Electric vehicle's stability study on low friction road based on driving simulator

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***Abstract**: This paper presents an overview of EV driving simulation development work on ULTIMATE simulator of Renault, Technical Center for Simulation (TCS). A user case of driving on packed snow road is developed in order to analyze the stability of the EV with regenerative brake on the one hand and to prepare the future ESC tuning scenario on the other hand. The real-time vehicle's dynamics model and the tyre model on low friction road are the prerequisites for achieving the realistic driving simulation. First of all, a process from Adams/Car multi-body dynamics to real-time functional model, such as MADA (internal vehicle dynamics model) or AMESim, is developed by TCS. Secondly, a special adjusted Pacejka internal model based on packed snow road measures is used in the vehicle's model. As the result, the precise modelling associated with a tilt coordination explicit MPC motion cueing algorithm gives a close fidelity of driving simulation.*

***Keywords**: EV stability, regenerative brake, packed snow driving, driving simulator, low friction tyre model*

I. Introduction

The design of electric vehicle has brought new challenges into the driving dynamics and drivability domains. The high torque dynamics of electric motors lead to particular problems such as motor oscillation in the transmission, torque splitting between the standard hydraulic braking system and the regenerative brake, or the stability problem in case of slippery roads. For instance, it is well known that Split-μ and tip-out in curves are typical manoeuvres under which the electric motor response has a great influence on vehicle stability.

During vehicle development, the indispensable different validation tests are currently carried out with physical prototypes and different configurations of ADAS systems for fulfilling the requirements of security, handling, drivability, durability etc.. These tests not only bring about high costs but also influence the project development cycle, among which the vehicle handling and stability behaviours evaluation on low friction road is a significantly costing one for different purposes (ESC tuning and validation, vehicle's stability, security study etc…). Generally, these tests are achieved by professional testers. However, as mentioned by van Zanten et al [Zan1], "The concept of the vehicle including the tires and the suspension should very strongly account for the normal human behavior", it is because the reaction of a normal driver is very often different in critical low friction situation compared with that of a professional tester. The driving simulator could be considered as an interesting test platform to accomplish these tasks. Actually, simulators are used as efficient virtual test platforms for the security evaluation [Pap1, Wat1, Bro1] and the subjective evaluation for optimizing the chassis design and ESC tuning [Wus1].

What's more, due to shorter time and more economic constraints, it becomes more and more important to expand the numerical simulation technique into the vehicle development process. Therefore, it is crucial to develop the robust numerical simulation to assess vehicle's dynamics behaviours. RENAULT's idea is to perform driving simulation in early stage of the vehicle development and integrate the driver in loop in order to highlight the stability problem and ESC tuning validation. The objectives of the RENAULT TCS are: (1) developing almost 100% numerical process for vehicle dynamics by using driving simulator, (2) performing driving simulations in the early stage of vehicle projects for engineering applications and studies of driver perception or behaviour.

The above concerns conduct us not only to develop a simulator engineering application: electric vehicle stability evaluation on low friction road, but also to redevelop the processes for driving simulation (The visual rendering of the simulation is considered here as a relative achieved technique):

- dynamics model integration process
- new motion cueing algorithm for 8 dofs simulator [Fan1]
- new feedback force control systems for steering wheel system and accelerator pedal

II. Development of a real-time vehicle's dynamics model

The vehicle's dynamics modelling plays a key role in driving simulation. Currently, the Adams/Car multi-body dynamics model, as well as other car's dynamics functional model, are used in Renault during vehicle's project development. The Adams/Car simulation results are compared with those of a real car and at this basis the model is improved if needed during its validation phase. Thus, the Adams/Car's model can be considered as the reference for the validation of vehicle's functional model used in simulator real-time environment. MADA (Modèle Avancé de Dynamique Automobile, Renault's internal model) and AMESim (LMS commercial software), both using suspension look-up tables provided either by K&C test rig or Adams/Car simulation, are integrated in SCANeR Studio^{TM} software. This chapter describes the efforts made by TCS on building such models. The tyre model has a critical effect on packed snow road simulation results. Thanks to the work of internal vehicle's dynamics team, a well adjusted internal Pacejka model based on packed snow road measures was integrated in the vehicle's dynamics model. As for the steering system, a simplified real-time system model is proposed and the parameters are tuned by means of the comparison with a real car's feeling. A powerful Sensodrive steering wheel was recently installed in ULTIMATE to improve the steering wheel force feedback rendering.

Due to the AMESim modularity, its collection of physical model libraries and its rapidity for prototyping numerical development, it is chosen as current EVs dynamics integration platform (see fig. 1). Note that the process to build the functional model is similar in AMESim as in MADA.

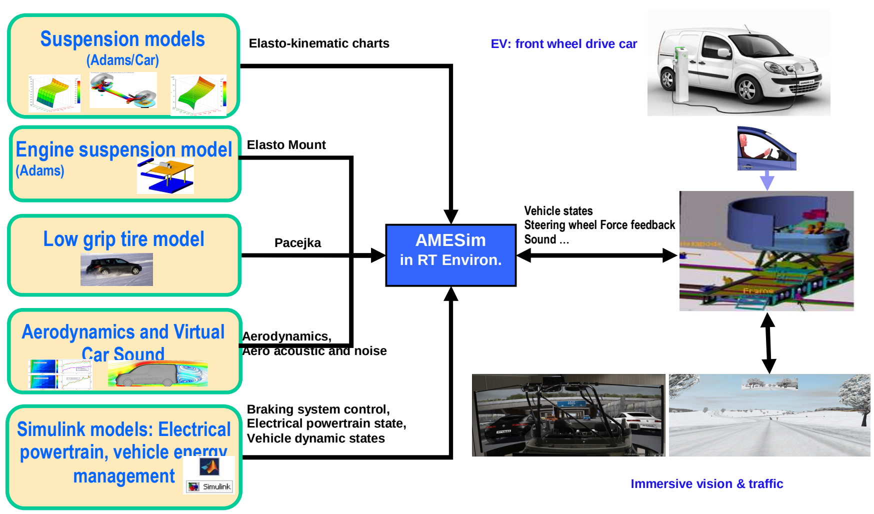

Fig. 1: Electrical vehicle models development & integration on the simulator

II.1. Vehicle's sub-system models development

a. Steering and Suspension model

The current EV suspension model is based on ADAMS/Car^{TM} which has been validated with K&C measurements. Some important lateral suspension parameters are presented in Table 1 under the standard RENAULT index.

Table 1: Correlation ADAMS vs K&C measurements

Axle	Method	Wheel Steering angle induced by roll	Camber angle induced by roll
Front	Adams/Car	-9,3%	75%~82%
	K&C rig	-9,6%	82%
Rear	Adams/Car	3~6%	59%
	K&C rig	2%	58%

To obtain accurate suspension parameters, the flexible bodies (front sub-frame, suspension arm, stabilizer bar etc.) for front and rear axles are introduced into the ADAMS/Car^{TM} model thanks to NASTRAN^{TM}. The bushing parameters (stiffness and damping) come from experimental measurements.
Starting from this, the suspension of the AMESim vehicle model is adapted by taking into account the suspension kinematic as well as the elasto kinematic (bushing contribution). The suspension kinematics are in form of look-up tables and the deformation of the suspension under five tyre forces are evaluated by a first order coefficient matrix

(see equation 1), all provided by ADAMS/Car™. The elastic contributions of the suspension bushings are considered as quasi static phenomenon on the one hand and as a compliance to correct the wheel centre location and the wheel orientation under tire forces and torques on the other hand.

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta \varepsilon \\ \Delta \eta \\ \Delta \delta \end{bmatrix}_{elas} = \begin{bmatrix} C_{xFx} & C_{xFy} & C_{xTx} & C_{xTy} & C_{xTz} \\ C_{yFx} & C_{yFy} & C_{yTx} & C_{yTy} & C_{yTz} \\ C_{\varepsilon Fx} & C_{\varepsilon Fy} & C_{yTx} & C_{\varepsilon Ty} & C_{\varepsilon Tz} \\ C_{\eta Fx} & C_{\eta Fy} & C_{\eta Tx} & C_{\eta Ty} & C_{\eta Tz} \\ C_{\delta Fx} & C_{\delta Fy} & C_{\delta Tx} & C_{\delta Ty} & C_{\delta Tz} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ T_x \\ T_y \\ T_z \end{bmatrix} \quad (1)$$

The suspension vertical stiffness and the associated damper in damper directions (damper rate and its ratio to convert vertical velocity into damper velocity) as well as the roll stabilizer are taken into account with tables as shown in Figure 2., which is the standard solution in RENAULT to model a suspension for functional design. A special Adams2AMEsim suspension conversion tool is developed to generate automatically the elasto-kinematic tables.

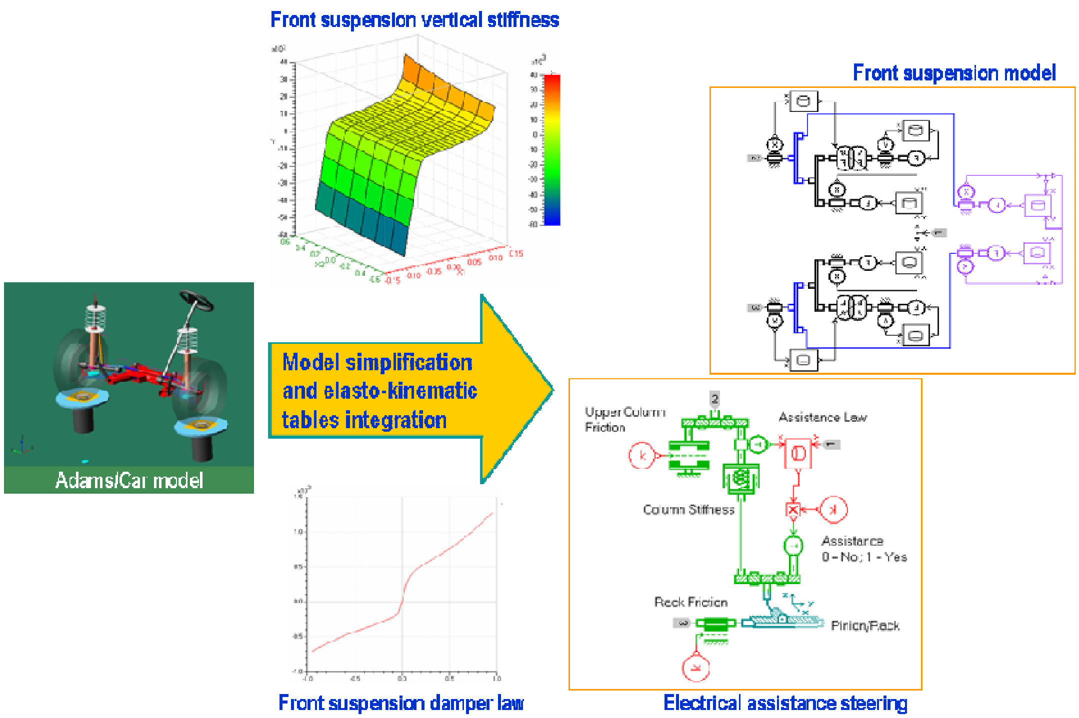

Fig. 2: Suspension and steering models from Adams/Car to AMESim functional model

An electrical assistance steering system is modelled with rack friction non linear model. The assistance law is obtained from available similar system, which is a function of vehicle's speed and measured steering torque. A powerful sensor driver (30N.m) system is newly equipped in ULTIMATE to improve the steering wheel force feedback rendering.

b. Power-train model and regenerative brake controller

The studied EV is based on existing thermal engine vehicle whose thermal engine is replaced by an electric motor with its inverter. The mass of these components is as important as that of the thermal engine. The motor suspension system including these components and motor mounts may greatly influence the drivability and ride comforts in some range of frequencies. In Renault's numerical process, they are modelled by ADAMS/View™ for the engine workspace, mounts durability evaluation and suspension design (kinematics and bushings). The model built here inherits from this simulation tool since most of the parameters are from ADAMS™.
The details of engine's dynamic model, as well as the corresponding Adams model, are illustrated in figure 3 where the flywheel of the motor is included into the "engine" icon representing the engine bloc (see fig. 3).

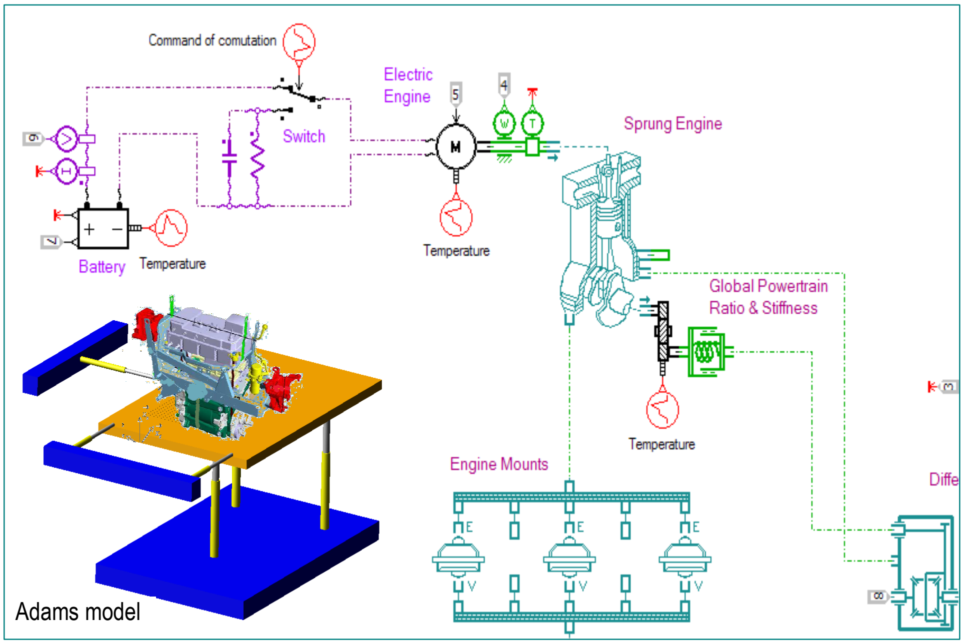

Figure 3: Motor adaptation and ADAMS model

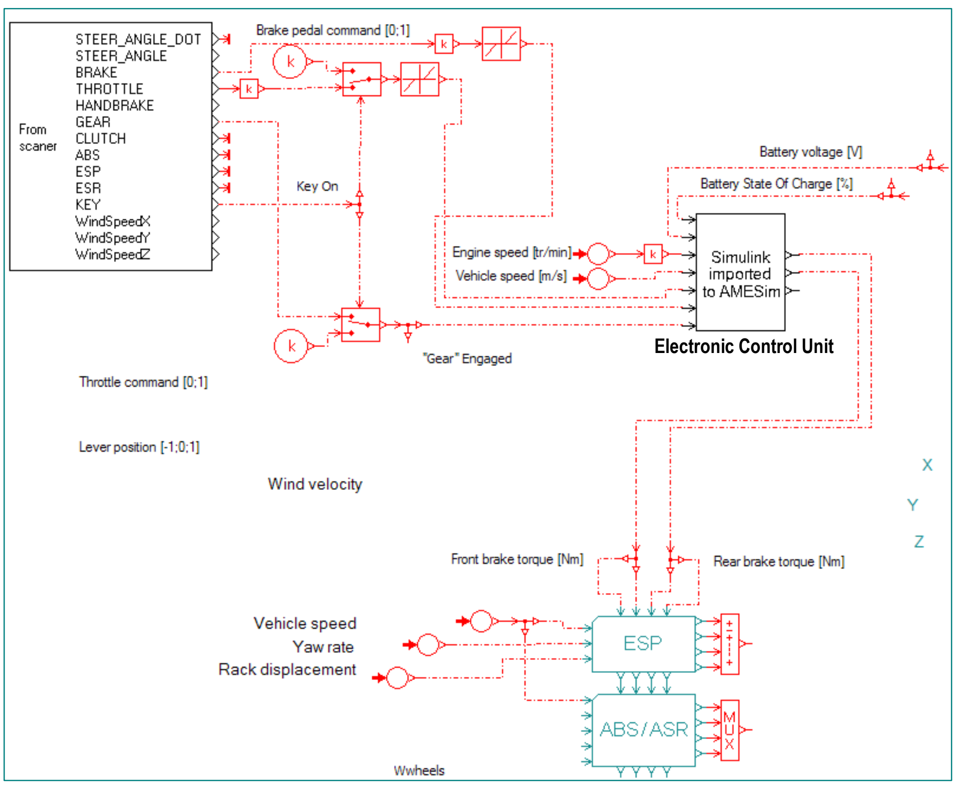

Figure 4: Connection for the Simulink imported model of the regenerative brake controller

Regenerative braking is an integral part of hybrid and electric vehicles. Regenerative braking re-captures and stores part of the kinetic energy during the stopping (at least deceleration) process that would otherwise be lost into heat and then utilizes it to recharge the electric batteries within driver's acceptable disturbed level. It is a truism to say that only the driven axle(s) can capture the regenerative brake energy.

As to the control logic of the regenerative brake, the internal Electronic Control Unit (ECU) in Simulink model [Ell1] has been integrated directly in AMESim thanks to its compatibility with RTW as an equivalent C code (see fig. 4).

This was done in order to produce only one *.rtdll for the ULTIMATE environment under control of SCANeR Studio™, thus making the integration much simpler.

c. Tyre model on low friction road

It is well known that the fast response of the electric motor influences the drivability as well as the driving dynamics aspects. Split-μ and tip-out in curves are typical manoeuvres under which the electric motor response has a great influence on vehicle stability. In order to highlight the stability problems, some efforts have been made on tire parameters to represent low adherence surface, mainly packed snow.

The Pacejka magic formula is a standard for vehicle dynamics simulation. For a low grip road such as packed snow or icy road, the standard model deduced from high adherence test rig cannot be extrapolated to these low grip roads. According to [Lac1], the magic formula model is not well suited for vehicle parameter analysis on vehicle stability performance if snow and ice are considered on the road surface. Despite this restriction, RENAULT has elaborated a procedure for parameter identification that works well for packed snow road. Figure 5 shows a comparison among experiments, a representative physical model presented in [Lac1] and the RENAULT's Pacejka model estimation based on the similar commercial car tyres.

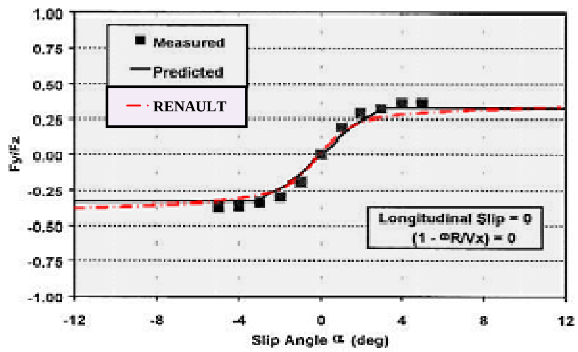

Fig. 5: Comparison between brush tire model [Lac1] and Renault's Pacejka model on packed snow road

d. Aerodynamics model

Based on the experiences and theoretical analysis, the aerodynamic resistance can be evaluated by a simple relation valid for turbulent flow:

$$F_{aero\ i} = 0.5.SC_i(\theta).\rho.V^2 \qquad \text{with } i = \{x, y, z \text{ for resistance force components and } l, m, n \text{ for moment components}\}$$

For personal cars, when the vehicle speed is between 80~90km/h, the longitudinal aerodynamic force is at the same magnitude order of mechanical resistance. It rises quickly as the velocity increases, e.g., twice as much as that of the mechanical resistance for a highway driving. The aerodynamic effects have been considered for the driving simulator by using a table of SC_i in function of air flow~vehicle incident angle, θ.

The coefficients from CFD (Computational Fluid Dynamics) simulation are validated in experiments in wind tunnel. The values are demonstrated in Figure 6.

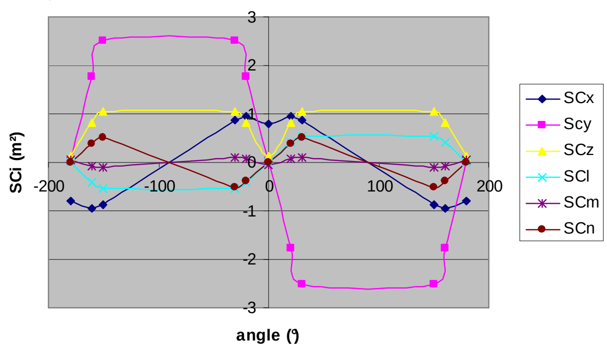

Figure 6: aerodynamics tables

II.2. Vehicle sound's model

Based on LMS Virtual Car Sound software and real car's acoustic measures, a VCS model is tuned to reproduce as closely as possible the EV's noise. The principle of audio synthesis is based on linear frequencies interpolation (see fig. 7). The aero-acoustic effect is not yet taken into account in the current model at the absence of the complementary measures.

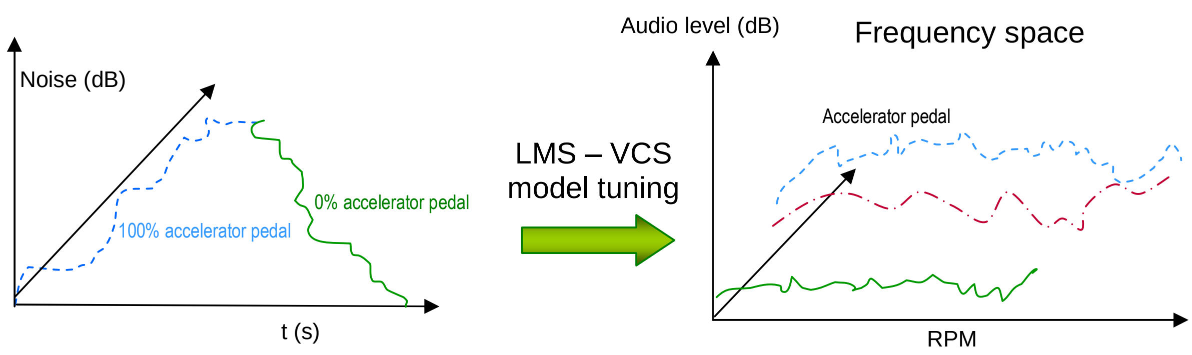

Fig. 7: Principle of audio synthesis

II.3. RTX real-time model generation and its performance evaluation

We use AMESim and RTX™ (http://www.intervalzero.com) to generate a real-time dynamic model. Runge-Kutta (R-K) algorithm is used in solving system equations. The calculation errors with different orders and time steps are evaluated to deduce the optimal combination set of the parameters involved.

a. RTX real-time model generation

The environment of a driving simulator is generally very specific. The ULTIMATE environment is based on RTX and consequently, some AMESim adaptations have been required for its integration and industrial use, including: a new developed interface with SCANeR software, the compatibility of AMESim with RTX, the improved C code optimization and compilation to allow including in one file all the modelling aspects of the vehicle inside the driving simulator, the improved start and stop features for the tire model, protections considering boundary limits of the Pacejka formulation and multi points contact handling for tire/road interaction.

b. Model's real-time performance evaluation

An analysis has been carried out to find the most efficient solver for the considered model. This analysis is based on the best compromise choice between the precision of calculation and CPU running time which are the function of time step and R-K algorithm's order. The reference values are calculated with the adaptive time step AMESim algorithm and the minimal error of simulated results for each order is given by a low fixed time step (=0.1ms) algorithm. The best compromise solution was order 2 R-K method with 1 ms as time step as shown in Figure 8.

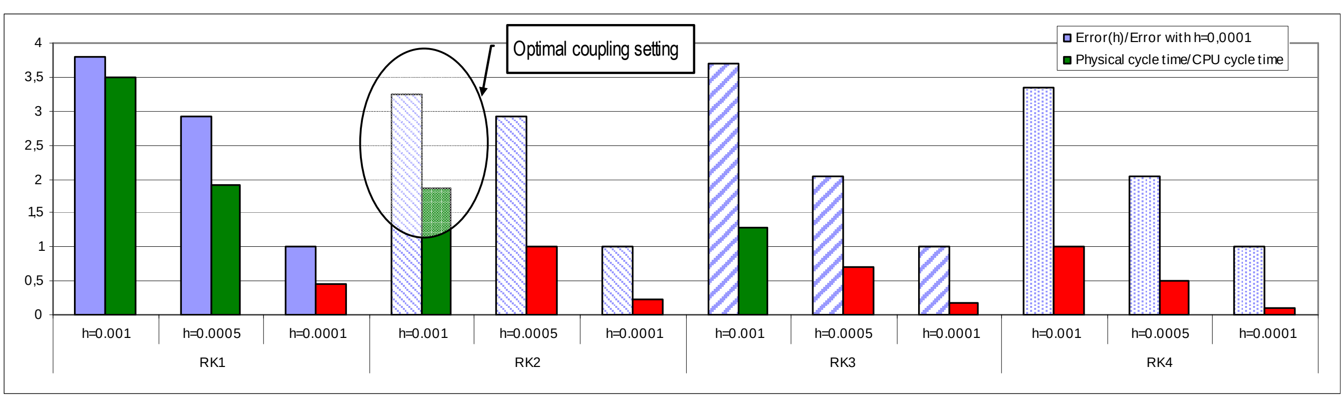

Figure 8: Comparison of the performances for different R-K algorithm's step sizes and orders

III. The ULTIMATE driving simulator's tests

II.1. The performance and limits of ULTIMATE

ULTIMATE is a high performance driving simulator based on an X-Y rail actuator system combined with a 6 degrees of freedom hexapod (Stewart platform). The driving simulator is used for vehicle dynamics engineering applications in the early phase of the vehicle design process. The motion system is driven in position by SCANeR Studio™ via a predictive motion cueing algorithm. Table 2 presents the linear motion performance limits due to actuator capability and the workspace of the simulator building.

Table 2: ULTIMATE linear motion performance limits

	X_{rail}	Y_{rail}	$X_{actuat.}$	$Y_{actuat.}$	$Z_{actuat.}$
Excursion(m)	±2,6	±2,6	±0.20	±0.20	±0.20
Velocity(m/s)	±2	±3	±0.70	±0.70	±0.40
Acceleration(m/s²)	5	6	6	6	5

The apparent lag motion feedback was deemed by some expert drivers as a disturbing factor for the subjective assessment of transverse dynamics especially under faster manoeuvres. Another problem is the attenuation of acceleration amplitude due to the system transfer function. The results from the driving simulator shown in Figure 9 illustrate this defect. The red line in Figure 9 corresponds to the simulation result, the blue dot line to the simulator's platform lateral acceleration simulated with its transfer function.

The simulator's delay (transport delay and phase delay due to its transfer function), one of the main factors for motion sickness is also measured and can be compensated by a PID controller [Fan2] or other more efficient state-space MPC algorithm (in coming). The delay between the simulation and the driving simulator around 200 ms can lead to perception troubles. In Figure 9, the green line corresponds to the result after compensation using a PID controller with better fitting (no delay).

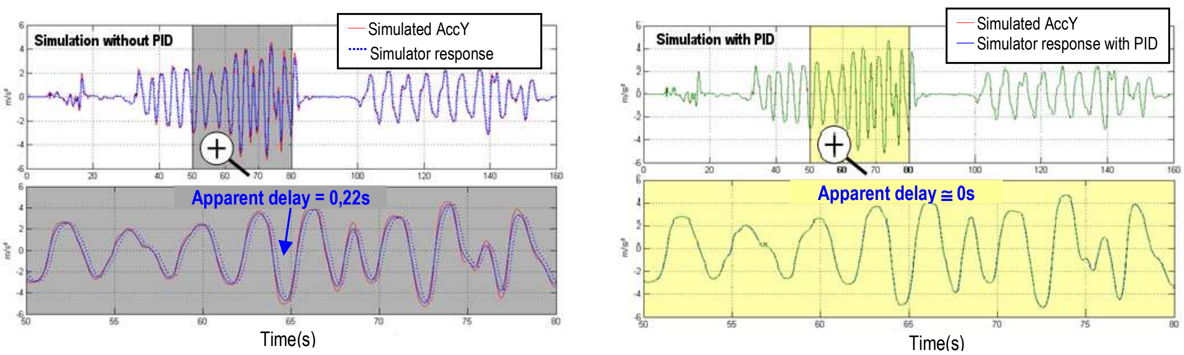

Figure 9: Slalom test with (right fig.) and without (left fig.) PID correction

II.2. Driving simulator tests

The strategy between regenerative brake and others ADAS systems should be coordinated in order to avoid conflicting decision during critical situation, such as driving in curves and losing the adherence. The driver's behaviour, as illustrated in figure 10, could influence directly the stability of vehicle in these situations. This application aims to reproduce as closely as possible the real car's behaviour to perform different tests discussed as follows:

- Tip-in and tip-out
- Low grip road with cornering maneuvers
- slalom

In scale 1 to 1, the tip-in and tip-out tests are quite difficult to be performed on ULTIMATE due to the already presented limitations (workspace and simulator performances). However for a tip-in or a tip-out with limited time schedule and with a driver having a good experience in driving simulator, the test is feasible. The first tests with professional drivers reveal that they can feel the real acceleration levels and are interested by the driving simulator.

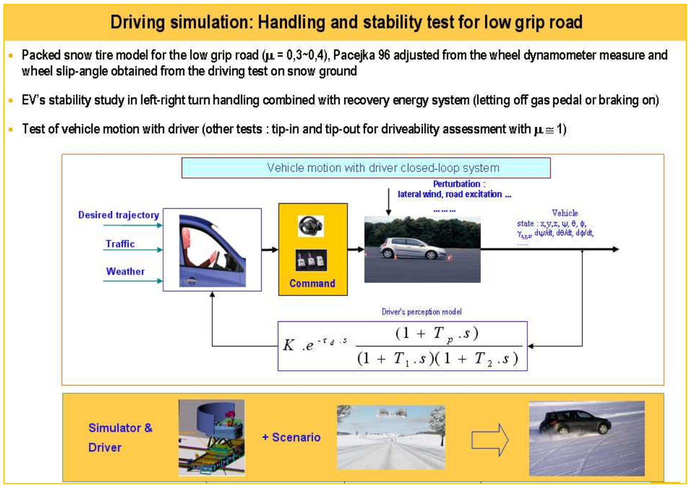

Figure 10: driving simulation on packed snow road

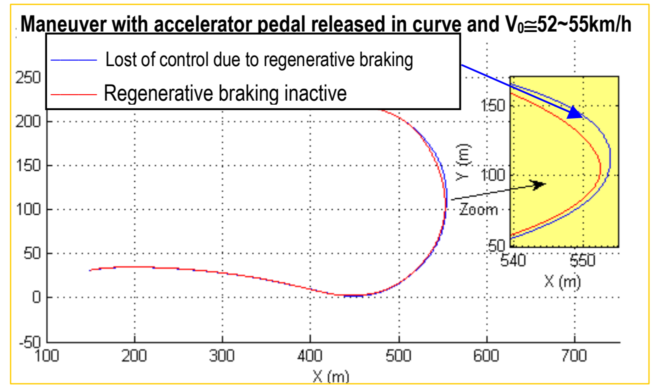

Figure 11: Vehicle trajectory in packed snow road with driver in loop

Packed snow road test aims to analyze the stability of the EV with regenerative brake on the one hand and to prepare the future ESC tuning scenario on the other hand. Note that the ESC control logic is not activated for the presented tests. Figure 11 shows the under steering phenomena in curve when releasing the gas pedal (back out or better said tip-out), with regenerative brake compared to a normal driving. Qualitatively, it can be explained by a limited adherence on the tires of the front axle since the regenerative brake is acting. The electric motor solicits more the longitudinal Fx forces and owing to the tire coupling, it reduces the lateral tire force Fy, hence leading to an under steering effect.

Figure 12 shows the decrease in lateral acceleration at time 35 seconds when the accelerator pedal is released and regenerative brake is activated. However in Figure 13 for regenerative brake disabled, even if the release of the accelerator pedal (t=20,5s) conduces a decrease in lateral acceleration, this decrease is less impressive. Note that the change in lateral acceleration may also be caused by the change in steering wheel angle.

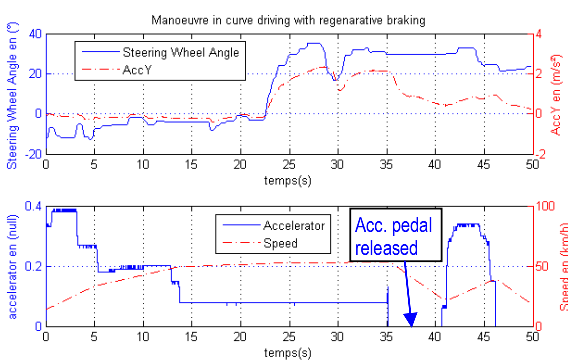

Figure 12: Tip out in curve with regenerative brake

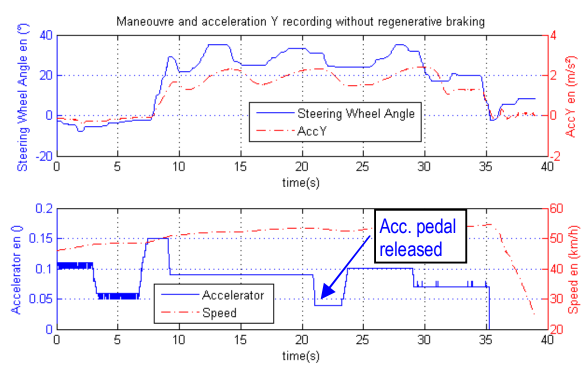

Figure 13: Tip out in curve without regenerative brake

Up to now, the regenerative brake alone has been explored within the driving simulator. As mentioned before, it is the first step to explore what can be the contributions of the driving simulator in the domain of EVs. Combining the ESC and the regenerative control laws is another foreseen task. The actual works on motion cueing algorithm adaptation and the improvement of modelling steering, braking, and powertrain systems received the promising feedbacks from RENAULT internal users of this complete virtual simulation tool (models and driving simulator).

IV. Conclusions

The feasibility to build a complete electric vehicle model from Adams/Car and Simulink controller to AMESim, able to treat with drivability, ride and handling and vehicle stability has been proven by means of running in the real time within the ULTIMATE environment. Even if the 3D vehicle model is mainly dedicated to ride and handling analyses, its adaptation as well for drivability aspects has been demonstrated.

The improvement of the model of the vehicle dynamics on low friction road and of the motion cueing algorithm has significantly ameliorated the driving simulation fidelity for the studied scenario on the ULTIMATE simulator. Promising feedbacks have already been reported by RENAULT internal users on this complete virtual simulation tool.

References

[Zan1] van Zanten A., Erhardt R. and Pfaff G., "*VDC, The Vehicle Dynamics Control System of Bosch*", SAE paper, n°. 950759

[Pap1] Y.E. Papelis, T. Brown, G. Watson D. Holtz, W. Pan, "*Study of ESC Assisted Driver Performance Using a Driving Simulator*", NADS, Iowa University, 2004

[Wat1] G.S. Watson, Y. E. Papelis, O. Ahmad, "*Design of simulator scenarios to study the effectiveness of electronic stability control systems*", NADS, Conference paper, 2005,

[Bro1] T. Brown, C. Schwarz, J. Moeckli & D. Marshall, NHTSA, "*Heavy Truck ESC effectiveness Study Using NADS*", November 2009

[Wus1] Klaus Wüst, Daimler AG, CAE Commercial Vehicles, "*Electronic Stability Program (ESP) for Trucks on the Daimler Driving Simulator*", SIMPACK News, September 2010

[Fan1] Fang Z. and Kemeny A.; "*Motion cueing algorithms for a real-time automobile driving simulator*", DSC Europe 2012, Paris, France

[Fan2] Fang Z., Reymond G., Kemeny A.: "*Performance identification and compensation of simulator motion cueing delays*", DSC Europe 2010, Paris, France, 2010, pp 111-120.

[Ell1] Eller B., Hetet J.F., André S., Hennequet G.: "*Electric vehicle platform for drivability analysis*", 8th IEEE International Conference on Control and Automation, Xiamen, China, June 2010, pp 2251-2257

[Lac1] Lacombe J: "*Tire model for simulations of vehicle motion on high and low friction road surfaces* ", SCS Proceedings of the Winter Simulation Conference, San Diego, CA, USA, 2000, pp 1025-1034