THE FUTURE
OF TRANSPORT

PUBLISHED PROJECT REPORT PPR957

Characterising the measurements made by sideways-force skid resistance devices

A desk study and proposal for an experimental study

P D Sanders and C Browne

Report details

Report prepared for:	Highways England, Pavements		
Project/customer reference:	1-407 Sub-task 2		
Copyright:	© TRL Limited		
Report date:	July 2020		
Report status/version:	Issue		
Quality approval:			
A Kaminski (Project Manager)	**Approved**	M Greene (Technical Reviewer)	**Approved**

Disclaimer

Executive summary

The effective management of road surface skid resistance is critical for providing a safe means of travel for all road users. The skid resistance on the English trunk road network is managed with the goal of normalising the skidding risk to motorists across areas of varying relative risk (known as site categories). Currently this is undertaken using a correlative approach which compares road surface skid resistance with the prevalence of wet skidding accidents for different site categories. Critically however, it is not understood, even at a fundamental level, how the skid resistance measurements made on the road network physically relate to the fiction properties exploited by vehicles carrying out manoeuvres.

In this paradigm there exists a major potential benefit to road authorities, and road users, in generating this fundamental knowledge, especially in areas of high skid risk. The work reported in this document represents the first stage in a wider programme of research which seeks to fully understand the relationship between the parameters outlined above. The overall result of this programme of work will derive advice to road owners as to how they can best use road surfacing materials in order to:

- Maximise the cost effectiveness of pavement materials used,
- Minimise the skidding risk to road users in areas of varying risk,
- Update the relevant management procedures in order to continually support the above points.

In the UK, the skid resistance properties of the trunk road network are assessed annually using devices utilising the sideways-force measurement principle, the Sideways-force Coefficient Routine Investigation Machine (SCRIM). Currently, a view of the measurement properties of SCRIM is in place. However, this is based on a theoretical analysis of the device, is unsupported by empirical evidence, and, in some cases could be considered contradictory to historical literature. During recent years this view has been challenged and it is the aim of this work to investigate the measurement properties of SCRIM in order to confirm the currently held view, or to provide an alternative.

A desk study produced the following characterisations for SCRIM but was unable to identify a single valid characterisation.

Summary of operating speed and % slip predicted by characterisations

Characterisation	operating speed	% slip
Current	The vehicle speed	34.2
Scalar	The vehicle speed	6.03
Vector	The vehicle speed x Cos(70)	100
Co-Axial	The vehicle speed	11.7

Experimental methodologies for assessing the predictions made by the characterisations are presented.

TRL

Table of Contents

1 Introduction

The effective management of road surface skid resistance properties is a critical factor in providing a safe means of travel. The measurement of skid resistance is a key component in the effective management of skid resistance. In the UK the skid resistance properties of the trunk road network, and many local road networks, are assessed annually using devices utilising the sideways-force measurement principle.

At the time of writing, all of the devices used for characterising the skid resistance properties of the UK trunk road network are Sideways-force Coefficient Routine Investigation Machines (SCRIMs). However, in Germany the SeitenKraftMessverfahren (SKM) is used, and in Belgium the Odoliograph is used, both of which operate under the same sideways-force principles as SCRIM. Understanding the fundamental measurement properties of sideways-force devices would therefore provide a major benefit to UK and international road authorities alike.

Currently, a view of the measurement properties of SCRIM is in place and is widely accepted. However this view is based on a theoretical analysis of the device, is unsupported by practical assessment, and in some cases could be considered contradictory to historical works. During recent years research into road surface skid resistance and friction has progressed in such a way that the specific measurement characteristics of SCRIM have become of particular interest. Owing to this interest, the current view of SCRIM has been challenged and it is the aim of this work to investigate the measurement properties of SCRIM and propose an experimental methodology by which the measurement properties of SCRIM can be confirmed.

2 Background to pavement friction and its influence on vehicle safety and highway management

2.1 Friction as a three dimensional parameter

The friction generated between a road surface and vehicle tyre is highly variable; the concept of a ubiquitous "level of grip" is a misnomer. This is because the friction between a road surface and vehicle tyre, is proportional to, amongst other variables, the speed at which the surface is being traversed, and the amount of slip between the tyre and road surface. Friction is therefore a three dimensional parameter[1]. This is illustrated in Figure 2-1 which presents the typical relationship between friction, operating speed, and wheel slip.

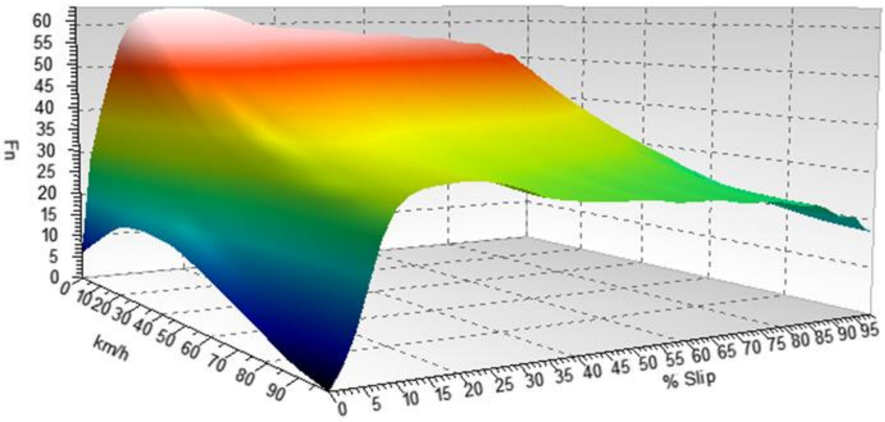

Figure 2-1 An example of the relationship between friction (Fn), operating speed (km/h) and wheel slip (% Slip), the friction profile.

Efforts to normalise the measurement of road friction using standardised devices and test procedures, can allow for the measurement of the roads contribution to friction, the "skid resistance". Skid resistance measurements can be made with reference to the speed and % slip at which the measurement was made for some devices for which these parameters are defined. For SCRIM this is not the case, as the speed and % slip of SCRIM measurements are not known.

2.2 The influence of friction on vehicle safety

Work reported in TRL report PPR815 (Sanders, Militzer, & Viner, 2017) demonstrated that vehicles undertaking a straight line braking manoeuvre use friction at a range of wheel slips and speeds. In other words, vehicles undertaking this manoeuvre use friction values at many

[1] In the same way that a map co-ordinate is a two dimensional parameter and that the knowledge of one of the co-ordinates is not meaningful without knowledge of the other.

different points on the profile presented in Figure 2-1. Furthermore, the work demonstrated that if Anti-lock Braking Systems (ABS) are activated, the areas of the friction profile used are markedly different to those used when ABS is not activated. This is illustrated in Figure 2-2 which shows a “plan view” of the profile shown in Figure 2-1 with the areas of the profile used by a vehicle undertaking a straight line braking manoeuvre with and without ABS shown.

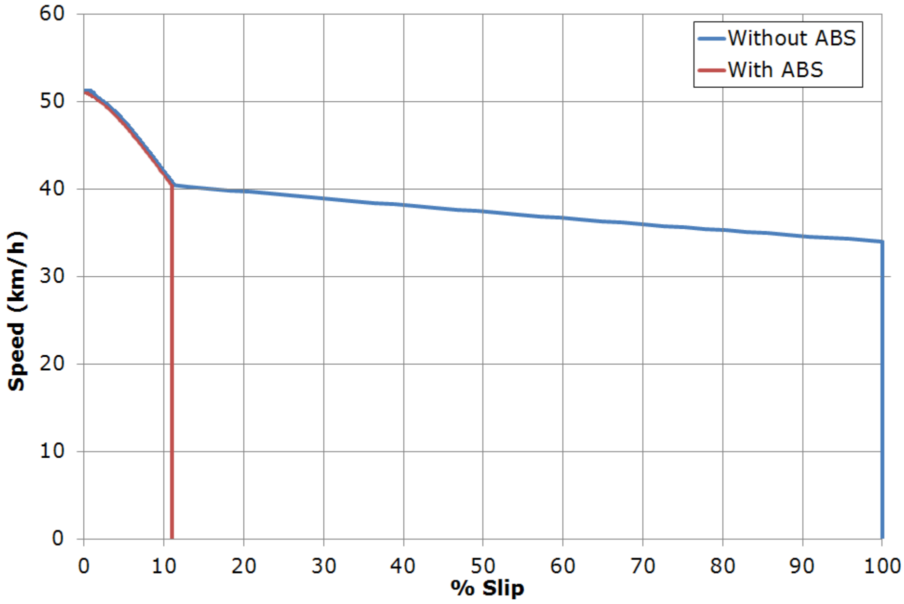

Figure 2-2 Friction used by a vehicle undertaking straight line braking

It is therefore likely that different manoeuvres, cornering or changing lanes for instance, will also use different areas of the friction profile than those illustrated for straight line braking. Clearly, gaining an understanding of the areas on the friction profile demanded by vehicles, and the ability of a road surface to deliver friction in these areas is an important consideration to highways authorities in delivering a safe network.

Sideways-force measurement systems, such as SCRIM, characterise skid resistance continuously, and as such it is a necessity that skid resistance be characterised at a single operating speed, and a single slip speed. To this end, sideways-force measurement systems can be thought of as characterising skid resistance in one dimension, or at a single point on the profile presented in Figure 2-1.

With this in mind, having a firm understanding of where measurements made with SCRIM sit on the friction profile is key in understanding the relationship between SCRIM measurements, vehicle manoeuvres and accident risk.

2.3 The implications for the management of road networks

The UK trunk road network is managed in such a way as to broadly normalise the risk of skidding across the network. To achieve this, the road network is split up into various site categories, which relate to the level of risk posed to road users. Each site category is assigned a skid resistance Investigatory Level (IL); high risk sites have higher ILs, whereas low risk sites have lower ILs.

The Investigatory Levels are based on measurements made with SCRIM and locations which fall at or below their IL are subject to investigation where other factors such as surface texture, road geometry and collision risk are taken into account to determine whether treatment to improve the skid resistance would be beneficial. Based on the factors outlined in section 0, it may be the case that SCRIM measurements are more relevant[2] in some areas of the network than others.

If these areas could be identified then the decisions made using SCRIM data can be better understood. One way of achieving this may be an adjustment of the width of IL bands to reflect site categories where SCRIM measurements are better or worse predictors of skidding risk. An alternate may be to give SCRIM measurements more or less weight over the maintenance decisions than other parameters such as texture or road geometry.

A third, more radical option, may be to employ other skid resistance assessment methodologies in areas where they make measurements closer to the prevailing skid resistance demand of road users and would be better predictors of collision risk than SCRIM.

[2] Better predictors of collision risk

3 Defining the parameters

Skid resistance measurement tools are typically characterised based on their operating principle:

- Longitudinal fixed slip devices. Devices with a test wheel mounted in the same orientation as the vehicle wheels which is forced to rotate at a fixed percentage of the operating speed.
- Longitudinal variable slip devices. Devices with a test wheel mounted in the same orientation as the vehicle wheels which during testing alternates between a freely rotating and a locked-wheel (or peak friction) state.
- Sideways-force devices. Devices with a test wheel mounted at an angle to the vehicle wheels. SCRIM operates under this principle.

Skid resistance measurement devices can be further characterised using the terminology outlined in the following sub sections. The definitions of the parameters detailed in these sub-sections will be used throughout the rest of this document.

3.1 Operating speed

Operating speed is often referred to as vehicle speed, and the two terms are frequently considered synonyms. However, for the purposes of this work it is necessary to introduce a subtle difference in these terms. For this work, vehicle speed is defined as per BS CEN/TS 15901-6-2009, *“Speed at which the device traverses the test surface”* (British Standards Institution, 2009).

Operating speed is defined as the effective vehicle speed of the test device. For two of the three cases considered in this work vehicle speed and operating speed are the same. In one case, which is discussed in Chapter 6, the operating speed differs to that of the vehicle speed.

3.2 Wheel speed

A pre-existing definition of wheel speed could not be identified. Wheel speed is therefore defined here as the tangential speed of the circumference of the test tyre.

3.3 Slip speed, Slip Ratio and Percentage Slip

Slip speed is defined in BS CEN/TS 15901-6-2009 as “relative speed between the test tyre and the travelled surface in the contact area” (British Standards Institution, 2009). This definition can be expressed formulaically using Equation 3-1.

$$Slip\ speed = Operating\ speed - Wheel\ speed$$

Equation 3-1 Definition of slip speed

Slip speed is often expressed as either slip ratio or slip percentage in order to be expressed a relative function of the operating speed. Slip ratio is defined in BS CEN/TS 15901-6-2009 as, "slip speed divided by the operating speed" (British Standards Institution, 2009).

Percentage slip (% Slip) is defined in Equation 3-2. For the purposes of this work, percentage slip will be used in preference to slip ratio.

$$\% \, Slip = \frac{100 \times Slip\ speed}{Vehicle\ speed}$$

Equation 3-2 Definition of % Slip

3.4 Vertical and horizontal load

Skid resistance is a unit-less parameter calculated as the ratio between vertical and horizontal load. For all skid resistance measurements systems, vertical load is the load acting on the test wheel in the direction of gravity. The definition of horizontal load however differs depending on the specific measurement device. In the case of SCRIM, horizontal load is defined as the load acting on the test tyre along the axis of rotation. These properties are illustrated in Figure 3-1.

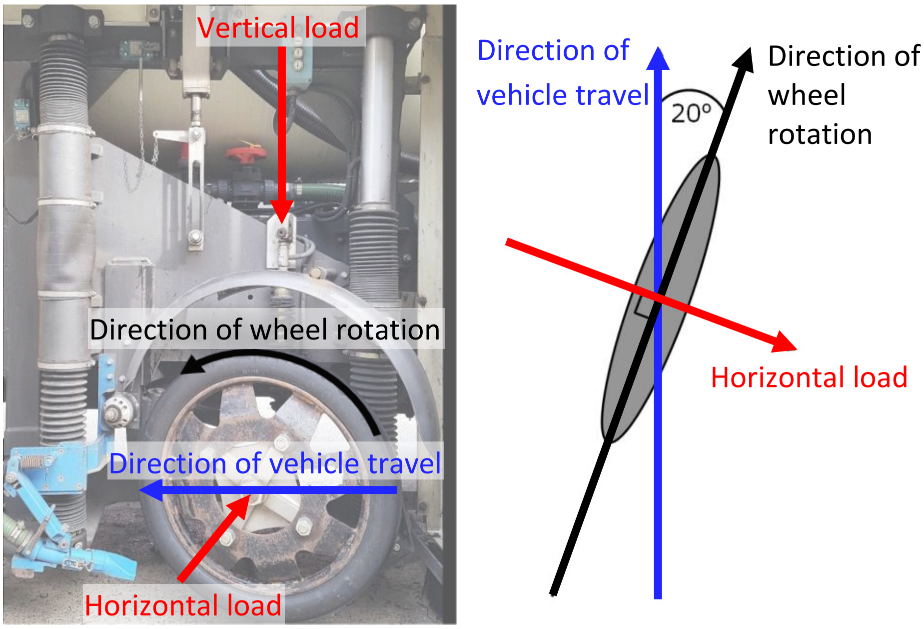

Figure 3-1 Image of the SCRIM measurement system with annotations (Left), diagram of the SCRIM measurement system in plan view

4 The currently accepted view, 34.2 % slip at 50 km/h operating speed

In order to demonstrate the currently held view of sideways-force skid resistance devices, a literature review was carried out and presented below are a selection of extracts from documents which report either the % slip, slip speed, wheel speed and/or operational speed for SCRIM.

Highways Agency (now Highways England) standard HD28/04 (which has since been superseded by CS 228) states "Because the test wheel is set at an angle to the direction of travel, the effective slip speed of the test tyre is much slower than the vehicle operating speed. The measurement is therefore one of low-speed skid resistance: at a 50 km/h standard test speed, the slip speed is approximately 17 km/h." (Department for Transport, 2004)[3].

The National Cooperative Highway Research Program (NCHRP) document "Evaluation of pavement friction characteristics" states under the heading "Side Force Devices" that "The relative velocity between the rubber and the pavement surface for these devices is approximately V Sin (α) (where α = yaw angle, and V = vehicle speed)." (Henry, 2000).

TRL report PPR564 states "At the standard test speed of 50 km/h, the test tyre contact patch slips over the road surface at about 17 km/h." (Roe & Dunford, 2012)

The NSW Roads and Maritime Services QA Specification R423 states "The parameter measured by the SCRIM. Generally the test wheel operates at an angle of 20° giving a 34% slip ratio and about 97% maximum friction." (NSW Roads and Maritime Services, 2013)

Work reported in Deliverable D1.1 of the European ROSANNE project states that "Three devices operate on the sideways-force friction principle and use test wheels which are set at an angle to the direction of travel: SCRIM, SKM and Odoliograph. The angle of the test wheel is 20° for all three devices which equates to a slip ratio of 34 %." (Greene, Viner, Cerezo, Kokot, & Schmidt, 2014)

Highways England standard HD28/15 states "The slip ratio is the ratio of the speed at which the test tyre slides over the surface (the slip speed), to the speed of the survey vehicle (the survey speed), normally expressed as a percentage." And "…For example, when a sideways-force coefficient routine investigation machine (slip ratio 34%) carries out a test at 50 km/h, the test wheel is sliding at a slip speed less than 20 km/h." (Department for Transport, 2015).

Figure 4-1 and Equation 4-1 present the current view of SCRIM in graphical and mathematical forms respectively, these are based on the definitions provided by (Henry, 2000). Equation 4-2 demonstrates that if the "relative velocity between the rubber and the pavement surface" is considered orthogonal to the wheel direction then an operational

[3] It is interesting to note that this text was omitted in later versions of this standard HD28/15 (Department for Transport, 2015) and CS 228 (Highways England, Transport Scotland, Welsh Government, Department for Infrastructure, 2019).

speed of 17.1 km/h and a slip percentage of 34.2 % (the currently held view of SCRIM) can be derived using Equation 3-2.

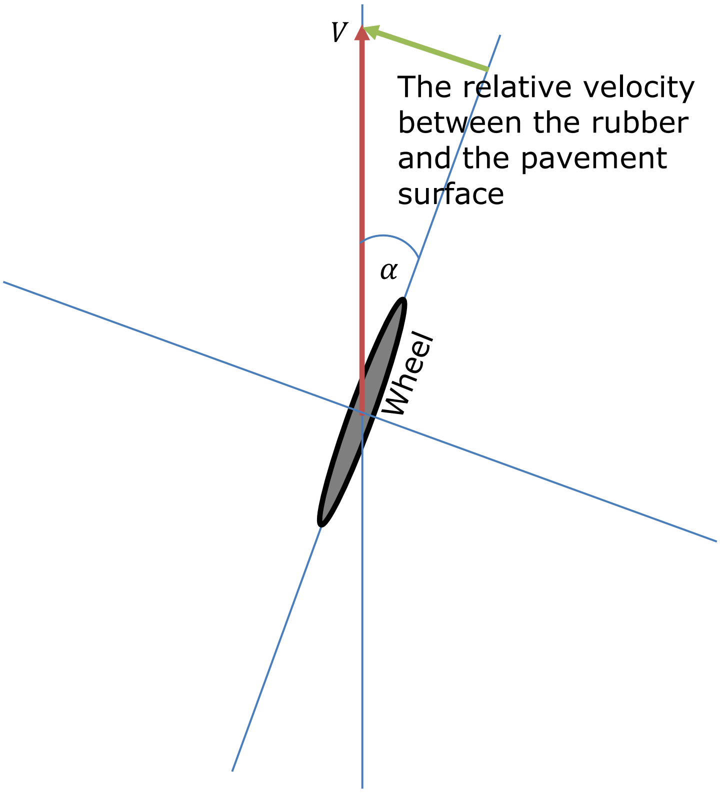

Figure 4-1 Calculation of the relative velocity between the rubber and the pavement surface presented by (Henry, 2000)

$$The\ relative\ velocity\ between\ the\ rubber\ and\ the\ pavement\ surface = V \times Sin(\alpha)$$

$$The\ relative\ velocity\ between\ the\ rubber\ the\ pavement\ surface = 50 \times Sin(20) = 17.1\ km/h$$

Where:

- V= the vehicle speed (for SCRIM this is standardised at 50 km/h) (British Standards Institution, 2006)
- α = the angle between the direction of travel and direction of rotation of the test wheel (for SCRIM this is 20 degrees)

Equation 4-1 Calculation of the relative velocity between the rubber and the pavement surface presented by (Henry, 2000)

Therefore using Equation 3-2:

$$\%\ Slip = \frac{100 \times 17.1}{50} = \mathbf{34.2}\ \%$$

Equation 4-2 Derivation of % Slip based on characterisation presented by (Henry, 2000)

5 Scalar characterisation, 6.04 % wheel slip at 50 km/h operating speed

If the definitions presented in Chapter 3 are directly applied to SCRIM without any other consideration it can be shown that the system measures skid resistance at 6.04 % slip and an operating speed of 50 km/h.

5.1 Operating speed

The operating speed is equal to the vehicle speed which is standardised at **50 km/h**.

5.2 Wheel speed

The linear wheel speed has been assumed to be the component of the vehicle speed acting in the direction of the test wheel. This is shown in Figure 5-1 and can be calculated using Equation 5-1.

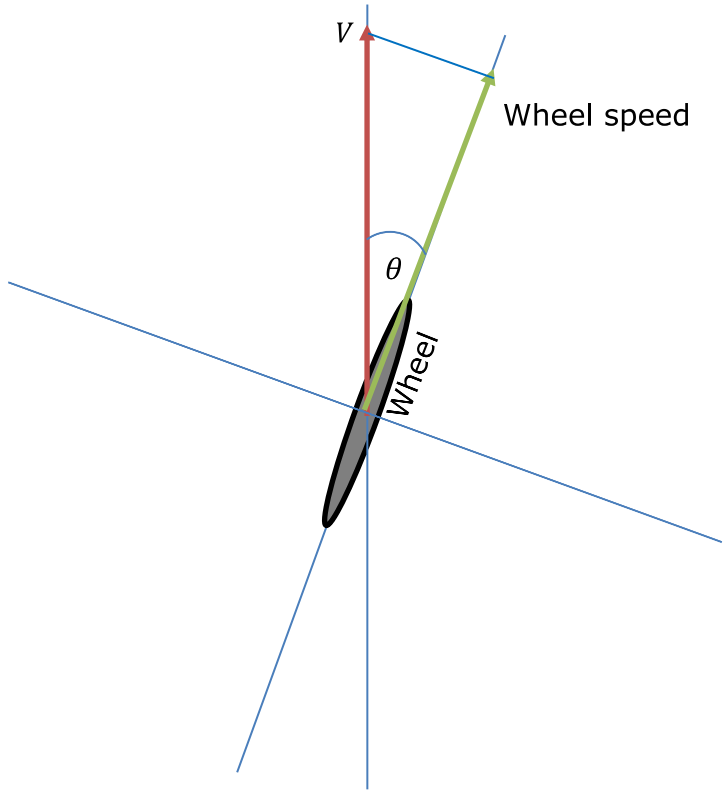

Figure 5-1 Diagram representing calculation of wheel speed (not to scale)

$$Wheel\ speed = VCos(\theta)$$

Where:

- V = the operating speed of the vehicle (km/h)
- θ = the angle between the test wheel and direction of vehicle travel

Equation 5-1 Calculation of wheel speed based on vehicle speed and wheel angle

The wheel speed can therefore be calculated as:

$$50Cos(20) = 46.98\ \mathrm{km/h}$$

5.3 Slip speed and slip percentage

Slip speed = $50 - 46.98 = 3.02\ km/h$ from Equation 3-1

Slip percentage = (100 x 3.02) / 50 = **6.02 %** from Equation 3-2

5.4 Discussion

The analysis in this chapter has presented the case for characterising sideways-force skid resistance measurement devices as making measurements at an operating speed of **50 km/h**, and a slip percentage of **6.02%**.

This scalar characterisation of skid resistance measurement devices may be appropriate for those devices (the PFT or GripTester for instance) that make measurements (with the exception of vertical load) in a single direction. That is, those devices which measure wheel speed, horizontal load and vehicle speed in the same direction, the direction of travel.

Sideways-force devices, however, add a vector component into the fabric of the measurement system through the angled nature of the test tyre. Chapter 6 explores how sideways-force skid resistance measurement devices may be characterised using a vector rather than scalar analysis.

6 Vector characterisation, 100% wheel slip at 17.1 km/h operating speed

By considering the inherent directionality of SCRIM, and by reviewing some historical literature, it can be shown that the system measures skid resistance at 100 % wheel slip and an operating speed of 17.1 km/h.

6.1 Historical evidence to support 100% wheel slip

The following excerpts were taken from historical documentation referring to sideways-force measurement devices preceding SCRIM.

Ministry of Transport document TP2 presents an analysis of the factors affecting skid resistance measurement. “It has been pointed out that the sideway force coefficient/speed relations shown in Fig. 1 were obtained with the angle theta of the sidecar wheel set above a critical value. It is now necessary to consider the meaning of the critical angle and the values of sideway force coefficient measured at a range of angles covering it. When the motor-cycle is driven along a road surface with the sidecar wheel out of alignment, the tyre on this wheel is subject to forces which produce lateral distortion. The distortion increases from nothing at zero wheel angle, up to a maximum, which occurs at critical value of wheel angle. Within the range of zero to critical angle, the sideway force coefficient is therefore dependent on tyre distortion; above the critical angle, when tyre distortion has attained its maximum and true sliding occurs, the coefficient is dependent, as has been seen, only on road characteristics.” (Bird & Miller, 1937)

A Road Research Laboratory (a predecessor to TRL) document on the interpretation of measurements made with the Road Research Laboratory’s motorcycle skidding machine states that “To measure skidding resistance, this wheel is set at an angle of about 18 degrees with the direction of travel of the machine, this being the minimum angle necessary to ensure that the tyre is skidding sideways and delivering the full sideways force.” (Grime, 1953)

Whilst not explicitly stating it, these documents heavily suggest that the test wheel for sideways-force devices, once beyond a critical angle enters a “true sliding” phase, this has been interpreted by the author as equating to a locked wheel (100% slip) friction phase.

6.2 The effect of the direction of measurement

For this analysis the effect of the direction of individual measurements made is crucial. For instance, most sideways-force measurement devices measure the following properties in the following orientations[4]

- Operating speed = 0 degrees (rotated around the vertical axis)

[4] Where the vertical axis is that which acts in the direction of gravity, and the longitudinal axis acts along the direction of vehicle travel.

- Wheel speed = N/A (not measured)
- Horizontal load = 70 degrees (rotated around the vertical axis)
- Vertical load = 90 degrees (rotated around the longitudinal axis)

In contrast, longitudinal devices measure the following properties:

- Operating speed = 0 degrees (rotated around the vertical axis)
- Wheel speed = 0 degrees (rotated around the vertical axis)
- Horizontal load = 0 degrees (rotated around the vertical axis)
- Vertical load = 90 degrees (rotated around the longitudinal axis)

The agreement in the measurement direction of operating speed, wheel speed and horizontal load for longitudinal devices means that a simple scalar assessment is appropriate. However, for sideways-force devices, because the horizontal load is measured at an angle to the direction of travel it is necessary to resolve the vectors so that the magnitude of vehicle speed and wheel speed agree with the direction of measurement of horizontal load.

This is analogous to measuring the weight of an object on an inclined plane using a platform scale. If the scale is placed on the plane, and can only measure weight perpendicular to the plane, then the weight of the object will be underestimated owing to a proportion of the weight acting in the direction of gravity. To ascertain the actual weight of the object, the angle of the plane must be considered to resolve the gravitational force and allow the true weight of the object to be calculated Figure 6-1.

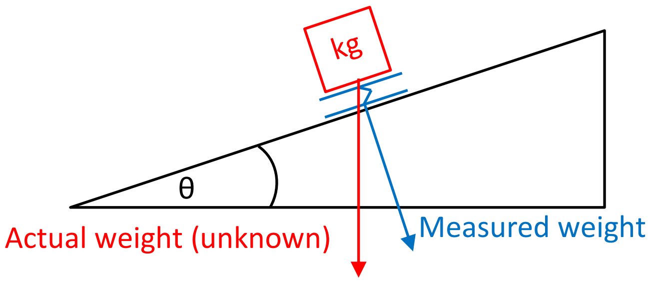

Figure 6-1 Resolving forces on an inclined plane to determine the actual weight of an object

6.3 Operating speed

The operating speed can be resolved in the direction of measurement as shown in Figure 6-2 by using Equation 6-1[5].

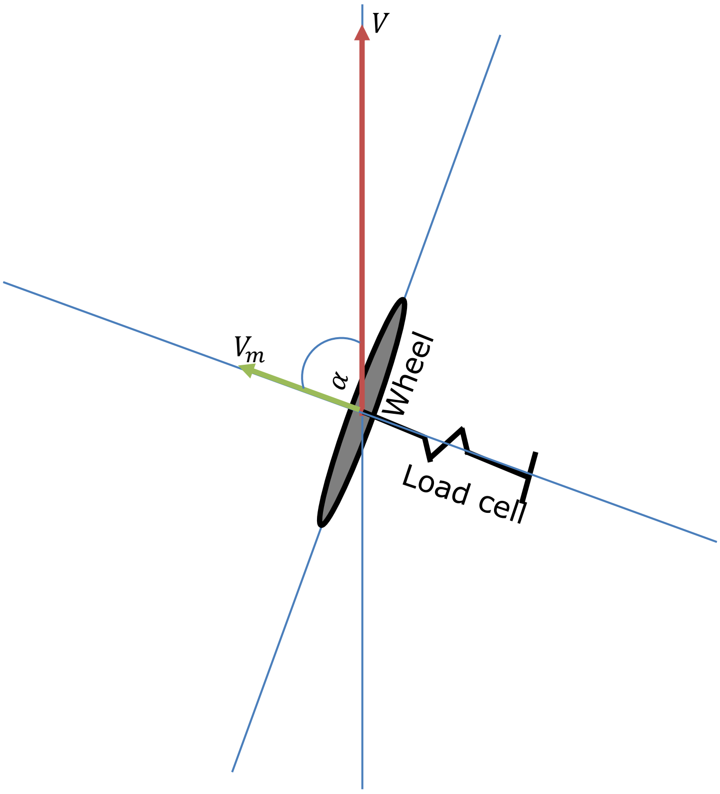

Figure 6-2 Diagram representing the operating speed and the direction to be resolved (not to scale)

$$V_m = VCos(\alpha)$$

Where:

- V_m = The vehicle speed resolved into the direction of measurements (km/h).
- V = The unresolved vehicle speed (km/h).
- α = The angle between the direction of travel and measurement.

Equation 6-1 Resolving operating speed

[5] It is interesting to note that this is very similar to the analysis reported in (Henry, 2000) that it is believed formed the basis of the current view. However in this case the results of the analysis are being considered as the operating speed, rather than the wheel speed as is reported in (Henry, 2000).

For the case of SCRIM:

- V = 50 km/h
- α = 70 degrees
- Therefore, $V_m = 50Cos(70) = \mathbf{17.1\ km/h}$

6.4 Wheel speed

For the purpose of this work it has been assumed that the wheel speed is the component of the vehicle speed acting in the direction of the test wheel. This has been calculated in section 3.2 as 46.98 km/h.

The wheel speed can be resolved in the direction of measurement by using Equation 6-1.

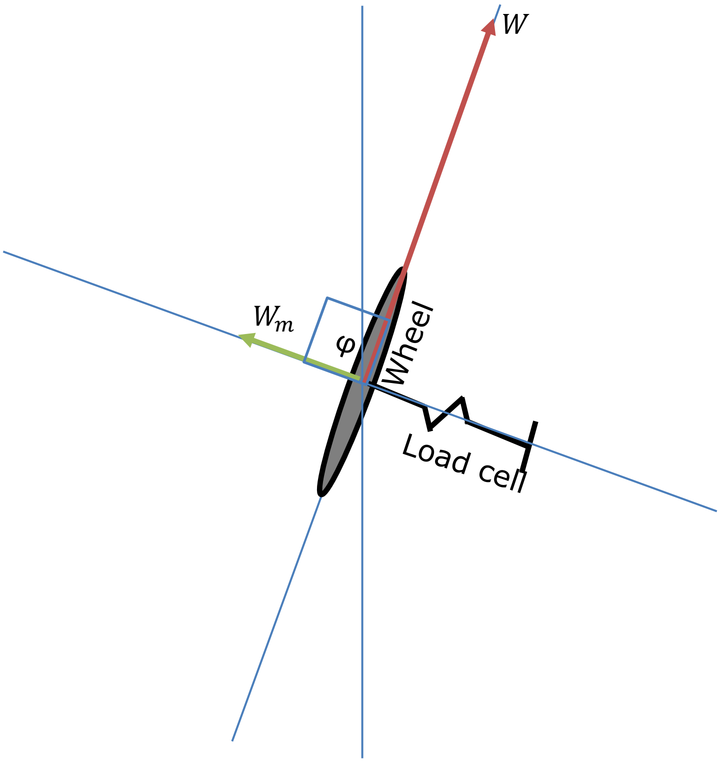

Figure 6-3 Diagram representing the wheel speed and the direction to be resolved (not to scale)

$$W_m = WCos(\varphi)$$

Where:

- W_m = The wheel speed resolved into the direction of measurements (km/h).
- W = The unresolved wheel speed (km/h).
- φ = The angle between the wheel rotational direction and the direction of measurement.

Equation 6-2 Resolving wheel speed

For the case of SCRIM:

- W has been assumed to be 46.89 km/h
- φ = 90 degrees
- Therefore, $W_m = 46.89Cos(90) = 0.0\ km/h$

6.5 Slip speed and slip percentage

Now that vehicle and wheel speed have been resolved into the correct direction, Equation 3-1 and Equation 3-2 can be used to calculate slip speed and slip percentage.

Slip speed = $17.1 - 0 = \mathbf{17.1\ km/h}$ from Equation 3-1

Slip percentage = 100x17.1/17.1 = **100 %** from Equation 3-2

6.6 Discussion

The analysis in this chapter has presented the case for characterising sideways-force skid resistance measurement devices as making measurements at an operating speed of **17.1 km/h**, and a slip percentage of **100%**.

7 Validating the characterisations

Owing to the highly theoretical nature of the work and as an addition to the normal TRL quality assurance procedures, the desk study reported in the previous chapters was independently validated. This verification was carried out by one of TRLs physicists, not familiar with SCRIM or the operation thereof, and without knowledge of the work presented in the previous chapters. The question which is the theme of this work was posed, and a brief explanation of the operation of SCRIM was provided, after which the physicist carrying out the verification was not corresponded with until their findings were presented.

The full verification is presented in Appendix A but can be summarised here as having fully replicated the characterisations presented in the above chapters and generated a fourth characterisation. The characterisations developed in Chapters 1 – 6 are summarised in Table 7-1; the additional characterisation developed as part of the verification process has also been included in Table 7-1 and has been called “Co-Axial”.

Table 7-1 Summary of operating speed and % slip predicted by characterisations

Characterisation	Operating Speed	Operating Speed (km/hr)	% slip
Current view	Vehicle speed	50	34.2
Scalar	Vehicle speed	50	6.03
Vector	Vehicle speed x Cos(70)	17.1	100
Co-Axial (from verification process)	Vehicle speed	50	11.7

In addition to quantifying the different possible operating speeds and slip percentages for SCRIM, the theoretical analysis carried out demonstrates that describing the performance of SCRIM cannot be carried out purely theoretically. This is because each one of the characterisations describes the same underlying physics. Identifying which characterisation is correct can therefore only be carried out by physical experimentation.

8 Support for characterisations in the existing literature

In order to assess if historical data could be used to support one or another of the characterisations summarised in Chapter 7 a literature review was carried out identifying pertinent historical literature and data referring to the function of SCRIM. This chapter presents the results of that review.

8.1 Observations of tyre striations from SCRIM testing

TRL operatives carrying out standard SCRIM testing have reported that worn SCRIM tyres possess striations which run at 90 degrees to the direction of rotation. This was shown to be the case for all the SCRIM tyres in TRL's stock and was present regardless of tyre age, or amount of use[6]. An example of this is shown in Figure 8-1 where the presence of the striations has been highlighted with white paint.

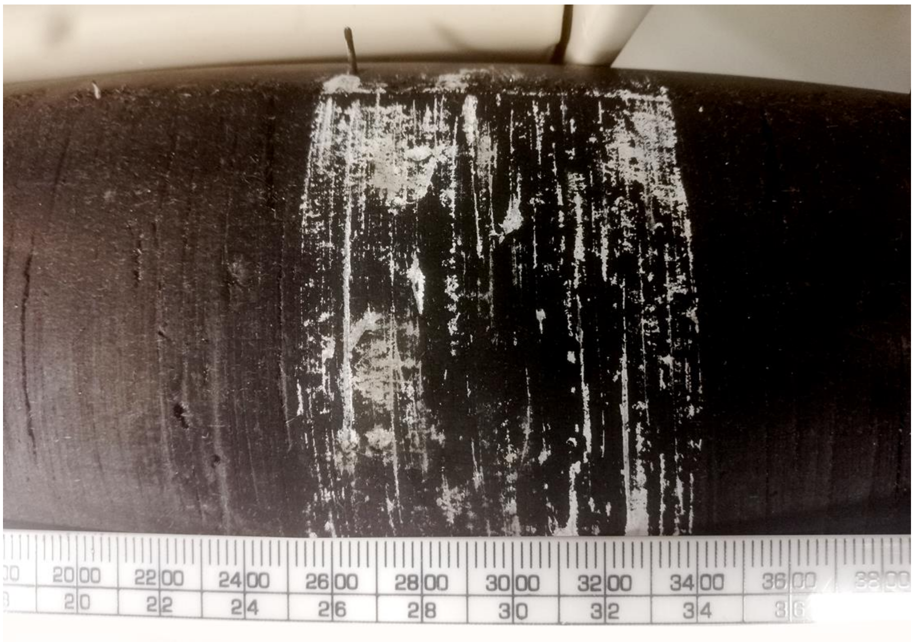

Figure 8-1 Striations observed on a SCRIM tyre due to testing

This observation is clear evidence that the tyre/road interface moves at 90 degrees to the direction of tyre rotation, or in other words, in the direction of horizontal load measurement. This seems to suggest that any characterisation that does not consider slip in this direction cannot be considered credible. Unfortunately from this evidence alone, it is not possible to infer the direction in which operational speed should be considered and so it adds equal weight to each of the characterisations in Table 7-1.

[6] So long as the tyre had been subject to the standard run-in process

8.2 (Bradley & Allen, 1930-31)

Fundamental work assessing the forerunner to modern SCRIMs was carried out by Bradley & Allen in 1930 and 1931. That work used a motorcycle and sidecar with an adjustable angle wheel, Figure 8-2. The sidecar wheel was fitted with sensor equipment capable of measuring the vertical load, horizontal load (along the axis of wheel rotation) and longitudinal load (in the direction of wheel rotation).

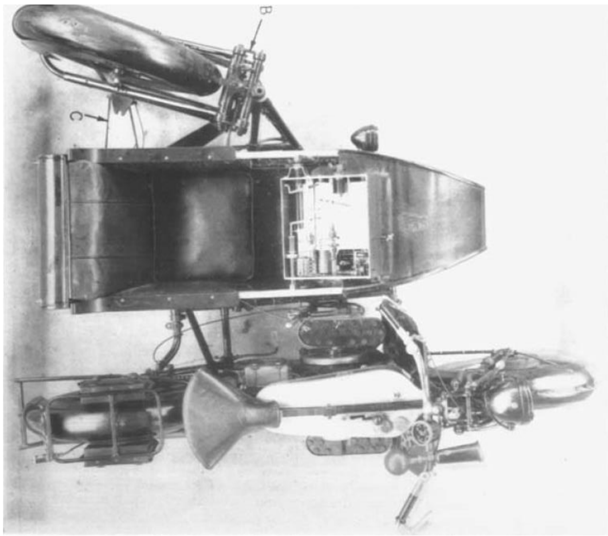

Figure 8-2 Test apparatus used by (Bradley & Allen, 1930-31)

Measurements were made using this device on materials of different types, including concrete, asphalt and wood blocks, with the device in two different configurations:

1. The configuration shown in Figure 8-2 with the sidecar wheel extended to an angle (relative to the direction of motion) of 20 degrees.
2. A configuration with the sidecar wheel retracted to an angle of zero degrees relative to the direction of travel[7] and where the sidecar wheel could be progressively braked using a manual hydraulic brake to induce different levels of wheel slip.

Measurements were also made using two different tyre types (tyre H and tyre B), neither of which reflect those used by today's SCRIM devices. In configuration 1 measurements were made at a variety of test speeds, and in configuration 2 at a range of % wheel slips, (Bradley & Allen, 1930-31) do not state at which test speed measurements were made in configuration 2.

The results from the measurements made are replicated in Figure 8-3. The relationship between speed and sideways-force coefficient was obtained making measurements in configuration 1. Of note here is that in some cases there is a positive relationship between

[7] (Bradley & Allen, 1930-31) did not explicitly state that this was the case and so this has been assumed.

speed and sideways-force coefficient. This is something that is commonly thought of as being a physical impossibility and so these findings are more likely to be related to the nature of data collection, rather than the actual skid resistance performance of the materials tested.

The relationship between % Slip and braking force coefficient was obtained using configuration 2. These results also demonstrate an odd behaviour as there is no evidence of a locked-wheel friction being achieved on any of the materials[8] as would be expected through long established observations. This is also likely an oddity of the measurement technique and could be due to a reduced vertical load force, or an artefact of the specific sensor equipment used.

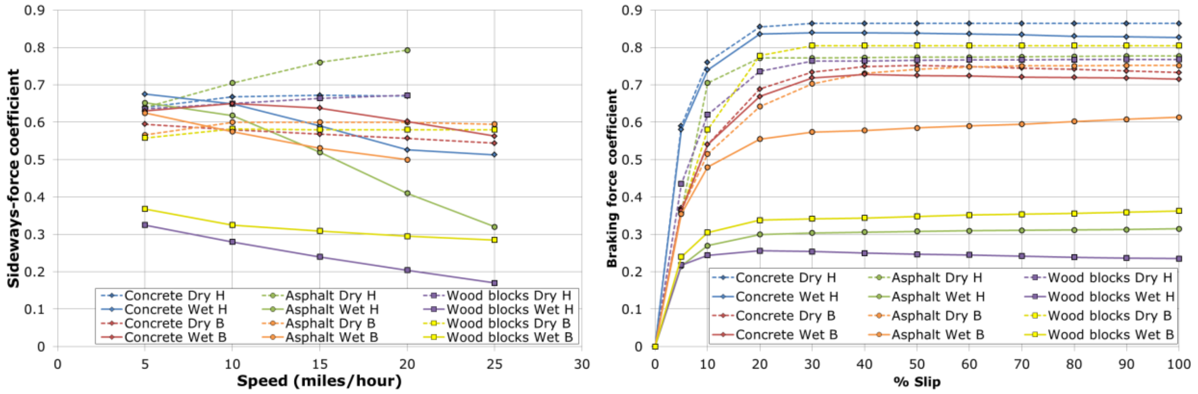

Figure 8-3 Replication of results reported in (Bradley & Allen, 1930-31)

Despite the limitations of this work, some insight can be provided by assessing the relationship between the measurements made using the two system configurations. To this end, the absolute difference between the braking force coefficient, and the sideways-force coefficient measured at 20 miles/hour, for each % slip was calculated for each material/tyre/wetting combination. The results of this analysis are presented in Table 8-1, the lowest values for each set of measurements assessed represent the best agreement in results between the two system configurations and these have been highlighted in green.

Table 8-1 Difference between braking force coefficient and sideways-force coefficient measured at 20 miles/hour

Material	Concrete				Asphalt				Wood blocks			
Dry / Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Tyre	H	H	B	B	H	H	B	B	H	H	B	B

[8] That is, there is no substantial difference between measurements made between 10 – 20 % slip and those made at 100 % slip.

% Slip	Absolute difference between braking force and sideways-force coefficients at 20 miles/hour											
0	0.67	0.53	0.56	0.60	0.79	0.41	0.60	0.50	0.67	0.20	0.58	0.30
5	0.08	0.05	0.19	0.24	0.43	0.20	0.24	0.15	0.24	0.01	0.22	0.06
10	0.09	0.21	0.02	0.06	0.09	0.14	0.09	0.02	0.05	0.04	0.00	0.01
20	0.19	0.31	0.13	0.07	0.02	0.11	0.04	0.06	0.06	0.05	0.20	0.04
30	0.19	0.31	0.18	0.12	0.02	0.11	0.10	0.07	0.09	0.05	0.23	0.05
40	0.19	0.31	0.19	0.13	0.02	0.10	0.13	0.08	0.09	0.05	0.23	0.05
50	0.19	0.31	0.20	0.12	0.02	0.10	0.14	0.09	0.09	0.04	0.23	0.05
60	0.19	0.31	0.19	0.12	0.02	0.10	0.15	0.09	0.10	0.04	0.23	0.06
70	0.19	0.31	0.19	0.12	0.02	0.10	0.15	0.10	0.10	0.04	0.23	0.06
80	0.19	0.30	0.19	0.12	0.02	0.10	0.15	0.10	0.10	0.04	0.23	0.06
90	0.19	0.30	0.18	0.12	0.02	0.10	0.15	0.11	0.10	0.03	0.23	0.06
100	0.19	0.30	0.18	0.11	0.02	0.10	0.15	0.11	0.10	0.03	0.23	0.07

It can be observed from Table 8-1 that in all but two cases the best agreement between the sideways-force coefficient and braking force coefficient is achieved between 5 and 20 % slip. In the other two cases the best agreement is observed at 100% slip. This lends some credence to the scalar characterisation as this characterisation predicts that SCRIM makes measurements at 6.03% slip.

8.3 (Bird & Miller, 1937)

In the late 1930s, Bird & Miller continued the work of Bradley & Allen into the development of sideways-force coefficient measurement technology. They conducted a series of experiments assessing the relationship between the angle of the sidecar device and the skid resistance value on different surfaces and at different speeds. The conclusions of this work act as the basis for defining the SCRIM wheel angle at 20 degrees.

The work carried out by Bird & Miller is best summarised by Figure 8-4 which in the interest of clarity has been replicated from the original text. Figure 8-4 presents the skid resistance values measured on three materials of different nominal friction levels, made at various test speeds. The general form of the results collected on each surface / test speed combination can be summarised as, a linear increase in skid resistance that reduces slightly once a critical wheel angle is met.

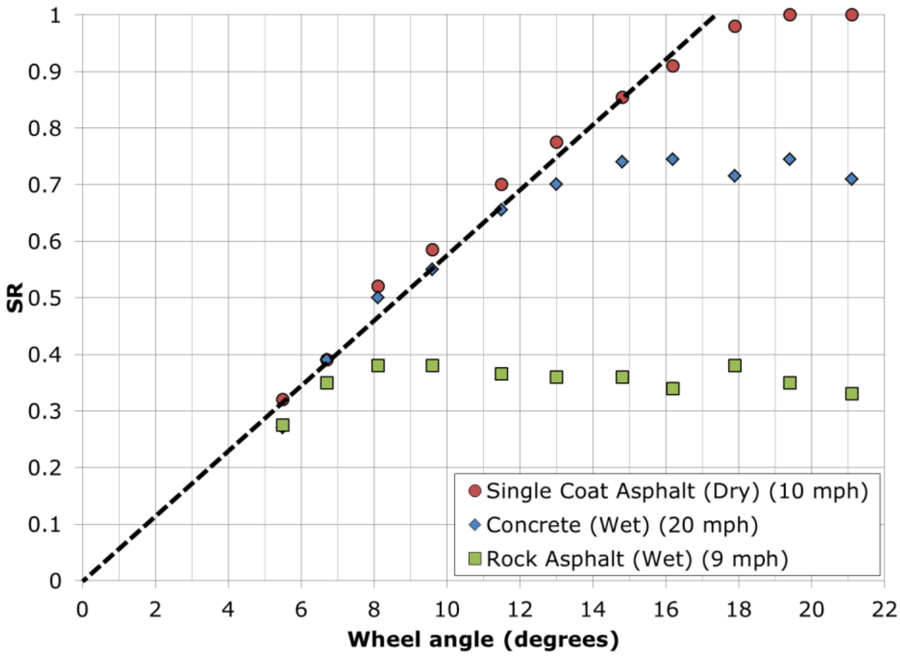

Figure 8-4 Replication of results presented in (Bird & Miller, 1937)

One of the key observations from Figure 8-4 is that regardless of surface type, test speed or the presence of water, the initial friction values from all of the tests carried out conform to the same straight line (represented by the broken line) until a critical wheel angle is met. Below is an excerpt from Bird & Miller explaining this observation.

"When the motor-cycle is driven along a road surface with the sidecar wheel out of alignment, the tyre on this wheel is subject to forces which produce lateral distortion. The distortion increases from nothing at zero wheel angle, up to a maximum, which occurs at the critical value of wheel angle. Within the range of zero to critical angle, the sideway force coefficient is therefore dependent on tyre distortion; above the critical angle, when tyre distortion has attained its maximum and true sliding occurs, the coefficient is dependent, as has been seen, only on road characteristics." (Bird & Miller, 1937)

This effect is demonstrated in Figure 8-5. In this figure a single particle is imagined approaching a SCRIM wheel, and then contacting the tyre in two cases. The case on the left of Figure 8-5 (small blue dots) shows a particle related to a "low grip" surface where the critical angle of the wheel is met. In this case the particle approaches the wheel in the direction of vehicle travel. As it makes contact with the tyre, it slides (is transposed due to the rotational action of the wheel) across the tyre in a direction perpendicular to the direction of travel.

The case on the right of Figure 8-5 (large red dots) shows a particle related to a "high grip" surface where the critical angle of the wheel is not met. In this case as the particle makes contact with the wheel it does not slide along the surface, rather, it grips the tyre and deforms it in the direction of rotation. In this case, in order to achieve full sliding, the energy applied to the tyre needs to be increased by either, increasing the wheel angle, or, increasing vehicle speed.

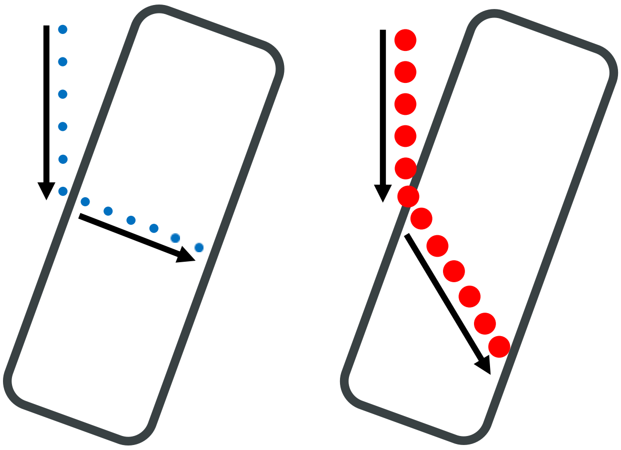

Figure 8-5 Measurements made on a "low grip" surface (left) and a "high grip" surface (right)

This observation, and explanation for it, seems to suggest that wheel angle and percentage slip are correlated. This is because the increase in skid resistance value to a peak, and a subsequent levelling off (Figure 8-4) is convincingly similar to the generation of friction with increasing wheel slip shown in Figure 8-3. However, the observations shown in Bird & Miller show that the relationship between maximum friction value reached with increasing wheel angle is correlated to the nominal friction value of the surface.

This is contrary to the observations of peak friction made by Bradley & Allen Figure 8-3 which show that maximum friction, percentage slip and nominal friction are not correlated. The observations of Bradley & Allen can be corroborated by more recent friction measurements made with the PFT which show that the peak friction of a material is independent at the percentage slip at which that friction is measured (Figure 8-6[9]).

Figure 8-6 shows that the correlation between Peak friction and the % Slip at which peak friction was measured is very poor. The box drawn with broken lines represents approximately 95% of the data present and it is approximately 15% wide. This shows only a very general trend for higher slip percentages to be present with increasing peak friction. Figure 8-4 however shows a very definite relationship between these two variables.

[9] Figure 8-6 shows data collected using the PFT, a locked wheel friction tester which reports levels of Locked-Wheel Friction (L-Fn) and Peak Friction (P-Fn).

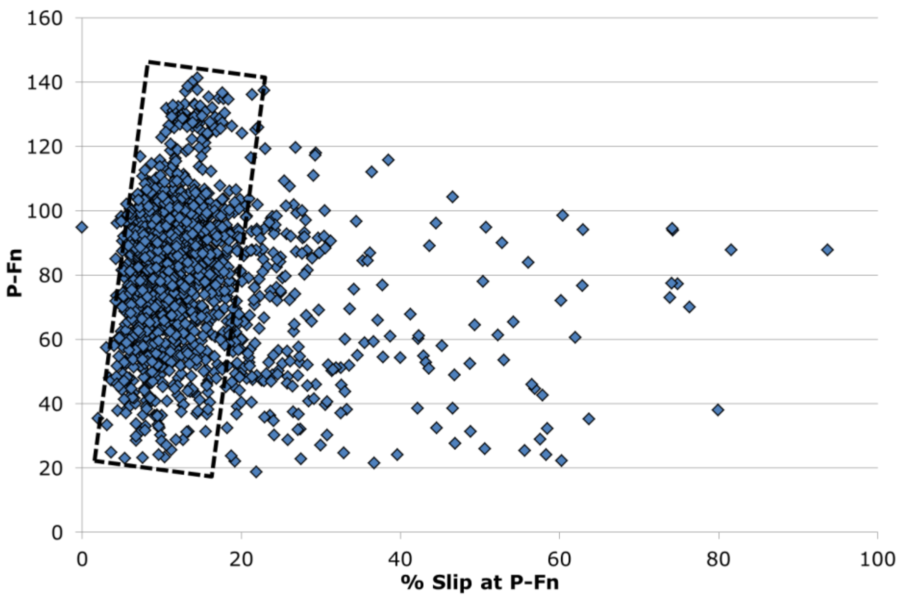

Figure 8-6 Relationship between Peak friction values and the % Slip at peak friction for 1883 individual friction measurements made using the PFT

The critical wheel angle observed by Bird & Miller must therefore be related to the properties of the tyre and is therefore not related to the peak friction of the surface. The results of Bird & Miller therefore lend themselves equally to supporting all of the characterisations of SCRIM reported in the previous chapter.

There is an important note based on the observations made in this chapter, whilst not strictly within the scope of this work, which is provided in Appendix B.

8.4 (Nordström & Åström, 2001)

During the late 1990s and early 2000s the Swedish National Road and Transport Research Institute, VTI, sought to update their skid resistance test device, the BV12. The updates made to the BV12 and an initial study into its performance are reported in (Nordström & Åström, 2001).

The update allowed the device to assess the skid resistance characteristics of road surfaces under combined turning and braking conditions. To achieve this VTI modified their BV12 to include an instrumented wheel capable of being held at an angle relative to the direction of travel and simultaneously braked. The wheel was instrumented such that the load applied to it could be measured in three directions, these were:

- Along the vertical axis,
- Along the axis of wheel rotation, referred to as the y-axis (such as that measured by sideways-force devices)
- In the direction of wheel rotation, referred to as the x-axis (such as that measured by longitudinal friction devices)

An initial set of measurements were gathered to explore the friction coefficients measured by the device in various testing configurations. A single test run was carried out whereby the test wheel was angled at 0, 5 and 10 degrees to the direction of travel. At each angle the test wheel was then braked and the friction forces acting in line with the direction of wheel rotation, and perpendicular to it were calculated for each percentage slip achieved by the wheel. Measurements were made at a test speed of 60 km/h with a nominal water thickness of 0.8 mm. It has been assumed that all of the measurements were made on a relatively homogeneous surface.

The original data referring to this work were not available in the literature assessed and so an approximation of the data has been re-constructed using the graphical representations of the data within (Nordström & Åström, 2001). The re-constructed data is presented in Figure 8-7 and in the interest of clarity data not pertinent to this work have been omitted.

Figure 8-7 presents friction coefficient measurements made with the updated BV12 with the test wheel at 0, 5 and 10 degrees to the direction of travel. For the 0 degree case, friction coefficients are presented for the full slip curve. For the angled cases, friction coefficients are presented for the 0 slip case, i.e. where the test wheel is not braked. Figure 8-7 therefore presents the comparative friction coefficients for a longitudinal test device, and a side force device with a test wheel at 5 and 10 degrees.

Based on the re-constructed data from (Nordström & Åström, 2001) three of the characterisations presented in Table 7-1 (the current view, scalar and co-axial[10]) can be tested. This can be achieved by comparing the friction coefficients measured at 5 and 10 degrees wheel angle at 0 % slip (free rolling), with those made with a 0 degrees angle at various levels of wheel slip.

[10] The Scalar characterization cannot be tested because this predicts that changes in wheel angle equate to changes in operational speed. The work reported by (Nordström & Åström, 2001) used a single vehicle speed of 60km/h and so the change in friction coefficient with operational speed is unknown.

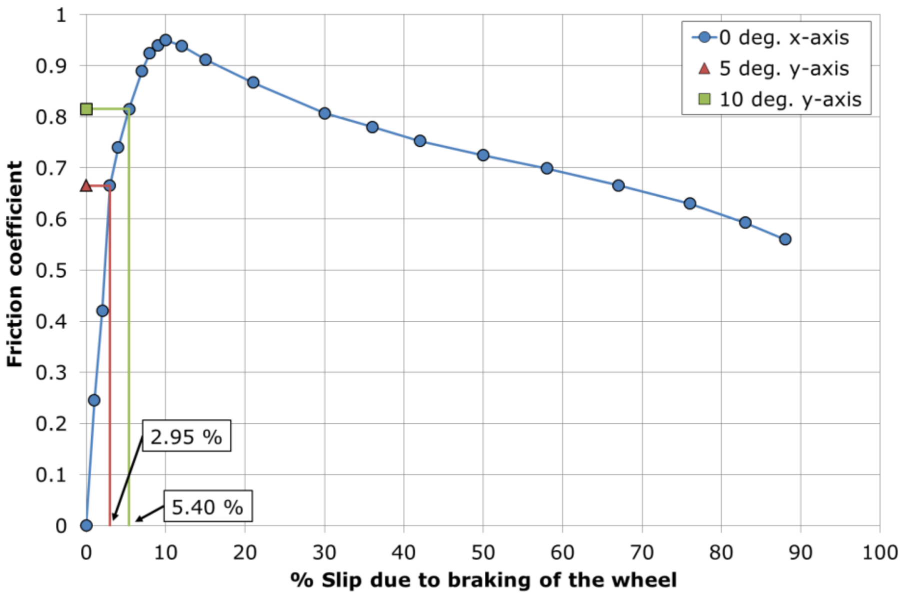

Figure 8-7 Re-construction of data from (Nordström & Åström, 2001)

The percentage slips calculated from the above exercise can then be compared to the percentage slips associated with wheel angles of 5 and 10 degrees for each of the three characterisations. This calculation has been carried out and is shown in Figure 8-7 by the red and green lines for 5 and 10 degrees wheel angle respectively. If the percentage slips defined by one or more of the characterisations match those shown in the data then this will support that/those characterisations.

The results of this analysis are shown in Table 8-2 and it can be seen that none of the characterisations that could be tested predict the % slips that were calculated from the data. One possible explanation for this is that the critical wheel angel for the surface being assessed was not reached at 5 or 10 degrees.

Table 8-2 Comparison of % slip for different wheel angles predicted by characterisations and calculated from (Nordström & Åström, 2001)

Characterisation	% slip	% slip at wheel angle (degrees): 5	10
Current view	$\sin\theta$	8.72	17.36
Scalar	$1-\cos\theta$	0.38	1.52
Co-Axial	$\sin^2\theta$	0.76	3.02
% Slip calculated from (Nordström & Åström, 2001)		2.95	5.40

Figure 18 of (Nordström & Åström, 2001), presented here in Figure 8-8, suggests that this could be the case for 5 degrees, but shows that this was not the case for the 10 degree wheel angle. Figure 8-8 shows a similar behaviour to that observed by Bradley & Allen, namely a linear increase in friction (represented by the broken red line) with wheel angle until a critical angle is reached (the solid red line). It has been assumed that the data reported in Figure 8-8 was collected from measurements made using the same surface / tyre combination as those data in Figure 8-7. Figure 8-8 shows that measurements made at 10 degrees are clearly above the critical angle. Measurements made at 5 degrees however seem to have been made in some transitional space that does not conform to the linear broken line, nor the solid red line.

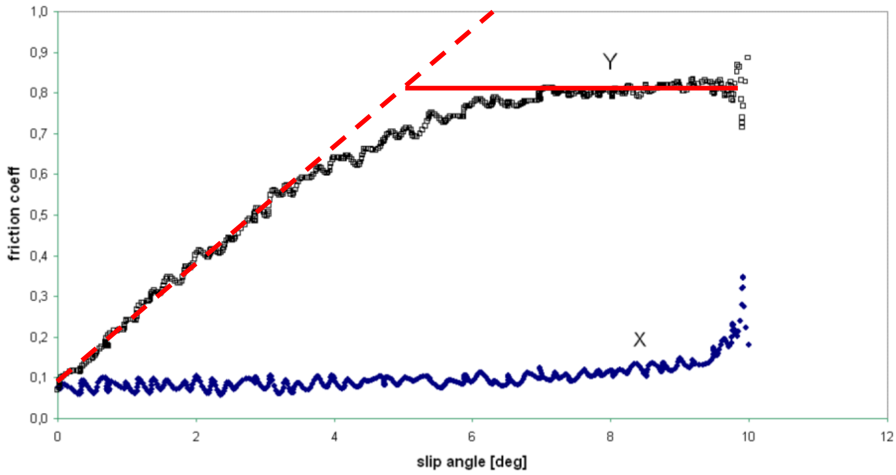

Figure 8-8 Relationship between wheel angle and friction coefficient for the updated BV12 device (Nordström & Åström, 2001)[11]

This analysis does not therefore support any of the characterisations developed which predict that changing the wheel angle of a sideways-force device is analogous to altering the percentage slip.

8.5 Summary of literature review

Based on the historical literature there is no justification for supporting any one of the characterisations summarised in the previous chapter. The literature has also shown that SCRIM can only be properly characterised when it is operating above the critical angle (when the tyre is undergoing full sliding) for any given surface. In order to properly characterise the measurement characteristics of SCRIM it is therefore necessary to collect empirical evidence comparing the performance of SCRIM with that of another measurement device.

[11] The solid and broken red lines have been added for clarification.

9 Challenging the characterisations

This chapter outlines experimental methodologies for empirically assessing the measurement characteristics of SCRIM.

9.1 Measuring the test tyre rotational speed

A key assumption of the scalar and vector characterisations is that the test wheel speed is equal to the component of the vehicle speed in the direction of rotation. Challenging this assumption is therefore critical in gaining confidence in these characterisations. One of the features of the current view is that at the standard vehicle speed of 50 km/h the linear test wheel speed is 46.98 km/h. This feature can also be examined using the methodology outlined below.

In order to challenge this assumption the rotational speed of the test wheel should be directly measured using a wheel speed sensor. Measurements made on surfaces with different nominal SC levels should be carried out at different vehicle speeds. If the assumption is correct then the linear speed of the wheel should follow the relationship defined in Chapter 5.

9.2 Full scale methodology

This section presents a full scale experiment utilising the Skid Resistance Development Platform (SkReDeP)[12], and another device, the Pavement Friction Tester (PFT)[13].

9.2.1 The experimental procedure

The data collection exercise for assessing operating speed and slip percentage is the same and is summarised in the following bullet points:

- Install a SCRIM wheel and tyre on the PFT and adjust the trailer weight to match that of the vertical load on SkReDeP,
- Make measurements using the PFT at different operating speeds on surfaces with different nominal friction levels,
- Make measurements with SkReDeP on the same surfaces and at the same vehicle speeds.

For each surface the measurements collected from the PFT can be used to build a surface profile. These surface profiles can then be interrogated and compared with the predictions of operating speed and % slip derived from the characterisations as summarised in Table 7-1.

[12] SkReDeP is a device owned by Highways England for the purpose of conducting skid resistance research and contains SCRIM equipment.

[13] The pavement friction tester is a device capable of making friction measurements over the full wheel slip percentage range at up to operating speeds of 130 km/h.

9.2.2 Data assessment

To assess the predictions of operating speed and % slip made by each of the characterisations, the change in friction measurements at various percentage slips with speed made using the PFT can be compared to the change in friction measurements made using SkReDeP. This analysis should be carried out for each of the surfaces assessed and in order to gain full confidence in the characterisations, a similar relationship should be observed regardless of the material being assessed.

To gain confidence in the current view, the change in friction with vehicle speed for the SCRIM should closely match the change in friction with vehicle speed of the PFT at 34.2 % wheel slip. To gain confidence in the scalar characterisation, the change in friction with vehicle speed for the SCRIM should closely match the change in friction with vehicle speed of the PFT at 6.03 % wheel slip.

To gain confidence in the vector characterisation, the change in friction with vehicle speed for SCRIM should closely match the change in friction with the vehicle speed multiplied by Cos(70) at 100 % wheel slip.

Idealised results of this analysis presenting hypothetical relationships demonstrating confidence in the current view and vector characterisation are shown in Figure 9-1.

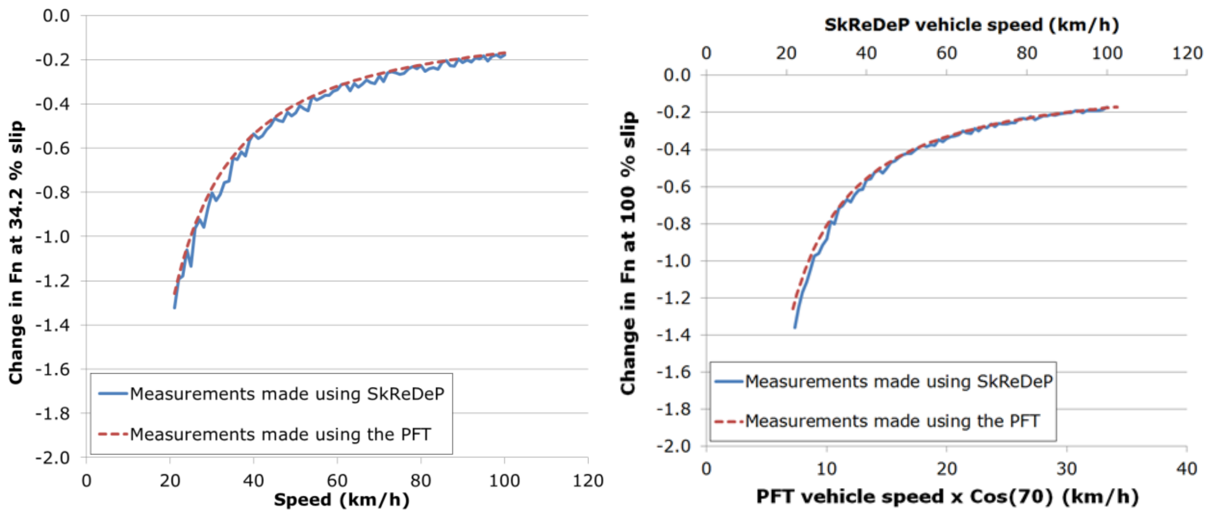

Figure 9-1 Idealised analysis results demonstrating confidence in the current view (left) and vector characterisation (right)[14]

Work reported in TRL report PPR815 (Sanders, Militzer, & Viner, 2017) demonstrated that the rate of change in friction with operating speed at various % slips is markedly different. Furthermore, the relationship between the rate of change in friction with operating speed

[14] This figure is an idealised representation of theoretical relationships and was NOT derived from test data.

differs for measurement s made on materials with different nominal levels of skid resistance. An analysis of this type should therefore be robust.

9.3 Laboratory methodology

The author of the verification work (Appendix A) presents a laboratory methodology for characterising the performance of SCRIM.

9.3.1 The experimental procedure

A laboratory experiment is proposed whereby a statically held, but rotating wheel, is loaded onto a conveyer belt. The following aspects of this system can be controlled:

- The angle between the wheel and conveyer belt
- The slip speed of the test wheel relative to the conveyer belt
- The speed of the conveyer belt
- The nominal friction of the belt through the use of different belt materials

The following aspects of the system would be measured:

- The vertical load applied to the test wheel
- The load in the direction of wheel rotation (the longitudinal friction)
- The load at right angles to the direction of wheel rotation (the horizontal friction)

This experimental setup will allow each of the characterisations in Table 7-1 to be independently challenged. To challenge the characterisations, measurements should be made under the following conditions using all of the different belts (belts with different friction characteristics):

1. With the wheel set to have a zero angle with the conveyor belt:
    1.1. At belt speeds of 10, 20, 30, 40 and 50 km/h
    1.2. For each belt speed, at % slips of 34.2, 6.03, 11.7 and 100
2. With the wheel set to an angle of 20 degrees with the conveyor belt:
    2.1. At belt speeds of 10, 20, 30, 40 and 50 km/h
    2.2. The test wheel should be allowed to freely rotate
3. With the wheel set to an angle of 90 degrees with the conveyor belt**:**
    3.1. At belt speeds of 3.42, 6.84, 10.26, 13.68 and 17.01 km/h

9.3.2 Data assessment

In order to challenge each of the characterisations, the longitudinal friction measurements made with the wheel angle at zero degrees should be compared to the horizontal friction measurements made with the wheel at a 20 degree angle. In order for a characterisation to be considered valid the friction values should match for the longitudinal friction measurements made at the corresponding percentage slip. In addition, in order for the scalar characterisation to be valid, horizontal friction measurements made with a wheel angle at 90 degrees and the augmented belt speeds should also match the other friction values gathered.

10 Summary and conclusions

The work presented in this report has summarised three theoretical characterisations of the measurement properties of sideways-force coefficient skid resistance test devices. An experimental methodology for the assessment of these characterisations has been presented. In addition, historical works have been reviewed which add some credence to two of the characterisations.

From the work carried out the following conclusions can be made:

- The current view of SCRIM characterises its performance as having an operating speed the same as the vehicle speed and a % slip of 34.2.
- The scalar characterisation of SCRIM demonstrates an operating speed the same as the vehicle speed and a % slip of 6.03.
- The vector characterisation of SCRIM demonstrates an operating speed as the vehicle speed multiplied by Cos(70) and a % slip of 100.
- Work carried out by (Bradley & Allen, 1930-31) goes someway to supporting either the scalar or vector characterisations, but is limited in its scope.
- The experimental study presented should be carried out to identify if any of the characterisations match the measured performance of SCRIM.
- Identifying the correct performance of SCRIM is critical in designing appropriate safety standards for highways.

Appendix A Verification of the desk study

The following analysis seeks to understand what SCRIM measures based on its configuration and the forces acting on it. The goal is to express the SCRIM configuration in language which can be equally applied to the other friction testing devices to enable a direct comparison.

This analysis has been carried out by me (Dr. Cormac Browne, July 2019) after receiving an explanation of the configuration of SCRIM and how the device operates. This is an independent note to be read in conjunction with the analysis carried out by P. D. Sanders. Both documents were produced by the respective authors without knowledge of the other's methods or definitions until after both notes were produced.

A.1 SCRIM Test Configuration

For clarity I have included a conversion from the terminology that I would employ to the language of slip percentages which is standard within the topic.

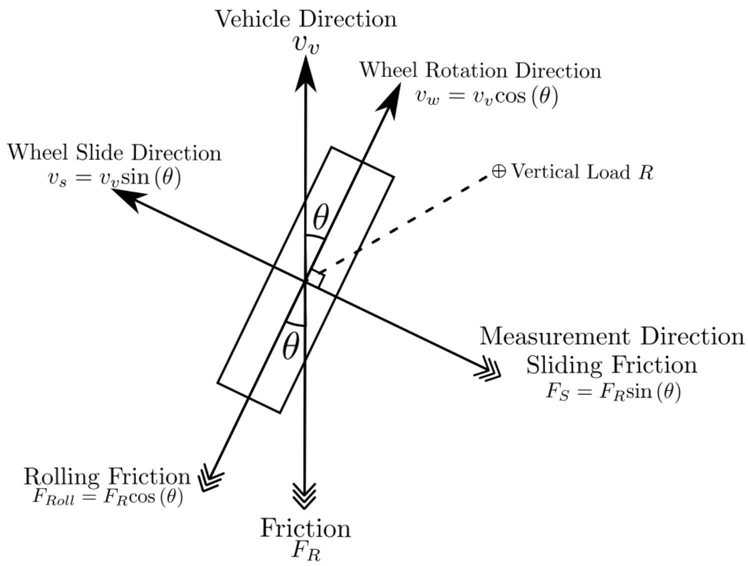

Figure A - 1 Diagram displaying the velocities and forces that act on the SCRIM test wheel

As a summary, my understanding of the SCRIM device is as follows:

1. To simulate the worst case scenario SCRIM utilises a smooth tyre and applies water to achieve an approximately constant thickness film.
2. The wheel can freely rotate around a fixed axle, and is held at an angle of $\theta = 20^0$ relative to the direction of vehicle travel.
3. During testing the vehicle travels at a constant v_v = 50 km/hr (13.8 m/s) and a constant Vertical Load R = 200g, where g is the acceleration due to gravity, is applied through the centre of the wheel and orthogonal to the axle.
4. I assume that the only source of opposing force in the system is due to the Friction F_R generated between the tyre and the road surface.

5. On the fixed axle is a load cell to measure the component of friction in the direction of the axle, which I am calling the Sliding Friction F_S.
6. SCRIM reports using the Sideways-force Coefficient $\mu s \equiv \frac{F_S}{R}$.

A.2 Interpreting the Configuration

SCRIM provides an indirect measurement of coefficient of friction that is experienced by the tyre. This can be seen using the fact that $F_R = \mu R$, meaning:

$$\mu s = \frac{F_S}{R}$$

$$= \frac{F_R \sin(\theta)}{R}$$

$$= \frac{\mu R sin(\theta)}{R}$$

$$= \mu \sin(\theta)$$

Equation A - 1

Figure A - 1 shows how the velocity of the vehicle v_v and the vertical load R create a resultant friction F_R which can be resolved in to an 'along wheel' component and an 'in axle' component. All frictions are dependent upon the relative velocity between the surfaces causing the friction. To characterise the action of the SCRIM device it is important to fully describe these velocities and the relationship between them. There are 3 velocities which are natural to consider in the configuration - the vehicle velocity v_v, the linear velocity of the wheel v_w (along the axis of rotation), and the sliding velocity of the wheel v_s.

To enable comparison with other devices (particularly the Pavement Friction Tester which is a longitudinal friction tester) we wish to define an Operating Speed u_{op} and a Slip Speed u_{slip} experienced by the system. It is standard to use the Slip Percentage $S_{\%} \equiv \frac{u_{slip}}{u_{op}} \cdot 100\%$ to refer to the slip speed in relation to the operating speed.

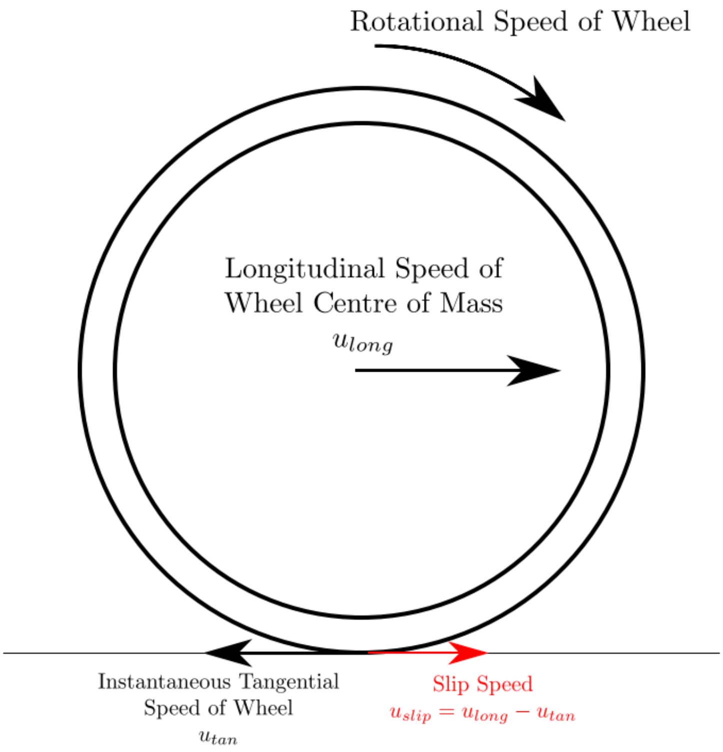

Figure A - 2 Diagram showing how slip speed is defined for a longitudinal friction tester

In the case of a longitudinal friction tester (LFT) there are natural values to associate with each of these parameters, see Figure A - 2. The operating speed can be defined as the longitudinal speed of the wheel's centre of mass u_{long}. This allows us to define the slip speed as the difference between u_{long} and the instantaneous tangential speed of the wheel u_{tan}:

$$u_{slip} = u_{long} - u_{tan}$$

Equation A - 2

Hence we can see that the slip percentage S% of the system is:

$$S_{\%} = \frac{u_{slip}}{u_{op}} \cdot 100\%$$

$$= \frac{u_{long} - u_{tan}}{u_{long}} \cdot 100\%$$

$$= \left(1 - \frac{u_{tan}}{u_{long}}\right) \cdot 100\%$$

Equation A - 3

Returning to the SCRIM device, we can see that there are range of possible definitions that could be employed to understand the SCRIM configuration. These definitions will produce different values for the slip percentage and are evaluated below. However, the fundamental source of the measured friction remains the relative velocity between the pavement and the tyre in the direction of the measurement.

A.2.1 Sliding Velocity Relative To Vehicle Velocity

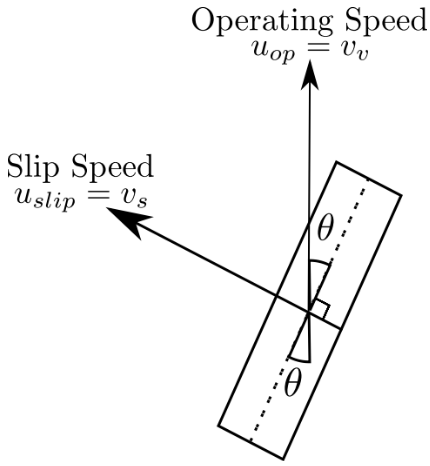

Figure A - 3 Sliding velocity relative to vehicle velocity

To attempt directly mapping the definitions for the LFT we can define the operating speed to be the vehicle speed: $u_{op} = v_v$. Considering the slip speed as defined for the LFT to be targeting the component of the longitudinal velocity of the tyre centre of mass that is due to sliding the tyre and not due to its rotation leads to the closest analogue being the sliding velocity so we have $u_{slip} = v_s$. Choosing these definitions allows us to see that the slip percentage $S_{\%}$ will have no dependence on the vehicle speed, and purely depends on the angle between the tyre and the vehicle direction:

$$S_{\%} = \frac{u_{slip}}{s_{op}} \cdot 100\%$$

$$= \frac{v_v \sin(\theta)}{v_v} \cdot 100\%$$

$$= \sin(\theta) \cdot 100\%$$

$$= 34.2\%$$

Equation A - 4

A.2.2 Wheel Rotation Velocity Relative to Vehicle Velocity

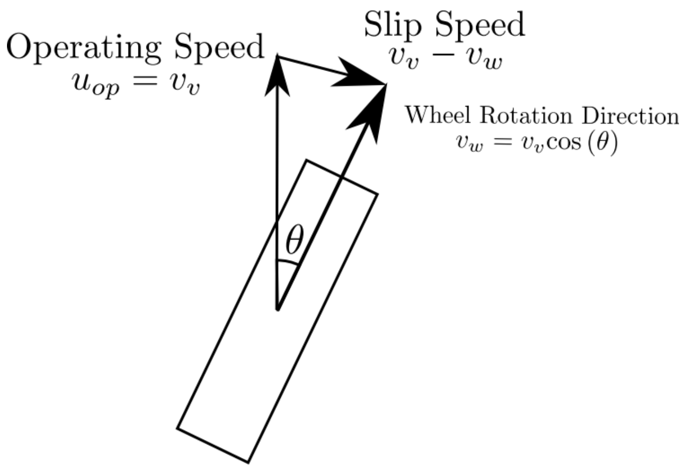

Figure A - 4 Wheel rotation relative to vehicle velocity

For the LFT the slip speed is calculated from the difference between the vehicle speed and the tangential velocity of the tyre. Applying this strict definition, using the equivalent terms for SCRIM leads to $u_{slip} = v_v - v_w$, and using this to calculate slip percentage gives:

$$\begin{aligned} S_{\%} &= \frac{u_{slip}}{u_{op}} \cdot 100\% \\ &= \frac{v_v - v_w}{v_v} \cdot 100\% \\ &= \frac{v_v - v_v \cos(\theta)}{v_v} \cdot 100\% \\ &= \big(1 - \cos(\theta)\big) \cdot 100\% \\ &= 6.03\% \end{aligned}$$

Equation A - 5

However an insurmountable flaw in this definition is that the SCRIM does not measure any forces in this direction. The friction measured is in an orthogonal direction to the wheel's rotation and so characterising the slip percentage in these terms is misleading.

A.2.3 Velocities Co-Axial to the Slip Direction

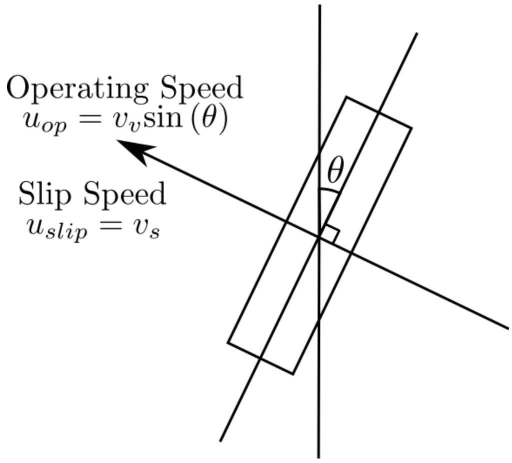

Figure A - 5 Velocities co-axial to the slip direction

An alternative interpretation of the LFT setup is that all the velocities are defined such that they are co-axial with the slip direction. That is, the operating speed is defined to be the vehicle velocity in the direction of the slip and the slip speed is defined as the difference between wheel rotation speed in the direction of slip and the sliding speed. As the wheel is rotating about a fixed axle that is in the same direction as the slip direction it is clear that the slip speed is then just the sliding speed. Thus the slip percentage is simply:

$$\begin{aligned} S_{\%} &= \frac{u_{slip}}{u_{op}} \cdot 100\% \\ &= \frac{v_s}{v_v sin(\theta)} \cdot 100\% \\ &= \frac{v_v sin(\theta)}{v_v sin(\theta)} \cdot 100\% \\ &= 100\% \end{aligned}$$

Equation A - 6

A.2.4 Velocities Co-Axial to the Vehicle Direction

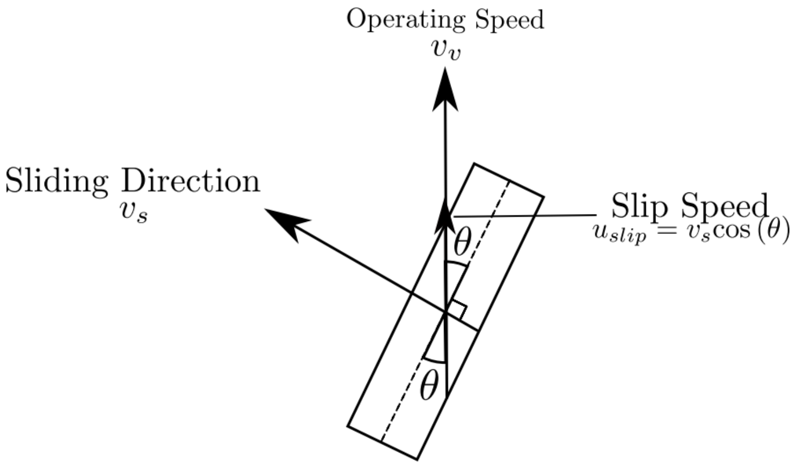

Figure A - 6 Velocities co-axial with the vehicle direction

Similarly, as the only source of friction in the system is due to the motion of the vehicle one could choose to 're-resolve' the velocities of interest to be co-axial with the direction of interest. Here we define the operating speed to be the velocity of the vehicle. Then the slip speed can be defined as either:

1. The sliding velocity resolved in the direction of the vehicle's travel.

$$u_{slip} = v_s sin(\theta)$$
$$= v_v sin^2(\theta)$$

Equation A - 7

2. The difference between the vehicle speed and the tangential speed of the tyre resolved in the direction of the vehicle's travel.

$$u_{slip} = v_v - v_w cos(\theta)$$
$$= v_v - v_v cos^2(\theta)$$
$$= v_v\left(1 - cos^2(\theta)\right)$$
$$= v_v sin^2(\theta)$$

Equation A - 8

As can be seen both definitions produce the same slip speed as can be expected - the amount of slip in the direction of travel should be the same no matter how you choose to calculate it. The slip percentage using this set of definitions is:

$$S_{\%} = \frac{u_{slip}}{u_{op}} \cdot 100\%$$

$$= \frac{v_v sin^2(\theta)}{v_v} \cdot 100\%$$

$$= sin^2(\theta) \cdot 100\%$$

$$= 11.7\%$$

Equation A - 9

The flaw in this interpretation is that measurement is not co-axial to the vehicle direction - thus we are characterising the measurement using parameters which contain components that the measurement does not interact with. One can also consider the act of 're-resolving' the forces to be an arbitrary choice that is ill justified although I would argue it does tell you the amount of slip an element of rubber would experience in the direction of travel. The measurement of friction occurs at an angle of $\frac{2}{\pi} + \theta$ relative to the direction of travel of the vehicle. As such it may be necessary to scale the measurement result by $(\sin(\theta))^{-1}$ when comparing to other friction testers.

A.2.5 Summary Table of Interpretations

Operating Speed u_{op}	Operating Speed Value (km/hr)	Slip Speed u_{slip}	Slip Speed (km/hr)	Slip Percentage %
v_v	50	v_s	17.1	34.2
v_v	50	v_v-v_w	3.02	6.02
$v_v\sin(\theta)$	17.1	v_s	17.1	100
v_v	50	$v_s\sin(\theta)$	5.85	11.7

A.3 Testing the Interpretations

There is some mathematical justification for using any of the above interpretations. I would argue Interpretation 2 is not an accurate representation of the SCRIM and is unlikely to produce results which can be compared to other devices.

The other three interpretations are different methods of representing the same underlying physics. If each definition is applied correctly it will result in the same resolution of the forces and produce the same relative velocity between the road surface and the tyre. Friction arises in the system due to the vertical load and this relative velocity producing a resistive force to oppose the vehicle's motion.

To test each of these interpretations there are two complimentary methodologies which can be employed:

1. Recreate each configuration using a longitudinal friction tester and measure the resulting coefficients of friction.
2. Recreate the SCRIM configuration and measure wheel velocity, slip speed, and the dependence on angle and operating velocities.

To implement Method 2, I would propose using a moveable conveyor belt system with a surface of known frictional properties applied to the belt. This makes use of the fact that there is no difference between a vehicle traversing a road surface at some velocity and a surfacing being moved relative to the vehicle at the same velocity. Such a system would allow for measurements of the resultant forces in all relevant directions (co-axial with the "vehicle" motion, the axis of rotation of the wheel, and the direction of rotation of the wheel) and for the relative angle between the direction of travel and the wheel to be varied.

The advantage of such a setup is all degrees of freedom in the system can be controlled and investigated. It is possible to set up any measurement configuration and iterate between them to fully map how the SCRIM depends on the different parameters and to determine at what points different kinds of friction become important. Should it be desired a more detailed methodology can be drafted and proposed.

Appendix B Note on the determination of SCRIM critical angle

The only work that was identified referring to the calculation of the SCRIM critical angle, was that work carried out in the 1930s by (Bradley & Allen, 1930-31) and (Bird & Miller, 1937). Both pieces of work were carried out using the motorcycle and sidecar device which was the precursor to modern SCRIM devices. It is not known to the authors if further work investigating the critical angle was carried out between the 1930s and when SCRIM was developed in the 1960s the results of which were not reported or have been lost over time.

Since 1937 numerous changes to the sidecar and motorcycle device have been made, the most notable of which are:

- The vertical load applied to the test wheel has been standardised at 200 kg
- The vehicle chassis has been updated to improve stability
- The test tyre compound has been changed, at least twice
- The vehicle test speed has been standardised at 50 km/h
- The application of water to the tyre surface interface has been standardised at a nominal depth of 0.5 mm
- The test wheel itself has been changed from a spoke to solid plate design

All of the changes listed above will have had a dramatic effect on the sideways-force system and could therefore also affect the critical angle. For example, increasing the vertical load on the wheel would increase the sideways force applied to the wheel for a surface of the same skid resistance[15]. According to Figure 8-4 and Figure 8-5 this would require the critical angle, or vehicle speed to be increased to overcome the additional force applied to the tyre from the road.

It may be the case therefore, that current SCRIM devices are operating using a wheel angle which is below the critical angle for some materials and above it for others. For materials where SCRIM operates below the critical angle, this would have the effect of producing a lower skid resistance measurements on these surfaces than would have been measured using a greater wheel angle. Crucially, these measurements are most likely to be made on materials with a high nominal friction level, which are typically installed on the highest risk sites, where accurate skid resistance characterisation is crucial for motorist safety.

It is therefore strongly recommended that a review is carried out to identify if critical angle was further investigated since 1937 and if not, the experiments of Bird & Miller repeated using a modern SCRIM device to assess if modern SCRIMs are operating above critical angle for all of the material types present on the UK road network, in particular for High Friction Surfacings that were not present on the UK road network in the 1930s.

[15] Because, skid resistance = horizontal force / vertical force

Bibliography

Bird, G., & Miller, R. A. (1937). *TP2 Studies in road friction II. An analysis of the factors affecting measurement.* Department of scientific and industrial research and Ministry of Transport.

Bradley, J., & Allen, R. F. (1930-31). Factors affecting the behaviour of rubber-tyred wheels on road surfaces. *Institute of automobile engineers proceedings*, pp. 63-92.

British Standards Institution. (2006). *BS 7941-1-2006 Methods for measuring the skid resistance of pavement surfaces – Part 1 SCRIM.* London: BSi.

British Standards Institution. (2009). *DD CEN/TS 1509-6:2009 Part 6: Procedure for determining the skid resistance of a pavement surface by measurement of the sideway force coefficient (SFCS): SCRIM.* London: British Standards Institution.

Department for Transport. (2004). *HD 28/04 Skidding resistance.* London: DfT.

Department for Transport. (2015). *HD 28/15 - Skid resistance (DMRB 7.3.1).* London: The Stationery Office.

Greene, M., Viner, H., Cerezo, V., Kokot, D., & Schmidt, B. (2014). *ROSANNE Deliverable D1.1 Definition of boundaries and requirements for the common scale for harmonisation of skid resistance measurements.* N/A: ROSANNE.

Grime, G. (1953). *RN_2029_GG The interpretation of measurements made with the road research laboratory's motorcycle skidding machine.* Road research laboratory.

Henry, J. J. (2000). *Evaluation of pavement friction characteristics.* NCHRP.

Highways England, Transport Scotland, Welsh Government, Department for Infrastructure. (2019). *CS 228 Pavement inspection and assessment - Skidding resistance.* London: Highways England.

Nordström, O., & Åström, H. (2001). *Upgrading of VTI friction test vehicle BV12 for combined braking and steering tests under aquaplaning and winter conditions .* Florence: 2nd International Coloquium on Vehicle Tyre Road Interaction .

NSW Roads and Maritime Services. (2013). *QA Specification R423 Measurement of surface friction by sideways-force coefficient routine investigation machine (SCRIM).* NSW Roads and Maritime Services.

Roe, P. G., & Dunford, A. (2012). *PPR564 The skid resistance behaviour of thin surface course systems.* Wokingham: TRL.

Sanders, P. D., Militzer, M., & Viner, H. E. (2017). *PPR815 Better understanding of the surface tyre interface.* Wokingham: TRL.

Characterising the measurements made by sideways-force skid resistance devices

The effective management of road surface skid resistance properties is critical for providing a safe means of road travel. The measurement of skid resistance is a key component in the effective management of road surface skid resistance. In the UK the skid resistance properties of the trunk road network are assessed annually using devices utilising the sideways-force measurement principle, the Sideways-force Coefficient Routine Investigation Machine (SCRIM).

Currently little is understood about the fundamental measurement characteristics of SCRIM. The relationship between the skid resistance properties of the UK road network, and the friction characteristics exploited by vehicles conducting various manoeuvres, is, by extension, also not fundamentally understood. In generating this fundamental knowledge, there therefore exists major potential benefits in terms of reducing vehicle incidents, reducing cost, and maximising the efficiency of road management.

This document presents the results of a desk study into the properties of SCRIM devices with the goal of characterising the measurement properties of SCRIM in terms of the fundamental properties of skid resistance devices, namely; the percentage slip and operational speed. Four equally valid characterisations were generated, and an outline experimental procedure for determining that which is related to SCRIM devices is presented.

Other titles from this subject area

PPR737 Performance review of skid measurement devices. Sanders P D, Brittain S and Premathilaka A. 2015

PPR850 Optimisation of water flow depth for SCRIM. Brittain S, Sanders P D and Viner H E. 2017

PPR702 Comparison of SCRIM and SKM sideway-force skid resistance devices. Brittain S. 2014

PPR815 Better understanding of the tyre surface interface. Sanders P D, Militzer M and Viner H E. 2017

TRL
Crowthorne House, Nine Mile Ride,
Wokingham, Berkshire, RG40 3GA,
United Kingdom
T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

ISSN 2514-9652

ISBN 978-1-913246-42-6

PPR957