VEHICLE DESIGN AND SKID RESISTANCE

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On slippery roads the limits of manoeuvrability are reached much earlier, lower cornering speeds result, stopping distances become longer and dangerous motions of vehicles occur more frequently. Some experimental and theoretical research work published by various authors in the last years has contributed for better understanding of the interaction between tire, vehicle and road.

The vehicles show a typical behaviour when reaching the limits of breakaway and beyond it. When driving on a circular path the steady state driving steering angles of understeering cars increase progressively with increasing speed whereas the steering angles of oversteering cars decrease rapidly after passing a maximum value. For both steering characteristics the torque which is felt at the steering wheel is always passing a maximum followed by the loss of feel for steering response. The behaviour of the car when the limiting condition is approached is determined by the location of the center of gravity, the suspension design with its kinematics, springs and shock absorbers and the tire characteristics. In order to force the breakaway intensified conditions of driving were applied, individually or combined, such as starting from a circular path steadily growing steering angle, sudden lack of skid resistance, emergency braking. Under these conditions, the vehicle deviates from its intended course, the understeering car continues on a wider circle whereas the oversteering car turns around its vertical axis. When braking with locked wheels the center of gravity of the car moves tangentially to the bend. The forces transferred from tire to road and their dependences are of decisive importance. The available max. values of the traction coefficients range between 0.1 on ice up to 1.0 on dry surfaces. They depend differently on the speed, on the cornering forces and the braking or traction forces. On wet roads important differences in cornering forces and locked braking forces are existing for tires of different design but for the same purpose of use. This becomes obvious at the limiting conditions of cornering and at emergency braking. To reduce as far as possible these differences only caused by tires and wet roads would present a very efficient contribution to improve traffic safety.

Skidding and long stopping distances of motorvehicles depend to a great extent on the tire-road friction which can differ and change in a wide range according to the type of road surfaces and to weather conditions. Besides at given friction conditions the possible manoeuvers of vehicles depend on the design of the vehicle. On the basis of several papers published recently a report shall be given on the origin and development of dangerous driving conditions and above all on the wide ranges and vaguenesses which make prediction difficult.

Critical Driving Limits

On principle there are two distinguishable limits for the feasibility to drive on roads: the limit of the tire-road friction and the limit of directional stability.

The directional stability of the vehicle motion, as given by the fact that by short time interfering forces without steering correction no increasing breakaway will be introduced, is determined by the tire cornering force characteristics and by the vehicle design which could be different in mass distribution, wheel kinematics and suspension systems, and in front or rear drive etc. We can proceed from the fact that all modern passenger cars show directional stability under normal operating conditions. However approaching the critical driving limits with too high speeds and at reduced tire-road friction coefficients - that means any time when due to an interfering force the slip angles of the tires at the rear axle increase more than at the front axle - the limit of stability is exceeded at a critical speed individual for the vehicle. Especially tail heavy rear driven vehicles and those suspensions, wheel alignments and tire characteristics which have an unfavourable effect tend in that direction. The course of the vehicle after having exceeded the limit of stability can be described approximately by a sum of exponential functions in the shape of

$$\Sigma \, C_i \cdot e^{\lambda_i t}$$

The coefficients λ_i determine the extent of instability. Provided this is low enough the vehicle motion can be kept under control more or less by fast steering reactions.

Simple criterias for the directional stability of real vehicles do not exist because of the great number of design influences which work partly in the same direction partly in the opposite direction.

A paper (2) recently published shows that simplified mathematical substitute models describe the tendencies mainly correct. For a single track substitute model with nonlinear tire characteristics easily surveyable conditions are given in (3)

$$b^2 \phi_1 \phi_2 - M(\phi_1 a - \phi_2 b) v^2 > 0$$

$$(a^2 + k^2)\phi_1 + (b^2 + k^2)\phi_2 \quad > 0$$

with the denotations: M vehicle mass, k radius of inertia, l wheel base, a and b distances of the center of gravity from the front and rear axle, v vehicle speed. The formulae

$$\phi_1 = \frac{dF_1}{d\alpha_1}, \quad \phi_2 = \frac{dF_2}{d\alpha_2}$$

denote the gradients of the cornering forces F_1 (front) and F_2 (rear) in relation to the corresponding slip angles α_1 and α_2: The exponential coefficients λ_i also depend on the values ϕ_1 and ϕ_2. That means that for the stability of the state of motion at which static balance of forces at slip angles α_1 and α_2 exists, not the figures of the side force coefficients are decisive but the gradients at both axles. If at small slip angles for moderate centrifugal forces these gradients do not change when proceeding from a skid resistant pavement to a less skid resistant one, the conditions for stability do not change either. In general a reduction of friction will reduce the critical speed of stability. If the gradients of the cornering forces change their sign as they usually do for high slip angles, the motion of the vehicle always will get instable as indicated by these conditions. When approaching the critical limits of friction the limit of stability can be exceeded in some cases and both conditions occur at the same time. Without separating them, these effects will be treated in the following by considering particular cases of vehicle motions. A vehicle can break away or skid if the steering wheel is turned too much or the brakes have to be activated too strong or if both actions occur at the same time particularly if the available tire-road friction is to low.

Vehicle motions when cornering

On a circular path the required steering angle is a criterion. It can be coordinated to the centrifugal force as shown in Figure 1 for three different vehicles (4).

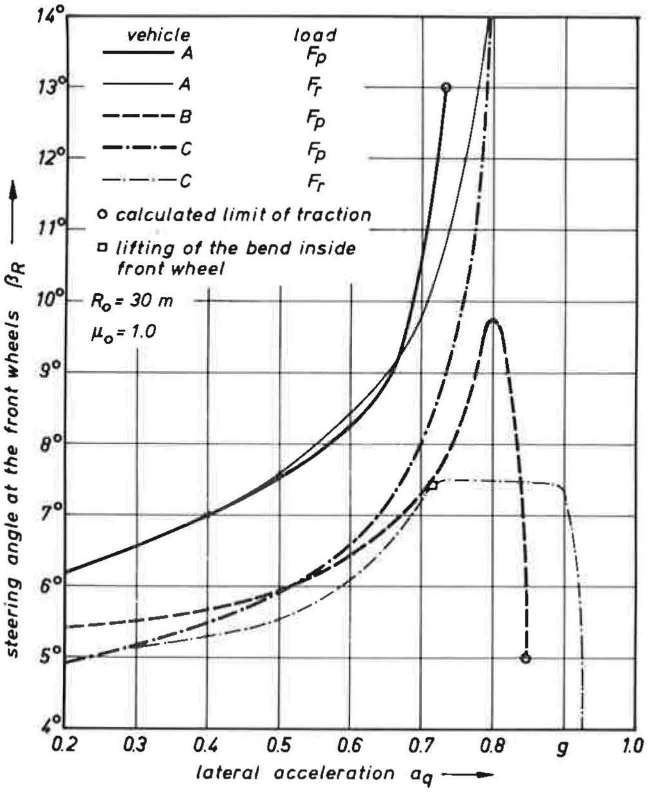
Vehicle	Drive	load on front axel % ready for service	permissible gross weight
A	front	62	53
B	rear	53	48.5
C	rear	39	45

There are two cases clearly distinguishable. In the first case, at the critical range the required steering angle decreases steeply after a maximum value. This is typical for vehicles and driving conditions for which a transition from a stable to an instable motion occurs. In the second case the required steering angle increases steeply. Obviously the steering torque which is felt at the steering wheel, reduced by the steering gear ratio, decreases always rapidly in the critical range, Figure 2. The maximum available value of centripetal acceleration never can exceed the peak value of the friction coefficient, Figure 3.

For these calculations (2,4) it has been presupposed that tire characteristics change in relation to the maximum friction coefficient which certainly is not completely exact, but nevertheless it is showing the tendencies. Some measurements indicated a good correspondence (4).

A typical behaviour of the vehicle can be ovserved when the circular path (2) shall be narrowed by a steadily increasing steering angle, Figure 4, and when for the purpose of aggravating of the conditions additionally the skid resistance falls down suddenly to a low value after the beginning of this steering manoeuver. The more the skid resistance decreases the less the vehicle follows the steering control. In addition, greater or smaller turnings of the longitudinal axis of the vehicle in re-

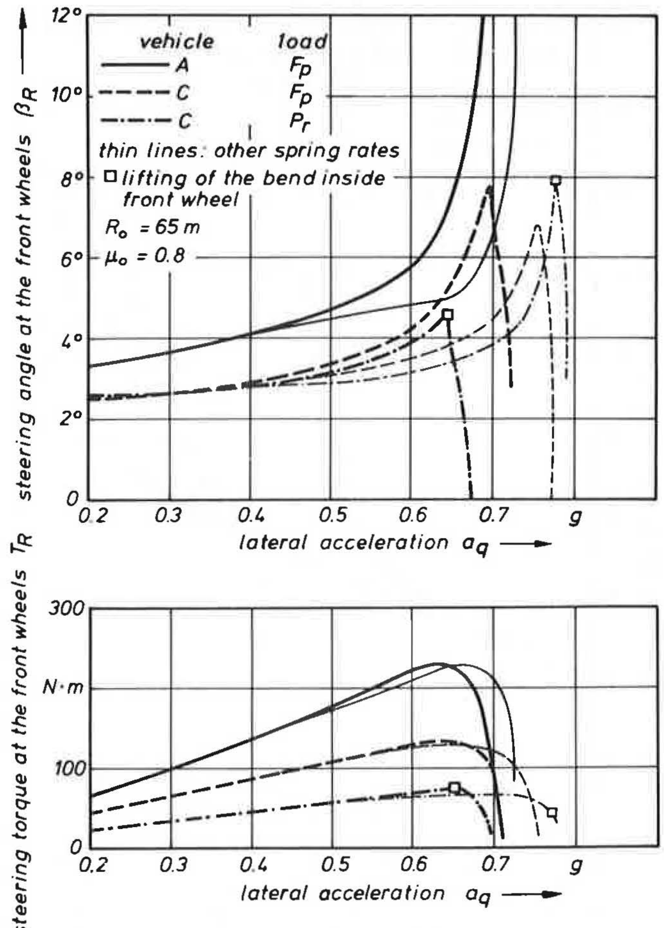
Figure 1. Calculated steering angle at the front wheels at steady state circular drive versus lateral acceleration for various vehicles with the loads F_r (ready for service) and F_p (permissible gross weight), (4)



Note: F_p permissible gross weight

F_r ready for service

Figure 2. Calculated steering angle and steering torque at the front wheels for steady state circular drive (2).



lation to the path of the center of gravity of the vehicle arise, depending on vehicle design and skid resistance. This can lead to a lifting of one of the bend inside wheels and to the critical limits of tiltover. Significant differences show up when at very fast cornering the skid resistance is declining suddenly to 2/3 of the initial value. Starting from a centripetal acceleration of 0.6 g for numerical examples, Figure 5, in order to compare the behaviour of vehicles with extreme load concentration on nose or tail (2/3 of the total weight), the radius of the path of the nose heavy vehicle increases immediately. The tail heavy vehicle turns additionally around its vertical axis at an angle of 180°, deviating from the circular path. However if on this circular path the skid resistance declines further to about 1/3 of the initial value both vehicles immediately follow an approximately tangential course of the center of gravity.

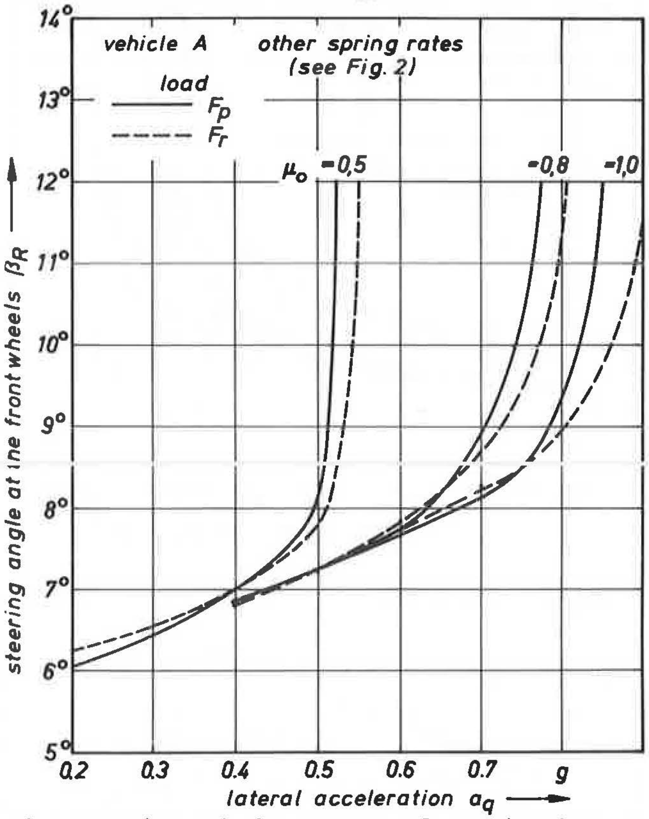
Such manoeuvers are intensified by braking. For this case it is not necessary as in the aforementioned numerical examples to assume extreme and rare events of sudden loss of friction. It is sufficient to consider a simple lane change caused by a sinusoidal steering manoeuver combined with emergency braking (5), Figure 6. For these calculations with a vehicle with equal loads on front and rear axles the tire force characteristics did correspond very well to actual measurements on dry and wet surfaces.

On dry concrete pavement the braking is effectuated at the beginning of the lane change manoeuver. To allow a better comparison the corresponding motion on wet pavement when steering back to the original lane also is plotted in Figure 6.

It is remarkable that the vehicle at hard braking moves in both cases in a line nearly tangential to that without braking. Even an antiskid device cannot improve the deviation of the controlled course to a reasonable extent, it only shortens the stopping distance and prevents the vehicle from turning around its vertical axis. In the case of moderate braking and low friction coefficient the breakaway course of a vehicle using an anti skid device deviates less from the controlled course. Nevertheless the vehicle turns more or less extensively around its vertical axis depending on its type.

Concerning their extents the different interactions of vehicle design parameters are not easily to ascertain. The horizontal forces between tire and road surface can be influenced considerably by the vertical tire load, and to a minor extent by the momentary position of the wheel (camber) and its relative motions (change of track).

Figure 3. Calculated steering angle at the front wheels at steady state circular drive for various friction coefficients μ_o versus lateral acceleration, (4).

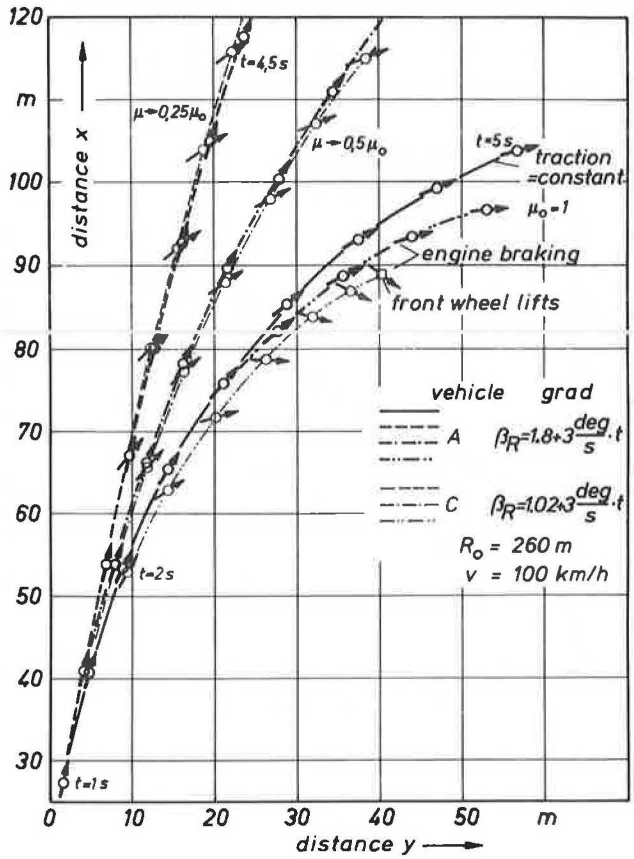


The location of the center of gravity has an important influence leading to nose heaviness or tail heaviness with their known tendencies of relatively reducing the available cornering forces. When cornering tire loads on the outer wheels become higher than those on the inner wheels. The distribution of the torque due to the centrifugal force to front and rear axles depends on the wheel suspension spring rates and on the torsion bar stabilizer as anti-roll spring for this purpose. According to the wheel suspension kinematics the vehicle roll can be connected with effects comparable to an additional steering effect. Near the critical driving limits the tire load relations can be changed by the progression of the springs rates and by spring stroke limitations thus changing also the vehicle behaviour, Figure 2. Undoubtedly tire cornering forces differ at different tire inflation pressures, and at the free rolling wheel and at the wheel transfering circumferential forces. The tire-road friction causes the greatest range of differences. Each of these influences can be made effective in the same direction as another or in the opposite direction.

Provided that axle loads differ only in an usual rate not exceeding 0.5 ± 0.10 a moderate tail heavy vehicle may show a behaviour comparable with that of a nose heavy one, as it is the case with the tail heavy vehicles A and C in Figure 1.

The results of the calculations mentioned up to now are verified at least in their tendency by observations and special

Figure 4. Calculated course of the vehicle and its position starting from a circular path with friction coefficient μ_o and a steadily increasing steering angle. After one second the friction coefficient jumping (from its initial value μ_o) to μ.



experiments. A high numerical accuracy cannot be expected because in view of the sensibility of the motion processes at the critical limits of driving small deviations of the test conditions when proceeding from one to another measurement can cause a distinct effect.

A test report (6) on observations with 4 vehicles of different design features nearly corresponding to the preceding examples has been published which with its defined extreme driving conditions is comparable to a certain extent with the aforementioned calculations. The following types of vehicles were tested: F (front drive, nose heavy), S (standard rear drive, nose heavy) R (rear drive, tail heavy), M (rear drive, central engine, slightly tail heavy), see Table 1.

On a steady state circular drive with a radius of 32.5 m on a wet asphalt pavement the largely nose heavy vehicle F reaches the highest speed and centripetal acceleration, the slightly tail heavy vehicle M reached a little lower though higher values than the nose heavier vehicle S. The largely tail heavy vehicle R reached the lowest speed. On a skid pad with an

Table 1. Driving limits of similar vehicles with different design features, (6).

	front drive nose heavy (F) Audi 100	standard rear drive nose heavy (S) BMW 1802	rear drive tail heavy (R) VW 411	rear drive, midengine slightly tail heavy (M) VW- Porsche
load on axle %	60 40	54,5 45,5	42,5 57,5	47,5 52,5
mass kg	1099	1020	1115	985
circular course, wet				
asphalt, 65 m Ø : speed km/h	52.1	51.0	50.0	51.3
lat.acc. m/s^2	6.46	6.18	5.95	6.3
basal, 75 m Ø : speed km/h	51.2	41.2	49.2	50.0
lat.acc. m/s^2	5.45	5.00	5.00	5.15
aquaplaning on circular course 190 m Ø, deviated of the 5 m lane at a speed of:				
80 km/h after a distance of m	8.25	9.5	8.7	10.6
90 km/h after a distance of m	5.0	3.0	6.0	6.6
aquaplaning on straight course and emergency braking				
turn of the longitudinal axis	**a few deg**	**swerving** up to 90°	540°	900°
slalom course				
distance: 18 m, **speed** km/h	55.1	54.0	53.0	56.2
distance: 36 m, speed km/h	105.4	107.5	101.0	108.8
hard packed snow, average ascent 7.4% and bends				
average speed km/h	32.2	28.4	32.4	30.9

Figure 5. Calculated course of the vehicle and its position starting from a circular path R_o with locked steering angle β_R and the friktion coefficient jumping from its initial value μ_o to μ .

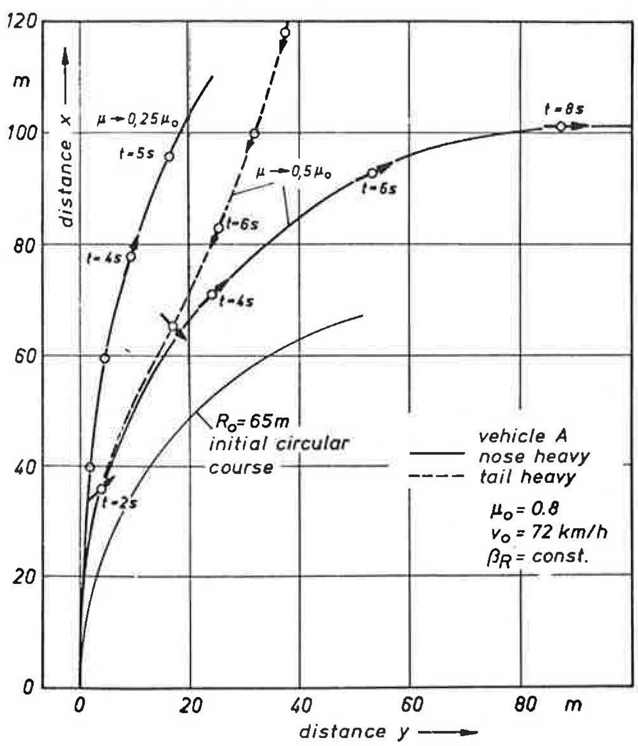
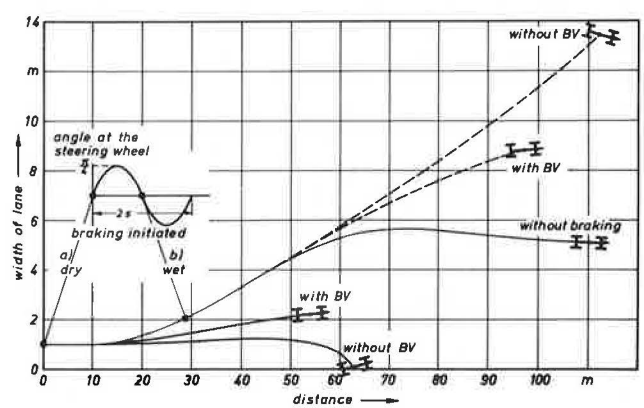


Figure 6. Calculated lane change motions on a dry road (a) and on a wet one (b) at emergency braking with and without an anti-lock device (BV). Standard vehicle (rear drive,front engine) with equal axle loads, (5).



aquaplanig section representing a sudden complete loss of friction the distance was measured up to the point when the braking away vehicle reached the periphery of the aquaplaning section. At a speed of 80 km/h vehicle M showed the slowest lateral off-set, vehicle F the fastest one. At a speed increased only slightly to 90 km/h the measured distances shortened but above all vehicle S did not follow the expected scheme for which no reasons can be given without the knowledge of all particular details.

At emergency braking when driving straight on an aquaplaning test course vehicle F turned around its vertical axis only a few degrees. Vehicle S turned up to 90 degrees swerving once but mainly moved straight on. Vehicle R turned one and a half times, vehicle M two and a half times

On a road covered with hard packed snow with bends and 7 % ascent together with descending sections the vehicles F and R showed the best performance. Vehicle M was less fast and vehicle S was the slowest one. The tests showed also remarkable differences in the requirements for skill in steering the vehicles. The vehicles S and R needed the highest requirements in this respect.

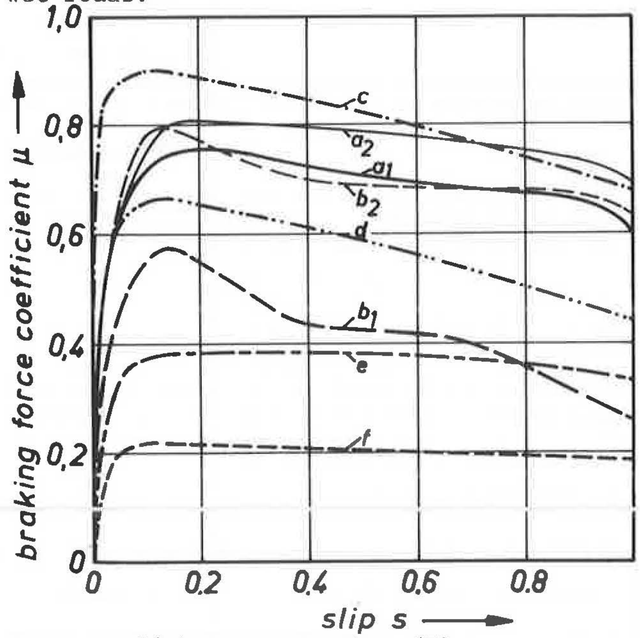
In general these vehicles demonstrated a behaviour as expected. However it is remarkable that the numerical values in the critical range do not differ much and that the effects caused by the differences in the location of the center of gravity can be balanced well by other design features.

Tire and Road Surface

Vehicle motions are decisivly determined by the characteristics of the forces between tire and road surface which differ on more or less skid resistant surfaces. Of course well patterned tires should be used, and therefore only such tires will be considered in the following. The transferable traction and braking forces increase with growing slip as shown in Figure 7 for different road surfaces. After reaching a maximum value these forces decrease on wet surfaces more or less to the value of locked wheel braking. The respective maximum values and the dependence on slip are determined by the condition of the road surface and by the tire. The friction coefficients range from 1.0 on well surfaced dry roads to less than 0.1 on ice and 0.2 on snow. The maximum value is a very unstable point in the force development thus being difficult to measure exactly. This point can be apporached better by using an anti skid device and thereby the differences between the practically attainable maximum value and the locked wheel value had been found. Both values decrease with increasing speed as shown in Figure 8 (8) for crossply tires.

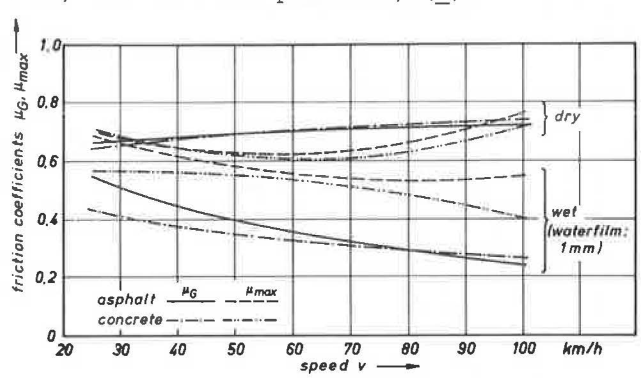
The considerable differences of road properties can be derived from the sliding coefficients which were measured in dependence on speed using a standard tire in crossply construction on wet roads wetted by controlled and defined watering (9), Figure 9. The wide range between 5 % and 95 % of the statistical collective of the tested roads with values from 0.2 to 0.6 at 60 km/h for example is remarkable. This statistical graph does not show the differences in the decrease of the sliding coefficients with increasing speed on certain roads. These values are not absolutely valid any more for modern tires, because at speeds from 60 km/h to 80 km/h modern radial tires reach about 25 to 30 % higher friction values than crossply tires which is to consider looking at Figure 9.

Figure 7. Braking forces coefficients related to wheel load versus slip on various wet roads.



Note: English measurements, (7).
asphalt a a_1 48 km/h a_2 16 km/h
asphalt b b_1 48 km/h b_2 16 km/h
Swiss measurements, (5).
asphalt c
concrete d
snow e
ice f

Figure 8. Max. friction coefficient μ_{max} available by an anti-lock device and locked wheel sliding coefficient μ_G versus speed on dry and wet asphalt (water film 1 mm) and concrete pavement, (8).



The great differences of the values and of the dependence on speed is significant for various types of radial tires (10), Figure 10. It ist unknown in detail which influences of construction, pattern, and rubber compound cause these variations.

The cornering forces of the tire increase strongly in the usually used range of small slip angles, Figure 11. They remain approximately constant or decrease at greater slip angles until the area of lateral sliding. On wet roads the cornering forces are smaller, and on icy surfaces only a fraction of the normal forces is transferable. On dry roads the speed is of minor

Figure 9. Sliding coefficients of a statistical collective of wet road surfaces. Standard test with locked wheel trailer and crossply standard tire, (9).

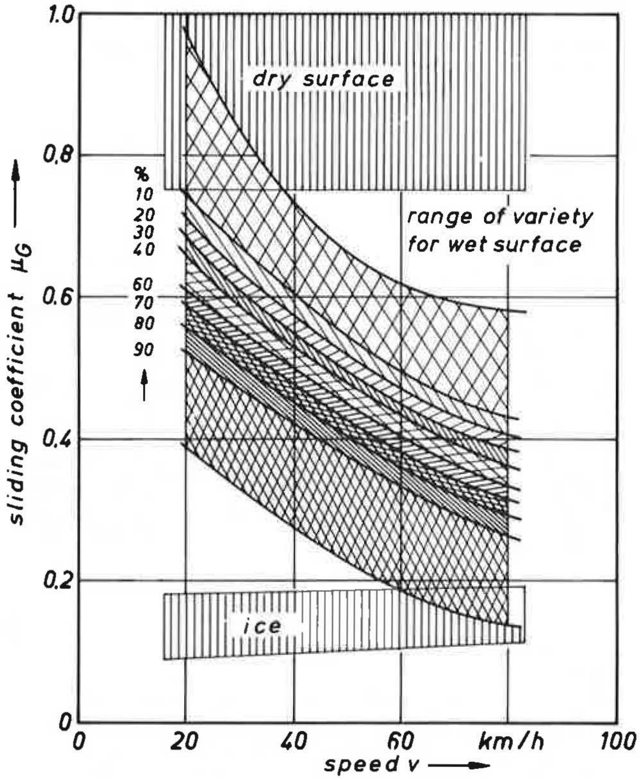
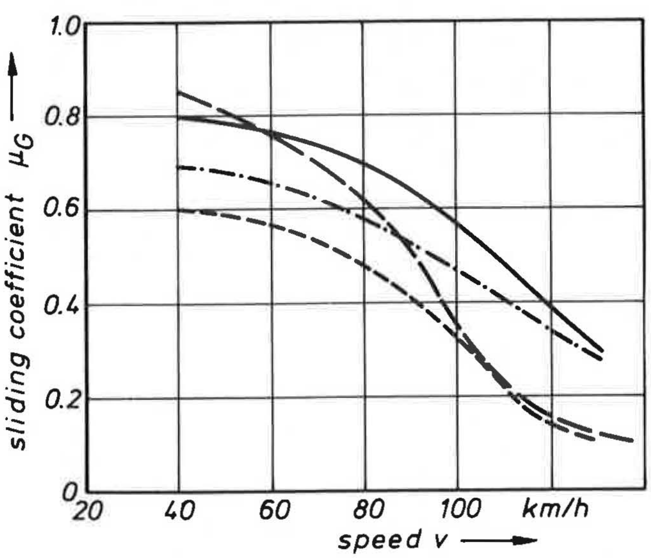


Figure 10. Locked wheel sliding coefficients for various steel and textile belted tires. Measurements on internal track drum machine, water film 1 mm, (10).



influence. On wet roads and on surfaces with low skid resistance the cornering forces decrease with increasing speed, (11), Figure 12.

Figure 11. Max. cornering force coefficients at a speed of 60 km/h. Swiss measurements on roads, (5).

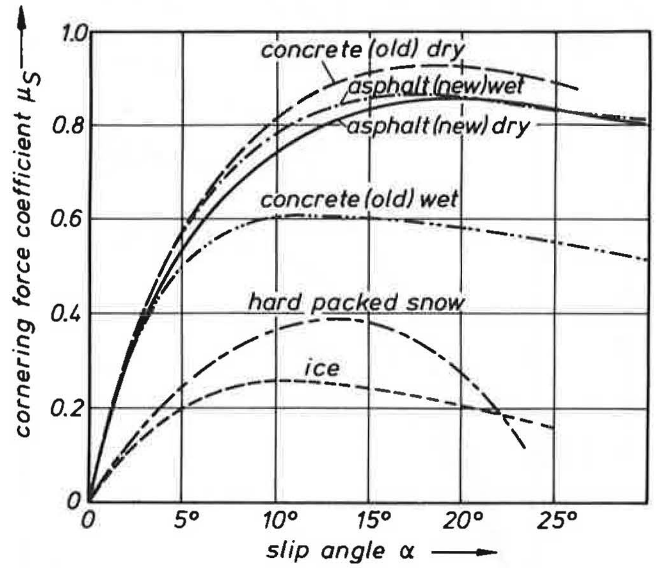
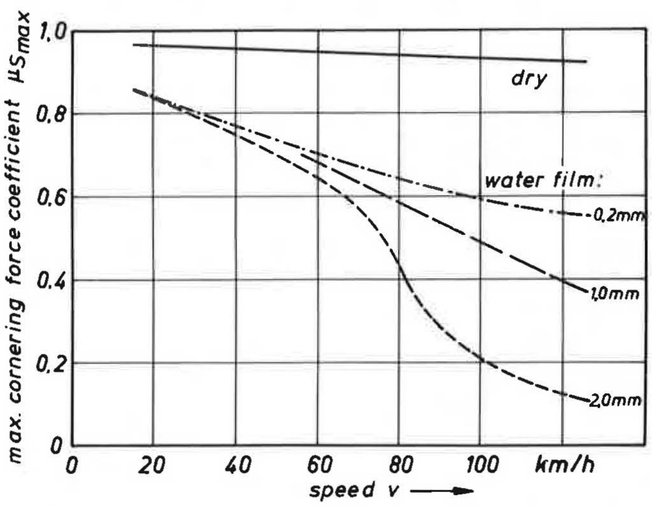


Figure 12. Maximum values of cornering force coefficients versus speed, measurements on internal track drum, (11).



The development of the cornering force depends to a high extent on the tire construction and may differ considerably for different types of radial tires designed for the same purpose of service, as shown in Figure 13 (10) for the modern tires of Figure 10.

The resulting forces at the coincidence of cornering forces and forces in the direction of the motion, Figure 14, apparently are determined by the vectorial strain characteristics of deformations in the tire contact area and can be described coherently by calculations based on measurements (5). The results are elliptic curves which show minor decreases for the cornering forces when small longitudinal forces coincide and sudden decreases together with large longitudinal forces. The amount of these decreases is smaller on wet roads than on dry roads. As demonstrated for example by the side forces at slip

Figure 13. Cornering force of various steel and textile bleted tires at a speed of 80 km/h, measurements on internal track drum, water film 1 mm, (10).

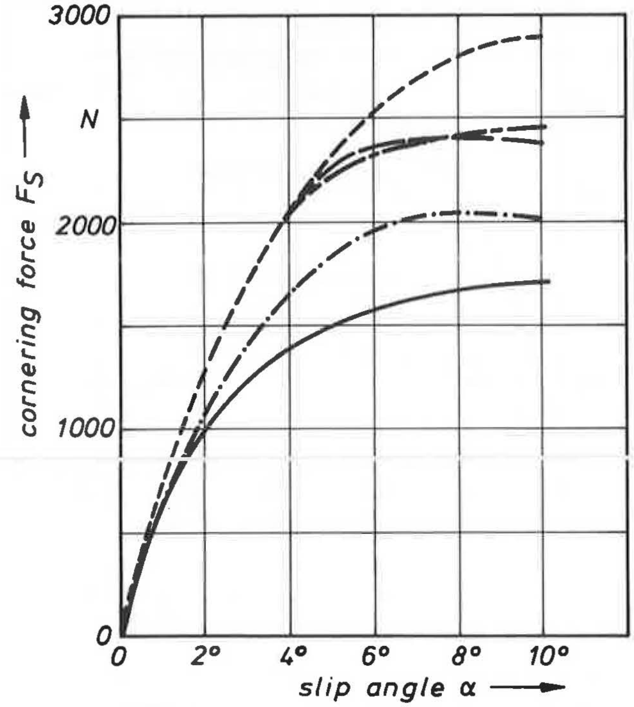
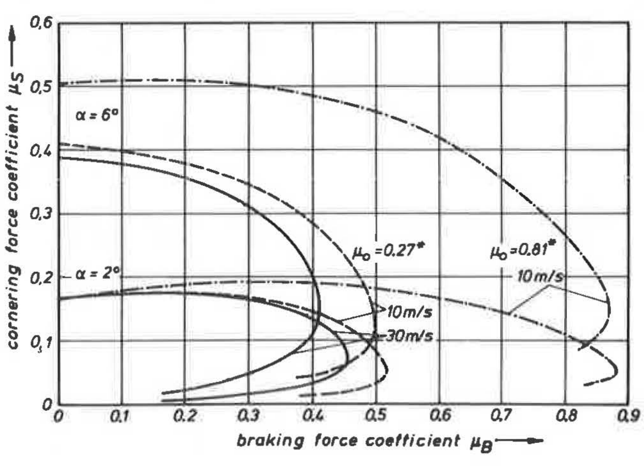


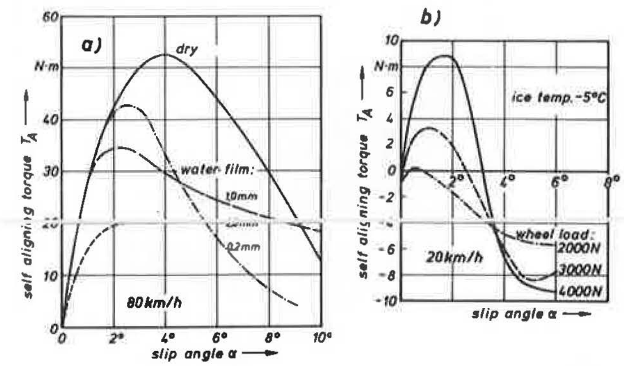
Figure 14. Calculated cornering force coefficients μ_S versus braking force coefficients μ_B for various friction coefficients μ_O, speeds and slip angles; calculations supported by measurements.



angles of 2 and 6 degrees the changes do not develop proportionally. A further additional reduction of the side forces occurs with increasing speed.

The reduction of friction due to vibrations combined with wheel load fluctuations only should be mentioned, as this effect is of minor importance on even roads. It would be favourable for the controllability of the vehicle on surfaces with low skid resistance if the driver could realize the loss of friction for instance by the change in the torque at the steering wheel. However especially on slippery roads the torque does not correspond to the forces transferable by the tires, Figure 15, and the steering feel can be lost completely.

Figure 15. Tire self aligning torque versus slip angle.
a - on dry and wet road, tire size 155 SR 15 (11)
b - on ice, temperature -5 deg centigrade, tire size 155 SR M+S (12).



This survey shows that the forces transferable by the tire can vary in a very wide range, and therefore the tire-road friction has the strongest effect on the controllability of the vehicle at the critical driving limits and represents the main source of insecurity.

The whole range is given by the various tire constructions, by dry and wet roads with their different skid resistance values, by the wintry conditions with ice and snow, and by the special case of aquaplaning of the tires at thicker waterfilms.

It is not possible to establish a simple evaluation for the tire-road friction which could be exactly characterizing for all critical conditions because of the different dependencies from cornering forces and longitudinal forces on dry and wet roads, furthermore because of the dependencies on the speed and the tires. Therefore the sliding coefficient at locked wheel braking which can be measured suits best as an approximate figure for the skid resistance.

Conclusions

What can be done to prevent the breakaway of the vehicle from the controlled course and to ensure short stopping distances?

First of all at all critical driving limits the breakaway motions should not occur suddenly, and should develop in a goodnatured manner announcing its impendence. Control by countersteering should be possible in due time in order to diminish the effect of the breakaway motion. This is effective only if the available tire-road friction is sufficient. Above all the vehicle should not turn around its vertical axis when the friction decreases. As examples show that can be achieved to a high extent by design features such as the location of the center of gravity wheel suspension kinematics, spring rate adaption and brake layout.

The motions of the vehicles are determined decisively by the characteristics of the transfer of the forces between tire and road, therefore the improvements by radial tires are remarkable. It would be useful for the optimizing of the whole system vehicle-tire-road to reduce the considerable variety in the cornering force characteristics of the various tires for the same purpose of service.

As the road surface is of decisive influence it is important to provide an always as much as possible constantly high skid resistance. This uniformity to which the driver can adjust himself seems to be more important than individual road sections with very high skid resistance followed by others with lower skid resistance which occurs not seldom in wet road conditions. That demands a road surface with adequate roughness which is advantageous at thin water films and moreover after their sudden freezing. The road surfaces should be as much as possible even but drain of water should not be prevented. Especially the development of puddles is very dangerous because of the risk of aquaplaning.

Provided these requirements are fulfilled as far as possible the inevitable dangers of the weather conditions remain. They can be met only by the drivers attention and skill.

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