TENDER FOR:
Study on wet grip of worn tyres

Procedure nº: 899/PP/GRO/IMA/21/21211/12118 for the conclusion of a specific contract in application of the Framework Contract No 850/PP/2020/FC with reopening of competition

Interim Report

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Acronyms and abbreviations

Acronym	Meaning
3PMSF	*3 Peak Mountain Snow Flake*
ACEA	*European Automobile Manufacturers Association*
ASTM	*American Society for Testing and Materials*
C1	*Tyres for vehicle category M1 / O1 / O2*
C2	*Tyres identified by a load capacity index in single formation lower or equal to 121 and a speed category symbol higher or equal to "N", used in the following vehicle categories: M2 / M3 / N / O3 / O4*
C3	*Tyres identified by a load capacity index in single formation higher or equal to 122; or a load capacity index in single formation lower or equal to 121 and a speed category symbol lower or equal to "M", and used in the following vehicle categories: M2 / M3 / N2 / N3 / O3 / O4*
DG GROW	*European Commission's Directorate for the Internal Market, Industry, Entrepreneurship & SMEs*
ETRTO	*The European Tyre and Rim Technical Organisation*
EU	*European Union*
GIDAS	*German In-Depth Accident Study*
GRBP	*Groupe Rapporteur Bruit et Pneumatiques, Working Party on Noise and Tyres*
IWG WGWT	*Informal Working Group - Wet Grip of Worn Tyres*
MTD	*Macro texture depth*
NASA	*National Aeronautical and Space Administration*
NHTSA	*National Highway Traffic Safety Administration*
NR	*Natural rubber*
SBR	*Styrene-butadiene rubber*
SRTT	*Standard reference test tyre*
TTI	*Texas Transportation Institute*
TWI	*Tread Wear Indicators*
VTI	*Swedish National Road and Transport Research Institute*
VUFO	*Verkehrsunfallforschung an der TU Dresden GmbH*

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Executive Summary

Context and objectives

The current document contains the first interim report of the work done in the tender *“Study on wet grip of worn tyres”* (tender nº 899/PP/GRO/IMA/21/21211/12118), in application of the Framework Contract No 850/PP/2020/FC.

The aim of this project is to provide DG GROW a deeper knowledge of the behaviour of C2 and C3 tyres regarding wet grip on worn condition compared to the performance of the same tyres in new condition. C1 tyres have been also included in the study to propose possible refinements of existing requirements.

Abstract of the report

This part of the project consists of gathering information and objective data to make a proposal of testing method regarding the wet grip performance of tyres in worn state.

The behaviour and performance of a tyre is something difficult to understand and predict. In terms of safety, the performance of a tyre in wet conditions is one of the most important topics, and it is believed that this performance is not the same during the lifecycle of a tyre. In this deliverable an objective evaluation of all the factors related to the performance of a tyre under wet conditions is shown (literature review and questionnaire). In the following pages, a status review for task 2 is shared as advancement of the next report. Then, some encountered problems during the realization of the first task and its countermeasures are shared. Finally, the description of the consumed budget shown.

1 Introduction

The aim of this first interim report is to show the results obtained, until now, with the achievement of Task 1 of the Study on wet grip of worn tyres project. The Task 1 has been focused on the gathering and review of information, and it has been divided into 2 subtasks:

In the first subtask, a state-of-the-art literature review related to C1, C2 and C3 tyres' wet grip at worn state has been done to get the necessary knowledge on the topic of the project to proceed successfully with it.

It also contains a summary of conclusions from the different Informal Working Group – Wet Grip of Worn Tyres (IWG WGWT) meetings.

For the second interim report, external information and opinions have been sought through a questionnaire sent to different sectors in the industry to define the most common type of C2, C3 tyres in the European market, as well as C1 tyres, and collect all the relevant information available related to C1, C2 and C3 tyres' wet grip performance at worn state.

A complete description of the tyre sizes selected for this study, based on the information obtained from the questionnaire, and a test method approach for Task 2 and Task 3 is presented.

The budget spent until December 2021 for each task (over the total budget) is also defined and explained.

2 Literature review

2.1 Background

Safety on wet roads is a major concern for drivers. One of the contributing factors to wet-road incidents is the lack of friction between the tyre and pavement, thereby leading to skidding accidents and possibly hydroplaning. The direct interrelationship of grip level and road safety is evident in actual accident statistics. In a research study [1], the correlation between grip level and the probability of accidents is plotted in Figure 1, indicating a lower grip level increases the probability of accidents. Furthermore, evidence from rainfall data shows how infrequently water film greater than 1 mm occur, and accident records confirm that most accidents involving skidding occur on lightly wetted roads. Hosking [2] reported that an improvement in the average skid resistance level of 10% could result in a 13% reduction in wet skid rates. These studies show the importance of adequate frictional characteristics between the tyre and pavement surface and its association with the risk of hydroplaning occurrences.

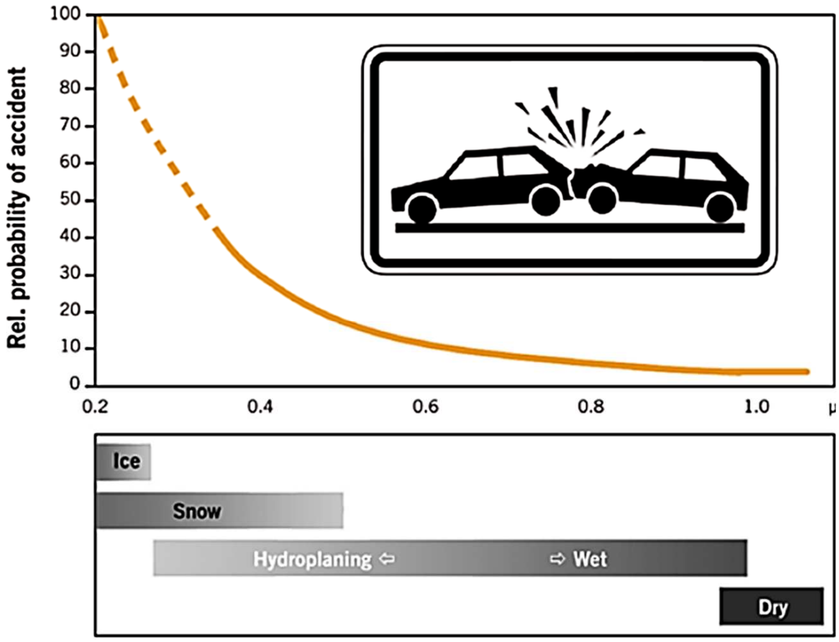


Figure 1 The probability of an accident increases disproportionally high with decreasing grip level [1].

A recent study done by VUFO (Verkehrsunfallforschung an der TU Dresden GmbH) [3] laboratory in Dresden, Germany, scientifically estimated the share of hydroplaning as an accident cause for European countries, as shown in Figure 2. It is observed that 62% of the wet accidents are tyre grip relevant, which are attributed to grip and partial hydroplaning situation, while 0.6% of the wet accidents are considered as a result of full hydroplaning. This means that full hydroplaning does exist on the European roads, but with a very infrequent occurrence.

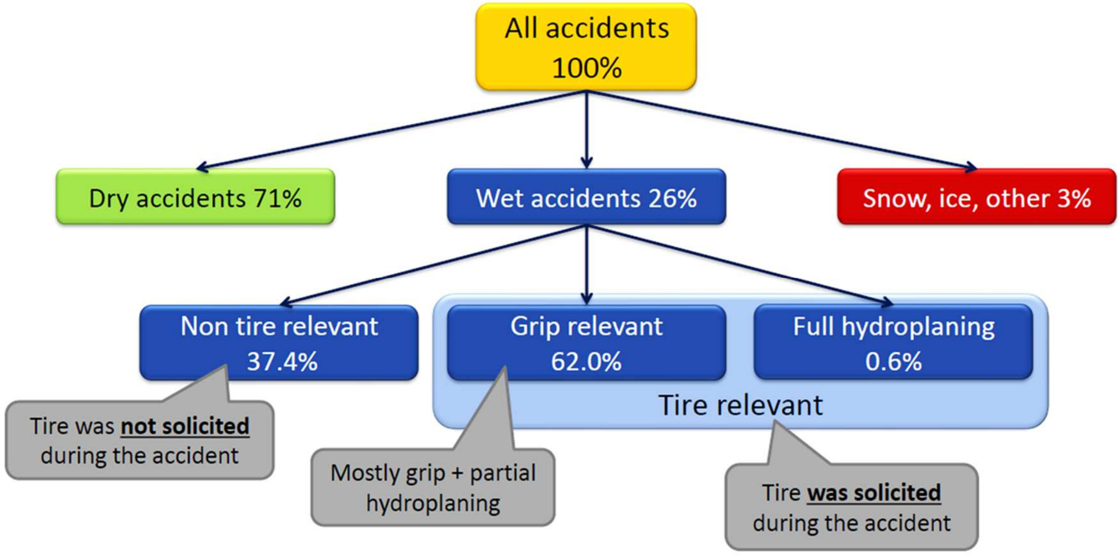


Figure 2 VUFO study on the share of wet accidents caused by hydroplaning [4].

The occurrence of road accidents is further related to tyre usage according to the accident records from the GIDAS (German In-Depth Accident Study) [3] database, and a study presented by NHTSA (U.S. National Highway Traffic Safety Administration) [5]. In GIDAS, tests are done with various temperature and road surface conditions that are relevant for tyre grip performance of summer and winter tyres, respectively. The population of specific tyre conditions in accidents is compared to a reference group that is assumed to be representative for vehicles on the road in general to assess the potential accident reduction. A similar approach has been used in NHTSA study, it relates the tyre tread depth, inflation pressure and existence of damages to accidents in general. Both studies conclude that maintaining a tread depth above the legal requirement of 1.6 mm will reduce accidents, which are assumed to be mainly grip accidents on wet and snow-covered roads. Passenger cars with tyres that have a tread depth below the legal required value of 1.6 mm are significantly more involved in accidents on wet roads. The NHSTA study indicates a reduction in accident probability of 86% when using tyres with adequate tread depth. The conclusion from these studies confirm that increased tread depth generally will improve the tyre grip level (and safety) on wet roads and snow-covered roads.

Today, wet grip labelling [7] has been implemented for new tyres, which gives consumers reliable information on the ability of tyres to stop in a limited distance in defined conditions, see in Figure 3. For instance, tyres with A label will have the shortest braking distances on wet roads, which is a key safety indicator when driving in rainy weather. However, during the tyre life, grip level evolves. Tyres are labelled based on the test results at new state, in which the dry grip is in its worst, but the wet grip in its best. Moreover, research study [6] shows that the percentage of overworn tyres on the roads is showing an increasing trend in recent years, see Figure 4. The lacking information on the wet grip of these worn tyres can lead to catastrophic safety concerns. Hence, it is an important task to deliver such message to customers and tyre manufacturers, so that both parties can be aware of the gradual evolution of the tyre performance throughout its lifespan. More importantly, proper actions can then be taken to avoid any further safety issues.

Table 1 Summary of identified safety potential by improving tyres [6]

Accident condition	Inadequate tyre	Improved tyre	Accident probability reduction / ARR*)	Source
Grip accidents on dry road, below zero	Summer tyre	Winter tyre	45.8% / 0.816	GIDAS
Grip accidents on snow covered roads	Tread depth Winter tyre below 4 mm	Tread depth Winter tyre 4 mm or more	56.1% / 1.147	GIDAS
Grip accidents on wet roads or snow covered roads (assumed)	Tread depth at or below 1.6 mm	Tread depth above 1.6 mm	84.1% / 3.722	NHTSA
Tyre related accident (assumed mainly tyre blowout failure)	Incorrect inflation pressure	Correct inflation pressure	35.1% / 0.446	NHTSA
Tyre related accident (assumed tyre blowout failure)	Damage	No damages	85.9% / 5.194	NHTSA

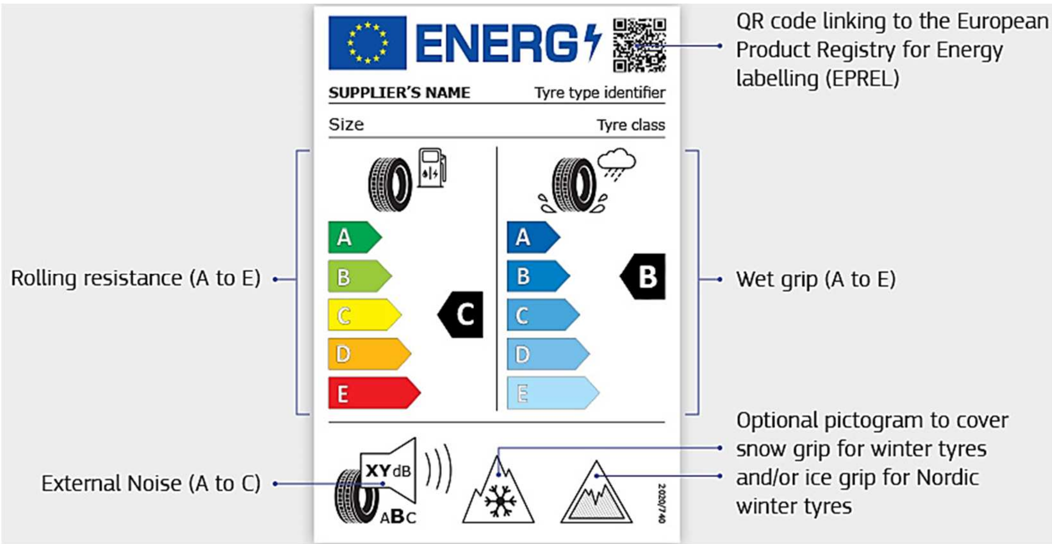


Figure 3 New EU tyre labelling rules apply from 1 May 2021 [7].

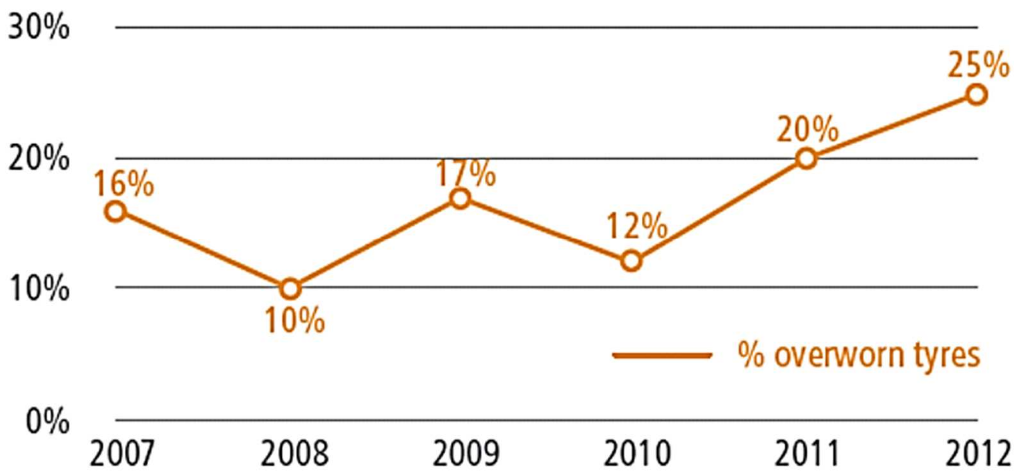


Figure 4 Share of over worn tyres assessed from roadside inspections in multiple EU member states in 2007-2012 [6].

With a shared concern of such circumstance, the Informal Working Group (IWG) on Wet Grip of Worn Tyres (WGWT) is established to evaluate the need of new requirements regarding wet grip at worn state tyres and the study is still ongoing. The group is aiming to make a proposal for testing method and new limits. The priority is given to C1 tyres, and followed by C2, C3 tyres. As aforementioned, the current regulation evaluates the wet grip of new tyres, including C1, C2 and C3 tyre types. During the 69th GRBP (Groupe Rapporteur Bruit et Pneumatiques, the Working Party on Noise and Tyres) meeting in 2019, it was pointed out that the wet grip performance of tyres decreases as the tyre wears out, so the current testing (performed on new tyres) does not represent the worst-case situation and the real usage of such tyres. The current progress of the IWG WGWT sessions

[8] indicates that the wet grip performance varies drastically for new and worn C1 tyres, as can be seen in Figure 5. Hence, it is imperative to establish a new test methodology that can further assess the wet grip performance of worn C1 tyres. However, in the case of C2 and C3 tyres, there is currently a discussion over the need of new requirements for wet grip on worn state for C2, C3 tyres, as commercial vehicle tyres may have a different behaviour when being in worn state if compared with the behaviour of C1 tyres. Preliminary results show no significant variation between new and worn C2 and C3 tyres. It is suggested that the wet grip performance of the worn C2 and C3 tyres can be predicted from the new tyres. The current study will gather information and objective data to assess the deterioration of wet grip index for C2 and C3 class tyres from new to worn state. Additionally, further assessment will be performed on the newly proposed testing method for C1 tyres at worn state.

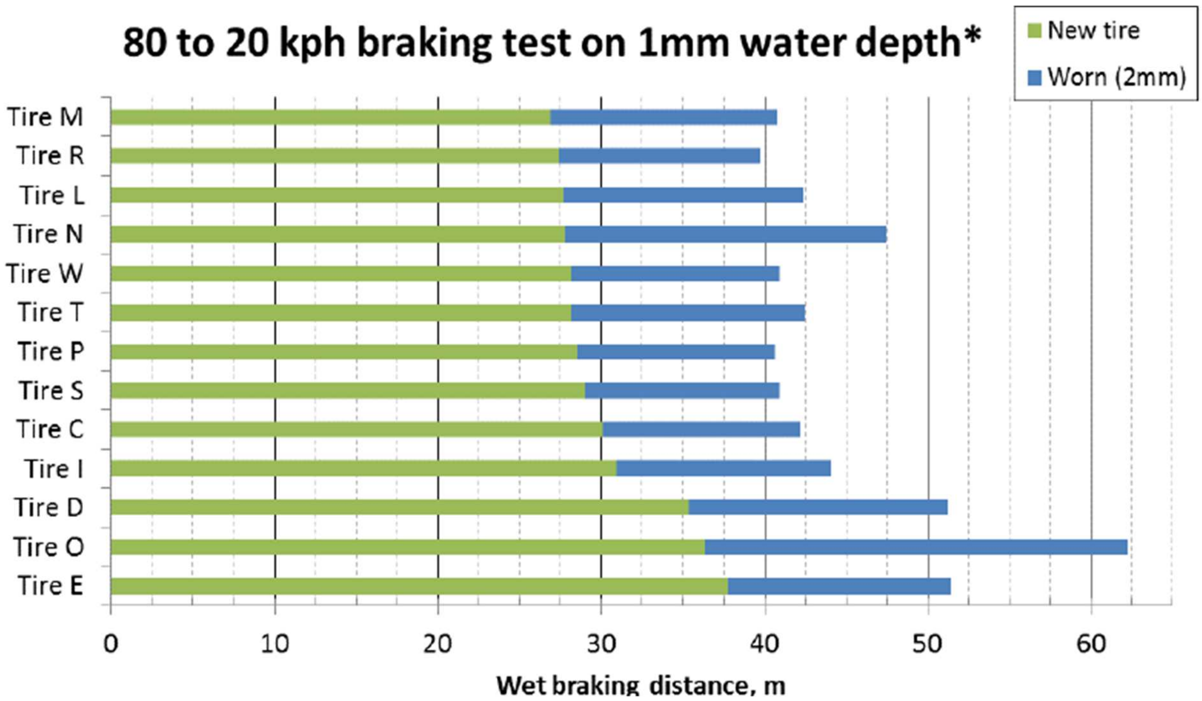


Figure 5 Variation of breaking test results between new and worn C1 passenger tyres.

2.2 Wet Grip Mechanisms

Research on pavement skid resistance started in the 1920s and since then, it has mainly focused on the following aspects: measurement and prediction of pavement dry and wet skid resistance, and methodology development to reduce wet weather accidents on motorways. The term "wet skid resistance" is rather vague, since it depends on various parameters such as the type of contaminant, the depth of fluid, etc. The occurrences of wet weather accidents, from the perspective of pavement surface characteristics, could be attributed to either poor skid resistance offered from the tyre-fluid-pavement interaction or hydroplaning. In this chapter, wet grip mechanism will be discussed. Moreover, further focus will be given on the evolution of tyre wet grip performance from new to worn state.

There are two mechanisms contributing to the wet grip performance of tyres, namely, rubber friction and hydroplaning, as seen in Figure 6. As indicated in Figure 2, wet skid situation involves grip and partial hydroplaning contribute to the highest percentage of wet accidents when the tyre loses some part of the contact patch and maintains the other. The lost part of the contact patch is attributed to the hydroplaning mechanism, while the grip mechanism determines the contact with the maintaining part [9].

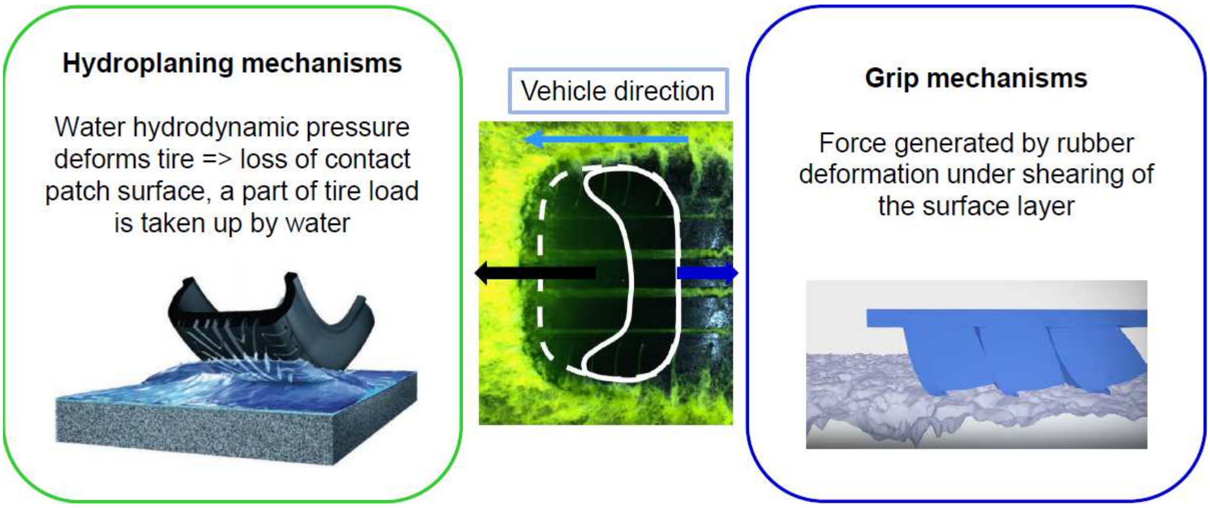


Figure 6 Wet braking: two main mechanisms [9].

2.2.1 Rubber friction on wet surface

Rubber material demonstrates unique viscoelastic properties. There are two major components that contribute to rubber friction: adhesion and hysteresis [10], [11]. Adhesion friction is the adhesive force induced by the Van der Waals interactions between rubber and road surfaces. On the other hand, the hysteresis frictional force is originated by the viscoelastic energy dissipation as rubber slides over rough asperities [12]. The subject of friction between tyres and wet road surfaces is more complex than that of dry roads. The presence of water interferes with friction mechanisms. The effective friction under wet condition is controlled by the water depth encountered at the tyre/road interface and its progressive removal throughout the region of ground contact. During this process, the molecular adhesion is not fully functioned as the rubber and road surface are not in direct contact (<10^{-6}m) [13], thus, the adhesion friction solely arises from localized areas where dry contact is established. As for the hysteresis component, the water depth can affect the energy dissipation induced by the bulk rubber deformation over rough asperities. If the water depth exceeds the height of the road surface textures, the energy dissipation would be defective. Therefore, maintaining grip on wet surfaces involves dispersing the water to restore dry contact between the tread and the road. The relative contribution to these terms is determined by the interactions of the different features of tyre and road surfaces, which can provide means of removing water within the contact area. Hence, it can be concluded that the effectiveness of the adhesion component depends upon the available drainage capacity at the tyre/road interface [14].

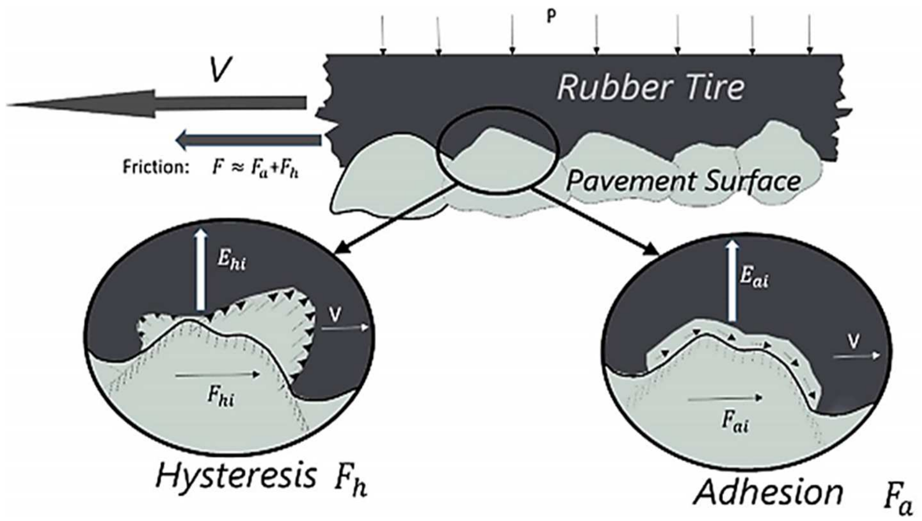


Figure 7 Two main components of rubber friction: adhesion and hysteresis [11].

Furthermore, it is reported that the adhesion component is reduced when particles or water film are present at the contact surface [15]. The difference between the effective friction coefficient of dry and wet surfaces is reported to be 20%–30% [16], as shown in Figure 8. A theoretical explanation on friction in tyre-pavement interaction is offered by Moore [12]. In the dry case, since the interfacial area has a maximum value, the mechanism of molecular-kinetic bonding is most widespread. However, upon wetting, the interfacial film of fluid is spread uniformly, and this effectively suppresses the surface roughness, thereby reducing the adhesion component to a very low value. On the other hand, Persson [17], [18] proposed the concept of "sealing effect", which is exerted by rubber on substrate "pools" filled with water, to further interpret the variation in grip performances on dry and wet surfaces. The theory states that on dry surfaces, the rubber can be in direct contact with the microscale asperity of the road surface, consequently, frictional force is developed, see Figure 9 (a). While, on wet surfaces, the water effectively smoothens the substrate, forming a boundary between the tread and the road surface, thus, reducing the major friction contribution induced by the viscoelastic deformations of the rubber by the short-wavelength roughness (microtexture), as seen in Figure 9 (b).

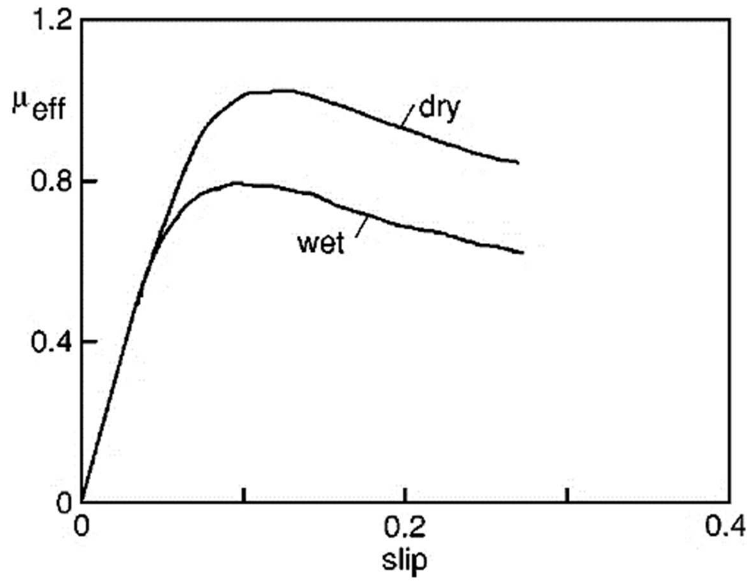


Figure 8 A typical measured effective friction coefficient as a function of slip for dry and wet road surface [18].

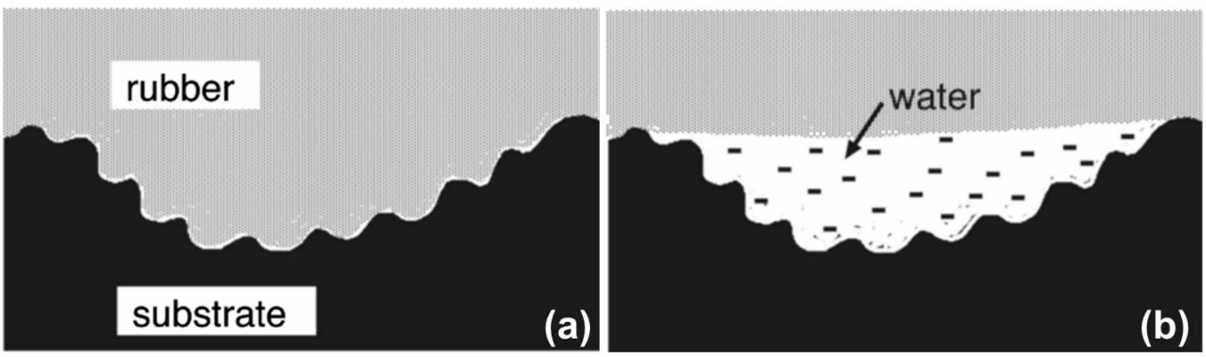


Figure 9 A rubber block sliding on a rough hard substrate. (a) The rubber penetrates into a large substrate valley and explores the short-wavelength roughness in the valley. The pulsating rubber deformations induced by the short-wavelength roughness contribute to the friction force. (b)On a wet substrate the water

trapped in the large valley forms a pool preventing the rubber from penetrating into the valley. It will hence remove the valley contribution to the friction force. This rubber sealing effect reduces the sliding friction [18].

2.2.2 Hydroplaning

Hydroplaning is a unique situation in wet pavement conditions when the tyre is lifted off the pavement surface by hydrodynamic forces. As the tyre gradually loses contact from the surface, the wet skid resistance drops to extremely low or near-zero values [19]. In order to better understand the hydroplaning mechanism, the three-zone concept should be introduced. The three-zone concept is proposed by Gough [20] on the basis of the lubrication theory (schematic presentation shown in Figure 10) to characterise the ground contact area of a tyre moving on a wet surface. The concept is further applied by Moore [21] to cover the case of a locked sliding tyre, as illustrated in Figure 11. This conceptual model has been useful to understand the effect of water and travel speed on tyre wet grip performance. The zones are described as follows:

1. Zone A, sinkage zone. In this forward region of the contact area, the tyre encounters the bulk of water covering the road. The bulk of the surface water is displaced away from the path of the tyre, or it can be forced into the grooves or voids of the road and tyre surfaces. Hence, this zone can also be called the Squeeze-Film Zone. The effective friction coefficient in this zone is considered as zero (corresponds to the hydrodynamic lubrication zone in Figure 10), indicating the tyre has lost contact with the pavement and is riding on a wedge of water. The length of Zone A represents the time required for the tyre at this speed level to expel bulk water from under the footprint
2. Zone B, transition zone. Following Zone A, in this region partial breakdown of the water film takes place. This means a mixed lubrication regime exists, indicating a transition from a lubricated condition to physical dry contact between the tread rubber and road asperities (corresponds to the mixed lubrication zone in Figure 10). Hence, the tyre is partially contacting the peaks of the surface asperities and partially bearing on a thin layer of water. The effective friction coefficient value in this region ranges between fully lubricated and dry conditions, depending upon a variety of factors. The length of Zone B represents the time

required for the tyre to squeeze out the residual thin water film remaining under the footprint after the bulk water has been removed.

3. Zone C, actual contact zone. In this region the lubricant water film has been totally or substantially removed. The tread rubber is in essentially dry contact with the peaks of the pavement surface texture. The principal component of the tyre to road friction coefficient is developed in this zone. Since water cannot develop shear forces of appreciable magnitude, it is only in Zone C (essentially dry region) that traction forces for steering, decelerating, and accelerating a vehicle can be developed between the tyre and the pavement. The ratio of the actual contact area (Zone C) to the total tyre footprint area (Zone A + Zone B + Zone C) multiplied by the friction coefficient the tyre develops on a dry pavement yields the friction coefficient the tyre can develop for this flooded pavement and speed condition [22].

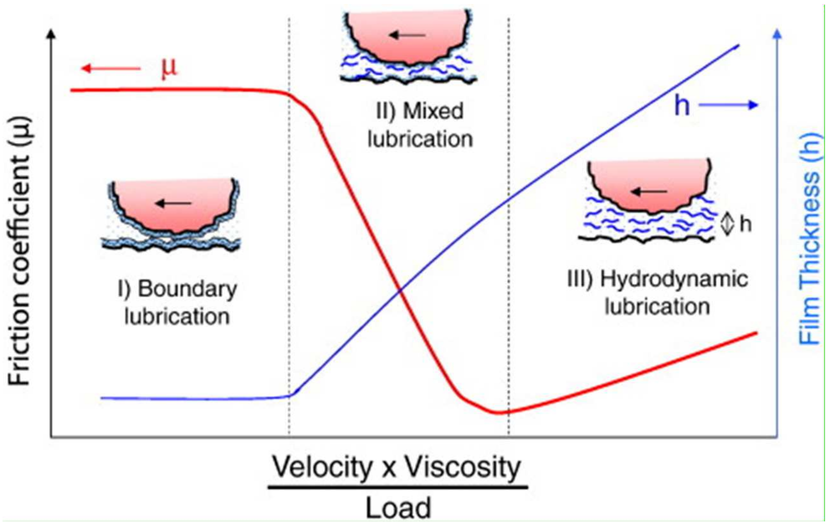


Figure 10 Friction coefficient plotted as a function of fluid viscosity and shear velocity divided by load (Stribeck curve) with corresponding lubrication film thickness. The schematic shows boundary, mixed, and hydrodynamic lubrication regimes [23].

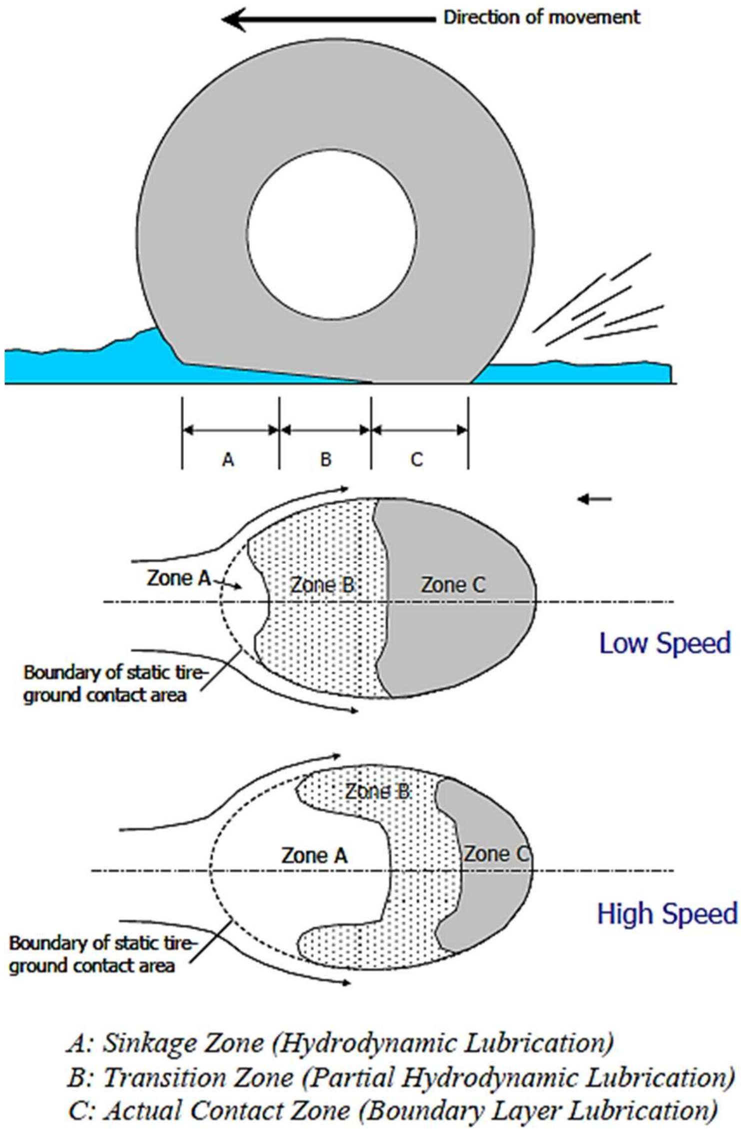
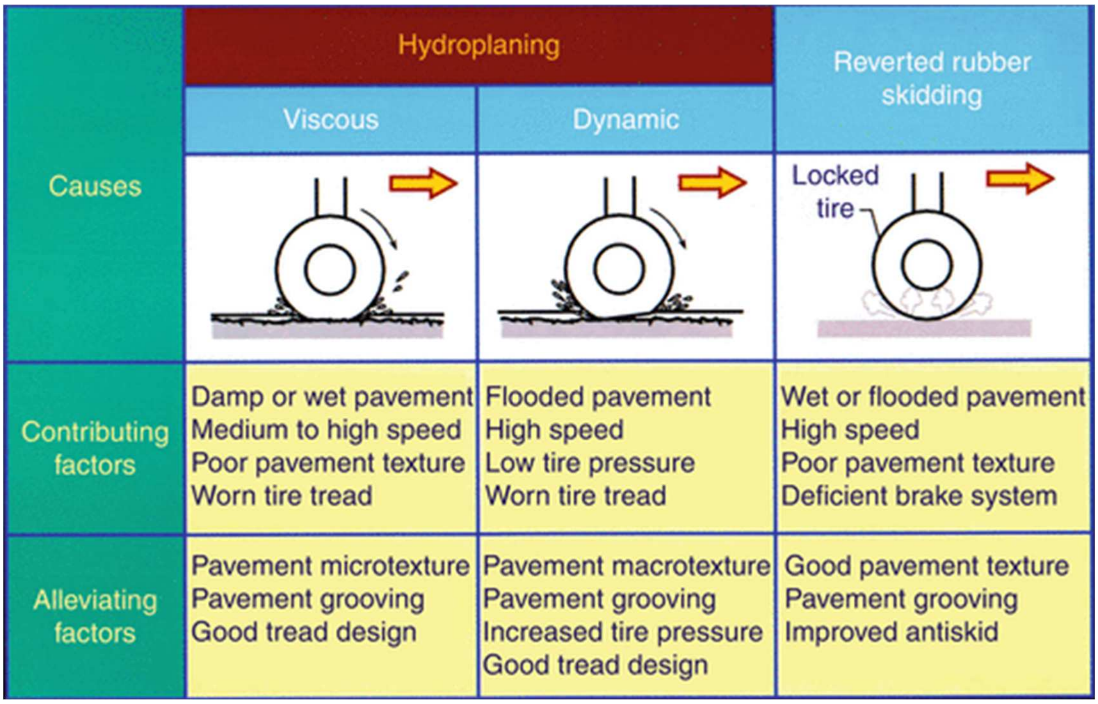


Figure 11 Tyre sliding on wet pavement surface, three-zone concept [21], [24].

It should be noted that hydroplaning occurs when the total hydrodynamic lift force acting on the tyre equals the sum of the weight of the tyre plus the downward vertical loading upon it [25]. As either speed or water film thickness increases, the fully developed Zone A would replace both Zone B and Zone C and the tyre would eventually appear as skidding on the film of water [26].

There are three types of hydroplaning: (a) viscous hydroplaning, (b) dynamic hydroplaning, and (c) tread rubber reversion hydroplaning [27]–[30], as shown in Figure 12. Viscous and dynamic hydroplaning are of concern for vehicle motorway operations on wet pavements that will be further discussed in the following sections. While tread rubber reversion hydroplaning is associated mainly with aircraft tyres under heavy braking that results in a prolonged locked-wheel skid. During this process, the heat is generated to cause the rubber in contact with the runway to revert to its original uncured state (‘melting’) [27].



	Hydroplaning – Viscous	Hydroplaning – Dynamic	Reverted rubber skidding
Causes			Locked tire
Contributing factors	Damp or wet pavement Medium to high speed Poor pavement texture Worn tire tread	Flooded pavement High speed Low tire pressure Worn tire tread	Wet or flooded pavement High speed Poor pavement texture Deficient brake system
Alleviating factors	Pavement microtexture Pavement grooving Good tread design	Pavement macrotexture Pavement grooving Increased tire pressure Good tread design	Good pavement texture Pavement grooving Improved antiskid

Figure 12 Principal causes of wet pavement tyre friction loss [30].

2.2.2.1 Viscous hydroplaning

Viscous hydroplaning is a phenomenon that takes place when vehicles operating even at low speed on wet pavements with little or no microtexture [25], [31] as commonly seen on basalt tiles. It results from a thin water film existing cohesively between the tyre and the pavement surface due to the insufficient microtexture to penetrate and diffuse the water layer. Hence, viscous hydroplaning is often referred as thin-film hydroplaning. It is reported that viscous hydroplaning can occur at any speed and with any fluid film depth. It can happen at very low vehicle speed, such as the speeds typical of city driving. Therefore, sufficient microtexture on pavement surfaces is beneficial to prevent viscous hydroplaning.

The most critical factors of influence during viscous hydroplaning are the viscosity of the fluid, tyre condition and the quality of the pavement surface. Viscous hydroplaning will not occur unless the tyre tread depth is very shallow, and the pavement has a "polished" quality. Even though viscous hydroplaning is considered as a rare event characterized by a bald tyre operating on a mirror-smooth surface [27], however, this can be a valid condition for hydroplaning of worn tyres.

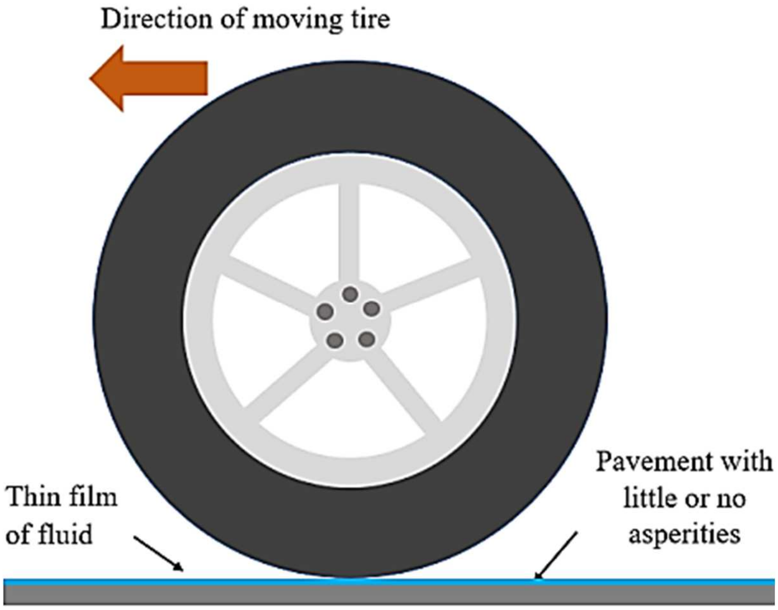


Figure 13 Viscous hydroplaning (thin-film hydroplaning) [32].

2.2.2.2 Dynamic hydroplaning

Dynamic hydroplaning results from uplift forces generated by the water wedge sufficient to separate the vehicle tyres from the pavement surface [25], [29], as shown in Figure 14. The risk of dynamic hydroplaning is high when fluid inertial effects dominate, such as the thick water film found on a flooded pavement. Dynamic hydroplaning can only occur when the water accumulation encountered by the tyre exceeds the combined drainage capacity of the tyre tread and the pavement macrotexture for a given speed [28], [33]. For extreme conditions with bald tyres on smooth, polished pavement surfaces, it is found that the water depth needed for a dynamic hydroplaning to occur can be as little as 0. 76 mm (0.03 in.) [33]. Hence, worn tyres can be more prone to dynamic hydroplaning. Additionally, the vehicle speed must be sufficiently high so that the inertial force developed in the fluid film is comparable to the tyre inflation pressure. This causes the tyre surface to buckle, thereby produces a large region of fluid capable to support the loaded tyre.

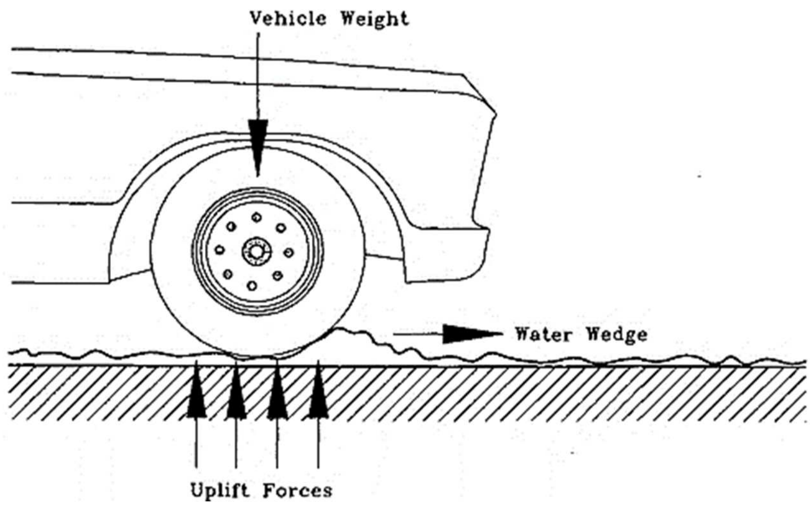


Figure 14 Dynamic hydroplaning [27].

Furthermore, a hydroplaning tyre may experience either partial or full dynamic hydroplaning. With partial dynamic hydroplaning, only part of the tyre rides on the surface of the water, maintaining the contact between a portion of the tyre footprint and the pavement surface. As for the full dynamic hydroplaning, it refers to a complete separation of the tyre from the pavement surface by the liquid layer. Hence, full dynamic hydroplaning indicates a greater hazard than partial dynamic hydroplaning as the vehicle steering and braking would be impaired due to the loss of contact [27].

In terms of the skid resistance mechanisms highlighted in the previous section, dynamic hydroplaning is said to occur when zone C and Zone B disappears, and the bulk water penetrates the entire footprint (Zone A). This creates a situation where the vehicle experiences low (or near-zero) coefficient of friction and the uplift force in the fluid film is sufficiently large to cause a loss of contact between the tyre and the pavement.

Vehicle speed and water film thickness are the governing factors for partial and full dynamic hydroplaning phenomenon. It is difficult to identify with precision the speed at which these phenomena occur, since many other variables, such as the roadway surface characteristics, the tyre condition, and the driving environment, etc., must be taken into consideration. The typical motorway operating speeds and water depths may give rise to partial dynamic hydroplaning, whereas higher vehicle speeds and a very thick water film, such as that produced by high-intensity rainfall, are essential conditions for full dynamic hydroplaning to occur

[34]. For most situations, the vehicle speed at which full dynamic hydroplaning is observed would be considered unsafe or not prudent for the amount of water on the roadway, assuming that the tyre tread is sufficient and that the tyres are properly inflated.

2.3 Wet Grip of Worn Tyres

The topic of wet grip of worn tyres has been discussed in early studies since the 1960s [14], [26], [28], [29], [35]–[44]. The wet grip performance is found to degrade with the tyre wear. Hence, it is important to evaluate the grip performance of worn tyres on wet surfaces as it is the principal performance that degrades as the tyres wear out. Dry grip performance, on the other hand, improves with wear, generally from 5% to 10%, as shown in Figure 15. It is recognized that the decrease in friction under wet conditions before the hydroplaning occurs is the most significant wet traction issue [14]. Full hydroplaning, on contrary, is not a major cause of skidding on wet roads [4], [14]. As for the tyres in worn state, the loss of tread pattern and tread depth adversely affect the drainage capacity of the tyre, which directly leads to the worsened friction development. It is stated that hydroplaning occurs with greatest facility when smooth or well-worn tyres operate on intrinsically smooth fine texture surfaces. Moreover, the vehicle speed and water depth for hydroplaning to occur on worn or smooth tyres are found to be much lower than those for new tyres [28].

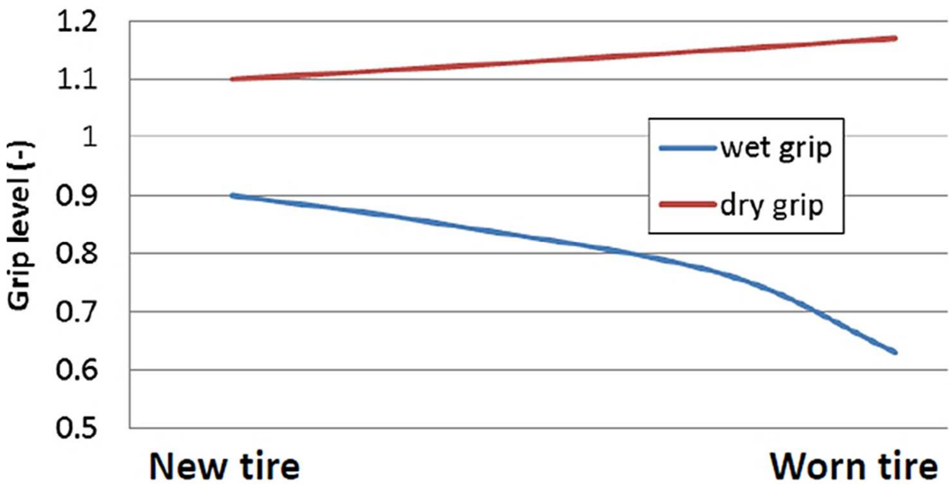


Figure 15 Evolution of grip through tyre life [9].

Experimental study [28] is carried out to assess the locked wheel braking force coefficient of the new and worn tyre for speeds up to 80 mph. The tests are performed under water depth representing normal rainfall (0.04-0.06 in. water film) and "flooded" road conditions (0.1-0.15 in. water film), as seen in Figure 16. The results are well aligned with the tests carried out on the cornering machine in full hydroplaning conditions in Figure 17. It can be deduced that tyre wear induced by normal usage leads to reduction of the tread depth, thus, decreasing the overall volume of the drainage channels. The test results indicate that the effect of tyre wear is relatively small at low speeds except near the fully worn condition. As the speed increases, tyre wear results in a progressively greater reduction in wet grip performance, reaching the maximum effect in conditions involving hydroplaning. Additionally, Figure 18 also provides further information on the spin-down of the wheel near the hydroplaning limit. The more the tyre wears, the more spin-down takes place. It is also stressed that any slight irregular tyre wear can further detrimentally affect the deterioration of the tyre wet grip performance [45].

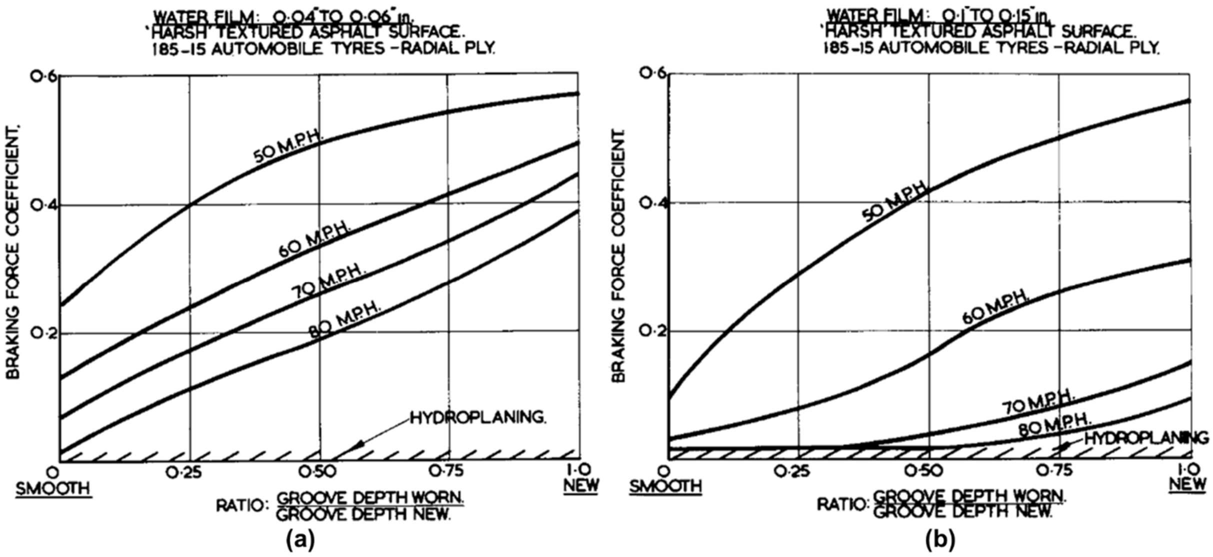


Figure 16(a) Effect of tread pattern groove depth on braking grip, normal wet road conditions; (b) Effect of tread pattern groove depth on braking grip, " flooded" road conditions [28].

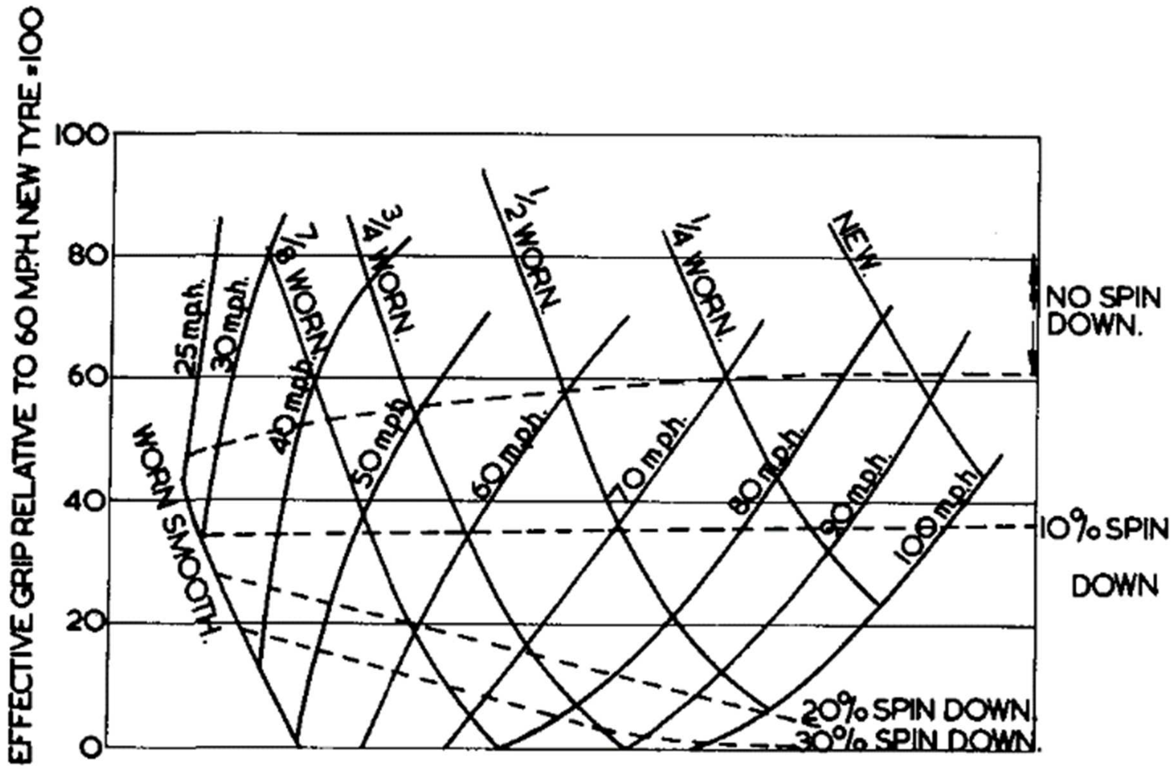


Figure 17 Effect of wear and speed on hydroplaning of multi-slotted radial ply tyre on smooth steel drum with 1 mm of water [28].

See previous comments on this, thin-film lubrication (viscous hydroplaning) is rare at normal vehicle operating speeds when rib tread tyres are used on wet rough-textured pavement surfaces. However, it can become a critical situation for smooth tread or excessively worn patterned tread tyres or rib tread tyres used on very smooth pavement surfaces. Thin-film lubrication does not require the presence of large fluid depths on pavements (the film thickness required is estimated to be less than 0.01 inch). It is suggested that full hydroplaning can occur at a speed that is at least 35% less than the speeds required for dynamic hydroplaning [29]. The same conclusion has been drawn in the research study [46] shown in Table 2. The worn tyres demonstrate much smaller ***μ*** values in comparison to new tyres under the same road conditions. The contact patch analysis shown in Figure 18 further validates the detrimental effect of worn tyres on wet grip performance.

More recent studies [9], [47]–[52] evaluated the contributions of the two wet grip mechanisms based on the states of the tyres, hereby referring to new or worn tyres. Braking tests have been carried out on new and worn tyres so that the failure mechanisms can be decomposed and quantified. The results indicate that for new tyres, wet grip performance is mainly contributed by the rubber friction mechanism. While in the case of worn tyres, both main mechanisms (rubber friction and hydroplaning) are present. The ***μ*** value obtained at low speeds reflects the friction potential of the tested tyres, while the decline of performance at higher speeds is attributed to hydroplaning mechanism, as seen in Figure 19. The analysis of the mechanism decomposition shows that the source of the performance decline from new to worn status varies greatly from tyre to tyre. Some tyres demonstrate most of the performance loss due to hydroplaning, some others due to the drop of rubber friction. Hence, it is concluded the performance drop induced by each mechanism is independent of performance at new state. This can be attributed to the loss of the tread pattern with tyre wear. Additionally, the tread mix can vary through the tread depth [9]. As for the tyre forces developed in new and worn states, studies on flat tracks in wet conditions were published to analyse longitudinal and lateral forces generated by tyres with different tread depths at various speeds and water depths [51], [52]. The results demonstrate that the longitudinal and lateral forces developed by the worn tyres are significantly lower than those of the new tyres at high speeds. Hydroplaning of worn tyres is seen as a feasible explanation for the decrease of performance between the two states.

Table 2 Friction quotient values at different speeds [46].

Vehicle Speed(*km/h*)	Tire condition	Road conditions				
		Dry	Wet	Rain (water<1*cm*)	Havy rain (water<2*cm*)	Ice
Coefficient of static friction						
50 *km/h*	New	0.85	0.65	0.55	0.52	<0.1
	Used	1.1	0.53	0.41	0.25	
90 *km/h*	New	0.82	0.62	0.32	0.06	
	Used	0.95	0.21	0.11	0.06	
130 *km/h*	New	0.75	0.43	0.23	0	
	Used	0.9	0.22	0.11	0	

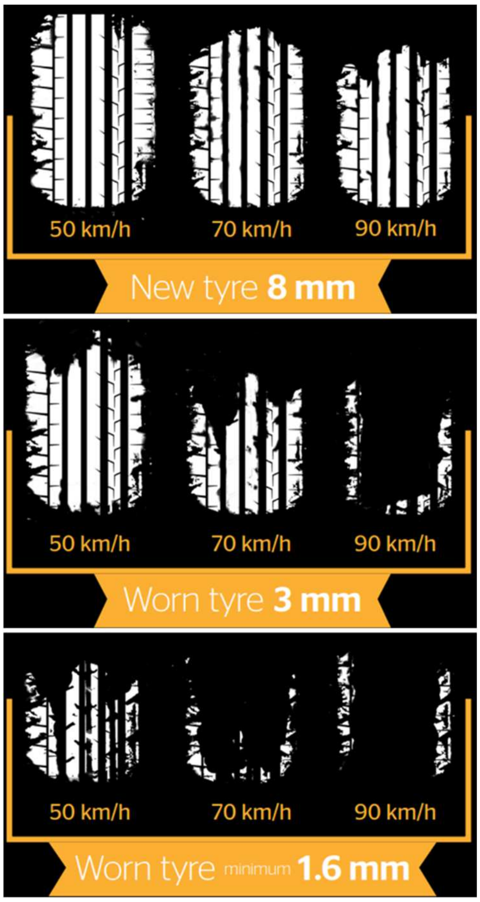


Figure 18 Reduction of tyre contact during hydroplaning [53].

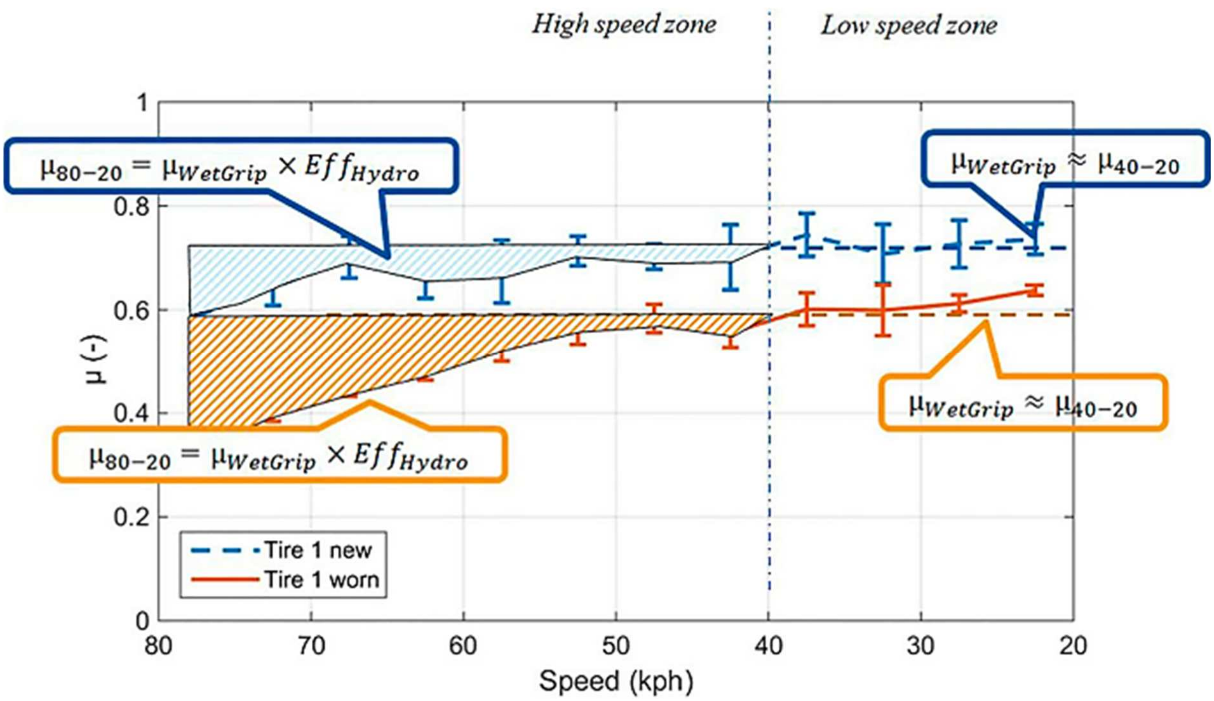


Figure 19 Decomposition of the performance in two mechanisms [50]. *Where μ80-20 is the overall μ deduced from the braking distance,* $\mu_{WetGrip}$ *is the average value of μ in the 40–20 km/h speed interval and* Eff_{Hydro} *is defined as the hydro efficiency of the tyre. The* Eff_{Hydro} *parameter quantifies the sensitivity of a tyre to*

hydroplaning, when Eff_{Hydro} = 1, the tyre is not sensitive to hydroplaning since it maintains its friction value above 40 km/h.

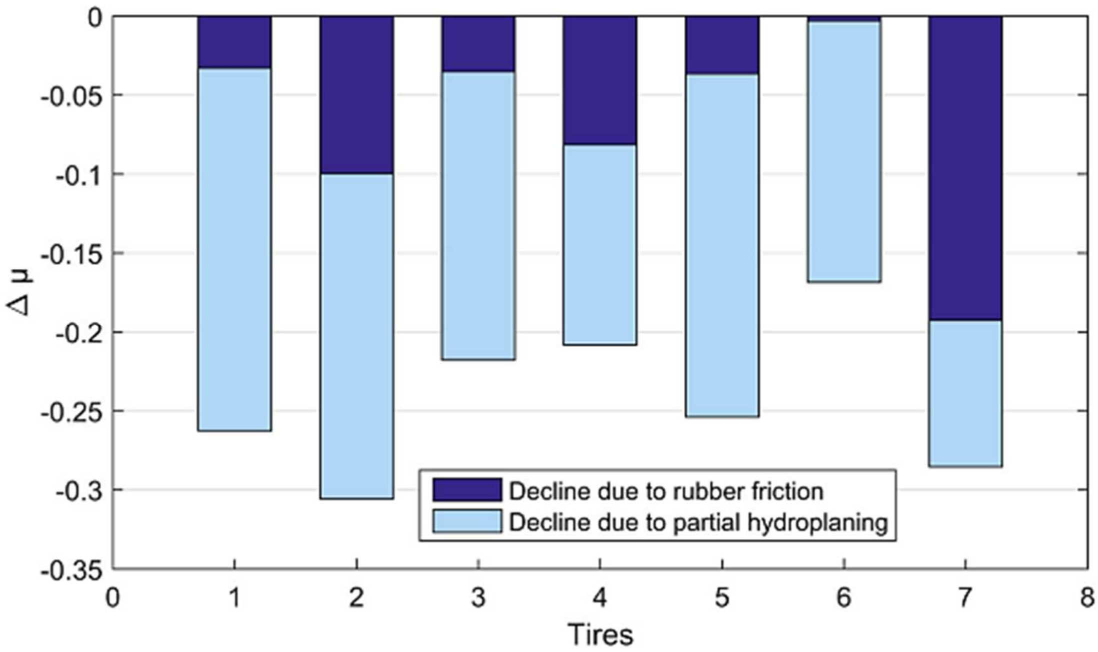


Figure 20 Performance decline from new to worn: share of rubber friction and hydro [50].

In summary, hydroplaning of new tyres, though very infrequent due to its limited occurrence in extreme cases of flooded road surfaces, is a danger to vehicle control on highways. However, a much greater danger exists for the vehicles fitted with smooth or well-worn tyres, since the requirements of speed and water depth for hydroplaning to occur are relatively much lower in comparison to new tyres. Past studies [24], [28] conclude that a large share of the responsibility for reduced incidence of hydroplaning must be shared by the vehicle users and the road engineers. Great caution is required for vehicle operators fitted with well-worn tyres when the most adverse wet road conditions described above are encountered. It should also be noted that one of the effective means of reducing hydroplaning would be achieved by road design to prevent the formation of thick water layers or large puddles on the road surface. Furthermore, regulations on the worn tyres in regard to wet grip performance can be imperative for further addressing this issue.

2.3.1 Variation among C1, C2 and C3 tyres

Most of the previous studies have focused on the analysis of hydroplaning for passenger car tyres (C1) while giving limited importance to bus (C2) and truck tyres (C3). Some early studies [36], [43], [54]–[57] evaluated the wet skid resistance of car, bus and truck tyres under various test conditions. It is reported that the difference in skid resistance between car and truck tyres is due to essentially three effects: the tread compound, the higher loads and inflation pressure of the truck tyres, and the tread pattern [54]. The NR (natural rubber) tread compound of truck tyres is found to demonstrate 10% to 15% lower μ values comparing to SBR (styrene-butadiene rubber, which is synthetic rubbers derived from styrene and butadiene) tread compounds when all other variables are kept constant [58]. Thus, when the tyres transform from new to worn, different performance is expected. As for the inflation pressure, Table 3 shows the variation in hydroplaning speed with respect to tyre types and corresponding inflation pressures. The tests are conducted with smooth tyres to eliminate the drainage effect induced by tread patterns. The results indicate that the hydroplaning speed increases with increasing inflation pressure, hence, truck and aircraft tyres demonstrate a much higher hydroplaning speed in comparison to car tyres [13]. Moreover, the design of tread patterns varies with tyre types due to the varied applications [37]. An example can be seen in Figure 21 of various tyres with different footprints. The tread pattern directly contributes to water drainage that is essential for the development of grip on wet surfaces and it will gradually disappear with tyre wear. Hence, the different design of tread patterns in different tyre types can potentially lead to varied trade-off of the tyre performance.

Table 3 Variation in hydroplaning speed with respect to tyre types [13].

Pressure (bar)	Tyre category*	Speed at which aquaplaning begins** (V_A, in km/h)
1	Car tyre (under-inflated)	50
2	Car tyre (properly inflated)	70
4	Light truck tyre	100
8	Truck tyre	140
16	Commercial aircraft tyre	200
32	Fighter plane tyre	280

* slick tyres
** on bituminous concrete

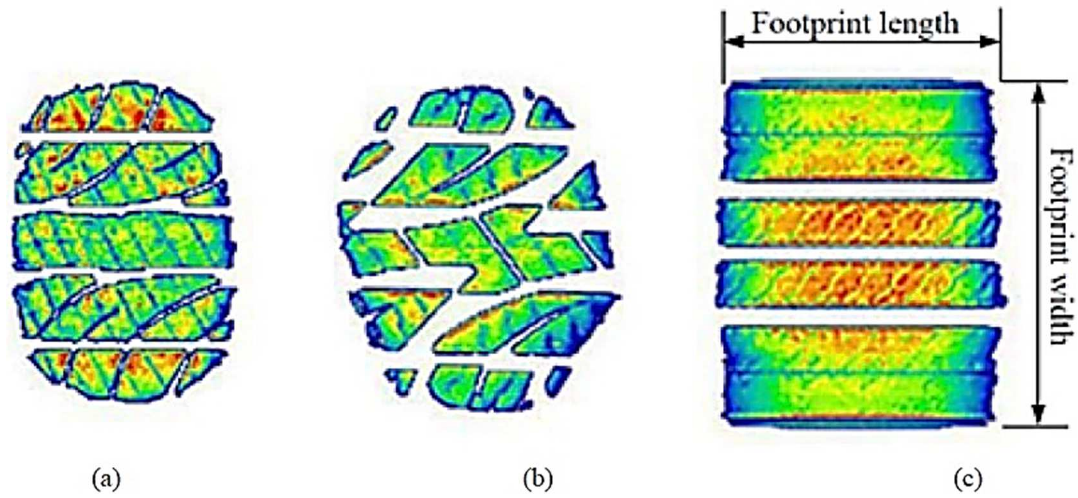


Figure 21 Different footprints resulted from various tyre types: (a) passenger car tyre; (b) light truck tyre and (c) commercial truck tyre [59].

Additionally, for the tyres in worn state, Dijks [54] reported that the impact of tread depth is significant on wet grip of car tyres, particularly when the tread depth decreases to below 2 mm. However, that of truck tyres is found less pronounced, as seen in Figure 22. The tests results show a general trend that the ***μ*** values reduce gradually with decreasing tread depth and all ***μ*** values are very low compared to car tyres. The braking force coefficient of truck tyres on wet roads amounts to about half of the value of car tyres, which is an important fact regarding traffic safety. This implies a rapid locking of the truck wheels and a braking distance twice as long. It is stated that the skid resistance of truck tyres with a few millimetres tread depth is so low that on a wet road locking of the wheels would be hard to prevent.

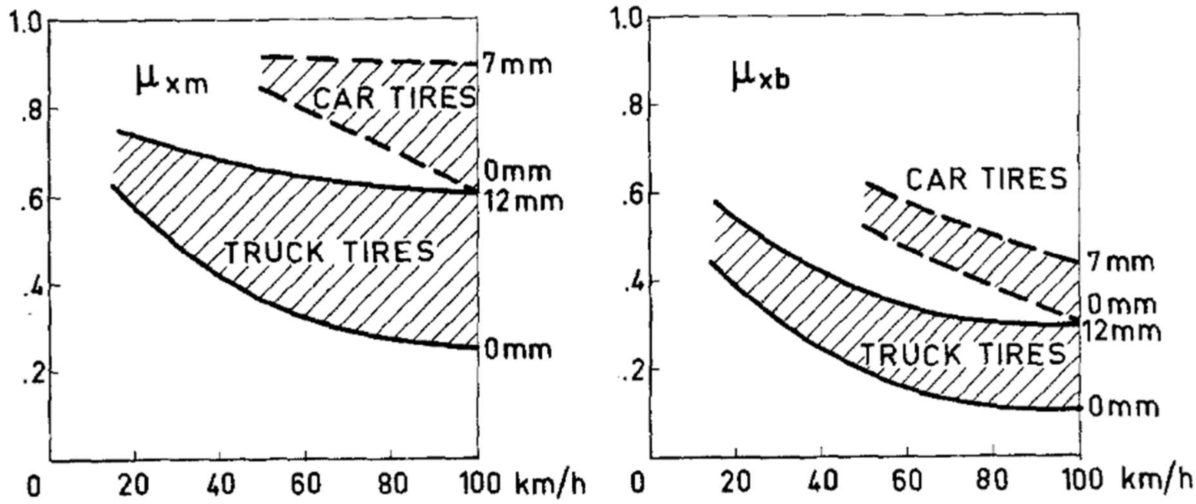


Figure 22 Wet skid resistance ranges for car and truck tyres [54].

In the case of passenger car tyres, radial tyres have greater resistance to hydroplaning than cross-ply tyres when the water film is thin, but there is almost no difference between the two when the water film is thick. As for the truck and bus tyres, the pattern exerts an extremely great influence on the speed at which hydroplaning occurs, and if sufficient tread grooves remain, there should be no problems with hydroplaning when it rains. If, however, the tread is worn, hydroplaning occurs at speeds considerably lower than those indicated by the NASA experimental expression. The speeds at which the worn tyres can be operated fall sharply and it becomes extremely dangerous for such worn tyres to be used at high speeds [43]. Recent study [56] applies analytical simulation models to study hydroplaning behaviour of a bias ply truck tyres under different inflation pressure levels, footprint aspect ratios, wheel loads and water film thicknesses. The results confirm that truck tyres do hydroplane and truck hydroplaning can occur within the range of normal highway operating speeds. In addition, some analysis results demonstrate that the truck tyre under sliding condition has higher hydroplaning risks than the tyre under free rolling condition. These factors are suggested to be considered when developing safety improvement countermeasures for driving safety [58].

Recent findings of IWG WGWT [8] have drawn similar conclusions. The wet grip tests are performed on new and worn C1, C2 and C3 tyres. The performance drop from new to worn state is shown in Figure 23. It is found that the C1 tyres demonstrate a drastic performance drop with tyre wear, while the cases for C2 and C3 tyres are found much less significant. Additionally, the assessment of the contact patch surface ratios seen in Figure 24 further confirms the argument. There is a significant reduction (55%) of contact patch surface observed for C1 tyres from new to worn state, while that for C3 tyres is much smaller (7%). Furthermore, a correlation factor is calculated for comparing the wet grip performances among new and worn C1, C2 and C3 tyres, see Figure 25. It is found that new and worn C2 and C3 tyres demonstrate a much greater value of correlation factor in comparison to that of C1 tyres. Further discussions on the effects of aforementioned factors on wet grip performance is presented as follows to better understand the introduction of such variations.

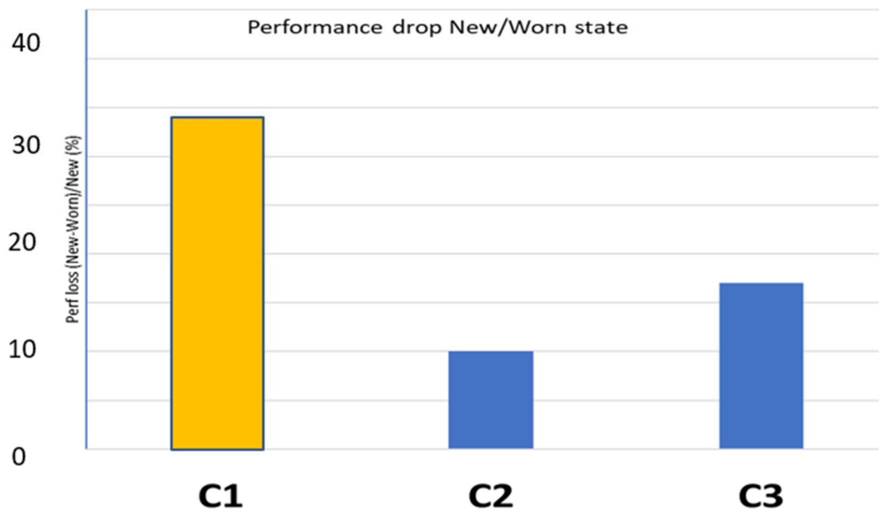


Figure 23 Wet grip performance drop of C1, C2 and C3 tyres from new to worn state [8].

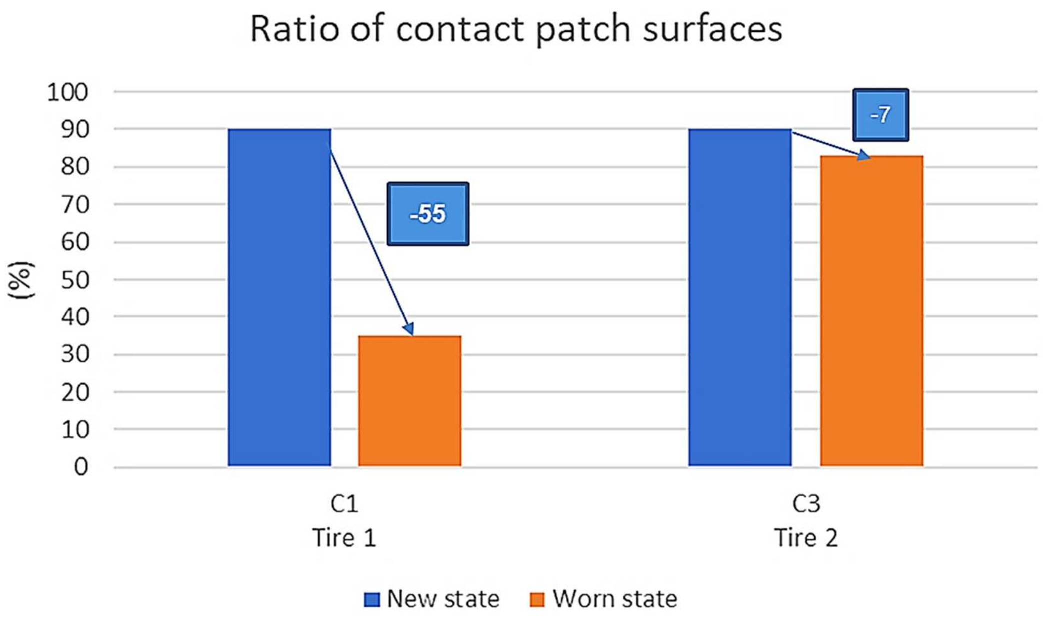


Figure 24 Ratio of contact patch surfaces from new to worn state for C1 and C3 tyres [8].

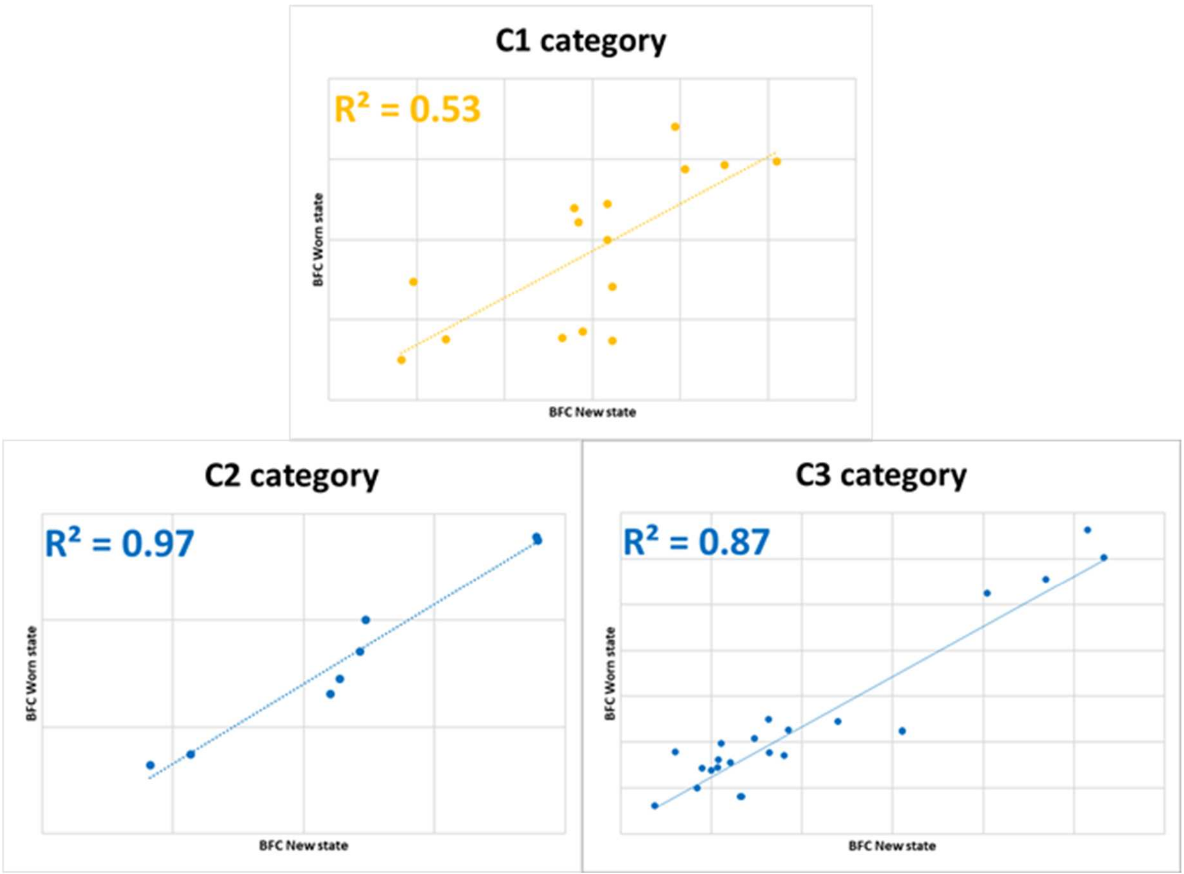


Figure 25 Comparison of New / Worn ranking assessment for C1 (GRB-69-08, C2 and C3). The correlation factor R^2 for C2 and C3 is significantly higher than for C1 strong wet grip performance correlation between new and worn stage [8].

2.3.2 Affecting Factors

The factors contributing to tyre wet grip performance have been intensively studied in the literatures [9], [14], [25], [26], [28], [36], [37], [39], [41], [47]–[50], [54], [55], [60]–[73]. Among them, the important ones are vehicle speed, road surface texture, tyre tread depth, tread pattern, tread compound, water depth, inflation pressure and vehicle load. Maintaining grip on wet surfaces is a complex phenomenon that involves dispersing the water to restore dry contact between the tread and the road. This process is determined by the tyre-fluid-pavement interactions. The effectiveness of the adhesion component depends upon the available drainage capacity in the tyre tread pattern or in the voids between road surface asperities, which can provide means of removing water within the contact area. In the case of tyres in worn state, the performance drop of each mechanism is independent of the performance at new state [9]. The grooves of the tread pattern can vanish with wear and the tread mix can also vary throughout the tread depth. Hence, a thorough understanding of these interactions of the factors would be beneficial to better understand the wet skid process and the occurrence of hydroplaning.

2.3.2.1 Vehicle speed

Many studies [26], [74]–[77] demonstrate that the rain intensity causes the vehicle speed to decrease compared to dry road conditions considering its impact on driving behaviour. It is highlighted that under light rain intensity (0–5 mm/h), speed decrease is in order of 10% on motorways. While under heavy or very heavy rain, it can potentially impair the visibility of drivers so that the majority of them slow down. Thus, there can be a speed drop up to 30% (see Table 4), which would make the hydroplaning situation quite unlikely based on statistical analysis. However, it is observed that the initial speed of the accidents is much smaller than the regular vehicle usage speed. On wet roads, more than 90% of the accidents are found with an initial speed lower than 80 kph [77]. This indicates that the safety concern induced by friction loss and occurrence of hydroplaning on wet surfaces is a joint effect of the vehicle speed and the other factors that will be discussed in this study.

Table 4 Speed reduction due to rain for several European countries [77].

Rain intensity	[3] Germany highway	[4] Hungary highway (fast lane)	[4] Hungary highway (slow lane)	[5] France motorway (fast lane)	[5] France motorway (slow lane)
Dry road	156 kph	125 kph	106 kph	107 kph	92 kph
0–5 mm/h (Light rain)	141 kph -10%	115 kph -8%	96 kph -9%	94 kph -12%	80 kph -13%
5–10 mm/h (moderate)	128 kph -18%	105 kph -16%	88 kph -17%		
>10 mm/h (heavy rain)	119 kph -24%				
25 mm/h (very heavy)		80 kph -36%	71 kph -33%		

The effect of vehicle speed on hydroplaning is progressive. The increase in vehicle speed will increase the hydrodynamic pressure developed at tyre/road interface, as illustrated in Figure 26. During this process, there can be the presence of partial hydroplaning and wet grip situation leading to gradual reduction of tyre/road contact patch, as shown in Figure 27 Zone A to D. Once the hydroplaning speed is reached under certain conditions, a full separation of tyre tread and road surface will then take place, as seen as E zone in Figure 27 [76]. At this hydroplaning speed, the steering ability of the tyre is completely lost, and the braking ability drops significantly.

Figure 26 Progressive effect of vehicle speed on tyre hydroplaning [78].

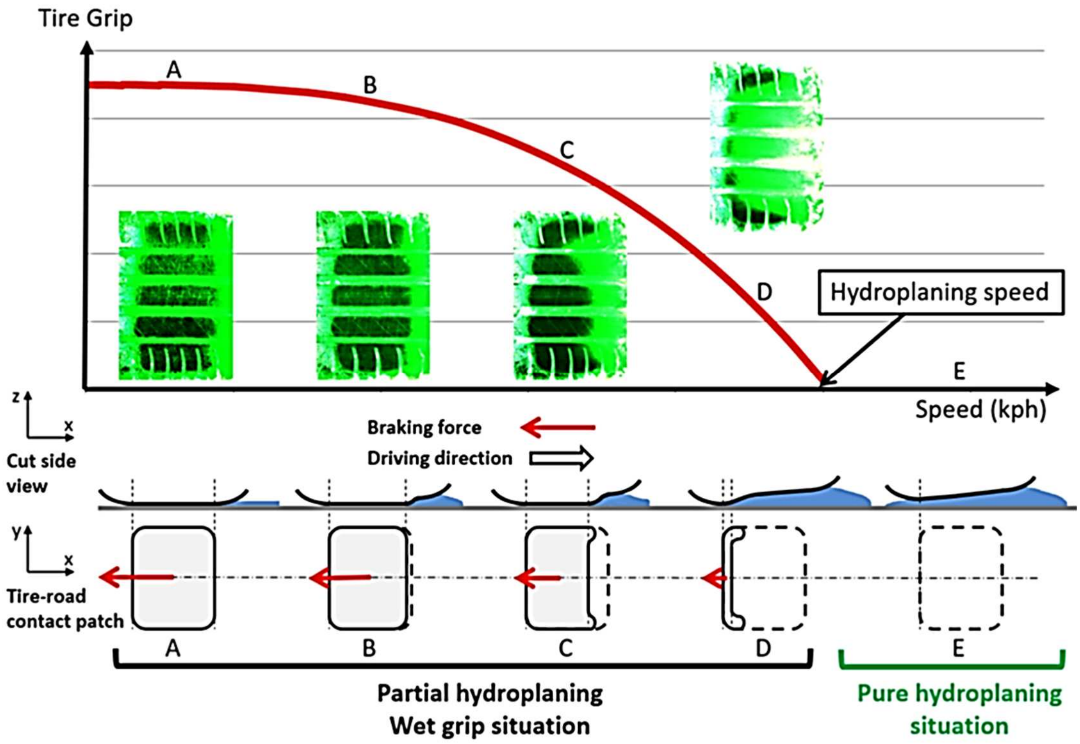


Figure 27 Hydroplaning phenomenon [76].

Extensive experimental research [27], [34], [36], [64], [79] has been dedicated to investigating hydroplaning speed since the pioneering work from the National Aeronautical and Space Administration (NASA) in early 1960s [19]. Dynamic hydroplaning is often set as the criteria for the calculation of the critical speed required. A brief description on some of the analytical and empirical techniques applied in past studies [27] is displayed in the following text. The well-known NASA hydroplaning equation developed by Horne is shown in Equation 1. It is employed to predict the minimum dynamic hydroplaning speed for pneumatic tyres [19] and has been used extensively in the aviation, automobile, and pavement engineering field.

$$V_p = 6.35 \times \sqrt{P}$$ *Equation 1*

where ***P*** is the tyre inflation pressure in kPa and V_p is the minimum dynamic hydroplaning speed in km/hr.

Later studies [36], [79] indicate that the minimum dynamic hydroplaning speed of automobile, truck, and bus tyres varies not only with the inflation pressure but also with the tyre footprint aspect ratio. Accordingly, Horne proposed a modification for the equation, as shown in Equation 2.

$$V = 4.87 \times \sqrt{\frac{P}{W/L}}$$ *Equation 2*

where ***W/L*** is the tyre footprint aspect ratio, ***P*** is the tyre inflation pressure in kPa, and ***V*** is the minimum tyre hydroplaning speed in km/hr.

Research at the Texas Transportation Institute (TTI) then investigated the validity of Horne's predictions of dynamic hydroplaning of lightly loaded truck tyres at typical highway speeds [36]. The relationship is normalized for the test aspect ratio of 1.4.

$$Vp = 24.99 \times P^{0.21} \sqrt{\frac{1.4}{W/L}}$$ *Equation 3*

Moreover, a study by Gallaway et al. [34] developed an empirical formula for dynamic hydroplaning speed when the water film thickness exceeds 2.5 mm (0.10 inch). Multiple linear regression yielded the following expression:

$$V = 0.902SD^{0.04}P^{0.3}\left(\frac{TD}{0.794} + 1\right)^{0.06} A$$ *Equation 4*

$$A = \text{Max of } \left(\frac{11.008}{WD^{0.06}} + 3.507, \left[\frac{26.871}{WD^{0.06}} - 6.861\right] TXD^{0.14}\right)$$ *Equation 5*

where ***V*** is the vehicle speed (km/hr), ***SD*** is the spin-down percentage, ***P*** is the tyre inflation pressure (kPa), ***TD*** is the tread depth (mm), ***WD*** is the water depth above the pavement asperities (cm), and ***TXD*** is the pavement texture depth (cm).

Later, Huebner et al. [80] developed a hydroplaning model that draws on the work of both Gallaway [34] and Agrawal [81], as seen in Equation 6.

$$HPS = 53.34\,(WFT)^{-0.259}$$ *Equation 6*

where ***HPS*** is the hydroplaning speed (km/hr) and ***WFT*** is the water film thickness (cm).

On the other hand, in the case of viscous hydroplaning, Equation 7 below describes the minimum hydroplaning speed for a pavement with slight microtexture:

$$V_H \geq \frac{L}{\Delta T_{sf}}$$ *Equation 7*

where, V_H is the minimum viscous hydroplaning speed; L is the tyre footprint region; and ΔT_{sf} is the time required for sufficient reduction of the fluid film for contact between the tread rubber and the pavement asperity to occur [82].

The complex evolution of the equations proposed by researchers further proves that multiple factors other than tyre inflation pressure, such as water depth, pavement surface texture, and tyre tread design affect the onset speed of hydroplaning. Hence, when the tyres are in worn state, the aforementioned factors and their interaction mechanisms will be affected, consequently, the hydroplaning speed will be different. Consider a new tyre rolling or sliding on a wet road surface at low velocities, there is a negligible hydrodynamic water build-up between the tyre and road surface. There is sufficient time for the water to be squeezed from the contact regions between the tyre and road surface, except for water trapped in road cavities and sealed off by the road-rubber contact at the upper boundaries of the cavities [18]. As the tyre tread becomes worn, the drainage provided by the tread becomes less efficient and the speed to cause a given amount of wheel spin-down (indicator for hydroplaning) is decreased. Hence, the hydroplaning speed of tyres in worn state is considerably lower than that of the new tyres [64], when other operating conditions are held constant.

The dynamic hydroplaning speed is often determined indirectly by measuring the brake force coefficient, the friction value that describes the tyre-pavement interface, under various conditions. It was assumed that full dynamic hydroplaning occurs when the brake force coefficient is zero [27], [81]. Furthermore, a recent experimental study is dedicated to measure the contact area of rolling tyres on wet ground at real scale and to further investigate the capacity of tyres to deal with the hydroplaning phenomenon. Three different worn tyres with 2mm of tread depth are tested on pavement with 1mm water depth at a speed up to 90 km/h and the contact patch images are captured in Figure 28.

The results show varied contact areas are preserved for different worn tyres. It demonstrates that each tyre has its own response depending on its internal architecture and sculpture design, etc. A tyre may not have reached the total hydroplaning speed as predicted by Horne's equation, a hazardous condition may exist when the wheel has spun down and its frictional characteristics have been impaired [64]. Hence, the hydroplaning speed cannot be the sole criterion to evaluate the tyre sensitivity to hydroplaning phenomenon. All the factors and effects involved can lead to differences in terms of wet grip.

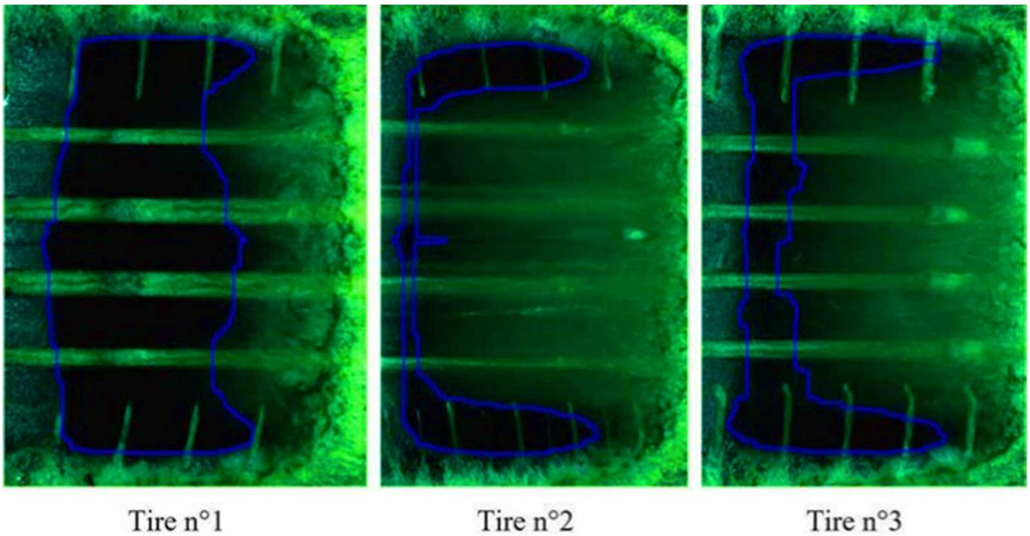


Figure 28 Raw images of the different worn tyres at 90 km/h on 1.0 mm of water depth with the contact patch contour [48].

2.3.2.2 Tyre tread characteristics

The tyre is one of the most critical factors influencing wet skid performance. Yeager [65] and Browne [25] have addressed that factors of tyre construction and condition can influence hydroplaning. Safe driving in wet weather conditions can be affected by the tread depth, the pattern design, the contact patch, and the rubber compound of the tyre tread. Even on a well-designed and properly maintained roadway, a tyre in worn state with reduced tread depth and blank pattern, experiences higher risk of hydroplaning than a tyre in good condition, considering normal rainfall condition and prudent speed level.

a. Tread depth

Effect of tread depth reduction due to tyre wear on wet traction has been identified in early studies [28], [37], [54], [83] and the same conclusion is drawn. A reduction in tyre tread depth causes a fall in available adhesion level that can lead to tyre spin-down at a lower speed, meaning a lower hydroplaning speed, as seen in Figure 29 and Figure 30. Additionally, it is found that the wet grip performance of passenger car tyres drops drastically with tread depth decreasing to below 2 mm, Figure 31. Legislation controlling minimum permitted tread depths is then introduced. Currently, in most European countries, the legal minimum tread depth for car safety is 1.6 mm, at which the tyres are due for replacement.

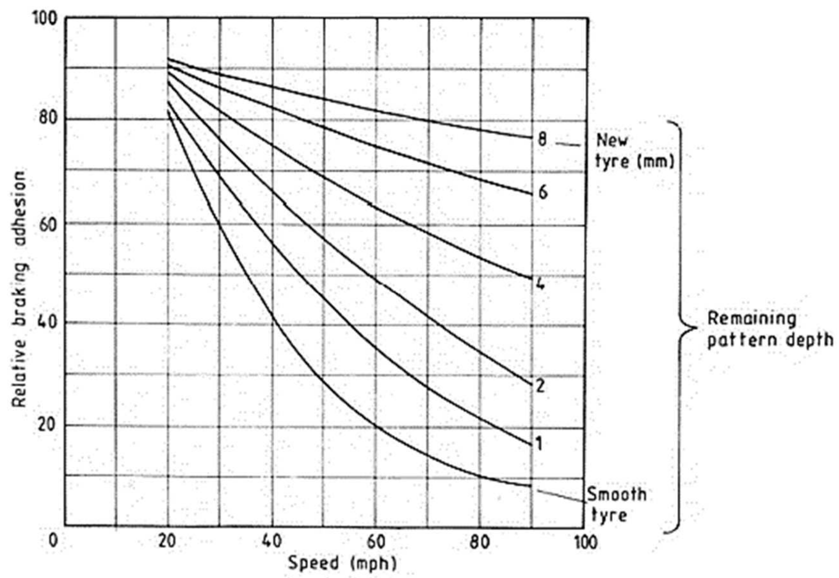


Figure 29 Relative braking adhesion with varying tread depths in 1 mm of water [37].

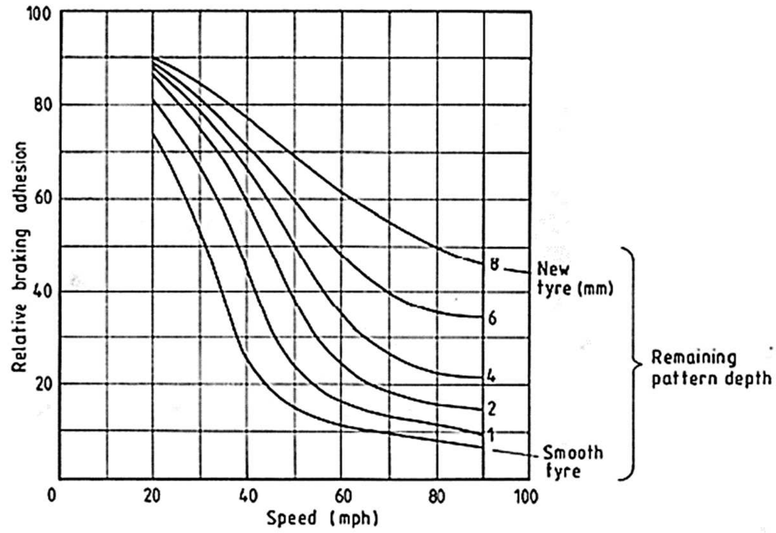


Figure 30 The catastrophic reduction in relative friction with tread pattern wear in 'flooded' conditions (2.5 mm water depth) [37].

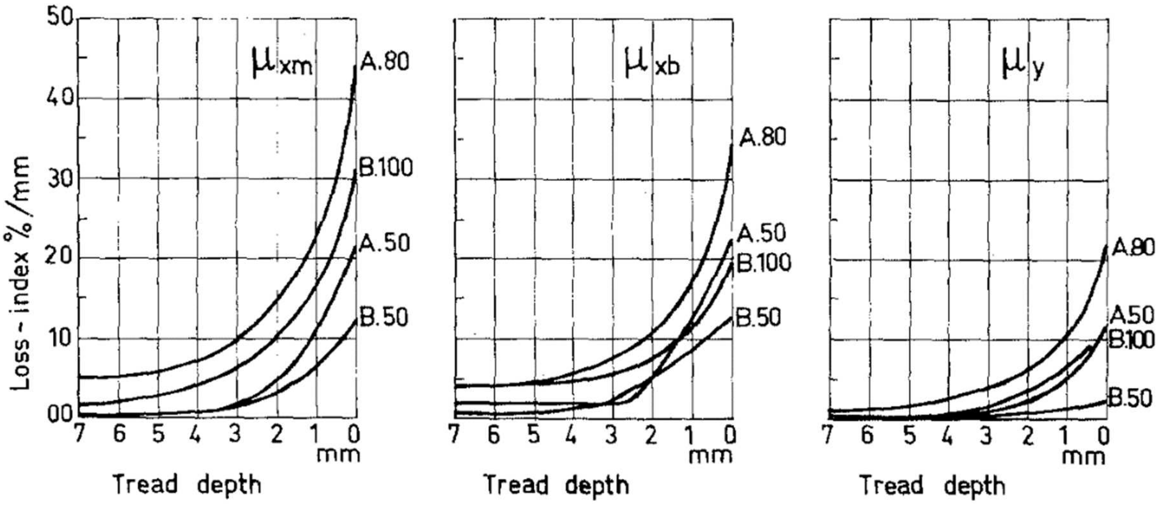


Figure 31 Loss index of radial car tyres [54].

In the case of truck tyres, wet grip evaluation of three tyres is presented in Figure 32, where I is a truck tyre, size 11.00 R 20; II is a bus tyre, size 10.00 R 20; and III is a re-treaded truck tyre, size 10.00 R 20. In general, the decrease is gradual, especially at higher speeds. The μ_{xb} values decrease gradually with tyre wear at all speeds. All the friction coefficient values are lower compared to car tyres. However, a minimum safe tread depth is found more difficult to select for truck tyres. Moreover, Fwa et al. [84], [85] applied numerical approach to analyse the hydroplaning of a worn ASTM standard E501 rib tyre at 1.6 mm of remaining tread depth and also compared the hydroplaning speed of tyres with various tread depths. They concluded that the tyres with lower tread depths reach hydroplaning speed before the new tyres. More specifically, the hydroplaning speed of worn tyres is found to be 15 km/h lower than those of the new tyres on all the tested water depths (from 1 to 10mm) [84]. One other study reported a similar drop of hydroplaning speed of 20 km/h or more for a worn tyre, compared to a new one [83].

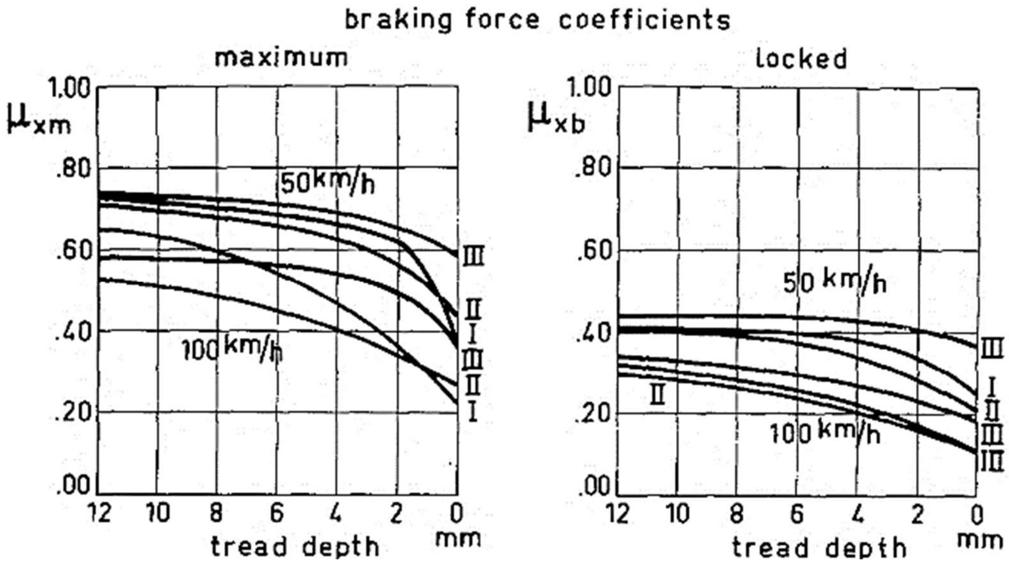


Figure 32 Influence of tread depth on the wet skid resistance of the truck and bus tyres on new asphalt concrete surface with a texture depth of 8 mm and SRT of 77 [54].

Furthermore, the decrease of tread depth can also change other characteristics, such as the flexibility is reduced. The stiffer tyre uses a smaller slip angle for the same amount of lateral force, leading to a more direct steering feel [83]. The reduced flexibility can also introduce more vibration into the vehicle. Moreover, the loss of tread material decreases the effective tyre radius. For instance, the nominal diameter of a 195/65-15 tyre in new condition is 322 mm. As the tread depth wears from 8 to 2mm, this diameter is reduced to 316 mm, which is a change of 1.9%, meaning the circumference is also reduced by 1.9%. This decrease in effective tyre radius can result in changes in acceleration, fuel consumption and a deviation in speedometer reading [83].

b. Tread pattern

The tread pattern influences the tyre performance in various aspects and its main contribution is to the traction development at the contact patch, as seen in Figure 33. On wet surfaces, an effective tread pattern will have adherent grooves and biting edges to displace water so that a maximum grip can be achieved in wet handling conditions [84], [86]. The adherent tread pattern works in conjunction with adherent rubber compounds, and footprint shape that will be discussed in the following sections. All three factors need to be present for maximum performance [62]. The design of the tread pattern can optimize the grip level. For instance, stiff patterns are better on dry surfaces with high μ values, while soft patterns with various edges perform better on low μ tracks, such as wet surfaces shown in Figure 34. It is reported that at the same water flow speed, the optimized tread pattern design can reduce hydrodynamic lift force by 14.05%, thus greatly improving safety performance of the tyre [87].

A tread pattern can be composed of the following components: lateral and longitudinal grooves, blocks, sipes, and ribs, as seen in in Figure 35. Grooves are the deep channels that run around the circumference of the tyre (longitudinal grooves) and across the tyre surface (lateral grooves). They help to prevent the formation of the water wedge by channelling bulk water through and out of the tyre footprint region, thus, stopping the occurrence of hydroplaning. Moreover, they function as reservoirs for thin water film squeezed from the tyre and the pavement surfaces, reducing the risk of viscous hydroplaning [27], [86]. The ribs are solid elements that run along the circumference of the tyre and contact the road. The rubber blocks or lugs evenly spread the pressure and load over the entire contact area and grip the road. The sipes are valleys cut across the lugs to allow water to escape to the shoulder (i.e., the tyre side). The sipes are equivalent to pavement microtexture. The purpose of this feature is to greatly increase the number of sharp edges of tread contact with the pavement that are provided by the tread grooves. Contact of the pavement surface at these sharp cornered tread sipe and groove edges creates local bearing pressures sufficiently high to quickly breakdown and displace the thin water film (Zone B in Figure 11) that creates viscous hydroplaning [37], [71], [88]. The drainage capacity is defined as the amount of water to be effectively handled at the road/tyre interface. From the tyre side, the water drainage is mainly handled by the tread pattern. Once the bulk water encountered exceeds the drainage capacity, the excess water must have sufficient time to be displaced without building up in front of the tyre and creating uplift pressure on the tyre. It is demonstrated that a change of tread pattern can result in a change of hydroplaning speed up to 30 km/h [88].

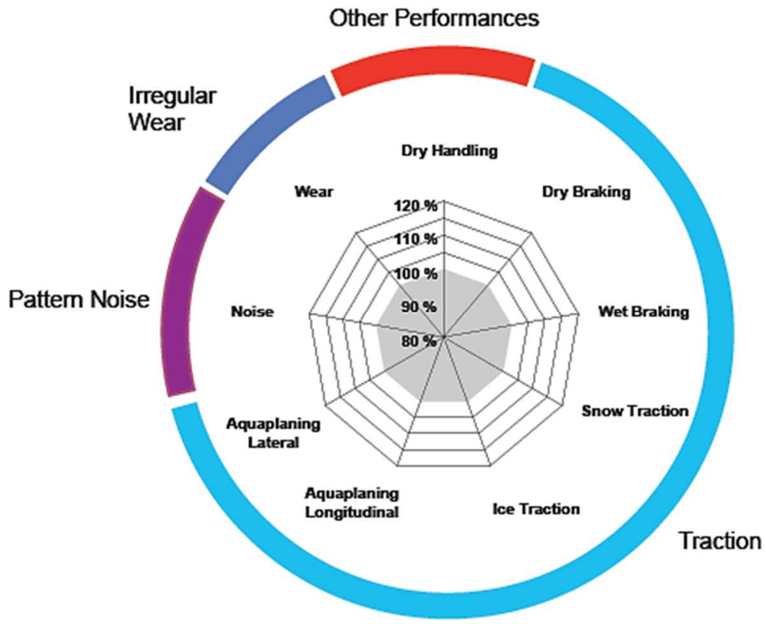


Figure 33 Main performance attributes influence by tread pattern [89].

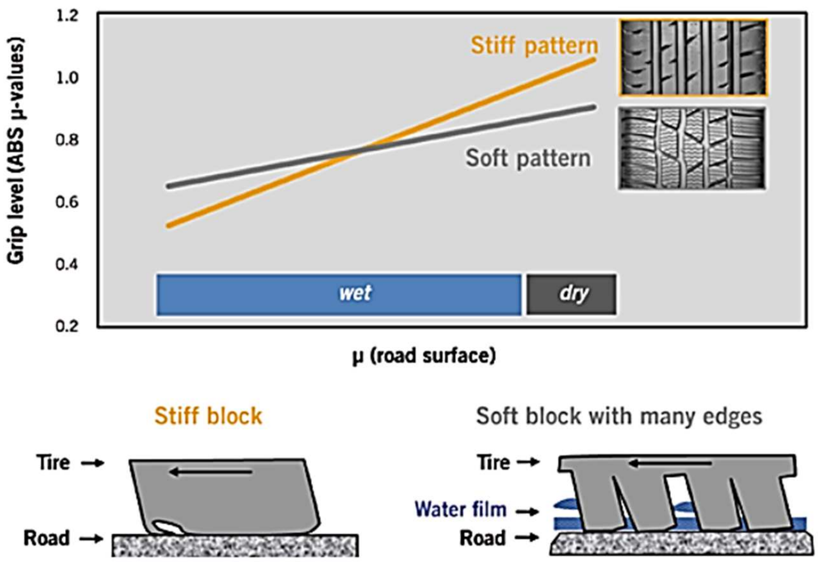


Figure 34 Interaction between tyre tread pattern design and roads grip level [1].

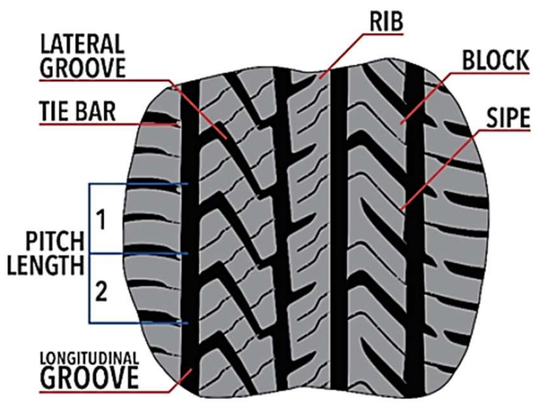


Figure 35 Tread pattern components [89].

Additionally, the tread pattern of truck tyres demonstrates a simpler design. The operating of truck tyres on unmade roads, construction and industrial sites imposes high load intensities and high localised stresses ion truck tyre treads. The extreme operating conditions of truck tyres promote the adoption of tread patterns with flexible elements or with stress-raising grooves, channels, slots, etc., closely spaced (2 mm to 3 mm apart with some car tyres), which are designed for maximum adhesion on wet, slippery road surfaces [37]. It is reported that the truck tyres do not grip the road as well as car tyres. Some published data show stopping distances from 35 mph entirely attributable to tyre $\boldsymbol{\mu}$ values on a wet, slippery road as 75 ft for a high-grip (normal) car tyre as compared with 200 ft (worst but fairly typical) and 125 ft (best) for heavy truck tyres [90].

With an understanding established on the importance of the tread pattern on wet traction, one can see how critical the safety situation can be for the tyres in worn state. Under wet conditions, a worn tyre has far less capacity to drain water. It is observed that as tyre tread depth wears from 8 to 2 mm, the grooves have less than 25% of the original area available to drain water [91]. This reduces grip in all directions, resulting in a lower hydroplaning speed. The importance of drainage becomes apparent at high vehicle speeds, especially when driving on roads having little or no macrotexture and with smooth worn tyres [44]. The comparison of the peak brake force coefficients for tyres in new and worn states on two extreme road surface textures can further validate the statement, see Figure 36. It is found that the tread pattern plays the most important role on surfaces with a smooth macrotexture since the tread pattern would be the sole mechanism contributing to the removal of the bulk water [39]. On such surfaces, the peak brake force coefficient at 48 km/h is reduced by 40% and at 112 km/h by 70% with the absence of tread pattern. The drainage capacity of the tyre is greatly reduced as the pattern depth reaches the legal limit. On the other hand, the results indicate that the role of tread pattern is not as significant for surfaces with a rough macrotexture. It is stated that a rough macrotexture with an adequate level of microtexture (in the range of 0.01 to 0.10 mm), would promote the generation of frictional forces at the tyre/road interface, even at the legal limit of tread depth.

More studies have studied the influence of tread pattern on hydroplaning process as well as the trade-off with several other performances [61], [92]–[94]. These studies demonstrate that a change of tread pattern design has an important global impact especially from ribbed to smooth tread patterns as the tyre transforms from new to worn state. Furthermore, as hydroplaning occurs when the hydrodynamic pressure exceeds the contact pressure, the hydrodynamic force is considered as a good criterion for hydroplaning. The effect of tread pattern on the development of the hydrodynamic force is studied in a numerical procedure [61]. Figure 37 shows the hydrodynamic forces with and without tread pattern are compared at 60 km/h. It is seen that the tread pattern decreases the hydrodynamic force, preventing the occurrence of hydroplaning.

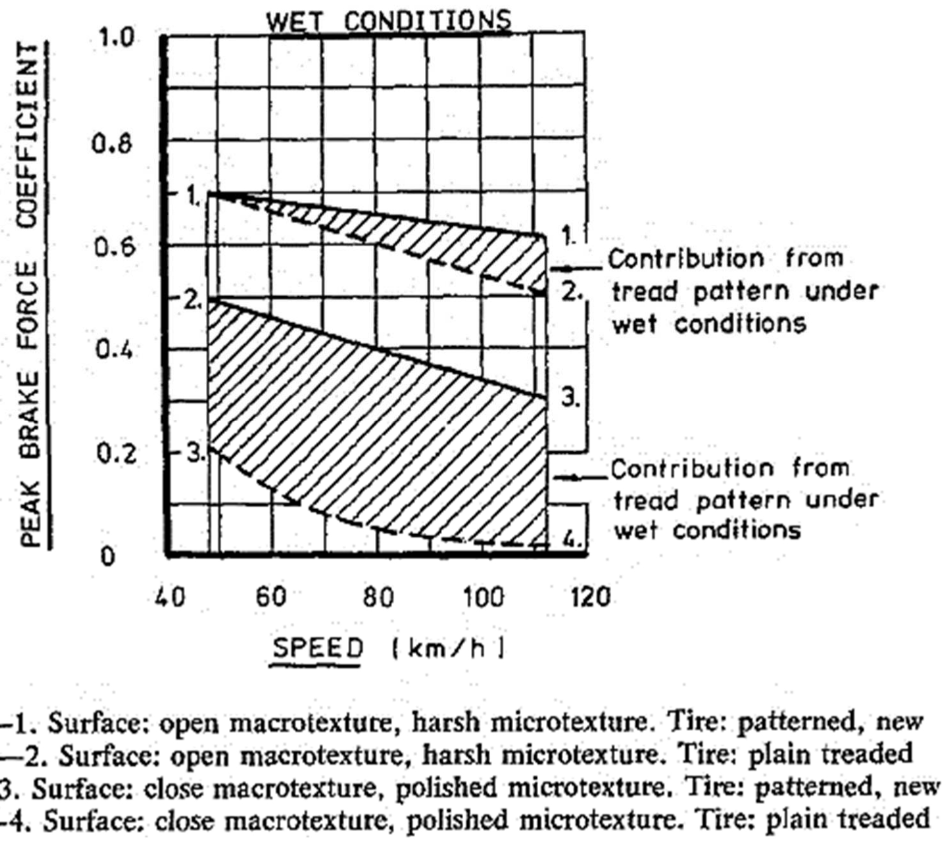


Figure 36 Levels of friction attainable for the range of road surfaces with plain treaded and patterned tyres. [39]*, where open macrotexture means rough macrotexture and close macrotexture means smooth macrotexture.*

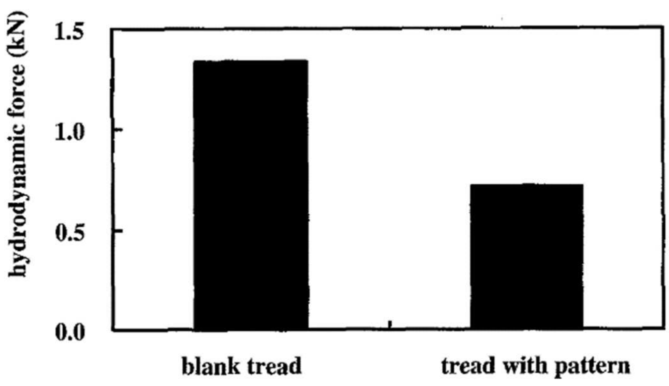


Figure 37 Effect of tread pattern on hydroplaning [61].

c. Contact patch

In addition to the tread pattern, the shape of the contact patch also plays an important factor on wet traction. The bank of water that builds up in front of the tyre must be quickly dispersed to the side so that the hydrodynamic pressure developed at the leading edge of the contact patch does not exceed the pressure induced by the vehicle load on the road surface. Thus, the tyres must be designed to disperse this water quickly and effectively by adjusting the shape of the contact patch, the tread pattern and the sipe arrangement [13]. A contact patch in rounded shape "ploughs" more easily through the water than a rectangular shape. The hydrodynamic pressure applied on the tyre decreases with increasing leading-edge angle β, as shown in Figure 38. The water is then pushed out and away from the path of the tyre. While with a rectangular patch, this pressure reaches its maximum as the water is just pushed forward, it remains in the travel path of the tyre [13]. Moreover, the effects of tyre footprint dimensions on dynamic hydroplaning speed have also been investigated [27], [36], [79]. As the tyre width increases, the width of the contact patch increases, which introduces a greater amount of fluid when encountering a wet or flooded pavement. Consequently, the collecting and channelling water away from the tyre footprint becomes more challenging and requires more of time, inducing higher magnitude of hydrodynamic forces acting on the tyre. On the other hand, the increase in footprint length enables greater amounts of dry contact within this region, leading to an enhanced wet traction performance and safety [27]. A recent experimental study examined the loss of surface of new and worn tyres [73] under wet pavement conditions. Three-axial accelerometers are used to monitor the length of the contact patch in dry and wet conditions. The water depth used in the test ranges from 2 to 7 mm with most of the track exhibiting 7mm water depth. The results show that there is a limited footprint length reduction up to 40 km/h for both new and worn tyres (3% for the new tyre and 10% loss of surface for the worn tyre at 40 km/h). While at higher speeds, the worn tyre loses footprint length more rapidly than the new tyre, which highlights that the worn tyres are more prone to hydroplaning.

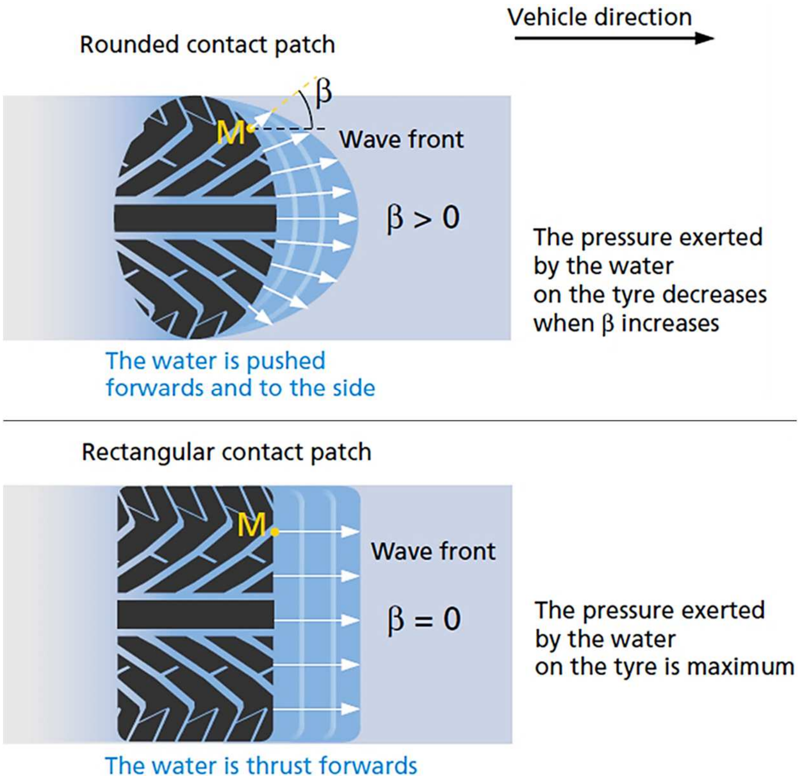


Figure 38 The rounded contact patch increases aquaplaning speed [13], *where β is leading edge angle at point M.*

The tyre footprint aspect ratio is another factor that is studied, often in conjunction with tread pattern. It is calculated as the footprint width divided by the footprint length (Figure 39). Smooth tread tyres having high-aspect-ratio footprints for similar conditions of flooded pavement, load, and inflation pressure will hydroplane at lower vehicle speeds than tyres with low-aspect-ratio footprints [22]. The aspect ratio of the tyre footprint is governed by the shape of the tyre cross section or the ratio of tyre section height to section width (also called the tyre aspect ratio). Moulding grooves (channels) in the tyre tread at time of construction is the tyre designers equivalent of pavement macrotexture. The tread grooves in the tyre footprint are vented to atmosphere and provide escape channels for the bulk water trapped in the front of the tyre/road interface (Zone A in Figure 11). Tread grooves thus raise the critical water depth required for a tyre to suffer dynamic hydroplaning, and for water depths less than the critical depth, raise the tyre hydroplaning speed. It should be noted that the benefits from grooving the tyre tread decrease in proportion to tread wear (depth of groove) and vanish when the groove depth decreases to 1.6 mm or less. Furthermore, the tyre footprint aspect ratio has been of particular interest in analysing the hydroplaning tendency of tractor-trailer trucks [27], [36], [43], [95]. Aspect ratios for trucks are influenced by the magnitude of the load. The footprint aspect ratio for an empty truck is considerably higher than for a loaded truck, when holding inflation pressure constant, due to shorter tyre footprints for empty trucks. As explained earlier, this results in less dry contact area between the tyre and the pavement. Furthermore, accident statistics show that the jackknife phenomenon (refers to the folding of an articulated vehicle so that it resembles the acute angle of a folding pocket knife, a trailer is considered to have reached in jackknife state when the trailer's orientation is perpendicular to that of the tractor [96]) of empty tractor-trailer trucks on wet pavements is a significant event that may be attributed to dynamic hydroplaning. It was determined that the footprint aspect ratio is a variable that must be considered when estimating dynamic hydroplaning speeds for pneumatic tyres [27].

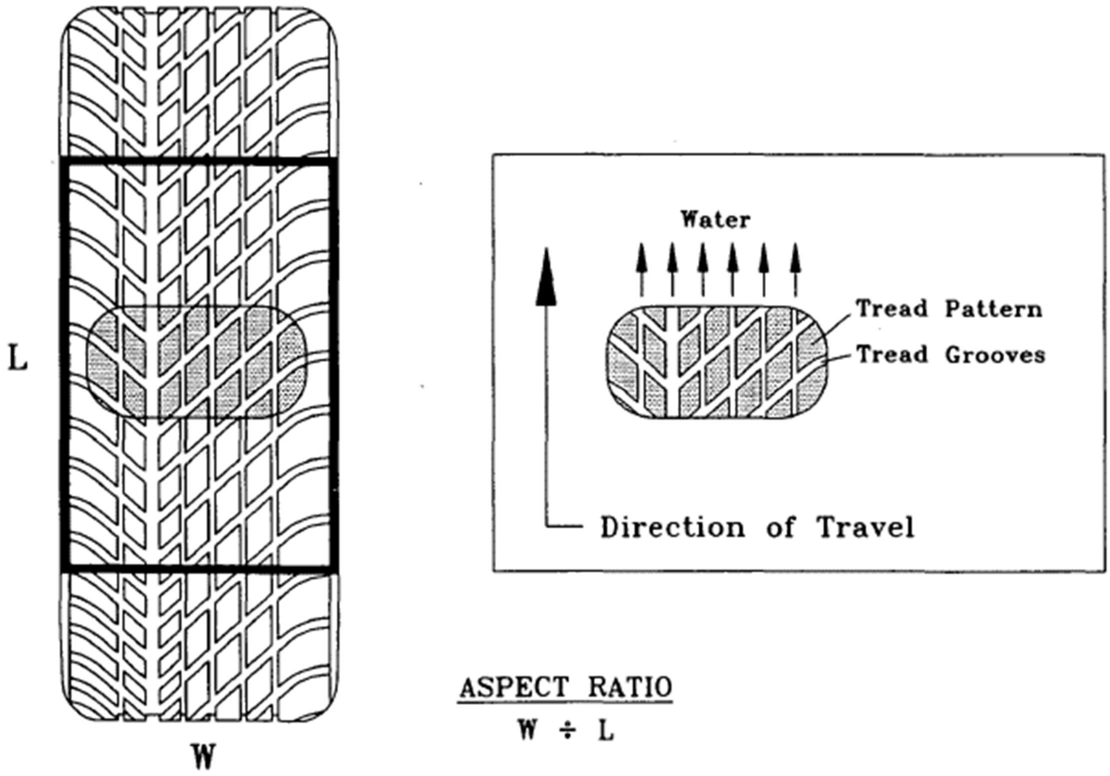


Figure 39 Tyre footprint – pavement view [27]*, where W and L are the width and length of the contact patch.*

d. Tread compound

Viscoelastic properties of the tread material can make a major contribution to the development of tyre/road friction in the wet. The discussion on tread compound is in close conjunction with the surface texture. To exploit the potential benefits of high-hysteresis tread materials, the road surface must have sufficiently large and angular asperities to deform the tread rubber, especially in the presence of a water film. The use of higher-hysteresis (lower-resilience) tyres on macroscopically rough surfaces can greatly promote friction development, while the same tyres would show no improvement on macrosmooth surfaces. Figure 40 demonstrates examples of the effect of tread material with tyres of resilience 30% and 50% (British standard Lupke rebound resilience test) on surfaces with varied macrotexture but similar microtexture [14]. The results validate the aforementioned statement that the effect of tread materials is prominent on macrorough surfaces. Additionally, the hysteresis component of friction, arising from energy loss in tyre tread material as it slides across road surface asperities, are of greatest importance at high speeds. In order to establish some localised dry contact with increasing speed, the necessary drainage between tyre and road should be achieved. This can be facilitated by macrorough surfaces, which is beneficial for a well-maintained friction coefficient throughout the speed range. On the other hand, the increased speed results in a rapid decrease in friction coefficient on macrosmooth surfaces due to the impairment of the hysteresis friction.

The tyre tread can consist of a variety of materials such as natural rubber (NR), synthetic elastomers such as styrene butadiene rubber (SBR) copolymers, reinforcement fillers such as silica which is a key component for wet traction, and various other chemicals. The right combination of materials assures maximum safety and tyre performance on wet surfaces. The section of tread compounds varies for different tyre types since significant differences exist in the intensity of tyre tread/ground contact loading. The heavy truck tyres can carry up to 12 kg cm^{-2} static load and 20 + kg cm^{-2} dynamic load, while passenger car tyres carry up to 3 kg cm^{-2} static load and 6 kg cm^{-2} dynamic load [37]. The high load intensities with heavy truck tyres necessitate the use of tread materials with high resistance to cutting and tearing, and with low-hysteresis internal temperature generation properties. Natural rubber compounds (which are expensive) are therefore widely used: these intrinsically provide lower $\boldsymbol{\mu}$ values, particularly on wet roads, than the various synthetic compounds universally used with car and racing tyres. Whereas the properties indicated for car tyres allow the adoption of synthetic-rubber-based compounds, which are cheaper and provide fundamentally high frictional values, particularly significant on most wetted surfaces. This, in conjunction with the simplified tread patterns used in truck tyres, contributes towards the unsatisfactory performance, whereby in normal mixed traffic, passenger car braking and cornering capabilities are appreciably better than those for most trucks [37].

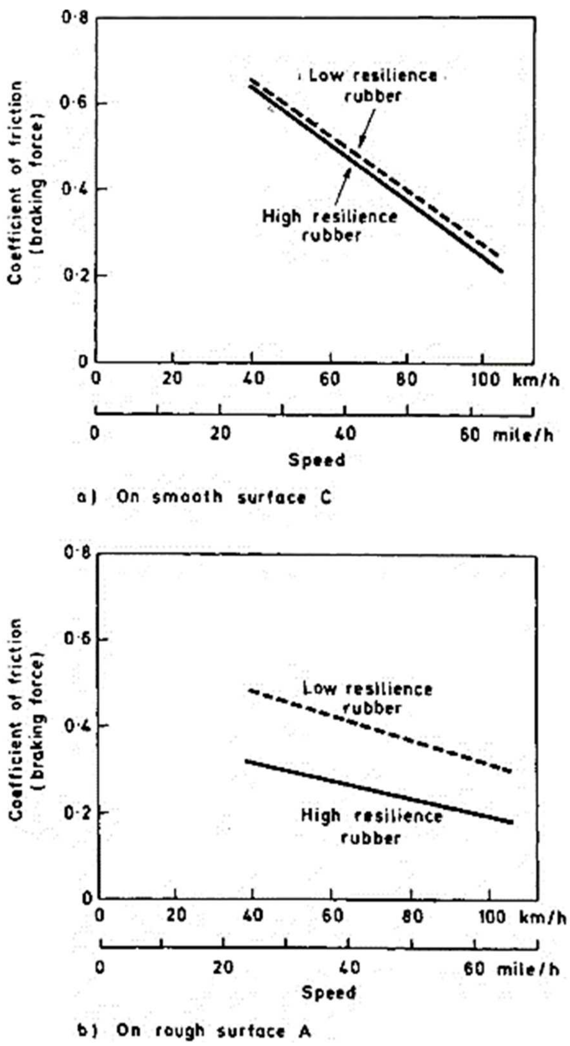


Figure 40 Tread material effect on smooth and rough surfaces under wet conditions [14]*, where A is macrorough harsh surface and C is macrosmooth harsh road surface.*

Many procedures are adopted for the development of rubber compound material. The dynamic mechanical properties of compounds are one of the important factors for tyre performance and essentially described by the compound storage modulus (***E'*** in tension, ***G'*** in shear) and the loss modulus (***E"*** and ***G"***). From these two measurements, a hysteresis coefficient, termed the tangent delta, or tan delta (***tan δ***), can be calculated from the ratio of ***E"/E'***, or ***G"/G'*** (see Table 5). The storage modulus, loss modulus, and tan delta terms are supplicated tools to predict tyre compound performance. For a given set of tread compounds, the one with the highest ***tan δ*** at 0°C would be expected to demonstrate the best wet traction performance, at 20°C, the best ice performance, and at +60°C, the lowest rolling resistance, as seen in Figure 41. This methodology is widely used in industry and academic research. One example can be shown from the study [97] that FS-SBR gives a tyre tread compound with the best wet-grip property as revealed by the values of ***tan δ*** at 0℃ in Table 6.

Table 5 Dynamic mechanical properties [98].

Property	Description	Measurement	Temperature for Measurement	Tire Performance Parameter	Improvement
E′, G′	Storage modulus	Tension, shear	T_g and 23°C	Irregular wear, cornering coeff. tread wear	Increase E′, G′
E″, G″	Loss modulus	Tension, shear	0°C, 60°C	Rolling resistance, wet traction	Decrease at 60°C for RR, increase at 0°C for traction
Tangent delta	E″/E′, G″/G′	Tension, shear	0°C, 60°C, 80°C	Rolling resistance, wet traction, high speed	Decrease at 60°C for RR, increase at 0°C for traction
T_g	Glass transition temperature		−80°C to 10°C	Glass transition temperature, controls hysteresis	—

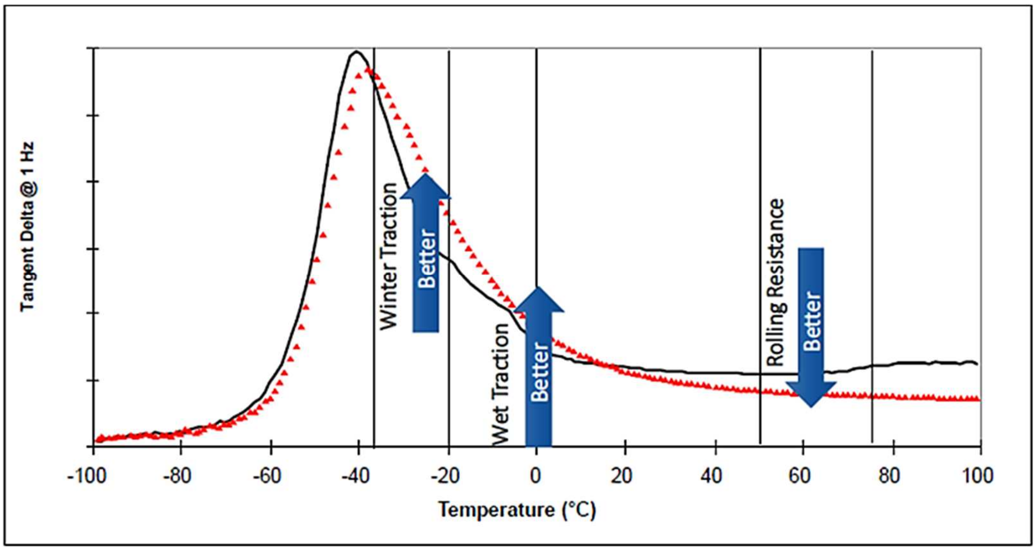


Figure 41 Tangent delta curve for tread compound property prediction [99].

As the tyres transform from new to worn state, the tread compound mix can vary throughout the tread depth, leading to a variation in tyre performance [9]. Experimental study on the effect of tread material on wet braking grip can further support this statement, see Figure 42. The tests are conducted with smooth tyres to eliminate the effect introduced by tread pattern. It is seen that the high-friction synthetic rubber compound demonstrates higher wet grip than the natural rubber compound. Hence, it should be noted that as the mix of tread material compound can change with the wearing of the tyres, the wet traction can be affected. Hence, the tread compound should be considered as an important factor when evaluating the wet grip performance of worn tyres. It should be however noted that the sustained effort should be made on incorporating and applying the knowledge of rubber friction and its interrelation with physical properties of tread compounds, such as effect of temperature on rubber properties, micro- and macro-characteristics of road surfaces, dry and wet mechanics, presence of water film (both thin film (viscous) and thick film (kinetic/hydroplaning)), etc, for the investigation of specific application.

Table 6 Values of tan δ at 0 °C of various rubber vulcanizates studied [97].

Rubber Type	Blend Ratio	tan δ at 0°C
FS-SBR	-	0.726
S-SBR	-	0.538
E-SBR	-	0.237
CNR	-	0.307
NR	-	0.183
BR	-	0.147
FS-SBR/CNR	60/40	0.552
FS-SBR/NR	60/40	0.493
S-SBR/CNR	60/40	0.527
S-SBR/NR	70/30	0.458
E-SBR/NR	70/30	0.231
S-SBR/BR	70/30	0.286
E-SBR/BR	70/30	0.147

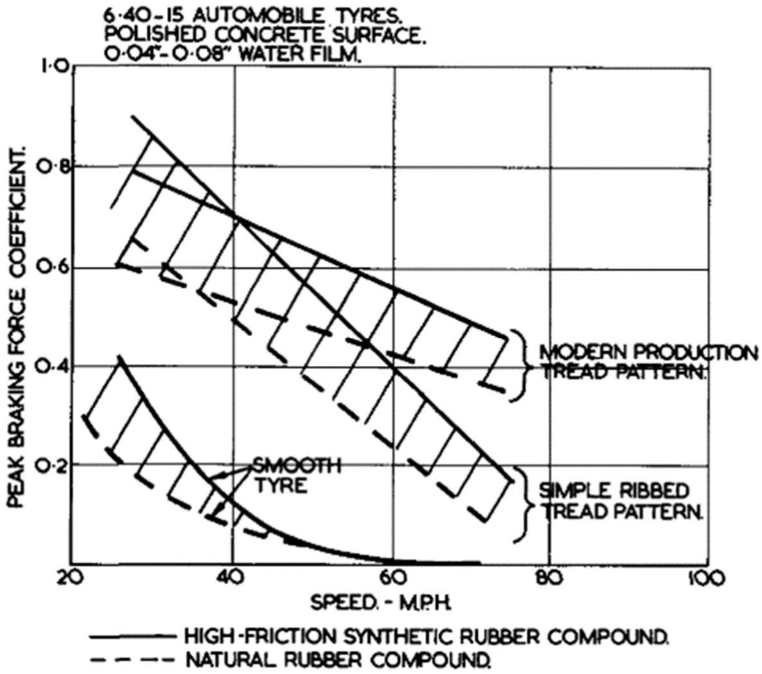


Figure 42 Effect of tread material on braking grip [28].

2.3.3 Pavement texture

Both the tyre-pavement interactions (under dry condition) and the tyre-fluid-pavement interaction (under wet condition) are heavily dependent on pavement surface texture [13], [27], [100]–[104]. Roadway surfaces are characterised by pavement microtexture and macrotexture [102]. Microtexture defines the degree of polishing of the pavement aggregates, varying from harsh to polished (Figure 43). On the other hand, macrotexture describes the size and extent of large-scale protrusions from the surface of the pavement, varying from smooth to rough (Figure 43). Under wet conditions, microtexture and macrotexture contribute to the development of friction in different mechanisms. When a thin layer of water film is present, the fine harsh asperities that make up microtexture on the pavement aggregates is imperative to break through the water film to enable direct contact between the tyre and pavement [105], as illustrated in Figure 44. During this process, high local bearing pressures can be generated at the peaks of the asperities, thereby allowing the tread rubber to establish adhesion friction with the roadway [22]. As for the macrotexture, it is a function of aggregate gradation, the pavement construction method, and special surface treatments such as grooving or chipping [103]. This characteristic of the pavement facilitates drainage in the means of channels and voids, thereby reducing hydrodynamic pressures developed between the tyre and pavement [104]. The effectiveness of the surface texture mechanisms on wet traction is determined by the vehicle speed. The microtexture governs wet friction at low vehicle speeds, while macrotexture is the critical factor for higher vehicle speeds. Further discussion is shown as follows.

The interaction between drainage mechanism and water depth is vital to the wet grip performance. It should be noted that even if the road surface macrotexture and the tyre tread depth provide adequate drainage, thin water film can still be formed continuously in viscodynamic zone of three-zone contact (Zone B in Figure 11) and locally at the asperity tips in damp zone (Zone C in Figure 11) [44]. This is attributed to viscosity induced by thin thickness, the water film cannot be evacuated through drainage, but can only be broken through by the road surface microtexture. Savkoor [44] defined two delubrication criteria as follows. In Zone B with the presence of continuous water film, delubrication is only possible if $\boldsymbol{h_m < \delta}$, where $\boldsymbol{h_m}$ is the minimum film thickness calculated on the basis of smooth profiles and $\boldsymbol{\delta}$ is the root mean square value of peak heights of the microtexture. Whereas in Zone C with localised water film at the tips of the asperities, delubrication is only possible when the intensity of local pressure exerted by microtexture asperities is high enough to break down the water film. Moore [106] further confirmed Savkoor's criteria and specified that the effective microtexture must be in the range of 10 mm to 100 mm. With respect to the local pressure, it is believed that the asperity slope and the curvature at the asperity tip are the important parameters [107].

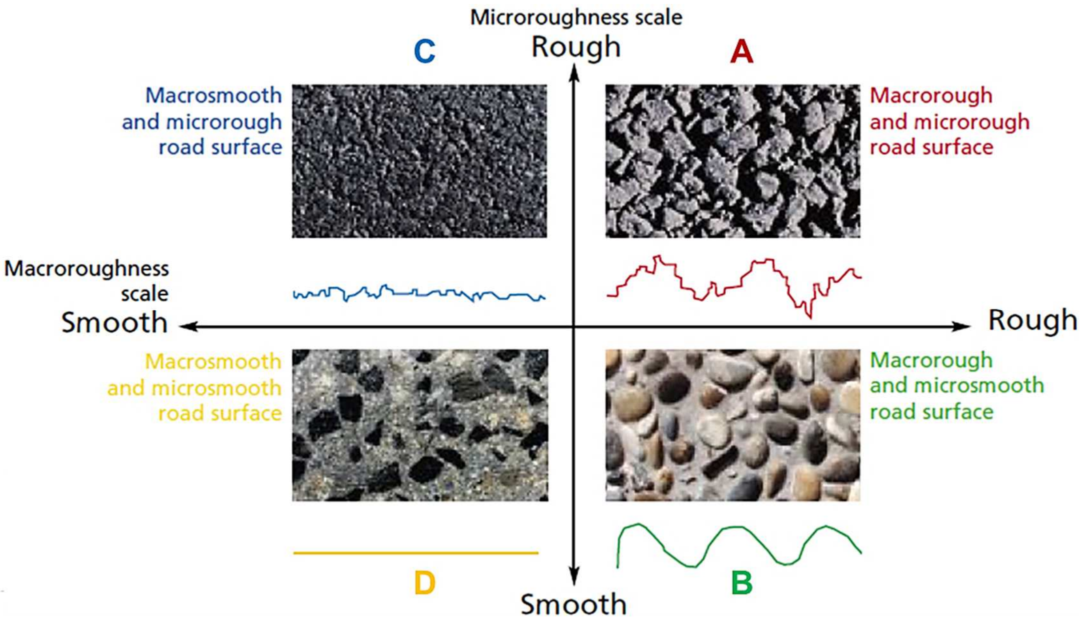


Figure 43 Road surfaces with different macro- and microroughness [13].

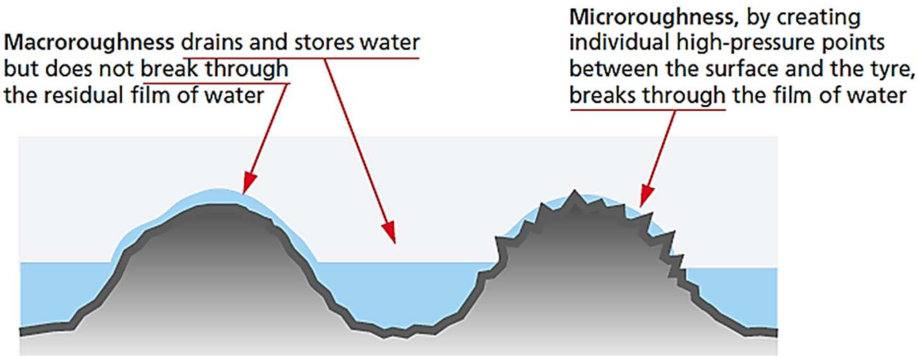


Figure 44 Effects of micro- and macroroughness on grip [13].

Measurements of the braking force coefficients with a locked wheel and a smooth-tread tyre on different surface textures are conducted to distinct the effect of pavement textures from that of the tyre characteristics, see Figure 45. Surfaces A and C (see Figure 43) with harsh microroughness demonstrate high coefficients at 50 km/hr, while surfaces B and D (Figure 43) with polished microroughness, indicating low coefficients at 50 km/hr. Moreover, the subsequent decrease in coefficient with speed is attributed to the macroscopic texture. For surfaces A and B with rough macrotexture, a subtle decrease in coefficient with increased speed is observed. While for surfaces C and D with smooth macrotexture, it shows a significant decrease in coefficient with speed. Hence, it is concluded that microtexture determines the level of skidding resistance at low speeds, and the presence of large-scale asperities in the surface determines whether the grip level can be reasonably maintained at higher speeds [14]. The similar conclusion is drawn by the VTI (Swedish National Road and Transport Research Institute) study [108] shown in Figure 46. It is reported that microtexture influences the wet grip in entire range of speeds with higher contribution at lower speed region. Macrotexture provides escape channels and spaces for water, where the essential condition of dry contact can be facilitated for the adhesion. When speed is low, there is sufficient time for water to be ejected from the tyre/road interface, irrespective of macrotexture, and in such cases, macrotexture is not considered as important. At high speeds, however, there is no adequate time for water drainage at the tyre/road interface. A deep macrotexture is then necessary to handle the excess water so that the water will not separate the tyre rubber from the road surface. Therefore, the higher the speed, the higher is the importance of macrotexture.

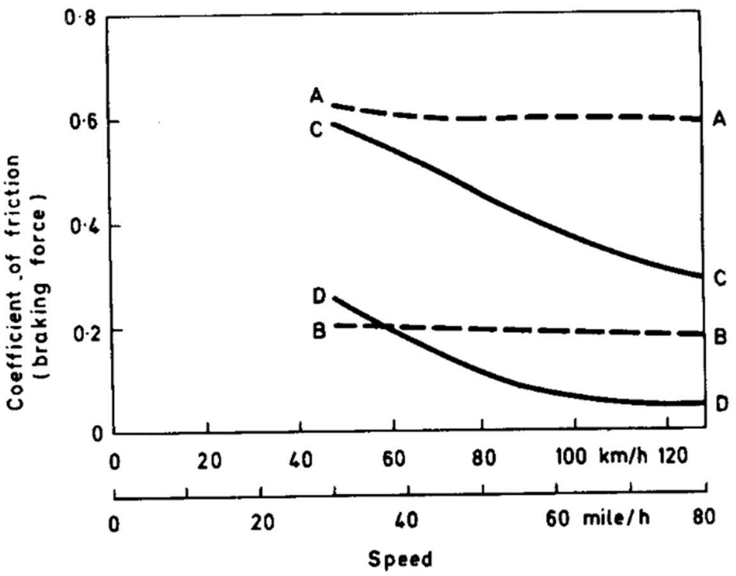


Figure 45 Wet skid resistance of difference surface textures presented in Figure 43. A is rough, harsh road surface; B is rough, polished road surface; C is smooth harsh road surface and D is smooth polished road surface [14].

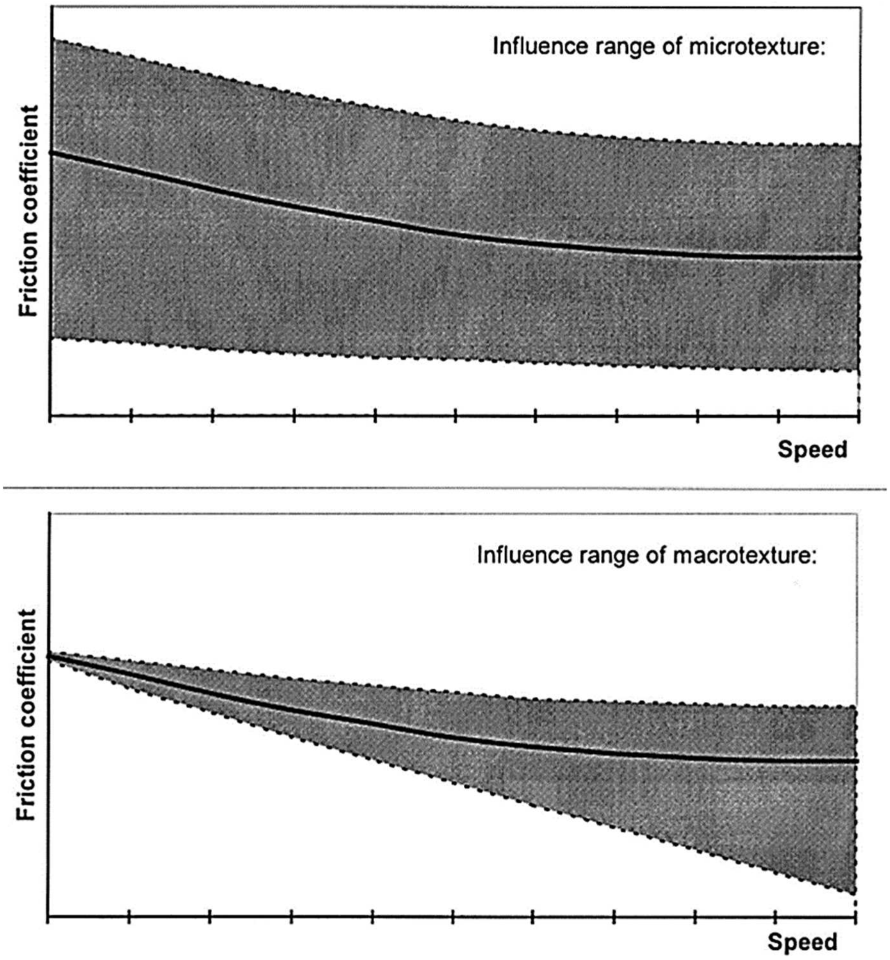


Figure 46 Typical relation on a wet road between friction coefficient and driving speed (as opposed to the sliding speed in Fig. 5). Note that microtexture significantly affects the entire range, while macrotexture affects only at high speeds [108].

As discussed in the previous sections, the drainage capacity at the tyre/road interface is determined by two components, the tyre tread, and the pavement. In the case of tyres in worn state, this drainage capacity will be mainly contributed by the pavement characteristics. The wet braking test shown in Figure 47 can give an insight of such circumstances. The tests are conducted with smooth tyres on surfaces with similar harsh microtexture, but varied macrotexture. It can be seen that on macrorough surface A, the smooth tyre and the patterned tyre perform similarly, indicating the effect of the surface texture on drainage capacity outweighs that of the tread pattern. However, on surface C with smooth macrotexture, where the drainage capability of the roadway is weakened, the two tyres behave very differently. At low speed, a similar friction coefficient is maintained for both smooth and patterned tyres. However, the smooth tyre experiences a drastic drop of wet traction with increasing speed in comparison to the patterned tyre. This is due to the absence of both components that contribute to the drainage capacity at the tyre/road interface.

The studies discussed above validate an important point: that drainage solely associated with rough road texture or with well-designed tread patterned, is not sufficient to provide good adhesion in the wet condition. The two components of the drainage mechanism at the tyre/road interface, the tyre tread, and the road surface texture, must be both positively present for the effective wet grip development. The last trace of water film (of the order of 0.01 mm) can only be removed by the fine-scale sharp asperities of the microtexture, on which high localized pressures (of the order of 7 MN/m^2) are built up [14]. Thus, slippery conditions will occur, even on a rough surface with a good, patterned tyre, if the individual aggregate of the surface is polished (surface B in Figure 43). Moreover, the tread patterns are found hardly effective on polished smooth surfaces, which concludes that the tread pattern cannot compensate for lack of road texture. An example of free-rolling test conducted with patterned and worn tyres on concrete surface and surface covered with polythene can further support the statement discussed above [14], see Figure 48. It validates that the best wet grip performance is established when both tyre tread and road texture are functioning for water drainage (see patterned tyre). The performance drops when one component is ineffective, such as worn (treadles) tyre on textured surface. The worst scenario is then represented by worn tyres on polythene with malfunction of both water drainage mechanisms.

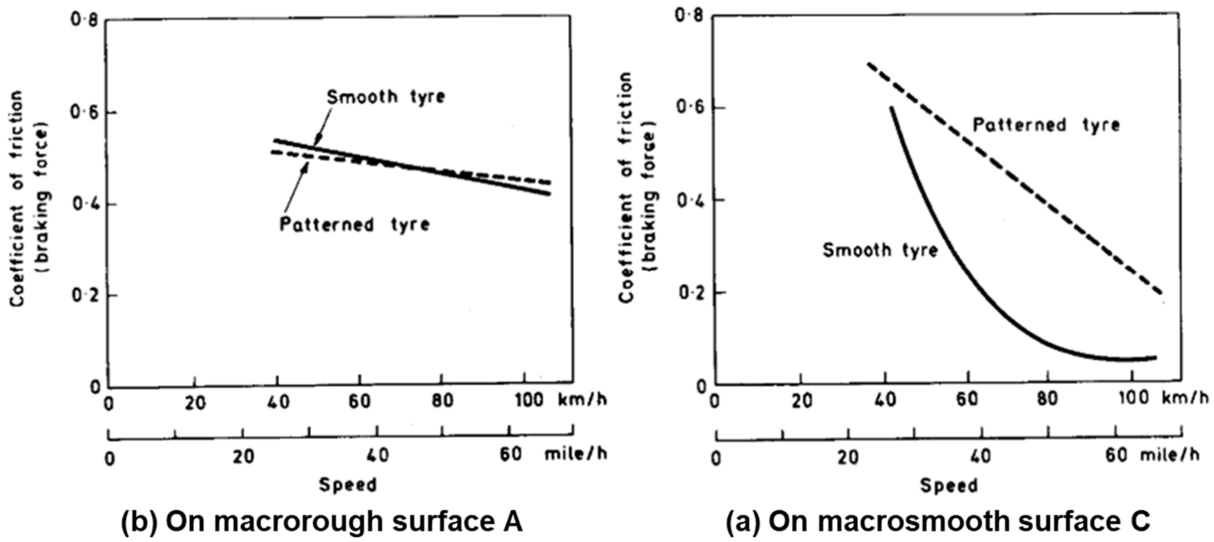


Figure 47 Tread pattern effect on macrorough surface A and macrosmooth surface C [14]*, where A is rough, harsh road surface and C is smooth harsh road surface.*

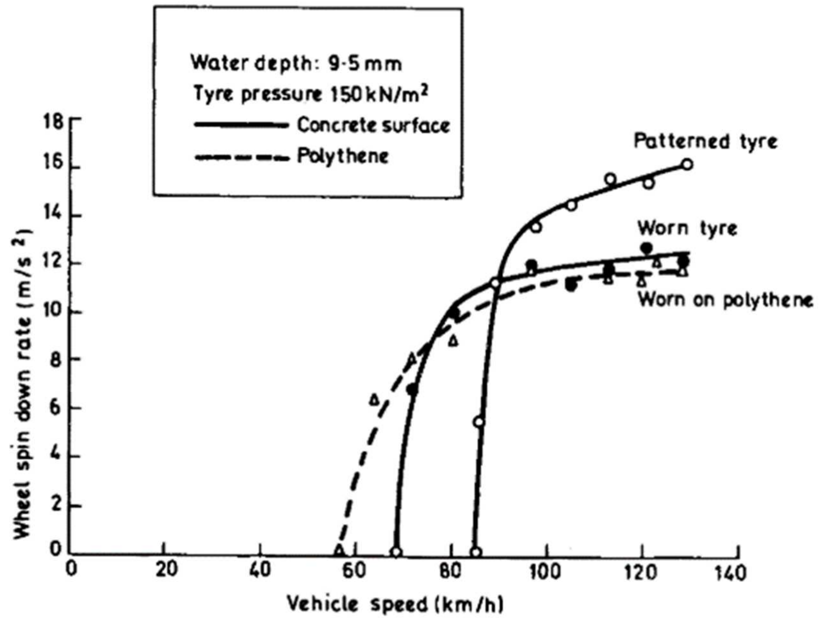


Figure 48 Effect of vehicle speed on wheel spin-down rate for a patterned and worn crossply tyre [14].

In summary, the effect of road surface characteristics on wet grip performance is best illustrated by Figure 49. The harsh microtexture of a surface determines the low-speed skid number while the coarse macrotexture of a surface determines its drainage characteristics. Drainage characteristics then determine the variation in wet skid resistance with speed. The way that surface microtexture affects the friction level is illustrated in Figure 49 (a). On a surface with constant macrotexture, adding microtexture leads to increased friction levels. The effect of macrotexture on a surface of constant microtexture is shown in Figure 49 (b). The friction level at low speeds remains relatively constant with increasing macrotexture, which can be attributed to the water inertial effects varying with the square of velocity [104]. At low speeds, the effect is minimal, but at higher speeds, it leads to a significant loss in friction. Increasing the macrotexture increases the number of water outflow channels and reduces the build-up of hydrodynamic pressure. It is important to note that whether it is thin-film or dynamic variety, hydroplaning occurs most readily with smooth tyres in combination with a smooth, fine textured surface. For surfaces categorized as coarse or open textured, dynamic hydroplaning does not occur until the depth of the water film exceeds the height of the surface projection [104]. The discussion on the water depth effect will be continued in the following section.

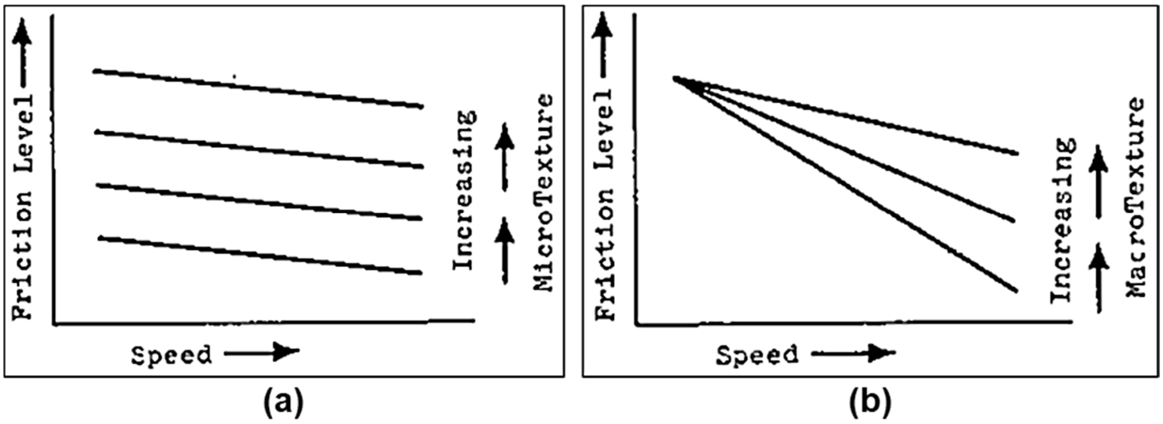


Figure 49 (a) Effect of microtexture on friction; (b) effect of macrotexture on friction [104].

2.3.4 Water depth

A significant loss in friction can occur when contaminants such as water from rainfall are present on a pavement surface, acting as lubricating agents that cause a loss in the braking ability of the vehicles and can potentially lead to the occurrence of hydroplaning under certain conditions [29], [64], [109]–[114]. The effectiveness of the aforementioned drainage mechanisms at the tyre/road interface is heavily dependent on the water depth encountered. Hydroplaning would occur when the water depth handled is exceeding the drainage capacity of the tyre tread and road surface characteristics. The three-zone contact discussed in section 2.2.2 describes the tyre/road interaction according to the hydrodynamic lubrication theory. These three water dispersal stages of the contact patch handle different levels of water depth: Zone A, hydrodynamic zone contains a water depth over 0.5 mm; Zone B, viscodynamic zone is dealing with the water film a few microns to 0.5 mm deep and Zone C, damp zone where intermittent residual water film in the order of 0.01 mm is present [13], [14]. The water depth is accounted above the summit of the road roughness, while the damp situation corresponds to negative water depth, as shown in Figure 50.

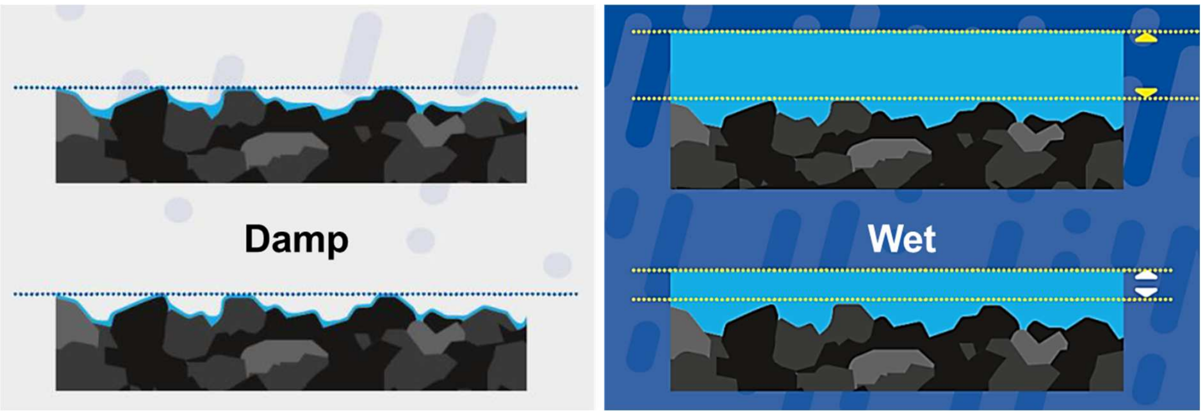


Figure 50 Water depth is accounted above the summit of the road roughness, while damp situation corresponds to negative water depth [13].

The effect of water depth on wet traction has been intensively studied [29], [64], [109]–[115]. One early study [14] conducted locked-wheel braking tests with increasing water depth from 0.25 mm up to 10 mm, as shown in Figure 51. The results show a significant difference in the braking force coefficient for water depth in the range of “just wet” to 4 mm, particularly at the higher speeds. However, the results vary less for the tests conducted with water depth from 4 mm to 10 mm. The study suggests that the critical water depth for wet traction should be no more than 4 mm. Kulakowski and Harwood [115] proposed that the friction coefficient reaches a level μ_F (final friction coefficient), at which there is no more variation with increasing water depths. A critical water depth h_{crit} is defined as the depth at which the dry friction $\mu_{(0)}$ has lost an equivalent of 75% of $\Delta\mu$ (see Figure 52). The 75% threshold was chosen arbitrarily. It should be noted that the critical water depth is significantly influenced by both the surface texture and the tyre characteristics [115].

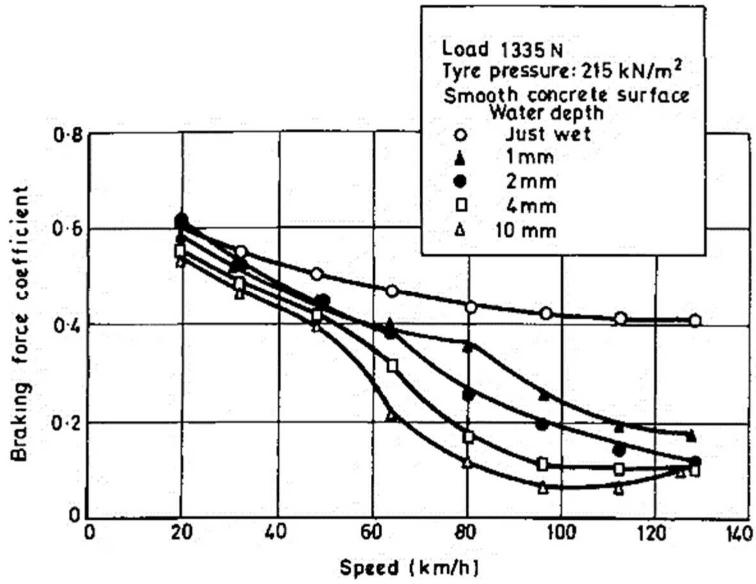


Figure 51 Effect of water depth on the locked-wheel braking force coefficient with a radial ply patterned tyre [14].

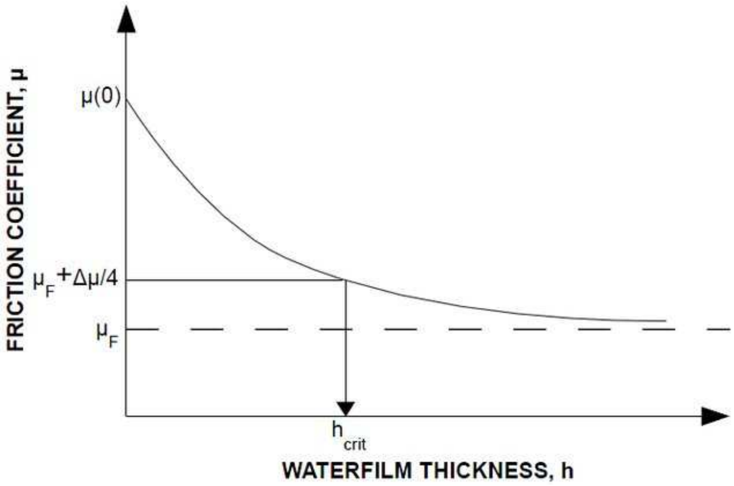


Figure 52 Relationship between tyre-pavement friction and water-film thickness [115].

Based on the factors discussed in the previous sections, a further understanding on the combined effect of surface texture, water depth and tyre pattern on the locked-wheel braking force coefficient can be demonstrated in Figure 53. The top band of the results shows the impact of water depth on different surfaces, and the lower band demonstrates the influence induced by tread pattern on wet grip on smooth concrete with increasing water depth. It is seen that at the low and medium speeds (50 and 80 km/hr), the tread pattern effects are larger than the surface texture effects, but at the higher speeds, the surface texture becomes more important. Regarding water depth, both bands show the same decreasing trend with increasing water depth, indicating the negative effect of water depth on wet traction. More importantly, the effects of road surface texture and tread pattern are found greatly strengthened within the water depth of 3 mm to 4 mm, particularly at the higher speeds of 80 and 120 km/hr.

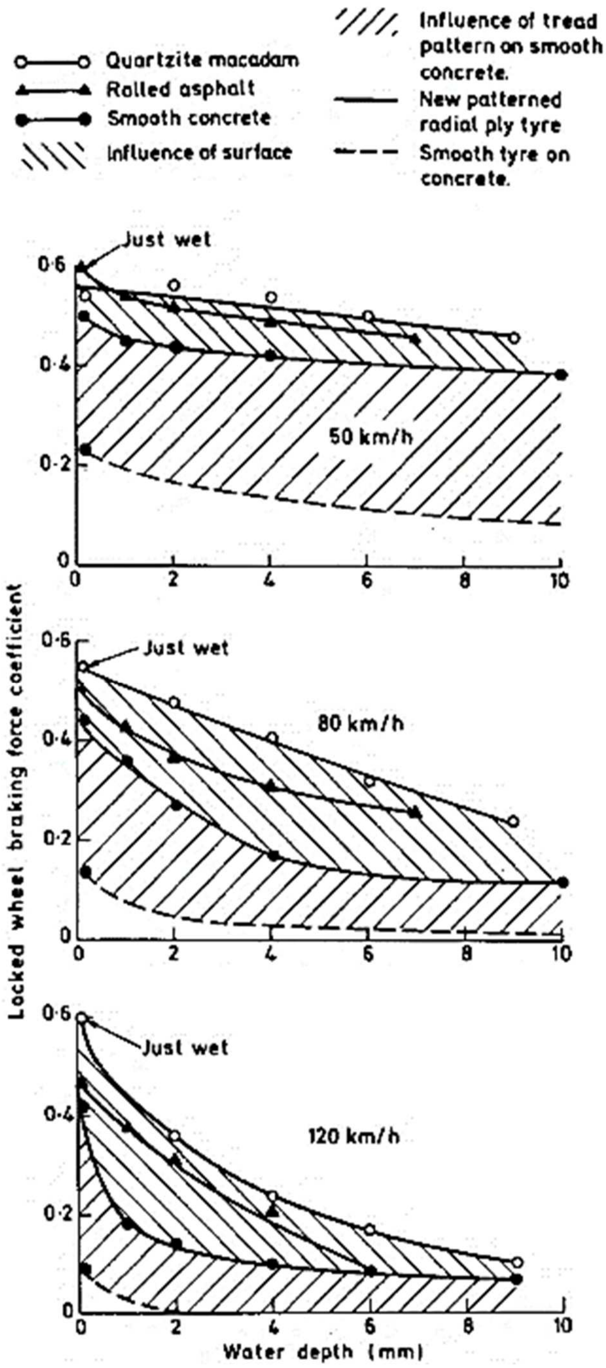


Figure 53 Effect of surface and water depth on locked-wheel braking force coefficient [14].

For the tyres in worn states, the interaction between the water depth and road texture is expected to be changed, considering the share of the water used to fill the cavity of the tread surface will no longer contribute to drainage capacity at the tyre/road interface. An example shown in Figure 54 further confirms this statement. The effect of water depth on the hydroplaning speed is evaluated through the onset of wheel spin-down. An increase in water depth generally has the effect of decreasing the hydroplaning speed, at which wheel spin-down is initiated. The first point to note from Figure 54 is that the smooth worn tyre starts to spin down at the minimum water depth in comparison to the same tyre type with full tread. This indicates that the tyre wear acts negatively on wet traction with increasing water depth. Since both tested tyres are smooth, the water drainage mechanism is only functioning from the road surface texture side. It can be suggested that wet grip performance under such conditions is dominated by tread depth. On the other hand, the study found that the vehicle speed is fairly constant for the larger water depth until, at about 3 mm depth, at which a vehicle speed of 130 km/hr is required for even the worn smooth tyre to spin down. Hence, the critical water depth for the investigation of loss of grip should not be more than about 3-4 mm [14] also applies for worn tyres. The statement can be further supported by the test results shown in Figure 55. The effect of tread depth level is seen more significant on surfaces with 1 mm and 3 mm water depths. Additionally, Veith [113] conducted tests with full and half skid depth tyres and showed that the friction coefficient is independent of water depth at low speeds (30 to 50 km/h), but it is strongly influenced by water depth at high speeds (96 km/h or greater). It was found that the friction coefficient varied as the logarithm of water depth (see Figure 56). Water film thicknesses greater than 0.12 mm were studied.

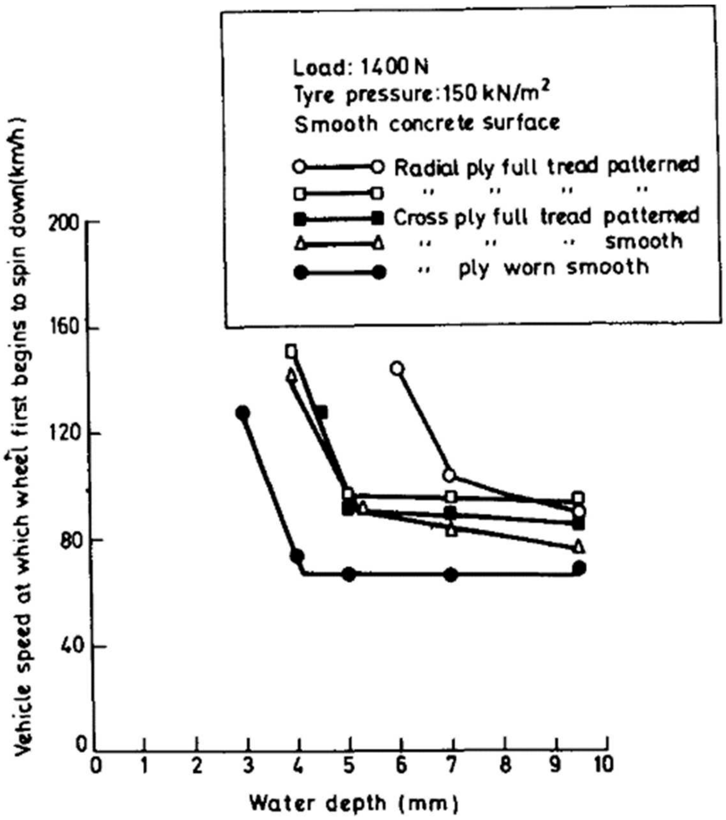


Figure 54 Effect of water depth on the vehicle speed at which test wheel begins to spin down [14].

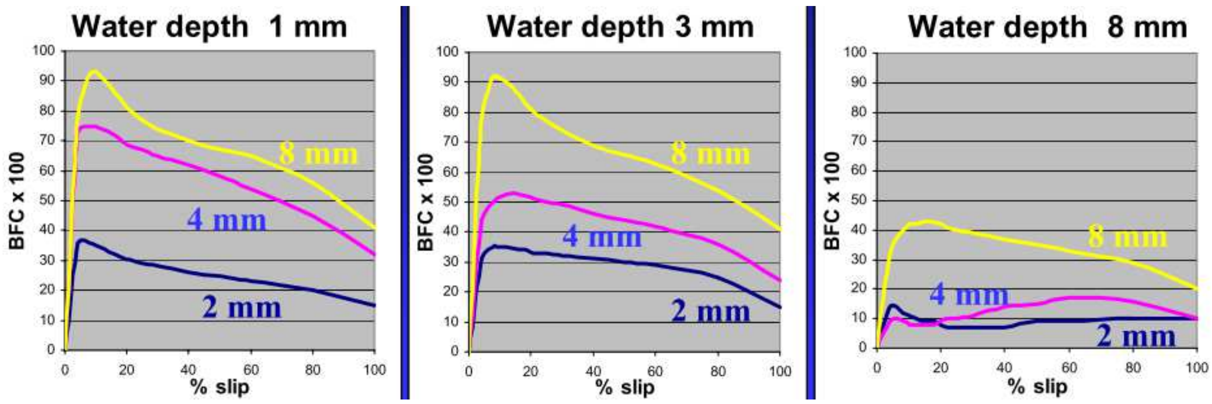


Figure 55 Water depth influence on wet braking test of summer tyre 195x65R15 with 3 tread depths levels [116].

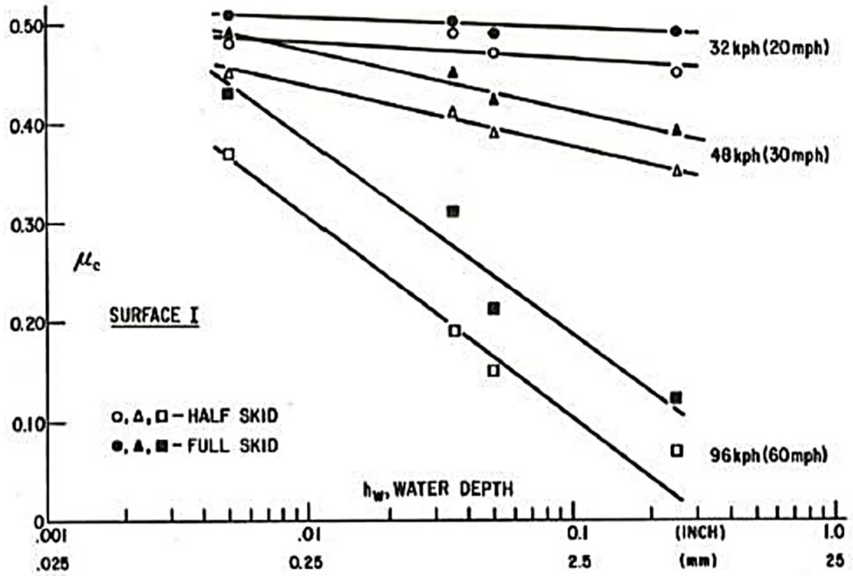


Figure 56 Friction versus water depth for full and half skid depth tyres [113].

2.3.5 Inflation pressure and vehicle load

The vertical load acting on a tyre divided by the tyre footprint area determines the average tyre/road contact pressure. For smooth tread tyres, this contact pressure is approximately equal or proportional to the tyre inflation pressure. The difference in the pressure within and without (atmospheric pressure) the tyre footprint creates forces that expel the water encountered by tyre/road interface at velocities proportional to the square root of the tyre/road contact pressures. Thus, increasing the tyre inflation pressure increases the flow rate of water drainage out of the footprint, leading to a higher hydroplaning speed [22]. As for a patterned tyre with grooves cut or moulded into the tread, the contact area between the tread rubber and the pavement surface is reduced. Consequently, the contact pressures on the tread ribs and blocks are increased that further increases the flow rate of water draining out of the footprint. This phenomenon contributes to the effectiveness of tyre tread patterns in improving wet traction and increasing the hydroplaning speed. Moreover, under- or overinflation of tyres can give rise to the contact pressure in the central region to be lower or higher than at the boundaries, as seen in Figure 57 (b) and (c). These are considered unfavourable conditions for wet grip [44]. A common misconception is that under-inflated tyres would reduce the risk of hydroplaning. However, underinflation of tyres can lead to reduced contact pressure that adversely affects the traction development. Furthermore, the bulk water at the contact patch tends to be channelled towards the centre due to the imbalanced pressure condition. Overinflation of tyres also increases the risk of hydroplaning. When the tyre is over-inflated, it becomes more stiff and it would maintain a significantly reduced contact area with the pavement, resulting in a reduced grip on the road [32]. Additionally, the deformation induced by overinflation tends to close the grooves and thereby increases the risk of dynamic hydroplaning at lower vehicle speeds [117].

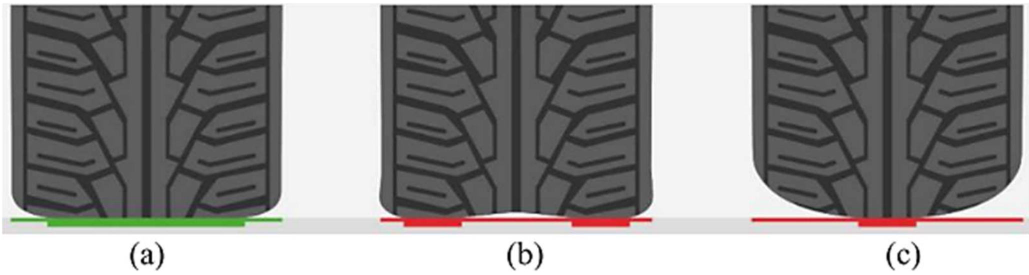


Figure 57 Tyre/road contact under different conditions of inflation pressure [32]*, (a) correctly inflated; (b) under-inflated and (c) over-inflated.*

Tyre inflation pressure is once considered as the single important parameter that determines the hydroplaning speed, as indicated in Equation 1 [29]. Later understandings (see section 2.3.2.1) also confirm its significant effect on hydroplaning speed. In a study on hydroplaning of passenger tyres [118], a simulation model is applied to evaluate the effects of the following four factors on wet grip of passenger car tyres, including wheel load, tyre inflation pressure, water film thickness, and vehicle sliding speed. It is found that under the normal operating conditions, hydroplaning speed increases with wheel load and tyre inflation pressure but decreases with the water depth. Tyre inflation pressure is identified to be the most important factor affecting the magnitude of hydroplaning speed, followed by water film thickness and wheel load. While in the case of truck tyres, Cao [119] reported that the inflation pressure does not have a significant effect on the hydroplaning speed of truck tyres. On the other hand, El-Sayegh and El Gindy [120] argue that the hydroplaning speed of truck tyres increases with the inflation pressure, but the increment is insignificant based on numerical study.

The effect of inflation pressure on the hydroplaning speed of passenger car tyres and truck tyres is further investigated in Figure 58. It is reported that the NASA equation correctly predicts the rate of increase of hydroplaning speed with tyre inflation pressure for passenger cars. However, the same rate of increase as predicted by the NASA equation leads to overestimation for the case of truck tyre. The hydroplaning speed of a truck tyre increases with its inflation pressure at a much slower rate. More specifically, the NASA equation overestimates truck hydroplaning speed by as much as 60 km/h over the normal operating inflation pressure of truck tyres. Hence, the study highlights that truck hydroplaning can occur within the normal highway operating speed range [56]. The analysis in this study suggests that different hydroplaning behaviours of truck and passenger car tyres are likely to be caused by differences in tyre properties and by the complicated interactions among the tyre, the pavement surface, and the water depth. These differences then consequently affect the development of hydrodynamic uplift forces at the tyre/road interface, which is the key factor to the occurrence of hydroplaning.

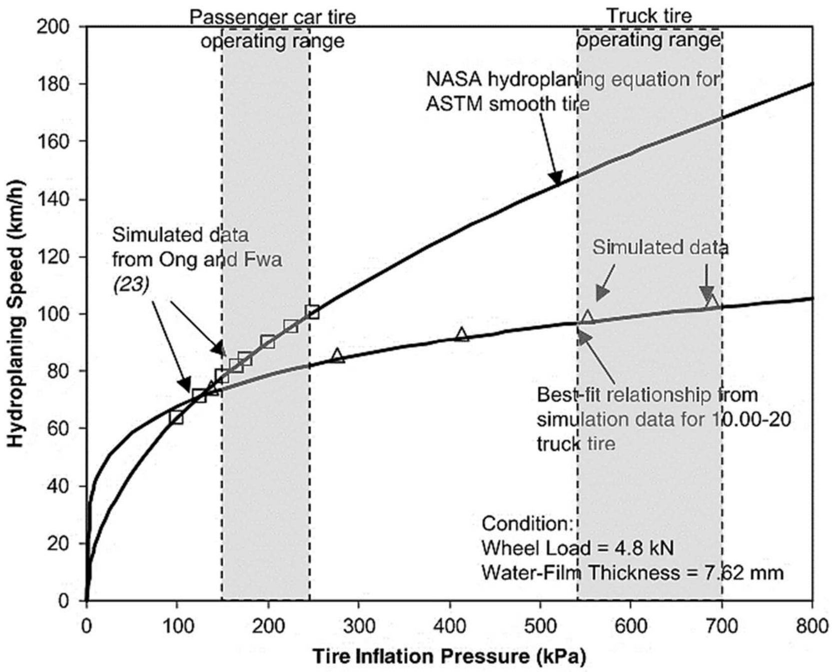


Figure 58 Comparison between truck tyre and ASTM smooth tyre hydroplaning [56].

On the other hand, the vertical load is found to have a small effect on tyre hydroplaning speed [29]. As the tyre acts as an elastic body, changes in the vertical load induce changes in the tyre footprint area so that the tyre inflation pressure would remain approximately constant. Early research on aircraft tyres finds that increasing the tyre load from zero to the maximum static load only leads to a 3% to 4% rise in the tyre inflation pressure, and less than 2% increase in the hydroplaning speed. Though, the effect of wheel loads may be positive or negative depending on tyre tread depth and construction [26], [64]. On the other hand, some studies [121]–[123] have reported that wet-pavement accident rates were higher for empty trucks than for fully loaded trucks. A numerical study examined the effect of truck wheel load on hydroplaning speed [56]. Figure 59 (a) shows the variation in hydroplaning speed for a 10.00-20 (10 means nominal cross sectional width in inches; 00 is aspect ratio defined as cross sectional height/cross sectional width expressed in percentage. In this case it is 100%. 20 is rim diameter in inches) bias-ply truck tyre with a tyre inflation pressure of 552 kPa and varying truck wheel load on a flooded pavement surface with 4.8 mm water film thickness. The results show that, as the truck tyre load increases from 2.5 kN to 22.3 kN, the hydroplaning speed sees a 25% increase (from 100.2 km/h to 125.5 km/h). The effect induced by wheel load on hydroplaning speed follows the same trend under various water depth levels, see Figure 59 (b). Moreover, with increasing water depth, truck tyre hydroplaning speed decreases. A less significant drop of hydroplaning speed is noted when the water depth is over 4.8 mm, which agrees with the conclusion drawn on critical water depth from the previous section.

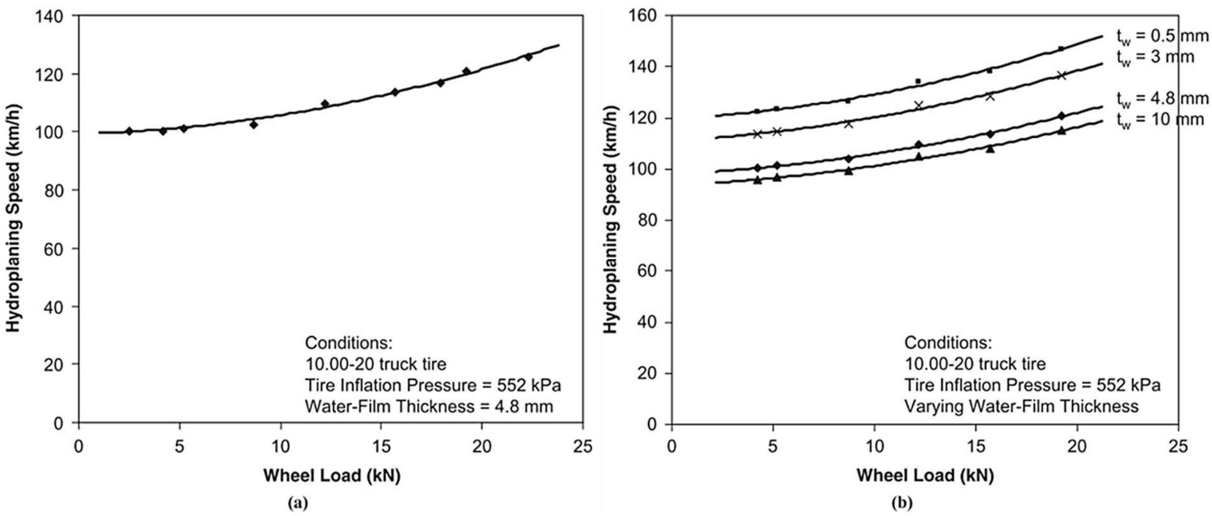


Figure 59 Effect of truck wheel load on hydroplaning speed: (a) 2.5 kN and (b) 22.3 kN [56].

Lastly, the effect of inflation pressure on hydroplaning speed of tyres in worn state has been discussed in the past study [28]. The tests are conducted on a smooth closed-textured (macrosmooth) surface. The results indicate the combined effects of the "water wedge" and viscous lubrication lead to the hydroplaning speeds significantly lower than that predicted by Equation 1. It is stated that the NASA formula is not applicable for worn tyres as the tests results show the hydroplaning of worn truck tyres operating at 100 psi and schedule load is found to occur at speeds as low as 80 kph (50 mph), which is at only 50% of the speed predicted from the Equation 1[28].

2.4 Wet Grip Evaluation Methods

Today, the regulatory wet braking test (R117) [124] specifies a vehicle braking from 80 kph to 20 kph on a road with a water depth of 1.0 ± 0.5 mm. The regulatory test conditions are considered having well represented the wet usage of tyres, since:

• More than 90% of accidents occur with an initial speed inferior or equal to 80 kph.

• 1mm water depth is an existing situation on the roads, for 1% of the wet time.

As discussed above, wet grip of tyres in worn state can significantly vary from new tyres. Evaluation of wet grip of worn tyres would be necessary since it is stated the worst condition for such performance. It is found the test conditions of R117 [124] are also relevant for tyres in worn state [9]. The wet grip performance of tyres in worn state is then proposed to be included in the future update of R117 with the assistance of the conclusions drawn from IWG WGWT and current study.

2.4.1 New tyres

As regulated in R117 [124], there are two tests can be performed to evaluate wet grip performance of new tyres (C1, C2 and C3), shown as below:

— Trailer test at 65 km/h on 1 ± 0.5 mm water depth.

— On vehicle braking test 80-20 km/h on 1 ± 0.5 mm water depth.

Reference tyres are used in the tests. With the test results, a wet grip index $G(T_n)$ of the candidate tyre Tn (n=1, 2, 2) is calculated as follows:

$$G(\mathrm{T}_n) = K_{\mathrm{trailer}} \cdot \{\overline{\mu_{peak}}(\mathrm{T}_n) - [a \cdot \Delta\mu_{peak}(\mathrm{R}) + b \cdot \Delta\vartheta + c \cdot (\Delta\vartheta)^2 + d \cdot \Delta MTD]\}$$

Equation 8

where:

$\overline{\mu_{peak}}(T_n)$ is the arithmetic mean of the peak braking force coefficients of the candidate tyre Tn within a braking test,

$$\Delta\mu_{peak}(R) = \mu_{peak,adj}(R) - \mu_{peak}(R_0)$$ *Equation 9*

$\mu_{peak,adj}(R)$ is the adjusted peak braking force coefficient in accordance with Table 7.

$\mu_{peak}(R_0) = 0.85$ is fixed as the peak braking force coefficient for the reference tyre in the reference conditions.

$$\Delta\vartheta = \vartheta - \vartheta_0$$ *Equation 10*

ϑ is the measured wet surface temperature in degrees Celsius when the candidate tyre Tn is tested.

ϑ_0 is the wetted surface reference temperature for the candidate tyre according to its sidewall marking as listed in Table 8.

$$\Delta MTD = MTD - MTD_0$$ *Equation 11*

MTD is the measured macrotexture depth of the track using the sand patch method (ASTM E-965).

MTD_o = 0.8 mm is fixed as the macrotexture depth of the reference track.

$K_{trailer}$ = 1.50 is a factor to grant consistency between previous calculation of the wet grip index and this one, and to ensure convergence between vehicle and trailer method and coefficient a, b, c and d are given in Table 8.

Table 7 The values of the constants used for calculation of $\Delta\mu_{peak}(R)$.

If the number and the sequence of candidate tyre sets within one test cycle is:	*and the candidate tyre set to be qualified within this test cycle is:*	*the corresponding adjusted peak braking force coefficients of the reference tyre is calculated as follows:*
1 $R_i - T_1 - R_f$	T_1	$\mu_{peak,adj}(R) = 1/2 \cdot [\overline{\mu_{peak}}(R_i) + \overline{\mu_{peak}}(R_f)]$
2 $R_i - T_1 - T_2 - R_f$	T_1	$\mu_{peak,adj}(R) = 2/3 \cdot \overline{\mu_{peak}}(R_i) + 1/3 \cdot \overline{\mu_{peak}}(R_f)$
	T_2	$\mu_{peak,adj}(R) = 1/3 \cdot \overline{\mu_{peak}}(R_i) + 2/3 \cdot \overline{\mu_{peak}}(R_f)$
3 $R_i - T_1 - T_2 - T_3 - R_f$	T_1	$\mu_{peak,adj}(R) = 3/4 \cdot \overline{\mu_{peak}}(R_i) + 1/4 \cdot \overline{\mu_{peak}}(R_f)$
	T_2	$\mu_{peak,adj}(R) = 1/2 \cdot [\overline{\mu_{peak}}(R_i) + \overline{\mu_{peak}}(R_f)]$
	T_3	$\mu_{peak,adj}(R) = 1/4 \cdot \overline{\mu_{peak}}(R_i) + 3/4 \cdot \overline{\mu_{peak}}(R_f)$

Table 8 The values of the constants used for calculation of wet grip index $G(T_n)$.

Category of use		ϑ_0 (°C)	*a*	*b* (°C⁻¹)	*c* (°C⁻²)	*d* (mm⁻¹)
Normal tyre		20	+0.99757	+0.00251	−0.00028	+0.07759
Snow tyre		15	+0.87084	−0.00025	+0.00004	−0.01635
	Snow tyre for use in severe snow conditions	10	+0.67929	+0.00115	−0.00005	+0.03963
Special-use tyre		not defined				

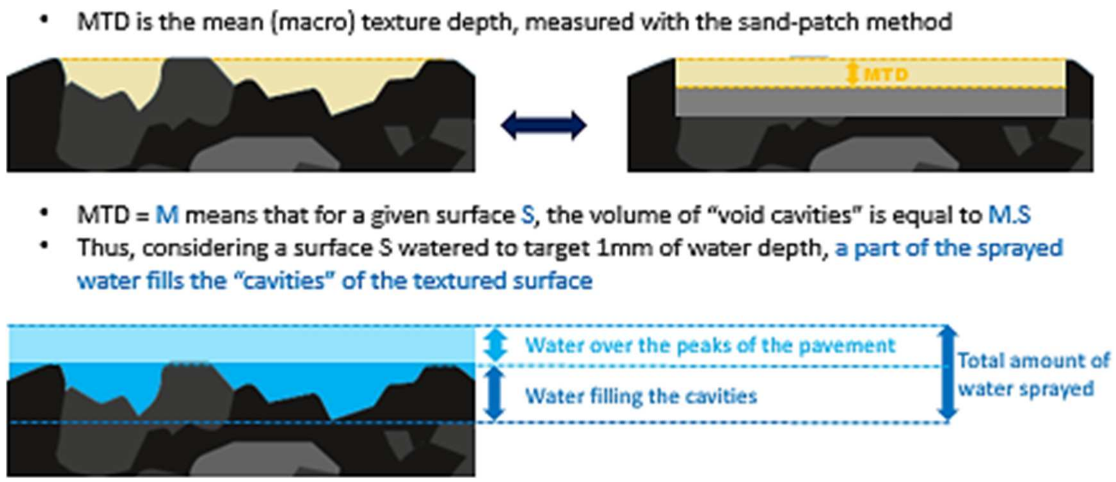


Figure 60 Definition of 1mm water depth considering MTD.

For the vehicle test, which will be used for this project, the wet grip index G(Tn) of the candidate tyre Tn (n = 1, 2 or 3) is calculated as follows:

$$G(\mathrm{T}_n) = K_{\mathrm{vehicle}} \cdot \{\overline{BFC_{ave}}(\mathrm{T}_n) - [a \cdot \Delta BFC(\mathrm{R}) + b \cdot \Delta\vartheta + c \cdot (\Delta\vartheta)^2 + d \cdot \Delta MTD]\}$$

Equation 12

where:

$\overline{BFC_{ave}}(\mathrm{T}_n)$ is the arithmetic mean of the average Braking Force Coefficients of the candidate tyre T_n within a braking test.

$$\Delta BFC(R) = BFC_{adj}(R) - BFC(R_0)$$

Equation 13

$BFC_{adj}(R)$ is the adjusted average Braking Force Coefficient in accordance with Table 9.

$BFC(R0)$ = 0.68 is fixed as the Braking Force Coefficient for the reference tyre in the reference conditions.

$$\Delta\vartheta = \vartheta - \vartheta_0$$ *Equation 14*

ϑ is the measured wet surface temperature in degrees Celsius when the candidate tyre Tn is tested.

ϑ_0 is the wetted surface reference temperature for the candidate tyre according to its category of use as listed in Table 10.

$K_{vehicle}$ = 1.87 is a factor to grant consistency between previous calculation of the wet grip index and this one, and to ensure convergence between vehicle and trailer method and coefficients a, b, c and d are given in Table 10.

Table 9 The values of the constants used for calculation of $BFC_{adj}(R)$.

If the number and the sequence of candidate tyre sets within one test cycle is:	*and the candidate tyre set to be qualified within this test cycle is:*	*the corresponding adjusted average Braking Force Coefficient of the reference tyre is calculated as follows:*
1 $R_i - T_1 - R_f$	T_1	$BFC_{adj}(R) = 1/2 \cdot [\overline{BFC_{ave}}(R_i) + \overline{BFC_{ave}}(R_f)]$
2 $R_i - T_1 - T_2 - R_f$	T_1	$BFC_{adj}(R) = 2/3 \cdot \overline{BFC_{ave}}(R_i) + 1/3 \cdot \overline{BFC_{ave}}(R_f)$
	T_2	$BFC_{adj}(R) = 1/3 \cdot \overline{BFC_{ave}}(R_i) + 2/3 \cdot \overline{BFC_{ave}}(R_f)$
3 $R_i - T_1 - T_2 - T_3 - R_f$	T_1	$BFC_{adj}(R) = 3/4 \cdot \overline{BFC_{ave}}(R_i) + 1/4 \cdot \overline{BFC_{ave}}(R_f)$
	T_2	$BFC_{adj}(R) = 1/2 \cdot [\overline{BFC_{ave}}(R_i) + \overline{BFC_{ave}}(R_f)]$
	T_3	$BFC_{adj}(R) = 1/4 \cdot \overline{BFC_{ave}}(R_i) + 3/4 \cdot \overline{BFC_{ave}}(R_f)$

Table 10 The values of the constants used for calculation of wet grip index $G(T_n)$ with vehicle test.

Category of use	ϑ_0 (°C)	a	b (°C^{-1})	c (°C^{-2})	d (mm^{-1})
Normal tyre	20	+0.99382	+0.00269	-0.00028	-0.02472
Snow tyre	15	+0.92654	-0.00121	-0.00007	-0.04279
Snow tyre for use in severe snow conditions	10	+0.72029	-0.00539	+0.00022	-0.03037
Special-use-tyre	Not defined				

It is reported that the wet grip potential of worn tyres cannot be inferred from that of the new tyres since the decline of performance may vary significantly from one tyre to another [50]. Additionally, testing tyres in the new state does not give any information on the hydroplaning performance of worn tyres, which would be essential factor that contribute to the overall performance of a worn tyre on under wet conditions. Hence, testing of tyres in worn state would be necessary to further comprehend the interaction between tyre wear and wet grip mechanisms.

2.4.2 Worn tyres

There are generally two steps for the wet grip evaluation of worn tyres: 1) preparation of the tyre in worn state; 2) wet grip index evaluation of the tyre in worn state.

2.4.2.1 Preparation of the tyres in worn state

Tyre buffing is a widely used process for the preparation of preparation of the tyres in worn state [125]–[131], an example of tyre buffing apparatus is shown in Figure 61. The purpose of which is to permit the preparation of test tyres with a uniformly reduced tread groove depth and tread geometry that will yield repeatable test results while avoiding the time-consuming and costly over-the-road natural wearing of tyres. Several patents have been issued for this purpose, as listed in Table 11.

Figure 61 Tyre buffing apparatus [8].

Table 11 The available patents regarding buffing process [125]–[130].

1	Tyre tread buffing apparatus and method	1941	United States Patent
2	Tyre buffing machine blades	1975	United States Patent
3	Tread buffing apparatus	1993	United States Patent
4	Tyre tread buffing apparatus and method	2014	United States Patent

5	Process for retreading worn tyres and the tyres obtained therefrom	2005	United States Patent
6	Expandable rim for tyre tread buffing apparatus and method	2020	European Patent Specification

The IWG WGWT proposed to achieve the profile of "tyre in worn state" or "worn tyre" by following a tyre buffing and grinding process. A minimum number of 4 positions (see in Figure 62) approximately equally spaced around the circumference should be chosen for the measurements and the final tread profile should be aligned with the measurement points illustrated in Figure 63. For all the measurement points defined in the central zone:

- The final groove depth at each individual measurement point of the central zone shall be 2 mm ± 0.4 mm.
- The average groove depth over all measurement points in the central zone shall be 2 mm ± 0.2 mm.

For each measurement point defined in the shoulder zone:

- The final groove depth in the shoulder zone shall not be greater than 2 mm.

Furthermore, the artificially worn tyres of class C1 after removal of predetermined amount of tread rubber with cutting and grinding, should reach a certain surface finish condition for subsequent wet grip index testing. Thus, the arithmetic average roughness of the final surface ***Ra*** shall not exceed 20 µm. The preparation of C2 and C3 tyres if necessary is currently being further discussed.

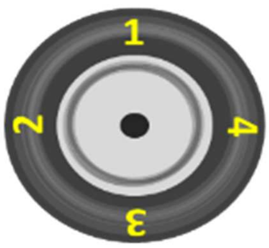


Figure 62 4 positions chosen approximately equally spaced around the circumference of the tyre [8].

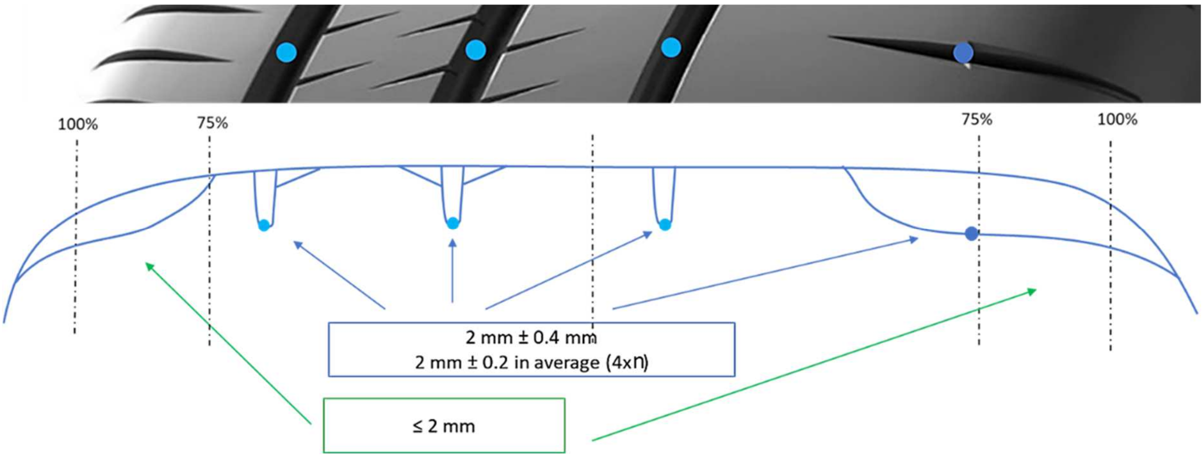


Figure 63 Final groove depth after tyre buffing and grinding process [8].

2.4.2.2 Evaluation and validation of worn tyre performance

As for the final evaluation of the wet grip performance, The IWG WGWT is currently under ongoing discussions to modify the wet grip index (G) formula for the worn tyre scenario. It is mentioned that an interaction is expected between water depth and MTD considering the part of water used to fill the cavity of the tread surface now will be released to the contact patch. Moreover, SRTT worn is also considered in the analysis as a possible descriptor of the above parameters and interactions. The IWG WGWT proposed a moulded SRTT worn to eliminate the variation induced by the buffing process. The group aims to assess and test a moulded worn SRTT and introduce the relevant provisions through amendment in the regulation as it is necessary to be set in the future.

Furthermore, it is important to note that the tyre buffing process though is considered as an efficient approach to prepare tyres in worn state, however, it can be unsuitable for some applications. In one study [131] regarding the effect of tyre wear on the reduction of rolling resistance, it is found that used tyres demonstrate generally less rolling resistance than a matched new tyre buffed to the same tread depth and crown radius. The introduction of artificial wear is found to demonstrate a rolling resistance result that is not representative of "real world" conditions [131]. Thus, the combination of an artificial wear process and experimental measurements of tyre rolling resistance is not considered as a good approach to predict the tyre performance at the end of its lifespan [131]. Some preliminary test results from IWG WGWT comparing wet braking performance of naturally worn tyres and buffed tyres are presented in Figure 64. It is reported that for C1 passenger tyres, the buffed tyres demonstrate comparable wet braking performances to the naturally worn tyres. However, some variation is noted for Tyre 6 and Tyre 3. Further information would be required to clarify the causes for such different performances.

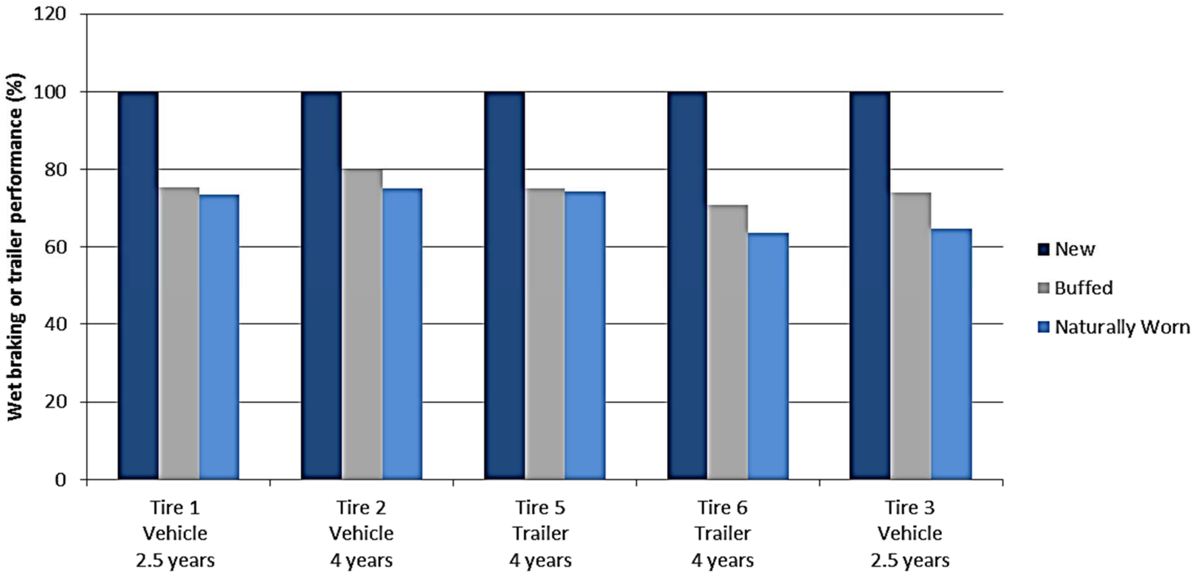


Figure 64 Loss of braking performance of worn tyre (buffed or naturally worn) versus new tyre (%) [8].

2.5 Summary

Safety on wet roads is a major concern for drivers. One of the contributing factors to wet-road incidents is the lack of friction between the tyre and pavement, thereby leading to skidding accidents and possibly hydroplaning. There are two mechanisms contributing to the wet grip performance of tyres, namely, rubber friction and hydroplaning. It is observed that wet skid situation involves grip and partial hydroplaning contribute to the highest percentage of wet accidents when the tyre loses some part of the contact patch and maintains the other. The lost part of the contact patch is attributed to the hydroplaning mechanism, while the grip mechanism determines the contact with the maintaining part. The rubber friction mechanism is discussed, and it offers an insight into the adhesion and hysteresis (deformation) frictional components. An understanding of the contact mechanisms involved in tyre-fluid-pavement is established. On the other hand, hydroplaning is a unique situation in wet pavement conditions when the tyre is lifted off the pavement surface by hydrodynamic forces. A hydroplaning speed can be reached under certain conditions, at which the tyre losses full contact with the road pavement and the wet skid resistance drops to extremely low or near-zero values. The concept of three-zone contact developed over classical lubrication concepts is introduced to characterise the ground contact area of a tyre moving on a wet surface. The three zones are categorised based on the varied tyre-fluid-pavement interaction, namely, sinkage zone (Zone A), transition zone (Zone B) and actual contact zone (Zone C). As either speed or water film thickness increases, the fully developed Zone A would replace both Zone B and Zone C and the tyre would eventually appear as skidding on the film of water. Furthermore, there are three forms of hydroplaning, namely dynamic hydroplaning, viscous hydroplaning, and reverted rubber hydroplaning. Of the three types of hydroplaning, viscous and dynamic hydroplaning are of the main concern to the vehicles operating on highways.

The hydroplaning of new tyres, though infrequent, is a danger to vehicle control on highways. However, a much greater danger exists for the vehicles fitted with smooth or well-worn tyres, since the requirements of speed and water depth for hydroplaning to occur are relatively much lower in comparison to new tyres. It is proposed that the worn tyres should be tested under wet conditions since the current regulatory conditions with a focus on new tyres cannot demonstrate the hydroplaning mechanism. The tests conducted on worn tyres indicate that the low-speed value of the μ(v) curve reflects the friction potential of the tested tyre while the loss of performance at higher speed is attributed to the hydroplaning mechanism. It is believed that the current regulatory wet braking test R117, when run with worn tyres, exhibits both rubber friction and hydroplaning mechanisms. The results also imply that worn passenger tyre performance cannot be deduced from the new tyre performance since the decline of performance may vary significantly from one tyre to another.

The wet grip performance is a complex phenomenon that is highly variable and factors affecting wet grip performance can be broadly classified into below categories: tyre tread characteristics (tread depth, tread pattern, contact patch and tread compound), pavement texture (microtexture and macrotexture), water depth, inflation pressure and vehicle load. Maintaining grip on wet surfaces involves dispersing the water to restore dry contact between the tread and the road. This process is determined by the tyre-fluid-pavement interactions. The effectiveness of the adhesion component depends upon the available drainage capacity in the tyre tread pattern or in the voids between road surface asperities, which can provide means of removing water within the contact area. In the case of tyres in worn state, performance drop of each mechanism is independent of performance at new state. The grooves of the tread pattern can vanish with wear and the tread mix can also vary throughout the tread depth. Hence, a thorough understanding of these interactions of the factors would be beneficial to better understand the wet skid process and the occurrence of hydroplaning.

Early studies evaluate the wet skid resistance of car, bus and truck tyres under various test conditions and concluded that the difference in skid resistance between car and truck tyres is due to essentially three effects: the tread compound, the higher loads and inflation pressure of the truck tyres, and the tread pattern. Since all these factors are of importance to wet grip performance, hence, the varied tyre types can behave differently when transforming from new to worn states.

The physical phenomena of dynamic hydroplaning can only be possible at a designated minimum speed when water depth on the roadway exceeds the drainage capacity at the tyre/road interface. Other factors of influence, such as tyre inflation pressure and tyre footprint size and shape, may adjust the calculation of the critical hydroplaning speed. A brief summary on the important affecting factors is presented below based on literature findings:

- The effect of vehicle speed on hydroplaning is progressive. When hydroplaning speed is reached, the steering ability of the tyre is completely lost, and the braking ability drops significantly.
- The hydroplaning speed of tyres in worn state is considerably lower than that of the new tyres when other operating conditions are held constant.
- The reduced tread depth can adversely affect the hydroplaning speed. For wet grip performance of passenger car tyres, the wet grip performance drops drastically with tread depth decreasing to below 2 mm. However, a minimum safe tread depth is found more difficult to select for truck tyres.
- A tyre may not have reached the total hydroplaning speed as predicted by Horne's equation, a hazardous condition may exist when the wheel has spun down and its frictional characteristics have been impaired. Hence, hydroplaning speed cannot be the sole criterion to evaluate the tyre sensitivity to hydroplaning phenomenon.
- As the tyre tread becomes worn, the water drainage provided by the tread pattern becomes less efficient and the hydroplaning speed is decreased.
- A contact patch in rounded shape “ploughs” more easily through the water than a rectangular shape, which is beneficial for decreasing the hydroplaning speed.
- Smooth tread tyres having high-aspect-ratio footprints will hydroplane at lower vehicle speeds than tyres with low-aspect-ratio footprints when other factors are held constant.
- For a given set of tread compounds, the one with the highest ***tan δ*** at 0°C would be expected to demonstrate the best wet traction performance, at 20°C.
- The harsh microtexture of a surface determines the low-speed skid number while the coarse macrotexture of a surface determines its drainage characteristics.

- An increase in water depth generally has the effect of decreasing the hydroplaning speed. It is suggested that the critical water depth for wet traction should be no more than 4 mm.
- Under the normal operating conditions, hydroplaning speed increases with wheel load and tyre inflation pressure. The truck hydroplaning can occur within the normal highway operating speed range.
- The vertical load is found to have a small effect on tyre hydroplaning speed.

Wet grip of tyres in worn state can significantly vary from new tyres. Evaluation of wet grip of worn tyres would be necessary since it is stated the worst condition for such performance. It is found the test conditions of R117 are also relevant for tyres in worn state. The wet grip performance of tyres in worn state is then proposed to be included in the future update of R117 with the assistance of the conclusions draw from IWG WGWT and current study. The IWG WGWT proposed to achieve the profile of "tyre in worn state" or "worn tyre" by following a tyre buffing and grinding process. Further details of the process are currently under discussion.

3 Feedback gathering

3.1 Questionnaire introduction

A 4-steps methodology based on the Delphi panel has been designed to collect the necessary information needed for this project. In the first step, it has been determined which information is relevant for the project objectives and which is the better way to obtain this information from the industry.

After receiving all the inputs, a questionnaire was designed as the main tool to gather information of the wet grip performance of tyres in worn state. A first version of the questionnaire was sent to ETRTO and ETRMA. Using their feedback, a second version of the questionnaire was prepared and sent to the Commission for final validation. The final questionnaire has been divided in 2 parts:

- Commercial Vehicle Tyres (10 questions)
- Passenger Car Tyres (8 questions)

Each part contains the necessary questions to gather information such as the main reason for replacing tyres, the average tread depth when tyres are replaced, if there is any perception of wet grip performance deterioration when the tyre is worn, the most representative tyre sizes, along with other questions that make us focus even more on the topic.

Taking the opportunity that bring us this questionnaire to gather information from the tyre market in Europe, there are also repeated questions from the last survey sent of the Commission study on tyre abrasion that will help us in this project, as they are directly related to the worn tyre wet grip performance knowledge.

The final version of the survey was distributed using the "EUSurvey"[1] tool. A total of 269 surveys were sent to six different sectors:

- Type Approval Authorities (92)
- Associations and Industry contacts (96)
- Technical Services (26)

[1] https://ec.europa.eu/eusurvey/home/about

- Environmental organizations and institutes (35)
- Non-governmental organizations (10)
- Large fleets (10)

The survey participation was very low. Of the 269 surveys sent, only 12 responses were received which gives us a participation of the 4.6%. Despite this, we believe that the responses received have great credibility as they are backed by large associations in the tyre industry. Finally, all the information obtained from the questionnaires was processed and analyzed by IDIADA.

3.2 Questionnaire

The questionnaire is divided into two parts: the first one for commercial vehicle tyres and the second one for passenger car tyres.

3.2.1 Commercial vehicle tyres

The main section of the questionnaire, related to commercial vehicle tyres (C2 and C3), contains 10 questions which intend to collect information from mileage, tread wear and wet grip performance as well as different questions that give us a picture of the current tyre population.

3.2.1.1 Main reasons for changing tyres on a heavy-duty Truck

The first question of the survey intends to know the reasons for changing tyres in heavy duty trucks. The question proposes several possible answers, and it is possible to mark multiple options. The obtained results are shown below:

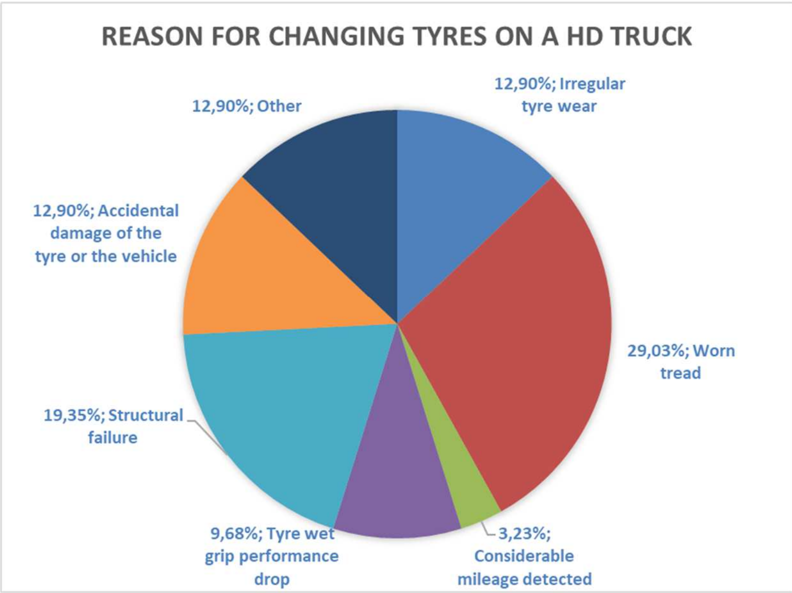


Figure 65 Reasons for changing tyres on a heavy duty truck

The result of this question is that the most important reason to change a C2 or C3 tyre is the lack of tread band (worn tread) with 29.03% of the answers. The second factor is the structural failure (19.35%) which leads to the importance of checking the integrity of the tyre during its whole lifespan. The third factor are two reasons, the accidental damage and the irregular tyre wear (both with 12.90%). The conclusion of this question is that C2 and C3 tyres are normally changed when they are worn or not possible to run (carcass breakage).

3.2.1.2 Average tread depth of replaced tyres

It is also important to know the remaining tread depth of the tyres once they are replaced in order to define a valid test method to analyse the wet grip performance in worn state. With this information, we will have a reference for the buffing process. The question has been divided into three types of tyres (premium, middle and budget) to have a better way to analyse the tyre market in Europe. The received feedback has been mainly focused on the average value, so information related to the types of tyres (premium, middle and budget) has been discarded.

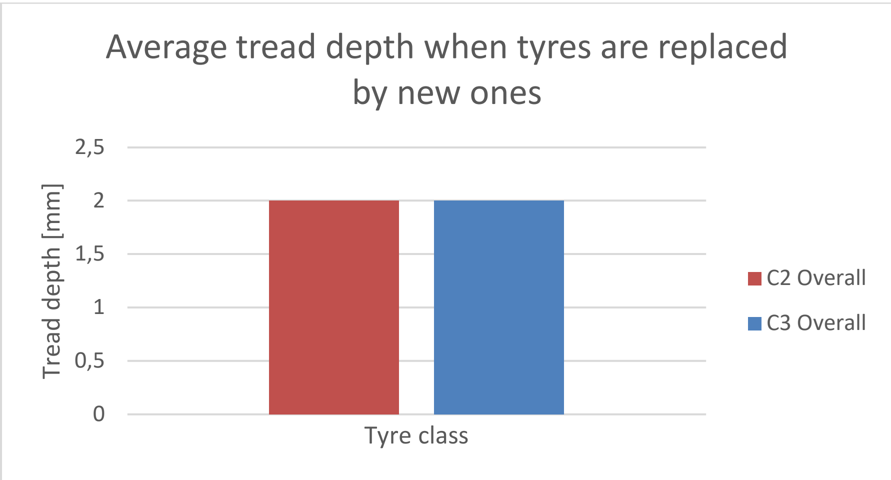


Figure 66 Average tread depth of C2 and C3 tyres before replacement

The average tread depth value for both C2 and C3 tyres is 2 mm, near the value of 1.6 mm of the tread wear indicators.

3.2.1.3 Wet grip performance perception on a worn tyre

This question has been defined to analyze the subjective feelings of commercial vehicles drivers regarding the wet grip performance of the tyres just before the replacement.

Figure 67 Wet grip performance perception on a worn tyre. C3 and C2 tyres

Considering in the above tables the blue as there is no drop of wet grip performance and the orange as drop of wet grip performance appreciation, in both classes there is a perception of drop of performance once the tyres are worn. The graphs also shown that C2 tyres users are more sensitive to the wet grip performance.

The following questions have been included only for those who didn't respond the previous questionnaire sent regarding tyre abrasion. Our intention is to obtain as much relevant information as possible, using the information received from the two questionnaires.

3.2.1.4 Percentage of summer and winter tyres in the market

The answers for this question were not relevant. According to survey sent for the study on tyre abrasion, the tyre category population in the EU is as follows:

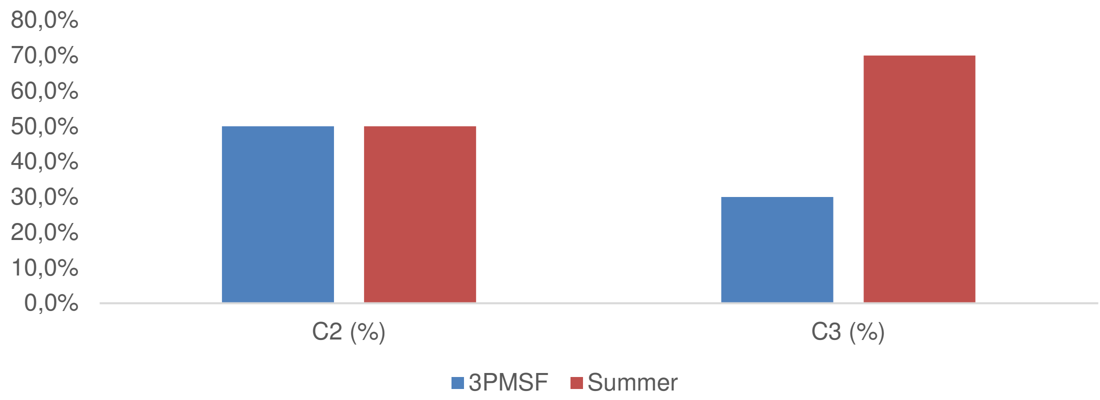


Figure 68 Tyre population in Europe ni terms of category of use. C2 and C3 tyres.

Thanks to these data, the tyres chosen to be tested will try to stick as much as possible to this distribution.

3.2.1.5 Percentage of tyres sold in the EU market according to Wet Grip Index class ranked in the Tyre Labeling

The answers for this question were not relevant. According to survey sent for the study on tyre abrasion, the tyre population distribution is as follows:

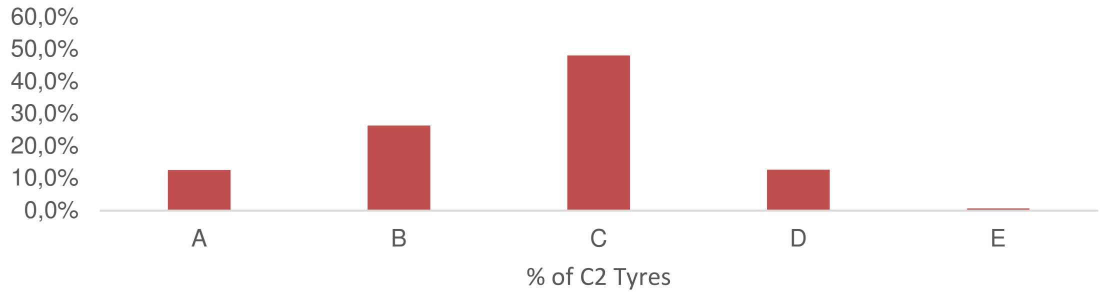


Figure 69 C2 tyre population distribution regarding wet grip performance

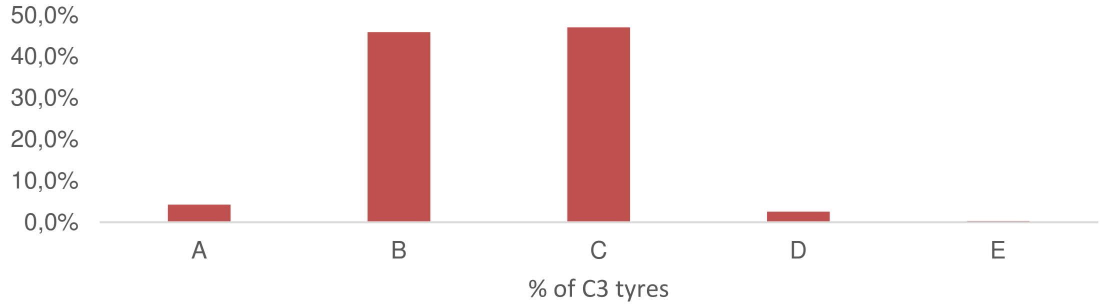


Figure 70 C3 tyre population distribution regarding wet grip performance

With this question we evaluate if it is important for the users of commercial vehicles the labeling grade of the tyres regarding wet grip. This information will be helpful in the process of tyre selection for the testing process.

As it can be seen in the graphs, the most usual tyre label is C. However, in C3 tyres, both B and C label are the most common.

3.2.1.6 Most popular C2 and C3 tyre sizes

Information regarding the most popular tyres used in Europe is necessary as it will help us design our test plan. This information has been also taken from the study on tyre abrasion questionnaire because of the lack of information received, and it is the third basic information needed for the tyre selection plan after the wet grip label range and the categories of use.

C2 tyres	C3 tyres
215/65R16C	315/80R22.5
235/65R16C	315/70R22.5
205/65R16C	385/65R22.5
205/75R16C	295/80R22.5
225/65R16C	385/55R22.5

Table 12 Most popular C2 and C3 tyre sizes.

3.2.1.7 Average percentage of truck driving in terms of road distance

As it was stated in the study on tyre abrasion, C3 tyres are mainly used on motorways:

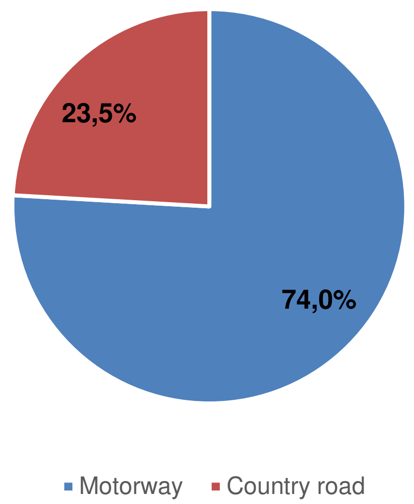


Figure 71 Percentage of truck driving in terms of road distance

3.2.1.8 Average percentage of bus driving in terms of road distance

There is no reliable information available related to that question

3.2.1.9 Average load in a truck in terms of Total vehicle weigh

Although not enough information has been obtained from this question to present it as a graph, one of the surveys has the following comment:

Given is estimate on the Truck Application vs. Average Weight (tonnes):
City Distribution: 11.3 Tonnes,
Demanding haul: 27.1 Tonnes
Heavy Construction: 20.7 Tonnes
Interregional haul: 24.5 Tonnes
Regional distribution: 20.8 Tonnes.

3.2.1.10 Average occupation in a bus

There is no reliable information available related to that question

3.2.2 Passenger car tyres

The second part of the survey is focused on passenger car tyres. This information will be useful to design the test program that will help us validate the work done in IWG WGWT during the last two years.

3.2.2.1 Main reasons for changing tyres on passenger car

As done in the first part of the survey, it is requested to know the reasons for changing the tyres. The results of the survey are as follows:

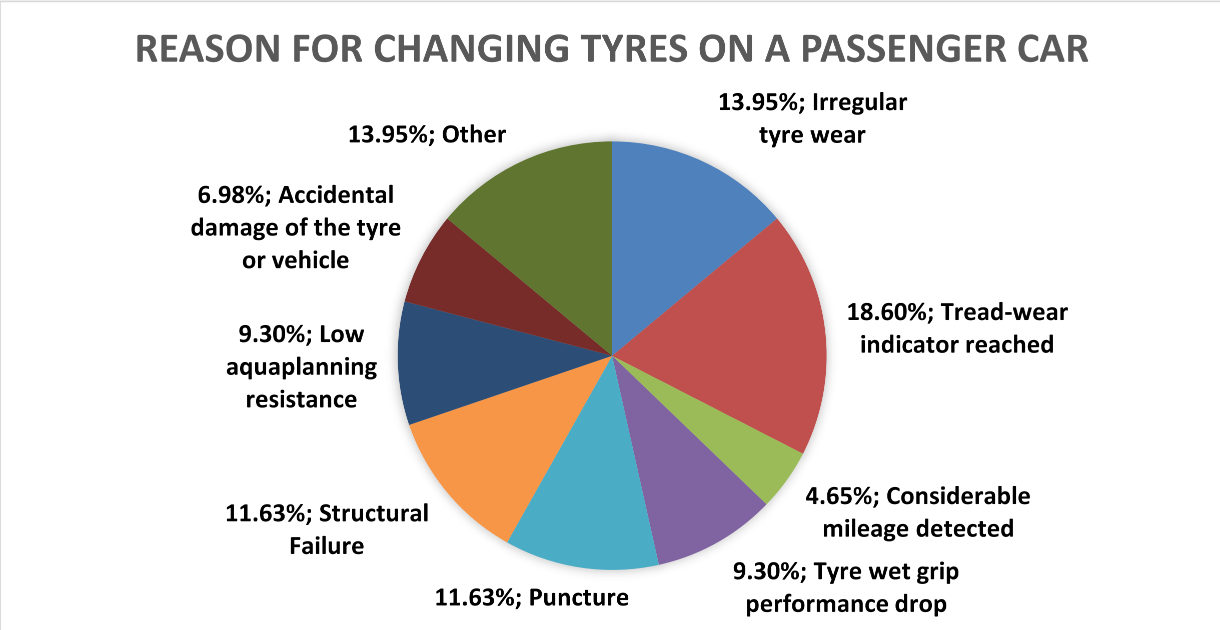


Figure 72 Reasons for changing passenger car tyres

It is possible to see that tread wear indicator reached (worn tread) is the most chosen answer (18.60%), followed by irregular tyre wear and other reasons unspecified (13.95%). The third factor is the first related to wet performance; the performance drop in wet grip and the low aquaplaning resistance were chosen by 9.30% both.

3.2.2.2 Average tread depth of replaced tyres

It is important to know if the users change their tyres before or after reaching the tread wear indicators. This question differentiates the type of tyre used between premium, middle and budget. However, only information about the overall value has been obtained.

All the responses were between 2 and 3 mm of tread depth before replacing tyres, with a mean value between the answers of 2.4 mm.

3.2.2.3 Wet grip performance perception on a worn tyre

It is also asked whether the passenger car drivers have a different feeling once the tyres are worn regarding their wet grip performance:

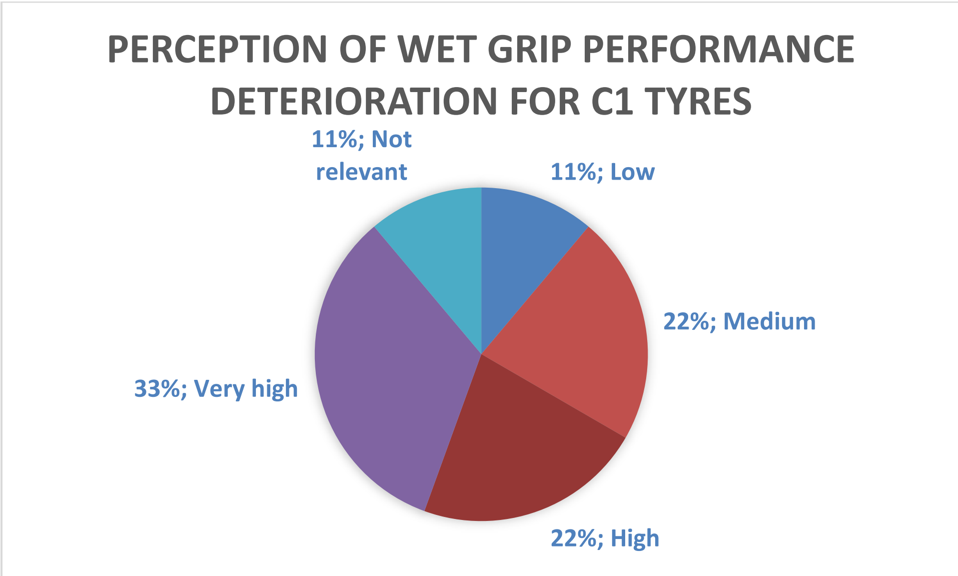


Figure 73 Wet grip performance perception on a worn tyre. C1 tyres

It seems that the feeling of performance loss in passenger car tyres is more evident than in commercial vehicles. However, some comments state that this is something subjective and, as the deterioration is gradual, often over years, most end-users do not notice this deterioration.

The following questions have been included only for those who didn't respond the previous questionnaire sent regarding tyre abrasion. However, as the participation was low, information from the previous study on tyre abrasion has been used.

3.2.2.4 Percentage of summer and winter tyres in the market

The information obtained will be used to define the testing plan for the next steps.

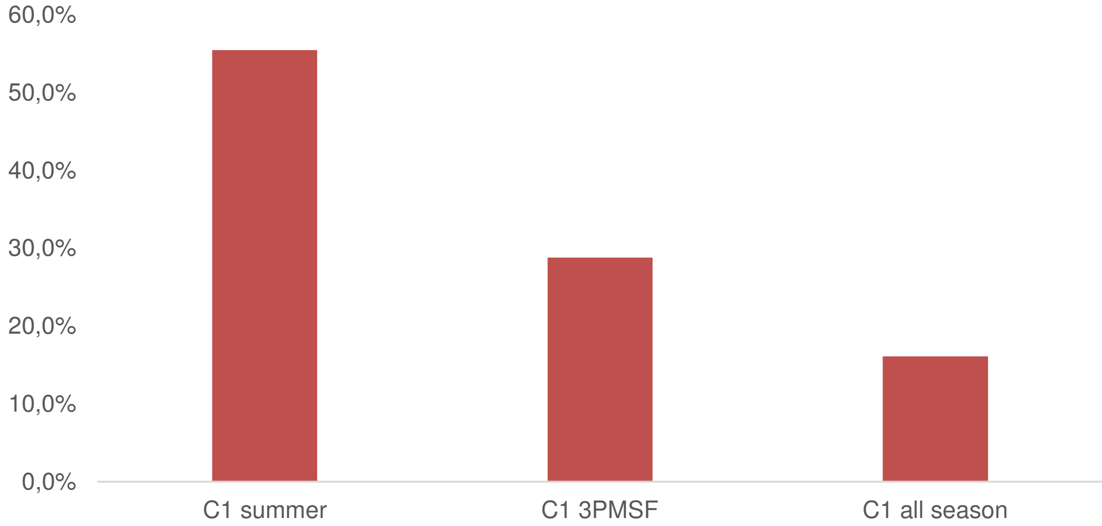


Figure 74 Tyre population in Europe ni terms of category of use. C1 tyres

Summer tyres represent the 55% of the total tyre population in Europe, followed by a 30% of winter tyres and 15% of all season tyres.

3.2.2.5 Percentage of tyres sold in the EU market according to Wet Grip Index class ranked in the Tyre Labeling

With this question we will determine if it is important for the users the wet grip index value.

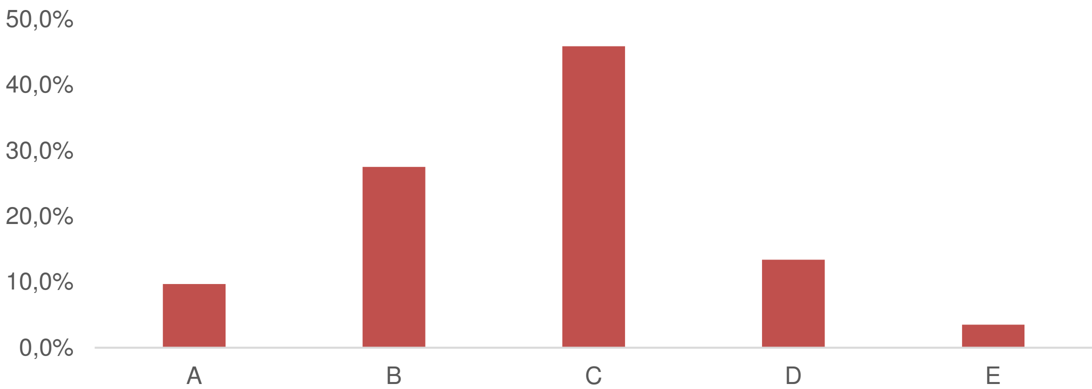


Figure 75 C1 tyre population distribution regarding wet grip performance

C (45%) and B (27.5%) are the most popular labels within wet grip performance.

3.2.2.6 Most popular passenger car tyre sizes

This question of the survey will bring us relevant information that will help us select the tyre sizes for the test plan.

C1 tyres
205/55R16
225/45R17
195/65R15
225/40R18
225/60R16

Table 13 Most popular C1 tyre sizes.

3.2.2.7 Average percentage of passenger car driving in terms of road distance

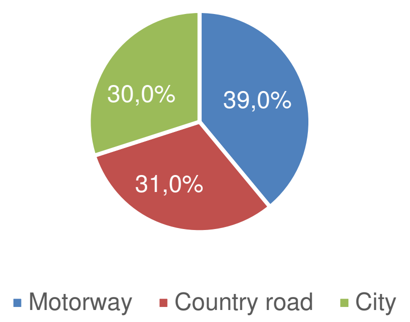


Figure 76 Percentage of passenger car driving in terms of road distance

As it can be seen in the graph above, the usage is around one third of each type of road (Motorway, Country road and City).

3.2.2.8 Average occupation

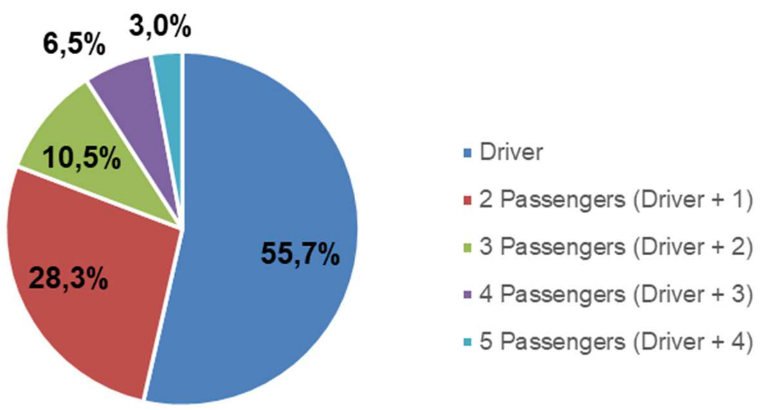


Figure 77 Passenger car occupation in Europe

According to the information received, the great part of passenger cars in Europe (55.7%) are only occupied by a driver, while less than 10% of the vehicles are fully occupied.

3.3 Conclusions

After reviewing all the data received from this questionnaire and the one from the previous study on abrasion of tyres, a clear image of the most representative tyres in Europe has been obtained.

The most popular sizes according to the questionnaire are:

C1 tyres	C2 tyres	C3 tyres
205/55R16	215/65R16C	315/80R22.5
225/45R17	235/65R16C	315/70R22.5
195/65R15	205/65R16C	385/65R22.5
225/40R18	205/75R16C	295/80R22.5
225/60R16	225/65R16C	385/55R22.5

Table 14 Most popular tyre sizes in Europe according to the questionnaire

The category of use distribution is:

- For C1 tyres:55.5% summer tyres, 28.8% winter tyres, 16.1% all season tyres
- For C2 tyres: 50% summer tyres, 50% winter tyres
- For C3 tyres, 70% summer tyres, 30% winter tyres

The most popular wet grip performance level is C, followed by B, in the three categories.

All this information will be used to create a test plan that uses the most representative sizes sold in Europe.

4 Test method approach for Task 2 and Task 3

The complete description of the tyre samples to be tested will be one of the next steps of the project. The list will be based on the information gathered in the survey and internal know-how from other projects. The next step for Task 2 will be to develop a buffing procedure harmonized with the current work of the IWG WGWT for C1 tyres.

It will be based on several international standards such as ASTM F1046 – 01 (Reapproved 2015) Standard Guide for Preparing Artificially Worn Passenger and Light Truck Tires for Testing, ASTM F421 – 15 Standard Test Method for Measuring Groove and Void Depth in Passenger Car Tires, and the documents presented to GRBP (WT-21-05 Result of Buffing Procedure, ECE/TRANS/WP.29/GRBP/2021/12 Proposal for amendments to UN Regulation No. 117). This doesn't mean that we will stick to only this documentation, so any other improvement that might appear while developing to the procedure will be included in it.

It is clear that the buffing procedure developed will be based on four phases:

1. Tyre preparation: Visual inspection and creation of 3D contour to follow the original runout of the tyre while buffing

2. Buffing of the main tread mass: Approximately 95 % of the desired groove depth reduction is made on a tyre tread removal machine equipped with a rotary electric knife cutter or other suitable device

3. Grinding of the final tread: To remove the rough cutting marks so that a smoothed finish is obtained on the tyre. This process uses a diamond coated tool to give the final finish. (<20 µm)

4. Measurement of the processed tyre: To measure the tread depth at control points and surface roughness

All four steps will be performed using the recommended rim size and using a sufficient tyre inflation pressure to keep the tyre tread surface shape up to 4 bar.

If any improvement is found during the execution of the project the phases will be modified accordingly.
Next steps for Task 3 will be to prepare the testing procedure which will be also harmonized with the work already done in IWGWT and according to the current regulation UN 117.02 and ISO 15222.

5 Task 6 - Project management & Quality Assurance

5.1 List of problems and countermeasures

The first problem encountered is a potential delay on the arrival of the buffing machine at IDIADA. The estimated delivery and installation date for the machine is March 2022, however some delay is foreseen due to the global semiconductor shortage problem.

Countermeasure: IDIADA will eventually subcontract the buffing and grinding process to an external supplier able to achieve the required tolerances in terms of tread depth and surface rugosity if needed.

Secondly, a very low participation in the survey made us rethink timings and find a way to receive more responses

Countermeasures:
Reminder mailings: reminder emails were sent regularly in order to inform that the survey deadline was about to end and that answers would be very helpful for the study.

Deadline extension: in addition to the reminders, the survey deadline was extended in order to give to the respondents more time to answer the questions. Summertime is difficult to get the people participate so, an attempt was made to extend the deadline if possible

5.2 Budget used

In the following table, shows a summary of the budget dedicated per task and the budget spent up to December 2021.

TOTAL	PRODUCTION	SPENT UNTIL DECEMBER
19,040.00 €	**TASK 1**	19,040.00 €
14,560.00 €	**TASK 2**	2,426.67 €
196,850.00 €	**TASK 3**	- €
27,000.00 €	**TASK 4**	- €
16,200.00 €	**TASK 5**	- €
21,960.00 €	**TASK 6**	4,392.00 €
295,610.00 €		**25,858.67 €**

Table 15 Budget Overview

The total budget assigned to this tender is 295.610,00€. The total amount defined for Task 1 is 19.040,00€. Task 1 finished in December 2021, therefore, the whole budget dedicated to this task has been consumed (19.040,00€). Task 2 started in November 2021 and an amount of 2.426,67€ has been spent over the 14.560,00€ defined. Finally, from Task 6, 4.392,00€ have been spent for the project management. For this task, a total budget of 21.960,00€ was defined. All in all, the budget spent up to December 2021 goes in line of the estimation made at the beginning of the project.

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7 Annexes

QUESTIONAIRE on Tyre Wet Grip at worn state
Presentation

The consortium formed by IDIADA Automotive Technology and Roland Berger has been assigned by the European Commission to evaluate the current context regarding tyre adhesion on wet asphalt at worn condition.

One target of this study is to collect as much information as possible related to C2 and C3 tyres as well as C1 tyres from all stakeholders with reference to wet grip performance of tyres in new state and in worn state to obtain statistical relevance.

Information related to mileage and the remaining tread depth of tyres fitted on road vehicles is also relevant for this study, to investigate its impact on driving safety.

Remarks regarding this questionnaire
A proper assessment on this topic wouldn't be complete without attempting to gather the feedback from all the involved parties. For this reason, we kindly ask you to answer any of the questions you may, or you believe you are concerned with. Please be informed that contact data won't be shared, and all answers will be treated anonymously.

Don't hesitate to forward this document to other members of your organization that may contribute to a richer feedback collection.

We are aware of the value of your time and we've tried to make clear and simple questions, but all the additional comments or complementing documents you may introduce will be very welcome for a better understanding of your feedback.

Please feel free to choose multiple options where this is meaningful. You may always explain the reasons for your choices.

We would be grateful if we could receive your replies not later than November 15th, 2021
A kind reminder will be sent a week before this deadline.

Contact data
Please complete the following fields with your personal and professional data

Name:

Organization:

Position:

E-mail address:

Telephone number:

Website:

Definitions

- *C1: Passenger car tyre*
- *C2: Light commercial vehicle tyre*
- *C3: Heavy commercial vehicle tyre*
- *3PMSF: 3 peak mountain snowflake (tyre for snow in severe conditions)*

A. COMMERCIAL VEHICLES (C2, C3 tyres)

Question No. A1

In your opinion, which is (are) the reason(s) for changing tyres on a heavy-duty Truck?
You can mark with X, multiple answers are possible.

( ) irregular tyre wear
( ) worn tread
( ) considerable mileage detected
( ) tyre wet grip performance drop
( ) structural failure
( ) accidental damage of the tyre or the vehicle (please specify)
( ) other, (please specify) ………………………
( ) don't know

Question No. A2

What is the average tread depth when tyres are replaced by new ones?

C2 Premium ( ) mm
C2 Middle ( ) mm
C2 Budget ( ) mm
C2 Overall* ( ) mm

C3 Premium ( ) mm
C3 Middle ( ) mm
C3 Budget ( ) mm
C3 Overall* ( ) mm

(*) you can use overall category if you do not have sufficiently detailed information for Premium, Middle, Budget.
You may clarify your experience or state the information source for your answer:

Question No. A3

In your opinion, is there any perception of wet grip performance deterioration when the tyre is worn?
You can mark with X

C2 tyres ( ) Not relevant ( ) Low ( ) Medium ( ) High () Very High

C3 tyres ( ) Not relevant ( ) Low ( ) Medium ( ) High () Very High

You may clarify your experience or state the information source for your answer:

Please reply the following questions A4 to A10 only if you have not replied them to the recent questionnaire of the Commission study on tyre abrasion. Please note that you have replied the corresponding questions for that study

Question No. A4

What is the percentage of summer tyres, winter (3PMSF) and all season tyres in your country ?

C2 summer (%)
C2 3PMSF (%)
C2 all season (%)

C3 summer (%)
C3 3PMSF (%)
C3 all season (%)

You may clarify your experience or state the information source for your answer:

Question No. A5

What is the percentage of tyres sold in the EU market according to Wet Grip index class ranked in the Tyre Labelling?

	R(EC)1222/2009	R(EU)2020/740	
C2 tyres:	A (1.40 ≤ G) - - - - - - - - - - - - -	A	(%)
	B (1.25 ≤ G ≤ 1.39) - - - - - - - - -	B	(%)
	C (1.10 ≤ G ≤ 1.24) - - - - - - - - -	C	(%)
	E (0.95 ≤ G ≤ 1.09) - - - - - - - - - -	D	(%)
	F (G ≤ 0.94) - - - - - - - - - - - - - - -	E	(%)

	R(EC)1222/2009	R(EU)2020/740	
C3 tyres:	A (1.25 ≤ G) - - - - - - - - - - - - - -	A	(%)
	B (1.10 ≤ G ≤ 1.24) - - - - - - - - -	B	(%)
	C (0.95 ≤ G ≤ 1.09) - - - - - - - - -	C	(%)
	D (0.80 ≤ G ≤ 0.94) - - - - - - - - -	D	(%)
	E (0.65 ≤ G ≤ 0.79) - - - - -	E (G ≤ 0.79)	(%)

You may clarify your experience or state the information source for your answer:

Question No. A6

Which are the 3 most popular C2 / C3 tyre sizes in your country (1= most popular)?

C2 Tyre size 1 …………
C2 Tyre size 2 …………
C2 Tyre size 3 …………

C3 Tyre size 1 …………
C3 Tyre size 2 …………
C3 Tyre size 3 …………

You may clarify your experience or state the information source for your answer:

Question No. A7

What is the average percentage of truck driving in terms of road distance (kms)?

Motorway (%)
Country road (%)

You may clarify your experience or state the information source for your answer:

Question No. A8

What is the average percentage of bus driving in terms of road distance (kms) ?

Motorway (%)
Country road (%)
You may clarify your experience or state the information source for your answer:

Question No. A9

What is the average of load in a truck in terms of Total vehicle weight?

15 Tonnes (%)
20 Tonnes (%)
25 Tonnes (%)
30 Tonnes (%)
35 Tonnes (%)
40 Tonnes (%)
You may clarify your experience or state the information source for your answer:

Question No. A10

What is the average of occupation in a bus?

<20 passengers (%)
20 - 40 passengers (%)
40 – 60 passengers (%)
>60 passengers (%)

You may clarify your experience or state the information source for your answer:

B. PASSENGER CARS (C1 tyres)

Question No. B1

In your opinion, which is (are) the reason(s) for changing tyres on a passenger car?
You can mark with X, multiple answers are possible.

( ) irregular tyre wear
( ) tread-wear indicator reached
( ) considerable mileage detected
( ) tyre wet grip performance drop
( ) puncture
( ) structural failure
( ) low aquaplaning resistance
( ) accidental damage of the tyre or the vehicle (please specify)
( ) other, (please specify) ....
( ) don't know

Question No. B2

What is the average tread depth when tyres are replaced by new ones?

C1 Premium ( ) mm
C1 Middle ( ) mm
C1 Budget ( ) mm

C1 Overall* ( ) mm

(*) you can use overall category if you do not have sufficiently detailed information for Premium, Middle, Budget.
You may clarify your experience or state the information source for your answer:

Question No. B3

In your opinion, is there any perception of wet grip performance deterioration when the tyre is worn?
You can mark with X

C1 tyre ( ) Not relevant ( ) Low ( ) Medium ( ) High () Very High

You may clarify your experience or state the information source for your answer:

Please reply the following questions B4 to B8 only if you have not replied them to the recent questionnaire of the Commission study on tyre abrasion. Please note that you have replied the corresponding questions for that study

Question No. B4

What is the percentage of summer tyres, winter (3PMSF) tyres and all season tyres in your country?

C1 summer (%)
C1 3PMSF (%)
C1 All season (%)

You may clarify your experience or state the information source for your answer:

Question No. B5

What is the percentage of tyres sold in your country according to Wet Grip index class ranked in the Tyre Labelling?

C1 tyres:	R(EC)1222/2009	R(EU)2020/740	
	A (1.55 ≤ G) - - - - - - - - - - - - - -	A	(%)
	B (1.40 ≤ G ≤ 1.54) - - - - - - - - -	B	(%)
	C (1.25 ≤ G ≤ 1.39) - - - - - - - - -	C	(%)
	E (1.10 ≤ G ≤ 1.24) - - - - - - - - -	D	(%)
	F (G ≤ 1.09) - - - - - - - - - - - - - -	E	(%)

You may clarify your experience or state the information source for your answer:

Question No. B6

Which are the 5 most popular C1 tyre sizes in your country (1= most popular)?

Tyre size 1 …………
Tyre size 2 …………
Tyre size 3 …………
Tyre size 4 …………
Tyre size 5 …………

You may clarify your experience or state the information source for your answer:

Question No. B7

What is the average percentage of passenger car driving in terms of road distance (kms) ?

Motorway (%)
Country road (%)
City (%)

You may clarify your experience or state the information source for your answer:

Question No. B8

What is the average occupation of passengers in a car?

Driver	(%)
2 Passengers (Driver+1)	(%)
3 Passengers (Driver+2)	(%)
4 Passengers (Driver+3)	(%)
5 Passengers (Driver+4)	(%)

You may clarify your experience or state the information source