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TOWARDS T.R.I.C.K. 2.0 – A TOOL FOR THE EVALUATION OF THE VEHICLE PERFORMANCE THE USE OF AN ADVANCED SENSOR SYSTEM

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Abstract. *In the last years, the tire technological development has played a fundamental role in motorsport and in automotive industry. The tire contact patch forces have a great influence on the vehicle behavior, so their correct estimation is a crucial task to understand how to improve the car performance. In order to identify the tire interaction characteristic, it is also necessary to use a procedure that allows the correct evaluation of the slip angles in the different operating conditions. This paper presents an evolution of the T.R.I.C.K. tool developed by the UniNa vehicle dynamics research group. In the first version of this tool an 8 degree of freedom vehicle model has been implemented and, starting from the experimental data acquired, the T.R.I.C.K. calculates the interaction forces and the tire slips using the equilibrium equations.*

Using more car parameters and further data obtained from track sessions and dedicated tests, in the presented release of the tool, new formulations have been developed for a more accurate calculation of the tire-road forces. The effectiveness of the treatments is assessed using experimental data and the simulator outputs.

The new formulations introduced in this paper allows, depending on the availability of additional vehicle data and acquisition sensors, to estimate the interaction forces with different and more accurate methodologies than the equilibrium equations, while retaining very reduced simulation times. In this way it is possible to carry out a more precise study of vehicle dynamics with the possibility of investigating and significantly improving performance.

1 INTRODUCTION

To investigate vehicle's behavior and performance it is necessary to study its dynamics in the various driving conditions. For this reason, the determination of the tire-road interaction forces and of the slip indices represents a crucial task to understand how the tire is working and, consequently, the vehicle. This problematic is directly related to the tire technological development that occurred in recent years and is the motive why several authors and carmakers have produced various contributions related to these issues.

To be able to effectively study the tire-road interaction it is necessary to define a simplified vehicle model [1,2,3] and find a methodology with which to estimate the interaction force [4, 5, 6].

This paper refers to the T.R.I.C.K. tool [7] developed by UniNa vehicle dynamics research group that comes from the idea of using the car as a moving laboratory to characterize tires without test bench and in their real operating conditions. The T.R.I.C.K. uses an 8 degrees-of-freedom (DOF) rear-wheel-drive vehicle model and is able to process experimental signals acquired from sensors mounted on the car providing a sort of virtual telemetry.

The main aim of this work is to present alternative formulations for roll angle estimation and aerodynamic forces calculation based on information obtained from additional laser sensors installed on the vehicle. This is possible because a racing car, usually, has a more advanced sensor system than the one required for the T.R.I.C.K. simulations. Moreover, vehicle manufacturers have additional material about the construction and performance characteristics of the car and carry on dedicated tests to analyze the behavior of certain components, such as wind tunnel simulations. Using this further information and validating the new formulations proposed in Sections 3 and 4 with simulator data, the foundations for the creation of an advanced tool, the T.R.I.C.K. 2.0, capable of exploiting the information provided by an advanced sensor system, have been laid.

2 LASER SENSORS

Laser sensors are instruments designed to measure the distance from the ground without any type of contact; their functioning is based on the principles of laser radiation and they are the most suitable solution for determining distances between moving objects. The vehicle is equipped with these sensors, securely mounted on the bottom of the frame, with the laser beam directed perpendicular to the road. The vehicle reference system, shown in Figure 1, is the same as in [1]: it is centered in the vehicle center of gravity, x is the longitudinal axis, positive forwards, y is the lateral axis, positive to the left, and z is the vertical axis, positive upwards.

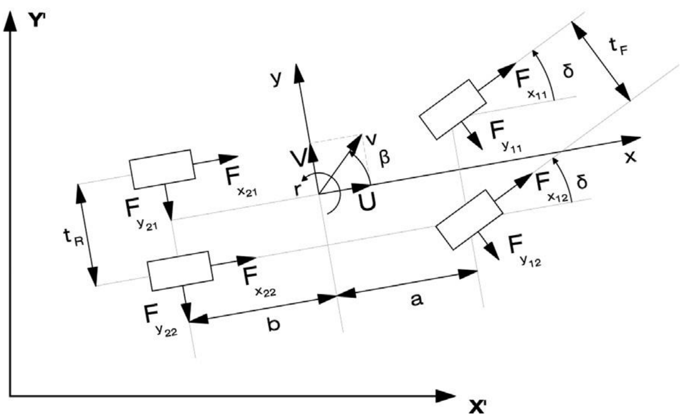

Figure 1: Vehicle reference system

These additional channels can be used for the roll angle and aerodynamic forces estimation. In particular, to calculate the roll angle, two laser sensors mounted on the same abscissa (along x-axis) are required; they must also be set symmetrically with respect to the xz plane with the same height from the ground in static conditions. For the study of aerodynamic forces, instead, it is necessary to have two instruments arranged along the vehicle centerline, preferably in correspondence with the front and rear axles. To study the phenomena mentioned above, at least three laser sensors must be mounted on the vehicle in the following way:

- The first mounted in the front of the vehicle at the centerline;
- The other two arranged as close as possible to the rear axle and mounted symmetrically with respect to the xz plane.

It is important to point out that, due to the pitch and roll motions that arise in ordinary driving conditions, the height from the ground determined by sensors varies and, above all, the inclination of the laser beams with respect to the road changes. However, generally the pitch and roll angles are small and, therefore, this inclination variation can be neglected.

3 ROLL ANGLE ESTIMATION

The roll angle is used to calculate the camber angle variation. In the first version of the T.R.I.C.K. tool, it was calculated as follows:

$$\phi = \frac{a_y}{|g|} rollrate \tag{1}$$

In which a_y is lateral acceleration, g is gravity acceleration and the roll rate is the roll angle obtained for a lateral acceleration equal to 1 g and its unit of measurement is therefore [deg/g]. It is clear that, in this case, the roll angle dependence from lateral acceleration is linear.

Usually, the roll rate is not necessarily a fixed value, it can be variable and is a characteristic of the considered vehicle. Thanks to the use of laser sensors, it is possible to obtain the roll angle in a different way:

$$\phi = \tan^{-1}\left(\frac{H_{LaserRL} - H_{LaserRR}}{d_{Laser}}\right) \tag{2}$$

Where $H_{LaserRL}$ and $H_{LaserRR}$ are, respectively, the heights from the ground measured by the rear left and rear right laser sensors and d_{Laser} is the distance between the instruments, calculated in y direction.

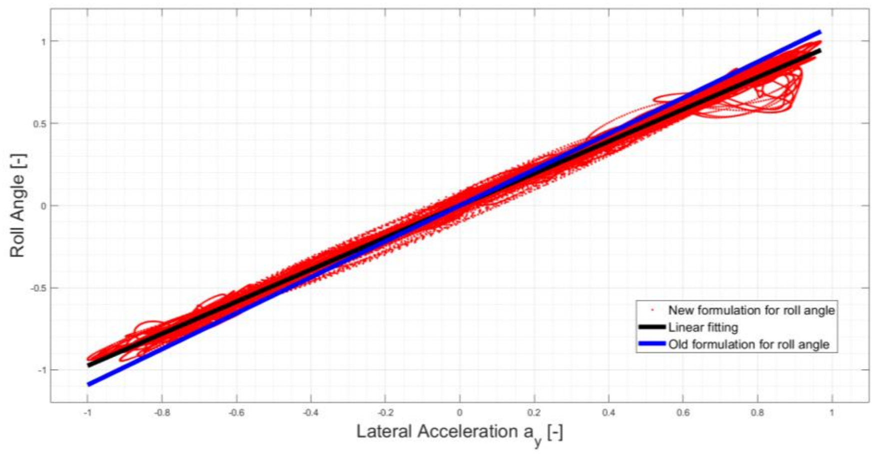

Figure 2: Comparison between old and new formulation for roll angle

To compare the roll angles found with the Equations (1) and (2), it is necessary to make a linear fitting of the signal got in the second case to obtain an approximate constant roll rate.

In the Figure 2 it is possible to see how the linear fitting has a greater slope than the original formulation, to understand the reasons for this difference a further comparison has been made with the data provided by the driving simulator, in which the same parameterization of the reference vehicle has been entered. Please note that for industrial confidentiality agreements, plots will be provided as normalized with respect to the maximum reported value.

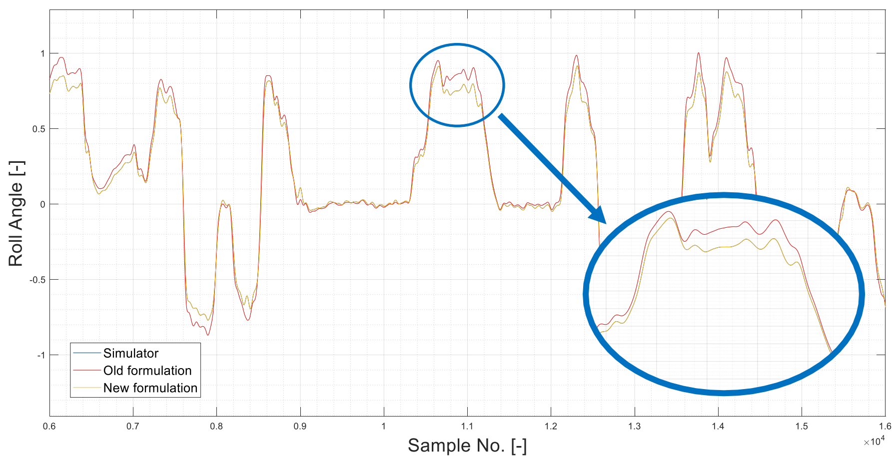

Figure 3: Roll angle comparison among simulator, old and new formulation

The comparison in Figure 3 shows that the new formulation is almost identical to that implemented in the simulator, which presents a vehicle model that is much more complex and detailed than the one present in the T.R.I.C.K. tool. In fact, in order to appreciate a difference between the two curves, blue for the simulator and yellow for the new formulation, it was necessary to realize an enlargement shown in the blue box in Figure 3. It is clear how the use of a fixed roll rate allows the roll angle to be calculated with an appropriate approximation, but the use of laser sensors, that consent instantaneous detection of the vehicle's conditions, provide a more accurate measurement comparable to that of a simulator.

4 AERODYNAMIC FORCES FORMULATION

4.1 Aerodynamic Maps

Racing cars generally have specially designed aerodynamic appendices, such as front and rear wings, undertray and sidepods, to convey the air flows around the vehicle in an appropriate manner [8]. To understand how these devices work, wind tunnel tests are conducted to study the variation of aerodynamic coefficients in different vehicle operating conditions.

Wind tunnel analysis provide so-called aerodynamic maps in which the values of the coefficients C_x, C_{zF} and C_{zR} are shown as a function of some vehicle parameters, including inclination angle of the wing flaps and height of the front and rear axle from the ground. With reference to the last three quantities, to define the maps it is necessary to fix two of these values and vary the third within the range of possible conditions. The output data obtained from the wind tunnel must be appropriately corrected because the tests conditions are not necessarily identical to those found during the vehicle driving [9].

Usually, the variation of the aerodynamic coefficients is not linear and to implement the aerodynamic maps correctly in the tool it would be necessary to reproduce them faithfully using a lookup table, but this would be too onerous from a computational point of view and would make the tool less versatile. However, to take into account the results obtained from the wind tunnel tests, it has been decided to linearly approximate the dependence of the aerodynamic coefficients on the reference parameters.

In this way the information got from the aerodynamic maps can be used to determine the linear variation coefficients with which to correct the static values of C_x, C_{zF} and C_{zR}. To be able to update these values instantly it is necessary to know the height of the vehicle from the ground while driving and to do this it is possible to use laser sensors.

4.2 Aerodynamic forces calculation

From the aerodynamic maps, a static reference condition is chosen, for this vehicle state are assigned:

- Wing inclination angle α_{Wing0};
- Front axle height from the ground $H_{Axle-F0}$;
- Rear axle height from the ground $H_{Axle-R0}$.
- Drag aerodynamic coefficient C_{x0};
- Front axle downforce aerodynamic coefficient C_{zF0};
- Rear axle downforce aerodynamic coefficient C_{zR0}.

The first three values identify the hypothetical driving conditions of the car, the last three return the aerodynamic behavior of the vehicle in that specific state.

It has been assumed that the inclination of the wing α_{Wing} is not variable during the motion of the car but could be different from that used as a reference; for this reason, the $\Delta\alpha_{Wing}$ is fixed and depends exclusively on the aerodynamic package mounted.

Laser sensors, instead, can be used to determine the height variations of the axles. These instruments are not mounted in correspondence with the axles, so the first step to be carried out is to correctly calculate the heights of the axles starting from the acquired signals. The variations of the reference parameters with respect to the static condition can be written as:

$$\begin{aligned} \Delta\alpha_{Wing} &= \alpha_{Wing} - \alpha_{Wing0} \\ \Delta H_{Axle-F} &= H_{Axle-F} - H_{Axle-F0} \\ \Delta H_{Axle-R} &= H_{Axle-R} - H_{Axle-R0} \end{aligned} \tag{3}$$

For each aerodynamic coefficient, starting from the aerodynamic maps, three linear sensitivity coefficients have been defined, referring to the three parameters just studied, for a total of nine coefficients. Referring to C_x, they are:

- $SC_{x-\alpha_{Wing}}$ for a unitary variation of the wing inclination angle, expressed in degree;
- SC_{x-H_F} for a unitary variation of the front axle height, expressed in mm;
- SC_{x-H_R} for a unitary variation of the rear axle height, expressed in mm.

The same applies to C_{zF} and C_{zR}.

Aerodynamic coefficients are therefore calculated as:

$$\begin{aligned} C_x &= C_{x0} + SC_{x-\alpha_{Wing}}\Delta\alpha_{Wing} + SC_{x-H_F}\Delta H_{Axle-F} + SC_{x-H_R}\Delta H_{Axle-R} \\ C_{zF} &= C_{zF0} + SC_{zF-\alpha_{Wing}}\Delta\alpha_{Wing} + SC_{zF-H_F}\Delta H_{Axle-F} + SC_{zF-H_R}\Delta H_{Axle-R} \\ C_{zR} &= C_{zR0} + SC_{zR-\alpha_{Wing}}\Delta\alpha_{Wing} + SC_{zR-H_F}\Delta H_{Axle-F} + SC_{zR-H_R}\Delta H_{Axle-R} \end{aligned} \tag{4}$$

As is known, aerodynamic forces can be determined using the following formulas [1]:

$$Aerodrag = \frac{1}{2}\rho A_v U^2 C_x$$
$$Aerodown_F = \frac{1}{2}\rho A_v U^2 C_{zF} \quad (5)$$
$$Aerodown_R = \frac{1}{2}\rho A_v U^2 C_{zR}$$

Where ρ is the air density, A_v is the master section of the vehicle and U is the vehicle longitudinal velocity calculated in the center of gravity. It is possible to notice that the downforce and the drag force have:

- a quadratic dependence on vehicle center of gravity longitudinal velocity U;
- a non-linear dependency on the corresponding aerodynamic coefficient.

The use of aerodynamic maps has introduced a variability in drag and downforce coefficients, which depend linearly on three independent vehicle parameters; for this reason, these coefficients are not linear.

In the Figures 4, 5 and 6 there are the graphs of the aerodynamic forces calculated with and without the use of aerodynamic maps and laser sensors compared with the data obtained from the simulator.

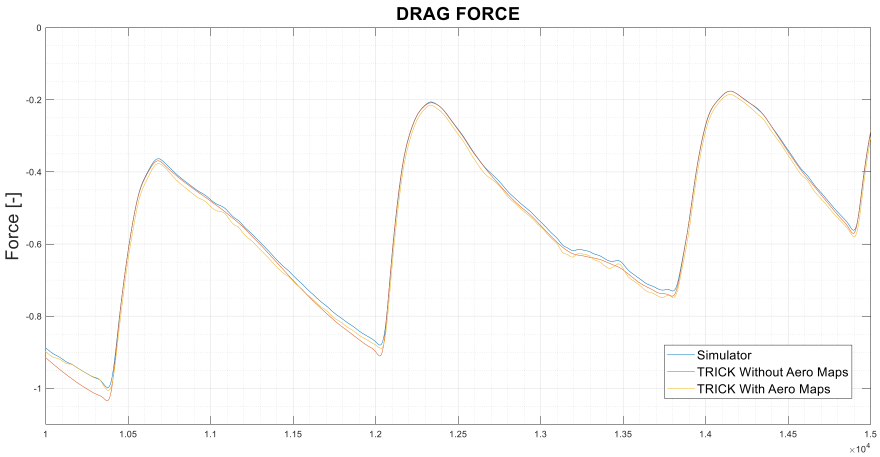

Figure 4: Drag force – Comparison among simulator, T.R.I.C.K. with and without aerodynamic maps

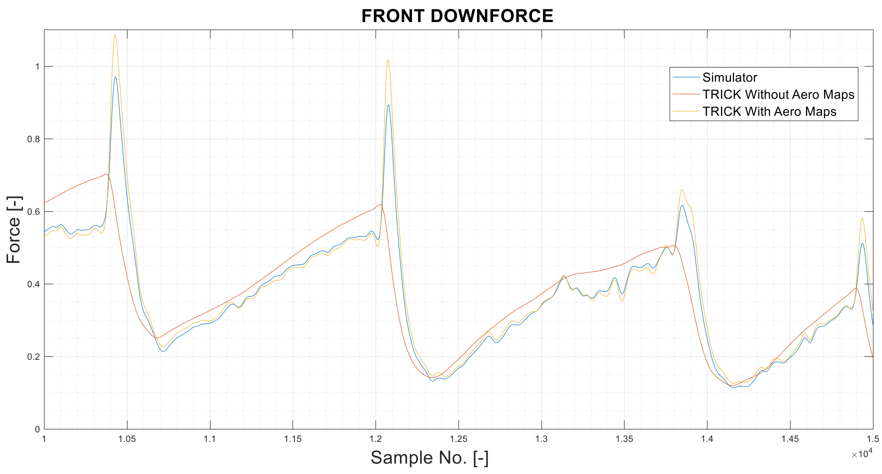

Figure 5: Front downforce – Comparison among simulator, T.R.I.C.K. with and without aerodynamic maps

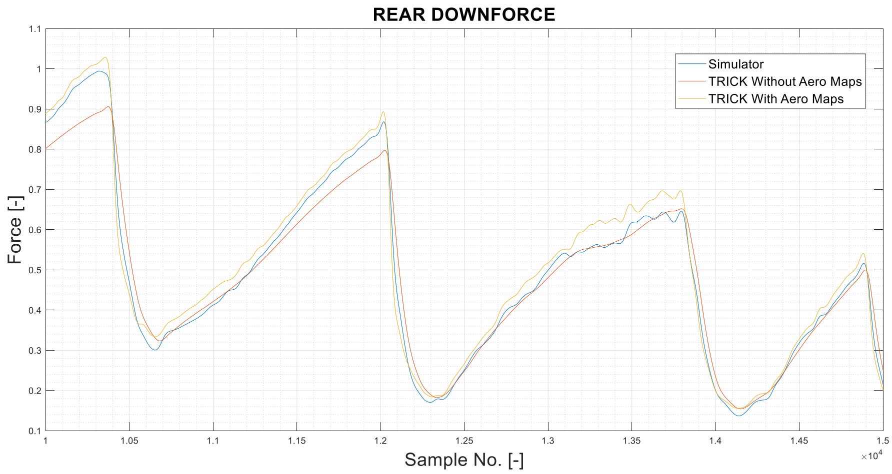

Figure 6: Rear downforce – Comparison among simulator, T.R.I.C.K. with and without aerodynamic maps

From Figure 4 can be observed that for the drag force, the formulation developed with aerodynamic maps and laser sensors follows the simulator slightly better.

The improvements of the new formulas are much more evident in the calculation of the front downforce, during the acceleration maneuvers with the previous formulation it was not considered all the force fluctuations due to the height change from the ground as a consequence of the longitudinal load transfers. With the formula present in the original version of the tool, the front downforce peak that occurred at the beginning of the braking phase was not highlighted, so in this case the new formulation is much more precise. For the rear downforce the behavior is similar, the trend of the simulator's forces is reproduced with greater fidelity.

The slight deviations in all three cases can be reduced by carrying out an appropriate correction of the output data obtained from the wind tunnel tests, despite this, the formulation developed in this section results to be a concrete overcoming of the old equations present in the first release of the T.R.I.C.K. tool.

5 CONCLUSION

In this paper an advanced version of the T.R.I.C.K. tool was described. The original version of this tool was developed with the aim to process the data acquired during experimental test sessions to estimate the tire interaction forces as a function of the slip indices and providing the curve of interaction without the requirement of expensive and complex bench characterizations.

The idea of an evolved version comes from the desire to obtain the most precise virtual telemetry as simulations output, exploiting all the vehicle information and available acquisitions. This is possible because a racing car is generally fitted with an advanced sensor system that is much more complex than that required to use the T.R.I.C.K. By appropriately using the additional data provided by the vehicle instrumentation it was possible to calculate the interaction forces more precisely and without any additional cost.

In this perspective, new alternative formulations have been developed that would allow a more accurate estimation of the roll angle and aerodynamic forces using aerodynamic maps and additional instruments like laser sensors. Thanks to the comparison with the data provided by the simulator, the new proposed formulas have been validated, confirming that the use of supplementary sensors allows to overcome the simplifying hypotheses generally adopted in vehicle dynamics models.

Future studies will involve the possibility to use other additional sensors and information, such as load cells mounted on shock absorber and on the driveshafts, pressure sensors for the braking system. In a similar way to what has been presented in this work, starting from this information new formulations will be developed to calculate interaction forces with greater accuracy, thus creating an advanced T.R.I.C.K. 2.0.

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