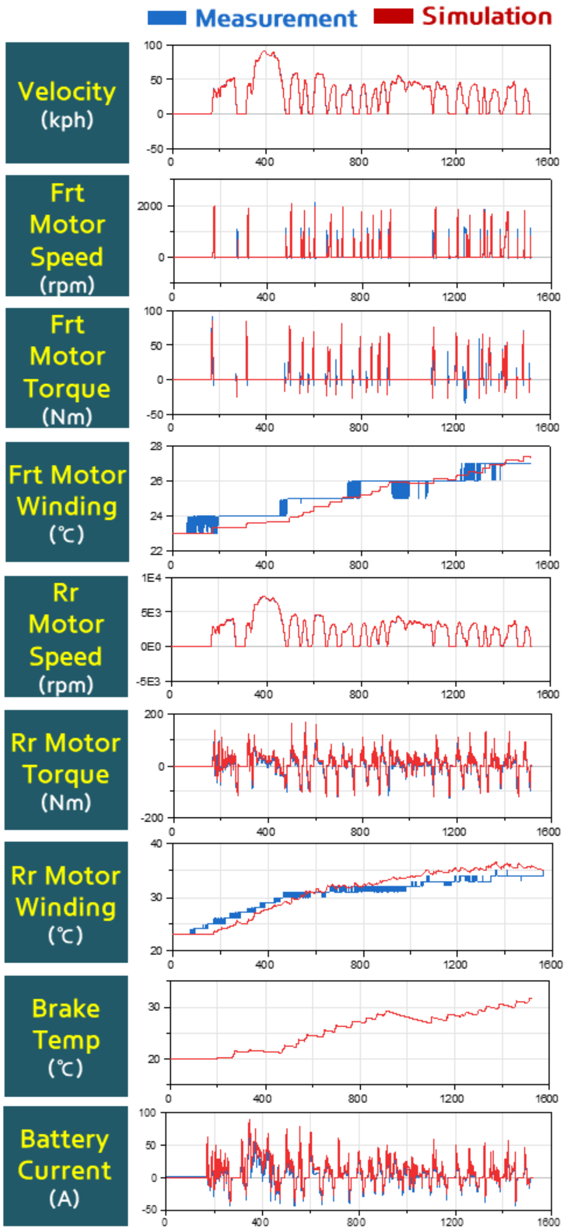

Figure 23. Powertrain / battery / brake related signals validation for the real-world scenario

4 Conclusion

In this study, Virtual RLDA platform has been developed for replacing vehicle measurement campaign for durability in early development stage as a best practice modelled for one of HKMC's electric vehicle.

For doing that first of all, required simulation signals aligned with the level of fidelity for system models are defined from vehicle simulation to quantify electrical, thermal and mechanical damages on each durability related components in systems.

Secondly, systems that are closely related to durability are modelled and validated with measurement. The system and vehicle level modelling templates from the study can be scalable and expendable for next HKMC vehicle development with minimal changes on the templates. In more detail, vehicle controller model is developed with Modelica library to control driving torque and regenerative torque for various driving situations. As for the degradation perspective of motor and battery system, in order to predict accurate working temperatures, electrical and thermal models for both motor and battery are developed along with the hydraulic brake model which generates brake disc heats. With those models, thermal management system modelled with TiL library for the entire vehicle level is coupled together with motor and battery model to cover the thermal behaviour occurred from actual driving conditions. For the perspective of chassis systems, one of the main development is the automated suspension modelling environment which directly imports HKMC's standard multi-body dynamics modelling template from the VeSyMA suspension library based suspension model not only for the initialisation of preloads on kinematic and compliance elements but also for the parameterisation of the suspension. As a result of this, it is expected that engineers can save huge amounts of time for modelling from basic K&C vehicle dynamics model to bushed vehicle dynamics model which can simulate nonlinear reactions on each suspension parts.

Lastly, the developed system models are integrated into one large vehicle model to simulate various different durability scenarios as similar as possible with the vehicle measurement. Different driver and road models are used for vehicle level simulation to validate vehicle model compared to measurement.

The Virtual RLDA platform developed in this study will be used and keep updated as a core model of our durability digital twin strategy to replicate realistic customer usages in virtual environment. By keeping the model upgraded, it is expected that many losses repeatably taken place from the development process could be minimised and it'll consequently result in reducing the number of prototypes for durability testing in the development.

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This project has been supported by Claytex and Dassault Systèmes for 1 year. Various multi-physical systems and vehicle level modelling and their validities are proceeded. The model shows a lot of potential to be used for various systems in terms of durability development and will continue to be updated in the future. I'd like to express my sincere gratitude to Claytex and Dassault Systèmes for their unbelievably enthusiastic support during the project.

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