Sine of the times

OLIVIER MACCHI AND **ALFONSO PORCEL** OF PSA PEUGEOT CITROËN, AND **CHARLES MIQUET** OF IPG AUTOMOTIVE PRESENT SOME OF THE CHALLENGES AND INNOVATION IN TYPE-APPROVING ESC BY MEANS OF VEHICLE DYNAMICS SIMULATION

Electronic stability control (ESC) is the first active safety system to have produced a quantifiable effect on road accident statistics. In fact all the studies investigating the impact of this system (Swedish, American or by the manufacturers themselves) have shown that, under the same conditions, a population of vehicles equipped with this system, compared with an identical but unequipped population, will see its risk of accidents reduced by between 10% and more than 60%, depending on the type of accident (loss of control, vehicle-vehicle impact, etc.), grip and type of vehicle (SUV, sedan, etc.).

In 2009 the European Parliament and the Council of Europe adopted Brussels regulation (EC) No 661/2009 General Vehicle Safety. This made several active safety features mandatory in Europe, including ESC (in conformity with Annex 9 of regulation ECE R13H). ESC was made mandatory for vehicles in categories M1 (passenger car) and N1 (light commercial vehicle) from November 2011 for new models and from November 2014 for all new vehicles.

Application with the official technical service provider

Historically lateral vehicle dynamics have been more or less unregulated. Annex 9 of R13H therefore introduced by way of regulation a new technical area, though the terms of reference remained to be determined.

PSA and UTAC have been discussing this subject since early 2010 with a view to starting to define the conditions under which Annex 9 of R13H will apply to type approvals of the ESC system in vehicle projects. Among other matters, the text permits the use of simulation to obtain type approval (Appendix 1 of Annex 9 of R13H).

In its development process for the functions of ABS/ESP systems, PSA uses a numerical model correlated with each vehicle body applied. It was therefore natural to try to use this numerical tool to reduce the number of physical vehicle tests, since the text explicitly authorizes this.

The principle underlying HIL simulation involves integrating a 'real' ESC control unit into a real-time platform, simulating the whole of the vehicle, sensors and actuators used by the computer. This means that ESC is engaged as if it were in a real vehicle. This approach has the advantage of using a serial ESC control unit.

Validation of the PSA HIL simulation tool

In order to demonstrate the validity of this simulation approach and to define the ESC type approval process, a scheme to share the maturity level of this tool has been undertaken with UTAC.

The exchanges between PSA and UTAC have made it possible to define a working program in order to validate the simulation tool for type approval. Based on a project that is still at the development stage, a

PROGRAM FOR TOOL VALIDATION

• Presentation of the PSA HIL process and the results of the numerical/physical correlations of the reference vehicle from the project under consideration
• Prior to the physical type approval test, construction of additional numerical variants of the reference vehicle
• Physical Sine with Dwell type approval tests on the reference vehicle
• Validation of HIL vehicle model performance compared with the results of physical type approval tests:
– Detailed verification of vehicle behavior (yaw rate, lateral acceleration, side slip angle, etc.) by incorporating different steering wheel angles into the model measured on the test vehicle
– Validation throughout the entire series of Sine with Dwell tests in accordance with type-approval criteria
• HIL simulation for all the project variants to be simulated
• Vehicle parameter sensitivity study to demonstrate the parameters affecting the type approval criteria

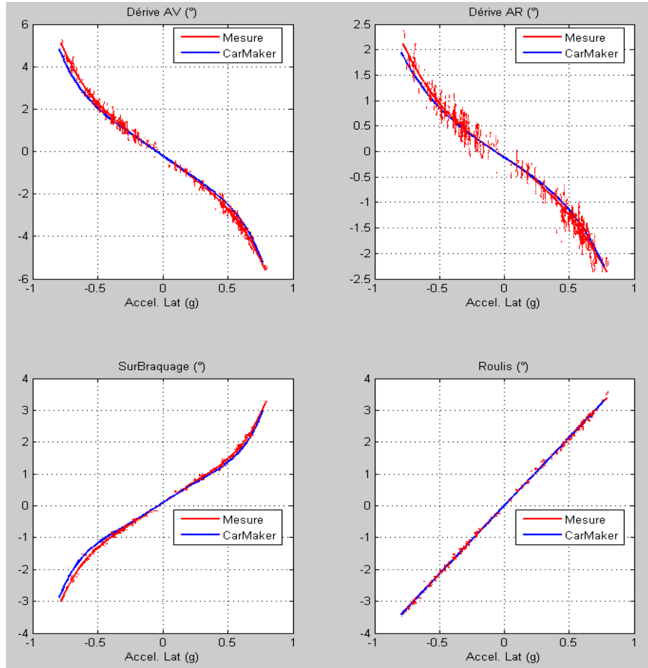


FIGURE 1: **EXAMPLE OF VALIDATION FOR STEADY STATE TEST WITHOUT ENGAGEMENT OF THE ESC SYSTEM**

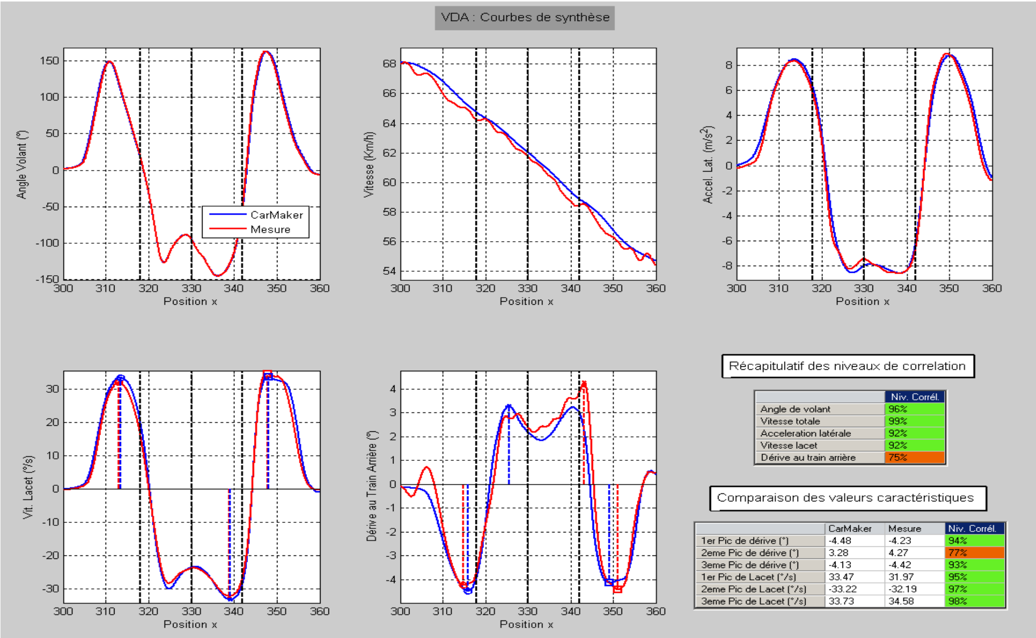


FIGURE 2 (ABOVE): **VALIDATION FOR A LANE CHANGE TEST WITH ENGAGEMENT OF THE ESC SYSTEM**

FIGURE 3 (BELOW): **SINE WITH DWELL MEASUREMENT FOR A STEERING WHEEL ANGLE OF 270°**

course of action has been implemented, (see sidebar p30, Program for tool validation).

PSA obtained representative models of real situations for vehicle dynamics applications integrating an electronic stability control (ESC) system. These models can therefore be subjected to extreme solicitations in situations close to the limits of controllability. The level of complexity involved in system modeling depends on how the model is to be used.

Given these objectives, the vehicle dynamics model selected by PSA for this type of simulation is CarMaker, from IPG Automotive. This model can be used in either a SIL (software in the loop) or HIL (hardware in the loop) environment.

PSA's choice was focused on HIL simulation, which produces realistic results and enables the user to test a standard ECU and its physical interfaces.

The first step in the model input data process concerns the recovery of functional characteristics necessary to define vehicle model parameters. This input data comes from different services within PSA or from external suppliers, and each item corresponds to a particular specification. This data includes architectural data (masses, inertias, center of gravity, wheelbase, etc.); chassis data validated against measurements on various characterization test bench (kinematics, compliance, flexibility spring, damping, anti-roll stiffness, tire characteristics, etc.); aerodynamic data derived from wind tunnel characterizations; parameterization of the braking circuit (absorptions, C*, diameter of master cylinder, etc.); and parameterization of the ESC hydraulic block (electrovalve cartography maps, accumulators, attenuators, etc.).

For some projects, it is also necessary to develop and integrate specific subsystem models (e.g. hybrid powertrain, EPS, etc.) into the HIL test benches to be sure of having the required representativity.

Beginning with this initial step, it is possible to create simulations with or without an ESC system, however the representativity of the model at this stage is not guaranteed. To verify the representativity of the model, it is necessary to have access to dynamic measurements taken on vehicles fitted with instruments. There are five types of measurements.

The first is hydraulic measurements with passive pressure control. The upstream pressure is exerted by the driver. It is modulated in the receptors by the outlet and inlet valves (ABS, EBD functions).

For hydraulic measurements with active pressure control, the upstream pressure is exerted by the ESC pump. It can be modulated in the receptors by means of the outlet and inlet valve, but also by the pilot valve (ESC, BASR functions).

Then there are vehicle dynamics measurements in steady-state behavior (ESC off); vehicle dynamics measurements in transient state (ESC off); and vehicle dynamics measurements in combined tire forces (lane change or braking in a turn).

From the model input data and measurement input data, the first level of correlation of the model can be established by comparing the curves produced by the simulation with those measured during the various maneuvers. When the results of the comparison are not satisfactory, a process to identify the model's parameters must be implemented to obtain the required degree of representativity.

This work is broken down into two distinct correlation activities – hydraulic model of the ESC system and the vehicle dynamics model.

Hydraulic model of the ESC system

After properly verifying the conformity of the parameters communicated by the PSA departments concerned, or by the suppliers, the action taken to identify parameters will concentrate on those that are not well known (e.g. pressure drop coefficients) in this model (made up of about 70 parameters).

A program of optimization based on experience gained in previous projects, coupled with a hydraulic model sensitivity study on each of the parameters, makes it possible to define a set of unique model parameters that accurately correlates all the measurements made on the vehicle (modulation of active and passive pressure, high and low pressure).

To carry out this process quickly, PSA has developed a tool that enables it to have representative simulation, undertake post-treatment and conditioning of the ESC signals recorded during vehicle maneuvers – necessary for reconstruction of electrovalve action – and activate the ESC pump, etc. The tool can also establish the initial level of correlation with the first parameters that are set, begin an identification procedure in order to improve the level of correlation, and validate the identified model.

Vehicle dynamics model

The objective of this phase is to obtain a vehicle dynamics model that corresponds to particular situations of life and where the validity conditions are known and limited (e.g. side slip angle of tire ≤18°, high level of grip, etc.). Sine with Dwell corresponds to these validity ranges.

To start, the performances of the model are evaluated with regard to the maneuvers measured on the vehicle. In the case of the HIL simulations, the maneuvers must cover a functionality range without and with engagement of the ESC system. This last case involves correlating the hydraulic model first. For each maneuver, specific technical criteria are used to determine the level of validity of the model (Tables 1 and 2).

If the model is not satisfactory, a process of identification to correlate the vehicle dynamics parameters is implemented in the same spirit as described for hydraulic model correlation, as explained above.

A compromise should be sought between the different operating points.

Figure 1 shows an example of the result of correlation for a steady state test. In the case of Sine with Dwell, it is important to have a good level of correlation for this type of maneuver because it is used directly to determine the initial angle A (SIS, Slowly Increasing Steer).

Figure 2 shows an example of the result of correlation for a transient state test (lane change). A good correlation on this type of test (ESC off and ESC on) is important, because it is representative of the demands of Sine with Dwell.

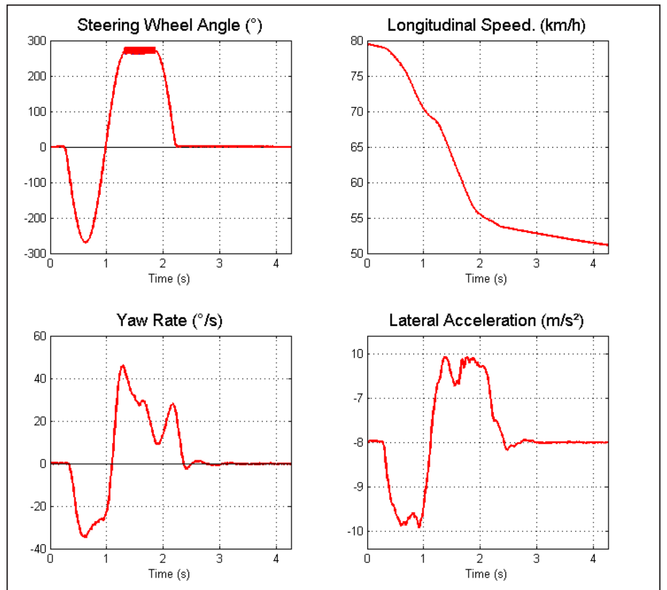
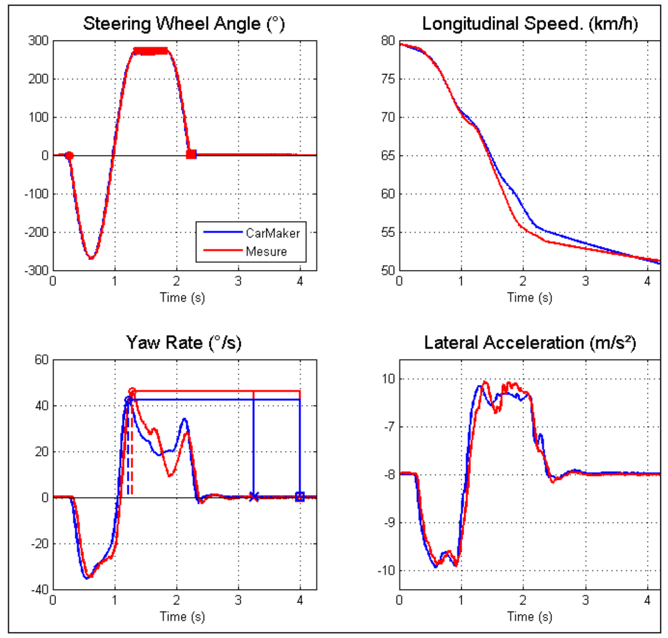


Table 1: ESC system disconnected

Type of maneuver	Validations	Acceptability criteria
Driving with different steering wheel angles at constant speed	Steady state	Oversteering, roll, side slip angle of axle
Step steer for different levels of lateral acceleration	Steady state (after step steer) and transient state	Yaw rate, lateral acceleration, side slip angle
Steer with increasing frequency	Transient state	Frequency analysis of the transfer function between steering wheel angle and yaw rate
Slalom	Transient state	Phase shift in yaw rate and lateral acceleration
Power off in a straight line	Engine braking, rolling resistance	Longitudinal acceleration
Braking in a turn	Longitudinal/ lateral tire coupling	Yaw rate, lateral acceleration, side slip angle
Lane change	Longitudinal/ lateral tire coupling	Yaw rate, lateral acceleration, side slip angle

Table 2: ESC system connected

Maneuvers	Validations	Acceptability criteria
Braking in a straight line with consistent grip	ESC longitudinal forces	Braking pressures, longitudinal acceleration, ESC regulation criteria
Braking in a straight line with asymmetric grip	Longitudinal/lateral tire coupling (ABS)	Braking pressures, longitudinal acceleration, ESC regulation criteria
Power off in a turn	Longitudinal/lateral tire coupling with engagement of ESC system	Yaw rate, transverse acceleration, drift, longitudinal acceleration
Braking in a turn	Longitudinal/lateral tire coupling with engagement of ESC system	Yaw rate, transverse acceleration, drift, longitudinal acceleration
Lane change	Longitudinal/lateral tire coupling with engagement of ESC system	Yaw rate, transverse acceleration, drift, longitudinal acceleration



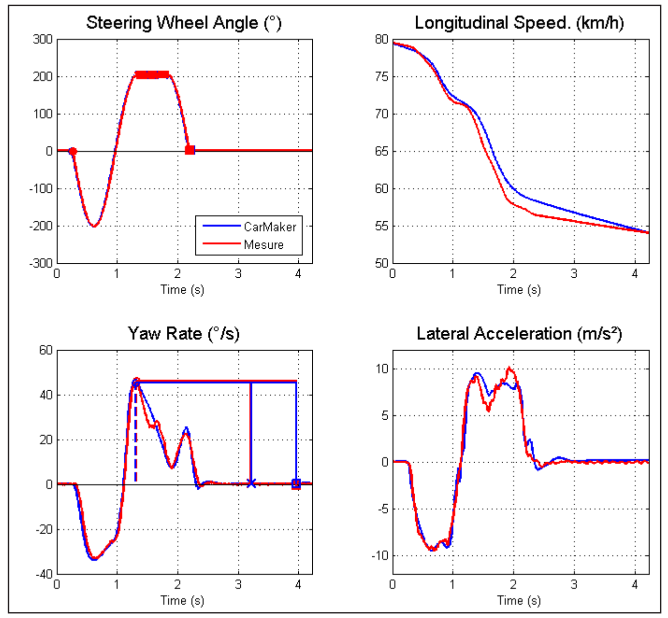


FIGURE 4A (TOP): **EXAMPLE OF TIME-BASED VALIDATION FOR STEERING WHEEL ANGLES OF 270°**

FIGURE 4B (ABOVE): **EXAMPLE OF TIME-BASED VALIDATION FOR STEERING WHEEL ANGLES OF 200°**

FIGURE 5 (RIGHT): **EXAMPLE OF A SIMULATION/MEASUREMENT COMPARISON FOR A SINE WITH DWELL TEST SERIES**

FIGURE 6 (BOTTOM): **COMPARISON OF THE EFFECTS OF CHASSIS/ MASSES(POWERTRAIN)/TIRES/ ADHESION**

SINE WITH DWELL MEASUREMENT

- **Data acquisition chain (minimum capture frequency: 200Hz)**
- **Motor-driven steering wheel measuring the angle, torque and speed of the steering wheel (precision: 0.25°, range ±300°)**
- **Vehicle speed sensor (precision: 1km/h, range 0 to 200km/h)**
- **Yaw rate sensor (precision: 0.15°/s, range ±50°/s)**
- **Lateral acceleration sensor (precision: 0.05m/s², range ±15m/s²)**
- **Body height lasers (precision: 0.6mm, range ±125 (front) or ±400 mm (rear))**
- **'Brake pedal' position sensor**
- **Anemometer**

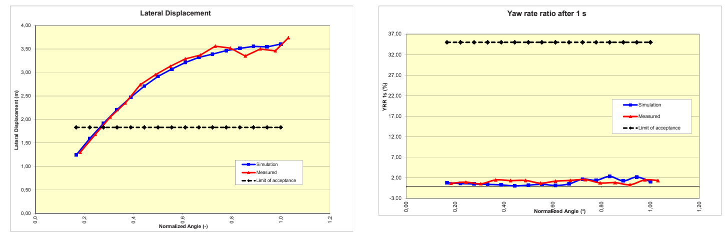


Figure 13: Example of a simulation/ measurement comparison for a Sine with Dwell test series

Table 3: Sine with Dwell results		
	Results	**Criteria**
Offset at 1.07s	~3 to 4m	>1.83m
% at T0+1s	~0%	<35%
% at T0+1.75s	~0%	<20%

When these two last steps are achieved the model should be ready for a Sine with Dwell simulation.

Sine with Dwell approval tests

A vehicle project undergoing development at PSA (C4 family) has been adopted to act as first line support for these Sine with Dwell correlation tests. To enable these tests to be carried out, the vehicle must conform to the specifications set out in paragraph 4.3 of Annex 9 of R13H. These specifications concern the conformity of the vehicle (defined in terms of chassis, architecture, aerodynamics, power steering and ESC software).

The measurement tools used by PSA to carry out the test are detailed in the sidebar Sine with Dwell measurement (above).

To perform the maneuvers described in section 5.9 of Annex 9 of R13H it is necessary to use a steering robot capable of producing the required steering wheel angles at a frequency of 0.7Hz.

After carrying out the processes of sensor calibration, brake and tires running-in and temperature setting, a series of Sine with Dwell measurements was started with UTAC in conformity with the specifications of section 5.9 of Annex 9 of R13H. Figure 3 illustrates an example of the result obtained during this test series (steering wheel angle = 270°).

The selected reference vehicle was the subject of the standard correlation process, as previously described. Based on this correlated model, the tests carried out in the presence of UTAC were reproduced on the HIL test bench. The exact test conditions (masses, grip, driver actions, speed, etc.) were incorporated into the model. In the first instance, a time-based comparison of the results was made.

Figures 12a and 12b show two of the Sine with Dwell maneuvers with their simulation results: steering wheel angle of 270°, the most unstable situation in the test series; and steering wheel angle of 200° with ESC intervention, giving a better level of stability.

Note that in the Sine with Dwell maneuver, after release of the accelerator, vehicle speed is the result of the model's functionality (engine brake, friction, braking action generated by the ESC system). Yaw rate and lateral acceleration are physical values useful for ESC type approval. A sufficient degree of precision must be achieved for all the simulated steering wheel angles.

Results of the Sine with Dwell test series on the right-turn direction are represented in Figure 5. These results – highlighted in Table 3 – show that the vehicle has no difficulty in fulfilling the type approval criteria.

Study of the sensitivity of vehicle dynamics parameters with regard to type approval criteria

A sensitivity study on vehicle parameters affecting Sine with Dwell maneuvers was undertaken to illustrate the potential impact of different parameters on type approval criteria (mainly lateral displacement).

All the main parameters were modified. They mainly concern the vehicle architecture data, masses and their distribution, kinematics and compliance of the axle units, suspensions (flexibility springs and damping), anti-roll stiffness, braking characteristics, tire characteristics (tire slip stiffness, inflation pressure, etc.).

The result of this sensitivity study (see extract in Table 4) shows that in the vehicle studied, the position of the center of gravity in Y and X are the parameters with the greatest influence on lateral displacement at tBOS+1.07s. Modification of the front toe and the tire parameters (inflation pressure and tire slip stiffness) are also road-holding parameters that exert an influence. But overall, the impact of these modifications remains weak. The discrepancies noted produce a delta for the maximum displacement of about 3%, which is very weak in view of the vehicle results and acceptability thresholds required by the regulations.

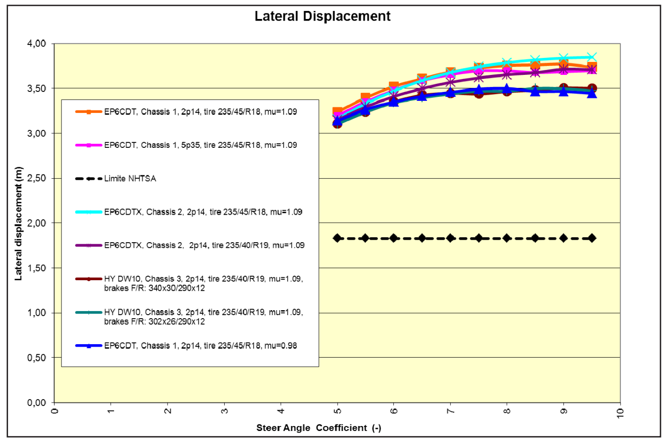
The coupling between the different parameters was not taken into consideration in this sensitivity study; an experimental plan will be required for this. In the meantime, this work is performed indirectly in each type approval when the variants of a project are qualified.

Figure 6 shows results regarding the displacement of distinctly different project vehicle variants (DS5 standard and hybrid). The details of the variants, to indicate their sensitivity to parameter changes, are shown in Table 5.

Figure 6 reveals that under the lateral displacement criteria of the vehicle, increasing the load (adding three passengers in the rear and 21kg in the trunk) for a given chassis definition, different chassis tuning (Chassis 1/Chassis 2) and a change of tires within a same range, each have a low influence with the same order of value. For the hybrid definition (in terms of axle definition and masses), its displacement curve is sensitive to parameter changes. It is also interesting to note that a slight reduction of grip produces an effect similar to moving from the standard to the hybrid definition.

Since the test needs to investigate high-level grip, it is important to control this parameter throughout the series of tests to obtain coherent results and good correlation. One of the advantages of simulation tools is to show this sort of tendency.

Table 4: Sensitivity study results		
Road holding parameters	**Variation**	**Lateral offset**
Position of the C of G in X	±50 mm	±3.50%(*)
Position of the C of G in Y	±10 mm	±3.15%
Front toe	±0.25 mm	±2.90%
Front tire pressure	±0.2 bars	±2.70%
Front tire slip stiffness	±5%	±2.10%
(*) An increase in the parameter entails a reduction of the criterion analyzed and vice versa		



Results

The technical sharing implemented with UTAC has enabled the consolidation of a process to approve the entire range of a project. The process adopted and accepted by UTAC includes several stages. First is the definition of the reference vehicle within a project (which can define more than one), which will be physically tested and additional variants, which will be subject to type approval by HIL simulation.

The next stage is the creation of the HIL models corresponding to the whole group of these variants. Then come a series of physical Sine with Dwell tests on the reference vehicle, followed by validation of the HIL vehicle model by means of simulation/measurement correlation of the reference variant. HIL simulations for all the vehicle variants defined above are carried out before the results are formatted and the documentation PSA requires for ESC type approval is supplied.

A vehicle family (Peugeot 208, Citroën C4, Citroën DS5, etc.), can consist of a number of different body shapes (sedan, station wagon, coupe-cabriolet, etc.). For each of these body shapes there is a large number of vehicle configurations: axle units, suspension types, engine types, tires, brakes, etc.

Table 5						
	Engine types	**Masses and distribution (front/rear)**	**Axle types**	**Tire sizes**	**Brake disc sizes**	**Tire / road surface adhesion**
DS5 Standard	EP6C DT	2P14: 1690 (62% / 38%) 5P35: 1896 (56.4%/43.6%)	Front: PMP(*) Rear: Torsion beam	235/45 R18	Front: 302x26 Rear: 268x12	μ = 1.09 μ = 0.98
DS5 Standard	EP6C DTx	2P14: 1740 (60.8%/39.2%)	Front: PMP(*) Rear: Torsion beam	235/45 R18 235/40 R19	Front: 340x30 Rear: 290x12	μ=1.09
DS5 Hybrid	DW10	2P14: 1946 (57.4%/42.6%)	Front: PMP(*) Rear: Multilink	235/40 R19	Front: 340x30 302x26 Rear: 290x12	μ=1.09
(*) PMP: Pseudo MacPherson						

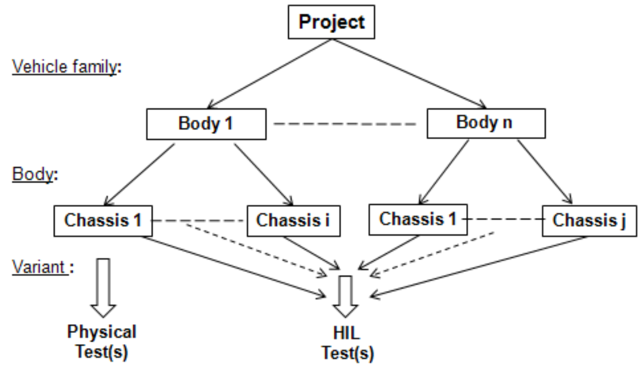


FIGURE 7: **VEHICLE VARIANTS DEFINITION**

The underlying principle is that a variant should correspond to a particular chassis tuning, and the engine chosen for each of these variants must cover all the brake system of the family. Figure 7 illustrates these views of variants.

To perform the ESC type approval process with 'industrial' HIL simulation, specific tools have been integrated into the PSA 'simulation tool box' so as to automate the launch of a series of Sine with Dwell simulations on the HIL test benches, post-process all the curves produced by the series of simulations, and generate the deliverables automatically in the format agreed with UTAC.

Conclusions and outlook

This article show that applying an internal simulation tool to the projects has enabled the fulfillment of the needs of R13H approval with limited effort. In addition to streamlining the number of test, this approach also has the advantage of facilitating technical exchanges with the official laboratory, through visualization of the results and showing how they change according to the technical diversity of a vehicle range.

Since the formalization of this registration process by the UTAC, five projects have already been approved. The reliability of the results confirms that the degree of maturity reached by the simulation tools today is sufficient to meet this type of requirement.

Mixed with physical tests of correlation, this approach proves that simulation is an effective tool for this kind of field and that it could be extended to support other areas of approval or similar activities such as ISO 26262.