Hydroplaning speed and infrastructure characteristics

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Abstract :

This paper exposes some results of a study, which aims at modelling the hydroplaning phenomenon taking into account the infrastructure characteristics, the water depth on the road, the load transfer between the rear and the front wheels, the skid resistance before total hydroplaning. First, a short bibliographical study determined the most relevant parameters that should be included in a global hydroplaning model such as the tires' characteristics (pressure, contact area, tread depth), the load, the water depth, the road profile and macrotexture. Among them, the water depth is the most difficult to evaluate because it deeply depends on the pavement irregularities (roughness and texture), the road geometry and the weather (rainfall intensity). Thus, a model calculating the water-film thickness by using road characteristics measurements is proposed. This initial water depth is included in a linear model with 2 degrees of freedom, which describes the longitudinal dynamics phenomenon. The load transfer between the front and the rear axles is calculated in straight line. Moreover, the water depth in front of the rear tire is calculated by considering the water displacement generated by the front tires. Then, the increase of the water thickness just in front of the tire due to the flow in the tire treads and the pavement macrotexture is modelled. Finally, this model provides a hydroplaning speed, which is used for warning the drivers.

1 Introduction

Hydroplaning is a physical phenomenon, which appears on wet road and can entail fatal accidents. Safety data reveals that a wide part of accidents occurs on wet pavement, whereas rainy days are not the main weather conditions on the whole year.

This paper proposes a simplified model predicting speed of aquaplaning in straight line depending on rainfall intensity and on road characteristics. These road characteristics are measured with a device currently used in French safety studies. It provides radius of curvature, longitudinal slope, crossfall, macrotexture, skid resistance all along the itinerary. The model takes into account the load transfer between front and rear axles, the increase of waterdepth generated by the fact that macrotexture and tire tread depth aren't able to evacuate the whole water-film and the difference of waterdepth that can exist between the front and the rear wheels.

In a first part, road texture is described and the hydroplaning phenomenon is remembered. In a second part, the model calculating water-film thickness is described. In a third part, the hydroplaning model is proposed.

2 Pavement texture

2.1 Definition

Pavement texture corresponds to the deviation of a pavement surface from a true planar surface with a texture wavelength λ less than 0,5 m. Thus, road profile is characterized by two values: the vertical amplitude "a" and the horizontal dimension of the surface irregularities "λ". The values of "a" and "λ" allow defining two levels of pavement texture: microtexture and macrotexture.

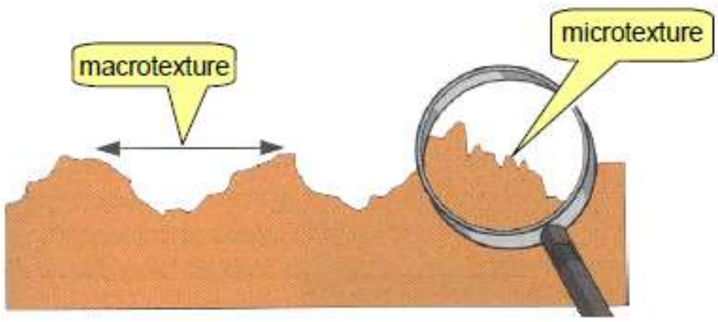

Figure 1 : Road pavement surface texture

2.2 Microtexture

Microtexture corresponds to surface irregularities with wavelengths of pavement profile inferior to 0.5 mm and vertical amplitude inferior to 1 mm. It is related to the unevenness of the surface of aggregates (gravel, sand, mortar) in contact with the tire's rubber. Microtexture is therefore an essential factor for a pavement surface. It facilitates the dispersal of the water microfilm (several tenths of a mm) located between the tyre and the surface of the uneven particles of the pavement. This dispersal is important whatever the speed, and the tyre alone cannot ensure this.

2.3 Macrotexture

Macrotexture corresponds to surface irregularities with wavelengths of a pavement profile lying between 0.5 mm and 50 mm and vertical amplitude inferior to 10 mm. It is related to the type of wearing course and to the manner in which it was applied, to damages and to periodic treatments made to the pavement surface. Macrotexture is characterized by a Mean Profile Depth (MPD) measured with the device RUGO (cf. 4.2). Macrotexture facilitates the drainage of the water macrofilm (1 to 50 mm) located at the tire-road interface. The water quantity to be drained increases with speed, but the tire can drain off a sizeable amount with its tread pattern.

3 Hydroplaning phenomenon

3.1 Description

Hydroplaning is a phenomenon in which the water on a wet pavement is not displaced from the nominal tire-ground contact area at a rate fast enough to allow the tire to make contact with the ground surface over its complete nominal footprint area, as would the case of operation on a dry surface.

Under wet conditions, there is a generation of hydrodynamic pressure on the leading edges of road asperities, as a result of the slipping action of tire tread rubber in areas of gross slip. When this pressure becomes too high, the tire is lift up and the contact between microroughness of pavement and the tire is destroyed.

When hydroplaning occurs, the tire rides on a wedge or film of water over a part or all of its footprint area, depending on the conditions. This creates a situation where the vehicle experiences low (or near-zero) coefficient of friction and uplift forces in the fluid film capable to cause a loss of contact between the tire and the pavement. This causes a loss in braking ability and could lead to accidents [1, 6].

3.2 Parameters of influence

Hydroplaning speed is defined as the maximum speed reached by the vehicle under given conditions, where hydroplaning phenomenon occurs. This speed depends both on infrastructure characteristics and vehicles characteristics. Former experimental studies proved that the following characteristics managed hydroplaning speed:

- Water-film thickness on the road,
- Pavement texture,
- Tire pressure and tire design (tread depth…),
- Load.

Thus, the hydroplaning model proposed in this article will take into account all these elements. A simplified waterdepth model taking into account infrastructure characteristics is developed in part 4. This model will focus on the evaluation of waterdepth both on front and on rear wheels, considering the fact that the front wheels separate water film and the rear wheels don't see the same water-film thickness during the displacement.

Moreover, the model predicting hydroplaning speed will include load transfer between front and rear axles in view of taking into account the real skid resistance generated in the contact area.

4 Water-film thickness evaluation

4.1 Principle

When rainfall appears, the water accumulation on the pavement surface is both due to the local rain and to the water flow coming from the neighbourhood. Moreover, water tends to follow the lines presenting the highest declivity.

A waterdepth model was developed taking into the rainfall intensity, the slope, the surface texture and the length of the line flow [3, 8]. This model was obtained by statistical analyses of experimental measurements realized on the special test tracks of LCPC (French Laboratory of Road and Bridges). The most intricate in the model is the calculus of the length L of the line flows. The originality of this approach lies on the fact that the calculus of L is based on data available for road managers. These data are measured by VANI device.

4.2 VANI device

VANI is a measurement device, which provides geometrical characteristics of infrastructure (crossfall, radius of curvature and longitudinal slope), surface characteristics (macrotexture, microtexture and vertical acceleration). These data are obtained with a path of one meter. The measurements are realized in the middle of the lane. The vehicle drives at 40 km/h.

The geometrical characteristics are measured thanks to gyroscopes, accelerometers and lasers sensors. The surface characteristics are measured with a GRIPTESTER and RUGO.

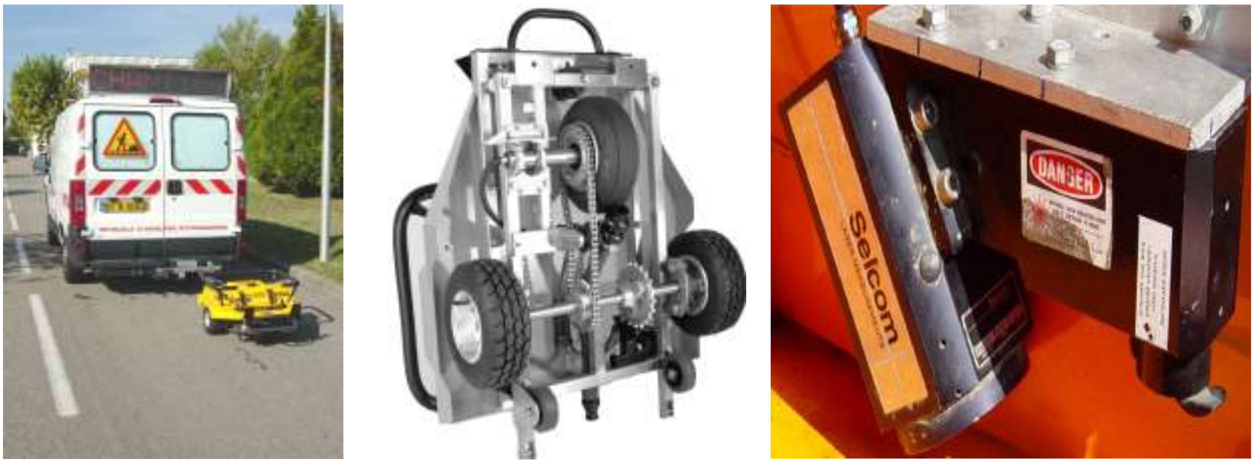

Figure 2 : VANI device (a), GRIPTESTER (b) and RUGO (c)

The GRIPTESTER provides a Longitudinal Force Coefficient (LFC) at 40 km/h with a waterfilm thickness of 0.5 mm. A smooth standard tyre is used for the tests. LFC is measured in the right wheel path and ranges from 0 to 1. This parameter is used to evaluate microtexture. A value of 0 corresponds to smooth pavement (like resin for example) 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 is measured with a profilometer called RUGO composed of a non-contact sensor, which measures the distance between its datum-line and the pavement surface examined. The device consists essentially of a laser transmitter and of an optical potentiometer: the emitted ray strikes the surface of the ground and reflects itself on the optical potentiometer fit to deduce the height which separates the point of reflection from the pavement surface, under an average angle of observation of 30°. RUGO provides a Mean Profile Depth in millimetres, each twenty meters, following the standard ISO 13473-1. RUGO is installed on the VANI and make the measurement in the right wheel path.

4.3 Length of water flow L

The road is divided into rectangular areas, which dimensions are 1 m length (patch of infrastructure characteristics measurements) and 3.5m large (width of the road). The geometrical characteristics corresponding to each rectangle are provided by VANI (slope, crossfall). Thus, direction of highest declivity is determined in each rectangle and the length L_i of the vectors are calculated by geometrical considerations.

Lastly, the total length L of different flow paths followed by water before leaving the road is calculated by the aggregation of these vectors. Software adds them automatically and provides each meter the length of the various flow paths (Figure 3).

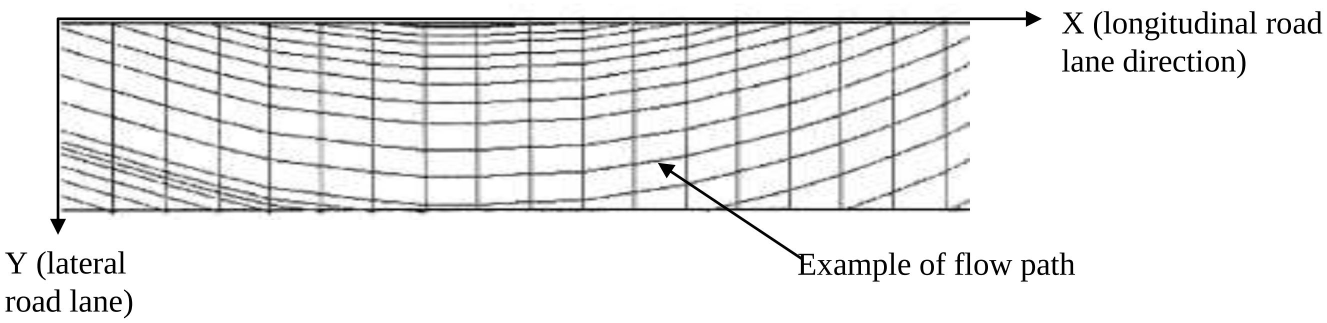

Figure 3 : Water flow paths on a road lane

4.4 Example of results

Figure 4 shows the infrastructure characteristics on a test section of 1400 m length. The water-film thickness values all along the section are calculated for three rainfall intensities (25, 50 and 75 mm/h). One can notice that five peaks appear due to the geometrical configuration of road (Figure 5). The first peak (700 m) is explained by the fact that this area is located on the bottom of a ramp with a decrease of crossfall. The second peak (800 m) is due to the combination of a change of the sign of the crossfall, a beginning of a curve and a bottom of a ramp. The third peak (1000 m) is due to a curve presenting a change in the crossfall orientation. The fourth peak (1250 m) and the fifth peak (1400 m) are due to curves with changing crossfall located in a section with a longitudinal slope around –4%. Moreover, figure 5 shows that the peaks generally appear when the macrotexture locally decreases. Indeed, the road texture is not sufficient to evacuate the water.

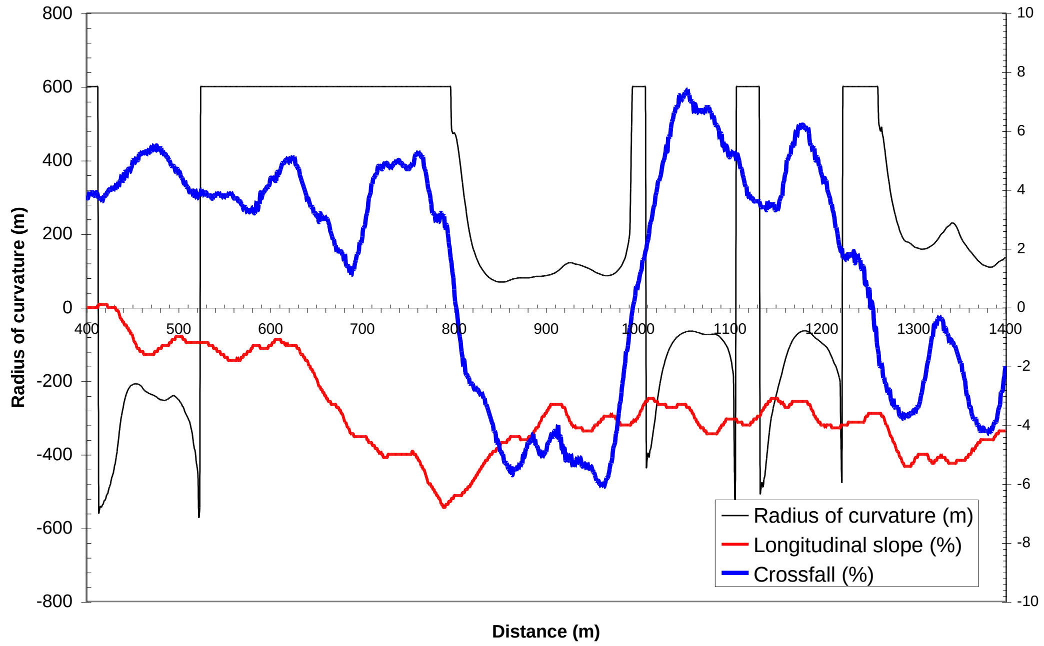

Figure 4 : Infrastructure characteristics

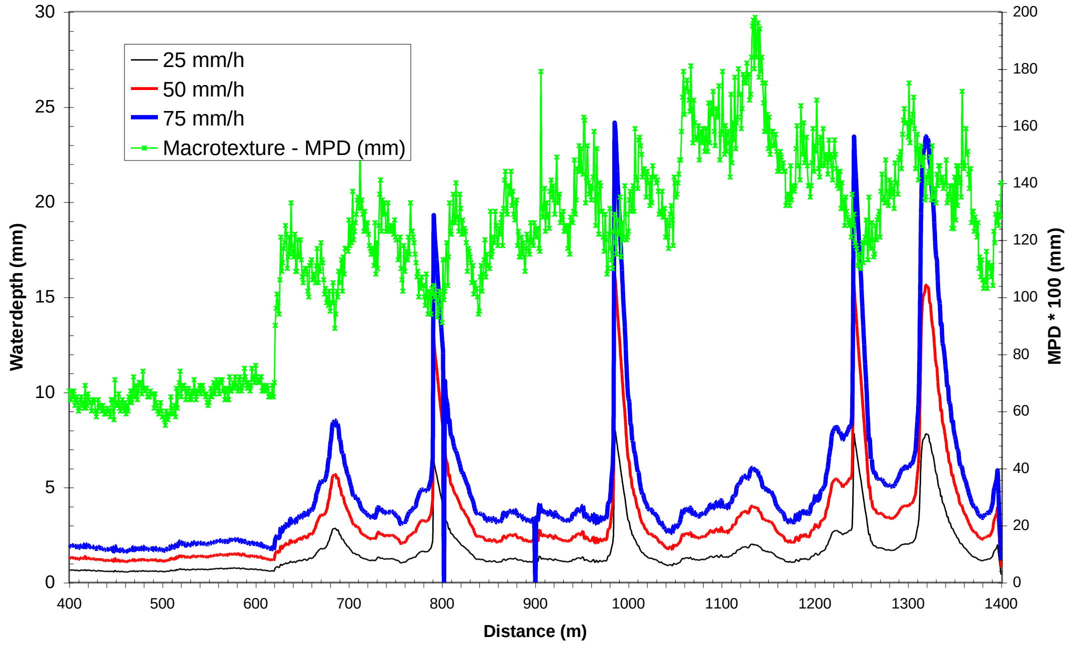

Figure 5 : Waterdepth for various rainfall intensity

5 Hydroplaning model

5.1 Brief overview of some existing models

In 1962, research in the NASA Langley Research Center involving bogie and nose-gear studies led to the NASA hydroplaning equation shown in Equation (1), which is still being commonly used in the tire, aviation and automobile industries, and the highway and airport authorities [2].

$$Vp = K \times \sqrt{P} \qquad (1)$$

where the P is the tire inflation pressure in kPa and Vp is the hydroplaning speed in km/h. This formula was extended and adapted to passenger cars in 1968 by Horne:

$$Vp = 6.35 \times \sqrt{P} \qquad (2)$$

where the P is the tire inflation pressure in kPa and Vp is the hydroplaning speed in km/h. Then, Horne included in 1985 the parameter AE in the model, which characterize the contact area. AE is defined as the ratio between the width and the length of the tire/road contact area [5]. Nevertheless, this model is valid for waterdepth superior to 10 mm and for high pressure values.

$$Vp = 5.55 \times \sqrt{\frac{P}{AE}} \qquad (3)$$

On the same period, Ivey proposed a similar formula for heavy vehicles with worn tires:

$$Vp = 29.4 \times \frac{P^{0.21}}{\sqrt{AE}} \qquad (4)$$

Nevertheless, it has been shown by researchers that other factors than tire pressure, such as water-film thickness, pavement surface texture, and tire tread design could affect the speed at which hydroplaning occurs [2].

For example, Gallaway proposed in 1979 a formula, which included texture parameters, tire tread depth and tire pressure. This formula was validated for high speed values (> 90 km/h).

$$Vp = 0.9143 * SD^{0.04} \times P^{0.3} \times (TD + 0.794)^{0.06} \times A \qquad (5)$$

With $$A = Max\,\{ \frac{12.639}{WFD^{0.06}} + 3.507\,;\, \left(\frac{22.351}{WFD^{0.06}} - 4.97\right) \times TXD^{0.14} \} \qquad (6)$$

P: tire inflation pressure (kPa)

TD: tire tread depth (mm)

TXD: mean profile depth (mm)

WFD: water-film thickness (mm)

SD: ratio between the rotating speed of the wheels on wet and dry pavement (≈ 10%).

A wide range of other models exists but only these three ones were considered to validate the hydroplaning model proposed in this paper.

5.2 Principle of the model

The determination of the hydroplaning speed is realized in three main steps (figure 6).

In a first step, the water-film thickness on pavement is calculated as a function of the rainfall intensity and road characteristics. The initial value of waterdepth WD is obtained.

In a second step, the waterdepth on the front and rear wheels is evaluated by considering both the fact that there is an increase of the water-film thickness just in front of the wheel when texture and tire tread depth cannot evacuate the water in the contact area and the fact that the front and rear wheels don't see automatically the same waterdepth.

In a third step, the wet length of the tire is deduced from the waterdepth and the hydrodynamic force on each wheel is calculated. The dry length of the contact area is deduced by considering the equilibrium of the forces applied on each wheel. When a transfer load between front and rear axle exists (braking or accelerating), it is taken into account in the calculus of the dry contact area. The load transfer is determined by considering a model with 2 degrees of freedom.

The process is implemented by increasing the vehicle speed from zero to the value where the dry contact area becomes null, which means that the hydrodynamic forces lift the tire.

The initial values of the parameters are calculated by considering a static equilibrium (figure 7). Thus, the radius of the wheel under load (Rec), the initial wet length (Lm0), the initial dry length (Ls0+L0) and the corresponding angles ($\alpha 0$, $\gamma 0$, $\theta 0$) are determined. The authors considered radial tires with a diameter ranging from 15 to 17 inches.

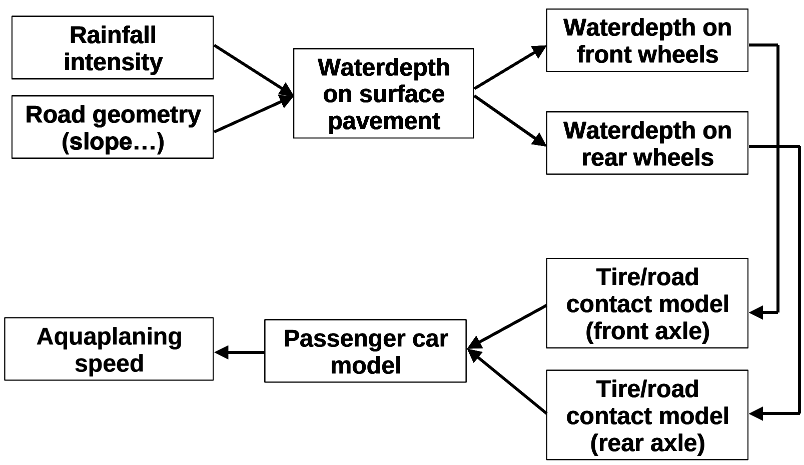

Figure 6 : Principle of calculus of hydroplaning speed

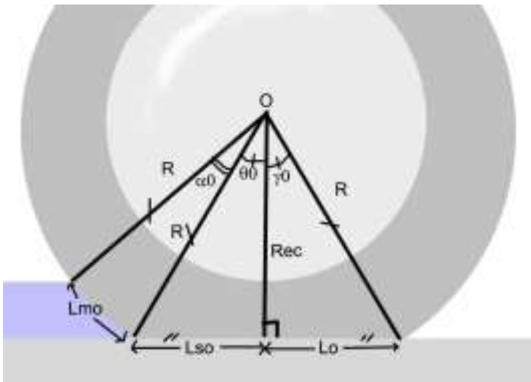

Figure 7 : Scheme of calculus of the tire wet length Lm0

5.3 Waterdepth in front of the each wheel

The initial waterdepth obtained by considering road geometry can increase locally just in front of the wheel when road texture and tire tread depth don't allow its evacuation. Thus, an equivalent area *Aeq* corresponding to the tire treads and the macrotexture of the road pavement is calculated (figure 8). On the same time, the water volume that the road and the tire should evacuate during one revolution of the wheel depends both on the speed of the vehicle and the water-film thickness on the road. Thus, the area *A* needed for evacuating this water is easily determined by making the hypothesis that the water don't move by the sides of the tires.

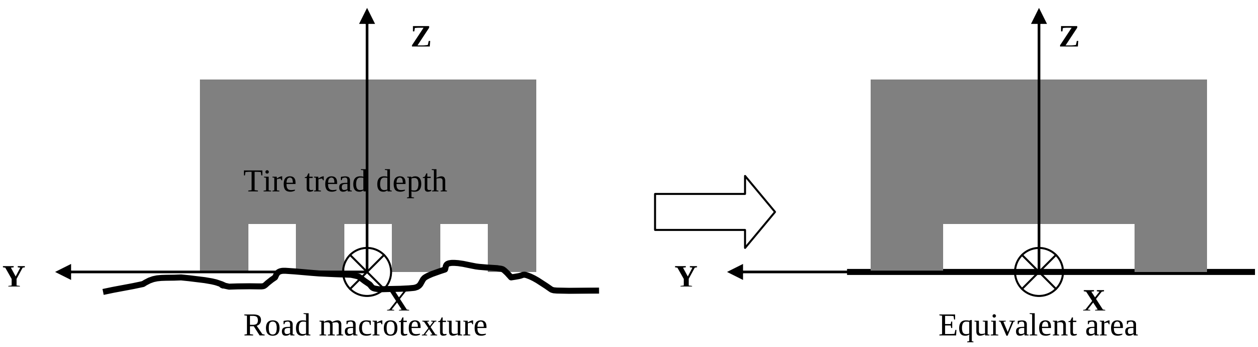

Figure 8 : Definition of the equivalent area *Aeq*

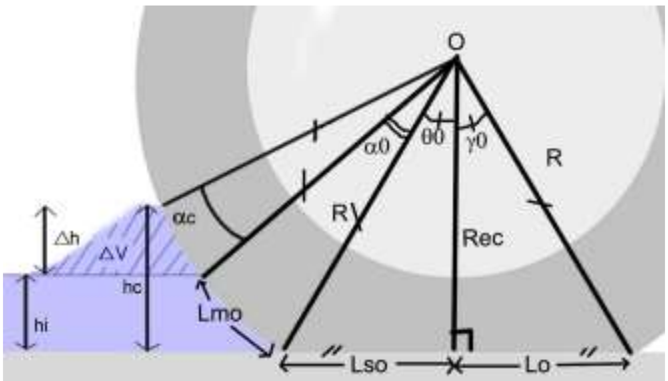

Figure 9 : Waterdepth increase in front of the wheel

Two cases are considered in the model. When the value of Aeq is superior to A, the whole water is evacuated through the tire. When the value of Aeq is inferior to A, a part of the water is evacuated by the tire and the other part generates an increase Δh of the water-film thickness in front of the tire (figure 9).

5.4 Final waterdepth in front of the rear wheels

The waterdepth is not automatically the same on the front and the rear wheels, considering the fact that the front wheels separate the water-film, which has not always the time of recovering the wheels' track before the rear wheels reach it.

The determination of the real waterdepth in front of the rear wheels is done by calculating the recovering speed *Vr* of the water after the crossing of the wheel.

$$Vr = \sqrt{g \times WD} \qquad (7)$$

With WD: initial waterdepth (m) and g: 9.81 $m.s^{-2}$.

Then, the recovering speed is used for determining the area covered again by water, which width is $x_2/2$ following the scheme given in figure 10. The move of water is supposed to be symmetric on the both side of the wheels. When the recovering speed is superior to the vehicle speed, the value of x_1 becomes null and the waterdepth is identical on the front and the rear wheels.

$$x_2 = \frac{2 \times Vr \times l}{V} \qquad (8)$$

With Vr: recovering speed (m/s), l: distance between the front and the rear axle (m), V: longitudinal speed of the vehicle (m/s).

When the recovering speed is not sufficient, an equivalent waterdepth is determined in front of the rear wheel.

$$WDr = \frac{x_1 \times h_1 + x_2 \times h_2}{x_1 + x_2} \qquad (9)$$

With WDr: waterdepth on the rear wheels.

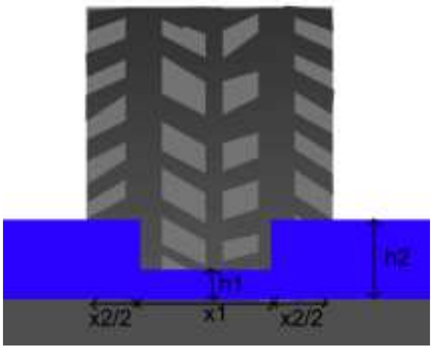

Figure 10 : Scheme of calculus of the waterdepth on the rear wheel

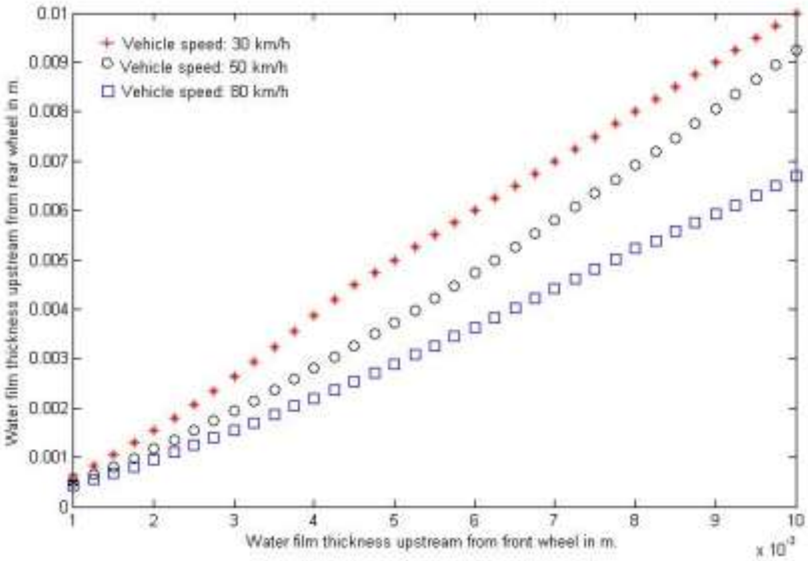

Figure 11 : Waterdepth on the rear wheels WDr depending on the vehicle speed and the waterdepth on the front wheels WDf

When the vehicle speed is rather low (30 km/h), the water-film thickness is the same on the front and the rear wheels. The recovering speed of the water is superior to the speed of displacement of the wheels. When the vehicle speed increases, the water-film thickness can decrease until 30% between the front and the rear wheels, which make an important change in hydroplaning speed considering the fact that the hydroplaning forces are not the same (figure 11). Moreover, hydroplaning occurs in most of the case at high speed (80 to 90 km/h) when the waterthickness is rather different between the two axles. Considering the fact that the tire treads depth and the tire pressure are not necessarily the same for all the wheels in the model, the model can determine the first wheel, which is hydroplaning by assuming the fact that in specific case hydroplaning can occur on the rear wheels before on the front wheels.

5.5 Hydroplaning speed calculus

The hydroplaning speed is calculated step by step by increasing the longitudinal speed of the vehicle until the moment where the hydrodynamic pressure exactly compensates the load on the contact area.

For a given speed, the wet length Lm is determined and the wet surface S_w is evaluated by considering in a first approximation a rectangular area. The hydrodynamic force F_{hydro} on the tire is then deduced by considering the following relationships:

$$F_x = \frac{1}{2}\rho S_w C_x V^2 \quad (10)$$

With V: longitudinal speed of the vehicle (m/s), S_w: wet surface (m²), ρ: water density (kg/m^3) and C_x: the drag coefficient.

$$F_z = \frac{1}{2}\rho S_w C_z V^2 \qquad (11)$$

With V: longitudinal speed of the vehicle (m/s), S_w: wet surface (m²), ρ: water density (kg/m^3) and C_z: the bearing coefficient.
The values of C_x and C_z were obtained in literature review [5, 7].
On the same time, the load transfer is taken into account in view of determining the vertical load on each wheel. Then, the program tests if the forces are balanced. If not, the speed of the vehicle is increased and another wet length is determined.

5.6 Validation of the model

The hydroplaning model was validated by comparison with other existing models (figure 12). Three models are considered: Ivey, Horne and Gallaway. The figure shows the results obtained with a tire pressure ranging from 1 to 3 bars. For each model, a waterdepth ranging from 1 to 10 mm is considered. Thus, the hydroplaning speed is represented as a sheet for each of them. Simulations are realized with a tire tread depth of 8 mm (new tires) and a weak level of macrotexture (MPD of 0.4 mm).
First, the values obtained by the model ranges from 60 to 110 km/h depending on waterdepth and tire pressure, which corresponds to experimental values found in literature. Then, the range of values of hydroplaning speed is wider for high tire pressure than for weak tire pressure. Moreover, figure 12 shows that for pressure higher than 2.2 kPa, the hydroplaning model is close to Horne model. On the opposite, for high waterdepth and pressure values higher than 2 kPa, the model comes close to the Ivey’s model. On intermediate values of waterdepth, the model is closer from Gallaway’s model with hydroplaning speed around 80-90 km/h. We can notice that we are on the edge of the valid area of the Gallaway’s model, which was validated for speed superior to 90 km/h.

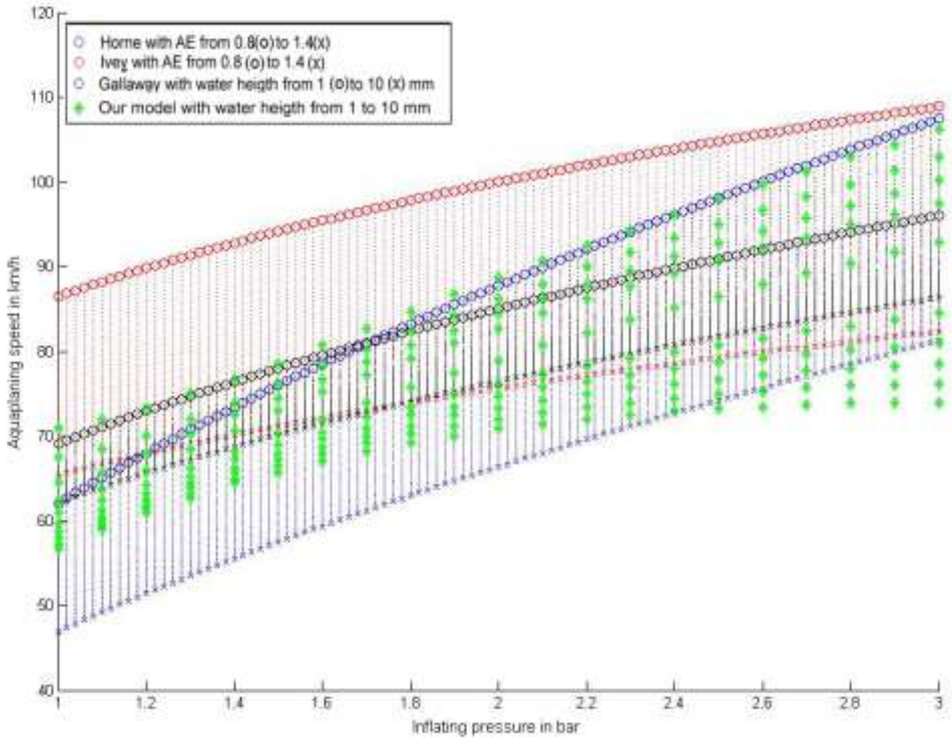

Figure 12 : Comparison of the hydroplaning speed obtained with various models versus tire pressure

6 Concluding remarks

This study aimed at proposing a simplified approach for the prediction of hydroplaning speed, by considering two constraints:

- use a limited number of parameters and degrees of freedom in the numerical model,
- use a limited number of road data.

The interest of this hydroplaning model lies in the fact that the water-film thickness on the road is calculated by using road data available in road databases. The method of aggregation of vectors allows a simply calculus of water flow path length and provides good results, corresponding to experimental data.

Moreover, the model includes both the increase of water-film thickness in front of the wheels due to a lack of evacuation of the water and the fact that the front and the rear wheels don’t see the same waterdepth because they drive in the same tracks. The global hydroplaning model was validated by comparison of numerical simulations. The next step of the work would be an experimental validation of the model on test tracks.

Acknowledgements:

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