POTENTIALITIES OF DRIVING SIMULATOR FOR ENGINEERING APPLICATIONS TO FORMULA 1

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ABSTRACT

In this paper the authors present the first results of a study for analyzing the engineering problems in the design and improvement of a Formula 1 or competition circuit and for the optimization of the pilots' race performances. The authors have used a driving simulator. The physical and mechanical characteristics of the simulated vehicle have been improved in order to reproduce as possible a competition vehicle. For the tests we have simulated the urban circuit of Rome that has been recently proposed. The circuit is 6056 m long, the maximum longitudinal slope is 3.5% and the curve radii are between 8 and 400 m. The geometrical standards of the circuit are basically coherent with the Fédération Internationale de l'Automobile (FIA) regulations. Two professional pilots have been requested to drive for the tests. During the tests we have observed an average speed of the best lap compatible with the speeds observed in analogous urban circuits. After the tests the time histories of longitudinal speed, longitudinal and transversal acceleration have been post processed. Moreover the vehicle trajectory and lateral displacement have been analyzed on the average and in the case of the best lap. Finally the rate between used and available friction has been studied following a two dimensional approach. In particular three curves have been isolated as most critical being the rate between used and available friction over 0.80. These mentioned rates have been visualized on the maps so that the spatial distribution of used friction is in evidence.

Keywords: driving simulation, formula 1, friction, trajectory analysis, longitudinal speed.

INTRODUCTION

In this last decade the driving simulator has become an important tool for assisting geometrical road design as well as for studying the driver performances under different traffic and environmental conditions (e.g. Kaptein et al. 1996; Yan e al. 2008; Trentacoste, 2008; Bella, 2009). The computer based technologies and the visualization systems (e.g. Hughes,

2005) have progressed so much that it is reasonable to investigate new frontiers in the application of driving simulators.
Here the authors present the first results of a driving simulation based study oriented to analyze the engineering problems in the design and improvement of a Formula 1 or competition circuit and in the optimization of the pilots' race performances. The optimization of the circuit mostly depends on:

- physical – structural features: e.g. the impact speed in the case of run off accident,
- geometrical – perceptive features: e.g. the influence of geometrical standard, as radii or lane dimension, on driving performances.

FIA has developed a specific software to improve the safety of the circuits related to the first point: Circuit Analysis and Safety System (CSAS). CSAS is used to evaluate the effectiveness of the run-off areas and protective measures, it means the passive safety of existing GP circuits. The software integrates the circuit digital maps and some dynamical data acquired by vehicular sensors. Finally CSAS predicts the severity of impacts in any circuit's point, basing on the speed, deceleration data and passive measures characteristics. Actually the geometrical – perceptive features are not in depth investigated. This paper gives a contribution to identify novel proposals for optimizing the circuit and the pilots' performance.

The authors have used a STI driving simulator (Benedetto et al., 2002). The physical and mechanical characteristics of the simulated vehicle have been improved in order to reproduce as possible a competition vehicle. For the tests we have simulated the urban circuit of Rome that has been recently proposed.

Two professional pilots have been requested to drive for the tests. Before the test a training protocol has been implemented so that the pilots familiarize with the simulation environment. Each pilot has driven for 15 laps during the test. During the tests we have observed an average speed (Klee et al., 1999; Godley et al., 2002; Bella, 2008) of the best lap (134.86 km/h) compatible with the speeds observed in analogous urban circuits (136.63 km/h Montecarlo 3340 m, 146.10 km/h Singapore 5073 m, 158.60 km/h Valencia 5419 m). After the tests the time histories of longitudinal speed, longitudinal and transversal acceleration have been post processed. Moreover the vehicle trajectory and lateral displacement have been analyzed on the average and in the case of the best lap. Finally the used and available friction rate has been studied following a two dimensional approach in the case of the most critical curves. In particular three curves have been isolated as most critical being the rate between used and available friction over 0.80. These mentioned rates have been visualized on the curves maps so that the spatial distribution of used friction is in evidence.

OBJECTIVE

The overall objective of the paper is to investigate the applicability and the potentialities of the driving simulation for Formula 1 circuits optimization, both in terms of geometry and in terms of pavement friction. Moreover the paper presents the first results in order to demonstrate the possible applications of driving simulator for improving the pilot performances and for reducing the time laps.

FIA REQUIREMENTS

The FIA has published some requirements for assisting in the basic conception of circuit projects for submission in view of future licensing. Here we have extracted and summarized some of these main requirements, for completeness. In plan the shape of the course is not restricted, but the FIA may recommend changes in the interests of good competition and from practical necessity. The maximum permitted length for straight sections of track is 2km. The maximum length (centerline) of any new circuit should not exceed 7 km. In general, unless otherwise stated, all references to straights and curves concern the actual trajectory followed by the cars with the highest performance and not the geometrical form of the layout. The track width should be at least 12 m. Where the track width changes, the transition should be made as gradually as possible, at a rate not greater than 1 m in 20 m total width. The width of the starting grid should be at least 15 m.

Any change in gradient should be effected using a minimum vertical radius calculated by the formula:

$$R = V^2 \cdot K \tag{1}$$

where
- R is the radius in meters,
- V is the speed in kph and
- K is a constant equal to 20 in the case of a concave profile or to 15 in the case of a convex profile.

The value of R should be adequately increased along approach, release, braking and curved sections. Wherever possible, changes in gradient should be avoided altogether in these sections. The gradient of the start/finish straight should not exceed 2%.

Along straights, the transversal incline, for drainage purposes, between the two edges of the track or between the centerline and the edge (camber), should not exceed 3%, or be less than 1.5 %. In curves, the banking (downwards from the outside to the inside of the track) should not exceed 10% (with possible exceptions in special cases, such as speedways).

A permanent track should be bordered along its entire length on both sides by continuous white lines clearly marked in anti-skid paint, minimum 10 cm wide, and compact verges, usually between 1 m and 5 m wide, having an even surface. A run-off area is an area of ground between the verge and the first line of protection. A run-off area should be graded to the verge. If the area has a slope, this should not exceed 25% upwards (does not apply to gravel beds) or 3% downwards, with a smooth transition from track to run-off area, in relation to the lateral projection of the track surface.

For standing starts, there should be at least 6 m length of grid per car (8 m for the Formula One World Championship). There should preferably be at least 250 m between the starting line and the first corner. By corner, in these cases only, is understood a change of direction of at least 45°, with a radius of less than 300 m.

When determining measures intended for the protection of spectators, drivers, race officials and service personnel during competitions, FIA recommends that the characteristics of the course should be taken into consideration (track layout and profile, topography, racing trajectories, adjacent areas, buildings and constructions) as well as the speed attained at any point of the track. Although when circumstances permit it may be appropriate to provide sufficient obstacle- and spectator-free spaces for the energy of a car leaving the track out of control to be completely expended.

As a general principle, where the estimated impact angle is low a continuous, smooth, vertical barrier is preferable, and where it is high energy dissipating devices and/or stopping barriers should be used, combined with a run-off area and deceleration system if there is sufficient suitable ground available. It is therefore indispensable to provide for sufficient space at such points in the planning stage. Such areas will be principally situated on the exterior of the corners and may typically have depths from 30 m to 100 m, according to the approach and cornering speeds expected on the track.

The length of a circuit for the calculation of race distances, race records and classifications is considered to be that of the centerline of the track. The centerline of the track is the median line between the left and right edges of the asphalt of the track as delimited by the required white lines. Particular attention should be paid to this in the case of circuits on city streets.

SIMULATION ISSUES

Vehicle

The vehicle dynamics are based on VDANL/RT that is capable of real time execution at high update rates (200 Hz or greater) which allows for numerical stability under extreme maneuvering and road surface input conditions and provides sufficient bandwidth for realistic steering torque feel. VDANL/RT includes lateral/directional and longitudinal dynamics, tire forces and aligning torque, wheel spin mode dynamics, and models for the power train and steering and braking systems. The following figures 1 to 5 have been adapted from Allen et al. (1998).

In Figure 1 the system for central torque and central angular rate generation is shown. The engine model provides torque as a function of throttle angle, RPM and load. Engine closed throttle drag torque can also approximate the operation of a Jake brake. Any number of transmission gears can be simulated based on the positions of gear shift and gear range controls. The power/drive train is shown in the figure 2. This is the system for torques and angular rates generation at any single wheel.

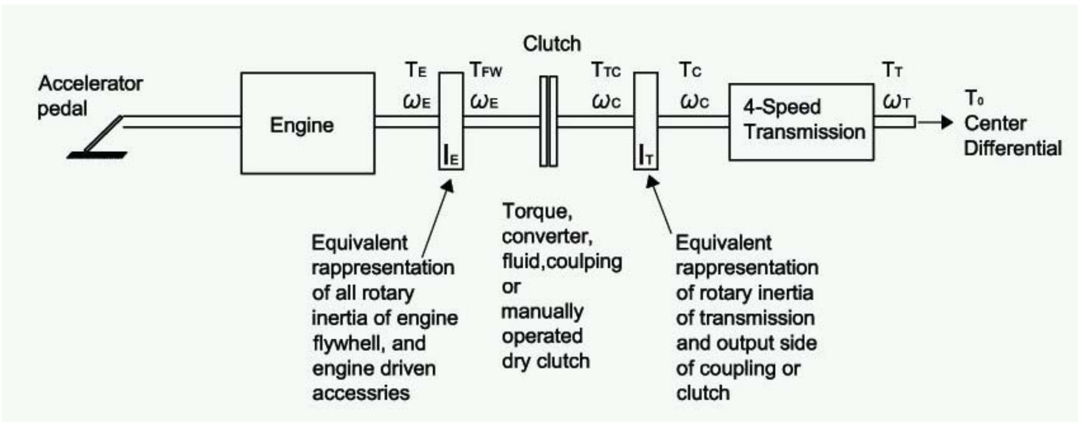


Figure 1 Simulation system for central torque and central angular rate generation

The steering system is modeled as a second order dynamic process with inputs provided by driver steering commands, power steering boost, and tire aligning moments. The steering system model provides wheel steer angle to the steering axle tire model, and steering wheel torque commands for steering torque cueing. Moreover the brake system provides torques at all braking axles based on brake pressure.

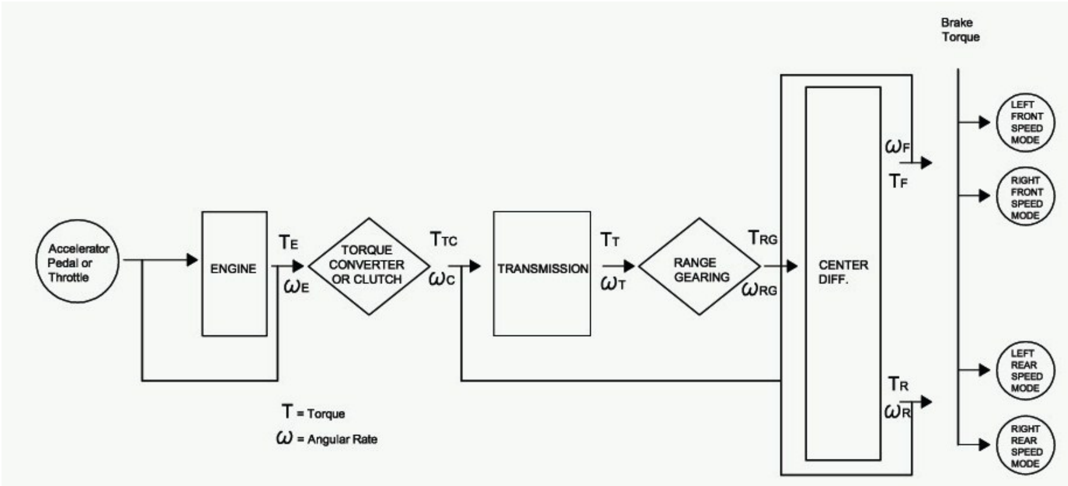


Figure 2 Simulation system for torques and angular rates generation at the wheel

The brake system model provides for pneumatic delays and generic antilock characteristics based on limiting wheel slip angle to some maximum value. The brake system model also simulates brake lining fade or reduction in coefficient of friction as a function of temperature. Brake temperature is based on a thermodynamic model that accounts for power absorbed minus heat conducted and convected away from the lining. In Figure 3 the system for computation of the dynamical parameters at the single wheels is shown. Figure 4 shows qualitatively as the net engine torque T_E varies as the angular rate at the engine ω_E.

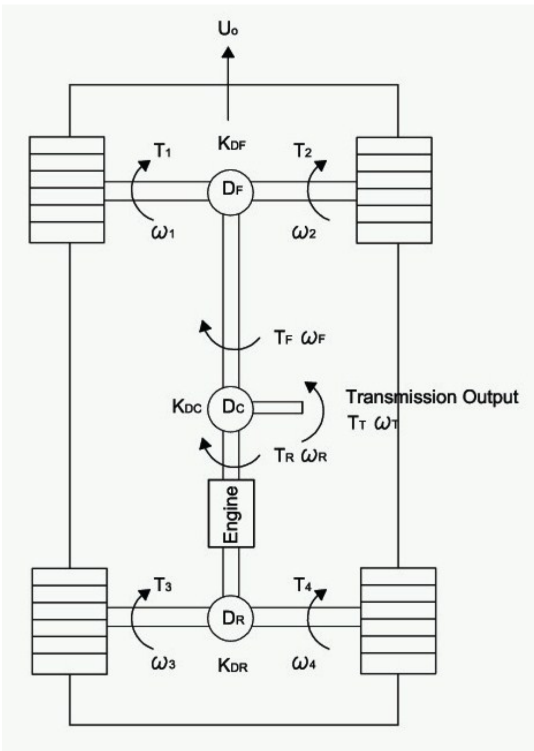


Figure 3 Simulation system for computation of the dynamical parameters at the single wheels

The net engine output torque can be specified using a second order equation and the engine characteristics can be defined by the coefficients of this second order equation:

$$Torque = Ep0 + Ep1 \cdot \omega + Ep2 \cdot \omega^2 \quad (2)$$

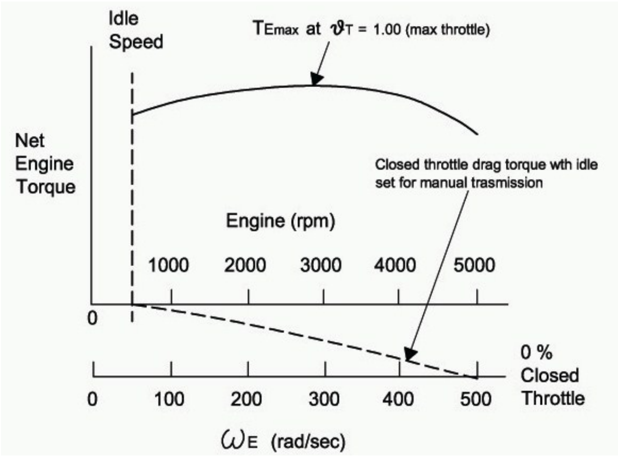


Figure 4 Net engine torque versus the engine angular rate

In the power-train parameters settings dialog box *Ep*0 is the "Engine idle gain", *Ep*1 is the "Linear engine torque gain" and *Ep*2 is the "Second order torque gain". In the torque map shown above, the engine idle gain sets the value of torque at 0 throttle and corresponds to the torque at the far left where the torque curve and Idle Speed line intersect. The linear engine torque gain sets the slope of the torque curve from the idle speed line to the right. The rounding of the torque curve and eventual drop off is handled by the second order torque gain. As the engine RPM gets higher, the available torque drops off faster.

The gear ratio KGRi is set according to the high performing vehicle requirements. The time shift Δt is the time needed for the gear ratio exchange (Figure 5). For simulating a high performing vehicle we have calibrated the parameters (DRT.KE1, DRT.KE2, DRT.KE3), that modulate the torque generated from the engine and transmitted in function of the angular speed rate. The time shift Δt has been reduced to 0.1 seconds, while the maximum value of the angular speed rate (DRT.OMEGAEMAX) has been increased to 2615 rad/sec.

According to FIA requirements for the vehicle configuration the following standards have been assumed:

- Minimum weight (full loaded) 620 kg
- Maximum transversal dimension 1.8 m
- Maximum vehicle high 0.95 m

Other main geometrical characteristics of the vehicle are shown in Figure 6.

The simulated vehicle maximum speed is about 250 km/h. The possible longitudinal acceleration of the simulated vehicle is 4.5 times lower rather than the possible acceleration of a real F1 vehicle.

Circuit geometry

The circuit can be reproduced in simulation starting from the real geometry. Road section, lanes dimensions, off run zones, signs can be easily implemented as well as the horizontal and vertical alignment through length of tangents, lengths and radii of curves, slopes and vertical radii. In addition the external environment, landscape and skyline are simulated capturing pictures or videos from the reality and generating 3D objects using advanced graphical software.

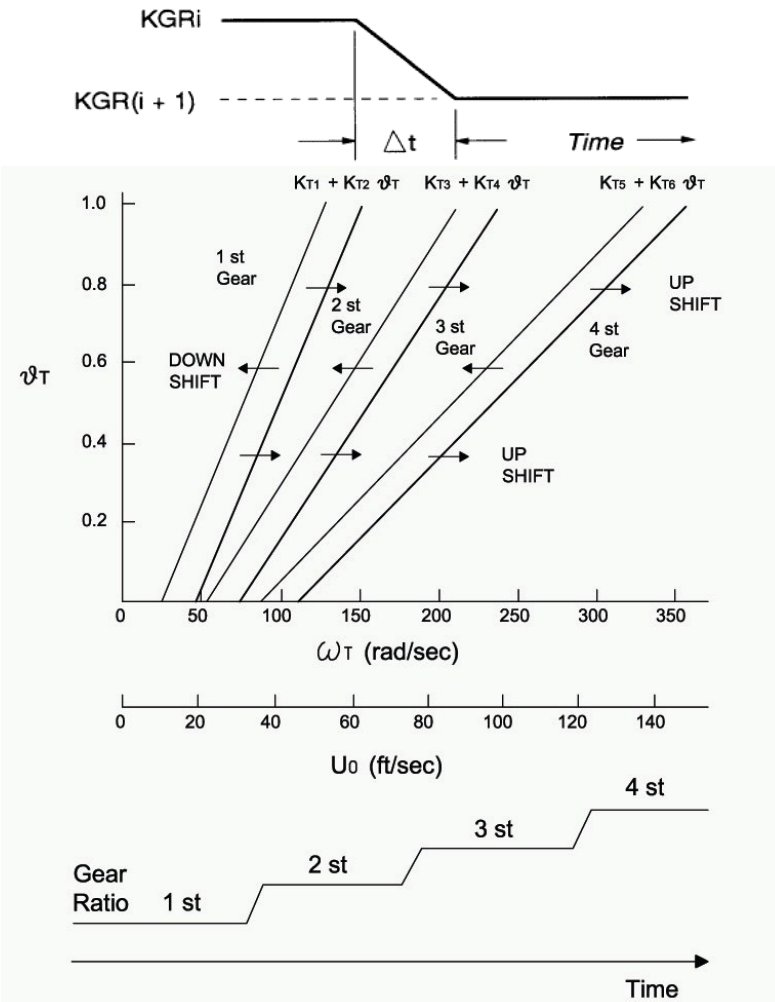


Figure 5 Time shift for four gear ratios and throttle aperture rate vs angular rate

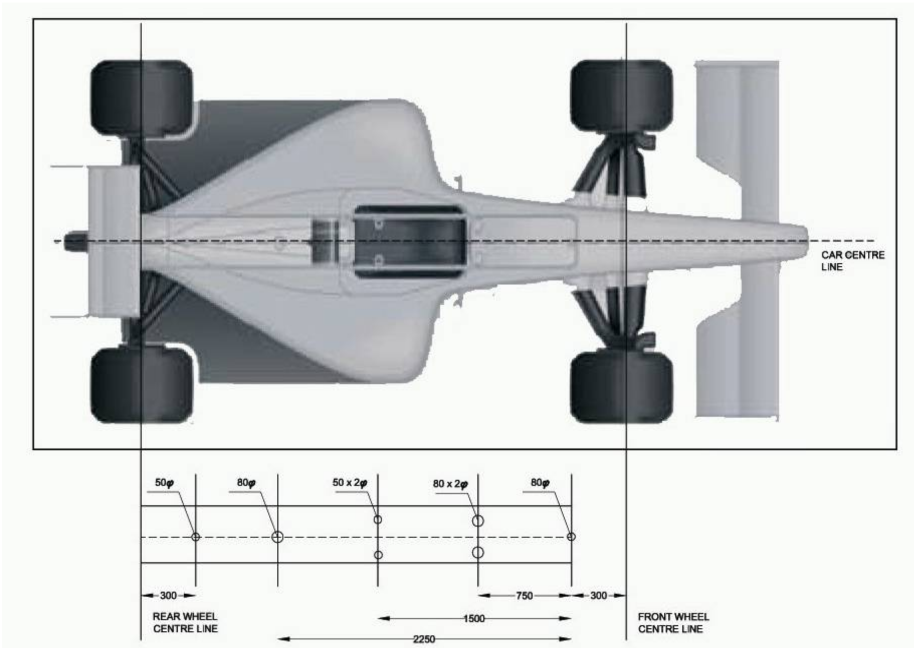


Figure 6 Geometrical characteristics of the vehicle
(adapted from: Formula One World Championship regulations www.fia.com)

Tire-pavement contact

The tire model generates lateral and longitudinal tire forces and aligning moments as functions of normal load, slip and camber angle and includes appropriate interactions between these input variables including force saturation.

The model equations are based on a composite slip formulation, which is basically a quadratic function of lateral and longitudinal slip. Lateral slip is expressed as the ratio of the side slip velocity of the tire patch relative to the longitudinal speed of the tire patch, which is the equivalent of the tangent of the tire patch slip angle. Longitudinal slip is defined as the ratio of the differential tire patch to ground longitudinal velocity divided by the longitudinal velocity of the wheel hub relative to the ground (Allen et al., 1997).

To reproduce at the possible best the characteristics of a highly performing vehicle, the longitudinal and transversal friction coefficients have been calibrated as well as some specific tire characteristics as stiffness coefficients and lateral and longitudinal slip.

CASE STUDY

The Circuit of Roma

In the 2010 the Major of Rome (Italy) has proposed the project for a new Formula 1 GP to be hosted in Rome (Figure 7). The urban circuit is located in the South part of the City (EUR district). The circuit is 6056 m long, the minimum radius of the horizontal curve is 8 m, there are no transition curves, the maximum length of the tangent is 969 m (Figure 8), the maximum longitudinal slope is 3.5% and it is 470 m long (Figure 9). Vertical and horizontal alignments are respectively shown in Figures 8 and 9. The 3D scenario has been generated using advanced graphical software. Three very realistic snapshots are shown in Figure 10.

Figure 7 The test F1 circuit of Rome

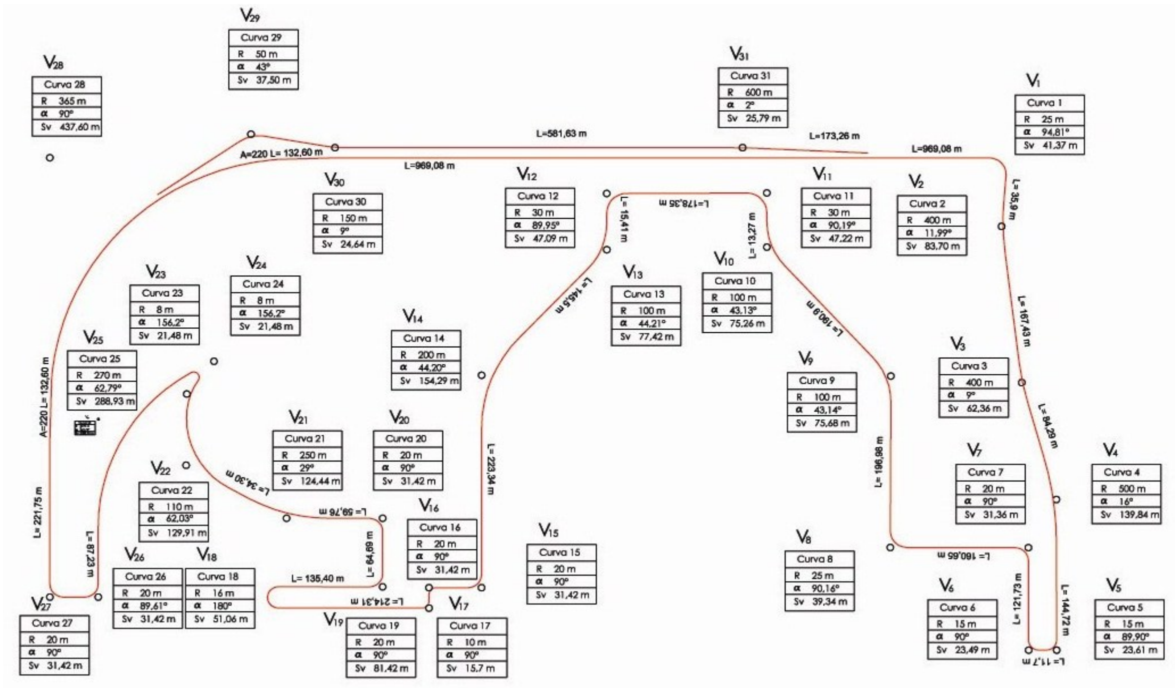


Figure 8 The geometrical characteristics of the test F1 circuit of Rome

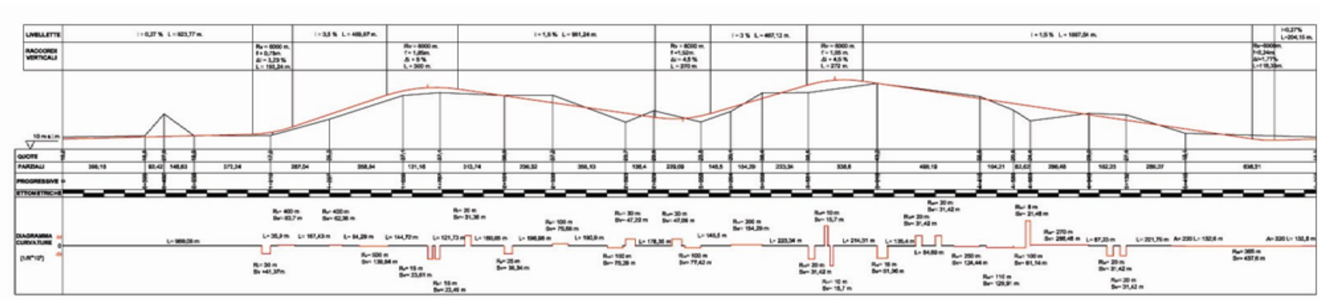


Figure 9 The vertical alignment of the test F1 circuit of Rome

Subjects

The participants have been selected in order to have the very reliable outcomes. With this major aim two subjects who have a significant experience as pilots have been invited to the experiments. One of them has a more relevant experience with the national and international races. After data processing it was evident that this pilot has demonstrated a much more stable performance and behavior during the test, the other experienced much more variable speeds and unstable maneuvers. For the study, considering that this is a preliminary investigation of the simulator capabilities and at this stage no statistical validity is requested, we have assumed the experimental outcomes only from the best pilot.

Tests

In the first phase of the test, the pilot is requested to drive some different scenarios in order to become familiar with the equipment. In the last step of the training the pilot drives on the Formula 1 EUR circuit. The training takes about twenty minutes in total.

Figure 10 Snapshots from the simulation scenario

In the simulation that is taken into account for the analysis the pilot is requested to do three separated identical tests. Between two consecutive tests the pilot rests for at least thirty minutes.
In the single test the pilot is requested to drive six laps. Finally 18 laps have driven. The first laps of each test is discharged because the long acceleration phase influences greatly the outcomes. It means that we have 15 laps available for data post processing. Each parameter (speed, accelerations, position,…) is sampled with a step of about five meters.

RESULTS AND DISCUSSION

At the first stage the average speeds for lap have been calculated. In Figure 11 the average speeds for the 15 laps are shown, compared to the maximum and minimum speeds. The average speed of the lap number 7th is the highest 37.461 m/s, the time lap is 161 seconds. The minimum instantaneous speed, 33.270 m/s, is in the 11th lap, the maximum peak speed is 67.656 m/s in the 15th lap.

By investigating the instantaneous speeds along the 7th lap, it is possible to identify the sectors of the circuit where the speed is largely over the average speed over the other laps. In particular these sectors are 4: the 1st at the end of the long tangent leading to the first curve, the 2nd between the curve number 9 and the tangent 10, the 3rd is the tangent 14 to the tangent 15, including the curve 14, and the 4th from the curve 25 to the tangent 23.

Comparing the speed profile observed in the 7th lap to the average speed profile, as in Figure 12, it appears that in the 7th lap the driver has a speed up to 40-45% higher rather than the average.

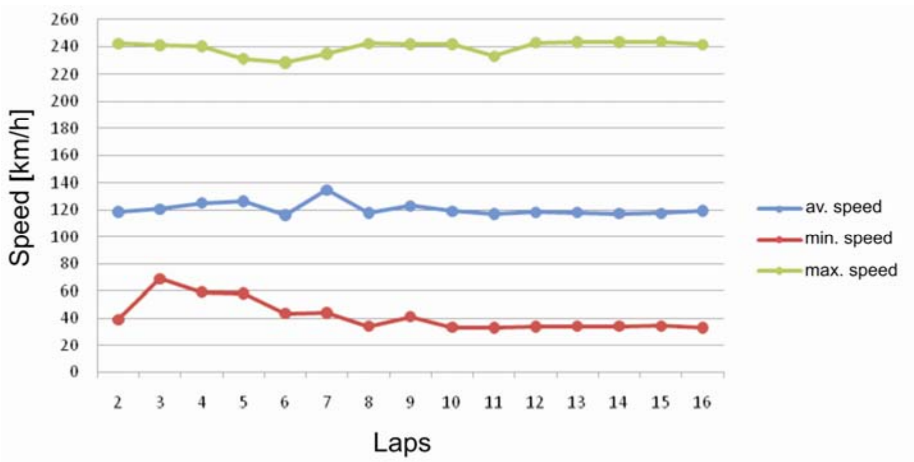


Figure 11 Average speed for the 15 laps

For an in depth investigation the trajectories of the vehicle along the lap have been analyzed. The trajectories of the vehicle in the four sectors for each lap are shown in Figure 13. From the trajectories geometry it is possible to extract the local curvature of the single trajectory.

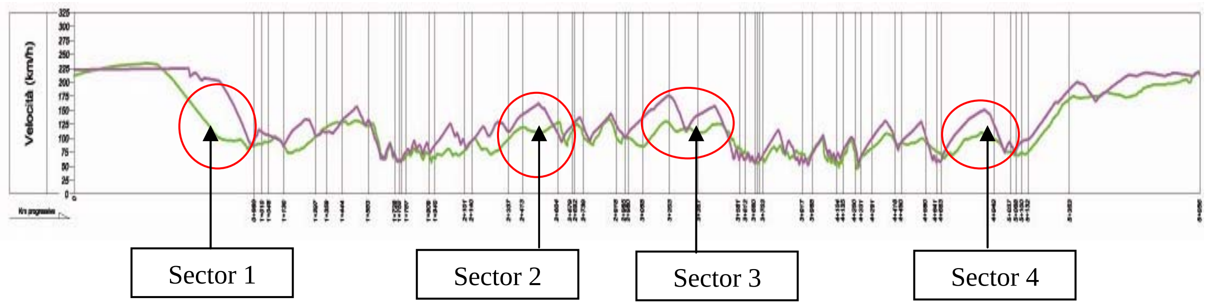


Figure 12 Comparison between the speed profile observed in the 7th lap and the mean profile

The local curvature observed in the 7th lap is compared to the mean local curvature of the trajectories extended to all the 15 laps for each sector (Figure 14).

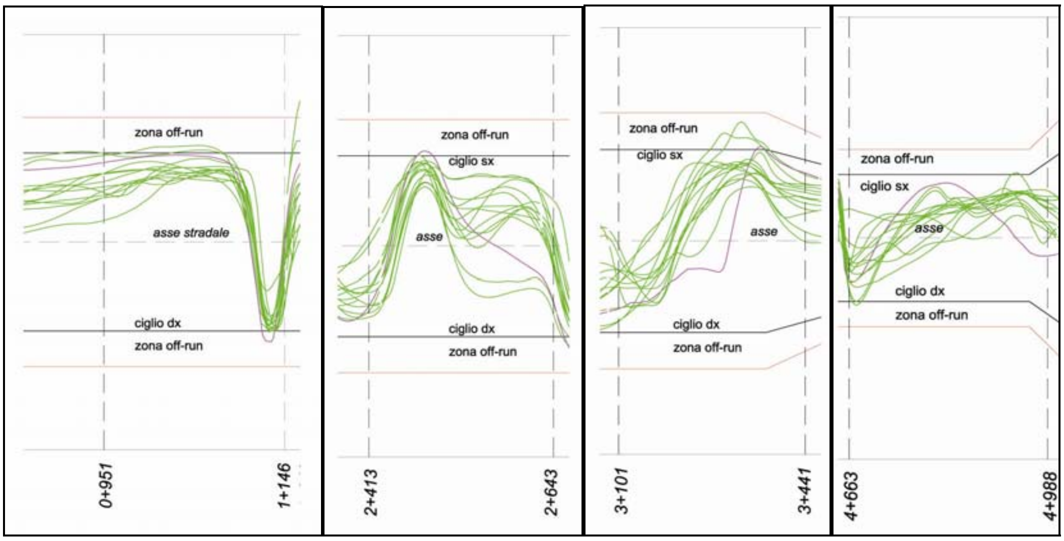


Figure 13 Trajectories of the vehicle in the four sectors for the 14 laps (green) compared to the trajectory observed in the 7th lap (red)

Figure 14 shows that the trajectory curvature of the 7th lap is always lower than the mean trajectory. It means that the vehicle has driven in these sectors of the 7th lap a longer path rather than the average, however the elapsed time is largely lower in the 7th lap, being the local speed significantly higher. The trajectory of the vehicle in the 7th lap can be considered the best compromise between the need for the highest speed and the need for the shorter path.

From the simulations output it is possible to extract the values of used friction related to the available friction at the tire-pavement contact. This analysis can be extended all over the circuit and to all the four tires of the vehicle. Following this approach the most critical sections along the circuit have been isolated considering where the rate between used and available friction at the contact is over 90%. Three sections along the circuit resulted critical:

- curve 5 – radius 15 m, deviation angle 90°, length 23.61 m,
- curve 10 – radius 100 m, deviation angle 43°, length 75.26 m,
- curve 26 – radius 20 m, deviation angle 90°, length 31.42 m.

It is interesting to note that the curves with minimum radii do not result critical because the speed is very low and consequently the transversal acceleration is limited.

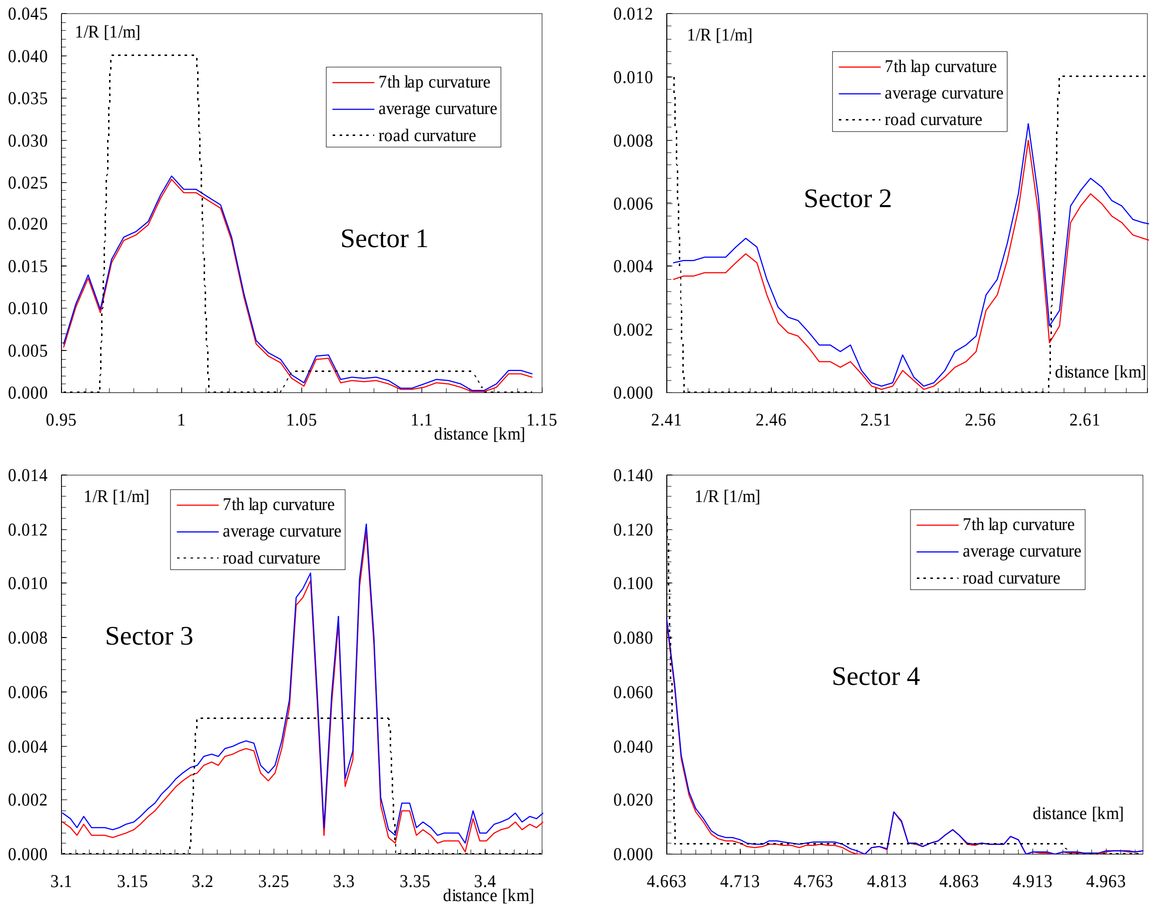
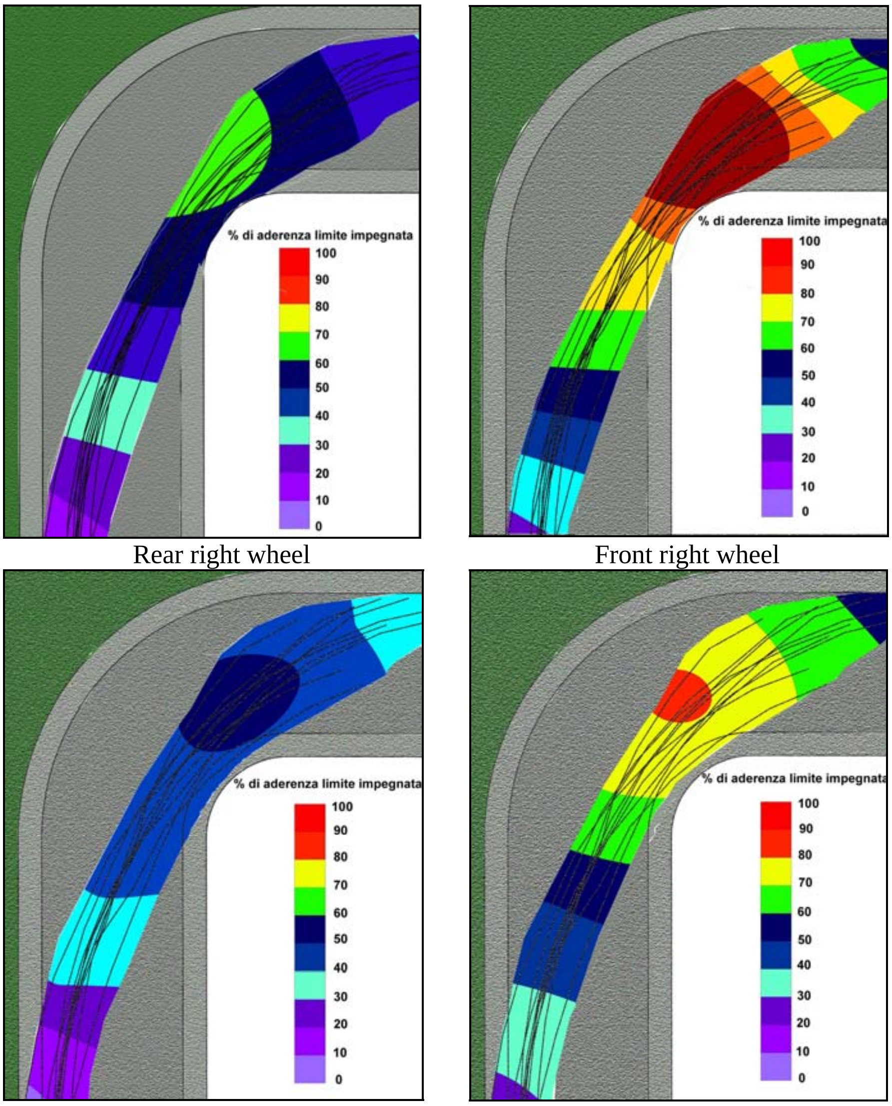


Figure 14 Local curvature observed in the 7th lap compared to the mean local curvature of the trajectories extended to all the 15 laps

Along the three critical curves it is identified the point where the used/available friction rate is maximum. It results that in the 50% of the cases the maximum rate is observed entering the curve, while braking, in the 32% of the cases in exiting from the curve and 18% in the center of the curve. Among the three, the most critical case resulted the curve 5.

Figure 15 shows the rate between the used and available friction all along the curve over a two dimensional map, for the four wheels. From Figure 15 it results as reasonably expected that the most critical wheel is the rear right wheel, because the weight results lower for combined effect of the centrifugal force and of the inertia for braking.



Rear right wheel | Front right wheel
Rear left wheel | Front left wheel

Figure 15 Two dimensional map of the used/available friction rate all along the curve for the four wheels

CONCLUSION

The outcomes of the study demonstrate that simulator is very promising for geometry optimization of the circuit according to the pilots trajectories and to the best performed laps as well as for the pilot training. Finally it has to be noted that the performances of the available simulators should be mostly increased to reproduce more adequately the characteristics of the F1 vehicles, especially regarding the acceleration, in order to carry out more realistic tests.

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