# PROPOSAL OF A NEW METHOD TO ANALYZE THE ROAD SAFETY CONDITIONS RELATED TO FRICTION

P. Colonna, A. Perruccio, N. Berloco, P. Intini, V. Ranieri

***Abstract*—** This paper represents a new method to analyze the problem of friction of road vehicles. Starting from the 3rd criterion of Lamm, the new concept of "Friction Capital" was introduced as the limit performance of the road in terms of friction. The method has been implemented in a software package called Design Skid Resistance (DSR), which reliability is tested providing the reconstruction of eight real skidding accidents. The output of the DSR is the Friction Diagram that represents the percentage of "Friction Capital" that a vehicle is using traveling on a given road. This percentage is defined as $F_{USED}$. During the design step, the Friction Diagram could be used in order to quantify the risk of skidding related to a given road layout. In this paper, the authors provide an example of DSR application to an Italian rural road, and investigate the influence of the vehicle type on the Friction Diagram, since it was observed that the type of vehicle used in analyzing a road segment makes the values of $F_{USED}$ change when the boundary conditions and the road geometry change.

*Keywords*— Friction Capital, Friction Diagram, Road Safety, Road Design, Pavement Condition, Risk Perception

## I. Introduction

It is universally accepted that the contribution of the infrastructure is not the only factor affecting road safety; in fact, improvements to the infrastructure do not always lead to a reduction in accidents, and this is due to the modification of human behavior toward the assumption of more risks [1]. This confirms that it is not only the road that causes accidents, but rather the interaction between five elements: man, road, vehicle, traffic and environment [2].

The phenomenon which enables the interaction between these elements is friction. It plays a key role in road safety and in crash severity [3]; In fact, the driver's choices, based on his/her perception of the road, of vehicle efficiency, of traffic and of environmental conditions, can become manoeuvres of the vehicle if there is friction, which in turn depends on the road, vehicle and environmental conditions. In particular, the maximum friction force $F_{max}$ that the road can offer to a single wheel, is given by (1), in which $f_a$ is friction coefficient between road and wheel, and $W_a$ is the adherent weight placed on the wheel.

$$F_{max} = f_a \times W_a \quad (1)$$

It is well known that if the friction between tyre and road disappears, the motion of the wheel will not be a pure rolling motion, but it will be a rolling motion with a sliding motion; so there will be a partial reduction in the directional power of the tyre.

For a driving wheel, there will be pure rolling motion if the following conditions (2) and (3) are verified; in the following equations M represents the agent torque on wheel axis [Nm], T is the traction force caused by M [N], R is resultant of the longitudinal forces acting on the vehicle [N] and r is wheel radius [m].

$$T = M/r \geq R \quad (2)$$

$$T \leq F_{MAX} \quad (3)$$

In particular the equation (2) represents the necessary condition for the motion, instead the equation (3) represents the necessary condition for the friction between wheel and road. However, for a driven wheel the condition of pure rolling motion is (4), in which $M_R$ is the resisting moment acting on driven wheel.

$$M_R \leq F_{MAX} \quad (4)$$

The resisting moment "$M_R$" that acts on a driven wheel is due to the phenomenon of hysteresis of the tyre, and it has a very low value. Therefore, equation (4) is often verified, so it is difficult for a driven wheel to slip. In contrast, for the driving wheel (3) is not always satisfied, because "T" must have a high value to test (2). We can therefore say that the driving wheels play a key role in determining the stability of the vehicle compared to the driven wheels. Unfortunately the common driver has not a quantitative perception of the phenomenon of friction, and makes an estimate of the road conditions according to his/her senses. He/she only gets alarmed when he/she sees a wet or snow-covered road surface, and therefore tends to have an on-off type perception of the risk skidding.

In other words, when a user sees an apparently "safe surface", he/she drives without paying attention to the problem of friction, ignoring the fact that the friction between the vehicle and the road surface can fail at any moment and especially without any prior warning. Therefore it would be desirable for the user to get a measure of the available friction reserves in real time, so the driver can change his behaviour before the vehicle skids.

The study presented here aims to analyze this issue using a new method. This method puts the designer in a position to predict, already at the design stage, critical situations, or better still to inform the user about the real friction conditions of road element he/she is driving on.

## II. Material and Methods

### A. *Critical analysis of the Lamm's third criterion*

Many authors have studied friction, and among them R. Lamm has an important role. His study (the 3rd Safety Criterion of Lamm) analyzes the influence of the road surface, vehicle performance and user behaviour on the friction conditions.

He defines the road consistency by a comparison between the friction that the road can provide to the vehicle, and the friction that vehicle requires from the road. Therefore Lamm gives a yardstick for judging the safety of a road section based on the comparison between the side friction factor assumed "fRA" and the side friction factor demanded "fRD" (the nomenclature is the same as in [4]).

The first coefficient "$f_{RA}$" is the maximum friction coefficient in the cross direction that the road can provide to a vehicle under the project conditions, and it is defined by the equation (5).

$$f_{RA} = n \cdot 0.925 \cdot ft \quad (5)$$

In (5) the value 0.925 represents a reduction factor that corresponds to tyre-specific influences [4], n is the utilization ratio of side friction and ft (maximum permissible tangential fiction factor) is the design friction coefficient (6), that is a function of the design speed "SD" [4].

$$f_t = 0.59 - 4.85 * 10^{-3} * S_D + 1.5 * 10^{-5} * S^2_D \quad (6)$$

The second coefficient "$f_{RD}$" (demanded side fiction factor) is the friction coefficient that a vehicle requires from the road when it runs on a curve at the speed "S85"; "$f_{RD}$" is calculated using the next equation (7).

$$f_{RD} = \frac{S_{85}{}^2}{127 * R_C} - e \quad (7)$$

In (7) $S_{85}$ is the operating speed, $R_C$ is the radius of the curve and e is the cross slope of the road section.

As the conclusion of his study of accident data from several European countries and in the USA, Lamm comes to a classification of road consistency, divided into good, fair or poor; this classification relates the difference between the two coefficients described above and the accident rates [5, 6].

Therefore the third criterion of Lamm only allows the friction condition to be studied in a curve section and arrives at an estimate of safety, by comparing the coefficients $f_{RA}$ and $f_{RD}$. These coefficients give a conceptual measure of the friction force that the road provides the vehicle, and that the vehicle transmits to road, in the hypotheses that they depend only on the speed.

Equations (5) and (7) lead to define the Friction Potential "$F_P$" and the Friction Demand "$F_D$" (Fig. 1); in particular the first represents the force of friction that the road can provide the vehicle, while the second represents the force friction that the vehicle requires from the road. This approach to the problem leads to determine the following factors as safety measures:

- Δ is the distance between the two curve in Fig.. 1 for a given speed; in other words Δ represents the friction reserve that the vehicle can use;
- $P_L$ is the limit equilibrium point "PL"; the point at which the two curves intersect;
- "$S_L$" is the speed limit; this is the speed beyond which the friction between the vehicle and the road surface is not assured.

Then $P_L$ and $S_L$ are identified in the hypothesis that:

- coefficient of friction is exclusively influenced by the speed;
- the vehicle speed is constant;
- the vehicle can be modelled as a mass material point; therefore the geometry of the vehicle has not any influence on redistribution of vehicle weight on the single axis;
- the topography factor "n" completely describes all the possible longitudinal actions.

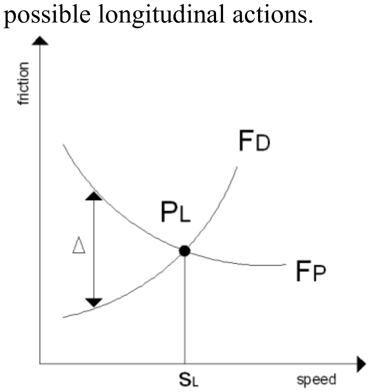


Fig. 1 - Conceptual representation of the relationship between Friction Potential and Friction Demand, varying the travelling speed (elaborated and completed based on [7]).

### B. *Presentation of the Design Skid Resistance (DSR) method*

The study presented here is an attempt to go beyond these hypotheses, and has the goal of providing a new method for analyzing the friction problem. This method consists of estimating the safety level of a road section by comparing the friction force that the road can potentially provide to a driving wheel "$F_P$" with the resultant force acting on it "$F_D$"; then "$F_P$" is a measure of "Friction Capital" available to the vehicle, while "$F_D$" is the part of "Friction Capital" used by the vehicle. The formulation of "Friction Potential" in generic direction is introduced in (8), which is given by the vector sum of the friction available in the longitudinal direction (FL) and in cross direction (FC).

$|F_P| = \vec{F_L} + \vec{F_C}$ = Wa($g$,s) x fa(c,s) = Wa($g$,s) x $\sqrt{f_{L(c,s)}{}^2 + f_{C(c,s)}{}^2}$ (8)

where:

- Wa($g$,s) = adherent weight acting on drive wheels; it varies with the speed "s" and with the road geometry "g";
- fa(c,s) = friction coefficient in a generic direction, the value of which is empirically obtained; it varies with the speed "s" and with the road conditions "$c$";
- $f_{L(c,s)}$= friction coefficient in the longitudinal direction; it varies with the speed "s" and with the road conditions "$c$";
- $f_{C(c,s)}$ = friction coefficient in the cross direction; it varies with the speed "s" and with the road conditions "c";

The Friction Potential calculated with equation (8) is the maximum value of the friction force that the tyre-road system can produce and it depends exclusively on the values of the friction coefficient and the adherent weight.
The friction coefficient is influenced by the road surface conditions, environmental conditions and the tyre wear [9]. The adherent weight is influenced by the road geometry and by the vehicle characteristics; this influence can be analyzed using a model of the vehicle similar to the one in fig. 2, which is referred to the case of a front wheel drive vehicle on an uphill road.

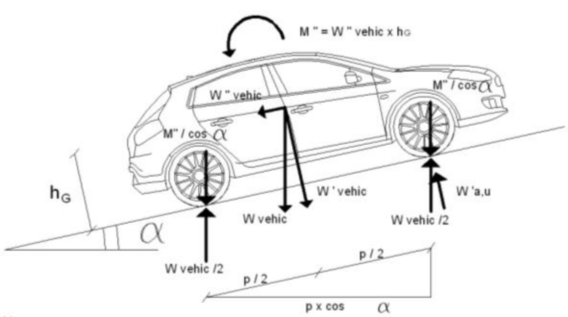


Fig. 2 - Model of the evaluation of the adherent weight "W'a,u".

To analyse the model of fig. 2 or similar models has been used the following symbols:

- $W'_{vehic,g}$= Weight of the vehicle, perpendicular to road pavement, varying the road geometry [N]
- W'a,u = Weight of the vehicle to the case of a front wheel drive vehicle on an uphill road.
- W'a,d = Weight of the vehicle to the case of a front wheel drive vehicle on an downhill road.
- P = longitudinal pitch of the vehicle [m]
- $h_g$= center of gravity height [m]
- m = mass of the vehicle [Kg]
- G = gravitational acceleration [m/s2]
- $\varphi = \sqrt{\alpha^2 + e^2}$ = geodetic slope of the roadway [rad]
- M'' = pitching moment due to the roadway slope [Nm]
- $R_{CX}$ = radius of convex connections [m]
- $R_{CV}$ = radius of concave connections [m]
- S = vehicle speed [Km/h]

This analysis has allowed the definition of the equations that provide the value of the adherent weight varying the following factors:

- Cross slope of road section "e" (9)

W'a,e = mg cos e (9)

- Longitudinal slope of the roadway "α", which causes a redistribution of weight between the front axis and rear axis going uphill (10) and downhill (11)

$$W'_{a,u} = \frac{1}{2}\cdot\left(\frac{W'_{vehic,g}}{2} - \frac{M''}{p}\right) = \frac{1}{2}\cdot\left(\frac{mG\ \cos\varphi}{2} - \frac{mG\ \sin\varphi\cdot h_G}{p}\right) \quad (10)$$

$$W'_{a,d} = \frac{1}{2}\cdot\left(\frac{W'_{vsihc,g}}{2} + \frac{M''}{p}\right) = \frac{1}{2}\cdot\left(\frac{mG\ \cos\varphi}{2} + \frac{mG\ \sin\varphi\cdot h_G}{p}\right) \quad (11)$$

- Presence of vertical curves, in which the centrifugal action causes the lightening of the vehicle in the convex connections (12) and the weighting of the vehicle in the concave connections (13); this effect reaches a maximum at the vertex

$$W'_{a,cx} = \frac{1}{4}\left(mG - \frac{m\times S^2}{R_{cx}}\right) \quad (12)$$

$$W'_{a,cv} = \frac{1}{4}\left(mG + \frac{m\times S^2}{R_{cv}}\right) \quad (13)$$

The high variability of the factors involved means that the Potential Friction cannot be described with a curve, but with an "Area of Potential Friction" (Fig. 3a). Similarly to the concept of Friction Potential the concept of "Friction Demand" has been introduced in the generic direction (14), and this gives the "Area of Friction Demand" (Fig. 3 b).

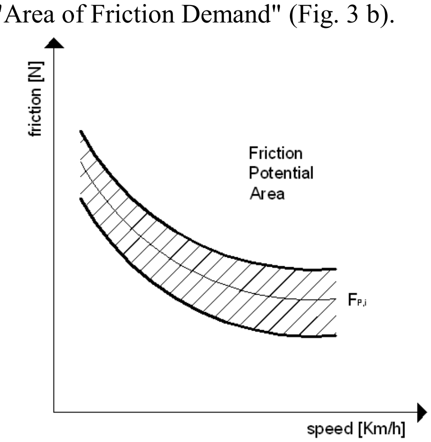


Fig.. 3a - Area of possible position of Friction Potential curve.

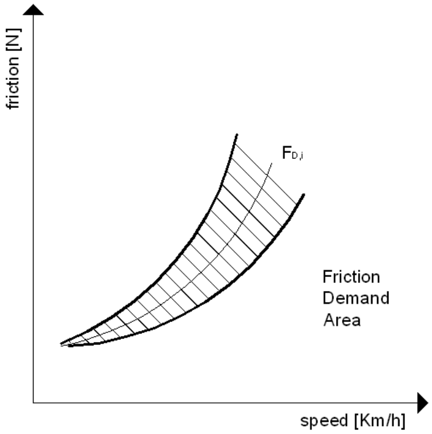


Fig.. 3b - Area of possible position of Friction Demand curve.

The Friction Demand represents the action that the vehicle transmits to and then requires from the road surface. As long as its value is smaller than the Friction Potential, the motion of the vehicle will be safe, when the value of the Friction Demand exceeds the value of the Friction Potential there will inevitably be a loss of vehicle stability.

$$F_D = \sqrt{L^2 + C^2} \quad (14)$$

where:

- L is the sum of the longitudinal forces
- C is the sum of the cross forces

Therefore this equation gives the values of Friction Demand in all road sections, including the straight sections, and takes into account all the longitudinal actions and cross actions through equations (15) and (16) [10,11].

$$L = R_2 +/- R_i + R_1 +/- R_{in} +/- R_{2(W,L)} \quad (15)$$

where:

- R2= aerodynamic resistance
- Ri= resistance due to longitudinal slope
- $R'_1$= rolling resistance due to hysteresis of the tyres
- $R_{in}$= inertial actions caused by accelerations and decelerations
- $R_{2(W,L)}$ = action due to frontal wind gusts

$$C = W_{||} +/- R_{2(W,C)} +/- F_C \quad (16)$$

where:

- $W_{||}$ = cross component of the weight force
- $R_{2(W,C)}$ = cross action of wind gusts
- $F_C$ = centrifugal force

Thus equation 14, using (15) and (16) calculates the value of Friction Demand varying the following factors:

- Plano-altimetric combination
- environmental conditions
- inertial actions due to changes in speed.

Therefore, also for the Friction Demand, given the high variability of the factor above reported, it is necessary to give rise to the concept of "Area of Friction Demand" (Fig. 3b). This area is representative of all conditions in which a vehicle can run: straight, curved, uphill, downhill, in the presence of wind acceleration, under braking etc. Therefore a complete analysis of the safety conditions requires the passage from concept of "Equilibrium Limit Point" to the concept of "Equilibrium Limit Envelope" (Fig. 4); it is identified by the intersection of the areas previously defined in Fig. 3,a and in Fig. 3,b.

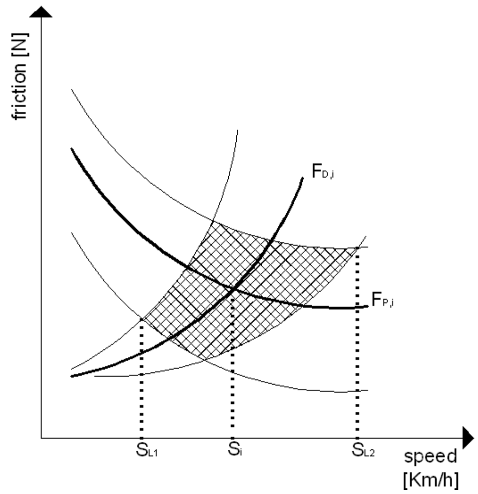


Fig. 4 - Equilibrium Limit Envelope

In other words, the high variability of the factors that influence the Friction Potential and Friction Demand, implies that, not only a $P_L$ but a set of possible limit equilibrium points can be defined for each road section. In particular, this set is delimited by $S_{L1}$ and $S_{L2}$ , where:

- $S_{L1}$ is the speed under which friction is always guaranteed;
- $S_{L2}$ is the speed over which friction is never guaranteed.

If the speed is between SL1 and SL2, the equilibrium is ensured if:

$$S \leq S_i$$

Where $F_{Pi}$ and $F_{Di}$ represent the "i" conditions and "$s_i$" is the speed at which the curves intersect.

Therefore, when a user drives along a road with a speed included between $S_{L1}$ and $S_{L2}$, he/she doesn't know his/her margin of safety with respect to skidding, because in this range of speed the stability of the vehicle is guaranteed, and even if his/her speed is very close to SL2, there are no warning signals for the risk. The risk level is defined by calculating $F_{USED}$ (17), which is the percentage of friction that the vehicle is using compared to maximum that the road can provide. In other words, $F_{USED}$ represents the portion of "Friction Capital" that the vehicle consumes in certain conditions, therefore $F_{USED}$ provides a measure of the distance from the limit condition in which FP=FD and the distance Δ between the two curves is null.

$$F_{USED} = (F_D / F_P) \times 100\ [\%] \quad (17)$$

This method has been implemented in a software package called Design Skid Resistance (DSR). The DSR draws the Friction Diagram, which represents the value of $F_{USED}$ along a road, according to the verification condition set by the designer. Safety conditions are defined by the distance of the $F_{USED}$ from its limit value which is 100%. So, in very safe situations $F_{USED}$ will have a low value; in situations in which the skidding risk is high $F_{USED}$ will have a value near 100[%]. While in situations in which vehicle stability is not ensured, $F_{USED}$ will have a value greater than its limit. The DSR takes account of the vehicle dynamics along the roadway [10,11,12] and calculates $F_{USED}$ once the following data has been set: pavement condition (fa), geometry road section (cross slope φ and longitudinal slope α), vehicle characteristics (longitudinal pitch (pL) and cross pitch (pC), height of centre of gravity (hG), longitudinal section (SL) and cross section (SC), longitudinal shape coefficient (C(N)L) and cross form factor (C(N)C), mass (m)) class of resistance tires (rolling resistance according to REGULATION CE No 1222/2009), vehicle speed, acceleration, deceleration, wind speed and wind direction. The output of the Program is a diagram of $F_{USED}$ according to the verification condition set by the designer; this diagram allows a new safety check on road design together with the speed diagram and the free visual diagram. The test simply consists of a visual check of the diagram, and then the identification of road sections for which the $F_{USED}$ values are close to 100 [%] or greater than 100 [%].

## III. RESULT AND DISCUSSION

### A. *Results from the case study: Italian Freeway A07*

In order to verify if the outputs that the DSR provides are reliable, some accidents, occurred in a curve section at the kilometer 126+500 [m] of the Italian freeway A07 Milano – Genova (Fig. 5), were reconstructed. In this road section in 2013, there were 8 accidents in total, and all accidents happened for skidding. The aim of this test (Test A) is to check if in an real skidding accident the value of $F_{USED}$ is close to its limit. Therefore to calculate the $F_{USED}$ values, all the factors influencing the Friction Potential "$F_P$" and the Friction Demand "$F_D$" were determined.

Fig. 5 – Road section considered in the test A

In particular the horizontal and vertical alignments, reported in Tab 1, were reconstructed by using a CAD. The friction coefficients were determined according to Canale et al. [13] and taking into account the pavement conditions, the tire tread conditions (information provided by police, who helped us in the accidents reconstruction) and the travel speed. Thus the value of fa was set to 0.42.

| Road element | Value |
|---|---|
| Radius of curvature | 84.50 [m] |
| Longitudinal slope | 4.5 [%] |
| Cross slope | 4.00 [%] |

Table 1 – Geometric values of road section considered in the test A

To determine the other data, essential for the reconstruction, the accident reports were required to the police. They provided the data in Tab 2: weather condition (a), pavement conditions (b), tread conditions (c), model of the vehicle (d), supposed speed (e).

| Num | a | b | c | d | e |
|---|---|---|---|---|---|
| 1 | rainy no wind | wet | good | Peugeot 206 | 65 Km/h |
| 2 | rainy no wind | wet | good | Fiat 600 | 65 Km/h |
| 3 | rainy no wind | wet | good | Bmw 320 | 65 Km/h |
| 4 | rainy no wind | wet | good | Fiat Punto | 65 Km/h |
| 5 | rainy no wind | wet | good | Alfa 147 | 65 Km/h |
| 6 | rainy no wind | wet | good | Fiat Panda | 65 Km/h |
| 7 | rainy no wind | wet | good | Mercedes SLK | 65 Km/h |
| 8 | rainy no wind | wet | good | Ford Fiesta | 65 Km/h |

Table 2 – Accident data provided by police

Thus, using the relation 8, 14 and 17 the Friction Potential "$F_P$", the Friction Demand "$F_D$" and the Friction Used "$F_{USED}$" were determined respectively (Table 3).

| Num | FP [N] | FD [N] | $F_{USED}$ [%] |
|---|---|---|---|
| 1 | 1019.74 | 1057.60 | 103.71 |
| 2 | 1210.48 | 1269.52 | 104.87 |
| 3 | 1257.05 | 1271.50 | 101.15 |
| 4 | 1213.95 | 1270.39 | 104.64 |
| 5 | 1216.37 | 1269.86 | 104.40 |
| 6 | 1179.39 | 1273.07 | 107.95 |
| 7 | 1252.02 | 1270.42 | 101.47 |
| 8 | 1517.11 | 1587.29 | 104.62 |

Table 3 - Values of Friction Potential ,Friction Demand and Friction Used relative to the accidents reconstructed in test A.

The values of $F_{USED}$ reported in the previous table are always greater than the limit values, in fact these values are included between 101.14 and 107.95; therefore it seems that the output of DSR are reliable.

However in the reconstruction of these 8 accidents the exact speed the moment of the loss of control of the vehicle, the real trajectory and the friction coefficient are uncertain.

Therefore, another case (Test B) in which a driving instructor makes his vehicle skidding in a road track (Fig. 6) was analyzed. In this case, the speed data and the trajectory, at the moment in which the vehicle skidded, were observed. In this second test the friction coefficient was set to 0.9 in according to [13] and taking into account the pavement conditions, the tire tread conditions and the travel speed.

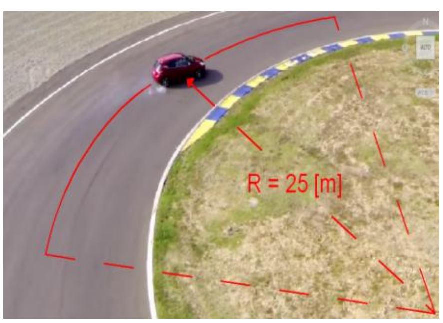


Fig. 6 – Reconstruction of the trajectory of the vehicle at the moment of skidding

The $F_{USED}$ value was calculated using the same data used in the test A; so the road geometrics characteristics, and all the boundary condition were defined; those data are reported respectively in Table 4 and Table 5.

| Road element | Value |
|---|---|
| Radius of curvature | 25.00 [m] |
| Longitudinal slope | 0 [%] |
| Cross slope | 1.00 [%] |

Table 4 – Geometric values of road track section considered in test B

| Num | a | b | c | d | e |
|---|---|---|---|---|---|
| 9 | sunny no wind | dry | good | Peugeot 208 GT | 55 Km/h |

Table 5 - Observed accident data

The values of Friction Potential, Friction Demand and Friction Used, relative to these data, are reported in table 6. In this second test the values of Friction Potential and of Friction Demand are double respect to the values, relative to the test A, reported in table 3.

| Num | $F_P$ [N] | $F_D$ [N] | $F_{USED}$ [%] |
|---|---|---|---|
| 9 | 2472,12 | 2586,88 | 104,642 |

Table 6 Values of Friction Potential ,Friction Demand and Friction Used relative to the test B

In particular the value of Friction Demand increases because the radius of the curve and the cross slope, are smaller than the values are reported in table 1. The value of Friction Potential increases because there is no a longitudinal slope, than the adherent weight do not decrease, and because the pavement is dry. Nevertheless the Friction Used do not change, and its value is included in the same range of the first test.

Therefore the study of variation of the $F_{USED}$ values, can be useful to verify the role of road geometry and of different conditions in defining the risk level.

As above explained, the output of the DSR is the Friction Diagram, that is the diagram of the variation of $F_{USED}$ along a road; in particular this diagram can be provided for different boundary condition. In Fig. 8, the Friction Diagram relative to the road section used in the test A, is reported.

In particular, it is provided for the road section (Fig. 7), which length is 200 [m] (from Start to End).

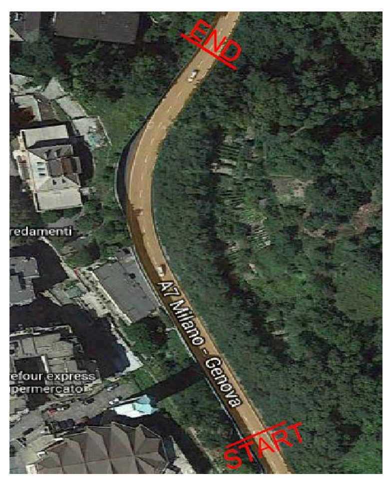


Fig. 7 - Map of the freeway A 07 Milano - Genova

In particular, the Friction Diagram is provided for the vehicle Fiat Bravo, whose characteristics are reported in table 7 and for a speed of 80 [Km/h] that is the posted speed limit.

In this diagram were reported the values of $F_{USED}$ according to two different condition:

- Dry surface, fa = 0.8 (red diagram)

- Wet surface, fa = 0.42 (blue diagram)

| | | | |
|---|---|---|---|
| C(N)L | C(N)C | hG [m] | p,long [m] |
| 0,50 | 1,15 | 0,60 | 2,60 |
| p,C [m] | m [Kg] | SL [mq] | SC [mq] |
| 1,80 | 1320,00 | 3,12 | 2,16 |

Table 7 – Fiat Bravo characteristics

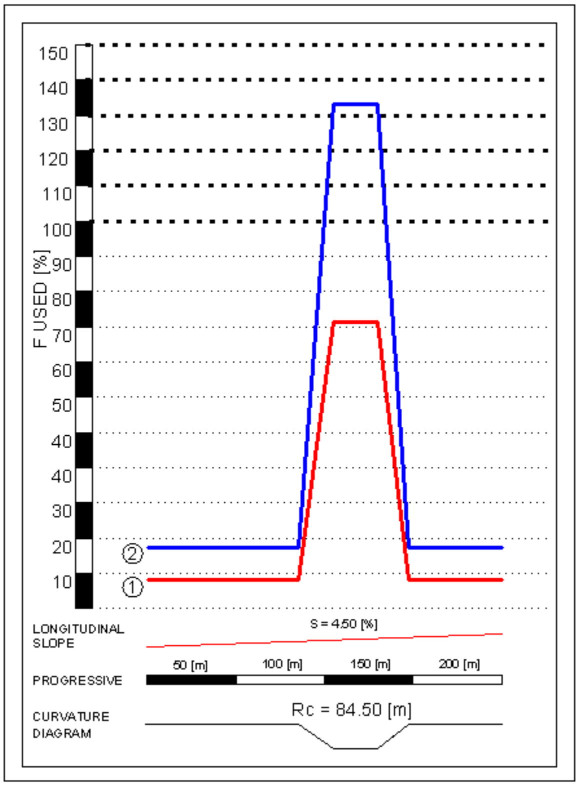


Fig. 8 - Friction Diagram in various conditions, relative to the freeway A 07 in Fig. 6

If the Friction Diagram was drawn during the design stage, then the skidding risk related to the analyzed curve, in wet the condition, would be detected.

Therefore the DSR, once calibrated, can be very useful in the design phase, or in the infrastructure management, as long as it can be employed in different ways:

- to determine any critical sections in project conditions and then identify the appropriate changes to the design;
- to identify the environmental conditions that make some sections critical and therefore to put a danger sign when these conditions occur;
- to define speed limits and safety distance limits for each vehicle type and for all weather conditions;
- to identify road sections that have priority in the maintenance
- to support the driving software used by the road navigation system when the communication system road to vehicle and vehicle to vehicle will be standard equipment [14] [15] [16].

### *B. Influence of the vehicle characteristics on the friction conditions*

In order to validate the DSR and to study the influence of the type of the vehicle on the value of $F_{USED}$, many road accidents and many road design were analyzed. The results showed that, as road geometry changes, the type of vehicle which shows greater values of $F_{USED}$ changes. Therefore to different type of vehicle are associated different the limit equilibrium envelope areas.

The influence of the vehicle characteristics on the limit equilibrium envelope areas is shown in figure 9, which shows the envelopes of some different types of vehicle obtained by using all the following boundary conditions:

- Geometric characteristics of the road section: horizontal curve on a crest curve; with horizontal radius equal to Rc = 500 [m] and radius of the vertical curve equal to $R_{CX}$ = 1500[m] (nomenclature as in [1]);
- Friction Potential Max: dry road surface (variation of the friction coefficient with the speed according to [9] );
- Friction Potential Min: wet road surface (variation of the friction coefficient with the speed according to [9]);
- Friction Demand Max: deceleration equal to 3[m/s2] and transverse wind equal to 50 [Km/h];
- Friction Demand Min: constant speed and absence of wind.

The envelope areas, while being all grouped in a small Δv (42-60[Km/h]), describe very different situations. In particular it can be noted how different the slopes of the curves $F_{PMAX}$, $F_{PMIN}$, $F_{P,MAX}$, $F_{P,MIN}$ $F_{D,MAX}$ and $F_{D,MIN}$ related to the different vehicles are.

This implies that given the same Δv (Δv>0) the Δ $F_{USED}$ related to the different categories of vehicle is different for:

- vehicles in which the $F_P$ and $F_D$ have a sub-horizontal trend, small Δv values are associated with small Δ $F_{USED}$ values, because when the speed increases, the decrease in the Friction Capital available to the vehicle and the increase in Friction Demand are very small;
- vehicles in which the $F_P$ and $F_D$ have a sub-vertical trend, small Δv values are associated with big Δ $F_{USED}$ values, because when the speed increases, the decrease of the Friction Capital available to the vehicle and the increase of Friction Demand are considerably large.

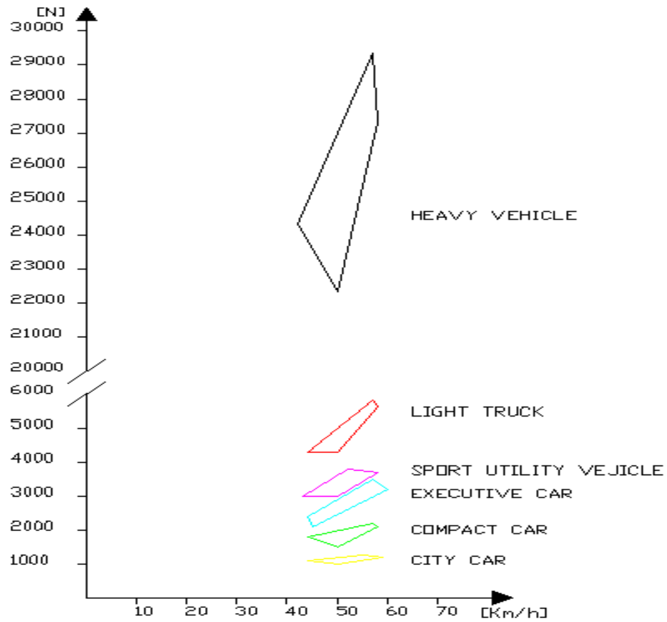


Fig. 9 - Limit equilibrium envelope areas of some different types of vehicle

This concept is explained in the following graphs (fig 10.a, fig 10.b, fig 11.a, fig 11.b) where the change in the value of the $F_{USED}$ diagram with the speed is shown in different categories of vehicle, in different combinations of the horizontal and vertical alignments and in different speed motions.

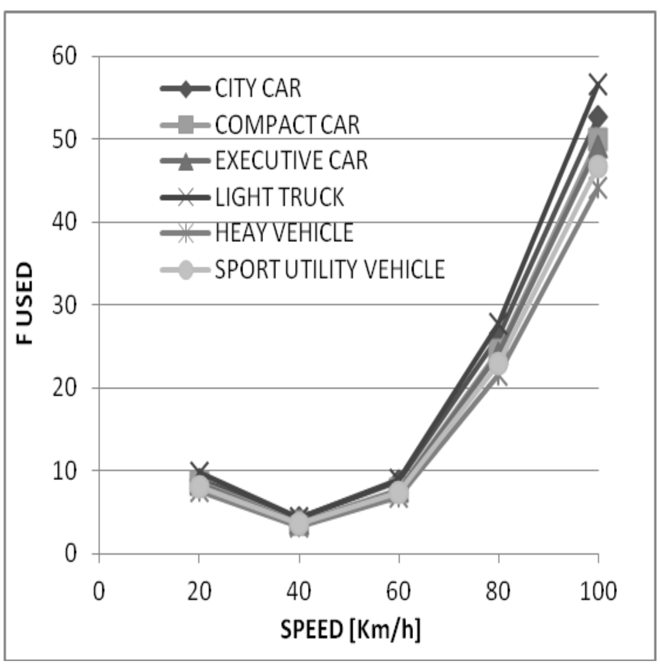


Fig. 10.a $F_{USED}$ diagram changing with speed, related to different vehicles, in the combinations of the horizontal and vertical alignments “curve on a level surface” and constant speed motion. Friction coefficient: fa = 0.72; wind speed: 0 [Km/h]; radius of the horizontal curve: R= 250 [m].

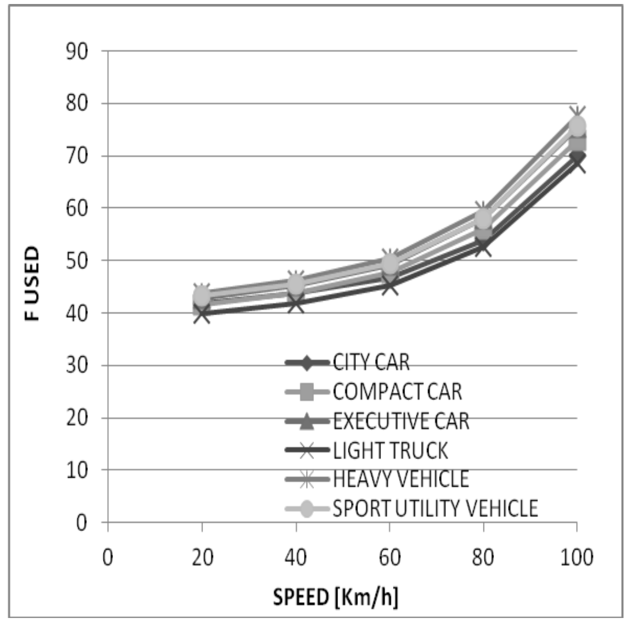


Fig. 10.b $F_{USED}$ diagram changing with speed, related to different vehicles, in the combinations of the horizontal and vertical alignments “curve on a level surface” and in braking motion. Friction coefficient: fa = 0.72; wind speed: 0 [Km/h]; planimetric radius curve: 250 [m]; deceleration: 3 [m/s2].

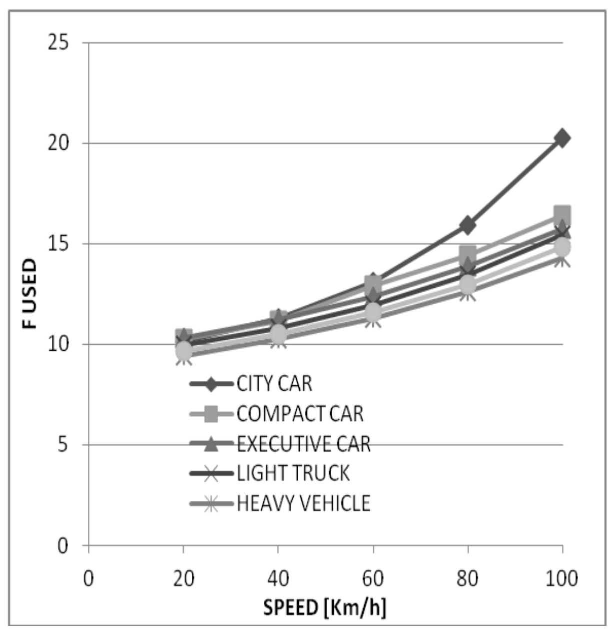


Fig. 11.a $F_{USED}$ diagram changing with speed, related to different vehicles, in in the combinations of the horizontal and vertical alignments “straight road with crest curve” and constant speed motion. Friction coefficient: fa = 0.72; wind speed: 0 [Km/h]; radius of the vertical curve: R= 1000 [m].

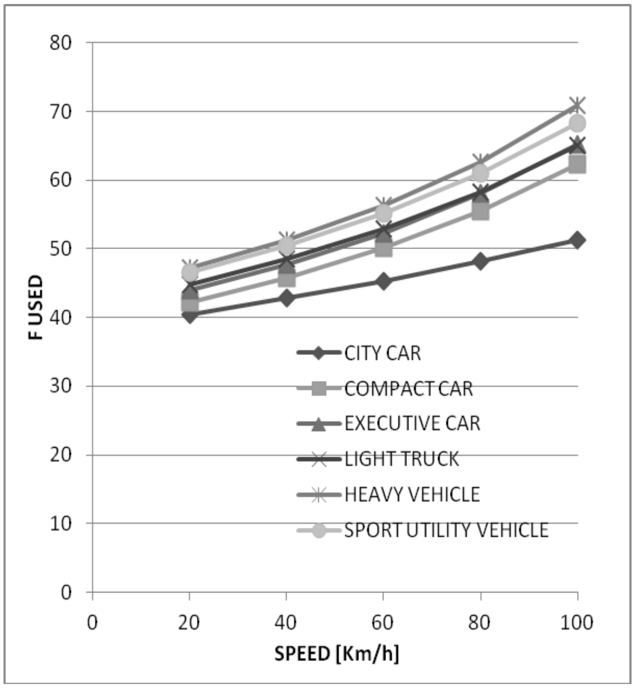


Fig. 11.b $F_{USED}$ diagram changing with speed, related to different vehicles, in in the combinations of the horizontal and vertical alignments “curve in a level surface” and in braking motion. Friction coefficient: fa = 0.72; wind speed: 0 [Km/h]; vertical radius curve: 1000 [m]; deceleration: 3 [m/s2].

In particular, the $F_{USED}$ diagrams related to the combinations of the horizontal and vertical alignments “curve on a level surface” are shown in figures 10.a and 10.b. The $F_{USED}$ graphs related to the combinations of the horizontal and vertical alignments “straight road with crest curve” are shown in figures 11.a and 11.b. Figures 10.a and 11.a are related to constant speed motion, while the figures 10.b and 11.b are related to /motion under braking.

The analysis of the diagrams show that:

- in the case: “curve on a level surface” with constant speed motion, the vehicle which shows the maximum value of $F_{USED}$ is the light truck;
- in the case: “curve in a level surface” case with braking speed motion the vehicle which shows the maximum value of $F_{USED}$ is the heavy vehicle;
- in the case “straight road with crest curve” with constant speed motion the vehicle which shows the maximum value of $F_{USED}$ is the city car;
- in the case “straight road with crest curve” with braking speed motion the vehicle which shows the maximum value of $F_{USED}$ is the heavy vehicle.
- Vehicles showing lower values of $F_{USED}$ in the case of constant speed motion have the higher values of $F_{USED}$ in the case of braking speed motion.

The results show that when the road geometry and motion conditions vary, the type of vehicle which shows greater values of $F_{USED}$ changes.

Therefore, the vehicle that should be used in the computation of the Friction Diagram, considering the combination of horizontal and vertical alignments, should be carefully selected. Otherwise, the risk of underestimating the skidding condition can occur.

A next step of this work could be identify the characteristics of the vehicle to be considered when studying the risk of skidding related to a given road layout.

## IV. Conclusion

This paper presents a new method for analyzing the friction conditions of a road, inspired by Lamm’s work [3]. The effort of the authors has been designed to provide a new approach to the problem of grip, based on assumptions less restrictive than those at the basis of the 3rd criteria of Lamm. Then the new concept of the “Friction Capital” was introduced: it represents the maximum friction force that the road provides to the vehicle according to the boundary conditions. In this method the concept of Friction Potential and Friction Demand have been made more generic; thus the Friction Potential is the measure of the “Friction Capital”, and Friction Demand is the measure of the part of capital used by the vehicle. Therefore a mathematical formulation is provided that takes into account all the variables that contribute to defining the skidding risk level: road geometry, vehicle characteristics, road surface conditions etc. The method was implemented in a software package called Design Skid Resistance "DSR", of which some applications are given. The output of the DSR package is the Friction Diagram that represents the percentage of “Friction Capital” that the vehicle is using. The DSR software has various applications from further safety verification of the design and decision on which road sections should be given priority for maintenance, to the identification of which road sections require a guard rail, as well as information in real time to the driver on safety levels.

At least, it was proved that the choice of the type of vehicle has a great influence on the Friction Diagram.

## References

[1] Noland R.B., traffic fatalities and injuries : the effect of changes in infrastructure and other trends, 2003, Results strongly refute the hypothesis that improvements have been effective at reducing total fatalities and injuries.

[2] P. Colonna, “Proposal for a safety function for evaluating the road efficiency level”, The third international conference on traffic and transportation, Guilin – Cina, luglio 2002.

[3] Yingfeng Lia, Chunxiao Liub, Liang Dinga, “Impact of pavement conditions on crash severity”, Accident Analysis and Prevention, June 2013.

[4] R. Lamm , B. Psarianos ,T.R. Mailaender, “Highway Design and Traffic Safety Engineering Handbook”, 1999, McGraw-Hill.

[5] R.Lamm, B. Psarianos, E. M. Choueiri, G. Solilmezoglou, A pratical safety approach to hoghway geometric design International studies: Germany, Grece, Lebanon and USA, Transportation Research Circular, 1998.

[6] R.Lamm, B.Psarianos, S.Cafiso, Safety evaluation process for two-lane rural roads, Transportation Research Record: Journal of the Transportation Research Board, Volume 1796 / 2002.

[7] J.W. Hall, K.L. Smith, L. Titus-Glover, J.C. Wambold, T.J. Yager, Z. Rado, 2009, “Guide for Pavement Friction”, National Cooperative Highway Research Program, Web only document.

[8] Padmanaban, S., Pawar, P., "Estimation of Tire Friction Potential Characteristics by Slip Based On-Road Test Using WFT," SAE Technical Paper 2015-26-0225, 2015.

[9] Wallman, C.G. and H. Astrom. 2001. "Friction Measurement Methods and the Correlation Between Road Friction and Traffic Safety," Swedish National Road and Transport Research Institute, VTI Meddelande 911A, Linkoping, Sweden.

[10] Jadav Chetan S. , Patel Priyal R., 2012, "Parametric Analysis of Four Wheel Vehicle Using Adams/Car", International Journal Of Computational Engineering Research.

[11] U. Kramer, D. Mary, R. Povel and W. Zimbal, "Technical Problems and Solution Attemps for the Research Programm Prometheus of European Automobile Industry", Automobile Technical Journal (ATZ) , Vol. 89 (1987) 3 , pp109-114, Germany , 1987.

[12] A.Schaar, "Driving simulation with Innovative Tools", Automobile Technical Journal (ATZ), Vol. 95 (1993)5, pp.256-262, Germany, 1993.

[13] S. Canale, S. Leonardi, F. Nicosia, "Nuovi criteri progettuali per una politica di sicurezza stradale", Atti del XXIII Convegno Nazionale Stradale dell'A.I.P.C.R., Verona - Maggio 1998.

[14] Yao Li, Jianwu Zhang, Xiqiang Guan, Estimation of Vehicle Parameters and Road Friction Using Steering Torque and Wheel Speeds, WSEAS TRANSACTIONS on SYSTEMS, January 2012.

[15] Kening Li, Jianyong Cao and Fan Yu, Adaptive Longitudinal Friction Control based on Nonsingular and FastTerminal Sliding Mode Method, WSEAS TRANSACTIONS on SYSTEMS, August 2012.

[16] Răzvan Andrei Gheorghiu, Iulian Bădescu, Radu Ş erban Timnea, Infrastructure to vehicle communications using inductive loops, WSEAS TRANSACTIONS on COMMUNICATIONS, 2014.