

# Some Remarks on Automatic Braking System Related to Pedestrian Safety

Mauro D'Apuzzo[1(✉)], Azzurra Evangelisti[1], Giuseppe Cappelli[1,2], Sofia Nardoianni[1], and Vittorio Nicolosi[3]

[1] University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
{dapuzzo,giuseppe.cappelli1,sofia.nardoianni}@unicas.it
[2] University School for Advanced Studies, IUSS, Piazza della Vittoria n.15, 27100 Pavia, Italy
giuseppe.cappelli@iusspavia.it
[3] University of Rome "Tor Vergata" Via del Politecnico, 1, 00133 Rome, Italy

**Abstract.** Collision avoidance systems (CAS) have greatly increased in automotive market since they have proven to be effective in reducing head-on crashes. An interesting application of these system has been used in pedestrian safety by means of automatic braking systems. The key operating parameter for these advanced emergency braking system is based on the Time-To-Collision (TTC) concept that, in turn, it is strongly affected by the actuated overall mean deceleration that on dry pavement surface is about 8 to 10 m/s2. However, since the corresponding stopping distance is mainly influenced by tire-road friction level, on wet pavement surfaces much lower deceleration values can be reached thus implying a dramatic recalibration of decision rules governing the operating conditions of the system. In this paper a methodology to evaluate the mean deceleration useful to estimate optimal TTC values on wet pavement surface is presented as far as an advanced emergency braking system designed to reduce the risk in pedestrian vehicle crashes is concerned. By making use of a correlation model between pavement surface characteristics and tire performance, this latter expressed by means of a conventional tire labeling value, according to current EU legislations, stopping distance and corresponding mean deceleration value can be derived on a stochastic basis. An example application is finally presented to illustrate the methodology developed.

**Keywords:** CAS · TTC · friction coefficient · braking · tire labeling

## 1 Introduction

Nowadays there is a great demand for intelligent transport systems (ITS) by car companies. ITS systems include driver assistance systems (ADAS) [1] that aim to increase safety and facilitate driving. These systems have allowed a marked decrease in accidents and injuries as they help drivers to distinguish between safe and unsafe driving situations. ITS on-board systems, most of which are mandatory on newly approved vehicles (from city cars to the most luxurious sedans, trucks and buses), are impacting a wide range of operating driving scenarios.

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Indeed, modern cars are equipped with different vehicle dynamics stability control systems. These systems regulate the forces transmitted to the tire that depend on the tire-road slip ratio. Among the numerous control systems for driving dynamics and driving safety are tire slip control systems such as Anti-Braking System (ABS) and Traction Control System (TCS) or Anti-Skid Control (ASC).

Anti-lock systems (ABS) aim to reduce the loss of friction caused by sliding; therefore, they prevent the locking of the wheels in case of sudden stop on slippery surfaces, thanks to the presence of sensors positioned on the single wheels that "interact" with an electronic control unit. This calculates the rotation speed of each wheel and, if the control unit detects the locking of one or more wheels during braking, it intervenes on the hydraulic pump to decrease the braking force. In a sudden braking, therefore, the driver will only have to worry about pressing the brake pedal without having to think about the possible locking of the wheels.

On the other hand, as far as Traction Control System (TCS) is concerned, this system intervenes on engine power and on the ignition system to reduce power if a drive wheel starts to spinning significantly faster than another.

The Anti-Skid Control (ASC), on the other hand, maintains the rotation of the drive wheel within the optimum range during acceleration, even on slippery surfaces. Regardless of the strength with which the driver presses the accelerator pedal, the ASC system intervenes on the power of the engine and on the brakes controls the acceleration of the car as efficiently as possible, ensuring that none of the drive wheels travel too far.

Other systems help to avoid accidents by alerting drivers of a potential collision and sometimes initiating a braking response. For example, these technologies include Forward Collision Warning (FCW), also known as "Safe Braking", "Collision Warning with Automatic Braking", "Pre-crash Warning Systems", "Collision Mitigation Braking System", "Predictive Warning "collision", etc. These systems combine sensors and brake controls and warn the driver in the event of an imminent collision with a visual/audible signal. The operation varies depending on the method used to detect collisions and how the vehicle is ready to stop or for a collision after an alarm is activated Alarm systems use radar, a laser, or a camera to detect previous vehicles. Braking assistance usually works in conjunction with *Anti-Lock Braking Systems (ABS)* to make braking more effective by avoiding the locking of the wheels. These are classified into two categories: electronic and mechanical, the difference is due to the method used to distinguish the "failure of panic" from normal braking, in fact, electronic brake assistance systems use an *Electronic Control Unit (ECU)* that compares the braking cases with pre-established thresholds. For example, if a driver pushes the brake hard enough and fast enough to cross the threshold, the ECU will determine that there is an emergency and increase braking power. While mechanical systems are found in older vehicles and use, as in the previous case, pre-established thresholds, but are not adaptable to individual drivers. That is, locking occurs when the valve stroke, which is related to the brake pedal push, passes to a critical point and exceeds the threshold, so the locking mechanism then provides braking assistance.

A key factor in the design of such systems is *Time-To-Collision* (TTC) [3]. Hayward (1972) [4] defined it as*: "The time required for two vehicles to collide if they continue at their speed and on the same path"*.

An analysis of the literature shows that the TTC has a maximum value of 4 s [5] and allows to distinguish situations of safety and discomfort. The most recurrent formulation of the TTC is the following:

$$TTC = t_s - \frac{d \cdot t_s^2}{2V} \tag{1}$$

where $t_s$ is the perception and reaction time, d is the deceleration and V is the initial vehicle speed.

The theory behind the determination of the TTC has been suggested by Burgett et al. (1998) [6] who believes that the alarm criteria can be summarized by considering:

- the leading vehicle that continues to decelerate at the current speed until it stops;
- the following vehicle maintains the same constant speed until the driver responds to the warning by applying the brake.
- the time required for a careless driver to respond to a warning by applying the brake pedal is 1.5 s.
- the following vehicle where the warned driver operates, must brake at a constant deceleration of 0.75 g.
- the minimum distance between vehicles during or after braking is two meters.

Given these premises, it can be observed that the TTC is a function of the vehicle deceleration, d, that, in turn, can be expressed by the following well-known kinematic relationship (according to the assumptions of uniformly accelerated motion) as a function of the Braking Distance, $D_b$:

$$D_b = \frac{V^2}{2 \cdot d} \tag{2}$$

If the vehicle is physically modelled as a point mass, the Braking Distance, $D_b$, can be evaluated (by assuming a flat road and neglecting both the vehicle aerodynamic and rolling resistances) by the following expression:

$$D_b = \frac{V^2}{2 \cdot g \cdot f_{long}} \tag{3}$$

where g is the acceleration of gravity and $f_{long}$ is the tire-road friction longitudinal coefficient.

In such hypotheses, by equaling the formulations (2) and (3) the tie between the constant deceleration in braking, d, and tire-road friction longitudinal coefficient, $f_{long}$, can be easily derived thus providing the evidence that the previously assumed constant deceleration of 0.75 g implies a 0.75 for the tire-road friction longitudinal coefficient that represents a realistic (and perhaps conservative) value for most of dry road surfaces.

However, it can be observed that tire-road friction plays a key role in the evaluation of TTC and therefore some additional remarks are needed on this issue.

The tire/road friction is a complex phenomenon, and it is affected by several factors as: the tire type, pressure, load and operating conditions, tread design, air and road temperature, vehicle velocity, road surface texture, interposed material between tire and

ground, etc. It means that the variation of even only one of these factors produces a modification of the friction force.

Meyer and Kummer [7] defined mainly two physical mechanisms responsible for tire/road friction: surface adhesion and bulk hysteresis mechanism. The first one is primarily due to intermolecular bonds between the rubber and the aggregate in the road surface; and the last one can be defined as the energy loss in the rubber deformation when sliding over the aggregate in the road.

The tire/road friction coefficient can be conventionally defined as the ratio between the friction force (longitudinal or transversal) and the normal force which occur within the tire/road contact area.

The most common tire/road friction model used in literature, takes into account that, within the tire-road contact area, during braking or traction operations, the tire deformation and slip occurs. Because of this physical phenomenon, longitudinal friction force and slip coexist, and it is possible to find a relationship between longitudinal friction coefficient μ, and the longitudinal slip rate s, defined as a percentage of the linear speed (v):

$$s = \left(1 - \frac{\omega \cdot r}{V}\right)100 \tag{4}$$

Where:

s = longitudinal slip rate (%);
r = rolling radius of the wheel (m);
ω = angular velocity of the wheel (rad/s);
v = linear velocity of the vehicle (m/s).

Following this definition, the absolute value of the slip rate belong to the interval [0, 100]: s = 0 means pure rolling (no sliding) and |s| = 100 indicates full sliding/skidding (see Fig. 1).

The evaluation of the friction coefficient assumes a crucial role for both road managers and tire producers which use different approaches to measure and estimate it. In particular, on the road agency side, a critical issue reflects the fact that in the world, several different measuring devices have been developed to evaluate tire/pavement friction and within the same country, different road management authorities use indifferently one or more of them.

To harmonize different skid measuring devices and methods, since the early 90's an international experiment [8] has been performed by the Permanent International Association of Road Congresses (PIARC). The result of this massive effort has been to identify a common scale, called *International Friction Index (IFI)* useful to convert measured of skid and macrotexture of different devices into the IFI parameter.

Further efforts have been needed to improve and update the harmonization: the standard CEN/TS 13036-2 [9] introduces the *Skid Resistance Index* (SRI) to convert the friction measured by some fixed dynamic devices into a common scale and the Standard ASTM E 1960 [10] disciplines the IFI calculation including new devices.

In particular, according to the Standard ASTM E 1960 [10], the IFI consists of two parameters; F60, which is the harmonized friction value at 60 km/h and Sp, the speed gradient coefficient related to the macrotexture of the tested surface. The IFI parameters

are calibrated using the following procedure:

$$IFI = (F60, Sp) \tag{5}$$

Where:

$$Sp = k_a + k_b \cdot TX \tag{6}$$

$$F60 = K_A + K_B \cdot FRS \ \exp\left(\frac{S - 60}{Sp}\right) + K_C \cdot TX \tag{7}$$

$Sp$ = Speed costant (km/h) related to the tested surface characteristics and given in ASTM E 1960 Appendix;

$k_a$ and $k_b$ = constants depending upon the method used to determine the macrotexture;

$TX$ = Macrotexture value (mm).

$F60$ = Friction Number (dimensionless),

$K_A$, $K_B$ and $K_C$ = calibration constants for a particular device and given in ASTM E 1960 Appendix;

$FRS$ = measure v.ed friction value at slip speed S,

$S$ = slip speed between tire and road surface (km/h).

Instead, on the tire industry side, the friction estimation becomes significant within the tire performance evaluation. For this reason, a different *Wet Grip Index* (*WGI*) has been defined within *Tire Labeling* procedures. In fact, with the aim to harmonize information about wet grip, external rolling noise and fuel consumption, and to assist end-users in tire choice, several regulations have been issued and now are mandatory throughout Europe.

In particular, according to the Regulations (EC) No 1222/2009 [11] and No 228/2011 [12], the *Wet Grip Index* (or *G* as titled in the Regulations), can be evaluated as:

$$WGI(T) = \frac{\left[125 \cdot \frac{\mu_p(T)}{\mu_p(R)} + k_1 \cdot (t - t_0) + k_2 \cdot \left(\frac{\mu_p(R)}{\mu_p(R_0)} - 1\right)\right]}{100} \tag{8}$$

Where:

$\mu_{p(T)}$ = peak braking force coefficients for the candidate tire;

$\mu_{p(R)}$ = the peak braking force coefficients for the reference tire;

$t$ = wet surface temperature (°C);

$t_0$ = wet surface reference temperature condition (20 °C for normal tires, 10 °C for snow tires).

$\mu_{p(R0)}$ = peak braking force coefficient for the reference tire and surface (= 0.85);

$k_1$ and $k_2$ = coefficients for temperature and surface adjustments given in Regulation No 228/2011.

It is important to observe that, according to the regulation and in the ASTM standards [11–13], the most important conditions of the test are: the Standard Reference Test Tyre (SRTT) as reference tire; 180kPa as tire inflation pressure; 547 dN (± 5%) as test static wheel load; 65 ± 2 km/h as test operating speed and 1 mm ± 0,5 mm as water film thickness.

**Table 1.** Wet Grip Classes [11].

| WGIndex | WG class C1 tires |
|---|---|
| *1.55 ≤ WGI* | *A* |
| *1,40 ≤ WGI ≤ 1.54* | *B* |
| *1,25 ≤ WGI ≤ 1.39* | *C* |
| *Empty* | *D* |
| *1,10 ≤ WGI ≤ 1.24* | *E* |
| *WGI ≤ 1.09* | *F* |

According to the Regulation [11], a wet grip classification of tires, based on the WGI, has been proposed and summarized in the Table 1.

Previous efforts have be done to define friction prediction models [14, 15] and, in particular, the European project FRICTION was sponsored for developing an on-board system to measure and evaluate tire/road friction [1]. The FRICTION system was based on three parameters as defined:

Friction used = tire/road friction currently used and it is mainly evaluated using standard vehicle based driving dynamics sensors;

Friction Potential = maximum tire/road friction available which is not directly measured.

Friction available = friction gap between potential and used.

These definitions are represented in the Fig. 1.

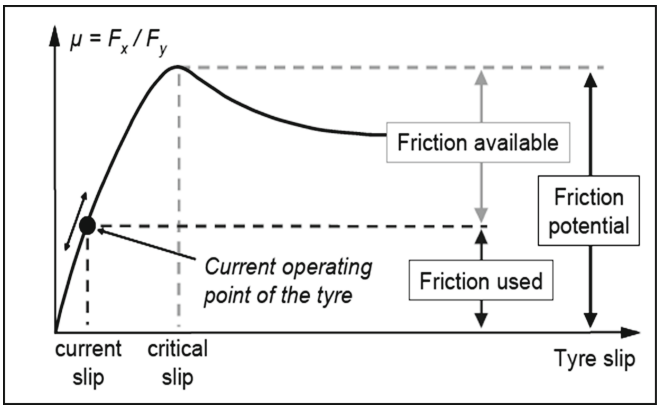



**Fig. 1.** Explanation of Friction definitions according to [1].

Usually, due to the impossibility of measuring the Potential Friction, the active safety systems contains proprietary algorithms for its estimation, which use indirect methods based on on-board vehicle information (as longitudinal and lateral motions, wheel speed and steering angle, environmental sensors and vehicle to vehicle communication).

Nowadays, different algorithms to estimate the road friction have been proposed, but the knowledge of the maximum available friction value (Potential) and of its reliability is still lacking and however this parameter is of paramount importance for TTC devices design. In this paper a novel methodology to tackle this problem is proposed.

## 2 Objective

The main aim of this work is to propose a methodology for the estimation of the potential friction value and therefore the corresponding deceleration rate and, at the same time, its variability range, which can be used by the automobile industries for the design of more efficient and safer TTC systems. Relevant novel features of the proposed method are the following:

- the evaluation of the maximum friction value is carried out for road wet condition.
- the corresponding probability density function is derived in order to allow the identification of plausible threshold design;
- the estimation of friction epitomizes the combined actual knowledge level on tire-road friction of the road agencies and tire industries.

## 3 Methodology

The general framework of the proposed methodology that can be easily decomposed in several calculation step is described in the followings.

The starting point of the methodology is represented by the probability density function of the Friction Number, FN measured by national Road Agencies. FN is intended to be the wet road-tire friction value collected by a friction measuring device (under specific tire and test operating conditions), currently used by Road Authorities, among those that participated to the PIARC Friction Harmonization Experiment. It is worth to remind that almost all National Road Agencies worldwide routinely collect wet road friction data for pavement works quality assurance and maintenance purpose. The amount of friction data collected on the national road network at different measurement speeds helps to define the so called "Friction Evaluation Background", FEB, that is used to define the friction values to be adopted in the National Road Design Standards and therefore each FEB, also reflects the pavement maintenance policy adopted by the specific country [16].

By making use of the (5) – (7) each FN value collected at a specific speed can be easily converted into equivalent F60 value that represents the corresponding International Friction Index measured at 60 km/h.

It has observed that a good empirical correlation exists between the F60 value and the peak friction value provided by the SRTT tire used within the Tire Labeling Procedure, namely μp(R), measured at 65 km/h, by means of the following relationship [17]:

$$\mu_P(R) = 1.3683 \cdot F60^{0.5967} \tag{9}$$

By rearranging (8), once that a specific tire grip class has been specified, it is possible to estimate the peak friction value for a conventional tire of i-class, μp(Ti), by the following formulation:

$$\mu_{p(Ti)} = \frac{\mu_{p(R)}}{125}\left[WGI_i \cdot 100 - k_2\left(\frac{\mu_{p(R)}}{0.85} - 1\right)\right] \tag{10}$$

where WGIi is the Wet Grip Index of i-class, according to Regulations (EC) No 1222/2009 [11] and No 228/2011 [12] and therefore it represents an information that is clearly available for the owner of the vehicle, once that the new tire set has been purchased and mounted on the vehicle itself.

Recalling the (2), the equivalent constant deceleration rate, d, that can be employed in the previous reported TTC formulation can be evaluated as:

$$d = \frac{V^2}{2 \cdot D_b} \tag{11}$$

where, $D_b$ is the braking distance and $V$ is the initial vehicle speed. However, if the $D_b$ has to be estimated on wet pavement surfaces by means of a point-mass vehicle model, motion resistance forces other than friction cannot be neglected and have to be taken into account. Basing on these premises, it can be easily demonstrated that the *Braking Distance*, $D_b$, can be calculated by the following relationship:

$$D_b = \int_{V_{ini}}^{0} \frac{V \cdot dV}{g\left[r_r(V) \pm i + \mu_{p(Ti)}(V) + \frac{\rho \cdot C_x \cdot A_f \cdot V^2}{2 \cdot W_v}\right]} \tag{12}$$

where:

$V$ is the vehicle velocity i.e. the integration variable (m/s),

$V_{ini}$ is the initial vehicle speed (m/s),

$g$ is the acceleration of gravity (m/s$^2$),

$r_r(V)$ is rolling resistance coefficient (dimensionless) that in most of analytical formulations can be expressed as a function of tire and road surface properties and of vehicle speed itself, $V$,

$i$ is the road longitudinal slope (dimensionless),

$\rho$ is the air density (kg/m$^3$),

$C_x$ is the aerodynamic drag coefficient (dimensionless),

$A_f$ is the vehicle frontal area (m$^2$),

$W_v$ is the weight of the vehicle (kg m/s$^2$), i.e. the vehicle mass, $M$, multiplied by the acceleration of gravity, $g$,

$\mu_{p(Ti)}(V)$, is the peak friction value for a conventional tire of i-class on wet surfaces (dimensionless), according to the tire labeling procedure that is a function of vehicle speed itself, $V$.

On this latter term, some additional observations are needed.

In the evaluation of Braking Distance, $D_b$, according to (12), the peak friction values has been employed. The choice of selecting the higher peak friction value that is reached for a critical slip (see Fig. 1) instead of the lower terminal value that is reached in full sliding/skidding condition, is justified by the worldwide diffusion of the anti-lock braking systems (ABS) in nowadays circulating vehicles.

Indeed, it has to be reminded that tire-road friction on wet surface is strongly affected by vehicle speed, $V$, if all the other influencing factors are keep constant. With vehicle velocity increasing, hydrodynamic pressure at the tire road interface builds up and therefore the detachment between the tire and road surface gradually affects the entire tire footprint area, till tire hydroplaning is reached. This implies a marked diminution of

tire-road friction as the vehicle speed increases as evidenced by all previous studies on this matter.

Among the several empirical and analytical models proposed to capture the velocity dependence of sliding friction values on wet road surfaces, the exponential Penn-State model (that also provided the theoretical background for the International PIARC Friction Harmonization Experiment) [8], is the most reliable. Recently this model has also proved to be effective in capturing the velocity dependence of peak friction values on wet surface and therefore the friction term appearing in the (12) can be easily expressed as [18]:

$$\mu_{p(Ti)}(V) = \mu_{p(Ti)0} \cdot e^{-K \cdot V} \tag{13}$$

where

$\mu_{p(Ti)0}$, is the peak friction value at null velocity i.e. when the wheel is stopped ($V = 0$) that is similar to the maximum dry friction value since there is a full contact in the tire footprint area [20],

$K$ is a calibration constant that can be easily derived, once that the peak friction value for a specific vehicle speed is known.

It is worth to be noticed that, basing on these premises, the evaluation of the Braking Distance, $D_b$, by means of (12) can be tackled only by a numerical approach. However, once that the $D_b$ has been calculated for a specific tire set and vehicle and according to different values of the initial vehicle speed, $V_{ini}$, in order to speed-up the evaluation of *Braking Distance* an *Equivalent Longitudinal Friction Coefficient*, $f_e$, can be derived as a function of the initial vehicle speed only, $V_{ini}$:

$$D_b = \frac{V_{ini}^2}{2g(f_e(V_{ini}) \pm i)} \tag{14}$$

where

$V_{ini}$ is the initial vehicle speed (m/s),

$g$ is the acceleration of gravity (m/s$^2$),

$i$ is the road longitudinal slope (dimensionless),

$f_e(V_{ini})$ is the *Equivalent Longitudinal Friction Coefficient* (dimensionless) that is a function of initial vehicle speed only, $V_{ini}$, and can be evaluated by means of the following expression:

$$f_e(V_{ini}) = \frac{V_{ini}^2}{2g \cdot D_b} \mp i \tag{15}$$

$V_{ini}$ is the initial vehicle speed, $g$ is the acceleration of gravity, $i$ is the road longitudinal slope and $D_b$ is the *Braking Distance* numerically calculated by the (12).

By equaling (2) and (14), it can be easily observed that a more rigorous estimation of the constant deceleration rate, $d$, useful for the *TTC* evaluation, can be obtained by the following expression:

$$d = g(f_e \pm i) \tag{16}$$

where

$g$ is the acceleration of gravity (m/s$^2$),

$i$ is the road longitudinal slope (dimensionless),

$f_e$ is the *Equivalent Longitudinal Friction Coefficient* (dimensionless) that, recalling all the previously described procedure, is, in turn, dependent on:

- the initial vehicle speed, $V_{ini}$,
- the *Friction Number*, *FN*, measured on the road surface by national Road Agencies,
- *Wet Grip Index* of i-class, $WGI_i$, for the tire set mounted on the vehicle,
- the features of the specific vehicle examined, expressed in terms of, weight, rolling resistance, aerodynamic resistance properties.

Therefore, once that a specific vehicle characteristics and *Tire Wet Grip Class* have been defined, a parametric analysis can be performed in order to obtain an $f_e$ estimation according to different values of initial vehicle speed, $V_{ini}$, and *Friction Number*, *FN*.

If a reliable regression model can be fitted following the parametric analysis, the probability density function of $f_e$ can be easily derived by a transformation of stochastic variables from the probability distributions of *FN* values, for each specific value of initial vehicle speed, $V_{ini}$.

In order to demonstrate the effectiveness of the proposed methodology, an application study is reported in the following section.

## 4 Case Study

To represent a realistic case study, the values used to describe the pavement road features has been chosen as follows: the Texture value (TX) has been supposed constant and equal to MPD = 0.5 mm (which can be considered a plausible and average value for most

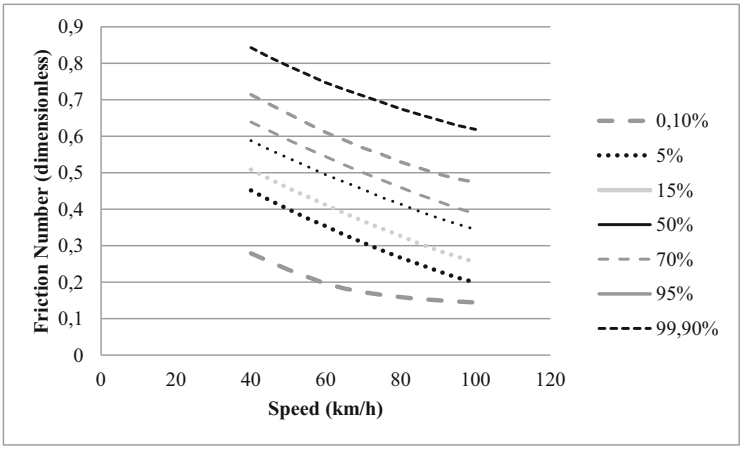



**Fig. 2.** Friction Evaluation Background, FEB, for Germand Road Network. Skid-resistance vs vehicle speed curves have been depicted according to the several percentiles derived by the statistical analysis of the overall tire-road friction data collected by Road Agencies throught standard tire-road friciton measuring devices [16].

of road pavement) and the Friction Number (FN) has been derived from the probability density curve of real pavement at different speed [16]. A typical FEB representation is depicted in the Fig. 2 for German road network.

For example, by choosing a speed of 60 km/h, and referring to the values indicated in Fig. 2, it is possible to obtain the probability density curve represented in Fig. 3.

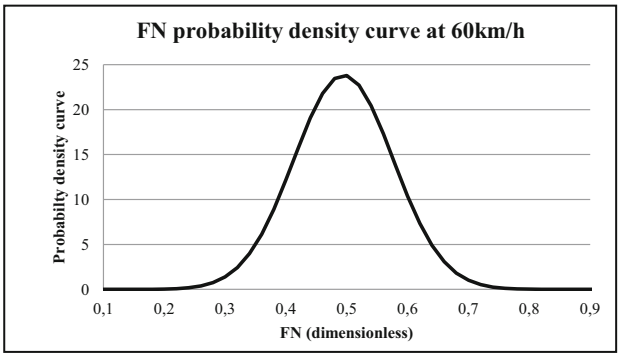



**Fig. 3.** Probability density curve of FN at 60 km/h extracted by the German FEB.

A set of eleven *FN* has been selected from the curve (from 0.2 to 0.7 with a step of 0.05), by means of the (6) and (7) the relative eleven IFI values have been evaluated and, for each one, the peak friction value μp(R) provided by the SRTT tire, measured at 65 km/h, has been calculated by (9).

Two different tire classes has been chosen among the values presented in the Table 1. The class C and the class E have been selected and the mean value of WGI for each class has been evaluated and used in the application. In particular, 1.32 and 1.17 have been selected as WGI values, for C and E tire classes respectively.

Then, by using the (10), the eleven peak friction values for a conventional tire of both classes, namely, $\mu_{p(TC)}$ and $\mu_{p(TE)}$, respectively have been evaluated.

A conventional sedan car has been selected in order to evaluate the *Braking Distance*, $D_b$, according to the different initial vehicle speed $V_{ini}$, Tire Grip Class, *WGI*, and *FN* value by numerically evaluating the integral reported in Eq. (12).

As an example, the *Equivalent Longitudinal Friction Coefficient* as a function of initial vehicle speed $V_{ini}$, $f_e(V_{ini})$, curves for both tire classes and $FN = 0.5$, have been reported in the Fig. 4.

Observing the trend in the Fig. 4, the analytical function used to represent the *Equivalent Longitudinal Friction Coefficient*, $f_e(V_{ini})$ can be effectively described by a the negative exponential form:

$$f_e(V_{ini} = a + b \cdot e^{cVini}) \tag{17}$$

Where a, b and c are function of the FN.

In particular two different calibrations, for both tire classes, have been performed and the results have been summarized in the Tables 2 and 3.

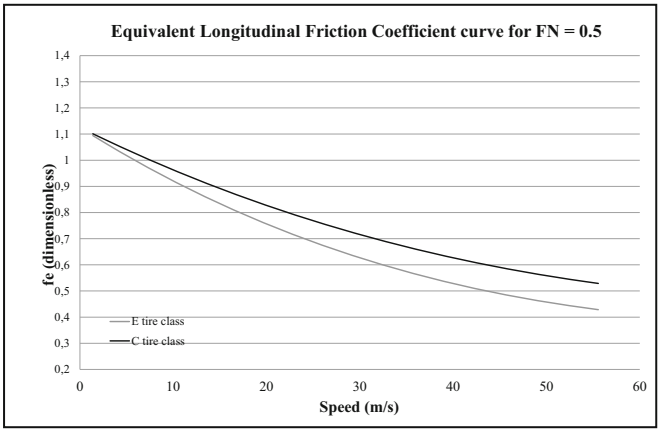



**Fig. 4.** Equivalent Longitudinal Friction Coefficient vs Initial Vehicle Speed curves for C and E tire classes and FN = 0.5.

**Table 2.** Calibration Values for C tire class.

| Function | Coeff. | Value |
|---|---|---|
| $a = A\,FN + B$ | $A$ | *0,571* |
| | $B$ | *0,0045* |
| $b = C\,FN + D$ | $C$ | $-0,5926$ |
| | $D$ | *1,1371* |
| $C = cost$ | $cost$ | $-0,025$ |

**Table 3.** Calibration Values for E tire class.

| Function | Coeff. | Value |
|---|---|---|
| $a = A\,FN + B$ | $A$ | *0,3216* |
| | $B$ | *0,059* |
| $b = C\,FN + D$ | $C$ | $-0,3463$ |
| | $D$ | *1,0864* |
| $C = cost$ | $cost$ | $-0,028$ |

Once that $f_e$ formulations have been derived as a function of *FN*, *Tire Grip Class*, *WGI*; and initial vehicle speed, $V_{ini}$, if the probability density function of *FN* is known, it is possible to perform a transformation of random variables to evaluate the probability density curve of the constant deceleration rate, $d$, (see (16)). Results obtained for a flat road (longitudinal slope, $i, = 0$), at four different initial vehicle speed values have been summarized in the following figures.

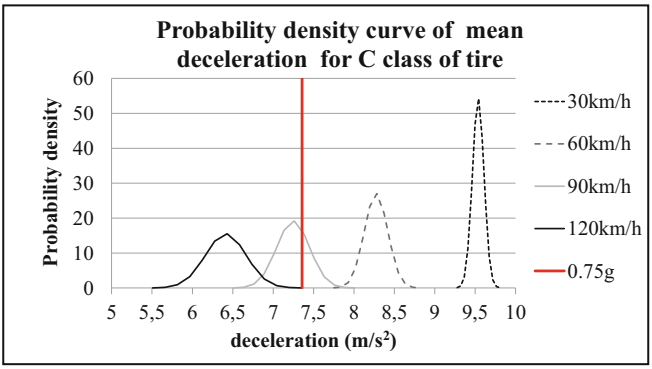



**Fig. 5.** Probability density curve of the deceleration rate for the C tire class for different initial vehicle speed values.

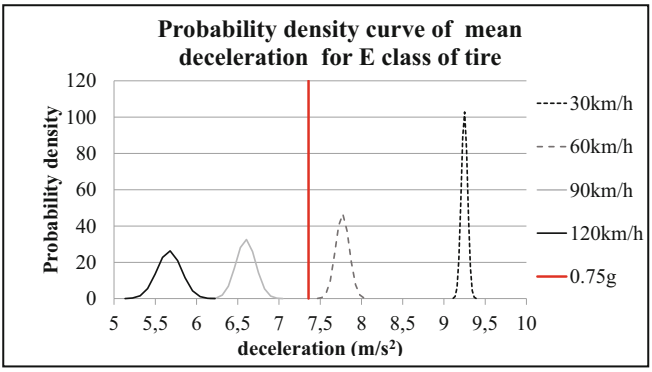



**Fig. 6.** Probability density curve of the deceleration rate for the E tire class. for different initial vehicle speed values.

It is worth to underline by observing these results that the constant deceleration of 0.75 g, usually adopted for the TTC evaluation (red line in the Figs. 5 and 6), appears a rather non-conservative values in case of high vehicle speed and wet road pavement.

The evaluation of the corresponding cumulated probability i.e., the probability to have a constant deceleration rate lower than 0.75 g, is expressed according to different initial vehicle speed and Tire Grip Class values in the Table 4:

**Table 4.** Probability to have a constant deceleration rate lower than 0.75 g for both tire classes.

| 30 km/h | 60 km/h | 90 km/h | 120 km/h |
|---|---|---|---|
| *Class tire C* | | | |
| *1,553E-201* | *1,260E-10* | *7,070E-01* | *9,999E-01* |
| *Class tire E* | | | |
| *0,000E + 00* | *4,614E-07* | *1,000E + 00* | *1,000E + 00* |

## 5 Conclusion

An innovative methodology for the estimation of the potential friction value and therefore the corresponding deceleration rate, useful for TTC evaluation, has been presented.

Starting from a probability density function of the *Friction Number* for wet road pavement, collected at different operating speed, the probability density function of the equivalent friction coefficient (directly related to the deceleration rate) has been calculated for different initial vehicle velocities and tire grip classes.

The proposed methodology has been applied at two tire class (C and E) and to four different vehicle initial speed values (30 km/h, 60 km/h, 90 km/h and 120 km/h). As it is possible see from Figs. 5 and 6, the conventional fixed deceleration rate value for the TTC evaluation, equal to 0.75 g, is fairly non- conservative in case of high vehicle speed and wet road pavement.

The proposed methodology shows several improved aspects:

- may take into account actual operating conditions (in some cases stricter than the standard ones, as the wet road pavement);
- the real variability of the road friction, achieved from conventional tire, has been considered;
- the system can be useful in case of on-board vehicle friction measurement device failure.

The preliminary results obtained have been encouraging, and future research developments will focus on the study of the influence of: water thickness, effects of braking distribution systems on the variability of friction and braking performance of the vehicle.

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