# The Influence of Roughness, Evenness and Road Geometry on Wheel-Road Interaction by Means of a Numerical Simulation Procedure

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## Synopsis

Starting from the analysis of the vehicle dynamics and from the description of both building and typological characteristics of pavements, this study faced some important features connected with road safety.

Indeed, referring to the former aspect, the research was focused on wheel-pavement interaction under different boundary conditions and, carefully varying certain parameters by means of an appropriate software, it simulated the vehicle behaviour in case of critical situations.

For this purpose a scientific model was arranged, the model itself being capable to simulate the real driving conditions, so as to single out a regressive law for the analysis of grip characteristics as function of both road texture and superficial degradations.

More specifically, the approaching qualitative analysis drove to the characterisation of the variation of several parameters as vehicle speed and acceleration, forces and momenta applied on the wheel, rolling and yaw velocity, etc, and the results were the basis for a further quantitative analysis.

The research developed through some simulations reproducing the real driving conditions on a track designed starting from parameters and characteristics which obeyed the Italian Standards, by assessing the vehicle performance variations and the trajectories changes of a virtual driver, as function of the superficial characteristics of the road pavement.

In short, referring to users safety, with this research the Author developed a scientific model that, after verifying the congruence of its output with the on-site investigations, gives a real and continuous measurement of all the parameters involved in the wheel-road interaction process, so that every situation with any sort of boundary conditions could be studied without troubles.

In addition, the analysis performs some braking simulation on straight roads, in order to find the experimental laws of the phenomenon as function of the boundary conditions (pavement roughness and tyre tread characteristics, unevenness of the contact surface), the outcomes being the starting point for a further investigation for the characterisation of the law regulating the grip phenomenon.

In practice, some of the most authoritative literature references were analysed (Lamm and Herring, Road Star and Stribeck Model), so as to properly interpret the results and validate the model created.

Eventually, the application of some theories coming from the re-elaboration of the above mentioned studies was proposed, the outcomes being very significant for further investigations on wheel-road interaction.

# The Influence of Roughness, Evenness and Road Geometry on Wheel-Road Interaction by Means of a Numerical Simulation Procedure

The very first part of this research considered the assembly of a scientific model which, starting from the vehicle dynamics analysis and considering the description of both constructive and typological characteristics of road pavements, would properly simulate the real driving conditions, so as to single out a regressive law for the analysis of the grip features as function of the superstructure texture and of the superficial unevenness and degradations, if any.

For this purpose, thanks to the help of an appropriate software, a virtual vehicle was assembled and several driving simulations were performed, the starting model for the overall process being, thus, obtained.

Subsequently the evenness and texture features of the contact surface were changed in order to express the variations induced on the model characteristics; in particular, the analysis highlighted changes on the following parameters:

- Vehicle speed (components);
- Vehicle acceleration;
- Forces and momenta applied on the wheel;
- Sliding;
- Distances and trajectories;
- Rolling radius;
- Breaking momenta, rolling and yaw velocity, etc.

The obtained outcomes, afterwards, were the starting point for the qualitative and quantitative (with further experiments) characterization of the laws ruling the grip phenomenon.

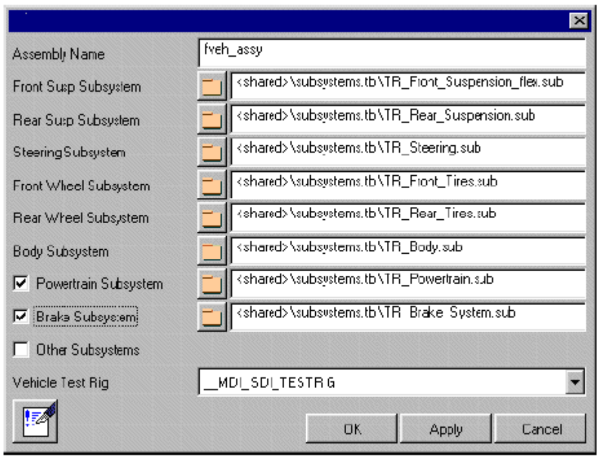
In order to reach this goal, further experiments were performed, the number of parameters being reduced after the exclusion of such quantities which would jeopardize the correct estimation of the results.

At the end of this analysis some studies from literature already put into practice in the past on the gripping power phenomenon (*Road Star* [5], *Lamm e Herring* [2],[4], SCRIM [9],[10] ,*Stribeck model* [7]) and from Standards [1] were considered for both a correct understanding of the outcomes obtained and for the simulated experience, so as to get to a validation of the arranged model and to interpret its limits, if any, compared to the positive results of the research.

## VEHICLE MODELLING

The vehicle modelling phase was improved by using the following subsystems: (Figure 1):

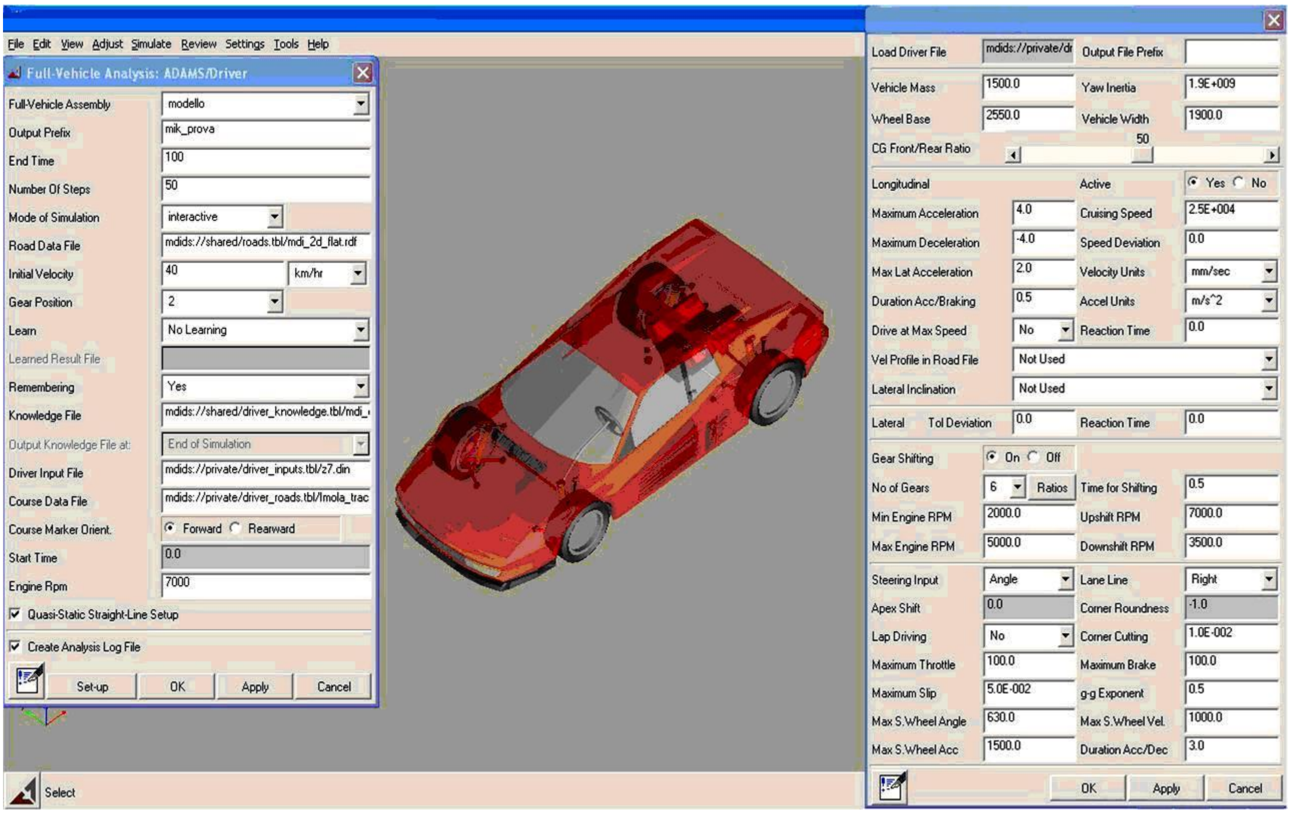
- Front and rear suspensions;
- Steering subsystem;
- Powertrain;
- Brake subsystem;
- Front/rear tires;
- Rigid chassis;



| | |
|---|---|
| Assembly Name | fveh_assy |
| Front Susp Subsystem | <shared>\subsystems.tb\TR_Front_Suspension_flex.sub |
| Rear Susp Subsystem | <shared>\subsystems.tb\TR_Rear_Suspension.sub |
| Steering Subsystem | <shared>\subsystems.tb\TR_Steering.sub |
| Front Wheel Subsystem | <shared>\subsystems.tb\TR_Front_Tires.sub |
| Rear Wheel Subsystem | <shared>\subsystems.tb\TR_Rear_Tires.sub |
| Body Subsystem | <shared>\subsystems.tb\TR_Body.sub |
| ☑ Powertrain Subsystem | <shared>\subsystems.tb\TR_Powertrain.sub |
| ☑ Brake Subsystem | <shared>\subsystems.tb\TR_Brake_System.sub |
| ☐ Other Subsystems | |
| Vehicle Test Rig | __MDI_SDI_TESTRIG |

Fig. 1: Subsystems assembly for the realization of the virtual vehicle

The following prototype was obtained after defining all the subsystems (Figure 2):



| | | |
|---|---|---|
| Full-Vehicle Assembly | modello | |
| Output Prefix | mik_prova | |
| End Time | 100 | |
| Number Of Steps | 50 | |
| Mode of Simulation | interactive | |
| Road Data File | mdids://shared/roads.tbl/mdi_2d_flat.rdf | |
| Initial Velocity | 40 | km/hr |
| Gear Position | 2 | |
| Learn | No Learning | |
| Learned Result File | | |
| Remembering | Yes | |
| Knowledge File | mdids://shared/driver_knowledge.tbl/mdi_ | |
| Output Knowledge File at: | End of Simulation | |
| Driver Input File | mdids://private/driver_inputs.tbl/z7.din | |
| Course Data File | mdids://private/driver_roads.tbl/Imola_trac | |
| Course Marker Orient. | ● Forward ○ Rearward | |
| Start Time | 0.0 | |
| Engine Rpm | 7000 | |

☑ Quasi-Static Straight-Line Setup

☑ Create Analysis Log File

| | | | |
|---|---|---|---|
| Load Driver File | mdids://private/dr | Output File Prefix | |
| Vehicle Mass | 1500.0 | Yaw Inertia | 1.9E+009 |
| Wheel Base | 2550.0 | Vehicle Width | 1900.0 |
| CG Front/Rear Ratio | 50 | | |
| Longitudinal | | Active | ● Yes ○ No |
| Maximum Acceleration | 4.0 | Cruising Speed | 2.5E+004 |
| Maximum Deceleration | -4.0 | Speed Deviation | 0.0 |
| Max Lat Acceleration | 2.0 | Velocity Units | mm/sec |
| Duration Acc/Braking | 0.5 | Accel Units | m/s^2 |
| Drive at Max Speed | No | Reaction Time | 0.0 |
| Vel Profile in Road File | Not Used | | |
| Lateral Inclination | Not Used | | |
| Lateral Tol Deviation | 0.0 | Reaction Time | 0.0 |
| Gear Shifting | ● On ○ Off | | |
| No of Gears | 6 Ratios | Time for Shifting | 0.5 |
| Min Engine RPM | 2000.0 | Upshift RPM | 7000.0 |
| Max Engine RPM | 5000.0 | Downshift RPM | 3500.0 |
| Steering Input | Angle | Lane Line | Right |
| Apex Shift | 0.0 | Corner Roundness | -1.0 |
| Lap Driving | No | Corner Cutting | 1.0E-002 |
| Maximum Throttle | 100.0 | Maximum Brake | 100.0 |
| Maximum Slip | 5.0E-002 | g-g Exponent | 0.5 |
| Max S.Wheel Angle | 630.0 | Max S.Wheel Vel. | 1000.0 |
| Max S.Wheel Acc | 1500.0 | Duration Acc/Dec | 3.0 |

**Fig. 2: Virtual vehicle used for the research simulations**

## Wheels characteristics

Once the vehicle was prepared, the attention was redirected on the tyre subsystem, which plays a fundamental role in the wheel-pavement interaction phenomena.

- ***Type of tyres used during the simulation process***

The model used during this work was ***MF-Tyre,*** which allowed the calculation of equilibrium equations of the wheel, where the ***Magic Formula*** **(MF)** is a set of mathematical expressions based on the physical behaviour of tyres, road and of the contact between both of them.
This formula aims at an accurate definition of the vehicle dynamics, deriving the $F_x$, $F_y$ forces, the momenta $M_x$, $M_y$, $M_z$ acting on the wheel in pure or combined sliding conditions and using as input the lateral and longitudinal sliding ($\kappa$,$\alpha$), the tyres camber ($\gamma$) and the force $F_z$ (Figure 3).

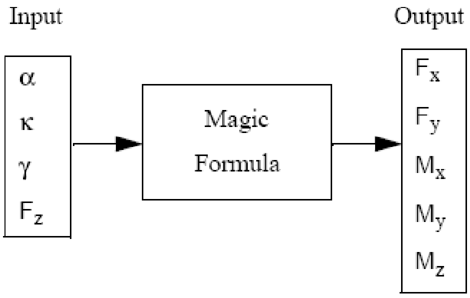


**Fig. 3: Input and output parameters of the Magic Formula M.F*.***

- ***Tyre-road interaction***

The contact between tyre and road pavement mainly depends upon the mechanical properties of the wheel (stiffness, vibration absorption capacity), on the road surface features (friction coefficient, tyre-road grip, surface structure) and upon the relative movement of the wheel on the pavement itself (modulus, direction and way of the sliding resistance).
Vertical loads do transfer the vehicle weight onto the road structure and the tyres deformability dampens the inconveniences that the pavements unevenness shift to the vehicle.

During traction and braking a series of longitudinal forces are generated, while the lateral forces come from the vehicle trajectory control; in the car dynamics the lateral forces are prevalent if compared to the longitudinal ones.

The system of reference used for the model representation is called ***ISO-W-Axis System*** (Figure 4) and is marked out by the following properties:

- The origin is located into the plane of the considered road, at the contact point between tyre and pavement (point C);
- The X axis orientation is positioned on the local plane of the road along the intersection between the wheel plane and the pavement one;
- The Z axis is perpendicular to the road plane, the direction being upward;
- The Y axis is on the road plane and is perpendicular to both X and Z axes.

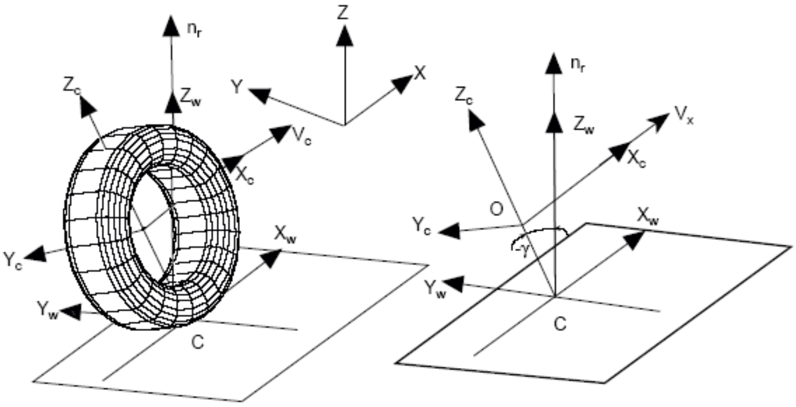


**Fig. 4: ISO-W-Axis system of reference**

As the curvature radium of the planimetric profile is definitely higher than the corresponding value of the tyre, it is assumed that there is a sole contact point between the wheel itself and the road surface profile.

So as to correctly find out the tyre motion, the pavement can be approximated with its own tangent plane passing through the point underneath the wheel centre.

The force $F_z$ representing the vertical load is expressed with the following equation:

$$F_z = C_z\, \rho + K_z \cdot \dot{\rho} \qquad [1]$$

where:

$\rho$ = tyre deformation;

$\dot{\rho}$ = deformation velocity;

$C_z$ = vertical_stiffness of the tyre;

$K_z$ = vertical_damping.

The wheel radius ***R*** is the distance between the centre of the tyre and the contact centre ***C*** (see Figure 5), while the effective radius $R_e$ is defined by the following expression:

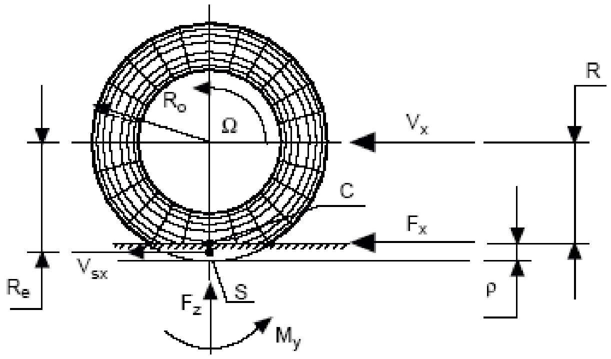


**Fig. 5: Tyre characteristics**

$$R_e = \frac{V_x}{\Omega} \qquad [2]$$

where$\Omega$ is the rolling velocity of the wheel.
For radial tyres, the effective rolling radius decreases if the vertical load increases.
When the vertical stiffness is considered constant, the radial deformation can be calculated by means of the following expression:

$$\rho = \frac{F_z}{C_z} \quad [3]$$

Referring to the Magic Formula, the effective rolling radium can be, therefore, found from the following expression:

$$R_e = R_0 - \rho_{F_{z0}}(D \arctan(B\rho^d) + F\rho^d) \quad [4]$$

where:
***$R_0$*** = not loaded radius;
$\rho_{F z 0}$ = nominal strain of the tyre, defined by:

$$\rho_{F_{z0}} = \frac{F_{z0}}{C_z} \quad [5]$$

$\rho^d$ = non-dimensional radial strain, calculated by the following equation:

$$\rho^d = \frac{\rho}{\rho_{F_{z0}}} \quad [6]$$

B, D, F = numerical coefficients whose values are, for most of the tyres:

- $3 \leq B \leq 12$ (it expresses the ordinate of the function arctang: a large value involves a significant slope for the values with $F_z = 0$);
- $0{,}2 \leq D \leq 0{,}4$ (it defines the asymptote displacement because of the strong weights on the wheel);
- $0{,}03 \leq F \leq 0{,}25$ (it describes the ratio between the tyre radium strain and its effective strain. Low values of this parameter are due to very stiff tyres.

➢ ***Tyre sliding definition***

There are three different tyre sliding typologies, all of them being influenced by the motion features, the wheels performances and by the pavement characteristics. Figure 6 explains all the sliding components:

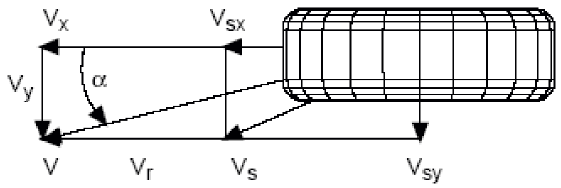


**Fig. 6: Sliding components**

where:
$V_{sx}$ = longitudinal sling velocity : $V_{sx} = V_x - \Omega R_e$ [7]
$V_{sy}$ = transversal sliding velocity : $V_{sy} = V_y$ [8]
$\alpha$ = sliding angle [rad]
$V_r$ = linear rolling velocity: $V_r = R_e\ \Omega$ [9]

For completeness of information the following expressions are to be considered, remembering that $\kappa$ represents the longitudinal sliding

$$\kappa = -\frac{V_{sx}}{V_x} \quad [10]$$

$$\tan\alpha = \frac{V_{sy}}{|V_x|} \quad [11]$$

***$V_{sx}$*** and ***$V_{sy}$*** are the components of the sliding velocity which can be defined as the point S velocity in the system of reference W-Axis System.

- ***Sliding typologies***

Different sliding conditions can be observed in everyday situations: Figures 7a, 7b e 7c, represent, respectively, longitudinal, transversal and transversal with included aligned couples simple sliding phenomena.

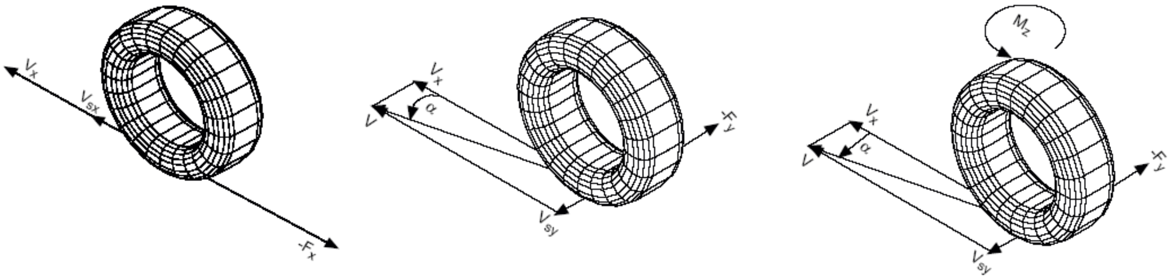


**Fig. 7a, 7b, 7c: long., transversal and transversal with included aligned couples simple sliding**

The employed model is able to consider the combination of the just mentioned sliding types by means of a series of expressions, whose mathematical formulation, for the sake of brevity, is neglected at this stage.

## MF-Tyre tyres typologies

The software adopted during the research permitted the use of several models of tyres, all of them being included in a specific archive, as function of the user characteristics:

- ***Car tyres***;
- Light truck tyres;
- Motorcycle tyres.

and the use of different analysis conditions:

- Pure cornering slip;
- Pure braking/traction slip;
- Combined cornering and braking/traction slip.

## Surfaces typologies

As for the surface, several types were considered by the software for the model formulation, in order to give a proper representation of the tyre-pavement interaction:

- FLAT – smooth surface;
- PLANK – Perpendicular or oblique axle, with respect to Y axle, single axle, with or without rounded edges;
- POLY_LINE – Linear description of the profile, the right and left parts being different from each other;
- POT_HOLE – single rectangular hole;
- RAMP – single ramp, uphill and downhill;
- ROOF – Triangular obstacle, roof shaped;
- SINE – Sinusoidal waves with constant wave length;
- SINE_SWEEP – Sinusoidal waves with increasing wave length;
- STOCHASTIC_UNEVEN – Casual unevenness on the surface profile, which basically represents the real conditions of road pavements. The left and right profiles can be independent to each other or linked by a specific correlation.

Additionally, the different types of surfaces were characterized by three parameters:

1. ***offset*** = constant variation of the surface height value; for a *flat* surface and an offset=0, this height is nil;
2. ***rotation angle xy plane*** **=** X-Y plane rotation angle around the Z axis;
3. $\mu$ = friction coefficient correction factor of the surface (not the real value of the engaged grip), which is to be multiplied by the corresponding tyre friction coefficient: its default value is equal to 1.

For a *flat* kind of road there were no additional parameters required.

A ***Stochastic-Uneven*** type, which was the one chosen for the study because of its completeness has a diffused unevenness on the road surface obtained by generating some discrete disruptions with semi-uniform casual values; amongst these quantities, two are assigned every 10 mm of the track.

Afterwards these values were assembled with respect to the covered distance by using a single first order integration as regards to time: in this case, anyway, rather than the time, the track was the independent variable.

The second input sent generated undulations within a fixed range obtained after experimental investigations on the spectral densities of road surfaces.

The last step for the arrangement of a ***Stochastic-Uneven*** surface was based on a linear combination of the results, sending some disruption signals $z_1(s)$, $z_2(s)$.

This procedure was followed for both left and right profile, considering also a correlation factor between the two of them (if correlation=0 the profiles are completely independent to each other, their aspect being the same when this value is 1).

## Kinds of analysis carried out

During the period of the research several simulations were carried out in order to characterize the interactions between tyre and pavement, varying the parameters that influence the phenomenon itself, with the purpose of validating the virtual model and deriving, from it, a regressive law for the analysis of the grip features with regard to both mega-texture and superficial unevenness of road superstructures.

For this reason investigations were performed on both large scale simulation, for the qualitative determination of the laws characterizing grip and on small scale experiments so as to focus the attention on such parameters that significantly influence the phenomenon, excluding the anomalies of the vehicle movement which would jeopardize the results (too large sliding, huge stresses on mechanical elements and, more in general, critical situations).

In particular, the following test session was followed:

1. Real driving simulations on a track whose dimensions and characteristics complied with the Italian Standards[3], determining the vehicle performance variations as well as the changes of the trajectories of a virtual driver as function of the variations of the surface. texture and evenness (First Experiment).
2. Braking simulations in straight parts of the track with regard to the changes of the pavement texture, of the tyre characteristics and of the superficial defects of the superstructure, so as to determine the experimental laws of the phenomenon (Second Experiment).

## FIRST EXPERIMENT: LARGE SCALE CHARACTERIZATION OF THE GRIP PHENOMENON

The first simulation reproduced a real driving situation referring to a track reproducing existing roads with ideal superficial characteristics (smooth surface, excellent grip, horizontal planimetric path) and superelevation on curves.

Subsequently the superficial features of the pavement were changed, the driving typology being unchanged, so as to analyse the dynamic variation belonging to the modifications themselves.

## Characteristics of the model – Planimetric development

The characteristics of the track considered for the first experiments were the following:

- Overall length: 2500 m;
- Width equal to a C1 lane (3.75 m), referring to Italian Standards (Figure 8);
- Straight parts long enough (400-500 m) to allow speed changes and overtake manoeuvres (Figure 9);

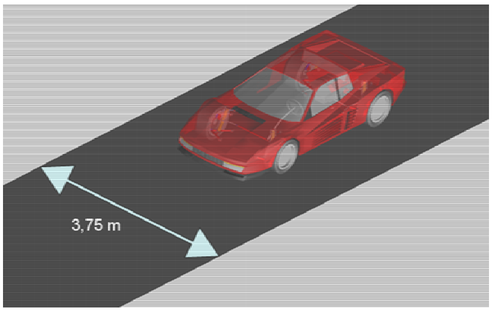


Fig. 8: Lane width

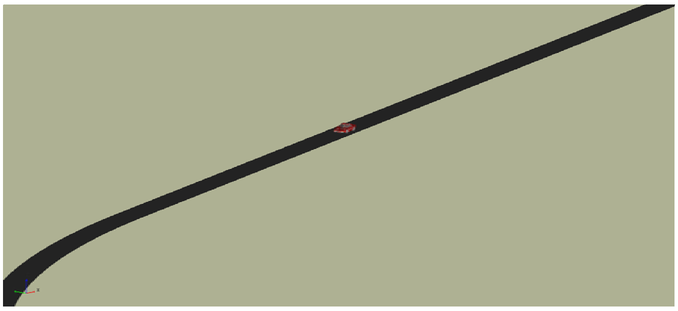


Fig.9: Straight part of the track

- Small and large radium bends: this assumption was needed to amplify the situation in order to get to useful considerations from the standpoint of road safety, even though the radii coordination was not the best, the result of the referring chart being labelled as “*unacceptable area*”;
- Presence of transition curves between two bends and between bends and straight parts;

- Speed limit equal to 100 Km/h, with respect to the Italian Standards for C1 category roads;
- Possibility for the car to shift inside the lane

Figure 10 represents the curvature diagram on the planimetric development of the track, showing the elements of the path as function of the progressive distance. The importance of this instrument is fundamental for the understanding of the charts obtained in the *Postprocessor* phase (*First and second experiments – Output analysis*)

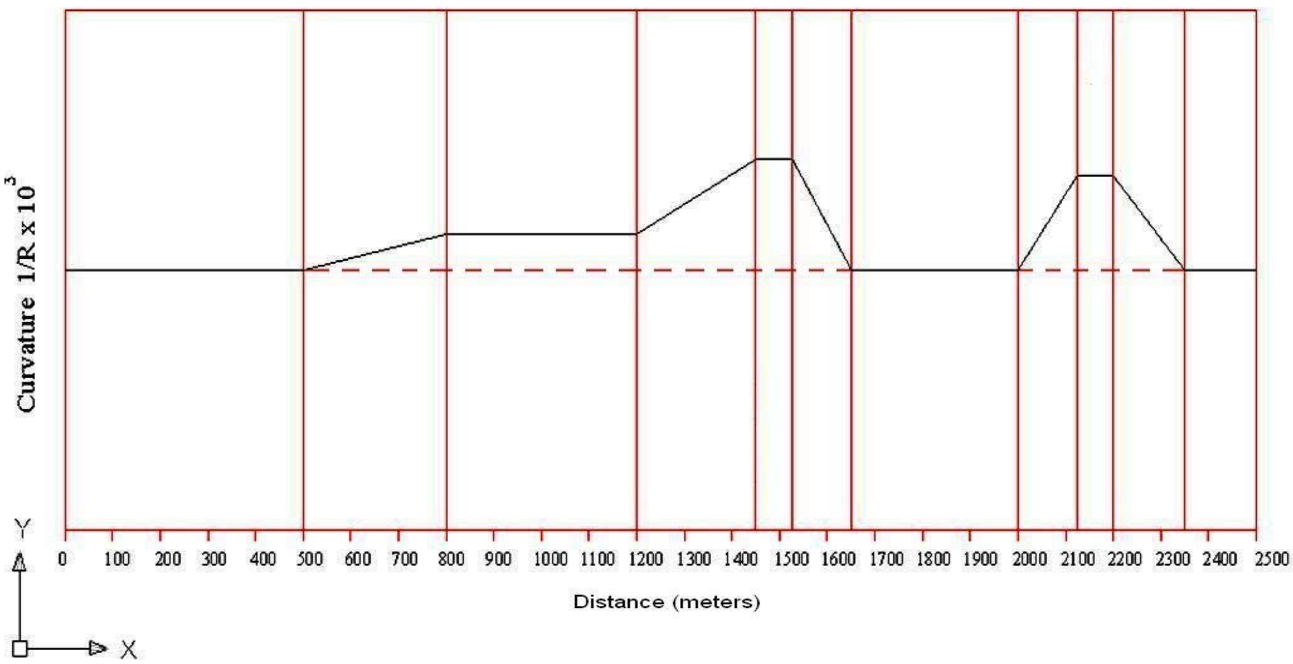


**Fig.10: Curvatures diagram**

## Characteristics of the model – Contact surface

The first typology of surface analysed during the simulation process had ideal characteristics:

- Superficial homogeneity and unevenness;
- Maximum values of grip and, as a consequence, excellent performances from the viewpoint of both micro and macro-texture;
- No deformations.

## Experimental simulations – Ideal Model n°1

As already stated, the software allowed the definition of real driving conditions. Moreover, this assumption is not very simple, since there are several parameters which are to be taken into account: as a matter of fact, a correct step by step calibration of the model was fundamental so as to give an understanding of the relevance of the modifications on the parameters themselves.

The variation of the driving parameters and of the vehicle performances generated a series of different models, only one amongst them being employed as the basis for the analysis of grip phenomena (ideal model n°1).

- ***Results***

The charts of Figures 11-14 summarize the results obtained and are a good starting point for the comparative analysis; for the sake of brevity, only the most significant outputs were reported at this stage.

It is important to note that the most relevant data are observed for bends (especially if characterized by a small value of the radius), which are basically the parts of the track where the manoeuvres are amplified (severe braking, fast starts, strong lateral accelerations, etc.).

So as to understand the vehicle dynamics and to be aware of the car location with regards to the covered distance, it is useful to refer to Figure 10, where the curvature diagram is represented.

**Fig. 11: Longitudinal velocity trend**

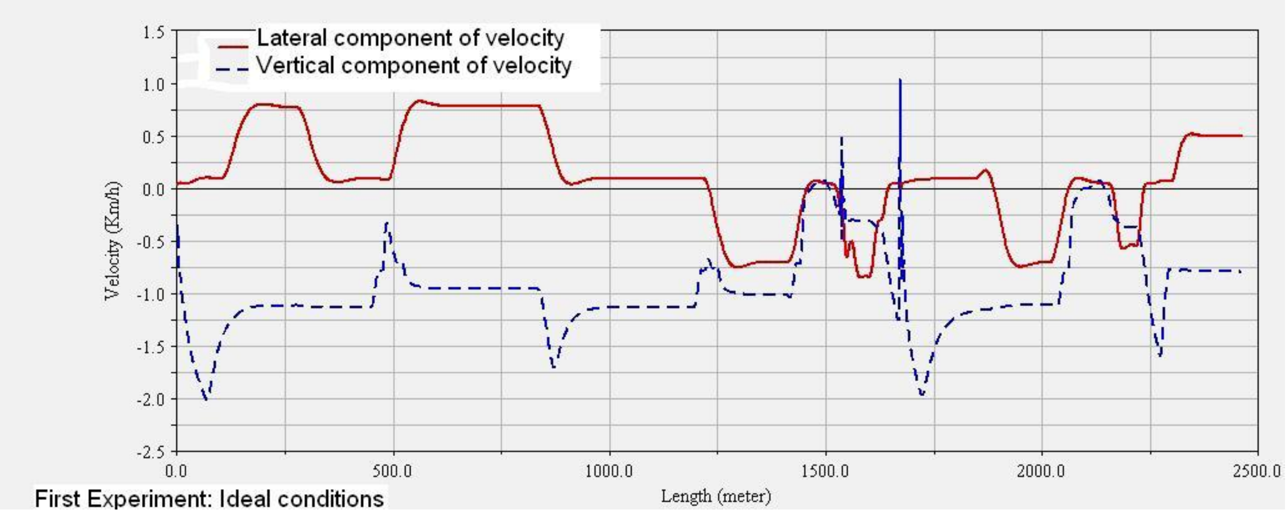


**Fig. 12: Vertical and lateral velocity components trend**

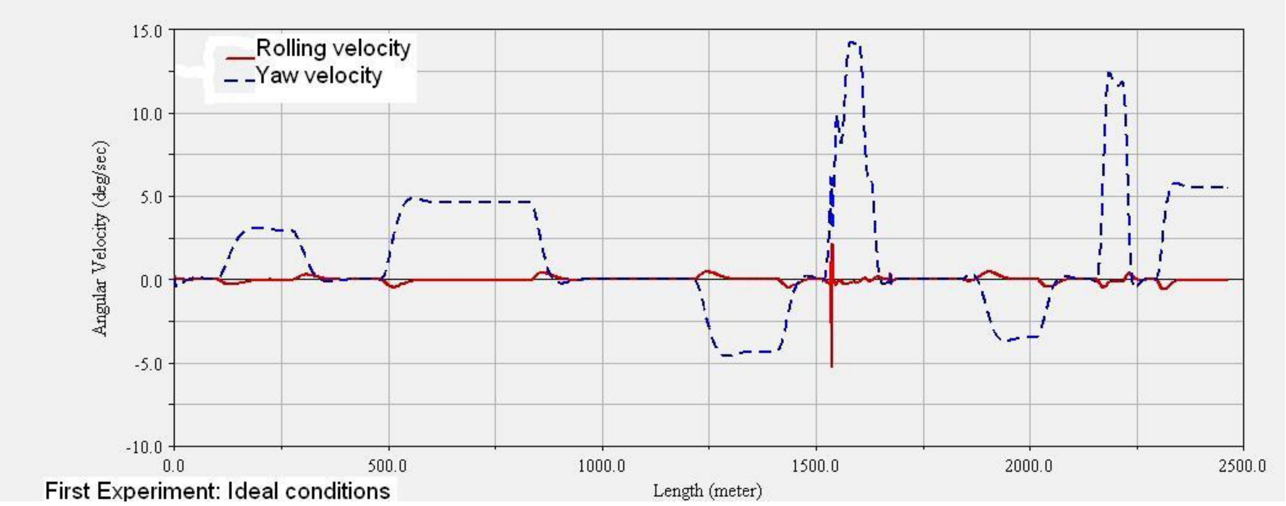


**Fig.13: Rolling and yaw velocity trend**

## Experimental simulations – Ideal Model n°2 (contact surface variation)

The following step of the investigation considered, the driving conditions being unaltered, a second model (ideal model n°2) which would take into consideration a ***stochastic-uneven*** surface; also in this case the model was ideal, since only infinitesimal unevenness were considered and the tyre-pavement friction coefficient was assumed equal to 1.

Inside this model, the virtual driver varies his actions only after detecting the induced changes on the pavement.

The following charts express the results and include a comparison with the ideal model n°1 ones.

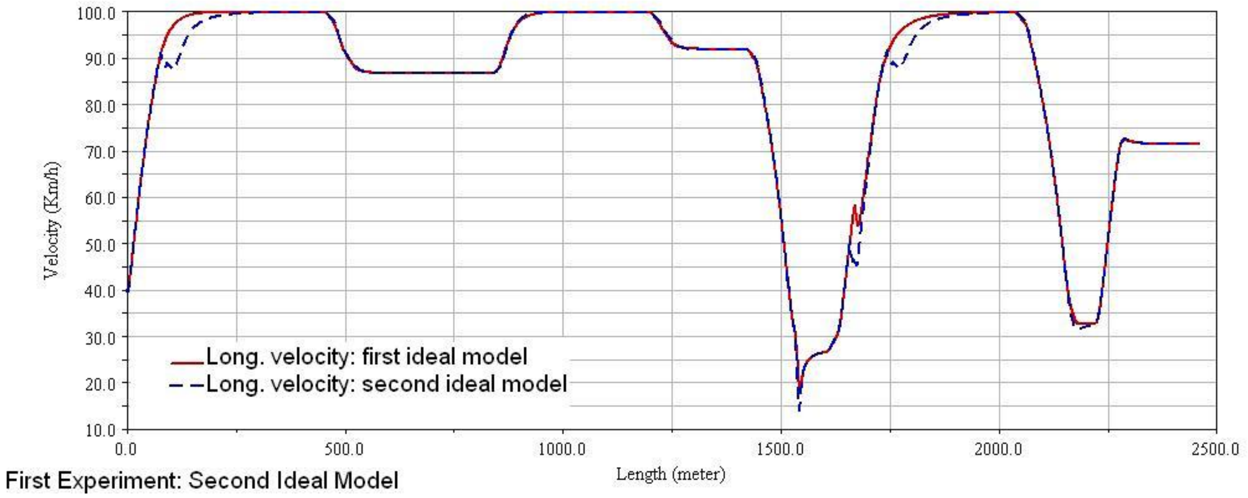


**Fig. 14: Longitudinal velocity trend**

Figure 14 shows that, after the addition of the ***stochastic-uneven*** characteristics to the surface the longitudinal velocity variation is limited and only concentrated on small spots of the track, therefore being negligible.

From the analysis of the vertical and lateral component of the velocity changes (Figure 15), on the contrary, one could easy realize smaller values for the second model; this phenomenon is due to the fact that, in the second hypothesis, the total velocity – which is the sum of the three components (vertical, lateral and longitudinal) – is surely smaller than the velocity the car could reach in the ideal conditions of the first model.

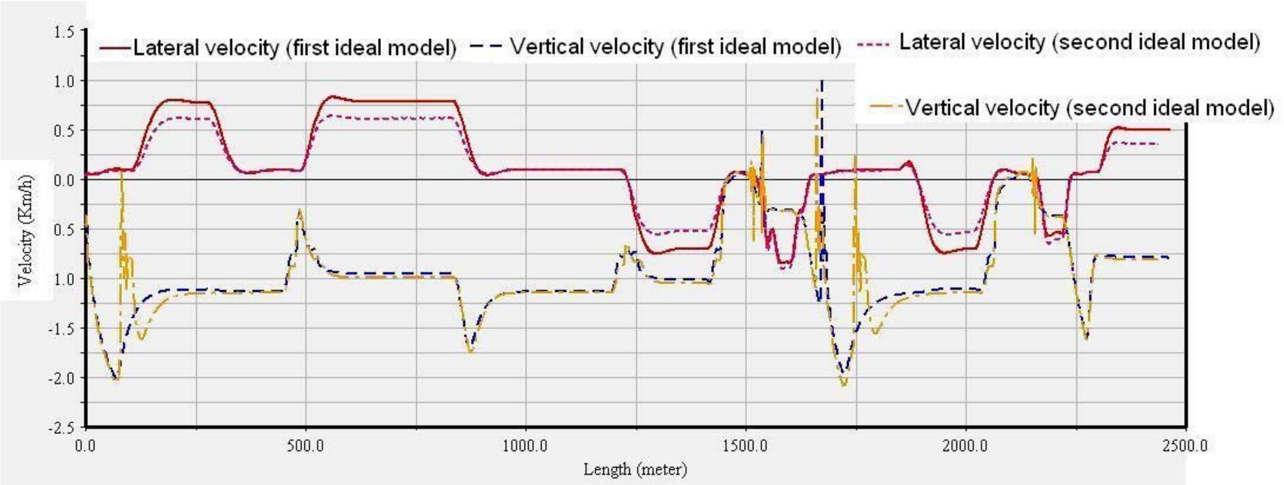


**Fig. 15: Vertical and lateral velocity components trend**

The investigation on the data of rolling and yaw speed, on the other side, did not give any significant variation, the corresponding charts being neglected in this paper.

With regard to that, the Author found these two parameters are mainly influenced by surface evenness variations of the pavement, rather than by micro and macro-texture changes.

Figure 16 illustrates that the variations of longitudinal and lateral acceleration highlight the presence of peaks where re-starting of the vehicle after strong breakings are experienced (e.g. the case of short radius bends near the stakes located at 1500 m and at 2200 m).

Therefore, from this point of view the analysis showed that an increase of the superficial unevenness, no matter the magnitude, causes a decrease of the tyre-pavement grip, causing both skid and accelerations peaks.

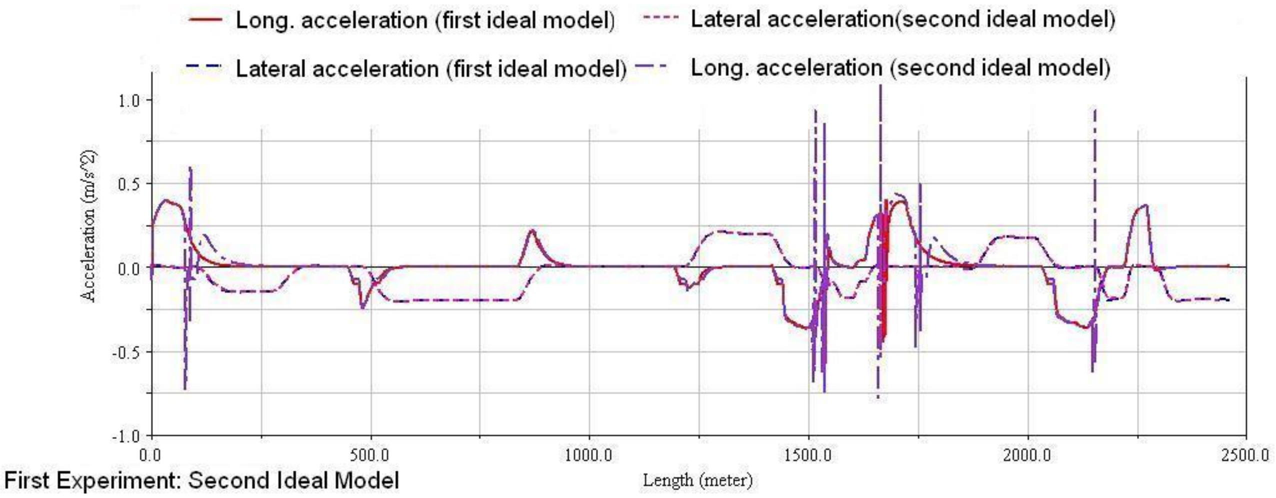


**Fig 16: Lateral and longitudinal acceleration trend**

- ***Analysis of the changes induced by the initial grip variations***

The analysis kept going considering a variation of the grip conditions defined by the introduction of the parameter ***mu*** which characterizes the tyre-road interaction, since it represents the value of the initial grip. Moreover, ***mu*** is not the value of the friction itself (that is, basically, the quantity coming from the micro and macro-texture measurements), but the term which should be multiplied by the corresponding tyre coefficient in order to get to the low velocity used grip value.

The comprehensive graphical representation included below compares the ideal model n°2 in standard conditions to the same model with a variation of the parameter ***mu*** (from 1 to 0.8).

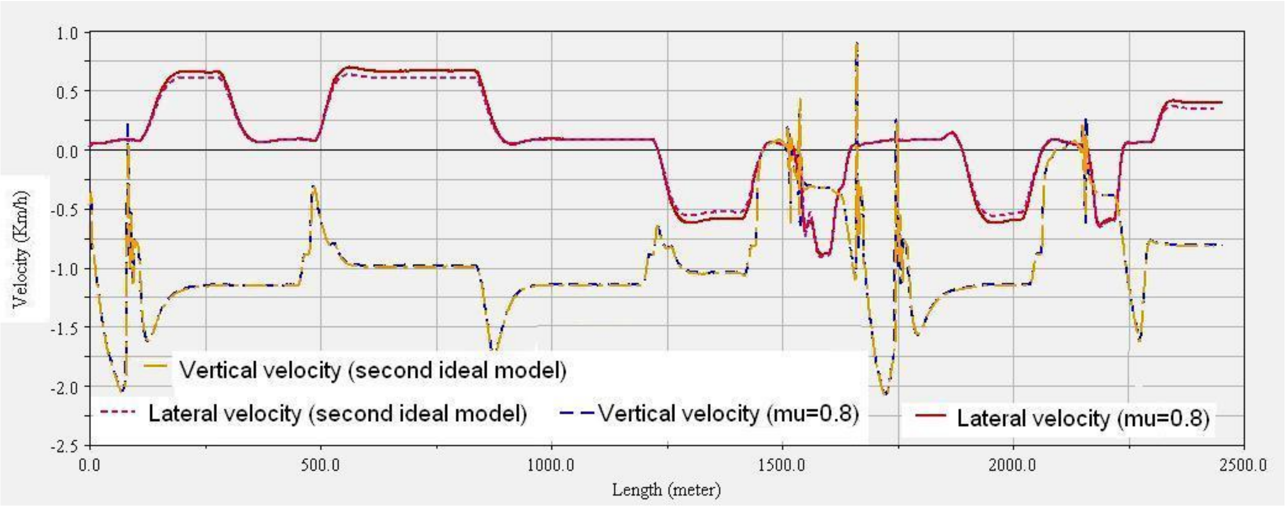


**Fig. 17: Lateral and vertical velocity components trend**

Figure 17 shows that mainly the lateral component is affected by variations, this phenomenon being more manifest for the model with ***mu*** = 0,8: this means that the vehicle tends to widen its trajectory as a consequence of the fact that the grip limit which can be used transversally is reduced.

- ***Analysis of the changes deriving from the variation of the superficial unevenness (i = 5%)***

This part of the analysis was concentrated on the comparison between the ideal model n°2 and the model arranged in the previous phase, with some changes of the unevenness of the contact surface.

As a matter of fact, an irregularity of 5% over the complete surface was considered, the distribution along the whole pavement being uniform. Consequently the Stochastic Uneven file of the software was changed by adopting the following values:

1. mu = 0,8
2. i = 0,05 [5%]
3. path_const = 30 [mm]

It is clear from the chart of Figure 18 that the most significant variations are measured for the lateral component of the speed, since the trajectories and the driveability in bends of the car change, as a consequence of the fact that the vehicle, in these spots of the track, generally tends to widen the path.

Moreover, looking at the vertical component of the velocity, one could notice that the overall behaviour is similar to the curve of the ideal model, no matter the increased instantaneous variability of the considered component.

This fact implies that unevenness influences short term phenomena which, if amplified any further, would bring to the complete worsening of the vehicular dynamics.

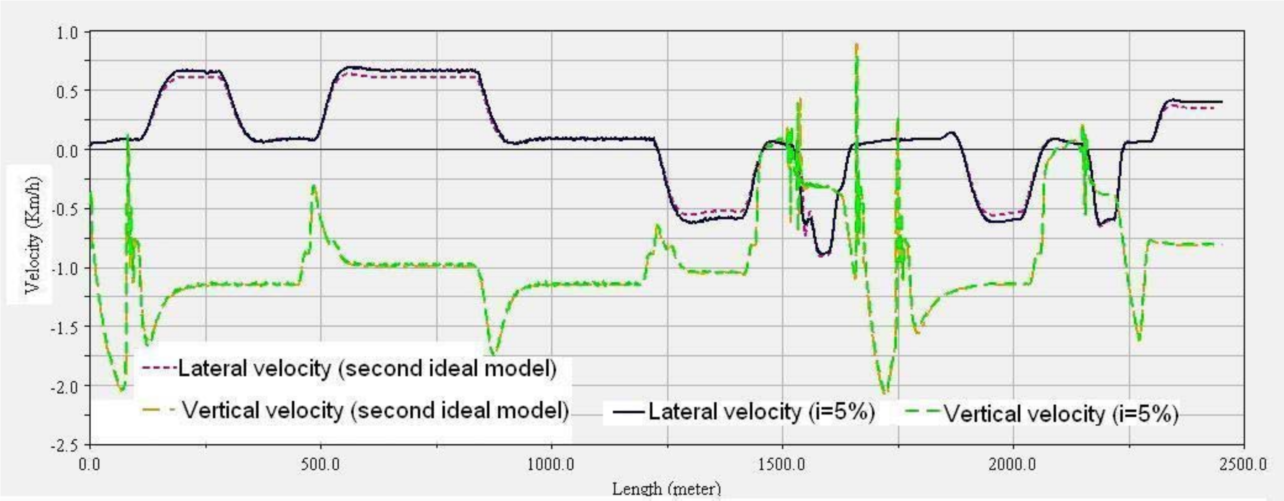


Fig. 18: Trend of the lateral and vertical components of velocity

So as to get to a clear understanding of the vehicle dynamics based on the variations of the superficial unevenness, one could analyse Figure 19 which shows an increased variability of the rolling radius because of the raise of the small scale vibrations on the wheel.

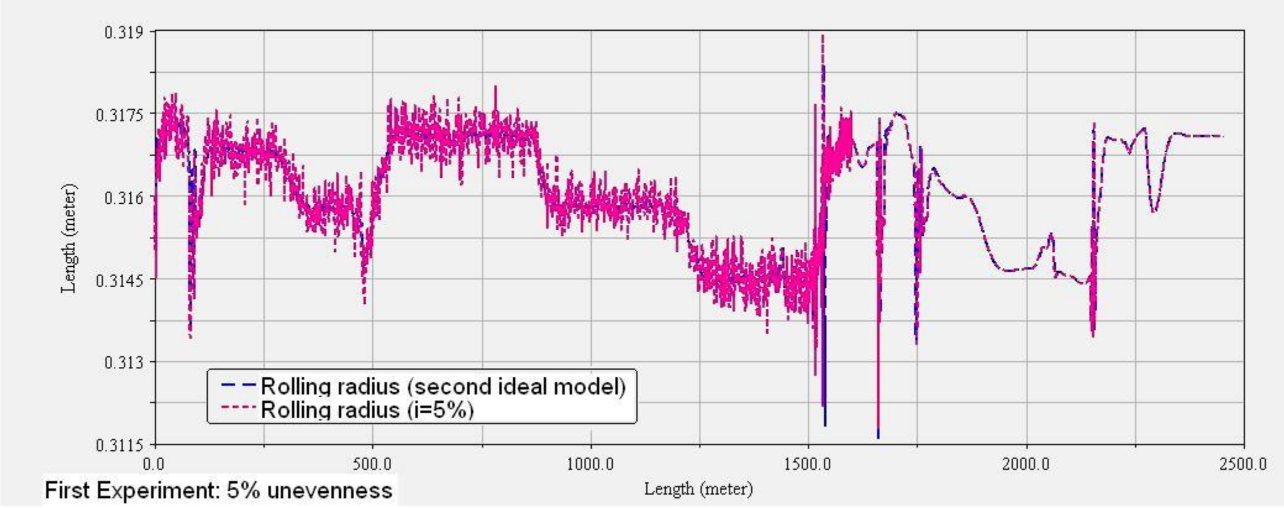


Fig. 19: Variation of the rolling radius

- ***Analysis of the changes deriving from the variation of superficial unevenness (Stage 1: i = 10 %) (Stage 2: i = 20%)***

The following analyses considered a much higher decrease of the characteristics of superficial evenness, compared to the previous case, in order to focus the attention on the way the induced variations modify in a relevant manner some characteristics of the vehicle movement and performances.

In particular, the following values of Table 1 were considered for both configurations:

***Tab.1: Configuration of stage 1 and stage 2 for the analysis of superficial unevenness***

| ***Stage 1*** | ***Stage 2*** |
|---|---|
| *mu = 0,8* | *mu = 0,8* |
| *i = 0,1 [10%]* | *i = 0,2 [20%]* |
| *path_constant = 30 [mm]* | *path_constant = 30 [mm]* |

In this case also the ideal model n°2 was the reference for the analysis, so as to set off the fact that the unevenness increase strongly influenced the width of the charts, generating a significant fluctuation of the observed values.

From the investigation it was found that the following quantities were most influenced by the deterioration of the superficial evenness:

- Variation of the longitudinal velocity (Figure 20);
- Rolling and yaw velocity (Figure 21);
- Applied forces, manly the vertical component (Figure 22);
- Rolling radius (Figure 23);
- Longitudinal and, with minor extents, lateral sliding (Figure 24).

The other characteristics investigated did not experience any significant variation, compared to the previous cases. For the sake of brevity only the charts of stage 2 are included in this section, since the stage 1 ones do follow the same pattern, the amplitude being higher for the former.

*Stage 2* ***i = 20 %***

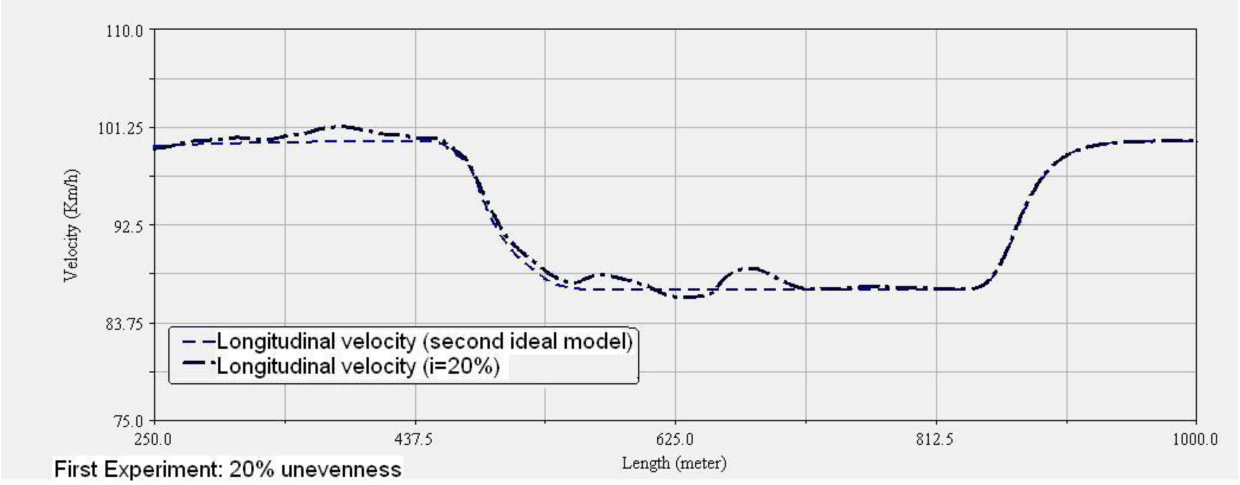


**Fig. 20: Trend of longitudinal velocity**

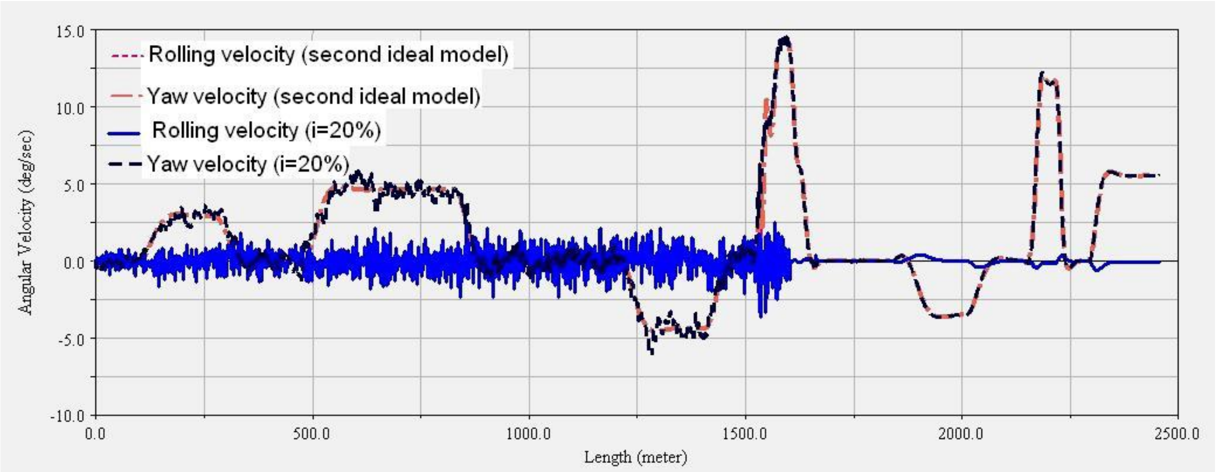


**Fig. 21: Trend of rolling and yaw velocity**

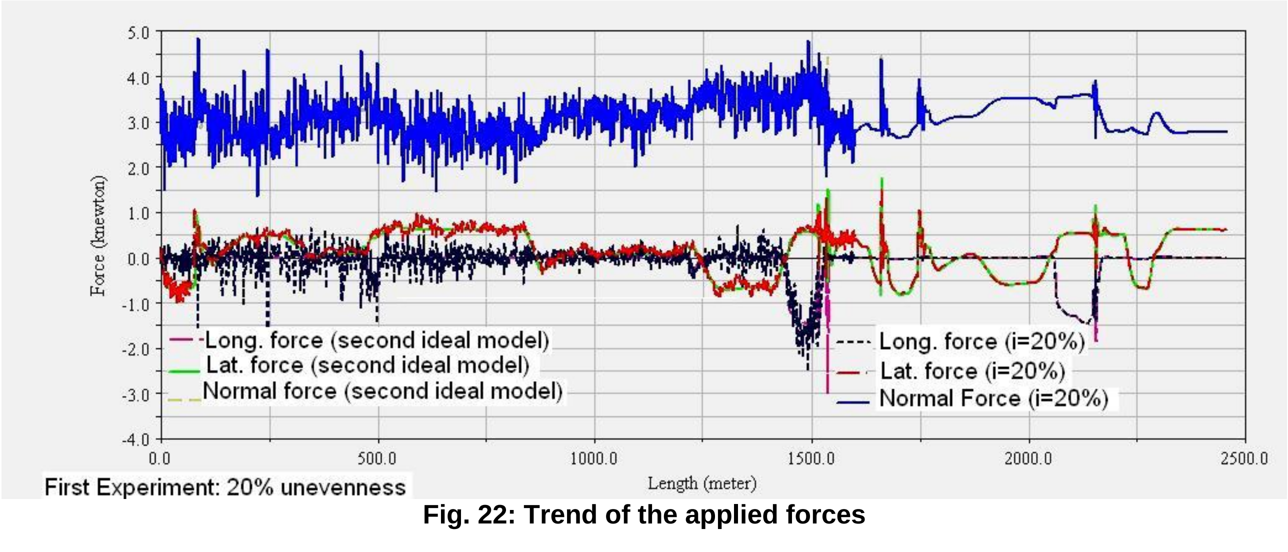


**Fig. 22: Trend of the applied forces**

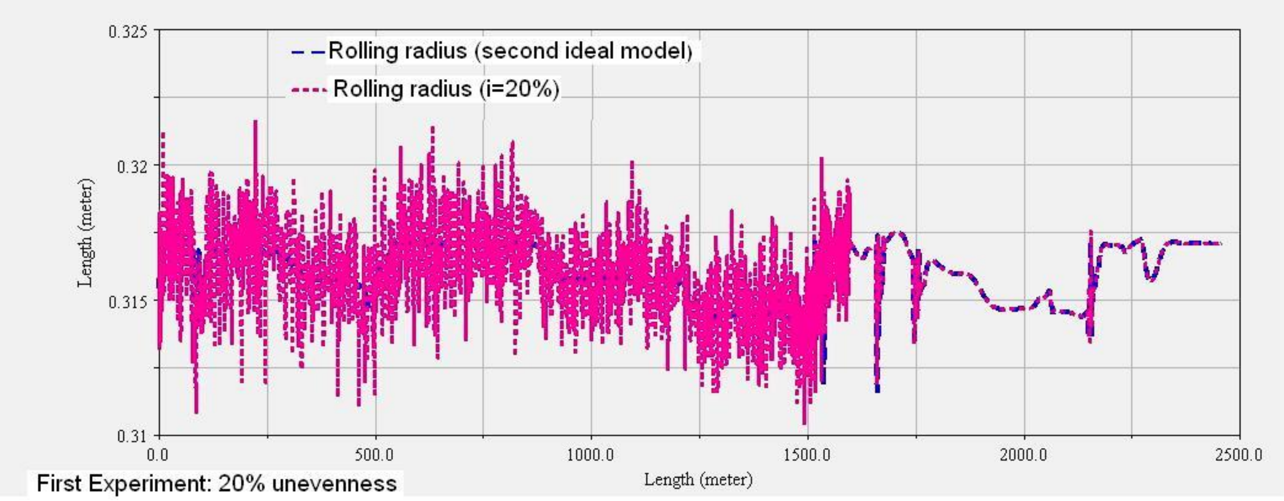


Fig. 23: Trend of the rolling radius

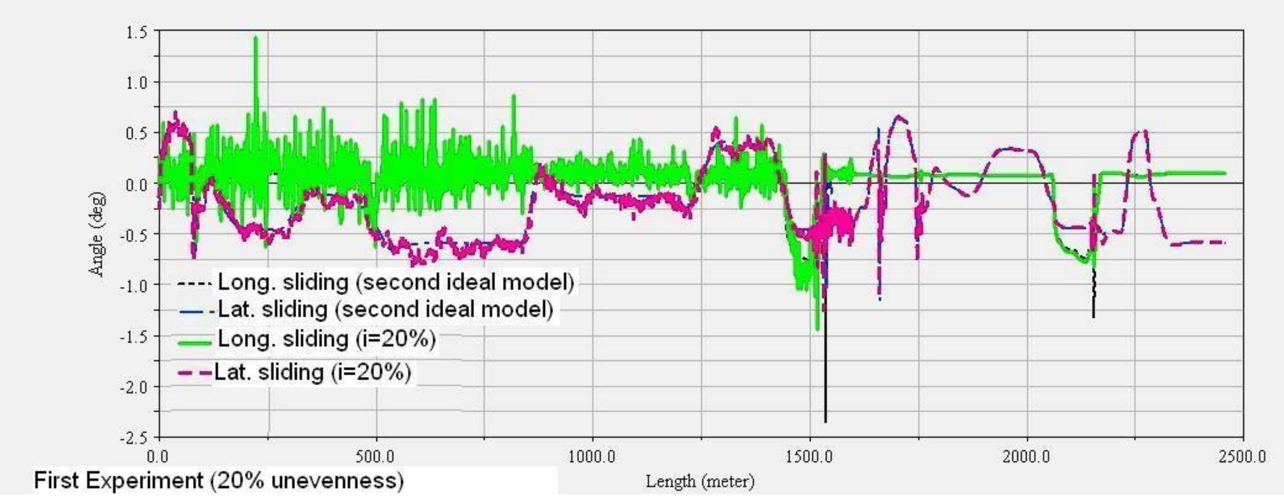


Fig. 24: Trend of sliding

## SECOND EXPERIMENT:EMPIRICAL LAWS OF THE GRIP PHENOMENON

The second part of the investigation aimed at the determination of an experimental law which would support the grip phenomenon study taking into account what already seen in literature [8] and, at the same time, analyzing the influence on vehicle dynamics of micro, macro and mega-texture variations (as well as of superficial evenness) of road pavements.

For this purpose the Lamm-Herring's law and the Stribeck Model were considered, determining for both of them the compatibility with the data derived from simulations and assessing the presence, if any, of indefinable parameters into the virtual analysis performed.

### Enforcement of Lamm-Herring's law

For the determination of tyre-road interaction, for the sake of safety, the values derived from wet roads and medium thread conditions tyres are generally considered [8] .

These values can be derived, as function of the velocity V, from the following expression proposed by Lamm and Herring, by performing a non-linear regression on several experimental measurements:

$$f_a = 0,214\,(V/100)^2 - 0,64\,(V/100) + 0,615 \qquad [12]$$

By applying the just mentioned formula with the velocity values coming from the report of the model analyzed so far as input, the Author obtained the following chart (Figure 25):

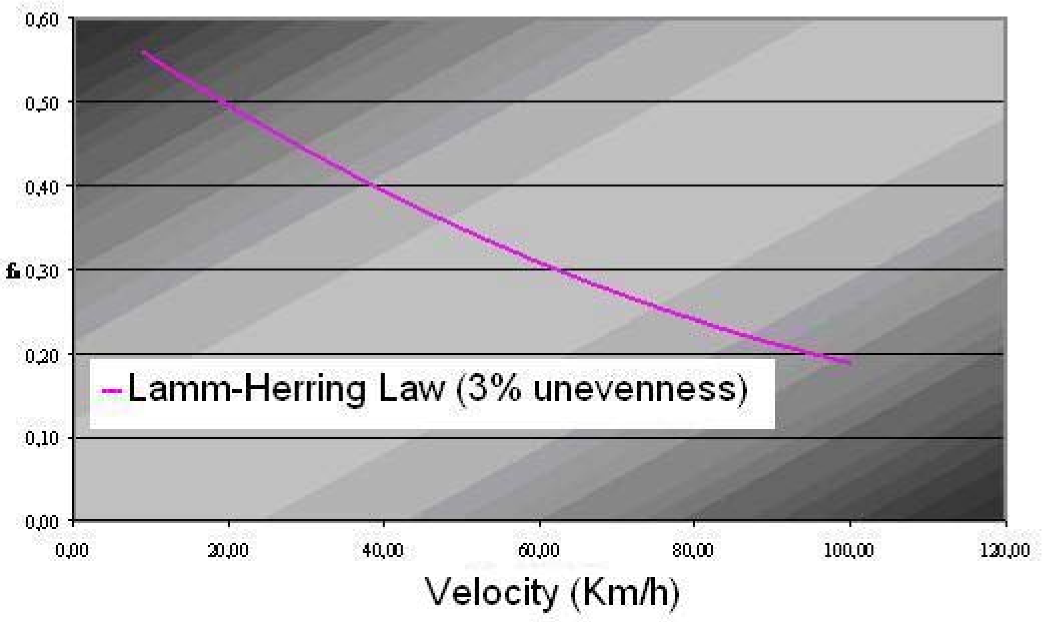


***Fig. 25: Enforcement of Lamm-Herring's law***

This instrument is a useful reference tool for further analyses of the investigation, since the determination of a model more flexible than the Lamm and Herring's one was the aim of this session, the latter proposing a unique interpretation of the problem by the definition of medium boundary conditions and by the assumption of the dependence of the results only upon the longitudinal velocity.

## Enforcement of Stribeck model

For the comparison of the results obtained so far, a second model usually adopted in literature [11] was used, the so-called Stribeck model, which is defined by the particular curve (Stribeck curve) derived from the following equation:

$$\mu = \mu_o \exp\left(-(V/V_S)^{\alpha}\right) + \gamma V \qquad [13]$$

where:

$\mu$ = grip coefficient;
$\mu_0$ = the same coefficient the theoretical velocity being nil;
$V$ = vehicle velocity;
$V_S$ = Stribeck velocity;
$\alpha$ = constant value depending upon the water film depth and on the tyre thread;
$\gamma$ = constant value defining the viscous component of the formula;

The following Figures 26a and 26b explain some examples of Stribeck curves coming from the application of Equation 13.

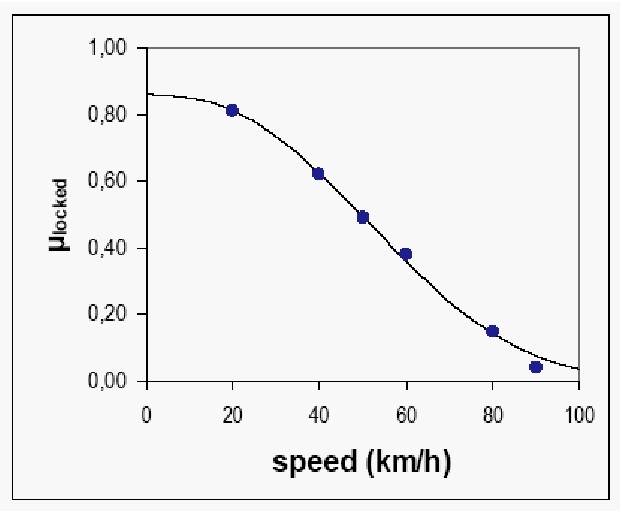


**Fig. 26a: Stribeck-curve (1 mm water film and 2 mm tyre thread)**

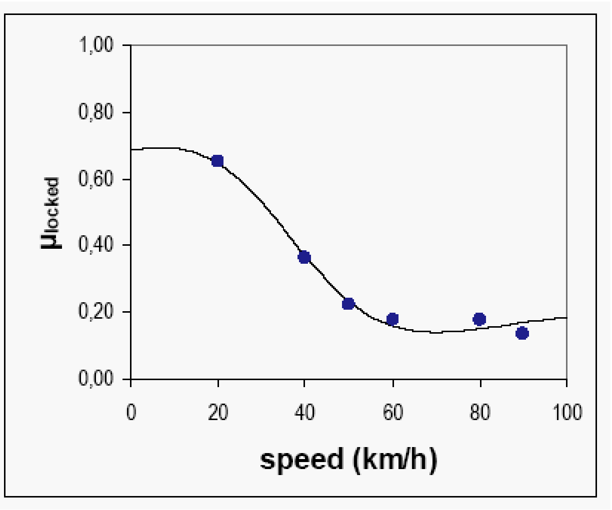


**Fig. 26b: Stribeck-curve (3 mm water film and 2 mm tyre thread)**

Anyway, the Author considered the simplified formula of such model, proposed by VERT (Veichle Road Tire Interaction), according to which the viscous term can be neglected (its magnitude being negligible) and $\alpha$ is equal to one (which implies the water film depth is equal to the tyre thread depth) [6].
The following Equation is the consequence of these assumptions:

$$\mu = \mu_0 \exp(-(V/V_S)) \qquad [14]$$

The $V_S$ value is constant and can be derived from the following expression:

$$V_S = 117\, MPD^a\, \kappa^{0,9} \qquad [15]$$

where:

- **MPD** = Mean Profile Depth;
- **a** = constant value depending on the apparatus adopted for the **MPD** assessment;
- $\kappa$ = wheel sliding equal to:

$$\kappa = (V - R\omega)/V \qquad [16]$$

- **R** = rolling radium of the wheel;
- $\omega$ = angular velocity of the tyre.

Fundamental was the importance of the ***MPD*** parameter and of the ***a*** coefficient determination for the aims of the research: as a matter of fact $V_S$, was derived from the values obtained for the Lamm and Herring Law. If, into Equation 13, $\mu$ is equal to the corresponding value found from the Lamm and Herring's law for a 100 km/h speed and $\mu_0$ is supposed to be 0.7 (medium value depending upon the micro and macro-texture characteristics of the surface as well as on the tyre features), $V_S$ will be about 80 Km/h, which was basically the value adopted for the analyses of this research.
As a consequence a ***Lamm and Herring's-like law*** was obtained by starting from the Stribeck model, whose result is included in Figure 27.

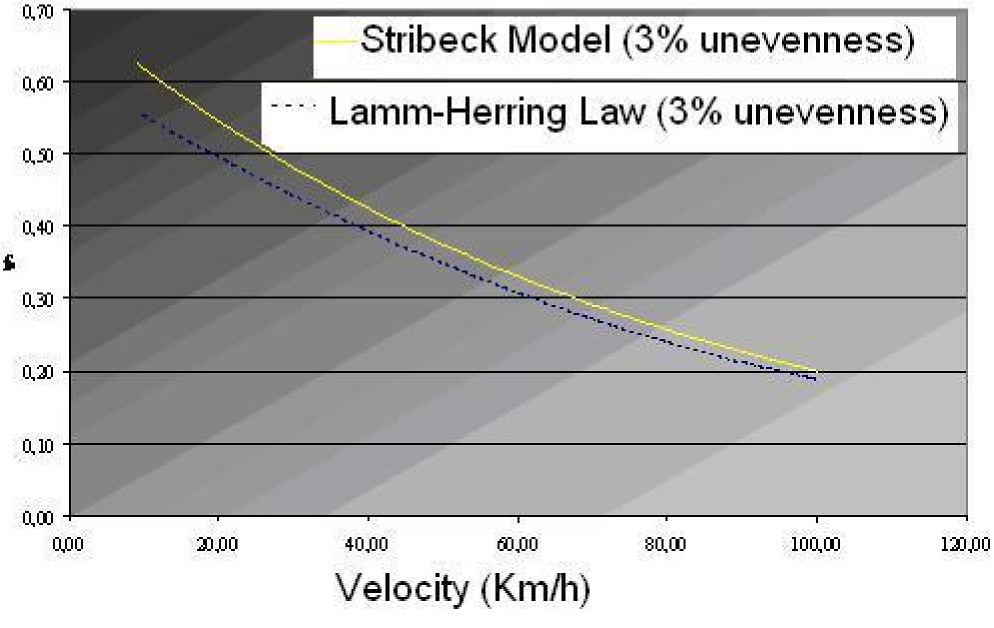


**Fig. 27: Comparison between Stribeck model and Lamm and Herring's law**

### Proposal for an experimental model

So as to get to an experimental model proposal derived from the interpretation of the above exposed models, the analysis went on making some interpretative changes to the Stribeck model: indeed, the term $\mu_0$ of Equation 13 is not explicitly defined, and this consideration means that its values can be changed, the variations induced by such variations being assessed.
In this part of the study the values of the grip coefficient previously found (part of the work omitted, for the sake of brevity) were assigned to the parameter $\mu_0$ of Equation 14, the procedure being called ***Inverted Stribeck model***.
The large number of outputs obtained were condensed in Figures 28 and 29, which allow the determination, for each velocity value, of the corresponding quantity of the longitudinal grip coefficient calculated through Equation 14.

These figures corroborate the considerations previously expressed from the standpoint of the comparison of the variations induced by the parameters modification; in this situation it is even more evident the fact that the superficial unevenness features variation prevails over the texture properties of the pavement.

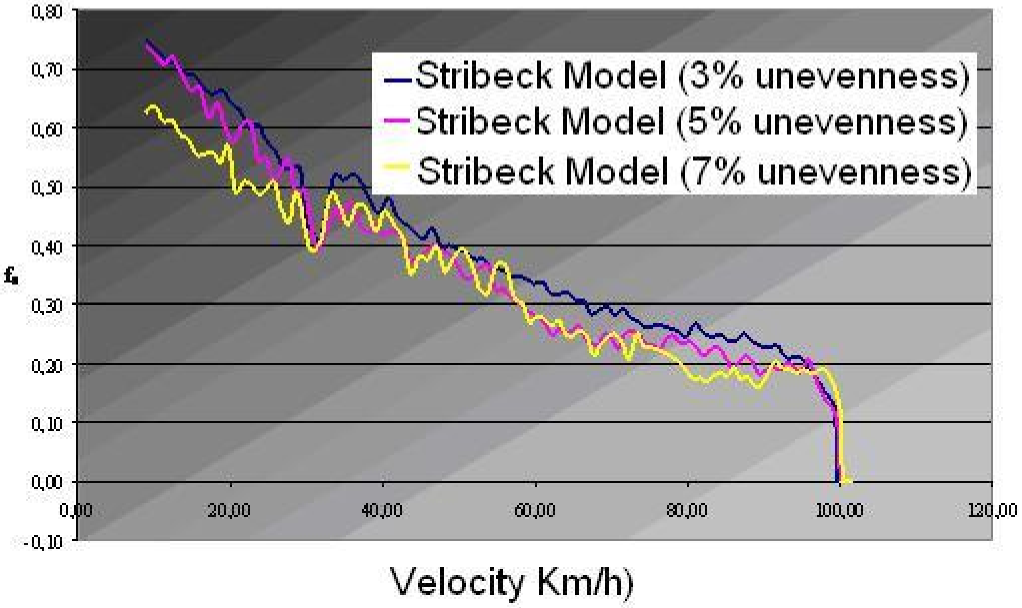


Fig. 28: Enforcement of the Inverted Stribeck model (superficial unevenness variation)

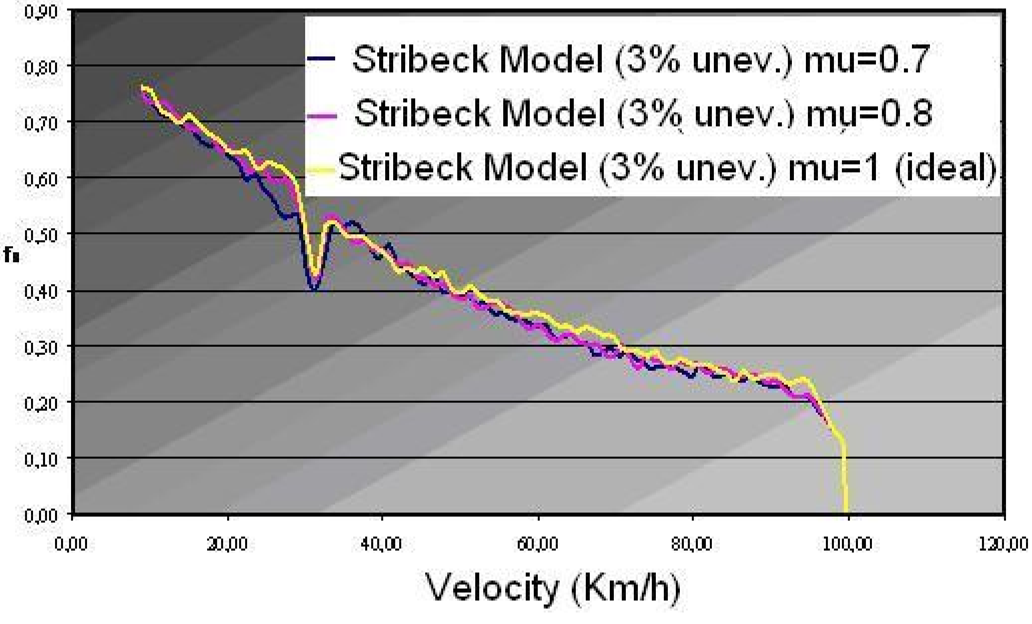


Fig. 29: Enforcement of the Inverted Stribeck model (mu parameter variation)

Since for a further in-depth analysis it was necessary to compare the investigation with the Lamm and Herring's law, the following part of the study aimed at the definition of an objective correlation between the laws derived from the Inverted Stribeck model and the Lamm and Herring's law itself, determining the application limits of the latter.

Indeed, such law is derived from medium kind data, the only input parameter being the vehicle velocity, and for this reason the modification of the parameters characterizing the surface will not affect the graphical behaviour belonging to Equation 12.

So as to deduce an average behaviour of the curves proposed in Figures 28 and 29, the Author adopted, for the $\mu_0$ value of Equation 14, the mean of the grip coefficients considered for the different situations (average of the $f_a$ values deducted from the investigations performed during the research).

The Inverted Stribeck model was applied on each of these boundary conditions, the different graphical behaviours of Figures 30 and 31 being the results compared to the Lamm and Herring's law.

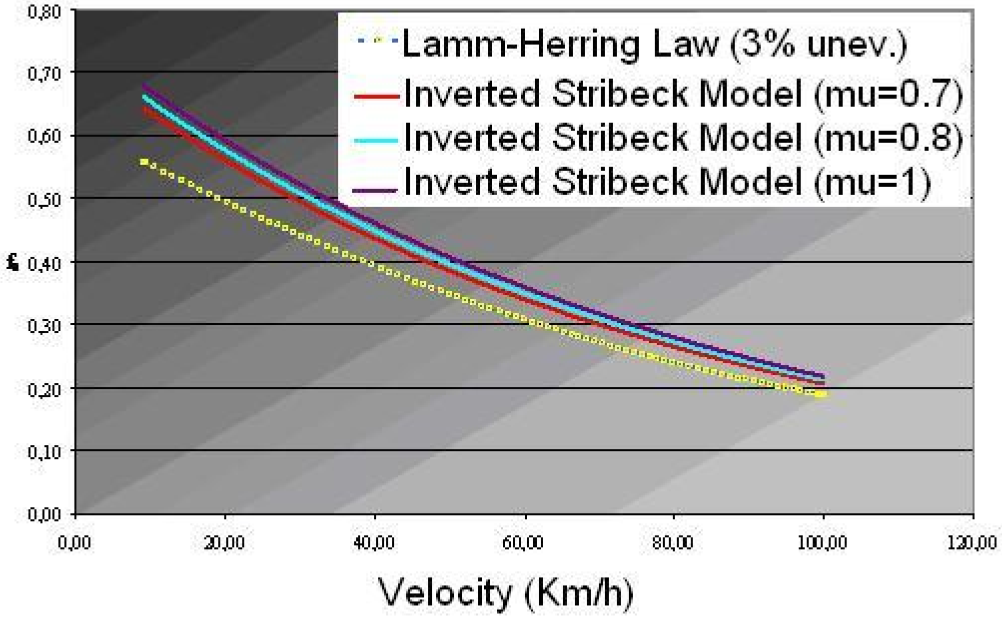


**Fig. 30: Comparison between Lamm-Herring's law and Inverted Stribeck model (mu parameter variation)**

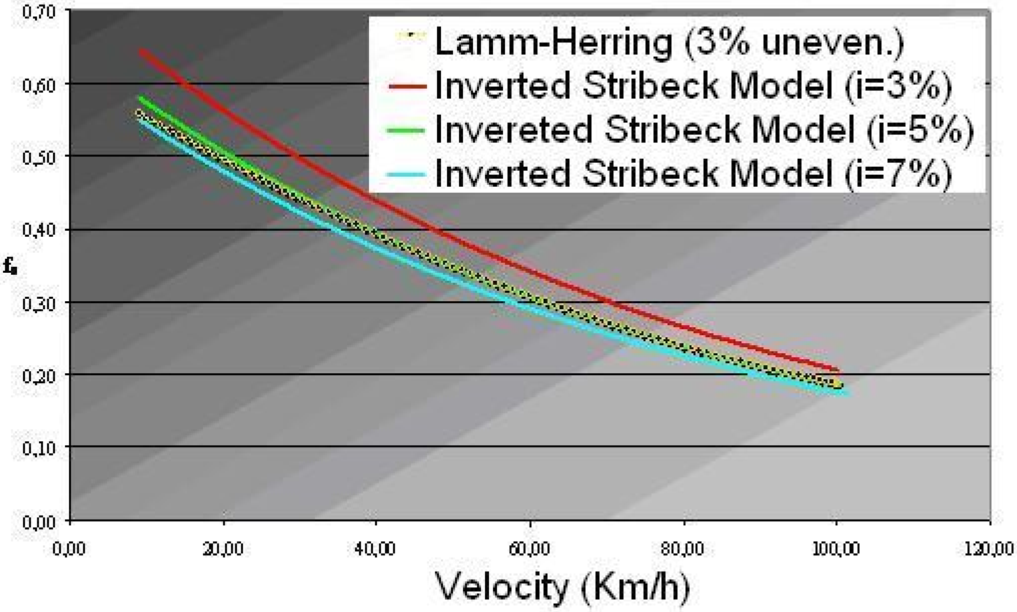


**Fig. 31: Comparison between Lamm-Herring's law and Inverted Stribeck model (superficial unevenness variation)**

This methodology is a useful support which allows a proper understanding of the fact the superficial features of road pavements are the characteristics that, more than others, do influence the grip phenomenon.
From the charts and the Figures above reported one can easily notice that, in case of the sole variation of superficial micro and macro-texture and/or of the changes of the tyre features, the Lamm and Herring's law is to safety advantage, compared to the Inverted Stribeck model.
On the contrary, when lager scale variations come into play, the superficial unevenness due to strong degradations increasing, as for the case of mega-texture, the former law is precautionary only for particular situations: indeed, as reported in Figure 31, for such pavements with good $\mu_0$ values and an unevenness smaller than 5%, it is advisable to refer to Lamm and Herring's law but, vice versa, if this value exceeds 5%, the model proposed in this research will give a better approximation and will allow for a less rigid estimation of the grip laws, considering the parameters variations that in the just mentioned law are not taken into account.

# CONCLUSIONS

Starting from the analysis of the vehicle dynamics and from the description of both building and typological features of road pavements, the presented paper faced the study of particularly interesting situations from a practical point of view, referred to road safety.

Indeed, the grip phenomenon between tyre and surface was examined, trying to take account of all the parameters that are actually activated by the process.

The created model and the results obtained by means of an electronic calculator are a good support instrument for both safety design and validation and, at the same time, in driving simulations, they enable the road designers to leave out of consideration human kind behaviours, which are obviously too much dependent upon the driver ability and conditions, their use being of uncertain help.

As a matter of fact the research proposed in this paper provided for the arrangement of a scientific model for the interpretation of the modifications induced on the vehicle motion by the changes of the parameters influencing the tyre-pavement interaction; in particular, the initial quantitative analysis brought to the characterization of the variation of the following vehicle factors:

- ☐ Speed components;
- ☐ Acceleration components;
- ☐ Forces and momenta applied on the wheel;
- ☐ Distances and trajectories;
- ☐ Sliding;
- ☐ Braking momenta, rolling and yaw velocity, etc.

The results obtained were the basis for a further quantitative analysis of the laws ruling the grip phenomenon.

For the purpose of this research some studies already performed in the past on the matter were considered (*Road Star*, *Lamm e Herring*, *Stribeck model, SCRIM*): they allowed for both the interpretation of the results obtained and the comparison with the simulated experience, giving a concrete validation of the created model.

Therefore, this research proposed the application of some theories coming from the revise of the just mentioned experiences and, from the outcomes obtained, a series of considerations on the laws on which the grip phenomenon is based were derived, both in general and in particular.

More specifically, the following important conclusions were found:

- ➢ The grip conditions assessment is based on the analysis of the vehicle in a whole, considering it is equipped with “elastic” mechanisms as suspensions and tyres which, in turn, withstand loads whose intensity may vary from one side to the other, according to the road track configuration. These considerations, evidently, involve significant consequences on the forces exchange mechanism between tyre and pavement, and therefore on grip.
- ➢ This research involved the measurements of the instantaneous and continuous engaged grip on virtual pavements reproducing real conditions; the outcomes considered the variation of the performance parameters of the vehicle (velocity, acceleration, etc.) and therefore the Author do believe the proposed model could be of great help for the analyses traditionally carried out on road pavements. Indeed, explicitly referring to the superficial characteristics of a road infrastructure, the current practice allows the technicians to obtain only a localized assessment of the features, the overall set of output being therefore rather approximated. The development of the suggested model, on the contrary, once the congruence of its output with the results of the in situ analysis is proved correct, gives a real and continuous measurement of all the parameters which are involved into the tyre-road interaction phenomenon, so as to allow the accurate determination of every situation, no matter the boundary conditions;
- ➢ Strong is the influence on grip of both mechanical and superficial properties of road pavements; in particular, extreme attention should be paid to the negative influence of mega-texture which, in most cases, is experienced also for recent and well maintained pavements with excellent performances from the standpoint of both micro and macro-texture.
- ➢ The presence of superficial unevenness (alligator cracks, rutting, localized holes, etc.), therefore, could nullify the complex study carried out by designers in order to improve the grip performances of a road surface, thwarting all the possible improvements deriving from an accurate study on materials.
- ➢ This result, on the one hand gives a confirmation of what experienced in the current practice and on the other hand validates the effectiveness of the proposed model;
- ➢ The superficial unevenness investigation is a very important matter from the viewpoint of road safety, since depressions, corrugations and deformations strongly stress the vehicle: such unevenness is very dangerous because the generated motions bring to an irregular repartition of the stresses on tyres, causing a destabilization of the vehicle and causing its trajectory to be, as a consequence, of difficult understanding and control by the driver;
- ➢ The engaged longitudinal grip charts accurately reflect the corresponding graphs of the Italian Standards (D.M. 5/11/’02) for both the shape and the values: this consideration, once again, is a

confirmation of the fact the model does represent a perfect finite element simulation of real conditions;

- The model proposed confirmed that, in case of the variation of only the superficial micro and macro-texture characteristics and/or the changes of the tyre features, the Lamm and Herring's law, which represents a reference point in this area, is an instrument to safety advantage, compared to the proposed model itself;
- When large scale variations of road surface (mega-texture) and, more in general, higher values of superficial unevenness are experienced, the Lamm and Herring's law is precautionary only within a certain range of application: indeed, for good values of the parameter $\mu_0$, but for a superficial unevenness rate higher than 5%, the model presented in this paper gives a better and rational evaluation of grip laws.

In conclusion, the experiences carried out so far, even though perfectible, permit to corroborate the proposed model for its own peculiarity and ability of correctly simulate the real phenomena connected with road-tyre interaction.

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