ENHANCEMENT OF CAR SAFETY USING IMPROVED ESC AND TYRE DEVELOPMENT METHOD

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ABSTRACT

ESC efficiency to reduce accident is now well proven. To obtain this accident reduction tests employed for the tuning of a car equipped with an ESC must be related to real world accident cases. With accident statistics obtained in France, two main categories of accidents are defined: loss of control in a curve and accidents in a straight line or at an intersection. For each of these categories, thanks to detailed analyses of real accidents, we can define tests scenarios that are related to real world. Several examples are given.
To measure the performance of a car equipped with an ESC during these tests, stability criteria are defined. In addition criteria to assess the quality of ESC intervention are defined. These tests pointed some limitations of ESCs. Some improvements of ESCs algorithms were specified to overcome these problems. Examples are given.
During this ESC tuning, it is decided if a rollover prevention module is necessary or not. This decision process, which includes both real tests and HIL (Hardware In the Loop) tests is described. One of the conditions that may lead to a rollover is a contact between the rim and the ground. This process also enables us to define test conditions to check there is no risk of rim contact on the ground.
A test method of a tyre on a bench to check these conditions are satisfied is described. It is also shown that the risk to have a contact of the rim on the ground is not significantly modified during the brake activation by the ESC.

1. INTRODUCTION

1.1 Efficiency of ESC's and pertinent accidents

ESC is an efficient equipment to avoid accident. A lot of studies have been published and show a statistically significant reduction of accident for cars equipped with ESC [1] [2] [3] [4].
The later is very interesting as it distinguishes the different accident scenarios.

Then it identifies accident situations for which the ESC is pertinent or not. For example ESC is pertinent for loss of control accidents while it is not for cars pulling out of a junction. According to this paper, the accidents for which the ESP is pertinent are related to loss of control or guidance problems. The given list is:

- Single car accident. Loss of control or guidance problem on a straight road outside junction
- Loss of control or guidance problem on a straight road outside junction. Collision with an opponent
- Single car accident. Loss of control or guidance problem in a bend outside junction
- Loss of control or guidance problem in a bend. Collision with an opponent
- Single car accident. Loss of control or guidance problem at a junction.

Then it is interesting to test the ESC's with driving conditions that are related to these pertinent accidents.
In this paper we will only deal with the loss of control that is initiated by a driver manoeuvre on a dry road: namely action on the steering wheel, the brake or the gas pedal.

1.2 Selection of the test procedures

The detailed method to select the procedures and the initial conditions is given in [5]. The test procedures are derived from ISO standard. The initial conditions are the one observed in the detailed analysis of real world accidents.
In the following different tests examples are given:

- Braking in a curve ISO 7975
- Power off in a curve ISO 9816
- Severe lane change manoeuvre ISO 3888-2

For these tests we give an example of a metric used to enhance the tuning of an ESC.

2. BRAKING IN A CURVE

2.1 Desired improvement

For our test the initial radius is 150 m and the initial longitudinal speed is 120 km/h. In [5] a metric was proposed to assess the stability performance of a car during a brake in turn test. In this metric the yaw speed variation and the side slip angle value were considered. But there is a need to improve this metric when the car is equipped with an ESC. This is because the yaw speed variation is only considered at given times after the beginning of the braking t_0. For a car equipped with ESC, the yaw speed variation may show a time history like the one of figure 1.

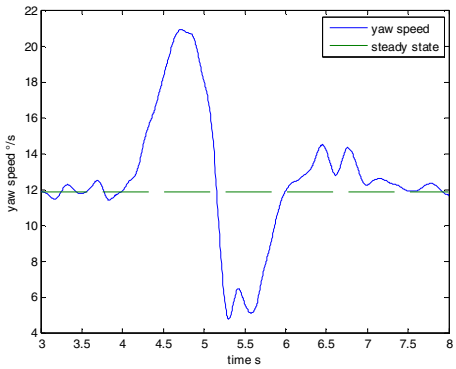

Figure 1: Example of yaw speed time history during a braking in a curve with an ESC intervention

In this case, the braking is initiated at time t_0=4s. With a measurement of yaw speed variation between t_0 and $t_0 + 1$ s, the oscillation will not be penalised.
The yaw speed oscillation is clearly something to avoid, it generates a sudden variation of the trajectory and significant yaw acceleration. The variation of trajectory is an objective stability problem and the yaw acceleration that is very well perceived by the driver is more a subjective problem. So this oscillation should be minimised and to quantify it we propose a new metric.

First we draw the horizontal line corresponding to the mean value of yaw speed during 1 second before the braking (i.e. in figure 1 between time 3 and 4 second). In the following this mean value is called $\dot{\psi}_0$. This line is the dotted line of figure 1 and is called "steady state" in the legend. Then we define two values:

- the positive integral which corresponds to the area between the mean yaw speed line and the actual yaw speed between t_0 and time t_1 when yaw speed first becomes lesser than $\dot{\psi}_0$
- The negative integral which corresponds to the area between the mean yaw speed line and the actual yaw speed between t_1 and time t_2 when yaw speed reaches $\dot{\psi}_0$

The proposed metric is the sum of the absolute values of those two integrals.

In figure 2 with a better regulation of the ESC the oscillation is almost inexistent and both integrals have been significantly reduced. The scale for the yaw speed axis is the same in figure 1 and figure 2 to make the comparison easier.

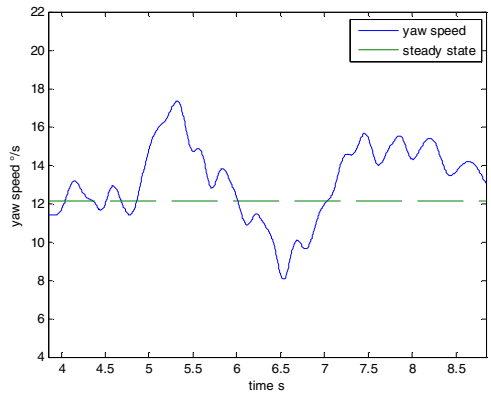

Figure 2: Example of yaw speed time history during a braking in a curve with an improved ESC intervention

2.2 Proposed modification of algorithm

The detection of the instability beginning has not been changed. When the difference between desired yaw speed and actual yaw speed becomes too large the correction is initiated with an open loop brake actuation. This has not been changed and can be seen on figure 1 and 2 where the gradient of yaw speeds is identical at the beginning of the manoeuvre.
In addition lateral acceleration a_y is observed. To be more precise the difference between the measured lateral acceleration and the desired lateral acceleration is calculated. The desired lateral acceleration is obtained with the steering wheel angle and the vehicle speed.
An increasing difference means an increase of side slip angle. If this difference is still increasing during the regulation this means the longitudinal effort on the front outside wheel has to be increased.
When the increase of side slip is stopped the pressure is kept constant if the steering wheel angle is constant or modulated according to this latter value if it changes until actual yaw speeds reaches the desired yaw speed.

3. POWER OFF IN A CURVE

This case is significant to test an ESC as there is no action on the brakes. So the action is typical of an ESC and is not possible with an ABS. For this test the initial

radius is 100 m and we test vehicle speed from 80 km/h up to the maximum of the car with increment of 5 km/h.

3.1 Desired improvement

To determine the vehicle behaviour the ESC measures the yaw speed and the lateral acceleration. There is no direct measurement of the side slip, this value as to be determined. If the increase of the side slip is a slow one, it is difficult for the ESC to detect this increase. This can lead to a big side slip angle and in our opinion this is a problem as we found the slip angle is a cause of driver's stress.
According to [6], 47% of the drivers do not make any action to avoid the accident. So we should not wait for a driver action at the steering wheel to limit the maximum of the side slip angle.
We believe the metric is the absolute value of the side slip angle and not the relative increase from the steady state value during the curve before the power off. That is because the stress is related to the absolute value of side slip and not to an increase from the steady state value.
The figure 3 shows an example of a car equipped with an ESC that allows the side slip angle to become large. We call this behaviour the slow side slip default.
The proposed modified algorithm aims at suppressing this default.

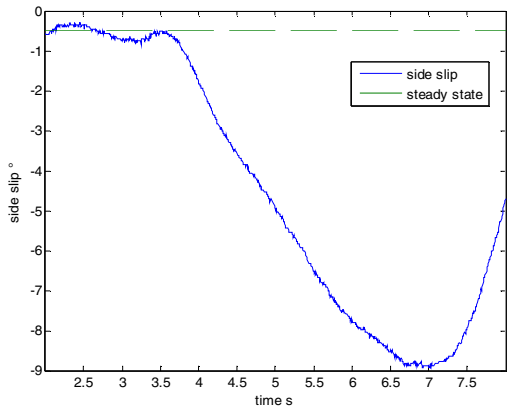

Figure 3: Example of side slip time history during a power off in a curve with the slow side slip default

The figure 4 shows an example of a car equipped with an ESC modified to enhance this behaviour.

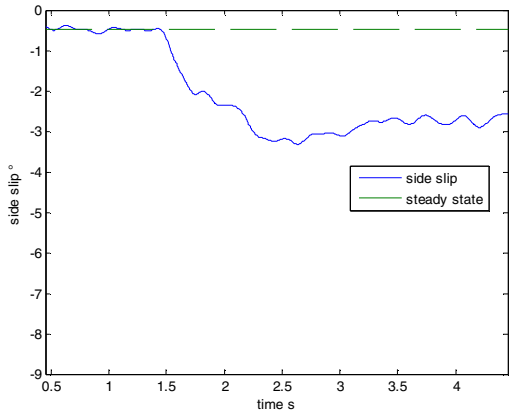

Figure 4: Example of side slip time history during a power off in a curve with correction of the side slip default

To determine the time of intervention of the ESC, it is interesting to look at the yaw speed time history. We can see on figure 5 that the yaw speed decrease begins at 2.07 s. It is important to mention that this decrease is the effect of the ESC intervention. So the initiation and the detection of the side slip is done before. The entire process duration i.e. the detection of the side slip, the decision of ESC intervention and the beginning of side slip increase limitation is around 0.4 second.

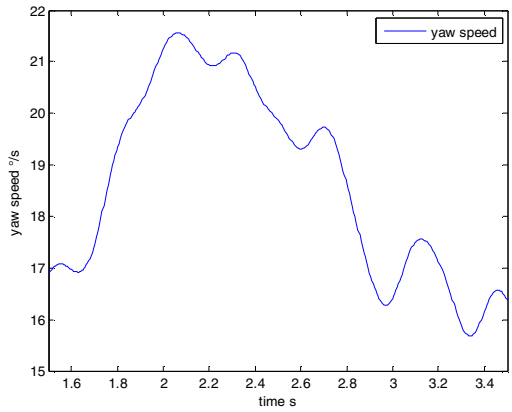

Figure 5: Yaw rate time history during power off in a curve: determination of the ESC intervention

Of course, as shown before with the braking in a curve, we want this ESC intervention to be progressive. This is the reason why the effective limitation of the side slip is obtained around 2.3 second that is 0.6 second after the power off initiation. We do not consider this to be a problem; between the time the first intervention is effective and the effective limitation of side slip, the magnitude of side slip increase is only 0.8° with a maximum at 3.3° for the side slip. All these values are small enough and the driver will not be scared.

3.2 Proposed modification of algorithm

As explained before for the braking in a curve the correction is a several step process. The beginning of the action of the ESP consists in an open loop actuation followed by a closed loop actuation.
All these actions are triggered by specific thresholds. The idea here is to make the thresholds of the closed loop actuation more aggressive as soon as the open loop actuation is initiated. Once the open loop actuation has been initiated there is no risk of undesired correction any more this is the reason why the thresholds are made more aggressive only at this time. Then thanks to these modifications, the closed loop regulation that is more efficient and more comfortable is activated sooner.

4. SEVERE LANE CHANGE MANOEUVRE

4.1. Choice of the test

One of the most popular tests for this situation is ISO 3888-2. Professional test drivers succeed in this test with vehicle speeds as high as 80 km/h. For a normal driver it is not possible to reach such a speed on such a track. The problem of the speed is an important one. In [7] the study of a panel of 72 accident cases shows that when there are multiple actions on the steering wheel the mean speed at the first action on the steering wheel is 88 km/h. Of course to follow the test track described in ISO 3888-2 there are multiple actions on the steering wheel. So this test is not related to real world accidents conditions: the actions on the steering wheel and the speed are not consistent.
Nevertheless as it is practised by a lot of journalists it is one of our test case and we find it interesting to test the rollover resistance.

4.2. The questions to be answered

If there is a risk of rollover, the ESC can activate a dedicated module: the RollOver Mitigation (ROM). To make it simple, this module limits the lateral acceleration when there is a risk of rollover. On the one hand, if a given car presents a risk of rollover this module must be fit in because it is an improvement of the safety. On the other hand, if the car does not present a risk it is better not to install this module to avoid any risk of undesired lateral acceleration limitation.
For this reason we need a process to determine if there is a risk of rollover or not

4.3. Process to determine if there is a risk of rollover or not

When one must answer this question two main difficulties are present:

- The great number of load cases to be tested
- The need for safe experiment

To obtain safe tests the cars are equipped with outriggers during rollover test sessions. The main drawback of this equipment is the bias it introduces in the inertia and the load distribution. How can we say that when car does not roll over with outriggers it will not without and vice versa? In order to answer this question we developed the process described in figure 6.
Of course, during the high dynamics tests, the ESC's regulations change the behaviour of the car. So the simulations need the ESC's regulations. This is the reason why we make these simulations with a Hardware In the Loop (HIL) test bench. For the correlation between simulation and measurement, we check the errors of dynamics variables of the body: yaw and roll velocity, roll and pitch angle, heave, side slip angle; accelerations and suspension movements. In addition, we check that the instant of activation of ESC are the same for real and virtual testing.

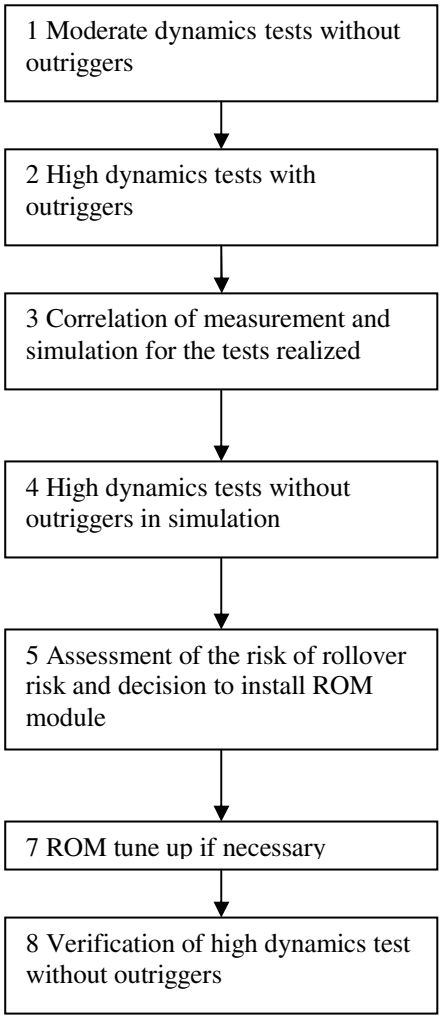

Figure 6: process to determine if the ROM is necessary

But only one problem has been addressed so far: the need for safe tests without bias in inertia or load distribution.
Once this process was initiated we decided to use it to reduce the number of load cases to be tested. The corresponding process is described in figure 7

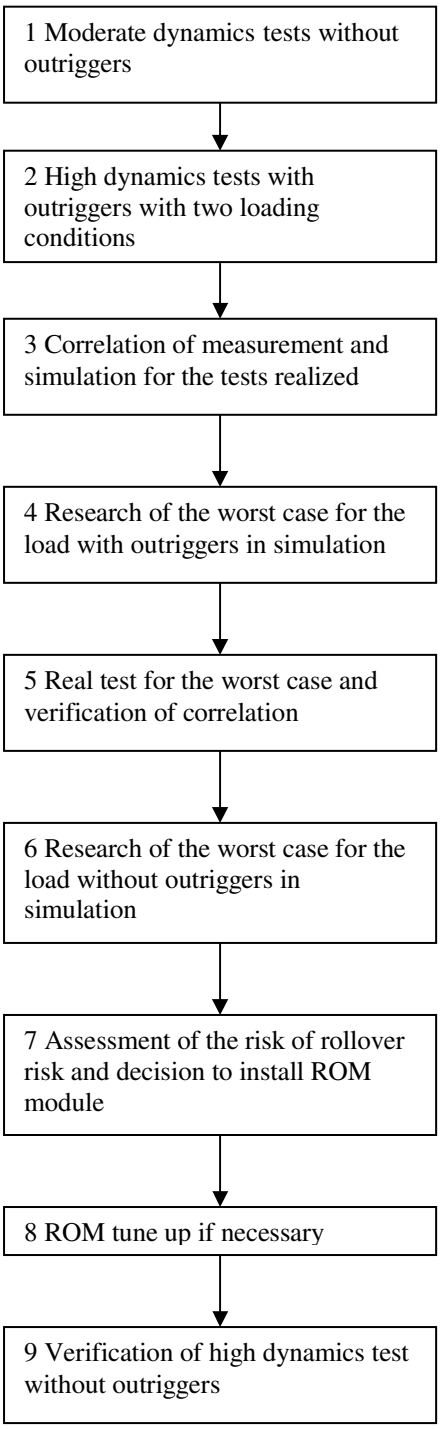

Figure 7: process to determine if the ROM is necessary with reduction of the load cases to be tested

The idea was to add "an optimisation" to find the worst case: the one with the higher risk of roll over during the step of simulation (4 and 6). The worst case is the one with the smallest load on the internal wheels or the case with two wheels lift up with the smallest speed in the test.

It is difficult to obtain a good correlation between simulation and measurement for high dynamics manoeuvres, this is the reason why we believe step 5 is useful. It enables to verify the correlation is still effective for the worst case.
One of the events that may lead to rollover is a contact of one rim with the ground. The described process is also useful to avoid this contact.

5. PROCESS TO AVOID THE CONTACT OF THE RIM ON THE GROUND

5.1. Michelin tire testing method principle

Testing tyres on a bench in conditions as close as possible to those encountered during high dynamics manoeuvres (e.g. up to rim contact) is not possible for evident safety reasons. A method to test tyres with minimal rim clearance has been developed. Because relation between rim clearance and load can not be presupposed, the bench is directly commanded in loaded radius mode. Appropriate loaded radius is deduced from target rim clearance and relation between rim clearance and loaded radius.

5.2. Test definition

For a given tire, the maximum loaded radius (e.g. free radius) and the minimum one (e.g. corresponding to minimum rim clearance allowed by bench or tire depending on conditions) are determined as functions of camber angle, tire dimensions (width, aspect ratio and internal diameter), rim dimensions (width, diameter, side height) and tire sectional thicknesses (summit, sidewall). From these functions, slip angle sweep sequences with various deflections objectives (and corresponding rim clearances) are defined with speed, pressure and camber effects.

5.3. Loaded radius formula

Usual acquisition channels are saved during testing (e.g. forces, torques, angles, speeds, pressure and loaded radius) and post-processed to fit a simplified loaded radius formula:

$$\begin{aligned} R_L = & \left(k_{0_0} + k_{0_V}.V + k_{0_P}.P\right) + |\gamma|.k_\gamma \\ & + F_Z.\left(k_{Z_0} + k_{Z_V}.V + k_{Z_P}.P\right) \\ & + |F_Y|.\left(k_{Y_0} + k_{Y_V}.V + k_{Y_P}.P\right) \end{aligned}$$

With V the speed in kph and P the pressure in bars.

Figure 8 shows the loaded radius measurement and fit during the measurement protocol.

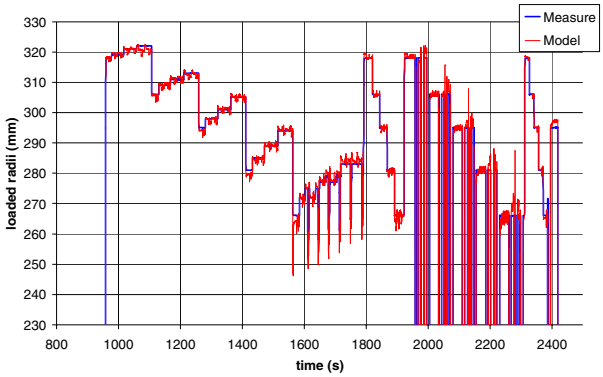

Figure 8: Loaded radius fitting quality

5.4. Rim clearance prediction

To define the test and to use the loaded radius model for rim clearance prediction, the relation between the previous has to be described according figure 9:

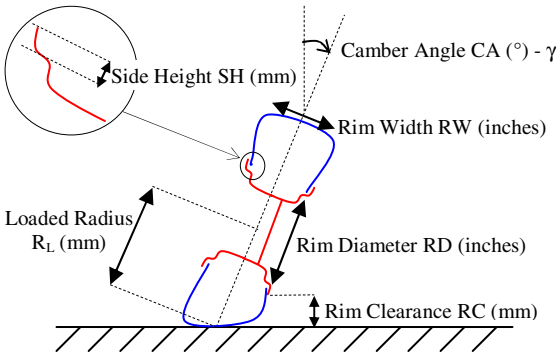

Figure 9: Rim clearance to loaded radius relation

$$RC = \left(R_L - \frac{RD}{2}.25{,}4 - SH \right).\cos(\gamma) - \frac{RW}{2}.25{,}4.\sin(|\gamma|)$$

5.5. Evaluation of the tyre loading conditions during high dynamics manoeuvres

When there is a risk to get a contact of the rim on the ground it not possible to make a measurement with a dynamometer wheel. These equipments are too expensive to take such a risk.
The idea is to make measurements with dynamometer wheels only during the test of step 1 of figure 7: the low dynamics tests. Then the correlation between the tests and the simulations of step 3 is also checked for the tyre efforts.

Then we assume the verification of the dynamics variables of the body : yaw and roll velocity, roll and pitch angle, heave, side slip angle, accelerations and suspension movements during the high dynamics manoeuvres is sufficient to validate the tyre efforts during these manoeuvres.

So we can use the tyre efforts obtained during the simulations as the loading case to be introduced in the formulae to check if there is a risk of contact or not.

5.6. Tire dimension effect example during high dynamics manoeuvres

As an example, 3 tires of different dimensions have been measured, fitted and their models used to replay the typical manoeuvre.
Figure 10 shows the results of the computed rim clearances.
Data show that tire dimension 215/55R16 has more rim clearance during simulated avoidance manoeuvre than tire dimension 215/50R17 and even more than tire dimension 215/45R18. Results have proofed to be consistent with on track tests made to check vehicle behaviour under high dynamics manoeuvres with the different tire dimensions.

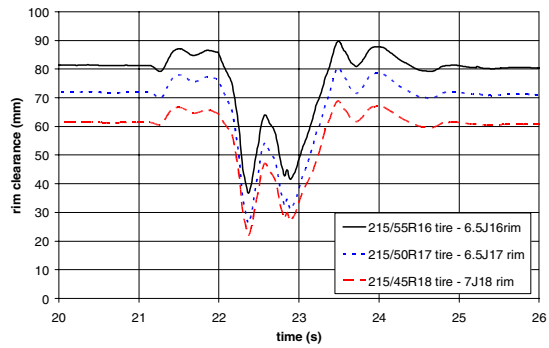

Figure 10: Computed rim clearances for 3 tires

5.7. Effect of longitudinal force on loaded radius

Indoor combined measurements have revealed that the perturbations introduced by the application of a longitudinal force are small. The effects of the ESC and ROM on loaded radius are so not requesting the Fx force knowledge but only the modifications on Fy and Fz forces, camber angle and speed. And the rim to ground distance is not impacted by the actions of the ESP and ROM as much as mainly Fx force is modified.

CONCLUSIONS

Accidents data analyses introduce classes of accident situations for which the ESP is pertinent. In this paper three situations are shown: braking in a curve, power off in a curve and severe lane change. Example of ESP enhancement are given for each test respectively a regulation that will improve the diver comfort and reduce trajectory deviation, a limitation of the side slip increase for a better stability and a reduction of the stress of the driver and a method to decide if the rollover protection module has to be install or not.
A method to determine if a contact of the rim on the ground is possible that uses mainly test bench measurement is proposed.

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