Tyre/ground interaction testing – Water contamination

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Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Sky Safety Project P3 Solutions for Runway Excursions. This report presents the initial testing results of tyre/ground interaction on dry and contaminated surfaces, and for veer-off conditions.

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Acronyms

Acronym	Definition
LHS	Left Hand Side
RHS	Right Hand Side

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EXECUTIVE SUMMARY

Problem Area

A runway excursion is the event in which an aircraft veers off or overruns the runway surface during either take-off or landing. Safety statistics show that runway excursions are the most common type of accident reported annually. The European Action Plan for the Prevention of Runway Excursions (EAPPRE) provides practical recommendations with guidance materials to reduce the number of runway excursions in Europe. The Action Plan also identified areas where research is needed to further reduce runway excursion risk.

In relation to this, one of the sub-objectives of Future Sky Safety P3 'Solutions for runway excursions' is to develop a tyre/ground model to be used for simulation of aircraft operation under crosswind conditions and contaminated (water) runways to predict runway excursions. In order to validate this model, it is necessary to compare the results of the model with experimental results. The work presented in this report corresponds to the generation of physical data for the validation of the model.

Description of Work

The work detailed in this report forms a pilot study to determine an appropriate test procedure for the main (follow-up) study. The tests for this pilot study were conducted on a pair of 22x8.0-10 12PR aircraft tyres (one of the tyres was new while the other was worn), as fitted to a Cessna Citation main gear. The test tyres were fitted to the Cranfield University self-propelled aircraft tyre test rig which allows the test tyres to be counter steered or braked whilst being subjected to a vertical load of up to 10 kN per tyre. The tests were carried out at a speed of 22 m/s (80 kph) on a straight level 600 m long tarmac surface under both dry and wet conditions. The wet surface conditions ranged from 0 to 20 mm of standing water. These tests were to simulate both crosswind and contaminated runway conditions.

Experimental Data

Data measured during the experiments include: test vehicle speed, test wheel slip angle, wheel forces (vertical, longitudinal and lateral) brake reaction torque and test wheel rotational speed.

Results & Conclusions

Preliminary observations indicate that the expected differences between dry and wet surfaces were observed in the data. Under dry surface conditions, lateral friction coefficient reaches a maximum value of around 0.85. On flooded surface, friction coefficient is reduced to a maximum value of 0.64 for the worn tyre and 0.58 for the new tyre.

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After the analysis of the results, it was identified that more experiment are needed in order to complete the characterisation of tyre/ground interaction using new tyres. Some of the next experiments will include:

- Testing at different slip angles (+5°, -10°, +15°) to complete the characteristic curves
- Monitor the degradation of the tyres by measuring the depth of thread after each test
- Testing at different brake pressure to populate the curves in the slip ratio range 20% to 90%. Brake pressure ramp tests would be considered
- Testing at different pond water depth (10mm and 20mm) to quantify the mu-slip ratio relation for contaminated runways. A new design for the controlled contaminated surface will be considered.

Applicability

The data generated in these tests will be used to validate the finite element (FE) models that will be developed within follow-up activities within Future Sky Safety P3 ‘Solutions for runway excursions’.

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TABLE OF CONTENTS

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

LIST OF FIGURES

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

LIST OF TABLES

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1. INTRODUCTION

1.1. The Programme

FUTURE SKY SAFETY is an EU-funded transport research programme in the field of European aviation safety, with an estimated initial budget of about € 30 million, which brings together 32 European partners to develop new tools and new approaches to aeronautics safety, initially over a four-year period starting in January 2015. The first phase of the Programme research focuses on four main topics:

- Building ultra-resilient vehicles and improving cabin safety;
- Reducing risk of accidents;
- Improving processes and technologies to achieve near-total control over the safety risks;
- Improving safety performance under unexpected circumstance.

The Programme will also help coordinate the research and innovation agendas of several countries and institutions, as well as create synergies with other EU initiatives in the field (e.g. SESAR, Clean Sky 2). FUTURE SKY SAFETY contributes to the EC Work Programme Topic MG.1.4-2014 Coordinated research and innovation actions targeting the highest levels of safety for European aviation in Call/Area Mobility for Growth – Aviation of Horizon 2020 Societal Challenge Smart, Green and Integrated Transport. FUTURE SKY SAFETY addresses the Safety challenges of the ACARE Strategic Research and Innovation Agenda (SRIA)

1.2. Project context

Within the FUTURE SKY SAFETY programme the project Solutions for runway excursions (P3) was initiated to tackle the problem of runway excursions. A runway excursion is the event in which an aircraft veers off or overruns the runway surface during either take-off or landing. Safety statistics show that runway excursions are the most common type of accident reported annually, in the European region and worldwide. There are at least two runway excursions each week worldwide. Runway excursions are a persistent problem and their numbers have not decreased in more than 20 years. Runway excursions can result in loss of life and/or damage to aircraft, buildings or other items struck by the aircraft. Excursions are estimated to cost the global industry about $900M every year. There have also been a number of fatal runway excursion accidents. These facts bring attention to the need to identify measures to prevent runway excursions.

Several studies were conducted on this topic. Most recently a EUROCONTROL sponsored research "Study of Runway Excursions from a European Perspective" showed that the causal and contributory factors leading to a runway excursion were the same in Europe as in other parts of the world. The study findings made extensive use of lessons from more than a thousand accident and incident reports. Those

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lessons were used to craft the recommendations contained in the European Action Plan for the Prevention of Runway Excursions, which was published in January 2013. This action plan is a deliverable of the European Aviation Safety Plan, Edition 2011-2014. The European Action Plan for the Prevention of Runway Excursions provides practical recommendations and guidance materials to reduce the number of runway excursions in Europe.

The present project, "Future Sky Safety P3 Solutions for runway excursions", focuses on a number of identified research areas to reduce runway excursions. Four areas of research were selected in this project for which additional research is needed:

1. Research on the flight mechanics of runway ground operations on slippery runways under crosswind conditions;
2. Research on the impact of fluid contaminants of varying depth on aircraft stopping performance;
3. Research on advanced methods for analysis of flight data for runway excursion risk factors, and;
4. Research into new technologies to prevent excursions or the consequences of excursions.

1.3. Research objectives

The objective of this pilot study is to obtain physical/experimental data to enable a more refined test program to be developed for the validation of the tyre/ground interaction model under crosswind conditions and contaminated (water) runway.

1.4. Approach

This study is conducted in Task 3.1.1 "Analysis of aircraft tyre dynamics" (part of research on the flight mechanics of runway ground operations on slippery runways under crosswind conditions research). The overall objective of this Task 3.1.1 is to develop a tyre/ground model to be used for simulation of aircraft operation under crosswind conditions and contaminated (water) runways.

In order to validate this model, it is necessary to compare the results of the model with experimental results. For this, an instrumented tyre test rig was used on a controlled contaminated track. Video was recorded and parameters (forces -vertical, longitudinal, lateral – speed, slip angle, etc.) were measured to obtain the relation/interaction between tyre and track surface. The effect of crosswind situation is represented by varying the slip angle of the tyres during testing. The effect of water contamination is measured by measuring the slip ratio and the variations of the friction coefficient when traveling over both dry and contaminated surfaces.

1.5. Structure of the document

In this document, chapter 2 presents the testing methodology, experimental data and analysis of the results; chapter 3 covers the discussion and recommendations for future testing; and chapter 4 the references.

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2 TYRE/GROUND INTERACTION - TESTS

2.1. Methodology

Field tests were conducted on the shut-down lane (a 600 m long flat tarmac surface) at Santa Pod Raceway (www.santapod.co.uk) (Figure 1).

Figure 1 The test surface (shut-down lane of Santa Pod Raceway)

The test pond (Figure 2) was constructed using two lengths of 75 mm diameter polythene lay-flat tubing filled with water to form the longitudinal water retaining barriers. The water depth was controlled by a convex weir formed from 150 mm x 1.3 mm Lead strip at the exit end of the test pond.

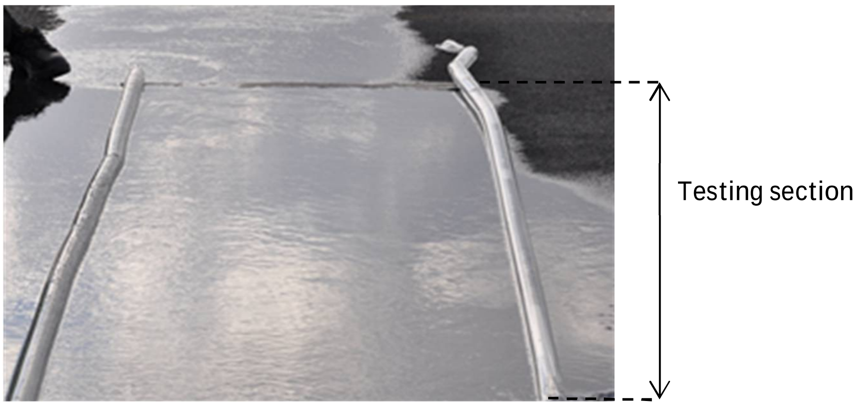

Figure 2 Picture of the controlled contaminated track area (pond)

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The test tyres were fitted to the Cranfield University self-propelled tyre test rig (Figure 3).

Figure 3 Images of the test rig showing the counter-steered wheels

The test wheel cell is attached to the rear of the test rig by a heavy duty linear guide that allows for unconstrained vertical movement of the test cell but constrains movement in both the longitudinal and lateral planes. A rolling lobe air spring is fitted between the test rig and test cell and is used to transfer load from the prime mover onto the test cell. For the tests carried out on this pilot study the vertical load on each wheel (at the contact patch) was set at 10 kN.

The test rig allows the two test wheels to be counter-steered in the range of -15° to +20°, relative to the direction of travel of the test rig, as shown in Figure 4. The test wheels are fitted with brakes that allow longitudinal slip ratios to be controlled from 0% to 100%.

The test rig is equipped with a suit of force, temperature and speed sensors. The force sensors allow the vertical (Fz) longitudinal (Fx) and Lateral (Fy) wheel centric forces to be measured. The infrared non-contact temperature sensors are positioned to measure the surface temperature of the central 10 mm of the tyre. Test wheel speed is measured using two proximity sensors (one per wheel) that register the presence of a number of targets positioned around the centre portion of the wheel hub. Vehicle speed is measured using a RACELOGIC VBOX GPS speed and position logging system, this system is also used to record video of the test wheels.

The type of tyre used was 22x8.0-10 12 ply rating.

In general, two types of experiments were conducted: 1) variation of the brake pressure at 0° slip angle; and 2) variation of slip angle and no brake pressure. The number of test and conditions are presented in Table 2.

Each test was recorded using at least two cameras. One of the cameras was integrated onto the rig focusing on the tyres. Another camera was placed on the track to record the test. In some experiments, a third camera was placed on the track and used to record the test from a different perspective. Examples of the recordings of these cameras are presented in Figure 5, Figure 6, Figure 7 and Figure 8.

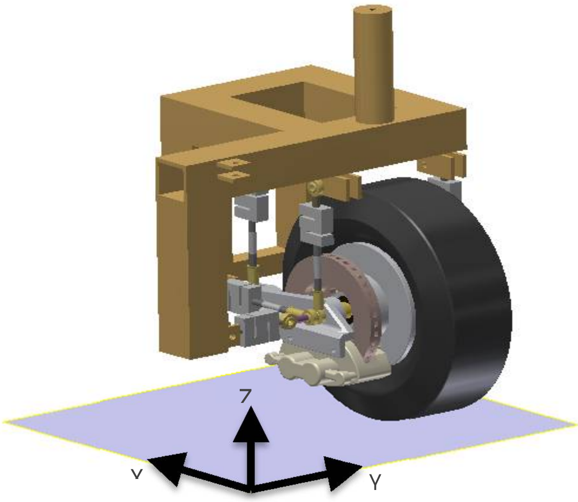

Figure 4 Schematic representation of test rig with coordinate system

Table 1 Test conditions

Parameters	Values
Test surface	Tarmac
Test speed	22 m/s (50 mph)
Wheel vertical load	10 kN
Tyre type & pressure	22x8.0-10 12 ply rating/ 7.8 bar (115 psi) LHS: worn tyre RHS: new tyre
Side slip angles	0°; ±5°; ±10°; ±15°; +20°
Longitudinal slip ratios	To be determined on site based on controlled brake pressure
Water depth*	9.4 mm on average
Data logging frequency	200 Hz, ~ 9 data points per metre of travel

(*) In test 10 the water depth was 20 mm

Table 2 Experiments conducted

#	Slip angle	Speed	Vertical load	Brake Pressure
1	10º	10 mph	10 kN	--
2	0º	50 mph	10 kN	10 bar
3	0º	50 mph	10 kN	ramp 10-90 bar
4	10º	50 mph	10 kN	--
5	-5º	50 mph	10 kN	--
6	20º	50 mph	10 kN	--
7	0º	50 mph	10 kN	50 bar
8	0º	50 mph	10 kN	75 bar
9	0º	50 mph	10 kN	25 bar
10*	0º	50 mph	10 kN	50 bar

(*) In this test the water depth was 20 mm

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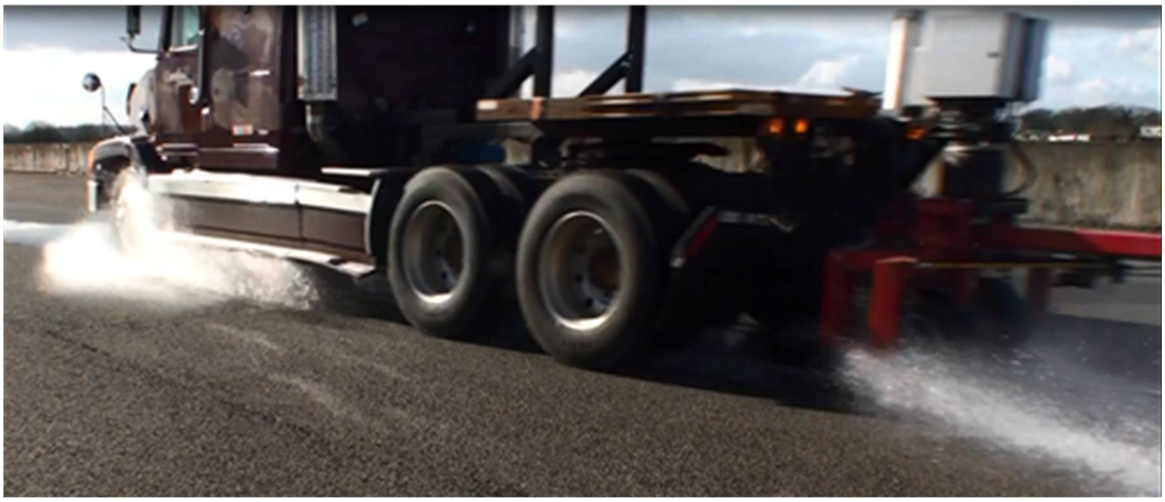

Figure 5 Image taken from a video recording with high resolution camera during testing

Figure 6 Image taken from a video recording during testing

Figure 7 Image from the video recording from the camera integrated in the rig during test 1

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Figure 8 Image from the video recording from the camera integrated in the rig during test 10

After this session of testing, the tyres were worn. Pictures of the tyres at the end of the test session can be seen in Figure 9.

a) b)

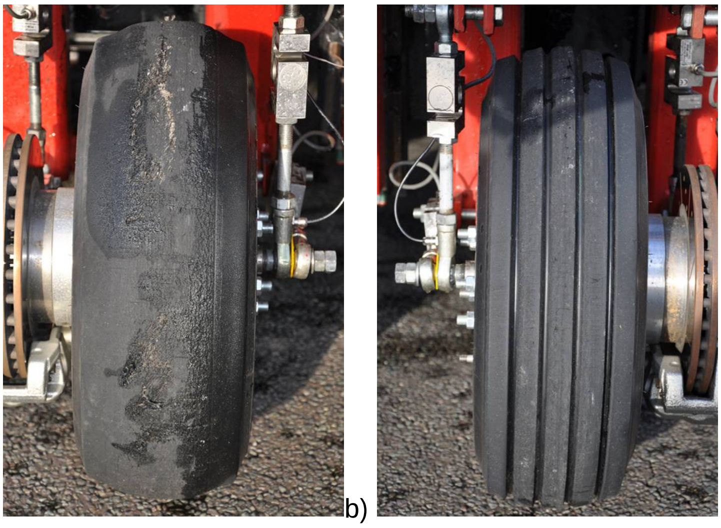

Figure 9 Images of tyres after the test session: a) left hand side (LHS) tyre and b) right hand side tyre (RHS)

2.2. Experimental data

Table 3 presents the data obtained from the experimental session on the track. The parameters measured were the vehicle speed, pressure applied to the brakes, slip angle, forces (vertical, lateral and longitudinal), and slip ratio. In each test, data was recorded when the track was on the dry part of the track and during the flooded part. Then, for each experiment there are sets of 'dry surface' data and 'flooded surface' data.

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Table 3 Results of the average values of the variables measured during the testing for dry and wet surfaces and for left hand side (LHS) and right hand side (RHS) tyres

Test		Vehicle Speed (kph)	Brake pressure (bar)	Steering angle (°)	Vertical Force (Fz, N)		Lateral Force (Fy, N)		Longitudinal Force (Fx, N)		Slip (%)	
					LHS	RHS	LHS	RHS	LHS	RHS	LHS	RHS
1	Dry	23.2	-1.7	9.8	-8949.4	-10811.0	-7632.8	-7259.4	530.7	335.9	-0.12	-1.02
	flooded	23.8	-1.7	9.9	-8495.9	-11533.6	-6455.3	-7072.6	516.2	385.1	0.43	-0.79
2	Dry	80.1	9.1	-0.1	-9499.3	-10856.6	810.5	430.2	1571.3	1411.4	-0.8	-0.5
	flooded	82.6	8.9	-0.1	-8627.2	-12181.9	323.7	562.7	1495.6	1345.6	1.5	1.3
4	Dry	79.1	-1.8	9.9	-9268.2	-10757.3	-7355.5	-7112.0	334.9	380.2	2.1	1.1
	flooded	81.0	-1.8	9.9	-9716.5	-10706.9	-4377.6	-5973.7	440.9	329.2	2.7	1.1
5	Dry	83.6	-1.8	-4.6	-10592.7	-9786.1	7108.3	5175.4	342.7	320.8	0.2	0.7
	flooded	84.8	-1.8	-4.8	-9826.6	-10619.1	6729.5	5300.6	224.5	315.4	0.5	0.6
6	Dry	83.0	-1.7	19.8	-9783.2	-10206.2	-7268.2	-8040.3	394.6	378.9	6.6	4.7
	flooded	84.2	-1.7	19.9	-9801.4	-10392.0	-4557.3	-6247.7	495.1	515.6	7.8	5.0
7	Dry	82.7	46.5	-0.2	-10366.1	-9512.8	1474.2	1070.3	4443.5	4390.4	2.8	6.6
	flooded	82.3	45.1	-0.2	-9811.5	-10391.7	1398.9	1086.2	4123.6	4048.9	3.9	5.6
8	Dry	76.4	69.5	-0.3	-9449.8	-10151.2	2226.9	1493.0	6384.4	5777.4	4.8	7.7
	flooded	73.6	69.5	-0.4	-8489.1	-11445.9	673.4	780.4	4537.6	5638.4	66.1	7.8
9	Dry	83.0	25.3	-0.1	-9991.4	-10252.1	1709.8	1262.5	2846.9	2524.4	0.9	2.2
	flooded	83.6	24.7	-0.1	-9145.3	-11182.6	1615.3	1200.3	2683.3	2571.2	2.0	2.3
10	Dry	83.0	44.7	-0.3	-9385.5	-10180.6	2404.2	1605.3	5221.5	4541.9	3.7	5.8
	flooded*	82.3	44.2	-0.3	-7743.6	-11897.7	787.8	904.8	4176.0	4175.7	46.4	22.1

(*) In this test, the water depth was 20mm

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2.3. Results

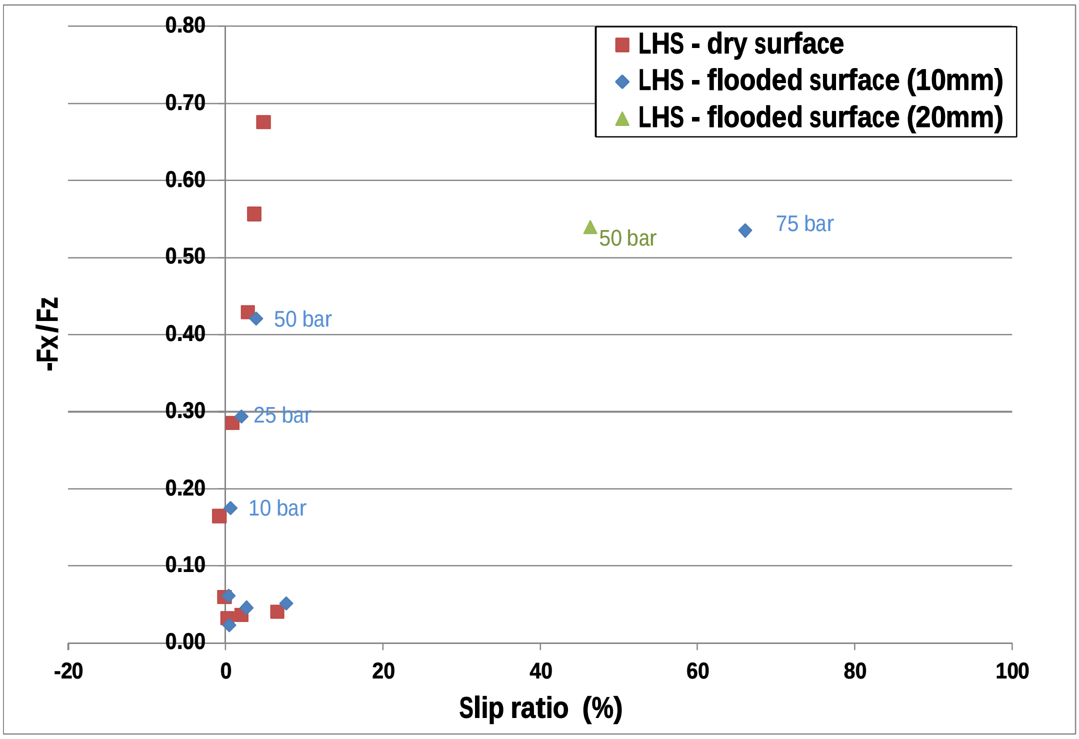

Figure 10 Friction coefficient (Fx/Fz) versus longitudinal slip ratio (%) for the old (worn)

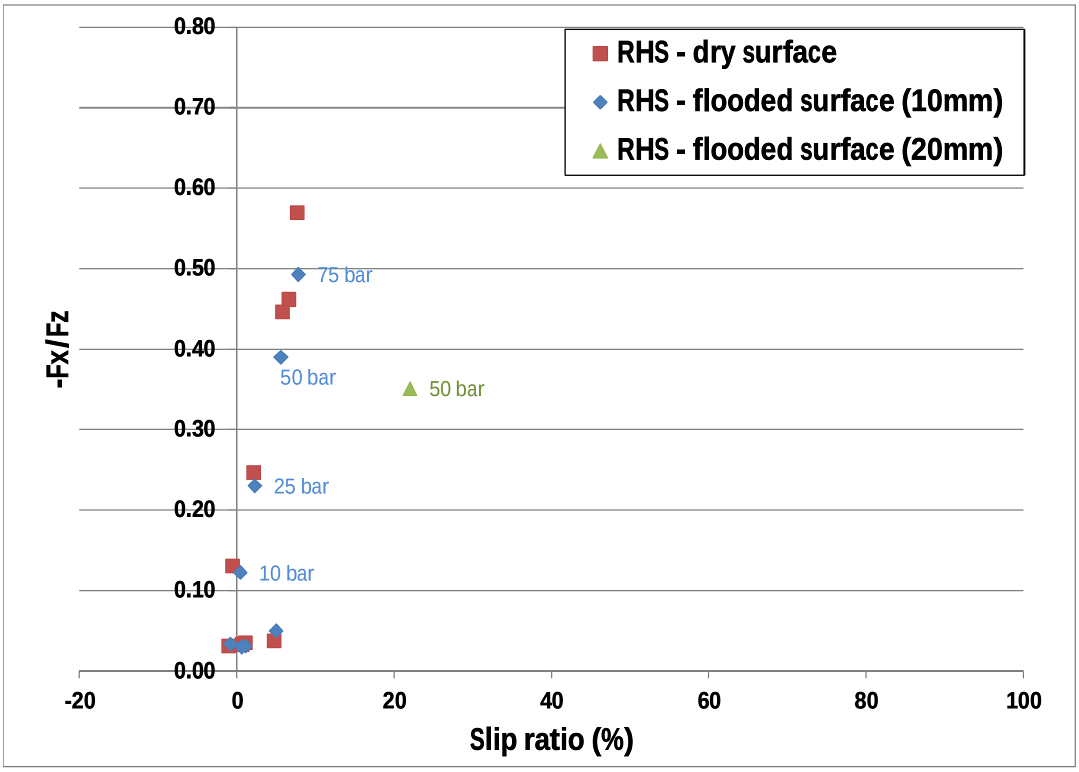

Figure 11 Friction coefficient (Fx/Fz) versus longitudinal slip ratio (%) for the new (thread) tyre

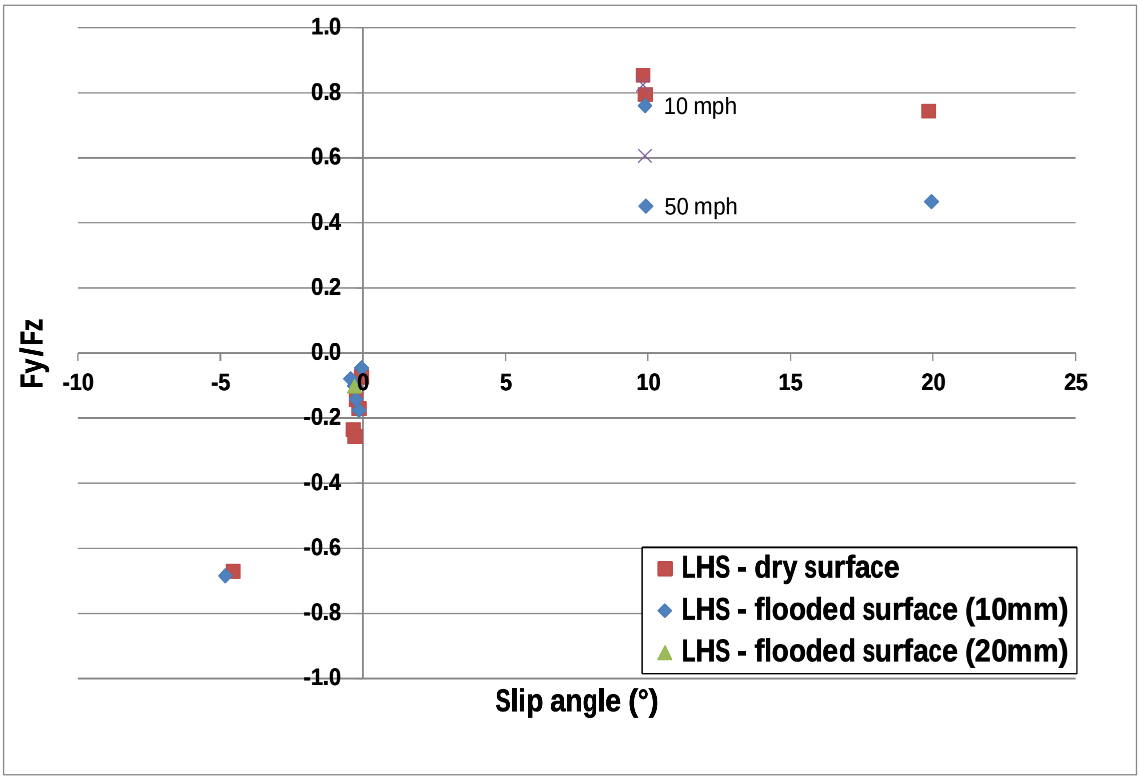

Figure 13 (Fy/Fz) versus lateral slip angle (°) for the old (worn) tyre

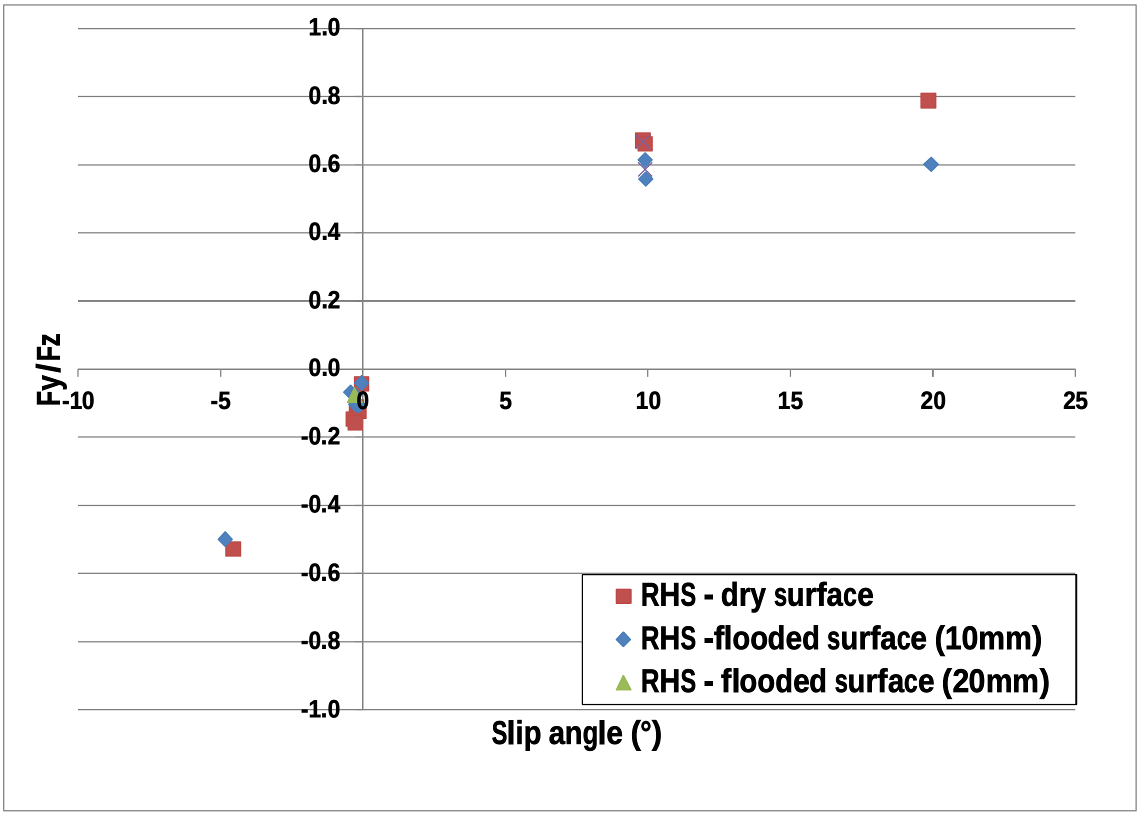

Figure 12 (Fy/Fz) versus lateral slip angle (°) for the new (thread) tyre

For the worn tyre (LHS), the lateral friction coefficient $\mu_{lateral}$ (Fy/Fz) reaches a maximum of 0.85 at slip angle of 10°, at vehicle speed of 10 mph, on dry surface. On flooded surface, the peak also appears at 10° and at 10 mph with a value of 0.76. From the test conducted at 50mph, the one at 10° slip angle presents peak values of $\mu_{lateral}$ of 0.79 and 0.45 for dry and flooded surfaces, respectively.

For the new tyre (RHS), the peak values of $\mu_{lateral}$ on flooded surface also appear at 10° slip angle, being 0.61. On dry surface, $\mu_{lateral}$ increases with the slip angle, with a maximum of 0.79 at 20°.

These results are in agreement with results obtained in previous experiments, where a maximum $\mu_{lateral}$ of 0.83 on dry surface and 0.44 on wet surface were observed at around 30mph.

Table 4 Friction coefficients from test results for left hand side (LHS) tyre (worn) and right hand side (RHS) tyre (new) for dry and wet surfaces

		Long Slip ratio (%)			-Fx/Fz		Fy/Fz	
Test	**Slip angle**	**LHS**	**RHS**	**Surface**	**LHS**	**RHS**	**LHS**	**RHS**
1	**10°**	-0.12	-1.02	**Dry**	0.07	0.03	0.85	0.67
		0.43	-0.79	**flooded**	0.07	0.03	0.64	0.58
2	**0°**	-0.8	-0.5	**Dry**	0.17	0.13	-0.07	-0.04
		1.5	1.3	**flooded**	0.17	0.11	-0.04	-0.04
4	**10°**	2.1	1.1	**Dry**	0.04	0.04	0.79	0.66
		2.7	1.1	**flooded**	0.06	0.05	0.35	0.47
5	**-5°**	0.2	0.7	**Dry**	0.03	0.03	-0.67	-0.53
		0.5	0.6	**flooded**	0.06	0.05	-0.37	-0.41
6	**20°**	6.6	4.7	**Dry**	0.04	0.04	0.74	0.79
		7.8	5.0	**flooded**	0.07	0.05	0.29	0.45
7	**0°**	2.8	6.6	**Dry**	0.43	0.46	-0.14	-0.11
		3.9	5.6	**flooded**	0.39	0.38	-0.10	-0.09
8	**0°**	4.8	7.7	**Dry**	0.68	0.57	-0.24	-0.15
		66.1	7.8	**flooded**	0.39	0.49	-0.01	-0.04
9	**0°**	0.9	2.2	**Dry**	0.28	0.25	-0.17	-0.12
		2.0	2.3	**flooded**	0.29	0.22	-0.14	-0.09
10	**0°**	3.7	5.8	**Dry**	0.56	0.45	-0.26	-0.16
		46.4	22.1	**flooded***	0.34	0.37	-0.01	-0.02

(*) In this test, the water depth was 20mm

Test 3 – Brake pressure ramp

In test 3, a brake pressure ramp from 10 to 90 bars was applied. The results are presented in Figure 14 and Figure 15. During this test, only the worn tyre (LHS) locked on flooded surface at a brake pressure of 74bar. The peak value of the longitudinal friction coefficient is 0.53 at 31.7% slip ratio.

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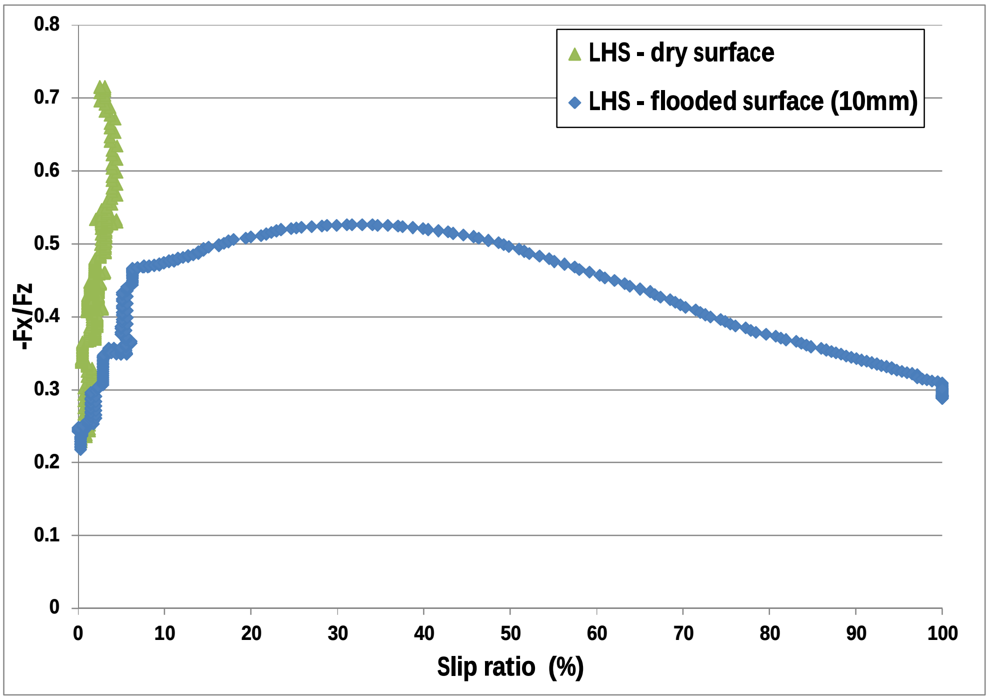

Figure 14 Friction coefficient (-Fx/Fz) vs Slip ratio (%) for the worn tyre during brake ramp experiment

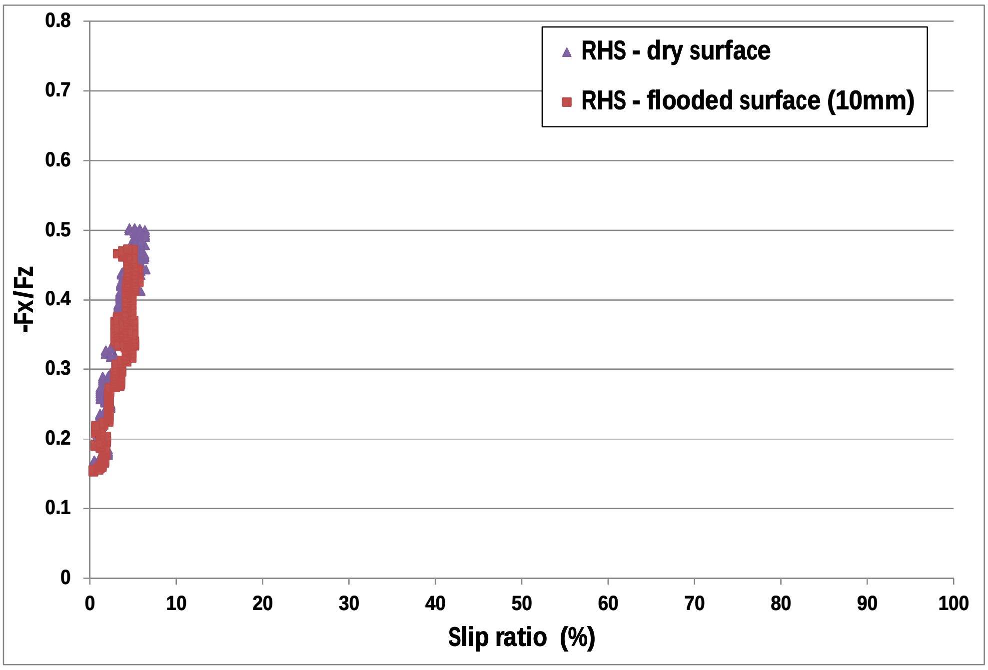

Figure 15 Friction coefficient (-Fx/Fz) vs Slip ratio (%) for the new tyre during brake ramp experiment

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Test 10 – Brake pressure steps

During test 10, break pressure was applied in steps of 25, 50 and 75 bars. Moreover, data was recorded in three different areas: dry surface, flooded area (controlled water depth – pond), and wet surface (not controlled water depth). In this test, the water depth in the pond was 20mm. The duration of the test during the different areas (controlled and not controlled water contamination) was identified using the video recording from the camera integrated in the rig. Some images from this recording are presented in Figure 16 and Figure 17.

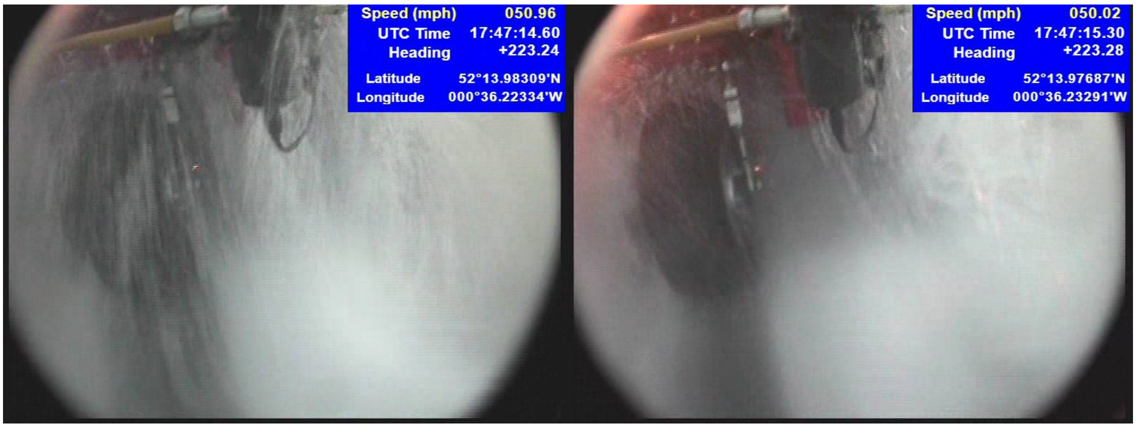

Figure 16 Video images of the starting and ending points of the not controlled contaminated area applying a brake pressure of 50 bar

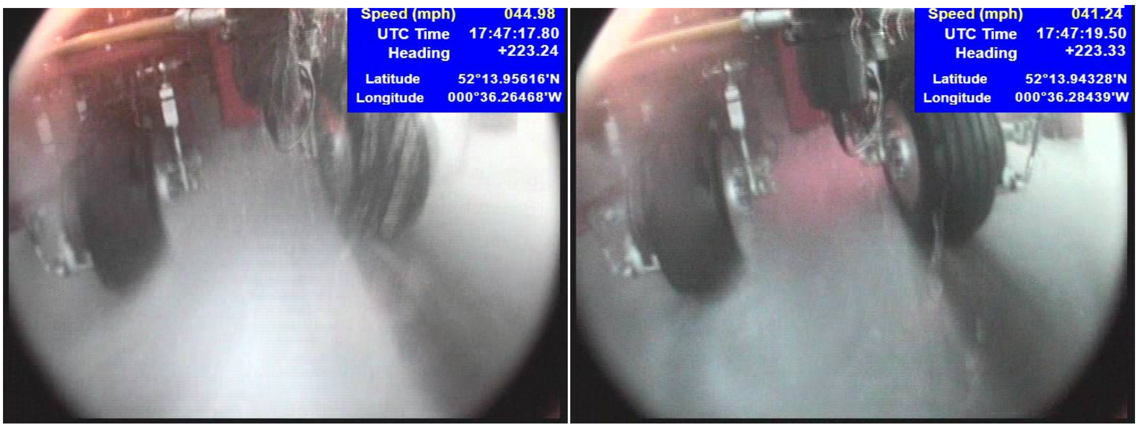

Figure 17 Video images of the starting and ending points of the not controlled contaminated area applying a brake pressure of 75 bar

A summary of the result from this test are presented in Table 5. These values are the result of the average in the different range areas. However, in the controlled contamination area, slip ratios of both tyres vary from 6% to 55% for the new tyre (RHS) and from 9% to 82% for the worn tyre (LHS). This

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variation can be observed in Figure 18. After the controlled contaminated area (pond with 20mm water depth), data revealed the worn tyre (LHS) locked completely and the new tyre (RHS) reached a slip ratio of almost 88%. Then, the new tyre (RHS) reduced the slip ratio to the initial value (around 5.5%), but when the brake pressure was increased to 75 bar (in a not controlled contaminated area), it locked completely (100% slip ratio).

Table 5 Summary of results from test 10 in different surfaces

Test 10 (0°, 50pmh)		LHS			RHS		
Testing surface	Brake pressure	Slip Ratio (%)	-Fx/Fz	Fy/Fz	Slip Ratio (%)	-Fx/Fz	Fy/Fz
Dry surface	25 bar	0.9	0.23	-0.192	2.1	0.21	-0.137
Dry surface	50 bar	3.7	0.56	-0.26	5.8	0.45	-0.16
Flooded surface	50 bar	46.4	0.54	-0.102	22.1	0.35	-0.076
Wet surface (not controlled)	50 bar	100	0.34	-0.008	5.9	0.36	-0.024
Wet surface (not controlled)	75 bar	100	0.41	-0.002	100	0.38	0.005

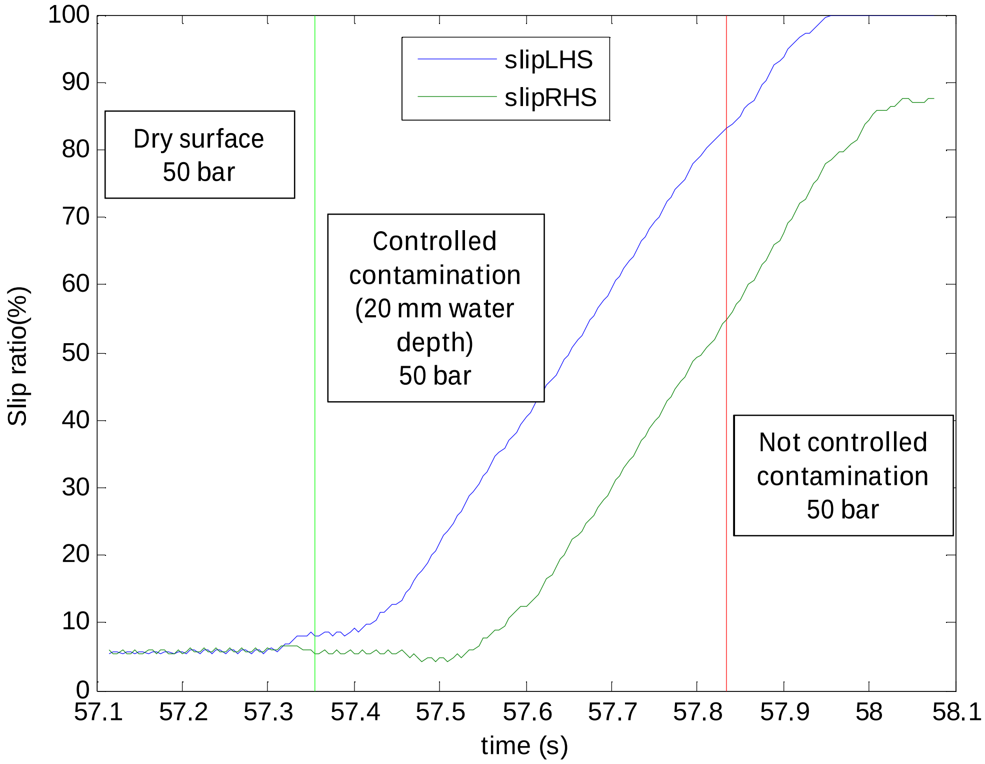

Figure 18 Variation of slip ratio for the worn (LHS) and new tyre (RHS) from dry surface to controlled contaminated surface (flooded surface with 20mm water depth) and to not controlled contaminated surface

3 CONCLUSIONS AND RECOMMENDATIONS

3.1. Conclusions

Preliminary observations indicate that the expected differences between dry and wet surfaces were observed in the data. Under dry surface conditions, lateral friction coefficient reaches a maximum value of around 0.8. On flooded surface, friction coefficient is reduced to a maximum value of 0.38 for the worn tyre and 0.58 for the new tyre.

Although the friction coefficient vs slip ratio curves need to be populated in the slip ratio range 20-90%, the shape of these curves follows the expected trend as reported in Deliverable D3.3 'Review of the Review of the state of current knowledge regarding tyre braking performance, anti-skid systems, and modern aircraft tyres on water contaminated runways" [1].

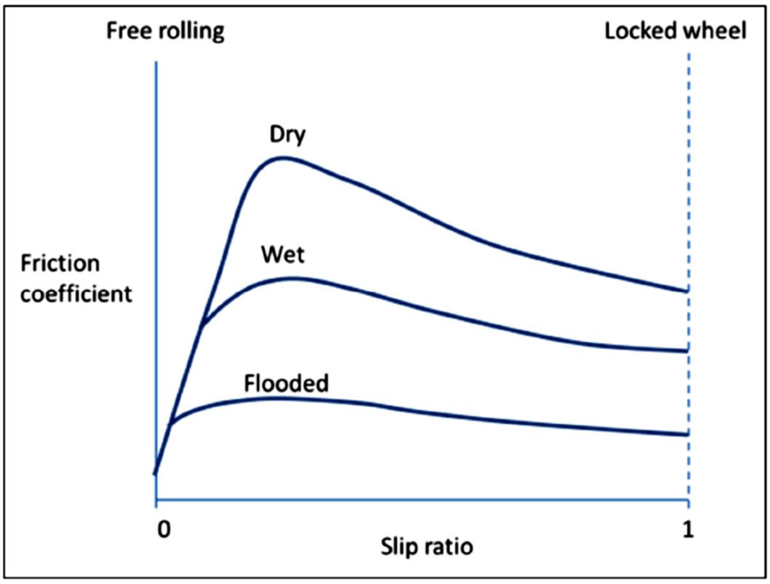

Figure 19 Illustration of influence of runway condition on Mu slip ratio relation (extracted from [1])

The worn tyre (LHS) locked on flooded surface for brake pressures of 75bar and 50bar when the water depth in the pond was 10mm and 20mm, respectively. The new tyre (RHS) did not lock during the tests, but the slip ratio increased from 5.94% to 15.2% when the water depth in the pond increased from 10mm to 20mm.

3.2. Recommendations

More experiments are needed to complete the characterisation of the interaction tyre/ground. Some of the next experiments will include:

- Testing at different slip angles (+5°, -10°, +15°) to complete the characteristic curves

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- Monitor the degradation of the tyres by measuring the depth of thread after each test
- Testing at different brake pressure to populate the curves in the slip ratio range 20% to 90%. . Brake pressure ramp tests would be considered.
- Testing at different pond water depth (10mm and 20mm) to quantify the mu-slip ratio relation for contaminated runways. A new design for the controlled contaminated surface will be considered.

These experiments will be conducted using new tyres.

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4 REFERENCES

[1] G.W.H. van Es (2015) ‘Review of the state of current knowledge regarding tyre braking performance, anti-skid systems, and modern aircraft tyres on water contaminated runways’, Future Sky Safety P3 Solutions for Runway Excursions, Future Sky Safety D3.3.

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