A GLOBAL APPROACH TO WARN THE DRIVERS BEFORE A CURVE BY CONSIDERING THE DECREASE OF SKID RESISTANCE DUE TO THE RAIN

Veronique Cerezo[1]
CETE of Lyon - Département Laboratoire de Lyon, 25, avenue François Mitterrand, Case n°1, 69534 Bron – FRANCE
veronique.cerezo@developpement-durable.gouv.fr

Minh-Tan Do
IFSTTAR, Department Infrastructures and Mobility, Route de Bouaye, CS4, 44344 Bouguenais – FRANCE
minh-tan.do@ifsttar.fr

Eric Violette
CETE Normandie Centre, BP 245, 76121 Grand Quevilly Cedex – FRANCE
Eric.violette@developpement-durable.gouv.fr

Submitted to the 3rd International Conference on Road Safety and Simulation, September 14-16, 2011, Indianapolis, USA

Keywords: Warning system, skid resistance, speed limit, experimentation

ABSTRACT

This paper presents the results of a research project called IRCAD, which aimed at developing a global system to warn drivers in real time, when their behaviour is not adapted to infrastructure characteristics. The warning system is based on the comparison between the speed of a vehicle before a curve and a safety speed. This safety speed is defined as the maximum speed value before crash all along the curve (safety speed profile). These thresholds values of speed are calculated in real time depending both on constant parameters like infrastructure geometry (radius of curvature, cross and longitudinal slopes) and changing parameters like skid resistance, which is evolving with the weather conditions (wind, rain).
This study is divided into three parts.
In a first step, a water-depth model was developed to predict the water film thickness in the curve taking into account the road geometry and the rainfall intensity.
On a second step, the skid resistance decrease due to the water film is evaluated. Then, the maximum speed is calculated by considering these corrected friction values.
In a third step, experimentation is realized on two sites located on French secondary roads. To conclude, this system is proved to be very efficient and useful considering the fact that the models use data easy to obtain for road managers and that the warning sign only starts when the situation presents a real risk.

[1] Corresponding Author

CONTEXT

The IRCAD project (French acronym meaning “driver information about risk under adverse weather conditions”) is part of the national PREDIT program named SARI (Gallenne et al., 2007). The project aims at developing tools assessing risks due to rainfall on a road section and associated driver-information system. It is well known that rain induces accident risk. A statistical study (Violette, 2002) shows more precisely that the number of accidents is higher after a rainfall than during it. This observation is explained by the fact that the road surface is still wet after a rainfall. Thus, road pavement does not recover its skid-resistance level under dry weather. Most of the drivers do not detect this risk and loss of control of a vehicle results from inappropriate manoeuvres requiring more skid resistance than what is available.

The methodology proposed in IRCAD project aims at informing drivers about slip risk and inciting them to reduce speed when they approach a road section judged as slippery. This information already exists through the presence of road signs indicating a speed limit or a slippery road. However, the main drawback of these signals is their permanent presence to which drivers tend to pay less attention in time. Warning messages must be then displayed only when it is necessary. Considering a so-called “permissible speed” which can be modulated by the road skid resistance, warnings will be activated only when the vehicle speed is above the permissible speed.

Literature is abundant about speed calculation based on road characteristics. Formulae take into account in most cases geometrical parameters like curve radius, longitudinal and cross slopes. In the IRCAD project, a new speed calculation method is proposed in view of being implemented in an information system. In addition to geometrical parameters, the new inputs of this method are meteorological data and the actual road skid resistance, which is influenced by weather conditions, mostly the road wetness. This paper presents the development of the method and its application to real case.

STATE OF THE ART

Since the main purpose of the IRCAD speed-calculation method is to modulate the permissible speed by the road wetness, the state of the art presented in the following sections is focused on the connection between speed, geometry, skid resistance and wetness.

Relationship speed/geometry/skid resistance

First of all, it is necessary to specify the speed notion used in various published calculation formulae. The state-of-the-art made by Louah (2009) shows three definitions of speed:

- design speed: speed used to determine minimal geometrical characteristics of a road section;
- legal speed: speed limit depending on the road type (2 lanes, 2×2 lanes, etc.) or a specific road section (curve for example);
- travelled speed: speed adopted by road users essentially based on their own perception of infrastructure.

Formulae found in literature are related to the travelled speed expressed by its mean value or, in most cases, by its so-called V_{85}, which is the speed value under which practice 85% of drivers. Only formulae frequently used in France (Louah et al., 2009) are presented here:

(1) $$V_{85}(km/h) = \frac{k}{\left(1+\frac{346}{R^{1,5}}\right)}$$

where R : curve radius in meter;

k : constant depending on the road type (k = 120 for 2×2-lanes road, k = 102 for 3-lanes road or 2-lanes road whose total width is between 6m and 7m, k = 92 for 2-lanes road whose total width is of 5m).

A formula exists also to calculate V_{85} as a function of road longitudinal slope:

(2) $$V_{85}(km/h) = k - 0{,}31 \cdot p^2$$

where p : longitudinal slope expressed in % ;

k : same constant than in (1).

Moreover, Chesterton et al. (2006) mentioned formulae to calculate speed limit mainly related to vehicle loss of control due to aquaplaning:

- formula from Gallaway (1979)

(3) $$V = 0{,}9143 \cdot SD^{0,04} \cdot P^{0,3} \cdot (TD + 0{,}794)^{0,06} \cdot A$$

where:

(4) $$SD = \frac{W_d - W_w}{W_d} \cdot 100$$

and V: aquaplaning-onset speed (km/h);

W_d: wheel rotating-speed on dry surface;

W_w: wheel rotating-speed on wet surface;

P: tire inflation pressure (kPa);

TD: tire tread depth (mm);

A: parameter depending on road texture, road geometry and rainfall intensity.

- formula from Anderson et al. (1998)

(5) $$HPS = 26{,}04 \cdot WFD^{-0,259}$$

where HPS: aquaplaning-onset speed (mph : miles per hour);

WFD: water depth (inch).

The equation (5) is developed for water depths under 2.4mm. For higher water depths, the Gallaway equation (3) is recommended.

- formula from Ivey et al. (1975)

(6) $$S_V = \frac{2000}{i^{0,68}} \cdot \frac{40}{V_i}$$

where S_v: visibility distance (ft);

i: rainfall intensity (inch/hour);

V_i: vehicle speed (miles/hour).

Skid resistance and road wetness

Theoretically, the relationship between skid resistance and road wetness is deduced from the contact scheme between a tire and a road surface in the presence of water (Fig. 1). The contact conditions in the three zones are the following (Fig. 1):

- zone 1: zone where water is accumulated and tends to lift up the tire;
- zone 2: zone where water is evacuated progressively until the water film becomes discontinuous;
- zone 3: zone where contact is established between the tire and the road asperities. Friction is mainly generated in this zone.

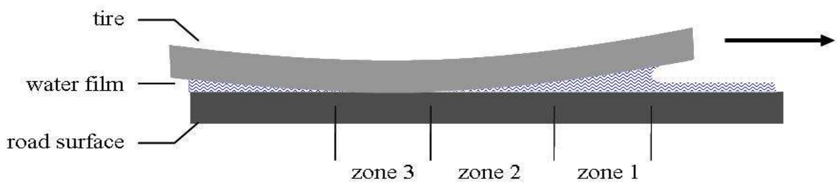

Figure 1. Scheme of tire/wet road contact

The friction coefficient μ measured on a wet road is then related to the friction coefficient μ_{dry} measured on a dry road by the following relation:

(7) $$\mu = \mu_{dry} \cdot \left(\frac{A_3}{A_1 + A_2 + A_3} \right) = \mu_{dry} \cdot \left(1 - \frac{A_1 + A_2}{A_1 + A_2 + A_3} \right)$$

where A_i (i = 1, 2, 3) : size of zone « i ».

The term $(A_1 + A_2)/(A_1 + A_2 + A_3)$ is the fraction of the contact area occupied by the water and then can be related to the road wetness.

In practice, few formulae exist to express the skid resistance/road wetness relationship. This limitation is due probably to the measurement of a water depth characterizing the road wetness. Indeed, the notion of "water depth", even widely employed, does not have any universal definition. On figure 2, two water depths can be defined: the "mean" water depth, taking into account the road surface macrotexture, and the thickness of the water film above the road surface summits. In the formulae given in the following sections, the exact definition of the water depth is not always provided by the authors.

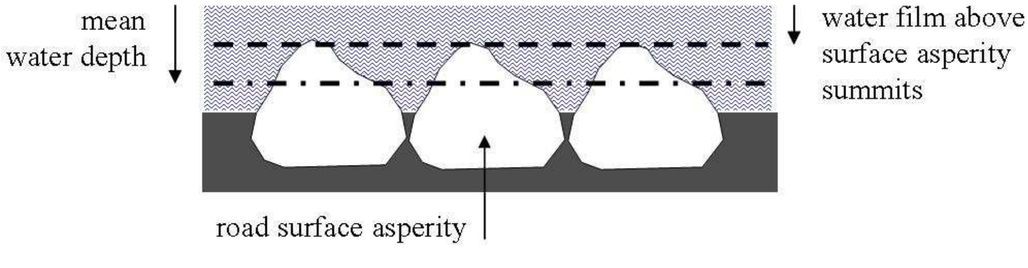

Figure 2. Water depth definitions from Veith (1983)

Veith (1983) shows that the friction coefficient varies linearly and decreasingly with the logarithm of the water depth. This author observes also that the slope of this linear tendency increases with the test speed. No formula was proposed for these experimental observations.

From their laboratory and on-site test data, Kulakowski and Harwood (1990) proposed the following formula:

(8) $$\mu(h) = \Delta\mu \ e^{-\beta h} + \mu_F$$

where $\mu(h)$: friction coefficient as a function of water depth;

h : water depth;

$\Delta\mu$: difference between $\mu(h = 0)$ and $\mu(h = 0.38 \text{ mm})$;

β : model parameter;

μ_F : μ ($h > 0.38$ mm).

Within the frame of the European VERT project (Vehicle-Road-Tyre Interaction), La Torre and Domenichini (2001) suggested the following relationship:

(9) $$\mu = \mu_{ref} \cdot \left(b_0 + \frac{b_1}{1 + b_2 e^{(b_3 + b_4 V)}} \right)$$

where μ : friction coefficient;

μ_{ref} : friction coefficient obtained under specific experimental conditions;

V : speed of the vehicle;

b_i ($i = 1, 2, 3, 4$) : model parameters related to variables like water depth.

Do et al. (2004) analysed VERT data and proposed another relationship:

(10) $$\mu = \mu_0 \cdot \exp\left[-\left(\frac{V}{V_s} \right)^{\alpha} \right] + \beta V$$

where μ : friction coefficient;

V : measurement speed;

μ_0 : friction coefficient at $V = 0$;

α, β, V_s : model parameters.

It was shown that the "α" parameter, controlling the shape of the μ-V curve, is related to the ratio between the water depth and the tire tread depth (Do et al., 2004).

Nevertheless, the parameters of these models need to be determined with a wide amount of experimental data and specific devices, which is not easy to obtain. Moreover, they do not take into account the skid resistance changes depending environmental conditions (rainfall intensity, drying, etc.).

METHODOLOGY

The studies results presented in the precedent section shows that the determination of a permissible speed based on road skid resistance is not straightforward. The formula (1) is generally used but it does not take into account the variation of skid resistance with weather conditions. In the other formulae, the skid-resistance term is not explicit enough. Formulae specific to the IRCAD project are then needed. Our methodology is illustrated in figure 3. The idea was originally developed by Gothié (1995).

First, the notion of "permissible speed" is introduced. It aims at:

- locating sections presenting a slip risk from a road profile provided by any monitoring device;
- warning a driver if his/her speed is higher than the permissible speed.

The permissible speed is defined as the minimum of two speeds (Fig. 3):

- speed V_1 deduced from the equilibrium of a vehicle passing a curve presenting a cross slope;
- speed V_2 deduced from the braking distance of a vehicle.

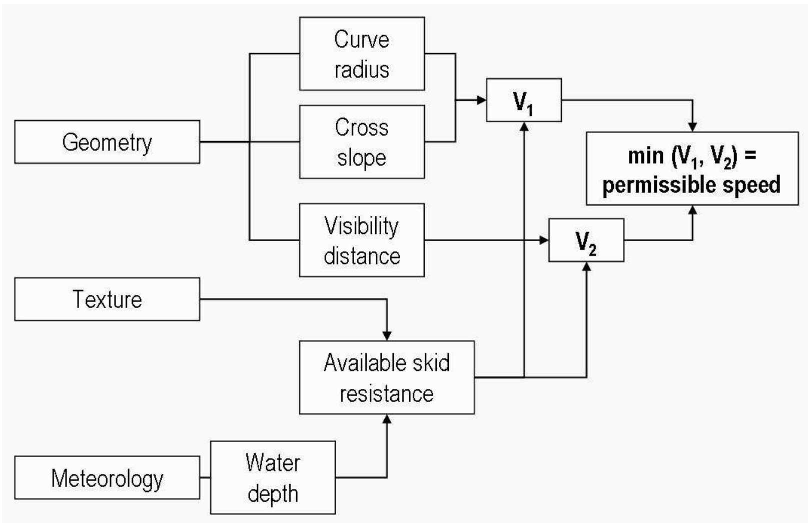

Figure 3. Methodology used in the calculation of the permissible speed

Formulae to calculate V_1 and V_2, as shown in State of the Art paragraph, already exist. However, the road skid resistance, whenever it is used as input in these formulae, remains unchanged whatever the weather. The innovation of our method lies in the fact that the friction changes now with meteorological conditions. In our scheme, geometry and texture inputs are provided by monitoring devices, the skid resistance being measured under specific conditions. Meteorological conditions are used to estimate – by means of a model – the water depth on pavement surface; another way is a direct measurement of the water depth. Another model is used to estimate the actual skid resistance related to the estimated (or measured) water depth. The actual skid resistance, which is now dependent on meteorological conditions, is used to estimate permissible speeds.

The available skid resistance depends both on microtexture and macrotexture of the pavement surface.

Microtexture of the road is evaluated through the measurement of a Sideway Friction Coefficient (SFC) at 60 km/h on a wetted surface by the SCRIM device. A smooth standard tyre is used for the tests. SFC is measured in the right wheel path and ranges from 0 to 1. This parameter ranges from 0 to 1. A value of 0 corresponds to smooth pavement (like resin) without any microtexture and a value of 1 corresponds to pavements with a very high level of microtexture (surface dressings with special aggregates of bauxite for example).

Macrotexture of the road is characterized by ETD (Estimated Texture Depth) expressed in mm. This parameter is evaluated by a non-contact laser sensor called RUGO, which measured the road profile (ISO 13473-1). ETD values ranges from 0.2 to 3 mm. It indicates the capacity of the surface pavement to evacuate water, when it is raining.

EXPERIMENTAL SITES

In the architecture of the information system (Subirats et al., 2009), the permissible speed is estimated in real time and compared to the travel speed; this comparison determines the activation of warning messages. As a pre-requisite, it is quite important to see how permissible speed detects hazardous zones on a road section and to compare the values deduced from models to actual travelled speeds.

Site description

Our approach is evaluated on two road sections located on a secondary road in the department of the Côtes d'Armor (Brittany, France). They are referred as respectively "road section 1" and "road section 2" in the rest of the text.

- road section 1 has mainly two curves whose radii drop locally to 128m. The road surface macrotexture is good (ETD > 0.7mm) but the skid resistance is low (SFC < 0.4 in several locations);
- road section 2 has locally a very low curve radius (64m). The road surface macrotexture is variable (0.55 < ETD < 1.42mm) and the skid resistance is as low as 0.3 in curves (Fig. 4).

Figure 4. Curve on road section 2

Both sites are part of seven ones selected by considering criteria based on the risk level provided by the ALERTINFRA software (Cerezo et al., 2010a) and accident data. The two road sections chosen, responded in addition to criteria related to water accumulation and skid resistance.

Site instrumentation

The two experimental sites are fitted out with sensors to provide meteorological data and traveled speeds. Variable message signs (VMS) are installed on the roadside for driver information (Fig. 5).

Figure 5. Equipments deployed at road section 1 (VMS and sensors)

The deployed sensors are:

- weather station;
- sensor measuring the water depth on the road surface;
- electromagnetic loops for speed measurement.

The weather station, provided by Campbell Scientific, measures: wind direction and speed, air temperature and humidity, solar radiation, rainfall intensity.

The water-measuring sensor is provided by Vaisala. Fixed on a spot at 7m height (Fig. 5), this sensor uses spectroscopic principle to measure water depths up to 2mm thick of a circular measured surface of 20cm in diameter. The waterdepth is measured with an accuracy of ± 0.01 mm.

On each site, three electromagnetic loops are embedded in the pavement; their locations are symbolized by ST1, ST2 and ST3 in the figure 6.

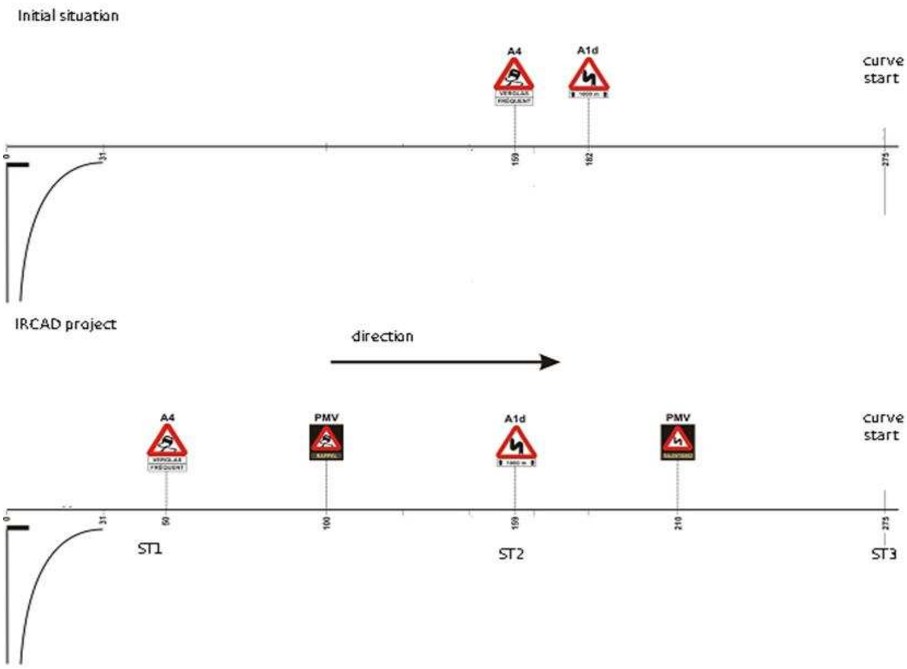

Figure 6. Location of sensors deployed at road section 1

Collection of road data (geometry and skid resistance)

VANI device

The collection of data related to the road geometry and surface characteristics is done by a device named VANI (Vehicle for ANalysis of road Itinerary), towing a friction-measuring device named GRIPTESTER (Fig. 7). VANI was developed at the end of the 80's for road safety studies (Cerezo et al., 2010a).

Figure 7. VANI device and GRIPTESTER (Laboratory of Lyon – France)

Available data

Curve radii between 20m and 600m are measured by means of a gyroscope; curves with radius higher than 600m are considered as straight sections. Slopes, expressed as %, are measured by means of a dual-axis gyro associated to lasers sensors to take into account changes of vehicle body height. Skid resistance is characterized by a friction coefficient named GRIPNUMBER (GN) provided by the GRIPTESTER device (Gothié, 2005). This device measures friction forces with a wheel slip of 15% on wetted road. The measuring speed is limited to 40km/h.

GN values can be converted in SFC values (SCRIM) with a linear relationship:

(11) $SFC = a \times \cdot GN + b$

with a : 1.16 et b : -0.13.

The constants a and b are determined by comparing SFC measurements and GN measurements on a set of experimental sections with various pavement surfaces. These coefficients depend on the GRIPTESTER device and the tire characteristics.

Road surface macrotexture (ETD) and rutting depths are also available. Rutting data are then used to modulate the water depth value on the road and the skid resistance value.

CALCULATION OF THE PERMISSIBLE SPEED

Speed V_1 adapted to a curve

For a curve, V_1 is given by the following formula:

(12) $V_1 = \sqrt{(\tau + dv) \cdot g \cdot R}$

where τ : friction coefficient;

dv : curve cross-slope;

g : gravity acceleration;

R : curve radius.

Formula (12) is obtained by considering the equilibrium of a vehicle in a curve (Fig. 8).

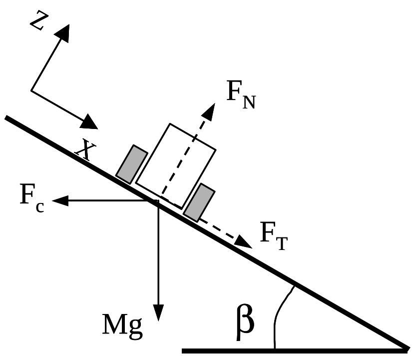

Figure 8. Vehicle in a curve with cross-slope

The balance of implied forces gives respectively on X and Z axes:

(13)
$$\begin{aligned} &F_T - F_c \cos\beta + M \cdot g \cdot \sin\beta = 0 \\ &F_N - F_c \sin\beta - M \cdot g \cdot \cos\beta = 0 \end{aligned}$$

where F_c : centrifugal force exerted on the vehicle;

F_T : transversal friction force;

F_N : vertical force;

M : vehicle mass;

β : angle inducing a cross-slope;

g : gravity acceleration.

Considering $F_T = \tau \cdot F_N$ and $F_c = \frac{M \cdot V^2}{R}$ in a curve, we obtain (14).

(14) $$V^2 = R \cdot g \cdot \frac{\tau + \tan\beta}{1 - \tau \cdot \tan\beta}$$

Writing τ = tan(α), one obtains:

(15) $$V^2 = R \cdot g \cdot \tan(\alpha + \beta)$$

The formula (12) is an approximation of (15) supposing angles α and β small.

<u>Use of data collected</u>

In our study, the friction coefficient "τ" is supposed to be equal to the SFC provided by the SCRIM device (Gothié, 2005), modulated by the water depth and a safety factor of 3, giving:

(16) $$\tau = \frac{SFC(h)}{3}$$

where SFC(h) : SFC measured by SCRIM and modified by the water depth h.

Since the water depth encountered during/after a rainfall might be different from that induced by conventional measurement conditions, the SFC provided by the SCRIM device must be modulated by the water depth. The relationship between the conventional SFC and SFC(h) is given by the following formula:

(17) $$SFC(h) = -0{,}081 \cdot \ln(h) + (SFC - 0{,}05)$$

where h : water depth expressed in mm.

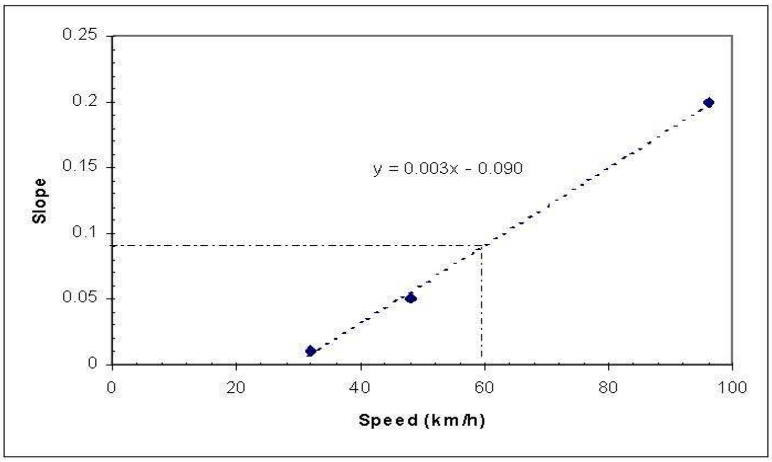

Figure 9. Slope of friction-logarithm (water depth) curves as a function of speed (Veith)

The formula (17) proposed by the Laboratory of Lyon from a limited data set corroborates observations made by Veith (1983) (linear relationship between friction coefficient and logarithm of water depth). The slope 0.081 for the SCRIM measurement speed (60 km/h) corroborates equally those provided by Veith (Fig. 9).

The water depth "h" is calculated from the rainfall intensity using the following formula:

(18) $$h = I \cdot L \cdot TA$$

where I : rainfall intensity in mm/h;

L : flow path length in m ;

TA : parameter given by the formula (24) (Delanne and Violette, 2001).

(19) $$TA = 0{,}57 + 0{,}85 \cdot MPD - 7{,}1 \cdot dv$$

where MPD : Mean Profile Depth in mm ;

dv : cross slope, expressed in m/m (cross slope of 2% signifies dv = 0.02).

Previous projects (Delanne and Violette, 2001) showed that the formula (18) gives better prediction than formulae from the literature. In case of ruts, the total water depth is the sum of that given by (18) and that cumulated in the rut.

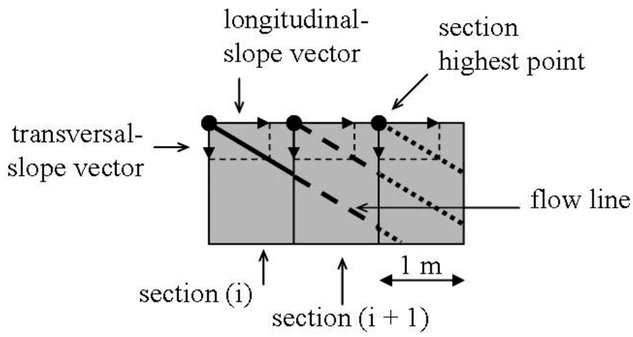

Figure 10. Principle of determination of flow lines

The determination of flow lines is illustrated in figure 10. The road lane is first divided into 1m-long sections. For section n° "i", the sum of vectors associated to longitudinal and transversal slopes is plotted from the highest point of the section. This line is then extended by that of section n° "i+1". The flow line is defined as the chain composed of these elementary lines. The water depth calculated from the flow line of section n° "i" is affected to section n° "i+1". More details are given in (Cerezo et al., 2010b).

Speed V_2 adapted to a visibility distance

<u>Formulation</u>

Another constraint imposed to the permissible speed is the stopping distance, which must be less than the visibility distance. For a vehicle of mass M braking at speed V, the relationship between the dissipated energy on a braking distance "d" and the loss of kinetic energy of the vehicle is:

(20) $$\frac{1}{2} \cdot M \cdot V^2 = M \cdot \ddot{x} \cdot d$$

where $\ddot{x}$: vehicle deceleration.

So

(21) $$V^2 = 2 \cdot \ddot{x} \cdot d$$

Since

(22) $$\ddot{x} = \frac{X}{M} = \frac{\mu \cdot Z}{M} = \frac{\mu \cdot M \cdot g}{M} = \mu \cdot g$$

where X : longitudinal friction force;

Z : load applied by the vehicle on the ground.

From which

(23) $$V^2 = 2 \cdot \mu \cdot g \cdot d$$

Utilization of data collected in IRCAD project

The limit value V_2 of the speed V in formula (23) is obtained by replacing "d" by the visibility distance, which can be estimated from the video function of VANI (fig.8). The friction coefficient μ is equal to SFC(h) given by (17).

RESULTS

In this section, the use of the permissible speed for diagnosis and information purposes is presented. Validation of models like water-depth prediction is given.

Comparison of water depths

Knowing the exact position of sensors measuring water depths, it is possible to calculate the water depth from the formula (18) and compare it to the measurements. Water depths recorded during 6 to10 minutes of rainfall are used for the comparison with theoretical values. The choice of 6-10min periods is justified by the fact that rainfalls of lesser duration do not wet uniformly the surface (this assumption is true for drizzle usually encountered in Brittany; it might not be valid for regions subjected to storms). Figure 11 shows a good concordance between calculated and measured values (a set of 10 values is considered). Some adjustments have nevertheless to be done since the comparison points are not exactly on the bisectrix (Fig. 11).

It should be noticed that the sampling size is very small. This remark stresses the difficulty to obtain enough data and the necessity to dispose of long-duration experimentations to study phenomena depending on atmospheric conditions. In addition, formula (18) calculates only water depths during rainfalls. Water depth becomes null as soon as the rainfall intensity term is equal to zero. A model calculating water depths during drying periods should improve the methodology. Development of this model can be found in (Kane and Do, 2011).

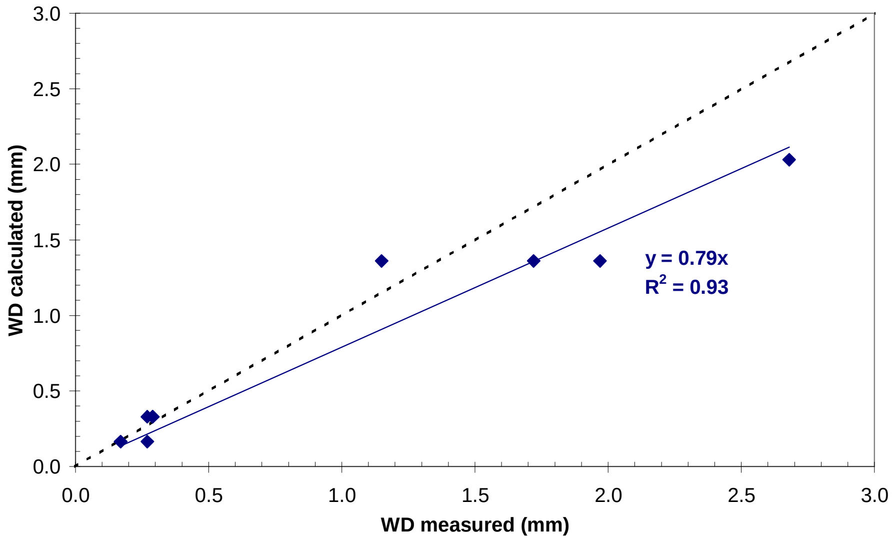

Figure 11. Comparison between calculated and measured water depths

Comparison of permissible speeds and travelled speeds

It is well known that travelled speeds depend on traffic. We study then firstly the distribution of daily traffic for which an example is shown in the figure 12.

Three periods of the day are defined:

- "night" period: 21h to 6h;
- "base" period: 8h to 14h;
- "peak" period: 15h to 19h.

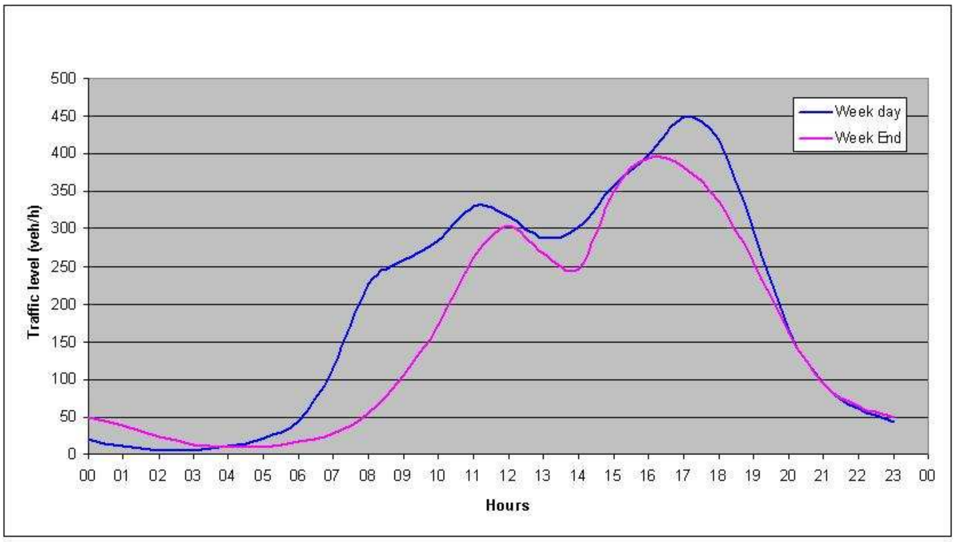

Figure 12. Distribution of daily traffic on road section 1

Speed analyses are performed for each of these periods. Weekdays (Monday to Friday) are analysed separately from weekend (Saturday and Sunday). Distributions of travelled speeds for free cars only are then plotted for each period of the day and for each modality weekdays/weekend. For each distribution, values of V_{85} are calculated on each electromagnetic loop location (ST1 to ST3). In parallel, the permissible speed is determined by applying the whole method proposed in IRCAD (i.e. minimum value between V_1 and V_2).

The comparison between permissible speed and V_{85} on road sections 1 and 2 are shown on figure 13 and 14.

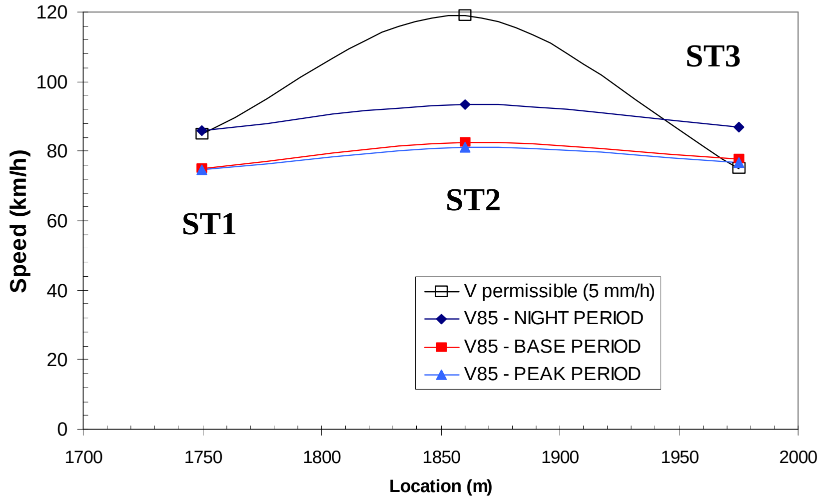

Figure 13. Comparison travelled/permissible speeds on road section 1

For road section 1 (Fig. 13), daily travelled speeds at loops ST1 and ST3 are close from permissible speed. For the night period, travelled speeds are clearly higher than permissible speeds at loops ST1 and ST3. Accordingly for ST2 location, permissible speed is higher than travelled speed. In this case the permissible speed could be limited to the legal speed (90 km/h). Excepted for night period, the permissible speed could be used as an alert speed for the fastest drivers (the threshold value for speed is V_{85}).

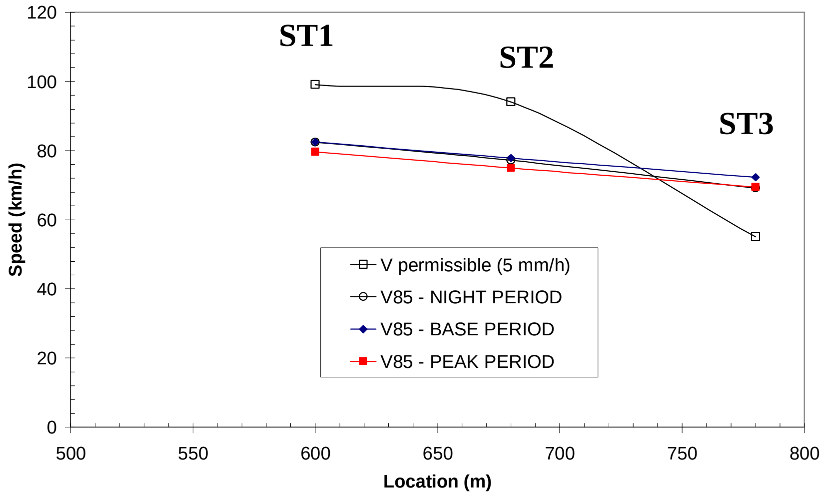

Figure 14. Comparison travelled/permissible speeds on road section 2

For road section 2, the gap between travelled and permissible speeds is on the safe side for loops ST1 and ST2 (Fig. 14). The comparison emphasizes the difficulty on loop ST3 where drivers go too fast in comparison with the site difficulty, in particular for the moderate rainfall intensity (5mm/h).

Thus, locations, where drivers do not adapt their speed considering the risk of accident, can be detected. Road managers can use this information to assess risk of accident on the road section and propose for example the addition of warning signs on the road edge.

Use of permissible speeds for the location of potentially slip sections

As indicated in figure 3, the calculation of permissible speed depends on meteorological conditions or directly on the road wetness (water depth), geometrical parameters being considered as constant. The choice of meteorological conditions as inputs imposes a weather station on the site and the use of a model weather-wetness like formula (18) or of a more comprehensive one taking into account the drying period. The main advantage of this method is that water depth can be estimated for the whole road section using available data collected by the VANI device. The only reasonable assumption to be made is that the rainfall intensity remains constant all along the road section.

The choice of water depth as input is more direct since skid resistance is directly modulated by water depth. In addition, the water depth represents current conditions and it is not necessary to know if we are in a rainfall period or after. Nevertheless, this choice imposes the presence of a sensor measuring water depth on the test site. In addition, the measurement being local (right at the location of the dedicated sensor), some assumptions have to be made to extrapolate the local water depth to the whole road section.

Regardless of the data type, the most important element is the relationship between skid resistance and wetness, such as in formula (17), which determines the permissible-speed profile all along a road section.

Speed calculation from meteorological data

Calculations were done for two intensities: 2.5mm/h and 7.5mm/h corresponding respectively to moderate and heavy rainfalls. Figures 15 and 16 show speed profiles for the two road sections and three skid resistance levels: measured SFC, SFC modified by respectively 2.5mm/h and 7.5mm/h rainfall intensities.

First, permissible speeds are not constant along a road section. At many locations, the permissible speed is even lower than the legal speed for this type of road (90km/h under dry weather, 80km/h under wet weather). The three speed profiles are almost similar, except at some specific locations:

- PR 1750 on road section 1 (Fig. 15) and PR 1000 on road section 2 (Fig. 16) where ruts increase significantly the water depth when it is raining and consequently reduces the permissible speed;
- PR 2200 on road section 1 (Fig. 15) which is a low-visibility section.

On road section 1 (Fig. 15), the peak on the speed profile is due to a straight section. The curve following this straight section causes a strong decrease of permissible speed at PR 1950. The same pattern (peak followed by a high decrease) is observed in the figure 16, which is due to a straight section followed by a series of curves reducing significantly the visibility (and consequently V_2).

The above analyses show that permissible-speed profiles can be used to locate road sections presenting potential risk of loss of control of the vehicle due to weather, to road geometry or to pavement surface skid resistance. This study shows that rain can reduce furthermore the permissible speed at rutted or low-visibility sections.

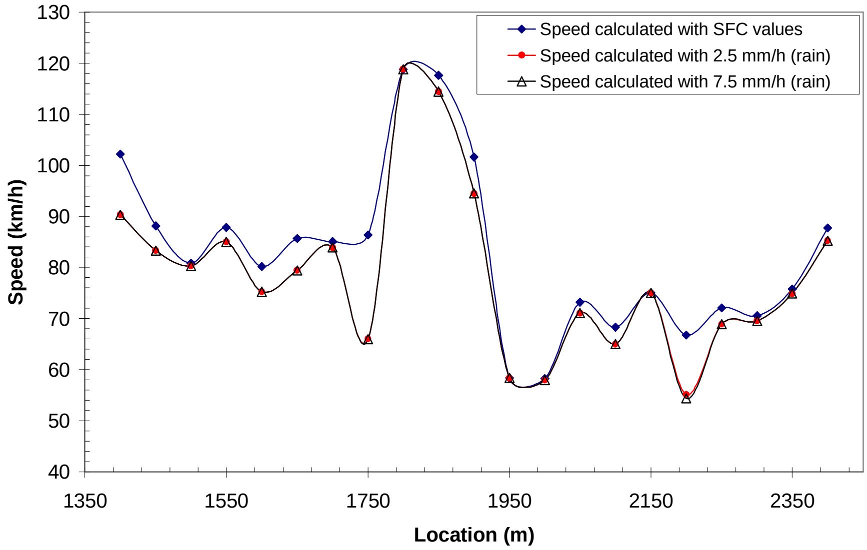

Figure 15. Permissible speed profile on road section 1 for two rainfall intensities

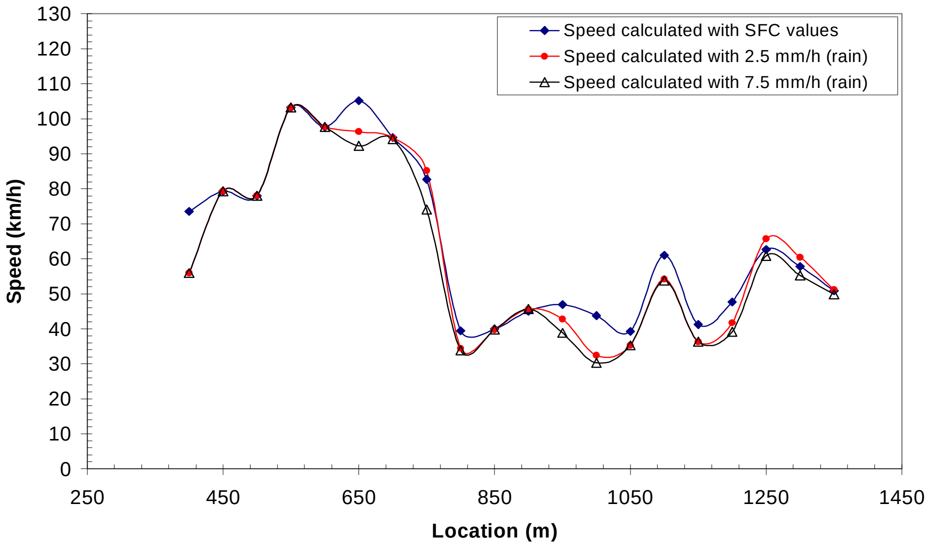

Figure 16. Permissible speed profile on road section 2 for two rainfall intensities

Lastly, road authorities can use this information (i.e. strong decrease of permissible speed) to choose the location of warning signs. Permanent signs can be implemented where risks are due to the road geometry. Weather-dependent signs, like variable message signs, can be implemented where risks depend on skid resistance and meteorological conditions. For our two experimental sites, potentially slip sections are located respectively at PR 2200 and PR 1000 for road sections 1 and 2 (Figs. 15 and 16). It means that warning signs must be implemented at a distance – determined by safety rules – upstream of these locations.

Evolution with time of permissible speed

Knowing the water depth measured locally and using geometry data provided by VANI, it is possible to calculate the maximum water depth encountered on the road section and to locate it. Calculations of permissible speed can then be done for two water depths: the water depth measured by the sensor and the deduced maximum water depth.

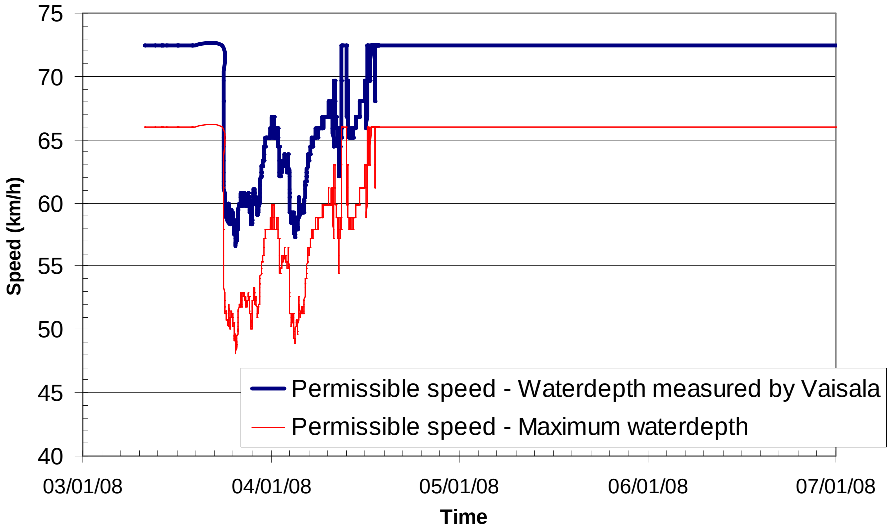

Figure 17. Permissible speeds calculated from measured and maximum water depths on road section 1 (PR 2200 m)

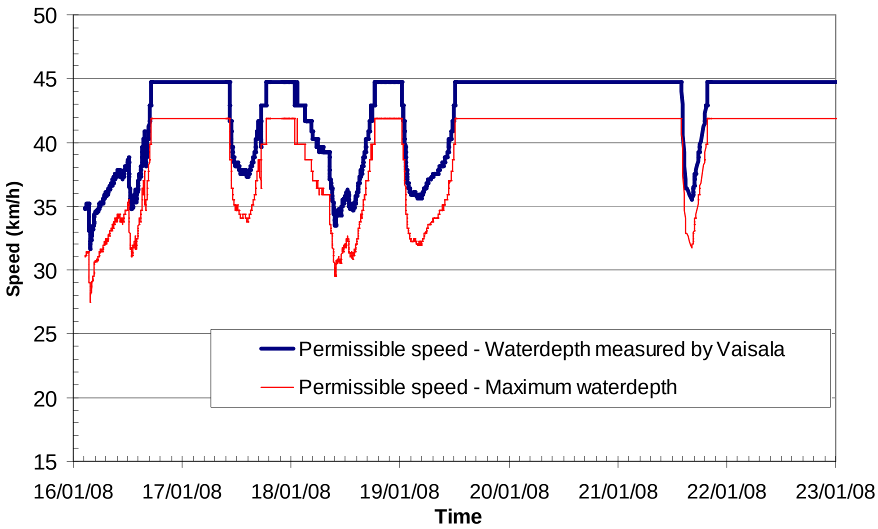

Figure 18. Permissible speeds calculated from measured and maximum water depths on road section 2 (PR 1000 m)

Figures 17 and 18 present an estimation of permissible speeds depending on time at the most dangerous section of both itineraries (i.e. located at 2200 m and 1000 m). One can see that the maximum water depth induces logically a further reduction of permissible speed compared with the speed calculated for the water depth measured at the sensor location. The speed reductions ranges between 6 and 9 km/h on road section 1 and between 3 and 6 km/h on road section 2. The gap between the values of permissible speed calculated with the two waterdepth is evolving with time.

To conclude, the use of local water-depth measurement alone is not sufficient to locate potentially slip sections. Nevertheless, as we have seen in the previous section, meteorological data alone cannot estimate water depth after a rainfall. Both types of data (meteorology, water depth) are then complementary to provide inputs for the calculus of permissible speed during and after rainfall.

Towards the development of an information system

In this section, the principle of the information system developed within the frame of IRCAD project is exposed. The system architecture, the experimentation (2-year duration) and the evaluation of the impact of warning messages on driver behaviour are detailed in (Subirats et al., 2009).

The main objective of IRCAD information system is to calculate in real time a permissible speed and compare it to speeds of approaching vehicles. A variable message sign is only activated when the comparison criteria exceed a threshold value. Two types of data are collected and stored in the system:

- "permanent" data: road geometry and surface characteristics (macrotexture, friction coefficient). These data are collected periodically by dedicated devices (VANI, SCRIM) and updated consequently;
- "volatile" data: meteorological conditions (only the rainfall intensity is used in this study) by means of a weather station, and water depths by means of a dedicated sensor (Fig. 5). As mentioned previously, both data are necessary at this stage of knowledge to provide water depths during and after rainfall. A wetting/drying model like the one developed by Kane and Do (2011) should help reduce the number of equipments.

The command function uses these inputs to calculate continuously the permissible speed. It should be noted that meteorological data are updated every 6 minutes during which the system assumes that data from the previous 6-minutes period remain valid.

A radar is used to measure speeds of approaching vehicles. Speed values are then compared to the permissible speed and commands are sent to the variable message signs to activate (or not) warning messages.

CONCLUSIONS

The purpose of this paper is to present a methodology to calculate speeds adapted to the actual road skid resistance. This work is needed because a skid resistance reduction, due to road wetness, is not always perceived correctly by drivers and one of the most efficient way to mitigate slip risks is to reduce speed. The so-called "permissible speed" is calculated taking into account the equilibrium and the braking distance of a vehicle passing a curve. The formulation depends both on road skid-resistance and wetness.

For a road section, the calculation method takes as inputs geometrical parameters (radius of curvature, longitudinal and transversal slopes, sight distance), skid resistance and water depth. The method provides a permissible speed for each road section. The road section length depends on the sampling intervals used by the monitoring device VANI.

The proposed method can be used as a diagnosis tool to detect potentially slip sections, or can be integrated in a comprehensive information system to warn drivers about upstream slip risks. For the diagnosis, it is possible to constitute a permissible-speed profile and detect sections with potential slip risk. The calculated speeds can be compared to legal speeds or travelled speeds to evaluate the necessity to implement a warning system, in case where permissible speeds are inferior to legal or travelled speeds. For the information, the calculation formulae are implemented in a command function taking into account permanent data like road geometry and surface characteristics, and volatile data like meteorological conditions and water depths. By this way, the proposed method enables the modulation of information sent to drivers as a function of meteorological conditions.

ACKNOWLEDGMENTS

This research was funded by the French DRI (Direction de la Recherche et de l'Innovation) and DSCR (Direction de la Sécurité et de la Circulation Routière). The authors thank the General Council (GC) of Côtes d'Armor for the provision of experimental sites and the assistance during experiment preparation. Outstanding works done on the experimental sites by Ronan Queguiner from Regional Laboratory of St Brieuc and David Doucet from CETE Normandie-Centre are highly appreciated.

A special thank is dedicated to Michel Gothié who highly contributed to this project before retirement.

BIBLIOGRAPHY

Anderson, D. A., Huebner, R. S., Reed, J. R., Warner, J. C. and Henry, J. J. (1998). *Improved Surface Drainage of Pavements*. NCHRP Web Document 16 (Project 1-29), National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C.

Cerezo, V. Conche, F. and Dupré, G. (2010a). *Alertinfra: a new tool for safety studies*, 89th Transportation Research Board (TRB), Washington, USA, 13th – 17th January.

Cerezo, V. Gothié, M. Menissier, M. and Gibrat, T. (2010b). *Hydroplaning speed and infrastructure characteristics*, Proc. IMechE vol.224 Part J: J. Enginnering Tribology.

Chesterton, J., Nancekivell, N., Tunnicliffe, N. (2006). *The use of the Gallaway formula for aquaplaning evaluation in New Zealand*. Paper available on line (www.transit.govt.nz/content_files/conference/J-Chesterton.pdf), New Zealand Institute of Highway Technology (NZIHT) and Transit NZ 8th Annual Conference.

Delanne, Y., Violette, E. (2001). *Wet road accident : Driver behavior, Safety margins and road design*. Traffic Safety on 3 Continents, Moscow.

Do, M.-T., Marsac, P., Mosset, A. (2004). *Tribology approach to predict the variation of tire/wet road friction with slip speed*. Proceedings of the 5th International Symposium on Pavement Surface Characteristics, 6-9 June 2004, Toronto, Canada.

Gallaway, B. M. (1979). *Pavement and Geometric Design Criteria for Minimizing Hydroplaning*. Federal Highway Administration, Report No. FHWA-RD-79-31.

Gallenne, M.-L., Goyat, Y., Do, M.-T., Bremond, R., Botrel, K., Somat, A. (2007). *SARI: How to Inform Drivers and Road Managers More Efficiently About High Level Risk of Vehicle Loss of Control*. Proceedings, ITS World Congress, Beijing (China).

Gothié, M. (1995). *Recherche thématique : Exploitation et sécurité routière, Thème ESR 05 « Influence des caractéristiques de surface dans l'insécurité routière »*. Rapport de clôture.

Gothié, M. (2005). *Les mesures de l'adhérence des chaussées en France et leur interprétation*. Bulletin des Laboratoires des Ponts et Chaussées, n° 255, pages 53-69.

Ivey, D. L., Lehtipuu, E. K., and Button, J. W. (1975). *Rainfall and Visibility – The View From Behind the Wheel*. Research Report 135-3, Texas Transport Institute, College Station, Texas.

ISO 13473-1 (2002). *Characterization of pavement texture by use of a surface profile – Part 1: determination of mean profile depth*.

Kane, M., Do, M.-T. (2011). *Kinematic wave approach to model water depth on road surfaces during and after rainfall events*. International Journal of Pavement Engineering First published on: 15 April 2011 (iFirst).

Kulakowski, B. T., Harwood, D. W. (1990). *Effect of water-film thickness on tire-pavement friction*. Surface Characteristics of Roadways : International Research and Technologies, ASTM STP 1031, W.E. Meyer and J. Reichert Eds., American Society for Testing and Materials, Philadelphia, pages 50-60.

La Torre, F., Domenichini, L. (2001). *Friction prediction models*. Proceedings of the 2nd International Colloquium on Vehicle Tyre Road Interaction, 23 February 2001, Florence, Italie, pages 133-147.

Louah, G., Menacer, O., Dupré, G., Violette, E. (2009). *Updating French Formulas for Operating Speeds on Horizontal Curves of Rural Two-Lane Highways*. Advances in Transportation Studies, Section B 18.

Subirats, P., Violette, E., Doucet, D., Aron, M., Louah, G., Do, M.-T. (2009). *Evaluation of a Speed Alert System on Curves by Rainy Weather*. International Cooperation on Theories and Concepts in Traffic Safety Workshop, Leeds, 22-23 October 2009.

Veith, A. G. (1983). *Tires – roads – rainfall – vehicles: the traction connection, Frictional interaction of tire and pavement*. ASTM STP 793, W.E. Meyer and J. D. Walter Eds., American Society for Testing and Materials, Philadelphia, pages 3-40.

Violette, E. (2002). *Projet APTP – Sujet 1 : Comportement des Usagers – Synthèse des Etudes Effectuées*. Research report, CETE Normandie-Centre, Division Exploitation Sécurité Gestion des Infrastructures.