ON-BOARD ESTIMATION OF WATER DEPTH USING LOW-COST SENSORS

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ABSTRACT

Last century has seen the emergence of many active safety systems, which have highly participated in reducing the number of car crashes. Nevertheless, those systems can be improved. In particular, information about the wetness of pavement surface could be of high importance to evaluate real tire/road friction.
This paper deals with a new way to estimate local water depths under the tires as the car is running. A direct measurement of the amount of water droplets thrown from rotating tires of the vehicle is used. Tests are performed on test tracks with a real passenger car equipped to estimate spray and splash of water created by the front right tire of the car. Different water depths are obtained by flooding test tracks then measuring while they are drying. An indicator linked to the amount of water droplets is defined and studied under different conditions. Effects of travelling speed, road texture or tire tread pattern are assessed. The relationship between the indicator and actual water depth is verified by using non-contact optical water depth sensors as a reference. This new method of measurement via water droplets is a major breakthrough in automotive engineering since low-cost sensors can be used to estimate the water depth.

1 INTRODUCTION

Advanced hydraulic/electronic active safety systems will highly improve road traffic safety in the next decades [1, 2]. Such systems need real-time information about the vehicle environment. In particular, systems like ACC or BAS need information about tire/road friction [3]. Indeed, friction decreases in the presence of water at the tire/road interface [4] and even very thin water depth could cause a significant drop regarding friction [5, 6]. Thus, an accurate estimation of water film thickness is needed in view of determining this real tire/road friction.

Nevertheless, only few devices are available to perform on-board measurement of thin water depth. Moreover, most of these devices are expensive thus not adapted to mass production [7]. That is why Renault, in partnership with Ifsttar, is developing its own measurement device.

This paper deals with the feasibility study of real-time estimation of water depth under rolling tires. A direct measurement of the amount of water droplets thrown from rotating tires of the vehicle is used. This paper is divided into three parts. First, experimental methodology, set up and procedure are described. Then, results are analyzed using a statistical method. Lastly, future works are proposed.

2 EXPERIMENTAL SETUP

2.1 Methodology

The purpose of this study is to find a relationship between water depth on a pavement and droplets created by a rolling vehicle tire. To achieve this goal, many tests are conducted with a well-equipped passenger car. The vehicle is implemented with an accurate – hence expensive – optical water depth sensor. This measurement is then considered as a reference regarding the water depth. The same vehicle is also equipped with a device specially designed to estimate water droplets acceleration [8]. The two sensors are set up so as to measure concurrently in the same track (right front tire of the vehicle) as the vehicle is running. Many tests are realized with different values for a set of parameters liable to have an influence on the results. Tested parameters are described in section 3. For each test, data provided by both sensors are analyzed and compared. A relation between water droplets created by rolling tires and actual water depth is found. For this purpose, an indicator related to droplets acceleration is developed. Impact of parameters on the water droplets indicator is studied.

2.2 Test vehicle

A Renault Laguna III is used within this study. Rim width of the vehicle is 17 inches. The vehicle is equipped with sensors and computers which allow the real-time record of data. Three sets of data are recorded:

- Water depth on the pavement (reference value for water depth);
- Acceleration of the car frame caused by water droplets thrown from rolling tires;
- Actual speed of the vehicle.

The three used sensors are described below.

2.3 Water depth measurement

The hydric state of circulated pavement is measured by means of a spectroscopic system labeled "Aquasens". This system is based on the specific absorption properties of water for radiation located in the near-infrared [9]. The device is composed of a light source modulated in frequency (broad spectrum) and receivers which analyze the retro-reflected light ray emitted by the source after it has been altered in the liquid on the road. Figure 1 presents the working diagram of the system.

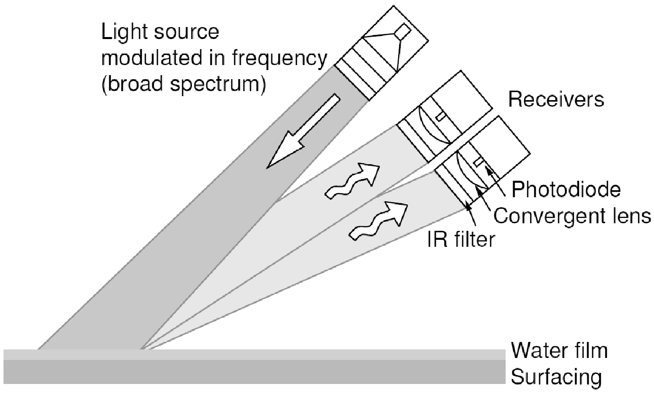


Figure 1 – Working diagram of the Aquasens. [9]

Results (in volt) are directly related to the water depth (in millimeters) on the pavement. The device has two sensitivity ranges: 0 to 1 mm and 0 to 10 mm. Within the frame of this study, the first range, 0 to 1 mm, is used. The device has been chosen because of its capacity to measure in real-time dynamically while the vehicle is running. The set up is shown in figure 2.

Figure 2 – Aquasens set up on the trial vehicle.

Figure 3 gives an example of data recorded by the Aquasens device. The chosen sampling frequency is 11025 Hz. This high frequency is adapted to real-time issues. Further description of the device is available in [10]. For each measurement, the mean value of water depth along the track is computed and used for the study.

In the rest of the paper, the term "water depth" will be used for the value given by the Aquasens device (in millimeters).

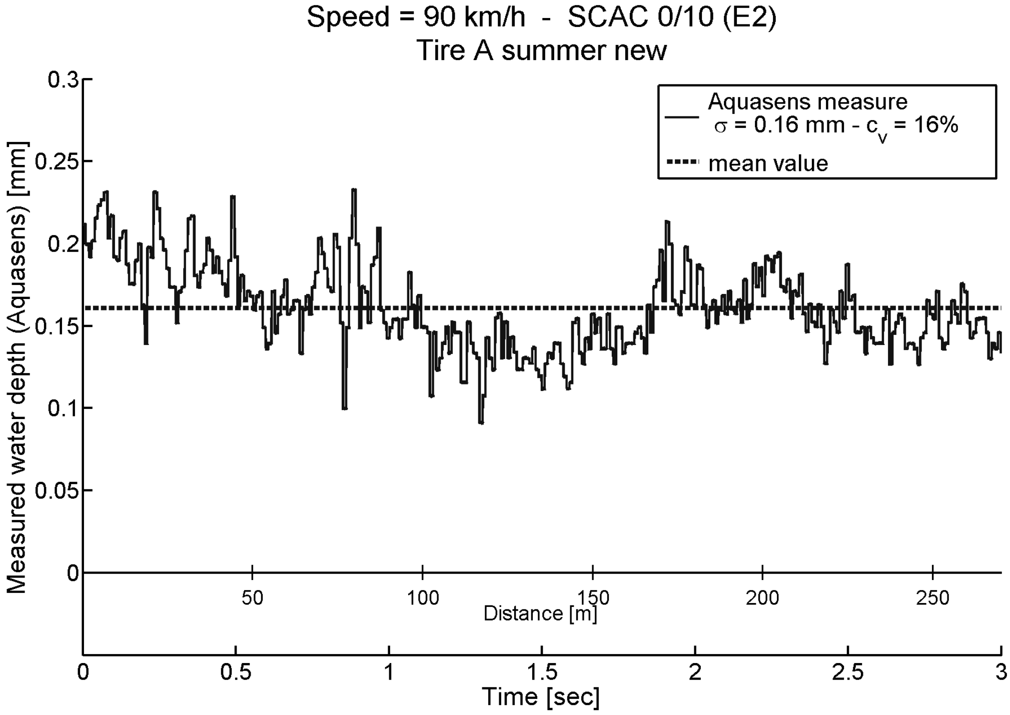


Figure 3 Example of Aquasens data

2.4 Water droplets measurement

A rolling tire throws water droplets while running on a wetted surface. Within this study, a water droplets measurement device has been set up. This device uses a low-cost accelerometer which measures vibrations of the car frame (splash guard) due to droplets created by the right front tire of the vehicle (Fig. 4). The measurement is realized dynamically while the car is moving. An indicator linked to the accelerometer signal is computed for each measurement.

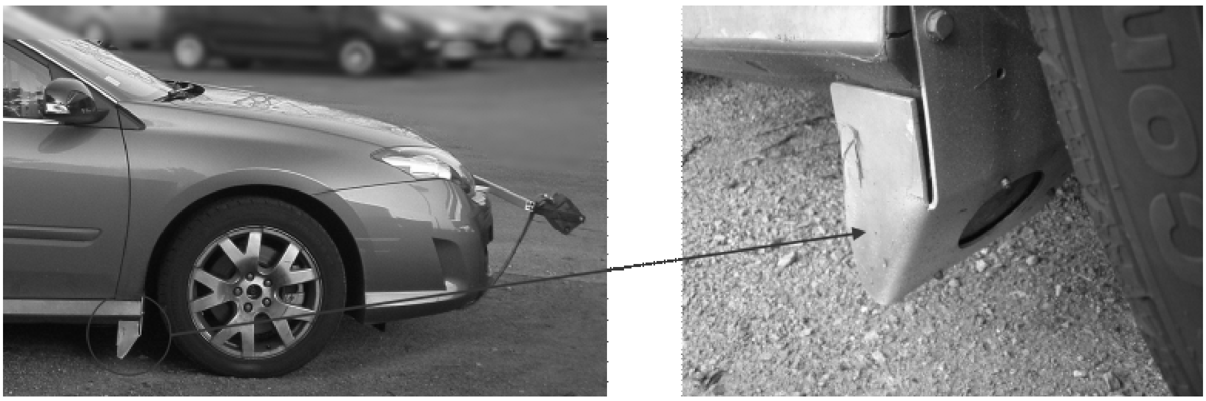


Figure 4 - Water droplets measurement point

2.5 Vehicle speed measurement

Passenger car speedometers are inaccurate. For this reason, another speedometer has been set up on the trial vehicle. It is a Correvit non-contact optical sensor by Corrsys-

Datron. This device allows a real-time visualization and recording. It produces a result in km/h. The chosen sampling frequency is 11025 Hz. Correvit accuracy is 0,2% and its resolution is 0.3 km/h [11]. For each measurement, the mean value of vehicle speed is calculated and used for the study.

3 EXPERIMENTAL DESIGN

A large scale of tire-road friction conditions is studied. Considered factors are:

- 5 pavements;
- 8 different tires;
- 5 speeds.

These factors are described below. The combination of these variables gives 200 modalities. For each one of them, many water depths are tested. Section 3.4 describes those different water depths.

3.1 Tested Pavements

One can distinguish two levels of texture within a surface pavement: microtexture and macrotexture. Microtexture corresponds to surface irregularities with wavelengths of pavement profile inferior to 0.5 mm and vertical amplitude inferior to 1 mm. 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. Figure 5 shows the two texture scales.

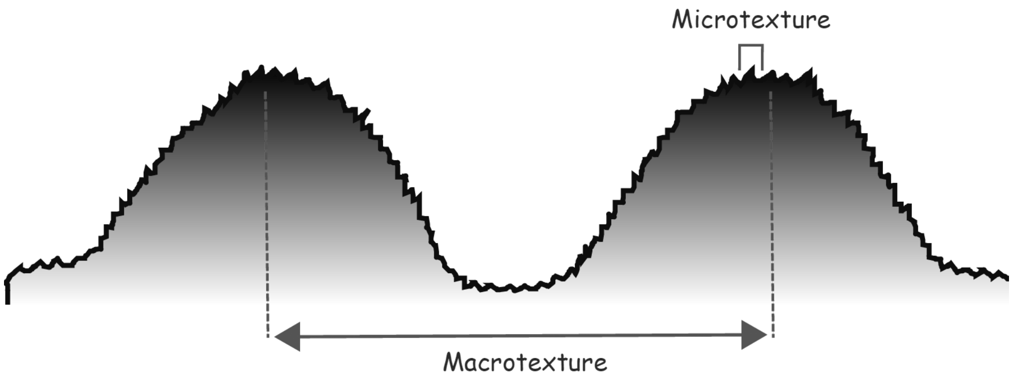
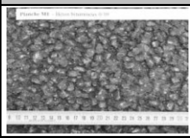
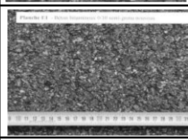
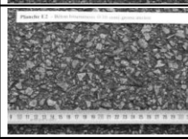
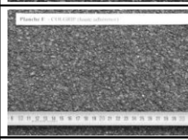
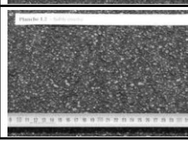


Figure 5 – The two scales of pavement texture

In order to study a large range of micro- and macrotexture, tests have been realized on the "Reference and Road Experiment Track" of Ifsttar in Nantes (Fig. 6). The measurement zone includes a number of test tracks; each zone represents a different pavement surface. Some of them feature "extreme" textural characteristics. The other tracks are representative of actual wearing course laid on the French network. Table 1 shows characteristics of the five different tracks used within this study. Figure 7 displays the interesting distribution of chosen pavements.

Figure 6 – Ifsttar Reference and Road Experiment Track

Table 1 – Tested surface pavement characteristics

Type of pavement	Size of aggregates (min/max)	Acronym	Track Name	Photography	SFC	MPD (mm)
Semi-coarse Asphalt Concrete (new)	0/10	SCAC 0/10	E1		0.73	0.66
Semi-coarse Asphalt Concrete (old)	0/10	SCAC 0/10	E2		0.59	0.82
Colgrip	1.5/3	-	F1		0.95	1.17
Sand-Asphalt	0/4	-	L2		0.63	0.5
Very Thin Asphalt Concrete	0/10	VTAC 0/10	M1		0.71	1.3

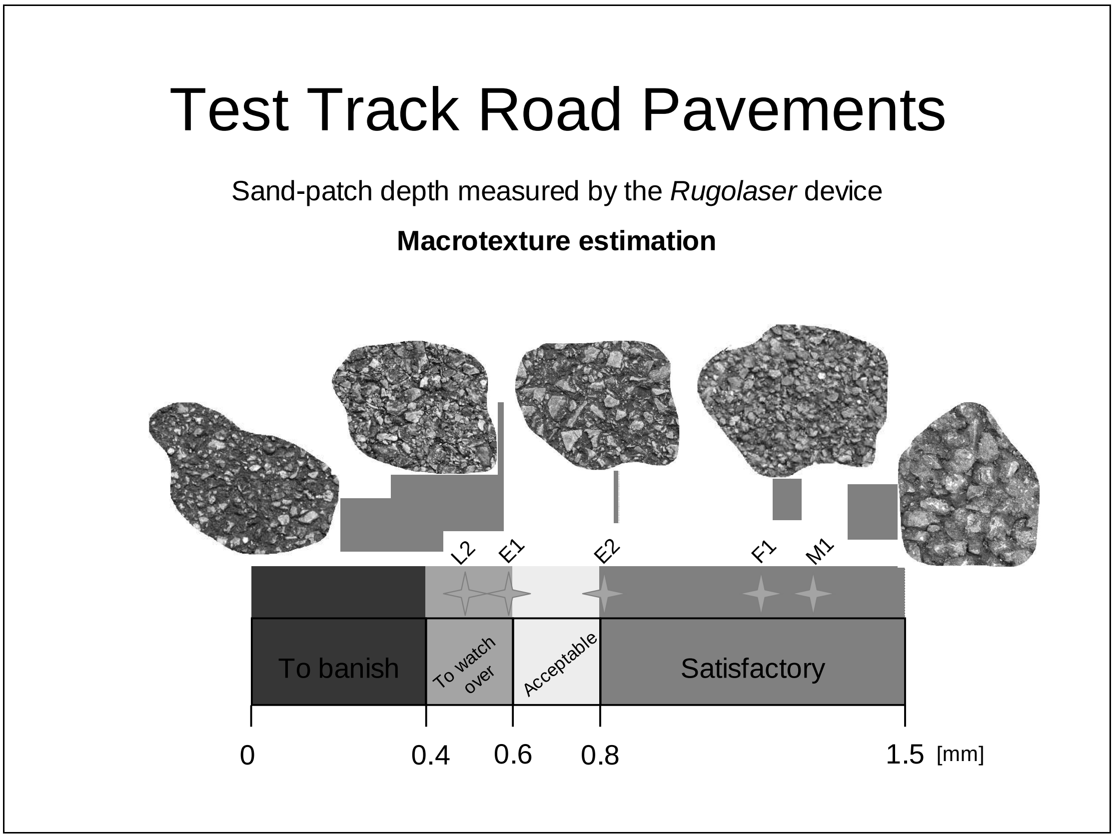


Figure 7 – Distribution of tested macrotexture

3.2 Tested tires

Eight sets of 215/50 R17 tires are used. Three different factors are considered:

- Type: summer or winter;
- Manufacturer: A or B;
- Wearing level: new or worn. Actually, worn tires are artificially worn out by manufacturers for the need of this study. They are not literally "worn" or "old". Their wear is at 80% of the legal limit, which is around 1.6 mm in Europe. Both of these tires are previously broke in for 1000 km in order to take off the silica layer on new tires and to get a normal cylindrical shape.

3.3 Speeds

Five speeds are investigated: 30, 50, 70, 90 and 110 km/h. Those speeds have been chosen in order to cover the range of legal speed limits on wet pavement in France.

- 30 km/h is the French speed limit in special urban areas (school, pedestrians…);
- 50 km/h is the speed limit in urban areas;
- 70 km/h is the speed limit in suburban areas;
- 90 km/h is the speed limit on national roads;
- 110 km/h is the speed limit on wet highways.

Speeds are maintained thanks to the electronic speed control system of the vehicle.

3.4 Surface wetting

The Ifsttar test track is equipped with a sprinkling system, which simulates a strong rainfall. This system is inspired by those used in farming (Fig. 8).

Figure 8 - Ifsttar test track sprinkling system

Preliminary studies have shown that after 10 minutes of wetting, water depth on the track is constant. Indeed, a balance is found between precipitation and stocking/drainage capacity of the track. For this study, as many number of water depths as possible are needed. To get those different water depths, measurements are realized while the track is drying after 10 minutes of wetting.

Figure 9 shows a typical drying curve obtained with this method. We can observe three parts in the curve. In a first part, the water depth value strongly decreases. This is due to the combination of drying phenomenon and spreading phenomenon generated by the transversal slope of the test track (around 2%). In the second part, the drying kinetics decreases due to the end of the spreading phenomenon. In a third part, the water depth has an asymptotic behavior. Figure 9 shows that water depth is not zero at the end of the set of measurements. Depending on the weather, the water depth decreases very slowly for a long time ranging between 2 hours and more than half a day. For this reason, measurements are realized only until water depth value has reached the asymptotic value.

Depending on the modality of the test, in particular the speed, one measurement is done every minute. It takes between 15 and 50 minutes to realize one set of measurements (one modality). This duration changes with meteorological conditions and the speed of the vehicle.

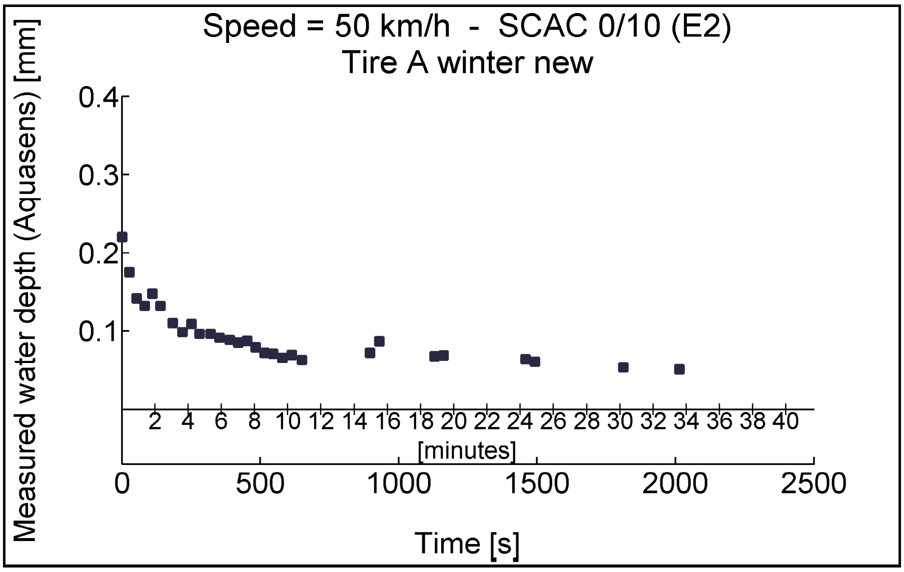


Figure 9 – Drying curve

4 DATA ANALYSIS

4.1 Relationship between water droplets speed and actual water depth

For each set of measures, a linear relationship is found between the indicator related to droplets acceleration and actual water depth measured by the Aquasens device. Figure 10 shows an example of results. For each linear regression, the correlation coefficient r^2 is computed. Almost 90% of r^2 are higher than 0.9 for all data.

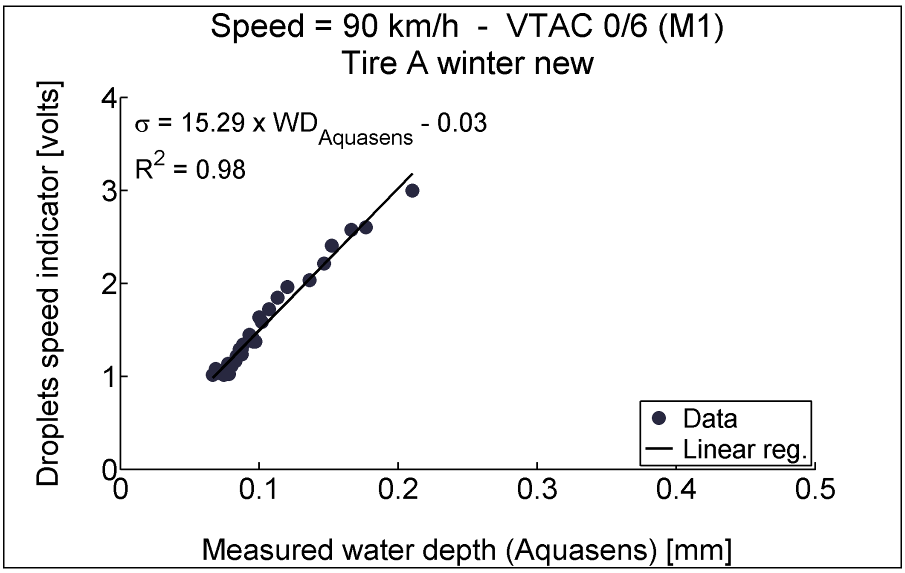


Figure 10 – Linear relationship between droplets speed and water depth

Results show that there is a strong relationship between the studied parameters (pavement surface, vehicle speed, tire type, tire wear) and the slope of the droplet indicator-water depth relationship. Moreover, observation of results shows strong interactions between the studied parameters. Therefore, parameters effects – through their respective effects on the slope of the droplet indicator-water depth relationship – cannot be studied individually. For this reason, an analysis of variance (ANOVA) is performed. The dependent factor is the slope and the factors are:

- vehicle speed;
- pavement surface macrotexture, expressed in terms of MPD values;
- tire type, expressed in terms of the season ("summer" or "winter").

Second order interactions between the factors are taken into account in the analysis. Table 2 presents ANOVA results (Statgraphics Plus software). The statistical analysis shows a very strong interaction between all parameters (p-values).

Table 2 - ANOVA results for speed, MPD and tire type parameters

Analysis of Variance for Slope - Type III Sums of Squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:MPD	201,692	4	50,4231	41,76	0,0000
B:Speed	215,837	4	53,9593	44,69	0,0000
C:Tire_Season	49,1635	1	49,1635	40,72	0,0000
INTERACTIONS					
AB	52,012	16	3,25075	2,69	0,0279
AC	47,2041	4	11,801	9,77	0,0003
BC	13,7755	4	3,44388	2,85	0,0584
RESIDUAL	19,3197	16	1,20748		
TOTAL (CORRECTED)	599,004	49			

All F-ratios are based on the residual mean square error.

4.2 Vehicle speed/macrotexture interaction

The mutual effect of the vehicle speed and the surface macrotexture on the slope is shown in the figure 11.

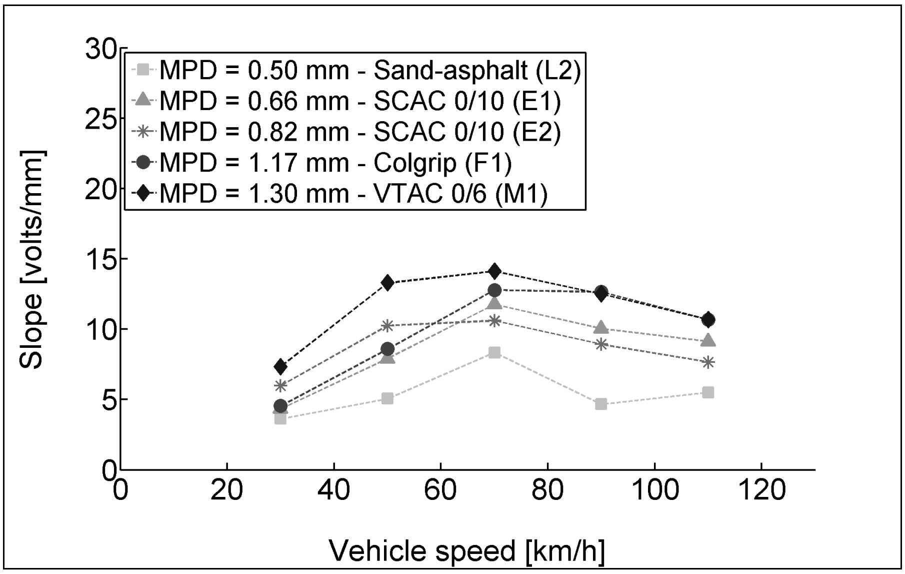


Figure 11 – Vehicle speed/macrotexture interaction

Effect of MPD is not clear. Nevertheless, extreme MPD values curves define the range of computed slopes. For each curve, a transition speed (around 70 km/h) can be defined where the slope value is the highest.

A change in spraying regime can explain the curves shape. Before the transition speed, droplets speed and size are increasing. Consequently, vehicle frame vibrations increase too. In the first part of the curve, the slope increases with the vehicle speed. One can assume that at low speed the tire treads can evacuate the water film by its edges. Thus, only a few part of the water is splashed and sprayed whatever the water quantity initially available on pavement surface. This small part matches to the water drops stuck on the tire rubber. When the speed increases, the tire tread cannot evacuate the whole water film by the edges and a part of water is splashed and sprayed on the accelerometer.

In the second part of the curve, the slope decreases with speed after having reached a maximum value, which depends on the pavement macrotexture. One can assume the fact that the high speed entails a change in the splash and spray behavior. A wide part of water is vaporized and a very limited amount of water drops can reach the accelerometer.

4.3 Vehicle speed/tire type interaction

A comparison between summer tire and winter tire is realized (Fig. 12). The shape of the curves is the same for the both types of tires with an increase of the slope with speed in a first part and a decrease after having reached a maximum value. Nevertheless, figure 12 shows that the winter tire creates a higher amount of drops than the summer tire. This can be explained by the differences regarding patterns. Winter tires have specially designed sipes which drive water off the contact area to avoid friction loss (Fig. 13) [12].

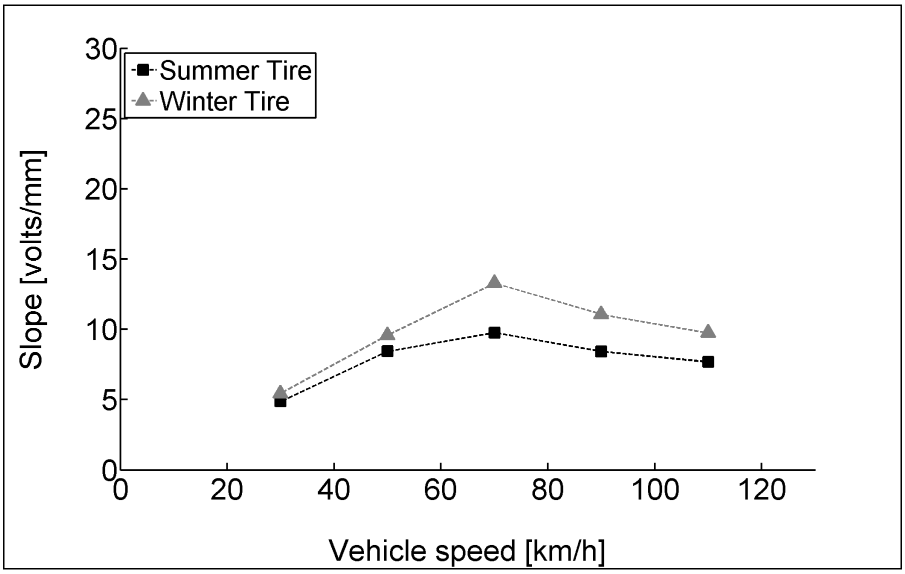


Figure 12 - Vehicle speed/tire type interaction

Figure 13 – Pattern differences between winter (left) and summer (right) tires

4.4 Macrotexture/tire type interaction

The mutual effect of the surface macrotexture and the tire type (in terms of season) on the slope is shown in the figure 14.

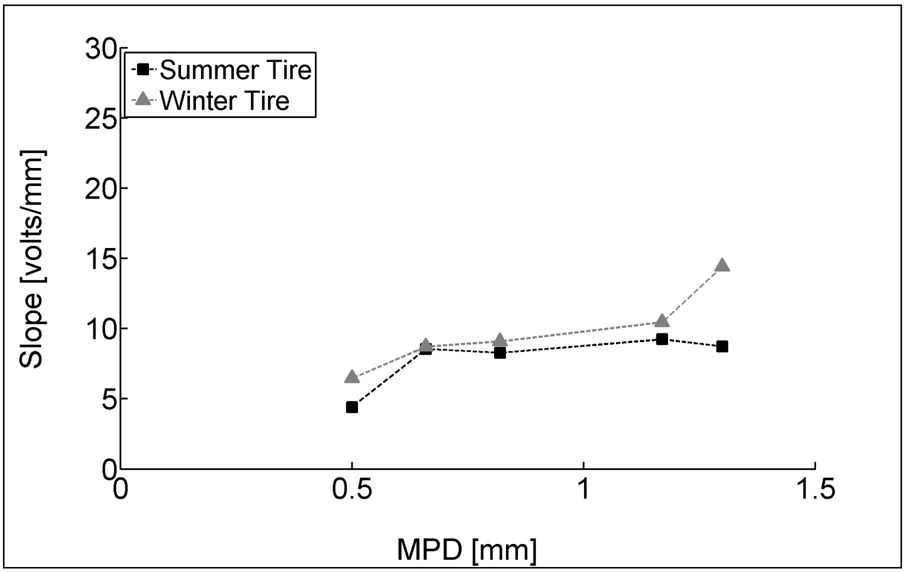


Figure 14 - Macrotexture/tire type interaction

For the summer tire, the slope does not depend on the surface macrotexture when MPD is higher than approximately 0.6 mm. For the winter tire, the macrotexture independency of the slope is observed for a more narrow MPD range (between 0.6 and 1.2).

4.5 Tire wear/vehicle speed interaction

A limited data set was used to assess effects of vehicle speed, pavement surface and tire wear. The mutual effect of the surface macrotexture and the tire wear is analyzed (Fig. 15). It appears that worn tires are more responsive to slope changes than new tires. This can be explained by the tire capacity to evacuate water by its edges. For a given quantity of water, new tire evacuates more by its edge than worn tire. As a consequence, more water is sprayed in direction of the accelerometer in the case of worn tire. However, it can be seen that the surface macrotexture is high (case of VTAC), the difference between new and worn tires is lessened. Again, this observation can be explained by the water evacuation mechanism: high surface macrotexture enables water to be evacuated rapidly and, by consequence, mitigates the effect of tire wear.

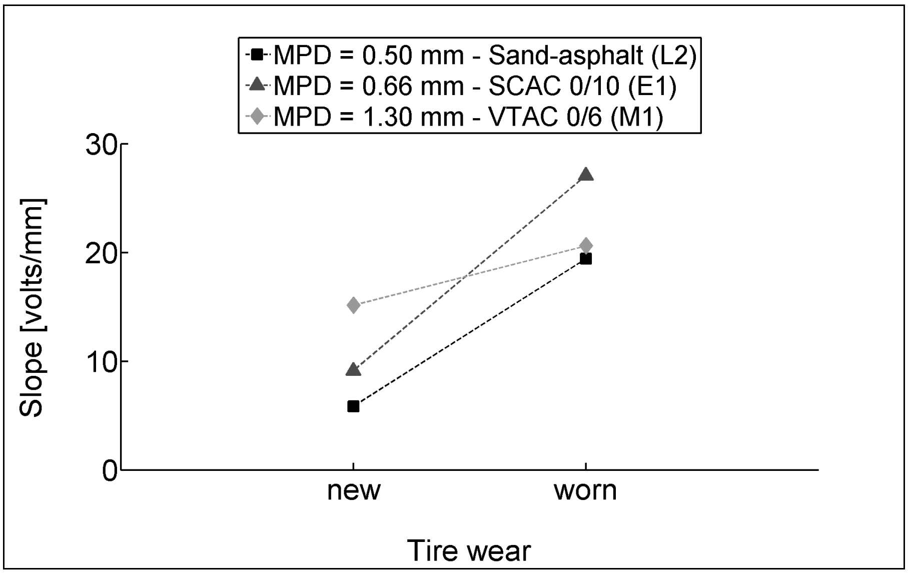


Figure 15 - Tire wear/vehicle speed interaction

5 CONCLUSIONS

In this paper, feasibility of a water depth measurement on pavement by indirect measurement of water droplets thrown from rolling vehicle tires has been demonstrated. Moreover, effects of vehicle speed, pavement type or tire type (summer or winter) on droplets have been investigated.

Results show a strong correlation between droplets forming and water depth on the pavement surface. Nevertheless, it is now necessary to quantify and understand effects of other parameters of the tire/road contact. In particular, result of a pavement change on the droplets forming has not totally been appreciated. Moreover, the study of effects of tire wearing level or manufacturer change is underway.

Results presented in this paper have direct benefits for automotive engineering. The droplets measurement set up has indeed been designed to be easily implemented in mass produced cars. Besides, the used sensor is a low-cost one. As discussed in the introduction, real-time information about hydric state of the circulated pavement is of major importance regarding on-board active security systems. Particularly, new systems such as ACC (Autonomous Cruise Control system) need this feedback information to evaluate the necessary braking distance hence the minimal distance to maintain with the front vehicle to avoid rear-end collision.

Finally, results will find an application in the road traffic safety research field. Specifically, numerous searchers are working on visibility loss due to droplets issues. The droplets measurement set up in this study is low-cost and easy to implement on any vehicle. It will ease future droplets measurements. The set up can be used for road monitoring on many pavement types. Then, droplets forming process can be broken down and it can be considered that, in the future, new pavements, for instance, could be designed to avoid visibility loss issues.

6 ACKNOWLEDGEMENTS

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