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Tire Skid Resistance on Contaminated Wet Pavements

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Abstract

An experimental test rig has been designed, fabricated, and used to study the effect of wet pavement contamination on the tire-pavement skid resistance. Results showed that although precipitation water reduces tire-pavement skid resistance, the presence of other contaminants plays a major role in further loss of this resistance. It has also been shown that the fractional constituents of pavement contaminants vary according to the vertical profile of the same road under the same traffic density. Traffic signal areas showed the lowest skid resistance when compared to other locations of the same road. Also, the skid resistance on a contaminated up-gradient was found to be lower than that of a contaminated down-gradient of the same traffic density. Among other contaminants, rubber particulates produced by tire wear appear to have minimal effect on the loss of tire-pavement skid resistance.

Keywords: Tire Skid Resistance; Pavement Contamination; Wet Pavement; Slippery Roads.

1. Introduction

Among other road surface conditions, slippery pavement during precipitation is of great concern to road safety authorities. Some statistics indicate that the number of accidents increases by up to two folds during rainy conditions [1-2].

Loss of skid resistance affects driver's ability to control vehicle. In addition to increasing the stopping distance while braking, lower skid resistance reduces steering controllability since both braking and steering depend on tire-pavement friction. This means that drivers need to change their driving habits when facing wet driving conditions. Some countries have realized the importance of educating drivers on how to act when facing slippery road conditions, such that they introduced the topic as a compulsory training course for new drivers [3]. It has been also realized that identifying spots with low skid resistance may help in reducing accidents [4].

Skid resistance is known to be a function of pavement construction materials [5-6], pavement roughness [7], and surface conditions [8]. As far as surface conditions are concerned, most of the work on wet pavement skid resistance appears to be dealing with the effect of the presence of precipitation water as a lubricant regardless of the other contaminants [9-11].

Pavement contaminants are expected to constitute of wear debris from pavement materials, pollutants from the surrounding environment, hydrocarbons leaking from motor vehicles, carbon particles, other vapors from the exhaust products, tire rubber wear particles, brake pads wear products, and metal wear debris produced by moving vehicle parts. Such diversity in the sources of pavement contaminants may lead to the assumption that the fractional amounts of these contaminants on any location is expected to vary according to the operating conditions. Vehicle speed, vehicle type, traffic density, surrounding environment, vehicle maintenance,etc are among the most influential in this regard.

In places where there are long periods between precipitations, the number of accidents increases during the first precipitation after a dry period. Then, with more precipitation, the number of accidents falls again. Eisenberg [11] has found that", if it rained a lot yesterday, then on average, today there are fewer crashes". His analysis also showed that " the risk imposed by precipitation increases dramatically as the time since last precipitation". These findings may indicate that the accumulation of pavement contaminants could be a suspect in loss of skid resistance.

The accumulation of pavement contaminants appears to be controlled mainly by the amount and repetition of precipitations. Many of these contaminants can be washed away during heavy rain.

The question which this work is trying to address is: What role do the pavement contaminants play in the tire-pavement skid resistance during precipitation? Also, do fractional amounts of these contaminants vary along vertical profile of the road such that it alters skid resistance?

2. Methodology

2.1. Experimental Set-Up

Since the aim of the work presented here is to compare the tire-pavement skid resistance under different wet contaminated pavement conditions, one may not be interested in obtaining absolute skid resistance numbers. In this case, comparison of the skid resistance under different contaminated contact conditions with the cases under dry

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contact may serve the purpose and give a good idea about the effect of different pavement contaminants.

A number of skid resistance evaluation devices can be used for this purpose. The British pendulum, which uses the loss of the potential energy of a swing pendulum as a skid resistance measure, is among the most widely used. However, for the experimental work presented here, and by use of the concept of the kinetic energy stored in a flywheel, a machine was proposed. If a flywheel is given a certain rotational speed via a power source, it stores a certain amount of kinetic energy depending on its mass, dimensions, geometry, and rotational speed. When the power is cut-off and the flywheel is kept rotating freely, its deceleration will totally depend on the frictional resistive torque. If this frictional torque is made to be that between the tire material and pavement, then deceleration of the flywheel will be a good measure for the skid resistance.

The proposed machine consisted of a flywheel connected via a shaft with a splined sliding joint to a variable speed gear box powered by an AC motor. Two sprockets and a drive chain connect the gear box output shaft to the top of the flywheel shaft. A unidirectional clutch fitted on the flywheel shaft ensures that the fly wheel is driven by the motor in such a way that when the power is cut off, the flywheel continues rotating due to its inertia only. The sliding joints ensure continuous contact between the flywheel and the pavement, and at the same time it guarantees that the normal force on the flywheel is constant, and it is limited to the weights of the flywheel itself and the lower part of the sliding joint. Three 5x5 cm ungrooved rubber pads, cut from tire material, are equally spaced and are secured to outer most radius of the bottom surface of the flywheel to form the contact between the tire material and the pavement.. Figure 1 is a schematic illustration of the machine.

The rotational speed of the flywheel is measured using a tachometer, whose signal is stored in a storage oscilloscope. The stored signal represents the velocity history of the flywheel speed from start to stop, from which deceleration of the flywheel during the free rotation is caused by the resistive frictional torque, and it can be calculated.

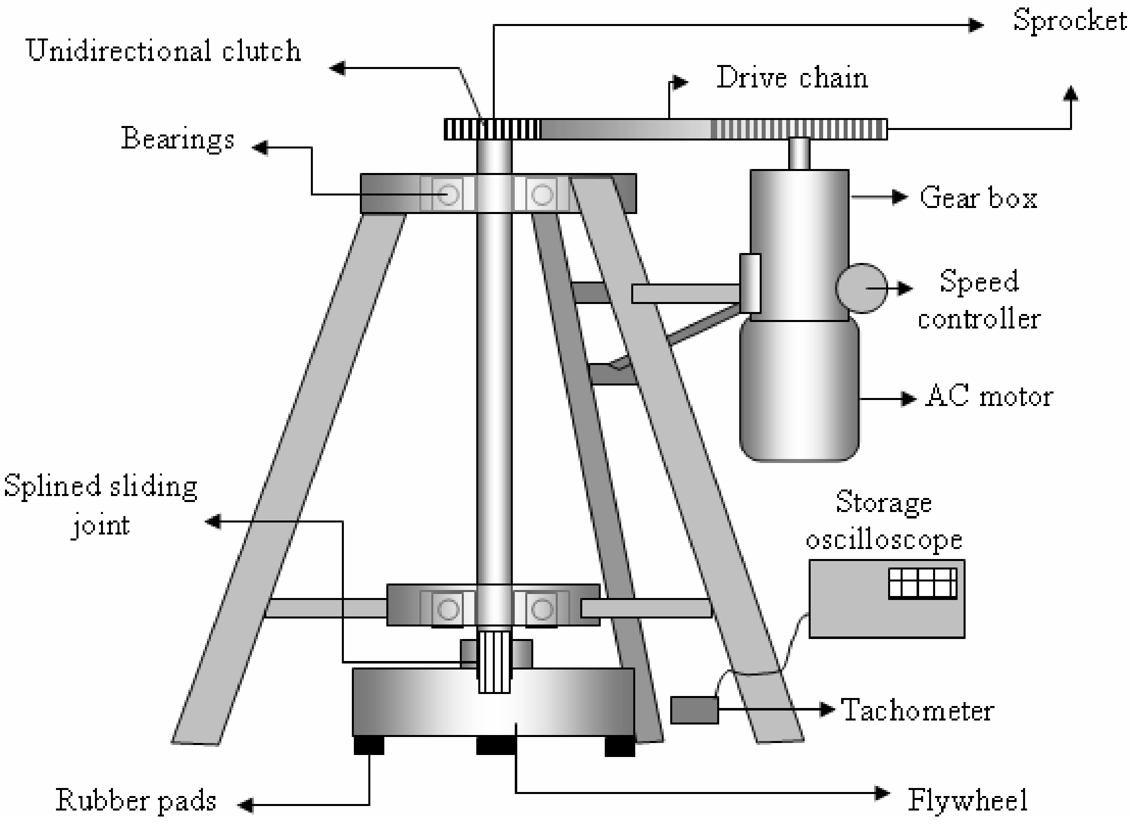

Figure 1. Schematic illustration of the skid resistance testing machine.

2.2. Test Procedure

A pavement of around one squared meter is vacuum-cleaned, washed, and dried before each test. Since all tests are carried out on this same spot of the pavement. Pavement material and surface parameters of the pavement will not be of importance as results are comparative. The flywheel is placed on the pavement such that the three rubber pads are in contact with the cleaned area. Motor is started, and fly wheel is given the required rotational speed using the speed controller. Once the required speed is reached, the motor is stopped to allow the flywheel to decelerate, driven by its inertia and resisted mainly by the frictional torque between the pavement and the rubber pads. The contribution of bearing friction in this case can be considered negligible compared to pad-pavement friction Tests with different contact contamination conditions are performed by applying the contaminants to the contact area as described later.

2.3. Samples of Contaminants

During first precipitation of winter season, after a dry period of five months, and before roads are washed by rain water. A vacuum cleaner is used to collect wet samples from a certain paved road. The samples are kept in sealed glass containers for further testing. No attempt has been made to know the exact composition of the samples.

For the purpose of this study and to ensure the same traffic density, amount of rain, operating conditions, and three different locations on the same one-way road were selected. The selected road profile consisted of a 3% down gradient length, followed by a level stretch with a traffic signal, then a 3% up gradient stretch. Since it is a one way road, the same amount of traffic passes the three locations. Figure 2 is a schematic illustration of the three sample collection locations.

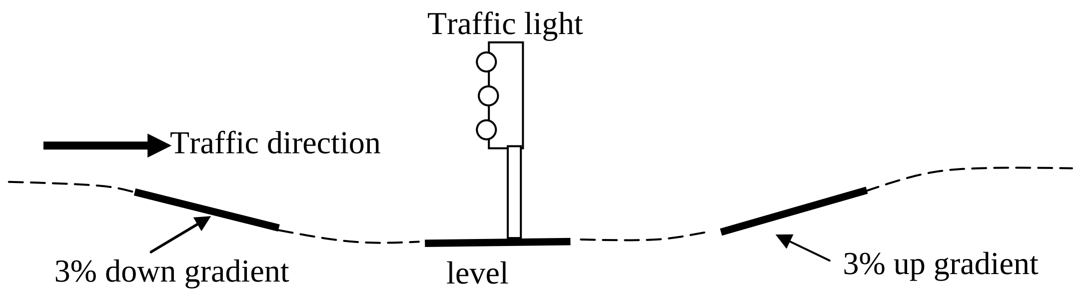

Figure 2.The vertical profile of the contaminated sample collection locations.

2.4. Test Schedule

In addition to clean dry pavement contact condition, testes were carried out on three other categories according to the contaminant type as tabulated in table (1)

Table 1. Test schedule.

Category	Contact contaminant
A	None (clean and dry)
B	Tap water on clean pavement
C	Wet contaminants collected from the three location described above
D	Artificial wet contaminants

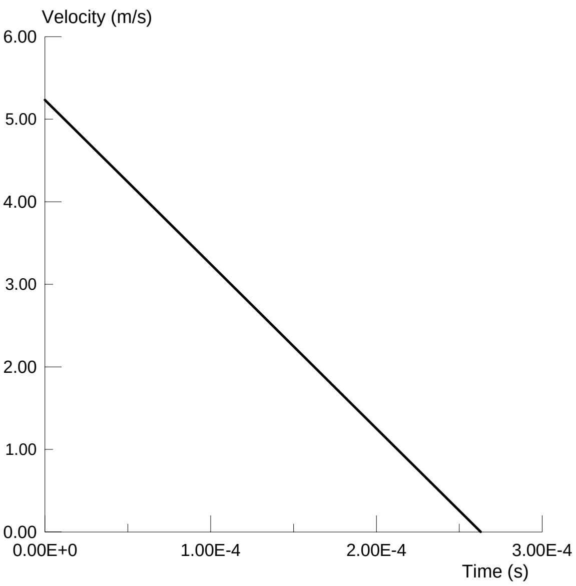

Figure 3. Time- velocity relationship for the dry contact condition.

The amount of contaminant used in this case is classified according to the quantity supplied to the contact area as mist, drizzle, and flood. Mist means that the amount of contaminant is just enough to wet the pavement surface without filling the pavement rough cavities whereas drizzle supply fills many of the cavities, but not enough to leak out. Finally, the flood contact floods the contact area to levels above the pavement cavities.

3. Test Results

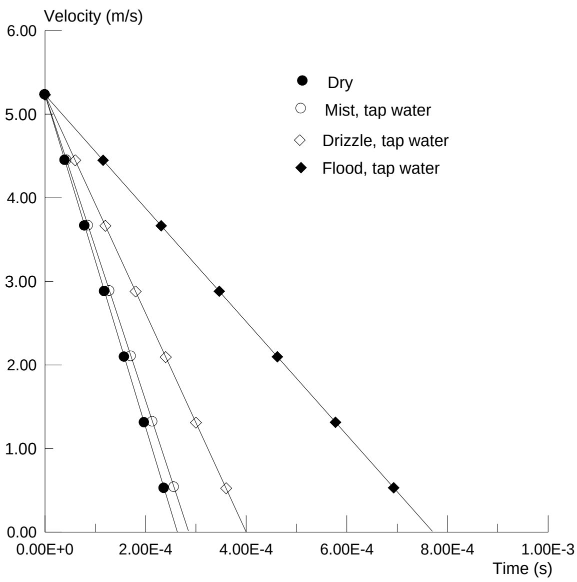

Figure 4.Time-velocity relationship for dry and wet contact conditions.

3.1. Dry, Clean Pavement

The time-velocity relationship under0 dry clean pavement condition is shown in Figure (3). The initial free rotational speed of the flywheel was 5.334 m/s. In this case, the slope of the plot represents the deceleration in m/s^2. This deceleration will be used as a measure of skid resistance. Since this test represents a non-contaminated condition, its results will be used as a reference for comparison purposes.

3.2. Tap Water on Clean Pavement

Figure 4 shows the time-velocity relationship for three cases in which tap water was used as the only contaminant. The only variable in the three tests is the

amount of tap water supplied to the contact area as described earlier. For comparison purposes, the dry pavement test results are also shown on the same plot.

It is evident that all the three water contaminated conditions show a lower skid resistance (higher deceleration compared to the dry contact). The lowest skid resistance is the one under flooded pavement contact condition, whereas mist contamination shows minimal effect on skid resistance when compared to the dry contact.

The decelerations for the three cases are related to that of the dry case, i.e. normalized, and shown in the bar chart of Figure 5. If this normalized deceleration is termed Normalized Skid Resistance (NSR), then the NSR becomes unity for the dry contact, 0.86 and 0.66 for mist and drizzle contamination conditions, respectively, whereas NSR is drastically reduced to only around 0.34 for the flooded contact condition.

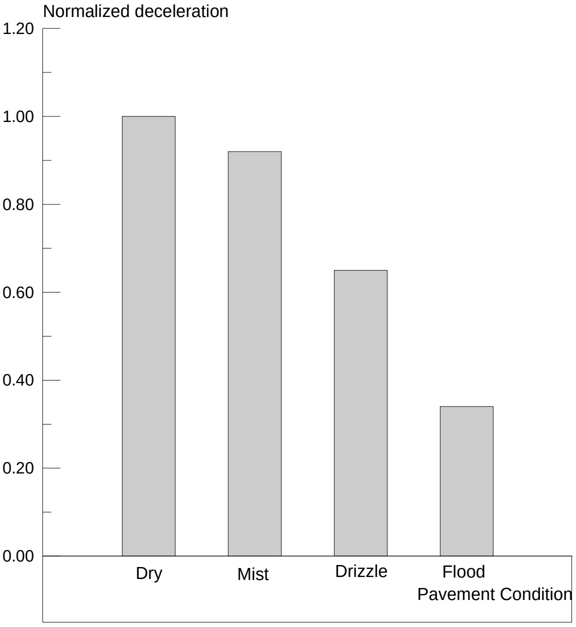

Figure 5. Normalized skid resistance as a function of different wet contact conditions.

3.3. Naturally Wet Contaminated Pavement

Three tests, using the three wet contaminated sample collected from the three locations, as described earlier, were conducted under drizzle supply. The drizzle supply was selected since it represents the operating conditions on the road, where the contaminants are neither washed out by flood, nor fully mixed with water during mist rain. Test results for this category are shown in Figure 6 as a time-velocity relationships along with that for the dry pavement condition.

The figure reveals different decelerations depending on the location where the contaminant sample was collected. The lowest skid resistance is obtained for the contact contaminant collected from traffic signal area. Also, the skid resistance for the up-gradient sample is much higher than that for the sample collected from the down-gradient area. These differences are better illustrated in figure 7, which shows the normalized skid resistance (NSR) for the three cases, and compared to that of the dry contact case.

The above figure shows that the NSR drops from unity for the dry contact to near 0.58 for the down-gradient

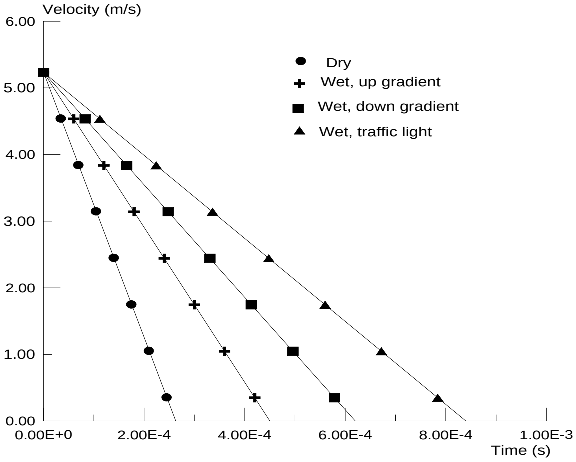

Figure 6. Time-velocity relationship for the different wet contamination contact conditions

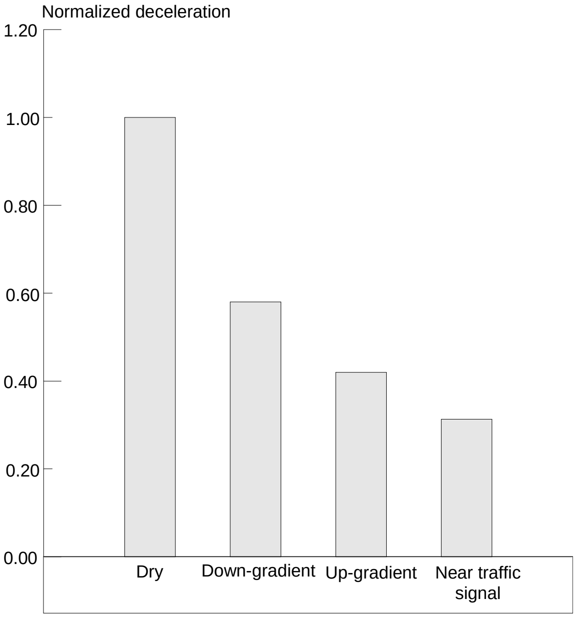

Figure 7. Normalized skid resistance under contact conditions of road contaminants collected from different locations.

contaminant contact, and to 0.42 for the up-gradient contaminant. The minimum NSR is obtained for the contaminant collected from the area near the traffic signal. These differences will be discussed in the sections to follow.

3.4. Pavement with Artificial Contaminants

Although the exact composition of the samples collected from the road is not known, it is expected that these samples may contain dust, fine particles of brake pads, rubber dust from tires, oil and other hydrocarbons, and fine metallic particles from wearing mechanical parts. In this case, the contribution these constituents in the loss of skid resistance may need to be known. Therefore, this effect could be better investigated by mixing one artificially prepared contaminant with water. Three artificially contaminated samples, containing silica dust, rubber dust, and cutting fluid, were prepared. The volumetric concentration of the two slid contaminants in the clean tap water was selected arbitrarily at 3%. The size of the silica dust and rubber dust particles was greater than

0 and less than 200 microns. The cutting fluid used was the mineral oil based type emulsion with 3:100 oil to water ratio. All the artificially contaminated samples were supplied as drizzle to the contact area.

Time- velocity relationships under the three artificially contaminated samples are shown in Figure 8. For comparison, the figure also includes the results for dry contact as well as that with uncontaminated tap water condition.

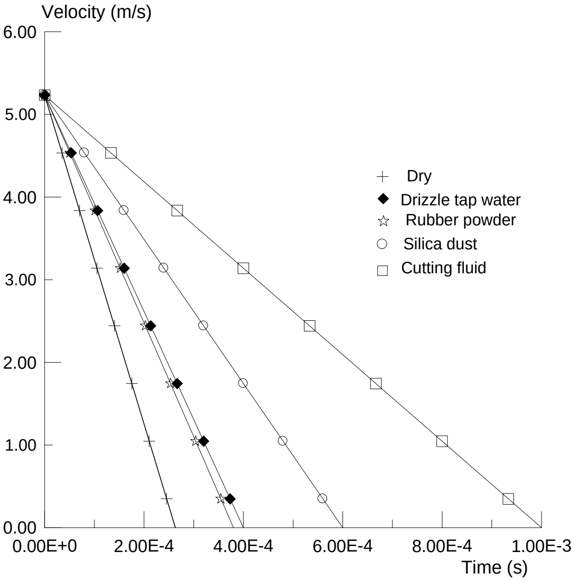

Figure 8. Time-velocity relationship under conditions of different artificially prepared contaminants.

The same results are shown in Figure 9 in the form of a bar chart where NSR is shown as a function of the type of the artificial contaminant.

The bar chart reveals that the pavement contamination with only rubber powder has almost no effect on the NSR. The NSR is 0.650 for uncontaminated tap water contact and 0.657 for rubber powder contaminated contact. But, a significant drop in the NSR is associated with the contact contaminated with oil-water mixture. Furthermore, the effect of dust, as a contaminant, in reducing the skid resistance is noticeable.

4. Discussion

The test program used in this study compares the normalized skid resistance NSR for different contaminated pavement conditions. The NSR of the dry pavement contact condition has been used as a reference since it represents the favorable contact condition.

The effect of other factors on the skid resistance is neutralized by conducting the experiments on the same spot of the pavement. In this case, the effect of pavement construction material and pavement surface roughness is isolated. Cleaning and drying of the test spot before each test guarantees that no residual contaminants remained from previous tests.

4.1. Tap Water On Clean Pavement

As expected, all wet contact conditions gave lower skid resistance when compared to the dry contact. However, the difference in skid resistance of the three tests under tap water contact of different supplies can be explained by

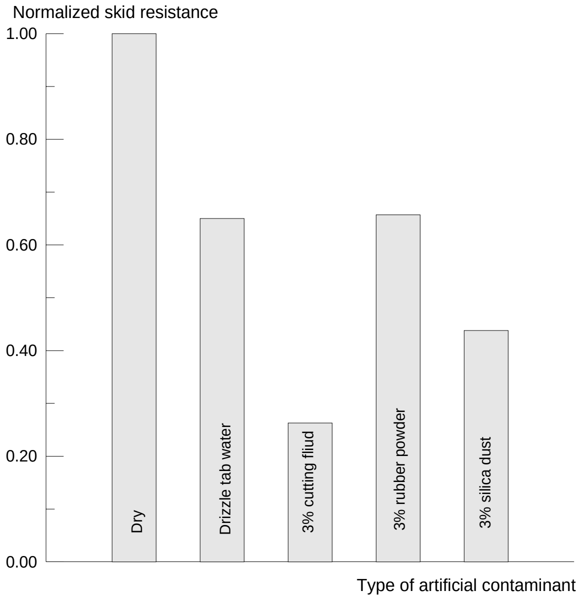

Figure 9. Normalized skid resistance for artificially prepared contaminants .

arguing that mist supply can not provide a thick lubrication film compared to the pavement roughness. In this case, no hydrodynamic action is possible. This may explain why the NSR for the mist contact does not drop significantly but rather recorded 86% of that of the dry contact. On the other hand, it can be noticed that the flood supply has a drastic effect on the skid resistance, where the NSR has dropped to 26% of that of the dry contact. This can be explained by arguing that the amount of water was enough to cause hydrodynamic lubrication. However, the result may appear contradictory to what drivers experience on flooded roads. The difference is the absence of other pavement contaminant, and that the rubber pads used during the tests were not grooved. Tire grooving allows water to escape from the tire-pavement contact area, and as a result prevents the hydrodynamic action between real vehicle tires and flooded pavements [12]. Furthermore, most of pavement contaminants are washed away by flood rain.

4.2. Naturally Wet Contaminated Pavement

The samples in this case were collected from three locations on the same road as described in section 3.3. Time of sample collection was during the first precipitation following a 5-month-dry period. To ensure same water content, the three samples were collected simultaneously but before flooding pavement.. As mentioned earlier, flood rain may washout the contaminants such that the samples may end up containing water only. Furthermore, accidents rates and severity are known to be higher during the first precipitation following a dry period [11]. This may explain why the three tests of this category were conducted under drizzle contact conditions.

The results described in section 3.3 and Figures 7 and Figure 8 indicate three different skid resistances. The sample collected from the traffic signal area caused maximum drop in the NSR, from 1 for dry contact to 0.31 for the contaminated sample. The samples collected from the up and down gradients showed 0.58 and 0.42 NSR, respectively. It can be concluded that contaminant content in the three samples may be different. The area near the traffic signal is expected to have higher contamination contents, mainly hydrocarbon, since many cars stop at the red signal for awhile. If there are leaks of fuel, oils and/or other materials, the share of a unit area of these leaks will be higher on the stop area. Whereas the same amount of leaks is distributed on a much larger area if the vehicle is traveling, depending on the vehicle speed. Furthermore, brake pads and tire rubber residuals are also expected to be higher near traffic signal due to the high number of start-stops in such locations. In addition, some internal combustion engine faults like worn intake and exhaust valves are known to produce oil vapor and oil combustion products during the first acceleration following an idle stop.

As far as the up and down gradient samples are concerned, the NSRs, as seen in Figure (7), are 0.42 and 0.58, respectively. The difference in this case may indicate different contaminants, attributed to the different operating conditions. On down gradient, speed is controlled by lower gear ratios and/or brake applications. In this case, engine is not loaded. Whereas in up-gradient, vehicles climb on throttle causing more exhaust residuals. Furthermore, speed is expected to be lower on the up gradient. This means that contaminants related to lower speed and higher engine loading are higher on the up gradient, whereas brake pad residuals are less.

4.3. Artificially Contaminated Wet Pavement

The set of tests described in section 3.4 aimed at examining the effect of the different contaminants in lowering skid resistance. Being wet tests, all gave lower NSR compared to the dry contact. However, if the effect of the contaminant is to be assessed, it is the comparison between the wet-uncontaminated and the wet-contaminated which is significant.

The test with 3% cutting fluid in water gave the lowest NSR. This finding is in agreement with the argument that the area near traffic signal contains higher concentration of oily products. The result of the test of rubber–water contamination is in an agreement with the finding of Chiu [6] despite the fact that his findings are for rubber mixed in the pavement construction materials rather than being a contaminant on the pavement surface as in the case of this study.

5. Conclusions

- Although pavement contamination with water alone reduces tire-pavement skid resistance, other pavement contaminants play an important rule in further deterioration of this resistance
- The fractional content of the different pavement contaminants on a certain road having same traffic density changes according to the vertical profile (up gradient or down gradient). As a result, the skid resistance along this profile changes accordingly
- Traffic signal areas are the most dangerous spots with regard to loss of skid resistance, when compared to up and down gradient spots of the same road and traffic density.
- Tire wear debris (rubber particulates), as a pavement contaminant, has no significant effect on the loss of tire-wet pavement skid resistance
- Pavement contaminated with dust particulates mixed with rain water has a lower tire-pavement skid resistance when compared to pavement contaminated with water only

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