TYRES AND ROAD SURFACES

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The study concerning the contact between a tyre and a road surface was conducted by means of an experimental multifactor investigation. It was attempted not only to determine the effect of variables such as type of road surface and speed on the skid resistance but also interaction effects. In the first phase the first and second-order factors were separated. The second phase served to determine the numerical influence of the road surface characteristics and the speed on the size of the brake and side way forces. It was found possible to compile a mathematical relation incorporating the contribution of the macro-roughness and micro-roughness of the road surface and also of the speed to the brake and side way forces. In the third phase a similar mathematical relation was drawn up for truck tyres. Car and truck tyres were compared by reference to the results. A main feature is that with truck tyres the values of the available brake forces are about a factor two lower than with car tyres. Among the characteristics of the road surface, the micro-roughness has mostly considerable influence on the skid resistance. The influence of the macro-roughness of the road surface counts heavily almost exclusively at high speeds. Finally, recommendations are made for official measures, with emphasis on standards to be met by the micro-roughness and macro-roughness of road surfaces.

Purpose of the Research

The basic assumption of the study was that skidding accidents arise from human behaviour in traffic as the result of incorrect, excessive expectations regarding the available brake and side way forces. A major factor involved is a local and/or temporary decrease of the brake and side way forces. This decrease is in particular attributable to the presence of water on the road surface. The study is therefore mainly concerned with wet road surface conditions.

Following the above train of thought, it would be possible to reduce the number of skidding accidents by preventing incorrect expectations of the road user. This could be achieved through making the local and/or temporary brake and side way forces decrease as little as possible. In braking and steering cars a distinction should be made between minimum brake and side way forces required for the movements of the vehicle, and the available forces between tyre and road surface. In order to achieve forces greater than the minimum required, the size of such forces must be known.

In view of this, the need arose to find out, under possibly most realistic conditions, what factors actually affect the size of the brake and side way forces. According to the relevant literature, many of the studies conducted so far had been single-factor investigations, in which the influence of one single variable on the size of the brake and side way forces was investigated. An experimental multifactor investigation to supplement the existing knowledge was therefore considered necessary for a sound study schedule. This would have to make it possible to measure the effect of each variable such as type of road surface and speed as well as the interactions such as type of tyre - speed and water depth - tread depth - tyre type on the skid resistance.

Criteria of the Investigation

Coefficients of Longitudinal and Lateral Forces

The object of the study of the available forces arising between a tyre and a wet road surface is to determine the influence of the variables on the size of the brake and side way forces. For comparison, dimensionless brake and side way coefficients are used, defined as follows (1):

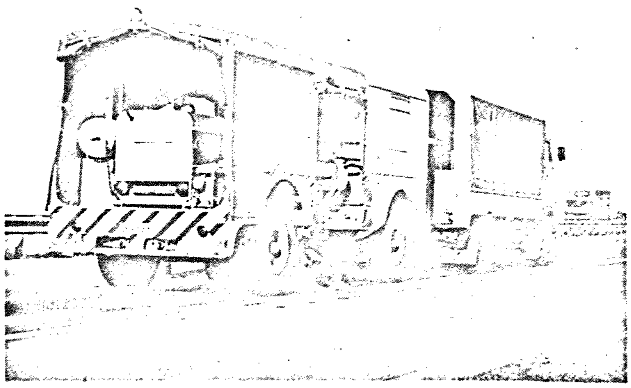
- μ_{xm}: the quotient of the maximum value of the brake force and the momentary vertical tyre load
- μ_{xb}: the quotient of the brake force and the momentary vertical tyre load if the wheel is locked
- μ_{y}: the quotient of the maximum side way force and the momentary vertical tyre load.

These three coefficients define the skid resistance. Each of them is important under certain conditions. A high μ_{xm} value means that braking hard is possible without the wheels of the vehicle locking. This permits of high deceleration whilst maintaining stability and controllability. In an emergency situation a driver will usually brake as hard as he can, which may cause the wheels to lock. Under these circumstances, the shortest possible braking distance depends on a high μ_{xb} value. A high μ_y value is desirable if the driver wishes to change direction, run through a bend or attempts to perform an evasive manoeuvre.

Measuring Method

Car tyre measurements were carried out with the measuring vehicle of the Vehicle Research Laboratory of the Delft University of Technology (see Figure 1). In a special measuring tower

Figure 1. Measuring truck for car tyres of the Vehicle Research Laboratory of the Delft University of Technology.



the vertical tyre load and the brake and side way forces can be measured with the aid of a measuring hub. The resulting brake and side way force coefficients are all averages of four observations. The vehicle used for the measurements is described in Tire Science and Technology (2).

Measurements with truck tyres were made with the single-wheel measuring trailer of the Vehicle Research Laboratory of the Delft University of Technology (see Figure 2). This vehicle permits measuring only brake force coefficients. The measuring criteria for truck tyres were therefore the maximum brake force coefficient μ_{xm} and locking value μ_{xb} (2).

Influence Variables

Literature Survey

Initially, the relevant literature was consulted to list the important factors influencing the contact between the tyre and the road surface. As these factors are undoubtedly known a brief description should suffice, dealing especially with the measuring method.

Figure 2. Measuring truck for truck tyres of the Vehicle Research Laboratory of the Delft University of Technology.

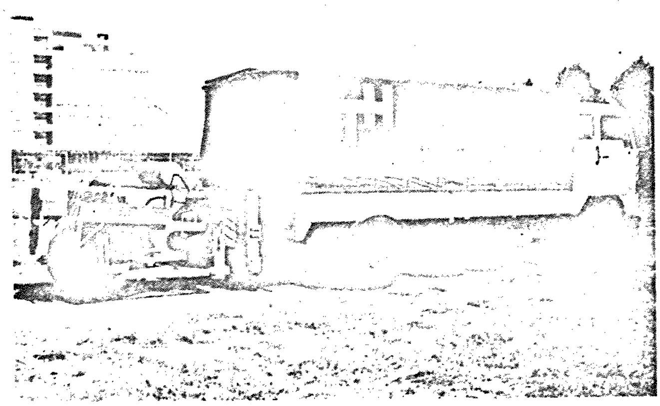
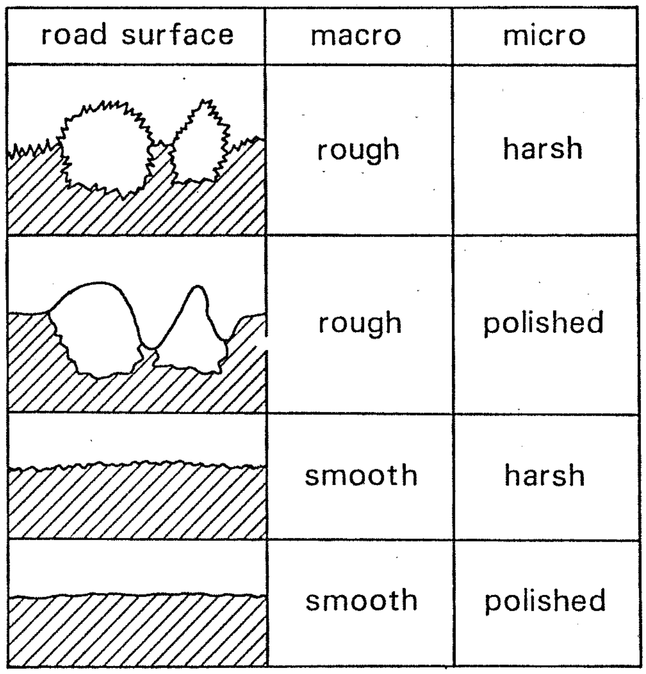


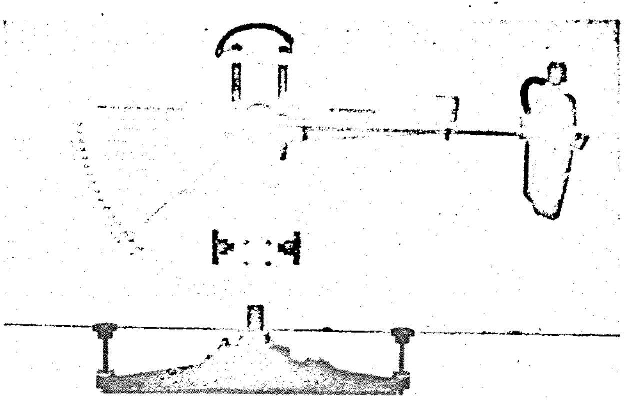
Figure 3. Illustration of terms of the road surface texture.



Road Surface Factors

The nature and composition of the road surface, and in particular the surface texture have much effect on the brake and side way force coefficients (3, 4, 5). The main characteristics important to the skid resistance are the macro-roughness and the micro-roughness (see Figure 3). The macro-roughness (uneven portions of 10^{-3} to 10^{-2}m) serves for quick disposal of water from the zone of contact between the tyre and the road surface. The micro-roughness (10^{-4} to 5.10^{-4}m) is meant to break the remaining water film and thus to allow adhesion between the rubber of the tyre and the road surface.

Figure 4. British Pendulum Skid Resistance Tester (SRT).



In the present study, the macro-roughness was measured by determination of the average texture depth TD according to the sand-patch method (6). A standard volume of fine sand is spread in a circle on the road surface to be measured. The diameter of the sand patch is a measure of the average texture depth TD. As it was not possible to measure it directly the micro-roughness was determined by means of the SRT device (British Portable Skid Resistance Tester), an instrument developed by the British Road Research Laboratory (7). A pendulum, with a small block of rubber attached to its end, slides along a wetted surface. The swing height, expressed in values between 0 and 100, is a measure of the micro-roughness (see Figure 4).

Tyre Factors

Tyres display characteristics connected with their design, tread profile and composition of the rubber (8). Among the characteristics of the carcass, it is probably only the cornering stiffness which is important for the side way force coefficient. The cornering stiffness is the side way force coefficient per degree of skid angle between +1 and -1 degree of skid angle. Within this, the side way force can be assumed to be linear.

The tread profile of the tyre serves to force away and take up water from the face of contact between the tyre and the road surface. Some of the water will be taken up in a groove or a sipe (small incision). The take-up capacity can be related to the air ratio. This is the quotient of the total area of the grooves and sipes, and the total contact surface. The water which cannot be taken up will have to be removed from the contact face. For the time being it is not possible to calculate the removal capacity and this was therefore determined by experiment. Water is forced through a slot into the tyre profile. Tread shapes can be compared with the aid of characteristic values (9).

The tread compound of car tyres consists of a mixture of synthetic rubber, carbon, oil and other additives. Truck tyres are still often made of natural rubber. The composition is difficult to analyse chemically. A number of derived characteristics was therefore determined for this aspect. The hardness was measured by means of a Shore hardness meter, and the resilience with a modified Lübke meter. Finally, the glass transition temperature was determined. The temperature at which the specific heat of the rubber changes, is referred to as glass transition temperature (10).

Tread Depth

The influence of the explicit tyre characteristic tread depth has been exhaustively covered by a single-factor investigation (11). On the whole, the brake force coefficient will decline fairly gradually with the tread depth decreasing. At less than 2 - 3 mm tread depth, the brake force coefficient will be reduced very progressively. This effect is most pronounced at relatively high speeds and on slippery roads. The influence of the tread depth on the side way coefficient appears to be smaller than on the brake force coefficient.

Speed

The influence of the speed on the skid resistance is very much dependent on the properties of the tyre and the road surface. This means that the results of single-factor studies should be approached with caution. Generally speaking, the skid resistance will become less as the speed increases.

Water Depth

By taking measures in road construction such as edging, planeness and transition to the verges, and also effective maintenance, bigger water depths on the roads can be largely prevented. On a plane, normally edged road a value of 1 mm after a heavy shower is already extreme (5, 12). At depths of a few millimetres and more the risk of aquaplaning arises.

Other Factors

Tyre load, tyre inflation, the material of the road surface and the temperature of the tyre and the road surface probably have a small influence on the skid resistance. About the interaction effects, however, little is known.

Qualification Study

Object and Execution

First of all, the study served to determine what factors and interactions were of primary importance to the skid resistance. To this end, an experimental multi-factor investigation (13, 14) was arranged for. The number of measurements to be taken is partly determined by the number of levels of the factors. According as the extent of the experiment increases along with the number of required measurements, unintended heterogeneity may grow in the results. With a view to eliminating this heterogeneity, the measurements can be divided into blocks.

For the purpose of the qualification study

Table 1. Level of variables in the qualification study.

Road	Characteristics TD (mm)	SRT	Tyre Type	Belt Material	Characteristics (New Tyre) Cornering Stiffness (N/deg)	Air Ratio (%)	Resilience (Rebound %)	Hardness Shore A	Other Factors	Level Low	High
KESteren	0.3	69	I	Radial Steel	760	29.7	36	59	Speed	50	100
LEIden	0.6	74	II	Radial Steel	800	23.4	39	62	Water Depth (mm)	0.3	0.6
RAAmsdonkveer	0.8	77	III	Radial Textile	650	30.6	42	59	Tread Depth (mm)	2	7
GORinchem	0.7	79	IV	Radial Textile	630	30.6	31	64	Tyre Load (N)	2500	4000
									Inflation (N/m^2)	1.4×10^5	2.0×10^5

Table 2. Results of the main effects of factors in the qualification study.

Main Effect	Average Value	Road Type				Tyre Type				Speed		Tread Depth		Water Depth		Load		Inflation	
		KES	LEI	RAA	GOR	I	II	III	IV	50	100	2	7	0.3	0.6	2500	4000	1.4	2.0×10^5
μ_{xm} (x100)	84.3	-13.9	+0.3	+4.5	+9.1	-2.3	-1.9	+1.5	+2.7	+6.3	-6.3	-2.8	+2.8	+1.7	-1.7	NS		NS	
μ_{xb} (x100)	50.6	-6.0	+0.2	+0.4	+5.4	-2.5	-2.5	-0.3	+0.3	+9.6	-9.6	-3.6	+3.6	+0.5	-0.5	+0.7	-0.7	+0.5	-0.5
μ_y (x100)	78.7	-9.7	+1.8	+1.0	+6.9	+2.1	+0.9	-0.9	-1.5	+4.2	-4.2	+1.0	-1.0	+0.5	-0.5	+1.2	-1.2	NS	

Note 1: NS = Statistically Not Significant

2: In the tables + and - means a higher respectively a lower value of the coefficients compared with the average value of the coefficient.

Table 3. Results of the significant interactions.

Two-factor interactions

μ_{xm}:
1. road surface type - tyre type
2. tyre type - tread depth
3. speed - tread depth
4. road surface type - tread depth
5. road surface type - speed
6. speed - tyre type
7. tread depth - water depth

μ_{xb}:
1. tyre type - tread depth
2. road surface type - tyre type
3. speed - tread depth
4. road surface type - speed
5. road surface type - tyre type
6. road surface type - tyre type
7. tread depth - tyre inflation

μ_y:
1. road surface type - tyre type
2. road surface type - tread depth
3. tyre type - tread depth
4. road surface type - speed
5. speed - tyre type
6. road surface type - tyre load
7. tyre type - tyre load
8. tread depth - tyre load
9. speed - water depth

Three-factor interactions

μ_y:
1. road surface type - speed - tread depth
2. tyre type - speed - tread depth
3. tyre type - tread depth - tyre load

the unit day was chosen as block. As it was not feasible to measure within one block, i.e. one day, with all combinations of factors, it was decided to confound some factors with blocks. The result of confounding a factor with blocks has the result of the effect of that factor not being distinguishable from the block effect.

In this experiment, the factor road surface type and the factor units of one tyre type have been confounded with blocks to cause any differences existing between the various tyres within the type to coincide with the differences between days. To confound effectively, it was desirable to select a large number of factors at the same levels.

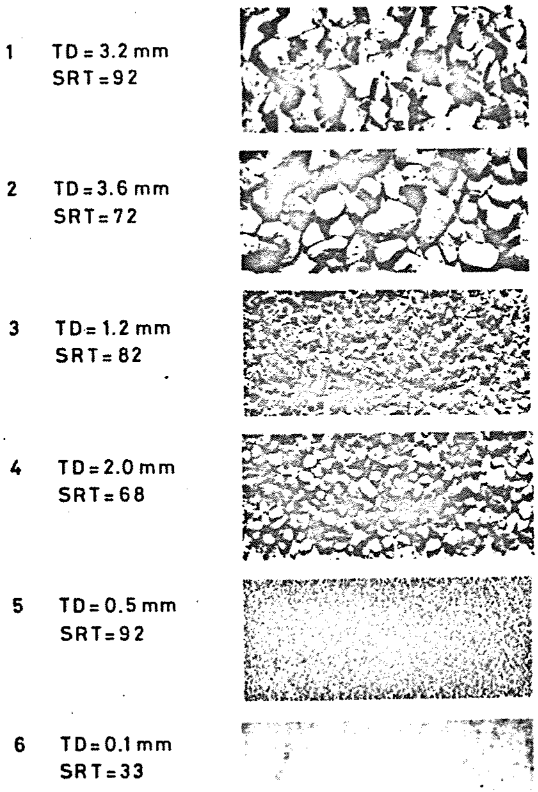
It was therefore decided to set the factors speed, water depth, tyre load and tread depth at two levels. For each of the other two factors, viz. road surface type and tyre type, four levels were included in the test.

In addition to these variables, there are a number of conditions which had to vary during the measurements. They include, the temperature of the road surface and of the spray water, air temperature, and other weather conditions. All these variables were recorded as consistently as possible throughout the measurements. The experiments were executed on normal highways. The location of the four test sites was a compromis between an easy performance of the experiments and a large difference in surface characteristics. The tyres were normal commercial-grade tyres. The levels of the other factors corresponded with high respectively low levels of these factors as found in practise (see Table 1).

Results of the qualification Study

The results of the main effects and inter-

Figure 5. Specially constructed road surfaces for the investigation of the influence of the road surface characteristics.



actions are shown in Table 2 and 3. The results of 32 repetitive measurements warrant the conclusion that the reprocibility is very high, owing to which small differences in brake and side way force coefficients can be significant. It may also be concluded that none other than the main influence factors have varied.

The conclusions from the qualification study can relate only to the area within which the levels of the factors were chosen. The choice aimed at involving the entire area which was important for practice.

First-order factors important for the contact between the tyre and road surface are: the type of road surface, the tyre type, the speed, the tread depth and the water depth. Tyre load and pressure appear to carry little effect. The influence of the water depth is very small, but significant within the levels chosen.

Functional Requirements

Object and Execution

After the qualification study the second phase concentrated on the road characteristics. It had appeared that these characteristics had the greatest influence on the skid resistance. Moreover, better policy decisions can be taken if quantitative data are available.

For the second phase, it was assumed that all main effects, two-factor and three-factor interactions had to be determinable. The result was that measurements had to be taken for any setting of factors. Again, a grouping was made into blocks, with the unit day as block. Twelve measurements were carried out each day. As it was again impossible to conduct all measurements within one block, it was decided to confound, and conduct the experiment in two measuring series.

In the first series, the factors road surface type and tread depth were confounded with the blocks. In the second the factors tyre type and speed. In view of the emphasis on road characteristics, six levels of road surface types were used in this phase. Furthermore, the factor tyre type was varied at four levels, the speed at three levels and the tread depth at two. Al other variables, including the water depth, were kept at constant level. The water depth is a rather intangible aspect in policy decisions because the amount of precipitation per unit of time is a given value. Another reason is that the influence of the water depth, though significant, was yet rather small. As pointed out already bigger water depths can be prevented by measures in road construction.

As road surfaces displaying the required characteristics were not available in practice or not suitable for carrying out measurements, test sections were laid on a test road (see Figure 5). By means of multivariate analysis four tyre types were selected from a group of sixteen commercial-grade tyres. The characteristics of the specially constructed road sections, the tyres and the levels of the other variables are set out in Table 4.

Brief Description of the Results

As could be expected, the road surfaces with very high macro-texture (1 and 2) yielded extremely high values (see Table 5). The high values measured on section 2 (macro high, micro low) can be attributed to the micro-roughness which was still rather much in evidence. Section 6 (no macro, no micro) displays very low values under all conditions.

The differences between tyres are very slight compared with the other main effects. There is a clear difference between new and worn tyres. The effect of speed is less for new than for worn tyres.

As the speed increases, the coefficients decrease practically linearly on all road surfaces. According as the macro structure increases the effect of the speed declines and is hardly noticeable on very macro-rough road surfaces. Very considerable interaction with the speed is found on a road with micro-texture only (road section number 5).

Mathematical relation

Quantitative Relation. The variables and their levels have been so chosen that it must have been possible to obtain a quantitative relation between the brake and side way force coefficients on the one hand and the road characteristics, tyre characteristics, the speed and the tread depth on the other hand. A

Table 4. Characteristics of the specially constructed road surfaces and levels of the other variables in the second test program.

Road	Road Characteristics $\overline{TD}$ (mm)	SRT	Tyre Type	Belt Material	Characteristics (New Tyre) Cornering Stiffness (N/deg)	Glass Transition Temperature (°K)	Air Ratio (%)	Resilience (Rebound %)	Hardness Shore A	Other Factors	Level		
1	3.2	92	V	Radial Textile	575	199	30	34	71	Speed (km/hr)	50	75	100
2	3.6	72	VI	Radial Steel	715	215	31	35	62	Tread depth (mm)	1		7
3	1.2	82	VII	Radial Textile	575	227	31	41	63	Water depth (mm)	0.6		
4	2.0	68	VIII	Radial Steel	705	223	30	35	60	Tyre Load (N)	3300		
5	0.5	92								Inflation (N/m^2)	1.8×10^5		
6	0.1	34											

formula was drawn up to form a model representing this relation. The model was based on the following considerations:

Tyre Characteristics. Difficulties arose in attempting to incorporate tyre characteristics in the model. The differences between the tyre type as main effect are but slight. For proper distinction between the effect of each tyre characteristic more tyres would have to be available. This study was conducted by the Vehicle Research Laboratory of the Delft University of Technology (9).

Roughly the characteristics glass transition temperature and air ratio are of importance for μ_{xm}, the characteristics air ratio and resilience for μ_{xb} and the characteristics glass transition temperature and cornering stiffness for μ_y. An average of four tyres was taken for the present study.

Tread Depth. Difficulties were likewise met with incorporating the tread depth in the model. For a good insight, the tread depth would have to be varied at more than the chosen two levels. This study was likewise carried out by the Vehicle Research Laboratory of the Delft Technical University (9). An average for the tread depth was taken for the present study.

Road Surface Characteristics. The $\overline{TD}$ and SRT values are a reasonable indication for the macro-roughness and micro-roughness of the road surface. These values can therefore serve to represent the road characteristics in the model.

Additional Measurements. The formulas are actually valid only within the range covered by the variables. With regard to the road surfaces the fact that no road surfaces from practice were available was considered a drawback. To remove part of this drawback, a series of additional measurements were carried out on road sections used by normal traffic. This was done on a number of trail sections of the Department of Roads and Waterways on State Highway 12. These sections display some diversity and their properties had been known for a number of years. The road characteristics and the measuring results are set out in Table 6.

Formula. For the model, it was assumed that the brake and side way force coefficients can be explained from an adhesion term and a hydrodynamic term. The adhesion term is related to the SRT value, and the hydrodynamic term to speed and texture depth. Out of a number of different ways of approach, the following form yielded the best results:

Table 6. Results of the additional measurements in the second test program.

Coëfficient of Longitudinal and Lateral Force	Right Lane of State Highway 12: Site 1		Site 4		Site 7		Site 9		Left Lane of State Highway 12: Site 1		Site 4		Site 7		Site 9	
	50	100	50	100	50	100	50	100	50	100	50	100	50	100	50	100
μ_{xm} (*100)	93	90	100	84	96	88	96	91	101	92	108	94	98	93	103	95
μ_{xb} (*100)	58	57	60	44	63	49	67	50	63	49	66	49	67	52	64	53
μ_y (*100)	71	69	67	64	75	69	68	65	74	73	71	71	77	74	72	71

Note: Conditions Right Lane site 1 SRT = 70, TD = 1.3; site 4 SRT = 66, TD = 0.5; site 7 SRT = 71, TD = 1.5; site 9 SRT = 69, TD = 0.5

Left Lane site SRT = 70, TD = 1.0; site 4 SRT = 71, TD = 0.6; site 7 SRT = 73, TD = 1.4; site 9 SRT = 70, TD = 0.7

Tyre: VII   Speed: 50 and 100 km/hr   Water Depth: 0.6 mm

Inflation: 1.8×10^5 N/m^2 Load: 3300 N   Tread Depth: 7 mm

Table 5. Results of the second test program.

μ_{xm} (*100)

Tyre		Road Surface																	
		1			2			3			4			5			6		
		Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)		
Type	Tread	50	75	100	50	75	100	50	75	100	50	75	100	50	75	100	50	75	100
V	New	121	127	127	102	104	108	112	110	109	105	107	106	115	113	108	59	40	57
		133	127	120	98	101	101	115	116	106	101	98	100	116	110	108	53	48	38
	Worn	110	113	122	91	95	90	115	116	104	101	106	101	101	70	48	38	33	16
		120	125	115	88	91	91	116	99	97	99	89	86	97	51	38	58	35	19
VI	New	130	128	131	98	101	103	129	122	109	113	111	106	107	108	98	65	36	29
		128	137	128	101	111	109	117	111	109	105	113	105	110	106	98	56	49	42
	Worn	123	111	114	106	92	101	127	115	103	114	112	105	82	51	41	41	26	14
		134	123	124	93	104	92	128	102	95	103	106	86	79	48	35	41	24	15
VII	New	109	125	124	91	101	98	113	112	109	104	104	101	105	104	104	50	48	43
		120	124	120	103	102	101	112	110	98	101	97	94	108	106	99	69	55	47
	Worn	102	112	119	78	92	88	105	107	99	98	94	92	111	98	65	35	29	30
		116	121	121	90	88	88	122	107	102	91	94	92	122	102	78	57	30	22
VIII	New	124	126	116	97	102	98	118	111	114	100	109	104	106	102	101	46	57	34
		123	125	122	99	99	101	113	108	103	103	106	96	108	100	94	59	50	46
	Worn	114	107	115	89	97	91	132	99	107	99	103	95	80	50	35	47	23	17
		119	123	119	88	87	85	118	107	95	98	89	79	79	57	33	59	38	24

μ_{xb} (*100)

		1			2			3			4			5			6		
		Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)		
Type	Tread	50	75	100	50	75	100	50	75	100	50	75	100	50	75	100	50	75	100
V	New	99	102	95	79	76	81	84	76	71	78	71	70	93	84	73	30	22	25
		95	92	92	75	75	72	79	72	69	68	65	59	92	80	77	31	25	18
	Worn	91	89	87	66	65	63	76	66	58	69	61	57	60	45	34	23	16	10
		90	84	72	61	60	56	66	60	50	64	51	46	75	38	26	25	19	10
VI	New	92	95	88	79	79	82	82	80	66	72	74	69	78	79	67	39	17	13
		92	89	84	78	77	74	79	71	65	70	67	61	80	79	64	34	28	22
	Worn	89	92	87	68	70	66	71	68	51	66	66	58	47	35	24	21	22	9
		92	83	75	63	63	59	71	57	48	62	50	44	55	34	24	20	14	8
VII	New	91	98	93	80	79	79	85	80	71	83	73	71	92	82	70	24	21	17
		94	90	88	80	77	75	81	78	66	74	68	65	91	82	72	34	30	21
	Worn	88	89	87	68	68	64	71	69	60	75	65	56	79	62	34	21	12	12
		89	85	75	62	59	59	82	65	60	66	62	55	87	69	49	26	16	11
VIII	New	103	90	95	82	78	73	76	74	70	71	71	67	75	73	62	30	28	15
		91	80	77	75	74	73	65	66	66	66	64	60	71	66	55	36	30	20
	Worn	95	88	78	69	66	65	72	59	59	74	63	57	56	35	24	26	13	10
		88	83	74	60	57	58	75	61	52	61	54	45	60	36	20	30	22	14

μ_y (*100)

		1			2			3			4			5			6		
		Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)			Speed(km/hr)		
Type	Tread	50	75	100	50	75	100	50	75	100	50	75	100	50	75	100	50	75	100
V	New	100	102	100	89	86	90	92	93	92	91	87	87	88	86	84	51	40	41
		111	96	94	91	89	89	95	90	85	88	86	89	89	84	87	51	49	40
	Worn	101	94	100	83	83	81	76	97	96	88	88	90	101	96	52	35	34	8
		105	107	109	80	79	82	106	104	101	88	85	87	107	85	53	47	30	13
VI	New	108	102	106	94	90	94	109	99	95	98	94	92	93	93	84	68	32	25
		114	112	111	96	96	93	103	99	101	93	95	90	92	104	85	59	54	43
	Worn	112	103	106	90	83	87	122	111	101	97	97	89	112	99	52	38	17	8
		115	106	113	84	85	85	119	118	104	95	94	87	131	104	60	46	22	10
VII	New	99	102	97	86	88	81	99	98	74	91	92	87	100	96	73	43	49	37
		109	107	106	88	89	89	102	94	94	91	87	86	101	97	95	61	55	47
	Worn	96	99	98	80	81	76	99	97	92	87	87	85	105	101	69	23	27	19
		107	110	108	79	81	78	107	103	94	85	82	82	111	101	80	37	33	14
VIII	New	105	105	102	91	89	84	100	98	91	94	92	85	95	93	83	39	54	27
		112	109	107	90	88	89	96	92	95	87	87	86	92	89	82	57	49	37
	Worn	100	96	93	85	83	77	116	103	93	89	89	90	83	107	93	47	25	10
		106	107	105	78	72	79	112	103	99	84	84	84	120	87	41	54	37	17

$$\mu = \left[1 - f\left(\frac{v}{TD} ; \frac{v}{D_{tyre}}\right)\right]\left[f\left(SRT ; A_{tyre}\right)\right] \quad (1)$$

where

v = speed of travel

TD = texture depth

D_{tyre} = tyre drainage term, connected with tread design and tread depth

SRT = SRT value

A_{tyre} = tyre adhesion term, connected with tread rubber compound

If the results of the measurements for the different tyres are averaged, the influence of the tyre characteristics drops out. The formula is then reduced to:

$$\mu = \left[1 - f\left(\frac{v}{TD} ; v\right)\right] \left[f(SRT)\right] \quad (2)$$

If linear relations are assumed, the following formula is obtained:

$$\mu = a_1 + a_2 \frac{v}{TD} + a_3 v + a_4 \; SRT + a_5 v * SRT + a_6 \frac{v}{TD} * SRT \quad (3)$$

The coefficients a_1, a_2, etc. have to be determined from the measuring results. Terms with two or more variables display interaction effects.

With the aid of a forward stepped multiple regression analysis, the coefficients were calculated, which produced the following formulas:

$$\mu_{xm} = 0.397 + 0.94 \frac{SRT}{100} - \frac{v}{100}\left(0.0017 \frac{SRT}{TD} - \frac{0.028}{TD}\right) \quad (4)$$

R = 0.990 s = 0.037

$$\mu_{xb} = 0.133 + 0.95 \frac{SRT}{100} - \frac{v}{100}\left(0.0017 \frac{SRT}{TD} - \frac{0.035}{TD} + 0.0010 * SRT\right) \quad (5)$$

R = 0.985 s = 0.038

$$\mu_y = 0.520 + 0.58 \frac{SRT}{100} - \frac{v}{100}\left(0.0010 \frac{SRT}{TD}\right) \quad (6)$$

R = 0.985 s = 0.034

(v in km/h; SRT dimensionless; TD in mm)

R is the multiple correlation coefficient and s is the standard deviation. The multiple correlation coefficient is very high. This means that the make-up of the μ-values is reasonable covered by the formulas. The standard deviation is approx. 0.04, in the order of magnitude of the scatter of the measurements.

Truck Tyres

Object and Execution

In the production of truck tyres, large-scale use is made of natural rubber. The resulting brake and side way force coefficients are much lower than those obtained with car tyres. As a rule, the tyre load, and also the tyre inflation are much higher. Important for the contact between tyre and road surface is the high surface pressure in the contact face.

It can be safely assumed that on account of the specific working conditions of truck tyres, the road surface would have to meet different requirements than if it were used for car tyres. The object of the third phase was therefore to see if conclusions from the study on car tyres would also apply to truck tyres. The study schedule therefore did not have to be so exhaustive.

For a similar relation as with car tyres, at least twenty observations are required. This was achieved by measuring on normal roads as well as on the test sections. On the latter, the measurements were carried out twice. Again, groups of blocks were made with the unit day as block. It appeared no feasible to change a wheel during the measurements, so that the measurements were conducted with only one tyre a day. This means confounding tyres with days. The road sections and the levels of the other factors are listed in Table 7. One of the very rough surfaces 1 and 2 has not been selected to prevent excessive tyre wear. The characteristics of the specially constructed road sections were measured again before the

Table 7. Levels of variables selected for the measurements of truck tyres.

Road	Characteristics		Tyre	Type	Characteristics		Other Factors	Level
	SRT	$\overline{TD}$ (mm)			Glass Transition Temperature (°K)	Hardness Shore A		
1	87	3.0	TI	Radial	208	62	Speed (km/hr)	50 75 100
3	74	1.2	TII	Radial	208	64	Water Depth (mm)	1 at 100 km/hr
4	67	1.8	TIII	Retreaded	208	63		2 at 50 km/hr
5	89	0.4		Same carcass as TI			Load (N)	25.000
6	84	0.1	TIV	Diagonal	210	66	Inflation (N/m²)	$6.25*10^5$
GORinchem	70	0.7					Tread depth (mm)	12
ZEVenaar	70	1.1						
WOUw	67	0.8						
BREda	68	0.8						
WILlemstad	77	0.6						

beginning of the tests. It appeared that the characteristics have changed somewhat, due to wear and erosion. The tyres were normal commercial-grade truck tyres.

Results

The measuring results are shown in Table 8. The four tyres did not differ much between themselves. In all cases, the bias-ply tyre reaches slightly lower values than the radial tyres. A feature is that the level of the brake and side way force coefficients are up to a factor 2 lower than those of car tyres. The effect of the speed is likewise virtually absent.

A formula was drawn up for truck tyres in the same way as for car tyres, for which the same model was used. In view of the limited scope of the tests the formulas can only be roughly indicative of the size and the sequence in which the factors and the interactions account for the brake force coefficients. The formulas are:

$$\mu_{xm} = 0.34823 - 0.00066\ \frac{v}{TD} + 0.00438\ SRT \quad (7)$$

$$R = 92.2 \qquad s = 0.06$$

$$\mu_{xb} = 0.46222 - 0.00042\ \frac{v}{TD} - 0.00456\ v + 0.00005\ v * SRT \quad (8)$$

$$R = 90.1 \qquad s = 0.05$$

where
v = speed of travel
TD = texture depth
SRT = SRT value

Discussion of the Results

Tyre Type

As the various tyres differed very little among themselves, further considerations have been simplified by working with averages for car and truck tyres. The measurements with the various tyres are then considered to have been taken with the same tyre in several observations.

Comparison of car and truck tyres (see Table 9) shows a consistent large difference between the two types. On public roads (passing lanes of state highways) the ratio between truck tyres and car tyres is 75% for μ_{xm} and 60% for μ_{xb}. These are averages calculated for all speeds. The test strips show roughly the same picture: 56% for μ_{xm} and 49% for μ_{xb}.

The definition of the measuring criteria already enlarged upon the importance of each of the three coefficients. For normal braking, a high μ_{xm} is favourable, but for an emergency stop, μ_{xb} is very important. Not only are the absolute values of μ lower for truck tyres. It appears also that the ratio μ_{xb}/μ_{xm} is more unfavourable for truck tyres than for car tyres. This means that trucks will not only find their wheels locking at relatively low

Table 8. Results of the measurements with truck tyres.

μ_{xm} (*100)

Road	TI			TII			TIII			TIV		
	50	75	100	50	75	100	50	75	100	50	75	100
1	58	60	61	68	62	63	61	59	61	56	56	54
	56	58	58	60	62	60	57	62	59	57	59	57
3	72	67	63	71	70	70	68	66	68	67	70	54
	69	64	66	71	71	75	70	69	63	68	70	63
4	63	58	61	64	61	66	64	61	58	58	58	59
	62	54	55	66	64	60	61	65	58	62	63	60
5	70	60	57	75	76	57	67	60	59	72	52	50
	71	62	58	71	68	60	66	56	52	69	58	48
6	28	20	13	20	21	11	24	21	21	17	16	6
	25	20	19	22	19	15	27	19	15	19	15	11
WIL	66	62	58	68	67	63	61	61	55	68	64	58
ZEV	69	62	56	69	70	61	62	60	53	67	63	55
WOU	57	53	48	63	66	57	58	56	53	59	54	55
BRE	63	62	59	65	66	61	60	60	54	62	64	47
GOR	65	62	55	70	65	60	61	60	54	65	58	48

μ_{xb} (*100)

Road	TI			TII			TIII			TIV		
	50	75	100	50	75	100	50	75	100	50	75	100
1	37	36	39	44	39	40	38	40	41	34	35	36
	37	37	34	38	37	36	37	38	40	39	39	37
3	42	39	32	48	39	34	45	39	34	43	39	31
	44	36	32	41	39	34	41	42	36	43	39	32
4	36	32	31	42	33	33	39	34	33	37	33	29
	37	32	28	36	33	31	36	36	33	37	33	29
5	45	38	31	46	39	26	44	39	36	42	28	21
	46	38	30	43	35	24	45	37	30	41	32	26
6	15	10	0	13	10	7	13	13	9	10	6	4
	13	8	8	12	8	7	11	9	7	11	9	7
WIL	43	36	32	42	35	28	44	38	31	44	37	27
ZEV	43	36	29	41	35	27	41	38	29	43	35	28
WOU	36	27	22	33	25	19	36	29	23	32	25	19
BRE	39	36	29	38	35	25	40	37	28	38	35	24
GOR	39	34	26	38	30	22	40	34	27	41	31	20

deceleration, but that the available brake force also decreases progressively more compared with cars.

Tread Depth

The tread depth always has a significant influence on the brake force and side way force coefficients, even on rough surfaces and at low speeds. The tread depth as separate factor varied at more levels is already exhaustively discussed elsewhere (11).

For the present study the approach is

Table 9. Interaction road surface - speed - type of tyre on the specially constructed road surfaces and on normal highways.

Road	μ_{xm} (*100)						μ_{xb} (*100)					
	Car Tyres		Truck Tyres		Truck Tyres/Car Tyres (%)		Car Tyres		Truck Tyres		Truck Tyres/Car Tyres (%)	
	50	100	50	100	50	100	50	100	50	100	50	100
1	100	101	59	60	59	59	79	76	38	38	48	50
3	119	108	70	66	59	61	81	68	44	33	54	49
4	108	104	63	60	58	58	75	67	38	31	51	46
5	111	100	71	56	64	56	84	66	45	28	54	42
6	56	38	23	14	41	37	30	15	13	8	43	53
Average Teststrips	99	90	57	51	56	54	70	58	36	28	50	48
GOR	81	85	65	54	80	64	60	48	40	24	67	50
ZEV	86	81	67	56	78	69	62	49	42	28	58	57
WOU	71	70	59	53	83	76	52	39	34	21	65	54
BRE	79	78	63	55	80	71	57	47	39	27	68	57
WIL	83	83	66	59	80	71	62	50	43	30	69	60
Average Highways	80	79	60	53	80	70	59	47	37	27	65	56

Table 10. Illustration of the numerical effect of the road characteristics and the speed using the formulas.

Effect $\overline{TD}$			Car Tyres μ_{xm}	Car Tyres μ_{xb}	Car Tyres μ_y (*100)	Truck Tyres μ_{xm}	Truck Tyres μ_{xb}
$\mu_{\overline{TD}=1} - \mu_{\overline{TD}=0.4}$	at 50 km/hr	SRT = 50	4.3	3.7	3.7	5.1	3.1
		SRT = 80	8.1	7.6	6.0	5.1	3.1
	at 100 km/hr	SRT = 50	8.5	7.5	7.5	10.0	6.5
		SRT = 80	16.2	15.1	12.0	10.0	6.3
$\mu_{\overline{TD}=1} - \mu_{TD=0.4}$	av. at 50 km/hr		6.2	5.6	4.8	5.1	3.1
	av. at 100 km/hr		12.4	11.3	9.8	10.0	6.4
	av. at SRT = 50		6.4	5.6	5.6	7.6	4.8
	av. at SRT = 80		12.2	11.3	9.0	7.6	4.7
$\mu_{\overline{TD}=1} - \mu_{\overline{TD}=0.4}$	total average		9.3	8.5	7.3	7.6	4.8

Effect SRT							
$\mu_{SRT=80} - \mu_{SRT=50}$	at 50 km/hr	$\overline{TD}$ = 0.4	21.8	20.6	13.6	13.2	7.2
		$\overline{TD}$ = 1	25.6	24.5	15.9	13.2	7.2
	at 100 km/hr	$\overline{TD}$ = 0.4	15.4	12.8	9.9	13.2	14.6
		$\overline{TD}$ = 1	23.1	20.4	14.4	13.2	14.4
$\mu_{SRT=80} - \mu_{SRT=50}$	av. at 50 km/hr		23.7	22.6	14.8	13.2	7.2
	av. at 100 km/hr		19.2	16.6	12.2	13.2	14.5
	av. at $\overline{TD}$ = 0.4		18.6	16.7	11.8	13.2	10.9
	av. at $\overline{TD}$ = 1		24.4	22.4	15.2	13.2	10.8
$\mu_{SRT=80} - \mu_{SRT=50}$	total average		21.5	19.6	13.4	13.2	10.8

Effect speed							
$\mu_{50\ km} - \mu_{100\ km}$	$\overline{TD}$ = 0.4	SRT = 50	7.1	8.8	6.3	8.3	16.5
		SRT = 80	13.5	16.6	10.0	8.3	9.1
	$\overline{TD}$ = 1	SRT = 50	2.9	5.0	2.5	3.4	13.1
		SRT = 80	5.4	9.1	4.0	3.4	5.9
$\mu_{50\ km} - \mu_{100\ km}$	av. $\overline{TD}$ = 0.4		10.3	12.7	8.2	8.3	12.8
	av. $\overline{TD}$ = 1		4.2	7.0	3.2	3.4	8.5
	av. SRT = 50		5.0	6.9	4.4	5.8	14.8
	av. SRT = 80		9.4	12.8	7.0	5.8	7.5
$\mu_{50\ km} - \mu_{100\ km}$	total average		7.2	9.9	5.7	5.8	11.2

simplified. Direct comparison between car and truck tyres was always made with full treads. In the discussion of the road surface characteristics and speed an average value for car tyres was determined from the measuring values of a new tyre and one worn to 1 mm. For the truck tyres the full tread was used again.

Road Surface Type and Speed

Illustration for a practical Situation. By reference to the formulas the variables carrying the greatest effect can be calculated for a practical situation. The road surface characteristics considered are the micro-roughness with the SRT values as criterion, the macro-roughness with the average texture depth as criterion, and the speed v.

On present state highways in the Netherlands, the SRT values vary between 50 and 80, the $\overline{TD}$ varies between 0.4 and 1. As to speed, the limits of 50 and 100 km/h can reasonably serve to delineate the speed interval for the practical situation. The numerical influences of the variables within the practical area are set out in Table 10.

Influence of $\overline{TD}$. According to the tables, the influence of TD can be rather considerable. It is biggest for μ_{xm}, followed by μ_{xb} and then for μ_y. In an absolute sense, the influence of $\overline{TD}$ is greater for car tyres than for truck tyres. As could be expected, the influence of $\overline{TD}$ is greater at higher than at lower speeds.

Influence of SRT. The SRT has mostly considerable influence. It is greatest for μ_{xm}, followed by μ_{xb} and then for μ_y. The influence of the SRT is greater for car tyres than for truck tyres. For car tyres, a high SRT value combined with a high $\overline{TD}$ value has an particularly favourable effect (interaction). With truck tyres, the influence of SRT is practically independent of $\overline{TD}$.

Influence of Speed. The speed can carry relatively much effect, which is greatest for μ_{xb}, then for μ_{xm} and then for μ_y. It is greater for car tyres than for truck tyres at a high SRT value, but the reverse at a low SRT value.

Overall Picture. Summarising, it can be said that at the chosen peripheral conditions the micro-roughness of the road surface has much influence on the skid resistance. This applies to any type of tyre, at any speed and at any level of macro-roughness. The macro-roughness of the road surface has much influence practically only at high speeds. Reversely, there is much influence from the speed only on roads with little texture depth.

Conclusions and Recommendations

First-order Factors important to the Skid Resistance

The following factors are important with regard to the size of the brake and side way forces between car tyres and a wet road surface: the type of surface, the tyre type, the speed of the vehicle, the tread depth of the tyre and the water depth on the road.

The type of road surface and the speed have much effect, the tread depth and the water depth (disregarding extremes in case of ruts, etc.) moderately so and the tyre type has little influence. Tyre load and inflation can be regarded as second-order factors for the skid resistance. Their influence is so slight that it can be further disregarded.

Factors other than those mentioned had no demonstrable effect on the skid resistance. Particularly, no relationship was found between temperature and skid resistance.

Characteristics important for ensuring the greatest possible Brake and Side way Forces

With a view to achieving the greatest possible brake and side way forces, the conclusion regarding the characteristics studied is: a high SRT value is favourable on all roads. On roads where vehicles travel at high speeds (100 km/h and over), increasing the average texture depth results in higher skid resistance, particularly with car tyres. Reducing the speed always increases the skid resistance, the least on roads with great micro-roughness and macro-roughness, the most on those without these two features. Large tread depth is favourable, also at low speeds and on rough roads. Normal commercial-grade tyres display little difference among themselves, and this applies to both car tyres and truck tyres.

Recommendations for offical Measures

In order to ensure the highest possible skid resistance through official measures, the conclusions give rise to the following recommendations.

A recommendation can be made with regard to a highest possible minimum requirement for the micro-roughness of road surfaces, expressed in an SRT value. Depending on the type of road and in connection with the customary speeds a minimum requirement may be added for the average texture depth $\overline{TD}$.

With a view to countering temporary and/or local reduction of the available brake and side way forces, speed limits might be considered. As it not realistic to introduce general speed limits on the grounds of the degree of skid resistance of the road surface alone, such limits should only relate to situations in which the road is wet. Combination with moistness indicators would then be required.

Although no value as regards tread depth can be directly derived from this study, setting a minimum is recommended. The level of the minimum value can be decided on the results of single-factor investigations already executed.

There is as yet no sufficient knowledge of tyre characteristics important to the skid resistance to warrant recommending official measures. This applies to both car and truck tyres. In an absolute sense, there is considerable difference between truck tyres and car tyres. Everything should therefore be done to ensure optimum use of the available brake forces of truck tyres. Such measures would relate to distribution of the brake force, with an anti-locking device supplementing it.

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The Foundation for Film and Science, Utrecht, has made a film of the study with the title "Tyres and Road Surfaces".

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