Skidding accidents

Considerations on road surface and vehicle characteristics

Summary of the present situation
Provisional recommendation concerning skidding resistance of road surfaces
Investigation programme

First interim report of the
SWOV Working Group on Tyres, Road Surfaces and Skidding Accidents

Institute for Road Safety Research SWOV

Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV

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Preface

The phenomenon of skidding is generally regarded as an important contributing factor to the occurrence of traffic accidents.
It is, however, difficult to estimate the incidence of this phenomenon, because:

a. skidding is not a clearly defined concept in the recording of accidents;
b. there is no specific examination for all accidents as to whether skidding was a contributory factor.

Skidding is probably underestimated in the statistics based on accident records, because only accidents attributed unequivocally to skidding are recorded as such. (The same applies to all causes of accidents.)
In spite of the many investigations of the relative importance of the different factors involved in skidding, our knowledge of the subject is still insufficient, as indicated previously by the Vehicle Research Laboratory of Delft University of Technology.

These considerations induced the Minister of Transport and Waterways of the Netherlands, in May 1966, to request the Institute for Road Safety Research SWOV to investigate the extent of the phenomenon of skidding and the influence of the various factors contributing to it.
Following this request, the SWOV Administration set up the Working Group on Tyres, Road Surfaces and Skidding Accidents. The Working Group includes representatives of the following bodies:
the General Board of Roads and Waterways (Hoofddirectie van de Waterstaat);
the Vehicle Research Laboratory of Delft University of Technology (Laboratorium voor Voertuigtechniek van de Technische Hogeschool te Delft);
the Laboratory for Road and Railroad Research of Delft University of Technology (Laboratorium voor Wegen en Spoorwegen van de Technische Hogeschool te Delft);
the Bureau of Public Works, Department of Roads, Amsterdam (Afdeling Wegen, Dienst der Publieke Werken, Amsterdam);
the Institute for Road Safety Research SWOV (Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV).

The terms of reference of the Working Group were as follows:

1. Establishment of the technical factors (associated with the vehicle and the road) which might contribute to skidding accidents.
2. Examination of the extent to which these technical factors actually contribute to the occurrence of skidding accidents, i.e. classification into first and second order factors.
3. Consideration of possible improvements to these technical circumstances, which might be expected to affect favourably the incidence of skidding accidents.
4. The development or adaptation of measuring equipment to permit simple quantitative determination of road surface characteristics which might be involved in the occurrence of of skidding accidents.

The present report is submitted as the first interim report of the Working Group. It is largely based on data from, and the experience of, the Vehicle Research Laboratory of Delft University of Technology and the State Road Laboratory, Delft. See Section 8 References: 8.1; 8.2; 8.3; 8.5.

Prof. Dr. A. J. Wildschut
Chairman, SWOV Working Group on Tyres, Road Surfaces and Skidding Accidents.

March 1969

Summary

Skidding is considered to be an important contributory factor in traffic accidents.
Skidding can in principle be prevented in two ways, viz:
a. reduction of the minimum necessary friction;
b. increasing the available friction.

The minimum necessary friction depends on the desired driving behaviour which is affected mainly by factors associated with the road, the vehicle, other traffic and the weather. The available friction depends on the nature of the contact between the tyre and the road surface. Various investigations have shown that, among other factors, the skidding resistance of the road surface influences the likelihood of skidding and hence of an accident. However, it has not yet been possible, on the basis of these investigations, to determine a definite 'minimum necessary' value for the skidding resistance of a road surface.
Nevertheless, the Working Group on Tyres, Road Surfaces and Skidding Accidents considers it very important for a fixed minimum skidding resistance for the surfaces of all roads in the Netherlands to be recommended immediately, even if this value is provisional.
Its conclusion is that—partly for the sake of uniformity—the guide value already employed by the State Road Laboratory for many years for State roads* and recently also for secondary roads, should be recommended as a provisional guide value for the skidding resistance of all roads in the Netherlands. This minimum skidding resistance for a wet road surface, expressed as the coefficient of friction, measured with a standardized patterned measuring tyre at 86% longitudinal slip and a road speed ot 50 km/h, is 0.51.
However, the Working Group considers that more research is necessary before a definitive value can be recommended.

It will also be necessary to seek other concrete measures the adoption of which might reduce the incidence of skidding. A research programme for this purpose is suggested.

* Rijkswegen (mainly trunk roads).

1. Introduction

The road, the vehicle and the human driver are the main factors in a single system, traffic. Although there are definite interactions between the road, the vehicle, the traffic situation and the driver, driving behaviour, whether dangerous or not, is ultimately determined by the driver. Starting with this human behaviour aspect, it is possible to evaluate the minimum values of the parameters of the other factors—i.e. the road, the vehicle and the traffic situation—necessary for keeping the vehicle under control.

The values of these parameters are defined as follows:

a. the minimum necessary characteristics of the road;
b. the minimum necessary characteristics of the vehicle;
c. the minimum necessary characteristics of the traffic situation.

Although the values of all these minimum necessary characteristics are primarily determined by human driving behaviour—which is in turn influenced by the informational characteristics of the road, vehicle and traffic situation—the limiting characteristics of the road and the vehicle will also contribute.

It is also important to define the actual available characteristics of the vehicle and the road. An accident—which can be regarded as the consequence of a fault in the system—will take place when the minimum necessary value of a characteristic for normal traffic participation exceeds the available value.

The emphasis of safety measures can therefore be directed both at improving the minumum necessary characteristics—e.g. by attempting to discourage road users from taking risks—and at improving the available characteristics. Safety is enhanced when the margin between the two values is widened. This approach can also be applied to the problem of skidding.

A moving vehicle is acted upon by various external forces, which often tend to oppose the movements required of the vehicle by the driver.

Examples are rolling and air resistance, gradients, inertial forces occurring on acceleration, deceleration and changing direction, and forces due to a cross wind or road banking.

To overcome these forces, and to ensure that the vehicle performs the movements required by the driver, acceleration, braking and lateral forces acting in the contact surface between the tyre and the road surface are necessary. Hence these forces could be defined as the minimum necessary friction corresponding to the required movement. The nature of the contact surface of tyre and road surface determines the limits of these forces. If the minimum necessary (horizontal) forces are greater than the limit values of the frictional forces between the tyre and the road surface—the available friction—skidding will occur.

Skidding can be defined as a movement of the vehicle involving sliding of one or more wheels This can manifest itself in:

a. considerable deviations from the desired path;
b. rotation about the vertical axis;
c. sliding onwards with locked wheels.

These movements—which often surprise the driver—can result in an accident, because in these circumstances the vehicle cannot easily, if at all, be kept under control.

The probability of skidding can in principle be reduced by traffic engineering or constructional measures:

1. By ensuring that the road user needs no greater frictional forces than are actually available. This can be done by favourably influencing the driving behaviour of the road user, by improving the informational characteristics of the road and the vehicle, by teaching the driver how to make use of this information, by influencing the road speed and by making the traffic as a whole more homogeneous.
2. By making the available friction higher than actually needed by the road user. As will be seen in the following Sections, this primarily signifies the improvement of technical (road and vehicle) characteristics.

2. Minimum necessary frictional forces

In discussing the factors relevant to the minimum necessary frictional forces, it is useful to distinguish between human, road, vehicle, traffic and weather factors.

2.1. Human factors

Under normal conditions acceleration, braking and lateral forces are determined by the actions of the driver, through his driving behaviour.
The human being as a a driver is the central factor in the complex determining driving behaviour because it depends on him whether traffic conditions are perceived correctly and in good time and acted upon.
To avoid disturbances of traffic movements, account must be taken of the characteristics of drivers and their limitations, in regard to the processing of information, decision taking and taking of the necessary action.
Traffic movements may be disturbed by:
a. excessive or insufficient demands on drivers.
b. impediments to vehicle movements due to road imperfections.
c. unjustified expectations of drivers.

The last point in particular could well be one of the reasons for the increase in the number of (skidding) accidents in the case of temporary and/or local falls in the coefficient of friction. The driver unconsciously expects a definite coefficient of friction, on the basis of which he evaluates the frictional forces necessary for him. If these expectations are not fulfilled, the driver will require greater frictional forces than are available, resulting in skidding. The technical factors influencing the behaviour of road users—and hence the frictional forces required—are dealt with in the following subsections.

2.2. Road factors

The geometry of the road can play a very important part in determining driving behaviour. Discontinuities in the geometry—particularly where these are unexpected and not indicated in advance— will result in the road user requiring high frictional forces. This may be the case if it is necessary to brake or swerve suddenly. Hence vehicle decelerations, accelerations and changes in direction may occur at intersections.
On bends, depending on the radius of curvature and the vehicle speed—which is partly determined by the preceding section of road—centripetal forces will arise; these must be transmitted by frictional forces between the tyre and the road surface. Banking on bends can, if the parameters are correct, reduce the necessary frictional forces, so that only part of the component of the centripetal force parallel to the road surface has to be transmitted through frictional forces between the tyre and the road surface. The other part is transmitted by a gravitation component.
Buildings and trees, etc., along the road can affect wind forces acting on the vehicle. In particular, interruptions may result in considerable gusts of cross wind, which (this factor also depending on the type of vehicle) may necessitate large and sudden steering corrections, thus increasing the minimum necessary frictional forces.

In contrast to the geometry of the road, the road surface has little or no influence on the behaviour of drivers, unless, depending on the characteristics of the vehicle, the surface is very bumpy indeed.

For example, speed measurements by the Institute for Road Safety Research SWOV showed that the condition of the road surface (wet or dry) has virtually no effect on speed, if it is not, or is no longer raining, all factors other than the condition of the road surface being equal. In addition, very little difference in speed is noted between different road surfaces, provided that they are sufficiently smooth.

2.3. Vehicle factors

The informational characteristics of the vehicle will also influence the actions of the driver. For example, the comfort of the vehicle will contribute to the driver's choice of speed; for the impression of speed in the vehicle depends, among other things, on comfort (i.e. the presence or absence of vibration, and the noise level—both wind noise and engine and transmission noise—etc.). The effect of road speed on the minimum necessary frictional forces will be dealt with in Subsection 2.4.
On bends rolling (rotation about the longitudinal axis) of the vehicle will contribute to the driver's choice of speed.
Visibility from the vehicle will contribute to determining how early the driver notices everything necessary to determine his actions. If the driver perceives a hazard early, he will be able to change his speed and direction gradually, so that the minimum necessary frictional forces can be lower.
Steering characteristics, such as the amount by which the steering wheel must be turned and the effort required, affect the manner of direction changing by the driver. In the case of sudden rotation of the steering wheel (e.g. when driving into and out of bends and avoiding obstacles), the minimum necessary frictional forces may be higher than when negotiating a curve of constant radius.

In general, with regard to the informational characteristics of the vehicle, the information about the behaviour of the vehicle in normal situations must also be relevant to its behaviour in critical situations. If this is not the case—as with certain vehicles, where there is a sudden transition from understeer to very considerable oversteer when the minimum necessary frictional forces approach or exceed the available frictional forces—this will increase the probability of a skidding accident.
In general terms, the minimum necessary frictional forces are necessary for acceleration, braking and the negotiation of curves. Of course, combinations of these cases are possible.

2.3.1. Acceleration

Skidding resulting from acceleration normally occurs only on very smooth and wet, uneven road surfaces. With rear wheel drive, if the driven wheels spin, they may break away, and the vehicle will rotate about its vertical axis.
With front wheel drive, if the driven wheels spin, the vehicle will proceed in virtually a straight line

2.3.2. Braking

The legal minimum braking deceleration laid down in the Netherlands Road Traffic Regulations (Wegenverkeersreglement) for checks on the road on passenger cars is 5.2 m/sec². The corresponding figure for buses is 4.5 m/sec², and for trucks 4.0 m/sec². For type approval, the value employed by the State Road Traffic Service (Rijksdienst voor het Wegverkeer) is 10% above these figures.

Regarding the attainable braking deceleration—even on a dry road—the brakes themselves are not the limiting factor for most passenger cars, but instead the coefficient of friction between the tyre and the road surface, and the distribution of braking force between the front and rear wheels.
A vehicle may attain maximum braking deceleration if this distribution of braking force is such that the maximum frictional force between the tyre and the road surface (μ_{lm} in Figure 2) is achieved simultaneously on the front and rear wheels. If locking occurs, both the front and rear wheels will lock with this distribution of braking force. This ideal distribution of braking force is, however, seldom achieved. Nearly always, either the front or the rear wheels lock first. If the rear wheels lock first, they may break away, as with wheel spin on acceleration; if the front wheels lock first, the vehicle will continue in a straight line.

A good approximation to the ideal distribution of braking force can in principle be achieved by (load-dependent) braking force regulators.
A higher mean deceleration can be achieved by the use of an anti-locking device on wet roads if the difference between the maximum frictional force and the frictional force with locked wheels is great enough, the vehicle moreover remaining steerable during braking.

The braking forces on the left and right hand sides of the vehicle must be substantially equal or else it will deviate from a straight path and may rotate about its vertical axis. Differences in braking force between the left and right hand sides of the vehicle can arise, for example, with having a pronounced self-servo effect, through differing coefficients of friction between the drum or disc and the lining or pad due to the brake temperature, through water or brake fluid in the drum or on the disc, or through burning of the lining or pad.

2.3.3. Cornering

Theoretically it should be possible to calculate the maximum attainable lateral (centripetal) acceleration from the available frictional forces, if all relevant vehicle characteristics (such as the characteristics of the tyres and the weight transfer) are known. This theoretically attainable lateral acceleration can, however, in practice not always be achieved, for the following reasons:
1. Since the available maximum frictional force between the tyre and the road surface is virtually the same in all directions, the acceleration forces present will reduce the value of the available transverse frictional forces.
2. The acceleration forces on the inside and outside wheels are the same because of the action of the differential gear. Since the wheels on the inside of the bend are subjected to a smaller load because of centrifugal force, the driven inside wheel is more likely to spin, as a result of which the lateral force on this wheel becomes very small.
3. In consequence of the steering angle and slip angles at the front and rear, the centripetal forces will only be transmitted by components of the lateral forces.
4. If there is a (reverse) banking or cross wind, additional lateral forces will be exerted on the vehicle.
5. The tyre characteristics (Figure 3) are unfavourably affected by irregularities in the road surface.
6. Additional complications can arise through changes in the steering angle and wheel loading when cornering, thus affecting the utilization of the available frictional forces.
7. Instability may occur before the theoretical maximum is reached.
On the other hand, however, a component of the driving force delivers a (small) part of the centripetal force.

2.3.4. Conclusion

It can be concluded that a vehicle will be able to exert a favourable influence on the minimum necessary frictional forces if:

1. The informational characteristics of the vehicle alert the driver in good time that the limit of the available frictional forces is being approached, in which case also correct information as to the behaviour of the vehicle must be given.
2. The vehicle design must be such that the use made of the available frictional forces is as effective as possible.

2.4. Traffic factors

The traffic situation naturally plays a large part in determining the driving behaviour of the road user. For it will largely depend on other traffic whether the road user accelerates, brakes or changes direction, for which manoeuvres he will require additional friction between the tyre and the road surface.

The road speed of the vehicle has a considerable effect on the frictional forces required. For example, to bring the vehicle to a halt within a given distance, the braking forces required increase as the square of the speed. At higher speeds lateral deviations through gusts of cross wind are greater, so that larger and faster steering corrections will be necessary to keep the vehicle to the desired path.

2.5. Weather factors

Weather conditions affect the behaviour of the driver. For example, road speeds will be slower in conditions of poor visibility, but in these circumstances the maximum available braking distance is also much smaller, because obstacles are detected later; hence in spite of the slower speed, the minimum necessary frictional forces in emergencies can be substantially higher than in normal conditions. This is indicated by the fact that multiple rear-end collisions occur primarily in poor visibility, or when the available frictional forces are (very) low.

Wind forces directly affect the minimum necessary friction. Cross wind in particular can deflect the vehicle from the desired path, in which case the tyres must supply lateral force to counteract the effect of the wind.

3. Available frictional forces

3.1. Symbols and definitions

F_x	horizontal force in the plane of the wheel (braking or driving force)	(kgf)
F_y	force at right angles to the plane of the wheel (lateral force)	(kgf)
F_z	vertical tyre load	(kgf)
V	road speed	(km/h)
α	slip angle	(degrees)
μ_{lm}	maximum longitudinal coefficient of friction	(F_x/F_z)
μ_{lb}	longitudinal coefficient of friction with wheel locked	(F_x/F_z)
μ_{lv}	longitudinal coefficient of friction with a fixed percentage longitudinal wheel slip	(F_x/F_z)
μ_d	lateral coefficent of friction at $\alpha = 15°$ (or 20°)	(F_y/F_z)
ω_r	angular speed of wheel when braking	(rad/sec)
ω_o	angular speed of freely rolling wheel	(rad/sec)

3.2. Frictional forces on a dry road surface

Although the skidding situation on a dry road surface is less critical than on a wet road owing to the higher available friction, it is best, for the sake of comprehension, to begin by discussing the factors affecting frictonal forces on a dry road.
The coefficient of friction between the tyre and the road surface is made up of three components, an adhesion or 'sticking' component, a hysteresis or 'deformation' component and a cohesion or 'wear' component.
Adhesion is a molecular attraction between the road surface and the particles of rubber of the tyre. On a dry road, the adhesion component is the predominant item in the coefficent of friction.
The *hysteresis* component arises on deformation of the tyre rubber through irregularities in the road surface, the 'spring-back' forces being smaller than those necessary to deform the rubber. The hysteresis depends on the temperature of the rubber and declines as the latter rises. The type of rubber is also very important in this process.
The rougher the road surface, the lower the adhesion component and the higher the hysteresis component; as a rule, the result is that the total coefficient of friction on a dry road will decrease somewhat with increasing roughness.
When a pneumatic tyred wheel locks, the coefficient of friction is determined mainly by the *cohesion* component, especially at high road speeds and on a dry road. (This is manifested in skid marks.)

The vertical loading on the tyre, the inflation pressure and the type of tyre determine the mean surface pressure in the contact patch between the tyre and the road. This mean surface pressure, which is roughly proportional to the inflation pressure, affects the coefficient of friction. On a dry road, the coefficient of friction will fall somewhat as the mean surface pressure rises. The local surface pressure between the tyre rubber and small irregularities in the road surface, and the extent to which the rubber hops over the irregularities, are largely determined by the hardness of the rubber.
The tyre loading and construction of the tyre and suspension also determine the deformations and slip speeds in the contact patch. Larger vertical loading of the tyre will result in greater sliding stresses in the contact zone, due to the greater flattening of the tyre. Any resulting horizontal force will for these reasons not increase linearly, and if the tyre is overloaded, may even decrease slightly as the vertical load increases.

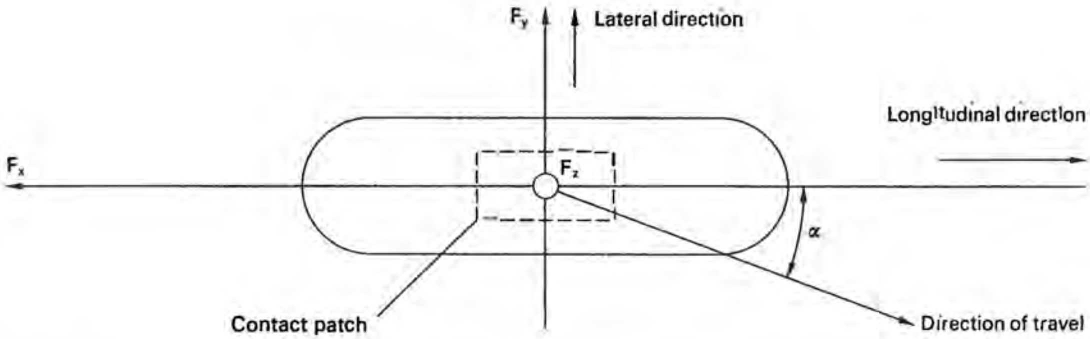

Figure 1. Plan view of a tyre.

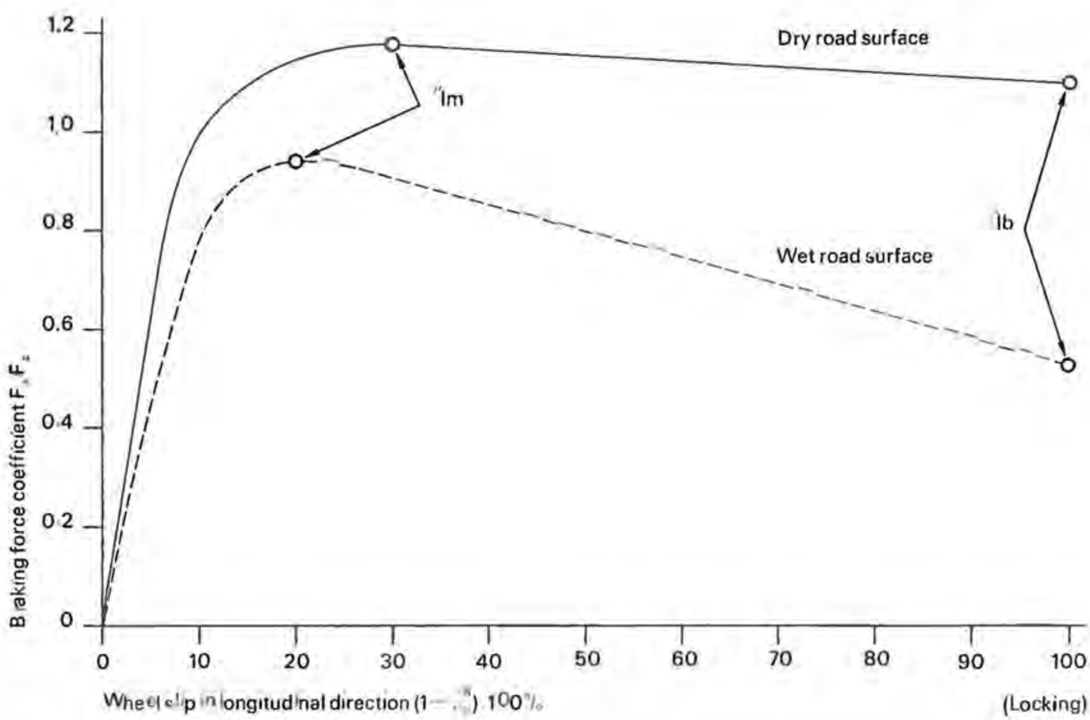

Figure 2. Example of relationship between braking force and wheel slip in the longitudinal direction.

The total horizontal forces in the contact patch between the tyre and the road surface can be broken down into forces parallel to the plane of the wheel (longitudinal forces) and forces at right angles to that plane (lateral forces) (see Figure 1). The resultant longitudinal force arises out of rolling resistance, braking or acceleration. The resultant lateral force arises in consequence of rolling with a slip angle (angle α in Figure 1) or with a camber angle (the angle between the plane of the wheel and a perpendicular dropped on to the road surface) and is necessary for cornering, in cross winds, and on banked roads.

Of course, combinations of longitudinal and lateral forces can arise, e.g. when braking or accelerating on bends.

Figure 2 shows an example of the relationship between longitudinal wheel slip and the braking force coefficient F_x/F_z. At low braking forces, it is mainly the particles of rubber at the end of the contact patch which slip; little or no slipping takes place at the front of the contact patch. As the braking forces increase, the size of the skidding zone and the slipping speeds increase, the wheel rotating slower and slower while the road speed remains virtually constant. The braking force coefficient mostly reaches a maximum at between 15 and 25% wheel slip, depending on the road speed and the condition of the tyre and road surface; after this the wheel soon locks and the slipping speed over the entire contact area becomes equal to the road speed of the vehicle.
The braking force coefficient is generally lower for a locked wheel than for a rolling wheel, especially at high road speeds and on wet roads.

Figure 3 shows the equivalent curves for the lateral force coefficient as a function of the slip angle. Here too, slipping begins at the end of the contact area, until at large slip angles in the entire contact patch lateral slipping occurs.
On a dry road the maximum frictional force is attained at a slip angle of 15 to 20 degrees. The lateral force resulting from the camber angle is smaller, being 1/6 and 1/10 of the lateral force due to an equivalent slip angle.

3.3. Frictional forces on a wet road surface

Although the phenomena described in Subsection 3.2. may also play a part on a wet road, the disturbing factor in this case is the water on the road surface. On a wet road, contact between a rolling or sliding tyre and the surface may be partially or wholly interrupted by a film of water. This may form between the rubber and the road surface if the hydrodynamic pressure in the water becomes locally equal to the vertical surface pressure.
The hydrodynamic pressure in the film of water arises in consequence of inertial forces and viscous forces. The hydrodynamic force F_v in Figure 4, due to inertial forces in the water, increases with the road speed.
The horizontal force F_h is an additional resistance force which must be subtracted from the measured horizontal force in order to obtain the actual frictional force at the contact patch.

Where the rubber is separated from the road surface by a film of water, no adhesion is possible. The consequence of the reduction of the area where adhesion between the rubber and the road surface is possible, is a lower total frictional force in the contact area than in the case of a dry road. See Figures 2 and 3.
Owing to the reduced adhesion component, the hysteresis component in the total frictional forces becomes much more important. The hysteresis component is probably not much affected by a thin film of water; the hysteresis may even be higher than on a dry road surface owing to the cooling effect of the water. The road surface must, however, possess a definite geometrical configuration in order to allow the hysteresis component to become effective.

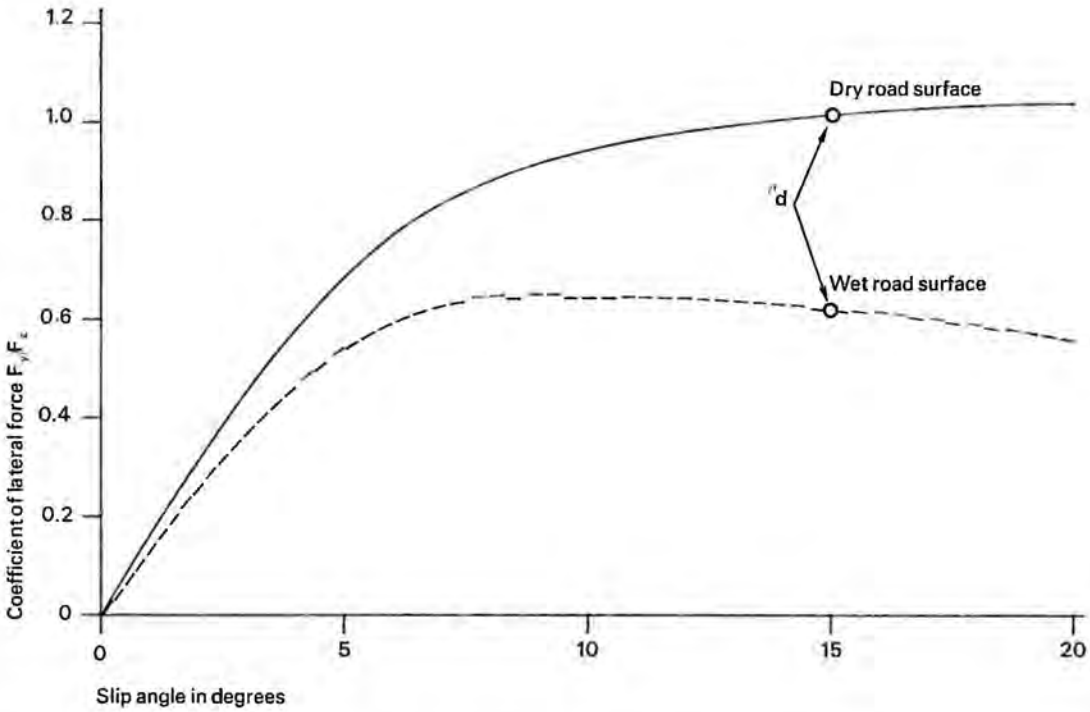

Figure 3. Example of relationship between lateral force and slip angle.

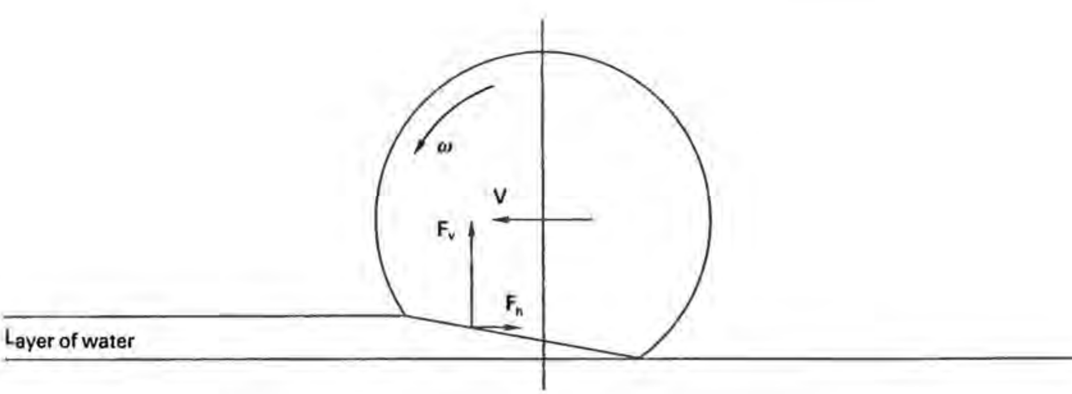

Figure 4. Hydrodynamic forces on tyre.

On main roads—where bituminous and concrete pavements are used—the wearing course consists in principle of a homogeneous mixture of a binder and a mineral aggregate.
The configuration of the surface as regards the available coefficient of friction depends on the size and form of the aggregate and on the grain spacing. We can use the concepts macroirregularities and microirregularities.

Macroirregularities are necessary in order to evacuate the water quickly from the contact zone on wet road surfaces, especially at high speeds (primary dynamic drainage). If most of the water is evacuated, the residual film must be broken up in a sufficiently large number of places in order to make adhesion between the tyre rubber and the road surface possible (secondary dynamic drainage). For the latter purpose it is necessary of the road surface to possess a pattern of sharp irregularities. This aspect of the surface configuration is termed microirregularity. The nature of the surface does not remain constant over the life of the pavement. In particular, the microirregularity will change owing to the polishing effect of traffic, resulting in general in a drop in the coefficient of friction. Traffic intensity and the material of the pavement, especially the aggregate used, are relevant here.

It seems that the coefficient of friction between a tyre and a road surface undergoes regular variations connected with the seasons.
In the summer the coefficient of friction on *wet* road surfaces is generally somewhat lower than in winter. These variations can be partially explained by fluctuations in temperaure. Another contributory factor is probably the fact that the surface characteristics of the pavement may be altered in winter by the physical effect of frost or by chemicals used to combat icing. Another factor is that in summer the road surface is dirtier than in winter. In a period of dry weather, amounts of material and particles detached by wear will increase. Rain following such a period can then also result in reduced skidding resistance, which is probably due to the higher viscosity of the mixture of water and material, as a result of which it is less quickly eliminated.

Besides the nature of the road surface, the tread pattern of the tyre is an important factor in dynamic drainage in the contact area between the tyre and the road. The tread pattern also provides better cooling of the rubber rolling surface.
On a wet road water under the ribs of the rolling surface can flow transversely from the contact surface to the longitudinal channels.
To prevent large hydrodynamic pressures from building up under the ribs of the rolling surface, a transverse tread pattern and zig-zag pattern are used. Small incisions are made in the ribs of the rolling surface, as a result of which places arise where large hydrodynamic pressures cannot be built up on the rolling type. The hollows can take up a certain quantity of water, which is thrown off after leaving the contact patch. These incisions become ineffective on a locked wheel. Dynamic drainage and the formation of hydrodynamic pressure are of course, also affected by tread wear. The rounding of the tread pattern forms small wedges, in which hydrodynamic pressure can be built up.
A smooth tyre has a larger actual contact surface than one with a patterned tread. Consequently, a smooth tyre can, especially at low speeds, give approximately the same coefficient of friction as a tyre with a patterned tread, an dry and almost dry road surfaces with good drainage characteristics. However, this is of little practical value. The effect of the tyre tread pattern on the coefficient of friction is greatest on smooth road surfaces.

Measurements indicate provisionally that—although the required tread depth depends on road speed, the thickness of the film of water, the nature of the road surface and the tyre construction and tread pattern— the tread depth should be at least 1 to 2 mm [8.7] *.
However, before final recommendations are issued for the tread depth, extensive and thorough research is still necessary.

* Figures between square brackets refer to Section 8. References.

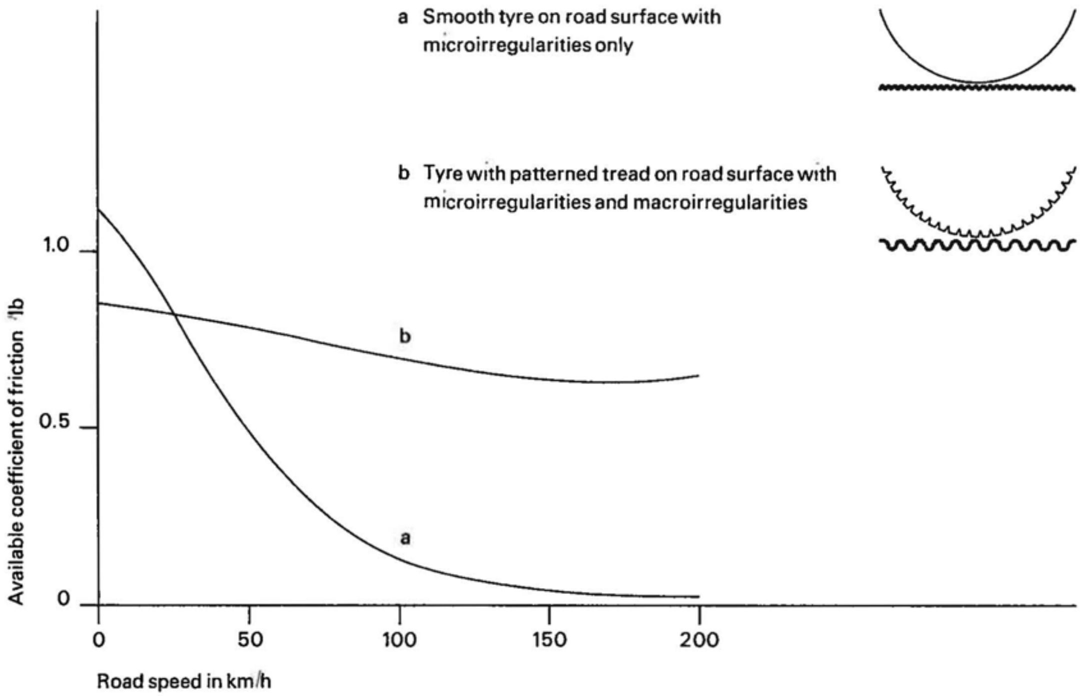

Figure 5. Example of relationship between the available coefficient of friction with a locked wheel and the road speed, with differing road surfaces and tyres.

If dynamic drainage on the contact surface is insufficient to evacuate the water, a film of water will remain between the tyre and the road surface. The available frictional forces are then very low, and the vehicle is unsteerable. This inadequate drainage may be due to unfavourable tyre and road surface characteristics. With a smooth tyre and a road surface without sufficient irregularity, it is possible for an uninterrupted film of water to build up even at relatively low speeds between the tyre and the road as a result of viscous forces in the water. If the film of water is thick because of inadequate static drainage (inadequate evacuation of water to the sides of the road) and high speeds, the dynamic drainage, even with good tyres and good road surfaces, may be insufficient. The forces due to the mass of the film of water will result in complete separation between the tyre and the road surface. This phenomenon is known as aquaplaning.
The only tyre characteristic which then has any relevance is the inflation pressure. Experiments indicate that the speeds at which aquaplaning occurs varies approximately with the square root of the inflation pressure.
In contrast to the normal situation, higher inflation pressure can in this case give a higher coefficient of friction, in the critical speed range.
Both inertial forces and viscous forces are strongly dependent on the speed. As the speed increases, the area of possible adhesion falls constantly, so that the coefficient of friction can decline sharply with increasing speed. On rough road surfaces the hysteresis component may increase with the speed, thus to some extent compensating for loss of adhesion.
Thus the effect of speed on the coefficient of friction is very much dependent on the tyre and road surface characteristics. The relationship between the coefficient of friction and the road speed is then frequently non-linear. Two extreme possibilities are illustrated in Figure 5.

3.4. Unusual conditions

So far we have referred only to dry and wet road surfaces. There are, however, circumstances in which the available frictional forces can become much lower, e.g. when the road is covered with show or ice, or has a layer of oil, clay, etc. Although the number of accidents in which such circumstances are an important contributory factor is certainly not small, an examination of these is outside the scope of this report.
Normally, a diligent road authority will be able to adopt appropriate measures to combat slipperiness and avoid the conditions referred to.

4. Methods of measuring the available coefficient of friction

4.1. Measurement conditions

Methods of measuring the frictional forces between a tyre and a road surface have been developed in most European countries and in many States of the U.S.A.; these methods aim at a maximum of control over the effect of the various factors. In this connection it is useful to distinguish between two concepts: the coefficient of friction (in a particular case) and the skidding resistance (as a parameter of the road surface).
The coefficient of friction is a variable which is dependent on the characteristics of the vehicle, the road and its condition, and the speed of the vehicle (see Section 3). It may be defined as the quotient of the maximum available frictional force between a tyre and a road surface, and the vertical tyre loading.
The skidding resistance is a criterion of the quality of the road. The coefficient of friction, as measured by a given technique under specified conditions (see also Subsections 4.2. and 4.3.), is taken as a measure of the skidding resistance. It is not automatically possible to derive the coefficients of friction between the tyre and the road surface in a particular case from measurements of skidding resistance using a standard technique.
The measured skidding resistance applies only for the conditions under which the measurement was effected.
It is also desired for the conditions of measurement to coincide as far as possible with practical conditions. Thus, the road surface must always be made wet by spraying, because a wet road represents the most critical condition.
The measured skidding resistance is within given limits independent of the thickness of the sprayed film of water [8.8]. The relationship between the skidding resistance and the thickness of the film of water depends, among other factors, on the nature of the road surface, the characteristics of the tyres (including the tread pattern) and the speed of measurement.

If comparative measurements of the skidding resistance of a large number of road surfaces are made, it is necessary for practical reasons to make a choice from a number of possibilities, but the conditions of measurement must then be determined carefully. It is necessary to take account of the influence of these conditions on the probability of the occurrence of skidding and of the frequency with these conditions occur in traffic an a given type of road.
In the case of a single measurement of the coefficient of friction available for a given vehicle under specified conditions, it is essential for the conditions of measurement, such as road speed, type of tyre and depth of water, to be matched to real conditions.
In the evaluation of the measurements, it is also necessary to allow for such factors as the effect of season, and the temperatures of the tyre, water and road surface, but it is not yet possible take these (small) effects into account.

4.2. Methods of measurement

The measurement of the skidding resistance of the road is executed virtually only in the longitudinal direction of the road. There are six methods. There are indications that for the classification of skidding resistance in different road surfaces it is largely irrelevant which method is used. The absolute validity of different measuring techniques will of course differ. In the following paragraphs a few particular features of each measuring technique are indicated, and the most important characteristics of the different methods are summarized in Table 1.

Characteristics	Method					
	Locked wheel (4.2.1)	Maximum braking force coefficient (4.2.2)	Fixed percentage longitudinal slip (4.2.3)		Inclined wheel or side slip (4.2.4)	Braking distance or deceleration (4.2.5)
			low	high		
Coefficient measured	μ_{lb}	μ_{lm}	μ_{lv}	μ_{lv}	μ_d	μ_{lb} and/or μ_{lm}
% longitudinal slip, or slip angle	100%	15–25%	approx. 20%	approx. 80%	15°–20°	15–100%
Reproducibility	inferior	poor	good	good	good	poor
Recording	non-continuous	non-continuous; difficult to read off	continuous	continuous	continuous	non-continuous
Wear on measuring tyre and temperature rise	local	local	uniform	uniform	uniform	local
Engine power required	high	very high	very low	low	low	low
Measurement on bends	possible	possible	readily possible	readily possible	readily possible	impossible
Variation in skidding resistance according to measuring speed	great	small	small	great	small	great
Value of the coefficient of friction	$\mu_{lb} < \mu_{lm}$ $\mu_{lb} < \mu_d$		$\mu_{lv} \approx \mu_{lm}$	$\mu_{lv} \approx \mu_{lb}$		

Table 1. Summary of methods of measurement of skidding resistance.

4.2.1. Locked wheel braking method

The coefficient of friction obtained—applicable to a locked wheel—is termed μ_{lb} (see also Figure 2). This coefficient is generally substantially lower on a wet road than the coefficient μ_{lm} (the maximum longitudinal coefficient of friction, see Figure 2) and μ_d (the lateral coefficient of friction at, for example, a slip angle of 15 degrees, see Figure 3).

4.2.2. Measurement of the maximum braking force coefficient by a locking procedure

This coefficient of friction is termed μ_{lm}. Depending on the road speed, the depth of water, the nature of the road surface and the tyre tread pattern, the maximum braking force can occur at between 10 and 40% longitudinal slipping, the usual values being between 15 and 25%. If μ_{lm} is determined by slowly increasing the braking force, it is difficult to measure its value, in particular on account of premature locking due to changes in the vertical load. The reproducibility of the measurements is poor. The brake soon attains high temperatures, because the braking force must be increased gradually.

4.2.3. Measurement with a fixed percentage longitudinal slip

This coefficient of friction is termed μ_{lv}. The value is of μ_{lm} is determined by introducing a small percentage of longitudinal slip; with a high percentage of longitudinal slip, the locking value μ_{lb} is approached (see Figure 2). This technique has the advantage over the two previous methods of uniform wear over the circumference of the tyre and the possibility of continuous recording. If the forced longitudinal slip is achieved by linking the measuring wheel with other wheels by means of a transmission, no energy is dissipated in the brake. Less stringent demands are made on the engine of the vehicle, thus often permitting higher measuring speeds.

4.2.4. Measurement with a wheel inclined to its direction of travel

The angle of slip with these measurements is generally 15 or 20 degrees, and the coefficient of lateral force μ_d is measured (see Figure 3). A drawback of this method is that the coefficient of friction measured is unreal for straight stretches of road. In this case too, the engine power required to propel the inclined wheel along the road is less than in the case of a locked wheel. To prevent a resultant lateral force from being exerted on the vehicle, it is, however, desirable to use two inclined measuring wheels.
The methods summarized in 4.2.1. to 4.2.4. are generally employed using a constant measuring speed. The measuring wheels are fitted under the test car or in a special trailer.

4.2.5. Measurement of the braking distance or braking deceleration

This permits determination of the coefficient of friction μ_{lb} and sometimes μ_{lm}. A test car is used with braking of two or more wheels (usually only the front wheels). The braking deceleration and/or—if the vehicle is brought to a halt—the braking distance is measured. From these measurements it is possible to derive the coefficient of friction, after somewhat complicated calculations connected with the weight transfer. This method is not readily reproducible [8,9], sensitive to disturbances, and can hardly be used on roads with normal traffic intensity.

4.2.6. Measurement with pendulum equipment

Small instruments are used with this technique. A small piece of rubber is secured to the end of the pendulum, and slides, as the pendulum swings, over a preset length (10 to 25 cm) of the surface to be measured. The energy thereby lost is a measure of the skidding resistance of the road surface. The advantage of this method is that the apparatus is small, portable and relatively cheap. Some disadvantages are:

1. Only small portions of a road surface are measured, thus necessitating a large number of measurements.
2. Large standard deviations may occur on rough surfaces.
3. The speed at which the rubber slides over the road surface is low (8 km/h).
4. The measurements are only slightly affected by primary dynamic drainage.

This equipement can, however, be used to gain an impression of the skidding resistance of a road surface, or to measure road sections where it is not possible to use other techniques.

4.3. Effect of test tyre on measurements

A tyre with no tread pattern has the advantage that tyre wear has little effect on the results. In addition, with a smooth tyre the difference between different road surfaces emerges more clearly. A disadvantage is that the measurements are to a great extent unrepresentative of actual conditions. A test tyre with longitudinal ribs only, with no incisions in them, such as the standardized American test tyre, gives a more realistic value for the skidding resistance, whilst tyre wear has little effect on the results.
Results obtained with a passenger car tyre are in general not applicable for truck tyres, because of differences in the contact pressure and type of rubber. The coefficient of friction for truck tyres will as a rule be lower.

4.4. The criterion for the skidding resistance of the road

As already stated, the skidding resistance of the road can be expressed by the coefficient μ_{lm}, μ_{lb}, μ_{lv}, or μ_{ld}.
In general, a statistical correlation is sought between (1) the coefficient μ_{lb} or μ_d and (2) the number of skidding accidents or accidents on wet road surfaces. Frequently, μ_{lb} is then also taken as a criterion for the skidding resistance, whether satisfactory or not, of roads. There are, however, road surfaces which have a low value of μ_{lb} but a normal value of μ_{lm} when wet. Because it may be assumed that the probability of wheels locking when braking on these roads is less than on road surfaces with a low value of μ_{lm} and the same value of μ_{lb}, the question is whether, in this case too, there is a relationship between the value of μ_{lb} and the number of wet road accidents.
But to take μ_{lm} as the criterion would only be reasonable if anti-locking devices were generalized in braking systems. In this connection it should be noted that anti-locking devices are advantageous in relation to the braking deceleration, only if the difference between μ_{lm} and μ_{lb} is large enough. The value of μ actually obtained with anti-locking devices lies between μ_{lm} and μ_{lb}.
However, since anti-locking devices are (at present) not very widespread, the coefficient μ_{lb} is, on the whole, probably a more appropriate criterion for the skidding resistance of the road surface. This is because in practice there is virtually always a difference between the actual and the ideal braking force distribution between the front and rear wheels—so that either the front or the rear wheels may lock prematurely—and because in (emergency) braking all wheels tend to lock, partly because of changes in the vertical loading.

Measurement of the coefficients referred to must be carried out of road speeds which are typical for the road sections concerned. Because of the desirability of comparing different road surfaces, measurements at standard speeds (e.g. 30, 50, 70 and perhaps 90 km/h) is recommended. Measurements at higher speeds require special measures such as closing of roads, police escort, measurement at night, etc., and in addition, it is necessary to overcome certain technical difficulties.

5. Interpretation of skidding resistance measurements

5.1. General

In countries where skidding resistance measurements are carried out by a standardized method, a qualification has normally been established for the numerical results obtained.
An important criterion for the road authority is the level at which the skidding resistance of the road surface can still be regarded as satisfactory. In this connection it is useful to make the following distinction:
1. A minimum skidding resistance for an *existing* (wet) road surface; this minimum determines when the road surface should be improved in order to obtain satisfactory skidding resistance.
2. A minimum skidding resistance for a *new* (wet) road surface; depending on the road surface, this value will be higher than or equal to the value under 1.

Substantial differences exist between the various countries, and also within individual countries, in regard to the measurement of skidding resistance, in the measuring instruments, methods, the test tyre used, the tyre loading, and other factors. Hence the numerical results for a given road surface will generally differ according to the equipment used. It is then necessary to have different qualifications for the different methods. However, this depends not only on the difference in the numerical results, but also on the procedures used in establishing the qualifications.

Comparative measurements are carried out both nationally and internationally, and in general a good standard of correlaton is found to exist between the various methods of measurement. This not only permits a reliable comparison of the skidding resistance of the types of road surfaces used in different countries, but also of the methods of evaluation of the numerical results.
Taking account of the correlations and differences between numerical results, it appears that on comparison the limit values assumed for the minimum permissible skidding resistance are substantially the same in different countries [8.16].

The procedures used in most countries to establish the minimum permissible skidding resistance are also largely in agreement. There is normally a statistical analysis of accidents, especially wet road accidents, in which skidding was reported to be the main or a contributory cause, and accidents interpreted as skidding accidents.
There are no generally accepted definitions of skidding accidents, and it is not easy to lay down objectively measurable values in this connection. Usually such terms as 'relative probability of skidding accidents', etc., are used.

It mights perhaps be possible to derive the form of a relationship between the probability of skidding accidents and the skidding resistance from an analysis taking account of all first order factors which might play a part in a skidding accident. See Section 7.

As skidding accidents can never be prevented with 100% reliability—skidding accidents occur even on dry road surfaces with good skidding resistance—a given minimum probability of skidding resistance then follows from the form of the relation found.
The minimum for the relative probability of skidding accidents is determined by experience on the basis of previous investigations. The choice of a minimum remains, however, arbitrary.
Sometimes varying skidding resistance requirements are laid down, so that there are different values for main roads, secondary roads, urban roads, intersections and roundabouts, depending on such factors as the prevailing vehicle speeds in each case.

Some examples of the investigations of the relationship between skidding resistance and (skidding) accidents and the conclusions drawn from them are given below.

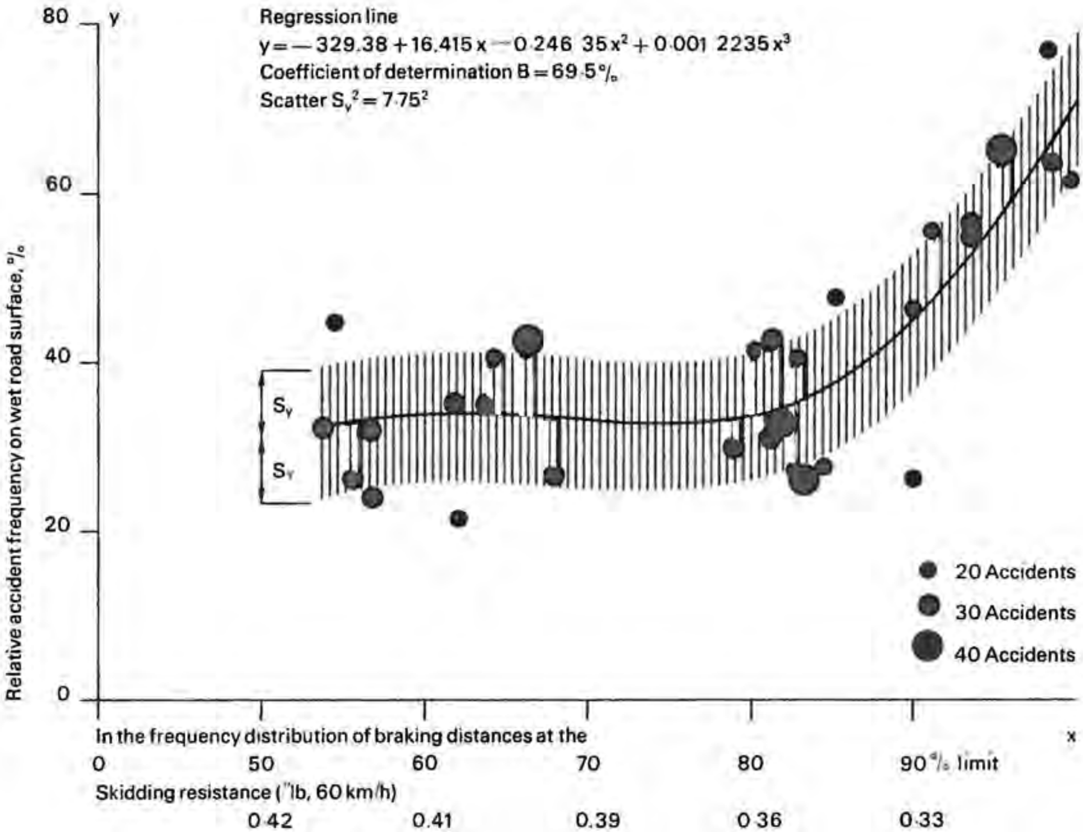

Figure 6. Relationship found in Germany between the relative accident frequency on a wet road surface and the place in the frequency distribution of braking distances (and skidding resistances) on 32 test road sections

5.2. Germany

The Institut für Strassen- und Verkehrswesen of Berlin Technical University investigated 32 road sections, mainly situated on motorways and main roads, over a period of three years. The number of injury accidents occuring on each road section was counted, and the 'relative accident frequency for wet road surfaces' determined from the result. This frequency is defined as:

$$\frac{\text{number of accidents on wet road}}{\text{total number of accidents}} \times 100\%$$

Of each road section the skidding resistance was measured regularly at different speeds by the locked wheel braking method, and the mean traffic speed determined. A braking distance corresponding to each road section was calculated from these data. A frequency distribution of the braking distances measured on these road sections was established from a previous investigation of braking distances on 640 road surfaces with modern dressings.

The braking distance corresponding to each road section was not adopted directly as a measure of the skidding resistance of each of the 32 road sections covered by the investigation, but instead its position in the above mentioned frequency distribution.
The result was the graph shown in Figure 6, which gives the relationship between the relative wet road accident frequency and the frequency distribution of braking distances. For the sake of clarity the skidding resistance as calculated from the graphs in the article [8.10]. is given alongside the frequency distribution (measured at 60 km/h by the locked wheel braking method).
When the skidding resistance falls below approximately 0.36, the probability of an accident on a wet road surface appears to increase sharply.
Provisional guide values for German roads have been established on the basis of this investigation [8.11.]:
over 0.42 at 40 km/h for slow traffic roads
over 0.33 at 60 km/h for fast traffic roads
over 0.26 at 80 km/h
Measurements were carried out with a locked wheel using the Riekert 'Stuttgarter Gerät'.

As shown in Figure 6, 90% of German roads with modern surfaces meet these guide values, at least at 60 km/h.
According to the Netherlands State Road Laboratory, the German standard of 0.33 at 60 km/h roughly coincides with its own value of 0.45 (at 50 km/h), because of the difference in measuring techniques (see also Subsection 5.5).

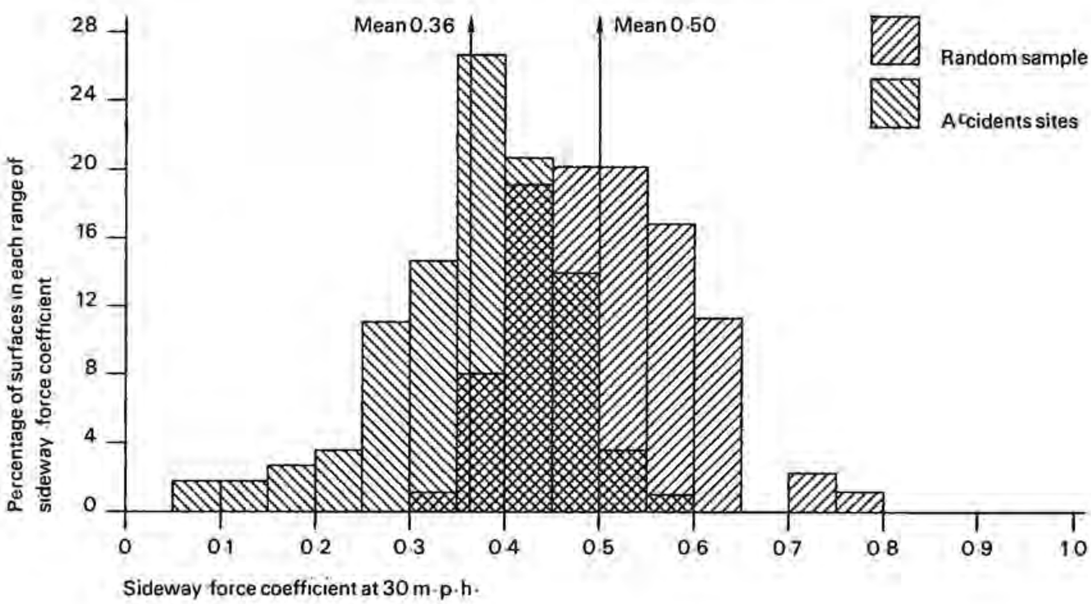

Figure 7. Comparison between the skidding resistance of skidding accident sites and comparable road sections without skidding accidents in England.

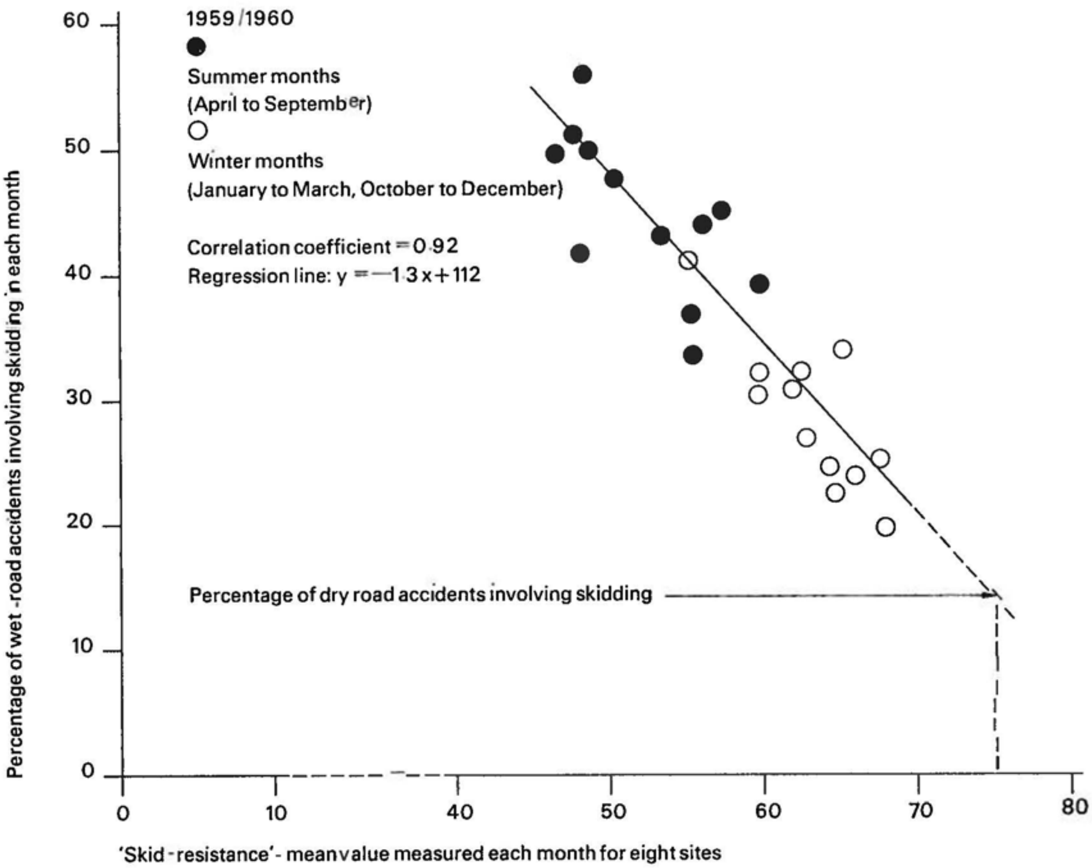

Figure 8. Relationship found in England between monthly frequency of wet road accidents involving skidding and the mean skidding resistance in the month concerned.

5.3. Great Britain

In Great Britain the Road Research Laboratory (R.R.L.) conducts a great deal of research into skidding resistance. This is concentrated on 'skidding accident site', i.e. road sections where a (relatively) large number of skidding accidents occur. Interpretation of an accident as a skidding accident is a matter for the police. These 'skidding accident sites' seem to be located primarily at intersections, on steep gradients, on bends, and in particular at roundabouts.
The skidding resistance of the road sections concerned was measured by means of a wheel inclined at 20 degrees to the direction of travel at 30 m.p.h., this being compared with the skidding resistance of road sections where no skidding accidents occurred and which were comparable in geometry and traffic configuration. To eliminate the effect of the season (see Subsection 3.3.), the skidding resistance figure used was the average of summer and winter measurements. See Figure 7 [8.12.]. It is clear that the mean skidding resistance of road sections where there are a large number of skidding accidents is significantly lower than on the reference road sections.

In an investigation into seasonal variation in skidding resistance, a striking correlation was found by the R.R.L. between the mean values of skidding resistance measured each month and the relative number of skidding accidents in that month for the whole of Great Britain. The skidding resistance was measured by means of the British portable skidding resistance tester (a pendulum instrument) at a number of sites typical of the British road system. The relationship found is shown in Figure 8[8.13]. The relative number of skidding accidents appears to fall virtually linearly as the skidding resistance increases.

The R.R.L. has issued recommendations as to skidding resistance to the road authorities in Great Britain. In the past these recommendations were based on measurements with a smooth tyre with a slip angle of 20 degrees at a speed of 30 m.p.h. These were:
0.4 for straight roads;
0.5 for bends, intersections, gradients and roundabouts.
The recommendations now issued are based on measurements with the portable skid resistance tester; these are respectively 55 and 65, with the additional requirement for high speed roads of a minimum texture depth of 0.025 inch.

5.4. United States (Texas)

The Texas Highway Department, together with the (Federal) Bureau of Public Roads, investigated the phenomenon of skidding on roads in Texas.
For this purpose 517 road sections were chosen, on which the wet road skidding resistance was determined by the locked wheel braking method at 20 and 50 m.p.h.

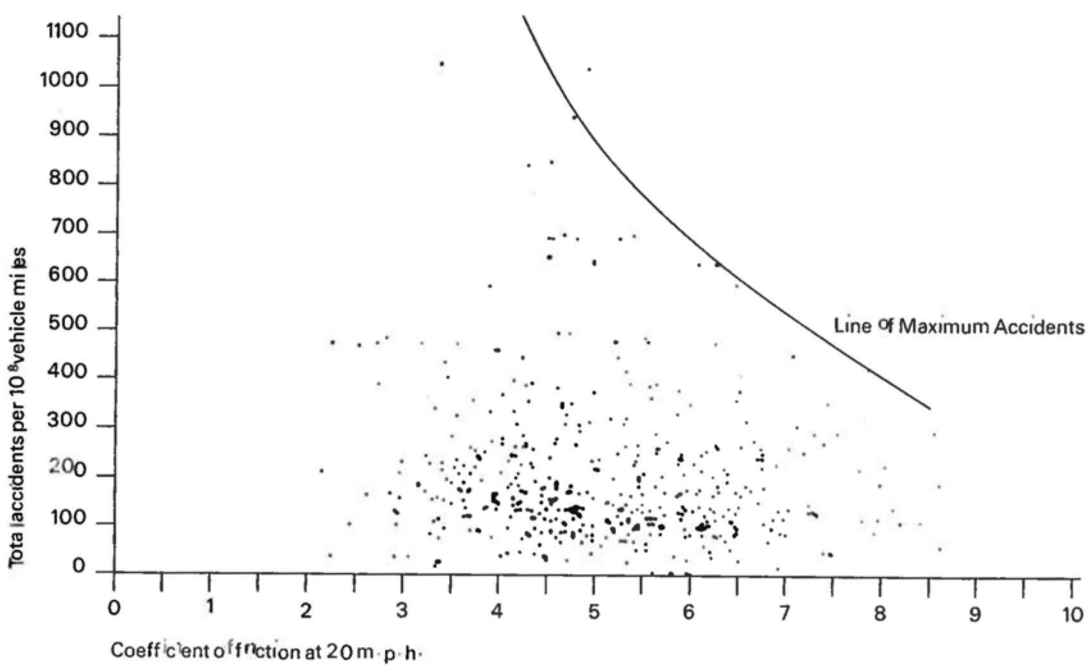

Figure 9a. Relationship found in Texas between the number of accidents per 10⁸ vehicle miles and the skidding resistance.

On the basis of the available accident records, a relationship between skidding resistance and accidents was sought. The types of accidents (all accidents, wet road accidents, or merely skidding accidents) taken as the criterion in this investigation were determined by a preliminary investigation conducted in two stages.
The criteria selected as a result were the total number of accidents and the number of injury and fatal accidents. This choice was based on the following considerations:
1. Virtually no difference emerged from the preliminary investigation between the different criteria (all accidents, wet road accidents, skidding accidents).
2. Classification of accident data into other criteria was time-consuming work, and the criterium of the number of skidding accidents is moreover unreliable, since it is difficult to define a skidding accident; with this procedure it would also be necessary to work with smaller numbers.
3. To exclude the possible effect of unsatisfactory recording, the additional criterion of the number of fatal and injury accidents was adopted; these are virtually always recorded.

Some of the results of this investigation are given in Figures 9a and 9b [8.14], in which the total number of accidents (and the number of fatal and injury accidents) per 10^8 vehicle miles are plotted against the skidding resistance (coefficient of friction).
Although the points display considerable scatter, the authors consider that in general the number of accidents is inversely proportional to the skidding resistance. This is particularly evident from the line of maximum accidents. The same relationship is evident with the fatal and injury accidents.

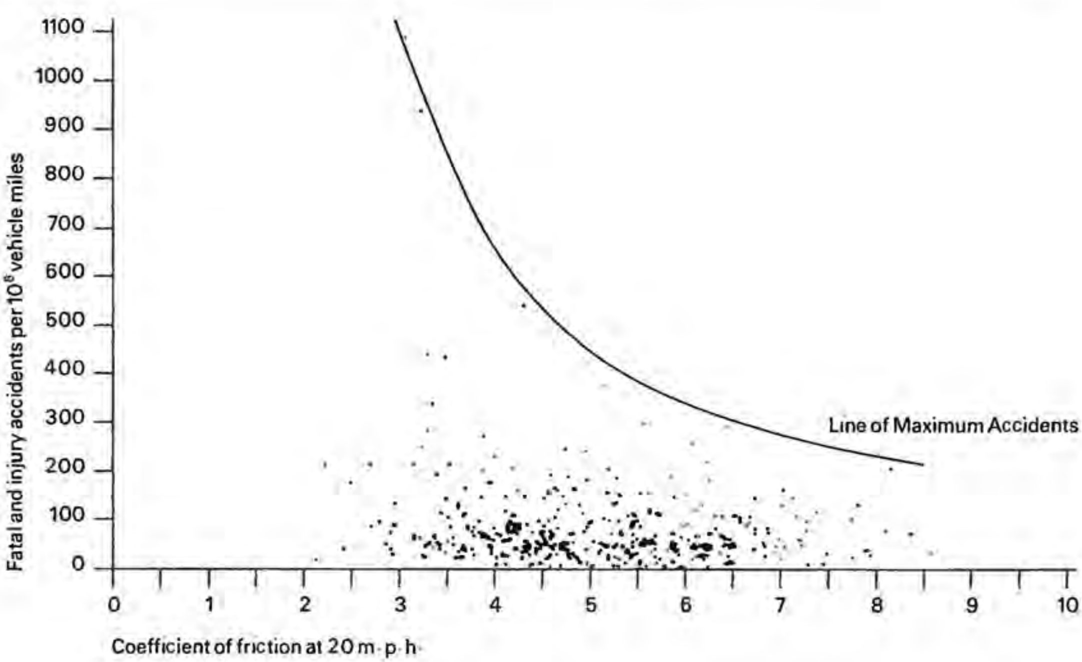

Figure 9b. Relationship found in Texas between the number of fatal and injury accidents per 10^8 vehicle miles and the skidding resistance.

The relationship between accidents per 10^8 vehicle miles and the skidding resistance at 50 mile/h is identical. At his speeds, however, the skidding resistance at which the line of maximum accidents has a steeper slope (in Figures 9a and 9b between 0.4 and 0.5) is approximately 0.1 lower, between 0.3 and 0.4.

On the basis of the results of this investigation, the authors made a proposal for a general recommendation for a minimum skidding resistance applicable to all roads in Texas, viz:
0.4 at 20 m.p.h.
0.3 at 50 m.p.h. measured by the locked wheel braking method.
This meant that some 30% of all roads in Texas must be regarded as presenting insufficient skidding resistance.

5.5. Netherlands

In the Netherlands measurements of skidding resistance have been carried out mainly on State roads, since 1933 by the State Road Laboratory.
Until 1959 the measurements were carried out with a trailer employing the locked wheel method at a speed of 20 km/h.
Since 1958 the State Road Laboratory has been conducting its measurements with a new trailer, and both the locked wheel braking method and the 86% longitudinal slip method can be used. The routine measuring speed is 50 km/h, but for other measurements—to obtain information about the variation of the skidding resistance with increasing speed— speeds of 70 and 90 km/h are also used.
To indicate to road authorities whether or not their roads presented adequate skidding resistance, it was necessary to draw up a qualification of the measured skidding resistance.
In 1936 the lower limit for satisfactory skidding resistance was fixed at 0.44 on purely subjective grounds ('no cause for complaint').
In 1946 a more qualification for the coefficient of friction f was introduced:

f less than 0.31	= dangerous
0.31 to 0.35	= very smooth
0.36 to 0.40	= smooth
0.41 to 0.45	= fairly smooth
0.46 to 0.50	= moderately skid-resistant
0.51 to 0.60	= skid-resistant
over 0.60	= very skid-resistant.

The raising of the recommended figure from 0.44 to 0.46 was carried out to give a tidier classification and not to make the requirement more stringent.

The method of measurement was changed in 1958. The numerical results of the two methods of measurement were found to be different on one and the same road surface. The values were generally 15 to 16% higher with the new method. A new qualification was then drawn up for the coefficient of friction f:

f less than 0.36	= dangerous
0.36 to 0.40	= very smooth
0.41 to 0.45	= smooth
0.46 to 0.50	= fairly smooth
0.51 to 0.55	= moderately skid-resistant
0.56 to 0.70	= skid-resistant
over 0.70	= very skid-resistant.

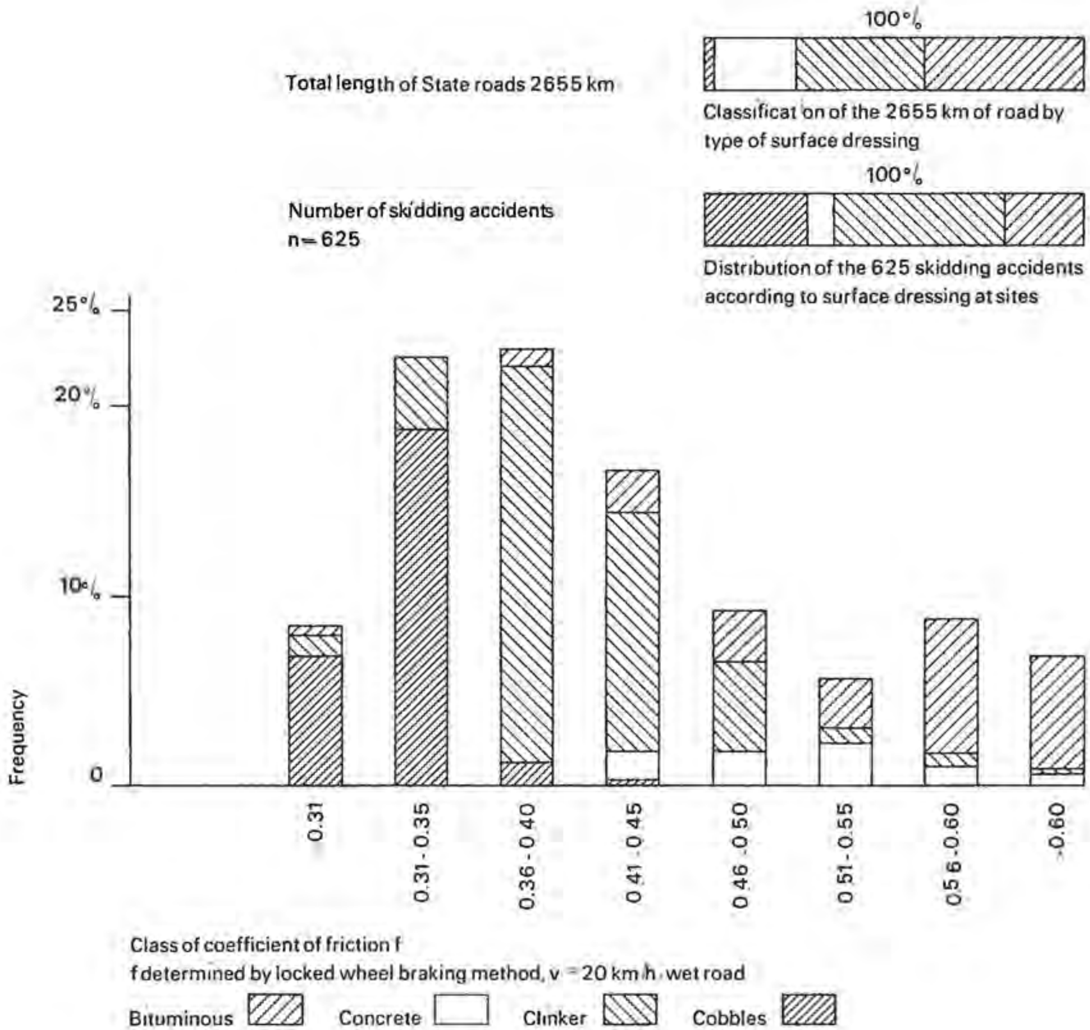

Figure 10. Frequency distribution of coefficients of friction measured on accident sites on State roads in the Netherlands in 1952

Since 1954 the State roads system has been measured systematically every year, except for a number of secondary roads. At present some 2000 road sections (approximately 100 m long) are measured, over a total road length of approximately 3500 km. The State Road Laboratory naturally wished to investigate whether the qualifications established were correct. Since about 1950, for this purpose, accident report forms for accidents considered by the General Board of Roads and Waterways (Algemene Dienst van de Rijkswaterstaat) to be skidding accidents (other than in snow or ice) have been abstracted from the forms for accidents reported by the police to the Central Bureau of Statistics in the Netherlands (Centraal Bureau voor de

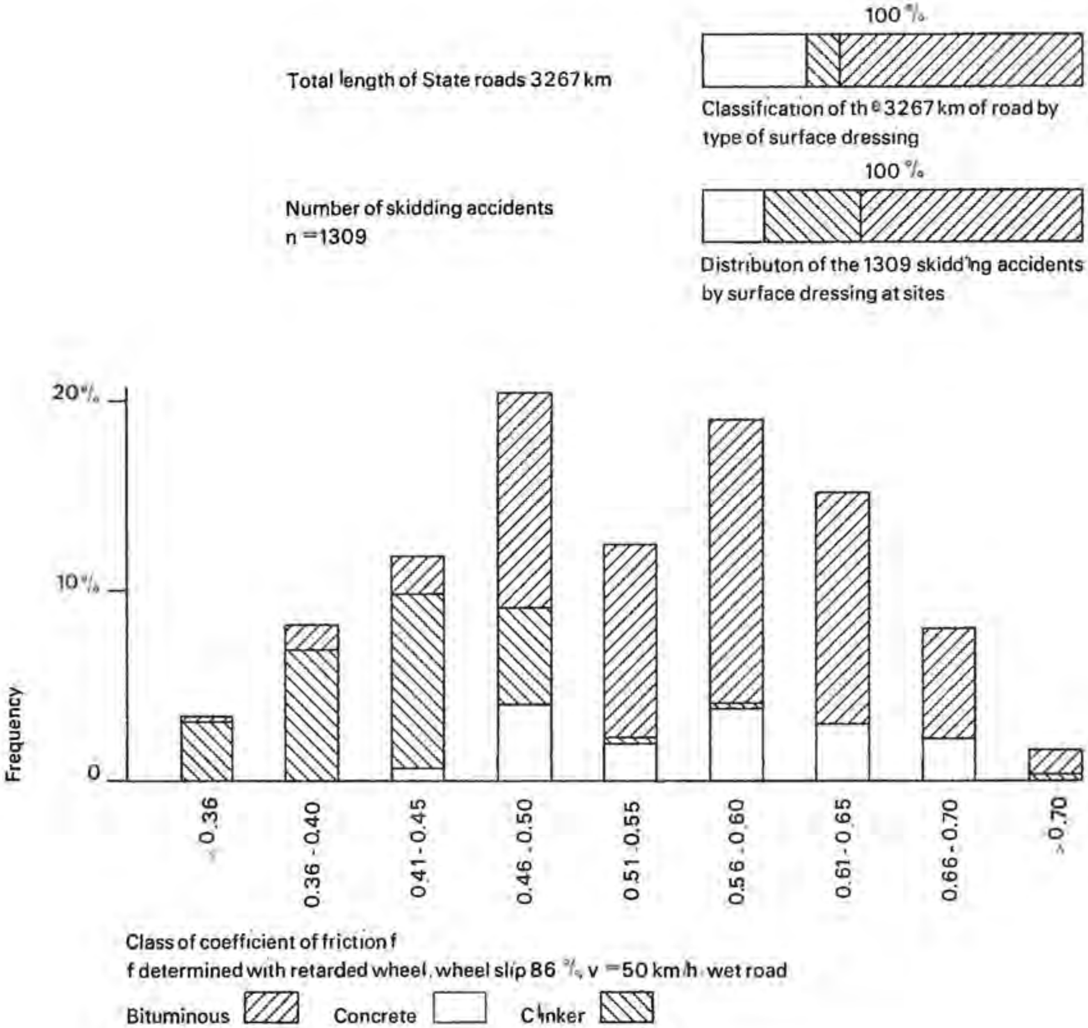

Figure 11 Frequency distribution of coefficients of friction measured on skidding accident sites on State roads in the Netherlands in 1962.

Statistiek CBS). These forms are transmitted to the State Road Laboratory for examination. Skidding resistance measurements are undertaken as quickly as possible at the sites of these skidding accidents.
With approximately 8% of the accident reports, no measurement is taken for various reasons— unclear indication of location, or change in surface dressing; this 8% is disregarded in the examination.
The results of these measurements in 1952 and 1961 are reproduced as frequency distributions in Figures 10 and 11 [18.5].

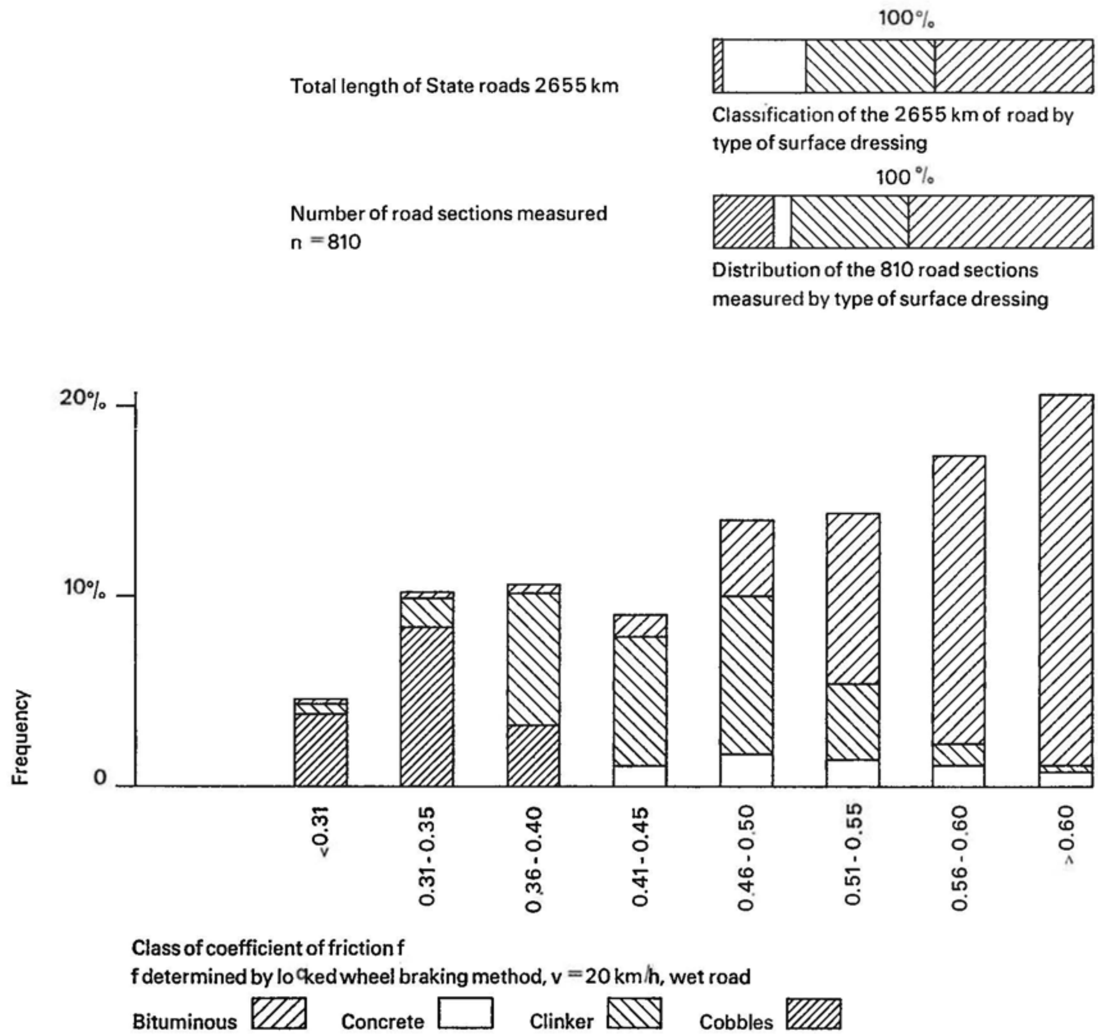

Figure 12. Frequency distribution of coefficients of friction measured on State roads in the Netherlands in 1952.

After 1961 it was no longer possible to carry out measurements on the site of the accident within a reasonably short time, since various delays in the submission of reports were taking place.

The frequency distribution of Figure 10 shows that in 1952, 70% of the coefficients of friction measured were below the recommended guide value (at the time still 0.46, measured with a locked wheel at 20 km/h).

In 1961, however, as Figure 11 shows, only 44% of the coefficients of friction measured were below this value (then 0.51, measured with 86% longitudinal slip at 50 km/h).

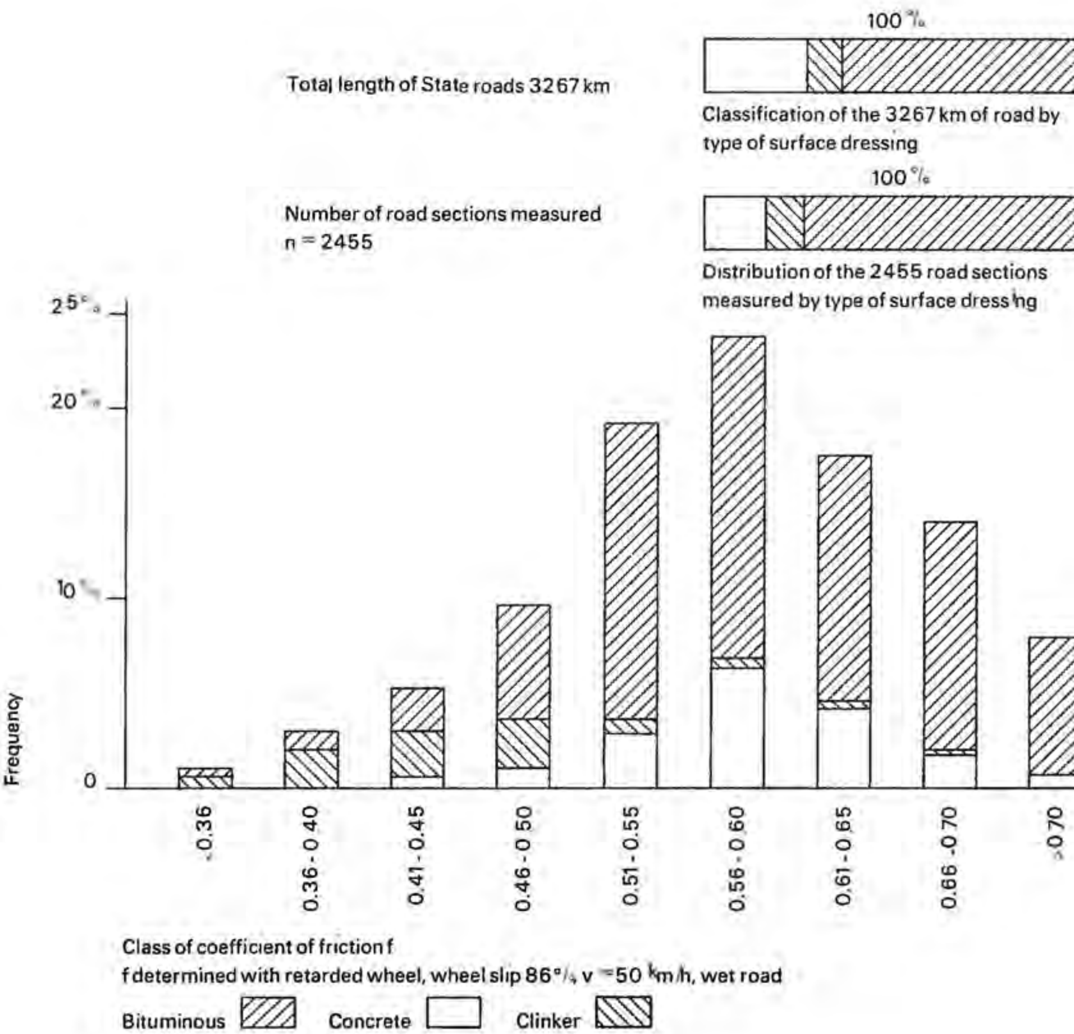

Figure 13. Frequency distribution of coefficients of friction measured on State roads in the Netherlands in 1961.

In 1952 this frequency distribution sufficed to conclude that the selected guide value was correct. This was certainly no longer the case in 1961. The shift in the frequency distribution was largely due to improvements in the skidding resistance of the State roads, as is clear from Figures 12 and 13 [8.15].

In order to assess the accuracy of the guide value, the concept of the skidding frequency factor was introduced. This is defined as the quotient of the percentage of the number of coefficients of friction measured at skidding accident sites and the percentage of the coefficients of friction

Class of coefficient of friction	Percentage of coefficients of friction measured on accident sites on State roads		Percentage of coefficients of friction measured on road sections of State roads		Relative skidding frequency factor	
	1952	1961	1952	1961	1952	1961
<0.31	8.3	—	4.4	—	1.9	—
0.31 to 0.35	22.4	—	10.1	—	2.2	—
<0.36	—	3.3	—	1.1	—	3.0
0.36 to 0.40	22.7	8.2	10.6	3.0	2.1	2.7
0.41 to 0.45	16.5	11.8	8.9	5.1	1.9	2.3
0.46 to 0.50	9.1	20.4	13.9	9.4	0.7	2.2
0.51 to 0.55	5.6	12.4	14.3	19.1	0.4	0.7
0.56 to 0.60	8.7	19.0	17.3	23.6	0.5	0.8
>0.60	6.7	—	20.5	—	0.3	—
0.61 to 0.65	—	15.3	—	17.3	—	0.9
0.66 to 0.70	—	8.0	—	13.8	—	0.6
>0.70	—	1.6	—	7.6	—	0.2

Table 2. Relationship between the skidding resistance of the Netherlands State road network as a whole and that of accidents ites in 1952 and 1961.

measured on State road sections. The basis for these percentages is the columns of Figures 10 and 12 for 1952 and Figures 11 and 13 for 1961; see Table 2 [8.15].
The steep rise in the skidding frequency factor when is skidding resistance falls below the guide values (both in 1952 and in 1961) is regarded by the State Road Laboratory as an indication that the guide values in use are wholly justified.

5.6. Discussion of research results

5.6.1. Introduction

In addition to the research described in the preceding paragraphs, other studies have been conducted in various countries, also indicating a relationship between the skidding resistance of road surfaces and the incidence of (skidding) accidents. The accuracy of the results of these studies depends on the reliability of the accident data and the procedure adopted. Normally the method of investigation is adapted to the available data from accident and road statistics. Although it would be more correct to cover a large number of parameters in an investigation, this was in most cases not possible, either because of the volume of measurements and the consequent high cost, or because the practical execution was prevented by other factors. Some of these factors are discussed below.

5.6.2. Criterion for reporting skidding accidents

In order to demonstrate a relationship between the skidding resistance of a road surface and the occurrence of skidding accidents, it is necessary to report the phenomenon of skidding. It is already plain from the definition of skidding at the end of Section 1 that it is very difficult to determine, in an accident report, whether the accident is caused by skidding. The British police have elaborate instructions for indicating in their reports whether an accident was a skidding accident. The category 'skidding accident' is a definite concept in British accident statistics. Certain locations are designated as 'skidding accident sites' in accordance with the frequency of skidding accidents taking place there.

'Skidding accidents' as such are not included in accident statistics in the Netherlands, but in cases where skidding has obviously taken place, this is often mentioned in the report. For this reason skidding accidents on State roads were selected for the study on the basis of the description of the accident in the report. Where it was found that skidding was an important contributing factor to the accident, it was regarded as a skidding accident.

In Germany 'skidding' does not appear as such in the accident statistics. To provide a basis of objective data, thus also permitting automated processing, the concept of 'relative accident frequency' for wet road surfaces has been defined and chosen as the criterion. For the purpose of comparison of this relative accident frequency for different road sections, it is strictly necessary to take account of variations in weather conditions with time and place. So far as is known, this factor is, however, not allowed for.

In the United States (Texas) it was found in a preliminary investigation that there was little difference between the criteria 'all accidents', wet road accidents and 'skidding accidents'. (If this is really the case, there are two possibilities: either the number of wet road accidents is a very large percentage of the total number of accidents and the wet road accidents are practically always skidding accidents, or there is little connection between skidding resistance and accidents. On this basis, an investigation of the German type could provide little or no result.) For the sake of simplicity in processing the large volume of data, the starting point with this preliminary investigation was the total number of accidents and, on account of the limited recording of accidents, at the same time all fatal and injury accidents.

It is evident from the foregoing that it is difficult to select a criterion for the designation of skidding accidents. Inaccuracies in the methods of investigation and in the accident data can result in a certain spread in the results, which must needs impair the significance of the relationship between skidding resistance and skidding accidents. It would generally be necessary to accept some identerminacy and to allow for it in the interpretation of results.

5.6.3. Effect of traffic intensity

Accidents being change phenomena, the frequency of which at a given location depends to some extent on the vehicle flow, traffic intensity is an important factor to consider in accident studies.
In the American study, accident rate is expressed as the number of accidents per million vehicle miles travelled.

If traffic intensity were taken into account in the German study, the number of vehicle-kilometres should have appeared in both the numerator and the denominator of the relation defined in Subsection 5.2. Since it was assumed that the intensity proportions on road sections, both when dry and when wet, were the same everywhere, this proportion was not allowed for, because of the problems of collecting the data required for this purpose. In this connection it should be noted that the form of the relation between accident rate and traffic intensity is non-linear. Consequently, the relative accident frequency for a wet road surface depends not only on skidding resistance, but also on the respective traffic intensities on dry and wet roads.

In the first British study adduced, traffic intensity is not taken into account, because it was not the number of accidents but the accident sites which were related to skidding resistance. The second British study also takes no account of traffic intensity, but this is justified, since it is assumed that the percentage of (wet road) skidding accidents does not depend on traffic intensities.

There is no allowance for traffic intensity in the Dutch study either.

5.6.4. Effect of road situation

Assuming that in different road situations the road user may also require different minimum coefficients of friction, the available coefficients of friction must at the same time differ in order to obtain the same probability of (the occurrence of) skidding on the different road sections. For this reason it should be possible to differentiate between different road situations and types in the skidding resistance recommendations. If there is no classification of accident investigations according to the road situation, a greater spread in the results may be expected for this reason.
Perhaps for practical reasons, no distinction has been made between different road situations in any of the investigations. It is true, however, that the character of the roads examined was substantially the same in all cases, viz main roads carrying fast traffic.
The British study, for which a 'black spot' investigation was carried out, showed that there was little difference in the mean skidding resistance between accident sites and the sites in the control group—both classified according to road situation (intersections, roundabouts, gradients, bends, etc.). For this reason, the different road situations were considered together in the overall evaluation.

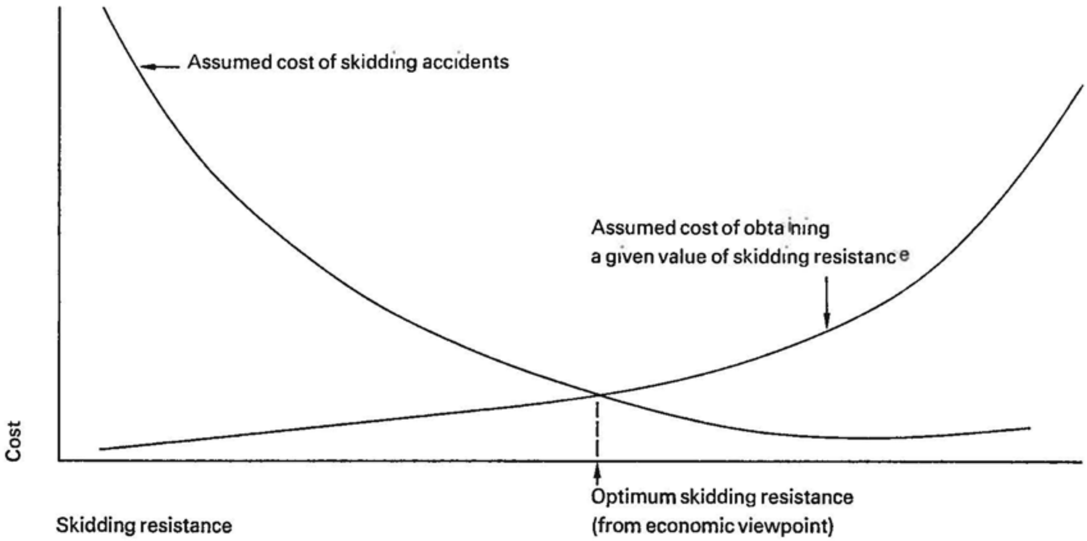

Figure 14. Example of determination of optimum skidding resistance from the economic standpoint.

5.6.5. Choice of parameters for investigation

For the achievement of a high standard of accuracy in the results, it is desirable for all factors discussed in the preceding paragraphs, together with certain other factors, to be taken into account.
As already indicated in 5.6.1. however, the desired accuracy must in practice be reconciled with with the volume of work, the organization required and the costs involved in taking account of individual parameters in the investigation. In certain cases, even the possibility of practical implementation may be called into question if all possible parameters are taken into account. Thus compromises are frequently necessary, which may reduce the accuracy of the results.

5.6.6. Choice of guide value for skidding resistance

It is plain from the preceding paragraphs that the probability of (skidding) accidents declines as the skidding resistance of the road increases. From the point of view of road safety, therefore, the road should be as skid-resistant as possible preferably in all circumstances.
The maximum skidding resistance is, however, limited by technical feasibility. In addition, with increasing skidding resistance, the costs of achieving (and maintaining) a given standard of skidding resistance increase.

From the economic standpoint, there will also be an optimum standard of skidding resistance, at the point of intersection of the curve showing the relationship of the skidding resistance to the cost of achieving and maintaining it, and the curve representing the relation between skidding resistance and the cost of skidding accidents at this standard of skidding resistance (Figure 14) [8.16].

Since accidents are not only economically disadvantageous but also cause much personal suffering, the question is whether this method of laying down a skidding resistance standard for road surfaces is ethically justified and whether for this reason a higher (minimum) skidding resistance should not be aimed at, in spite of the higher cost.
It is, however, impossible to determine whether such a calculation is possible and whether the above question is then still relevant, in the light of present knowledge of the form of the relationshiop between the probability of (skidding) accidents and skidding resistance.
But it is possible, on the basis of present knowledge, to recommend provisional measures concerning the skidding resistance of the road surface, which may lead to a reduction in the number of skidding accidents (see Section 6).
However, in order to make definitive recommendations for anti-skidding measures, extensive and thorough research is still necessary (see Section 7).

6. Implications for the Netherlands

It is not possible, from the research carried out hitherto, to deduce the exact extent of the phenomenon of skidding in the Netherlands. But it is quite clear, for example from the investigations of the State Road Laboratory (Subsection 5.5.) that skidding, in particular on wet road surfaces, results in a not inconsiderable number of accidents. Measures to reduce the number of skidding accidents are thus necessary. It also follows from the State Road Laboratory study that certain measures can be adopted right away.
As already stated in the introduction, two kinds of measures are possible:
a. reduction of the minimum necessary frictional forces;
b. raising of the available frictional forces.

6.1. Reduction of the minimum necessary frictional forces

Section 2 shows that driving behaviour—which determines the minimum necessary frictional forces—depends on a large number of factors.
Since the studies referred to above all deal with the available frictional forces—and except for one instance completely disregard the minimum necessary frictional forces—it is very difficult at this stage to lay down generally applicable measures to influence driving behaviour. Locally, mostly where a large number of (skidding) accidents occur, attempts will be made to reduce the minimum necessary friction, e.g. by alteration of the geometry of the road (by such measures as reconstruction of intersections), better indication of discontinuities and possibly by the imposition of speed limits.
It will often be the case that these measures, since they may affect the behaviour of road users as a whole, may have an influence on accidents other than skidding accidents.

For a more direct assault on the problem of the minimum necessary friction, a great deal of research is still necessary. These investigations will be conducted together with studies of other points by the Institute for Road Safety Research SWOV. The Working Group on Tyres, Road Surfaces and Skidding Accidents will be concerning itself at first with research into more technical aspects (see Section 7).

6.2. Increasing the available frictional forces

Taking driving behaviour as the starting point, it may be assumed that in order to achieve as great a margin as possible between the minimum necessary friction and the available friction, it is necessary to make the available frictional forces as high as possible. As shown in Section 3, the available friction is largely determined by the characteristics of the tyres and the road surface.
The realization that tyres contribute to a great extent in this connection has already led to the laying down of requirements for tyre treads [8.17].
For the tyres of lighter vehicles (in general, passenger cars), the requirement is that the entire road contact surface must have a conspicuous tread pattern. The road contact surface of tyres for buses and trucks may be completely smooth, without any tread pattern, under the existing guide lines, provided that the carcass is not visible.
It will be necessary to conduct further studies in order to determine whether these tread pattern requirements are adequate so far as skidding is concerned. More research is also necessary to determine whether it is necessary and possible to stipulate other (functional) requirements for (new) tyres and possibly for vehicles (see Section 7).

Regarding the road surface, there are in the Netherlands considerable local differences in the available coefficients of friction (skidding resistance values). There are differences, for instance, between the skidding resistance of the various types of surface dressings, but there

are also variations between individual sites with the same surface dressing (e.g. smooth patches due to wear); see Figures 12 and 13. Various studies (including speed measurements by the Institute for Road Safety Research SWOV) have shown that driving behaviour is scarcely, if at all, influenced by the skidding resistance characteristics of the road surface, other factors being equal. Thus, road speeds on dry and wet road surfaces—between which the skidding resistance can vary substantially—are practically the same if other factors remain unchanged (see Subsection 2.2.).
In conclusion, it can also be said that it would be very desirable for road surface skidding resistance to be as uniform, and as high as possible in all places and at all times.
To achieve this, all road authorities in the Netherlands must be aware of the condition of the roads in their charge with respect to skidding resistance at all times. In the case of new roads they must be familiar with the skidding resistance before these are opened to traffic.
At the present time, the autorities in charge of State roads and secondary roads in the provinces and in a few local authority areas, are familiar with the skidding resistance of the roads for which they are responsible as this is measured by the State Road Laboratory when these roads are opened to traffic, and annually thereafter (see Subsection 5.5.).

The measurements of skidding resistance are qualified by a statement of which skidding resistances are permissible and which are not. As already stated in Subsection 5.6., it is not at possible to determine categorically a minimum skidding resistance which can be regarded as permissible. Pending the work to be carried out, the Working Group considers it desirable to recommend a provisional guide value for all roads the same value as is used by the State Road Laboratory (viz. 0.51 -measured with 86% longitudinal slip at 50 km/h on a wet road surface). This would at the same time promote the desired uniformity.
More research will be necessary before definitive guide values and measuring techniques can be laid down. It is also necessary to conduct research into vehicle characteristics which may increase the available frictional forces. These studies are at the present time being prepared by the Working Group (see Section 7).

7. Research programme of the Working Group on Tyres, Road Surfaces and Skidding Accidents

7.1. Introduction

It is clear from the preceding Sections that there are a very large number of factors which contribute to skidding. Many studies of the influence of these factors have been undertaken. These investigations have largely been concentrated on the effect of a single factor, the other factors being kept or assumed to be constant as far as possible (single factor studies).
This research has certainly contributed to increasing our knowledge of the problem of skidding, but the relationship of the factors amongst themselves, and their relative importance, are frequently not brought out by a study of this kind. As a result, certain difficulties arise in the interpretation of the results, and this is probably the reason why the different national research bodies investigating skidding sometimes contradict each other.
For this reason it is necessary to carry out a comprehensive statistical examination of the first order factors involved in skidding. The most efficient method for this investigation will be a statistical multi-factor study (VI)*. But selection of the first order factors for this investigation is only possible when sufficient knowledge of the problem has been accumulated. Some of this knowledge can be drawn from previous work. The remainder must be obtained by means of preliminary studies carried out by the research body itself, taking the form of either very thorough single factor investigations or limited multi-factor investigations.

Some of these preliminary studies can already be of use to the authorities as a basis for guide lines or recommendations. It is then essential for these investigations to be given the highest priority (see Subsection 7.4.).

It can be deduced from the terms of reference of the Working Group (see Preface) that the Working Group should restrict itself to considering the primarily technical factors contributing to skidding. The primarily human factors will therefore not feature directly in the Working Groups research programme. The Working Group must, of course, take cognizance of the results of studies in this field, as there would otherwise be a risk of an unrealistic selection of first order factors. For these reasons this Section does in fact take account of research into the behaviour of the road user.

7.2. Experimental research

7.2.1. Research into available frictional forces

7.2.1.1. Vehicle factors (of importance in connection with available frictional forces)

Of the vehicle factors, the tyres have a considerable effect on the available friction. The relevant tyre factors are:
a. condition of road contact surface (tread pattern, wear);
b. tyre construction (cross-ply, radial-ply, type of rubber);
c. inflation pressure (as a percentage of the recommended value);
d. wheel loading.
It will be necessary to distinguish between passenger car and truck tyres. The road speed is also very important.

* The Roman figures in brackets refer to 7.5.1: Summary table.

To arrive at the most efficient method of examination, it is desirable to include these factors together with the road surface factors (7.2.1.2.) in a single experimental multi-factor investigation (I).
Before this investigation can begin, it is, however, necessary to establish a relevant classification of the tyre factors (Ia).

7.2.1.2. Road factors (of importance in connection with the available frictional forces)

Of the road factors, the road surface has a great influence on the available friction. Road surface factors will also have to be included in the experimental multi-factor examination mentioned in 7.2.1.1. (I). For this purposes, however, it will first be necessary to classify the road surface factors (Ib).

The skidding resistance of the road surface is, of course, the most important road factor affecting the available coefficient of friction. This skidding resistance is largely determined by the configuration of the surface. Depending on the form and dimensions of the irregularities in the surface layer, the components of the frictional forces arising, mentioned in Subsection 3.2. (viz. the adhesion, hysteresis and cohesion components), will assume different values. In addition water evacuation between the tyre and the road surface (dynamic drainage) is to a great extent affected by the nature of the road surface, as well as the static drainage, although the latter characteristic is also strongly influenced by the flatness of the road and the banking.

Measurement and classification of the configuration of road surfaces in the widest sense are to form the subject of a development study (IV). It is particularly important to develop simple apparatus to measure, the drainage capacity, since the dynamic drainage determines the gradient of the coefficient of friction as a function of speed. It will then be sufficient to measure the coefficient of friction at low speed and the drainage characteristic, in order to obtain the coefficient of friction at high speed by extrapolation. To verify this method measurements of skidding resistance at high speeds will also be carried out (part of I).

7.2.2. Examination of minimum necessary frictional forces

7.2.2.1. Driving behaviour

Human factors play a very large part in the minimum necessary frictional force (see Section 2). Although consideration of driving behaviour does not directly form part of the Working Group's research programme, it is nevertheless taken into account, as it is relevant for a correct choice of first order factors for the statistical multi-factor investigation. It is intended that measurements will be carried out by or on behalf of the Institute for Road Safety Research SWOV of longitudinal and lateral accelerations or decelerations in traffic. This can be done either by the driving of test vehicles fitted with acceleration recording apparatus in normal traffic, or by filming the traffic (III). These accelerations and decelerations can be related to the type of vehicle and the road and traffic situations arising. In this way it will be possible to gain an impression of the behaviour of road users in traffic in so far as this is relevant to skidding.

7.2.2.2. Utilization of available frictional forces

There is a relationship between (1) the longitudinal and lateral accelerations or decelerations and (2) the frictional forces between the tyres and the road surface required for these. This relationship is influenced by various vehicle characteristics. However, these characteristics generally have an intense feedback effect on driving behaviour, so that it is for the present very difficult to lay down official guide lines or recommendations in this connection.

Only an examination of the relation between (1) the distributions of braking force between the front and rear wheels and between the left and right hand wheels and (2) the attainable braking decelerations and stability of the vehicle is possible, because in this case there is presumably little or no feedback effect on driver action (II), and hence it is easier to stipulate guide lines.

7.3. Statistical investigation of accidents

7.3.1. Statistical investigation of the relationship between skidding resistance and accident rate

The aim of all the studies mentioned in Section 5 is to establish the above relationship, or an equivalent parameter. It may be assumed that this relationship exists and must be fairly simple. The above mentioned examinations have, however, in no case given a satisfactory result. This is because the relationship can only be found it all other technical factors contributing to the probability of (skidding) accidents are or can be kept constant. This is not the case with these studies.

For this reason, the Working Group wishes to carry out as accurate as possible a single factor examination of the relationship between skidding resistance and the probability of an accident at given values of skidding resistance (V). This accident rate is defined as the total number of accidents for (million) kilometres on a road surface having this value of skidding resistance. The other contributing factors will be kept as constant as possible. For this purpose a number of accidents on carefully chosen road sections will be related to the skidding resistance of the road surface at the time of the accident.

In order to be able to limit the variation in driving behaviour—which determines the minimum necessary frictional forces—as far as possible, the examination must be carried out for straight road sections without discontinuities and with approximately the same traffic composition and intensities. This will, however, present difficulties.

1. It will be difficult to find road sections with the same geometry and the same traffic intensity and composition.
2. When these road sections are found, because of their restricted length and/or number, it may take a long time to gather sufficient accident rate data. There will then also be a risk that one or more factors may vary with time.

It is nevertheless considered possible to carry out such an examination on a number of State roads, with the following available data:

a. result of skidding resistance measurements by the State Road Laboratory, in conjunction with the known data about changes in surfacing on the road sections concerned;
b. accident data from the Central Bureau of Statistics in the Netherlands;
c. knowledge, for a number of State roads, of speeds, distances between vehicles, traffic compositions and intensities; this is available to the Institute for Road Safety Research SWOV in connection with its work on speed limits.

With these data, these is a good chance of gaining an idea fairly swiftly of the relationship between skidding resistance and accident rate.

7.3.2. Statistical multi-factor study of first order factors

This study, already mentioned in the introduction to this Section (see Subsection 7.1.), can be regarded as the conclusion of the Working Group's activities.

It will be rendered possible by the data obtained from the partial studies dealt with above. The multi-factor study will serve to test the various research results and hypotheses put forward in connection with skidding.

7.4. Order of priority for tests

As mentioned in Subsection 7.1., the partial studies will have differing priorities. These may be listed in priority classes 1, 2, 3 and 4.

Priority class 1:

Partial study the results of which can lead direct to practical requirements or guide lines of importance for road safety.

Priority class 2:

Partial study the results of which will not yet lead direct to practical requirements or guide lines relevant to road safety.

Priority class 3:

Partial study the results of which are relevant only to the concluding statistical multi-factor examination.

Priority class 4:

Concluding statistical multi-factor examination and development study for simple measuring equipment. The results of these studies will only be applicable at a later stage.

It will be possible to work simultaneously on studies in different priority classes.

7.5. Summary of research

7.5.1. Summary table of research programme

See Table 3.

7.5.2. Schematic representation of research programme

Figure 15 shows the relations between the various studies schematically.

No.	Description	Priority class	Body responsible*
I	Investigation of relationship between available frictional forces, the characteristics of the road surface and tyres, and speed (experimental multi-factor investigation)	1	Vehicle Research Laboratory State Road Laboratory Laboratory for Road and Railroad Research Institute for Road Safety Research SWOV
The following are preliminary studies for I			
Ia	Classification of tyre factors	1	
Ib	Classification of nature of road surface	1	
II	Experimental and analytical examinations of the relationship between braking force distributions and braking deceleration and vehicle stability	2	Vehicle Research Laboratory
III	Consideration of driving behaviour by means of acceleration recorders and filming	3	Institute for Road Safety Research SWOV
IV	Development of simple measuring apparatus	4	Vehicle Research Laboratory State Road Laboratory
V	Statistical single factor study of the relationship between accident rate and the skidding resistance of the road surface on straight road sections without discontinuities	1	State Road Laboratory Institute for Road Safety Research SWOV
VI	Statistical multi-factor study of first order factors contributing to skidding	4	Institute for Road Safety Research SWOV

Table 3 Summary of the research programme

* Where necessary, other bodies outside the Working Group will be asked for advice or involved in the research.

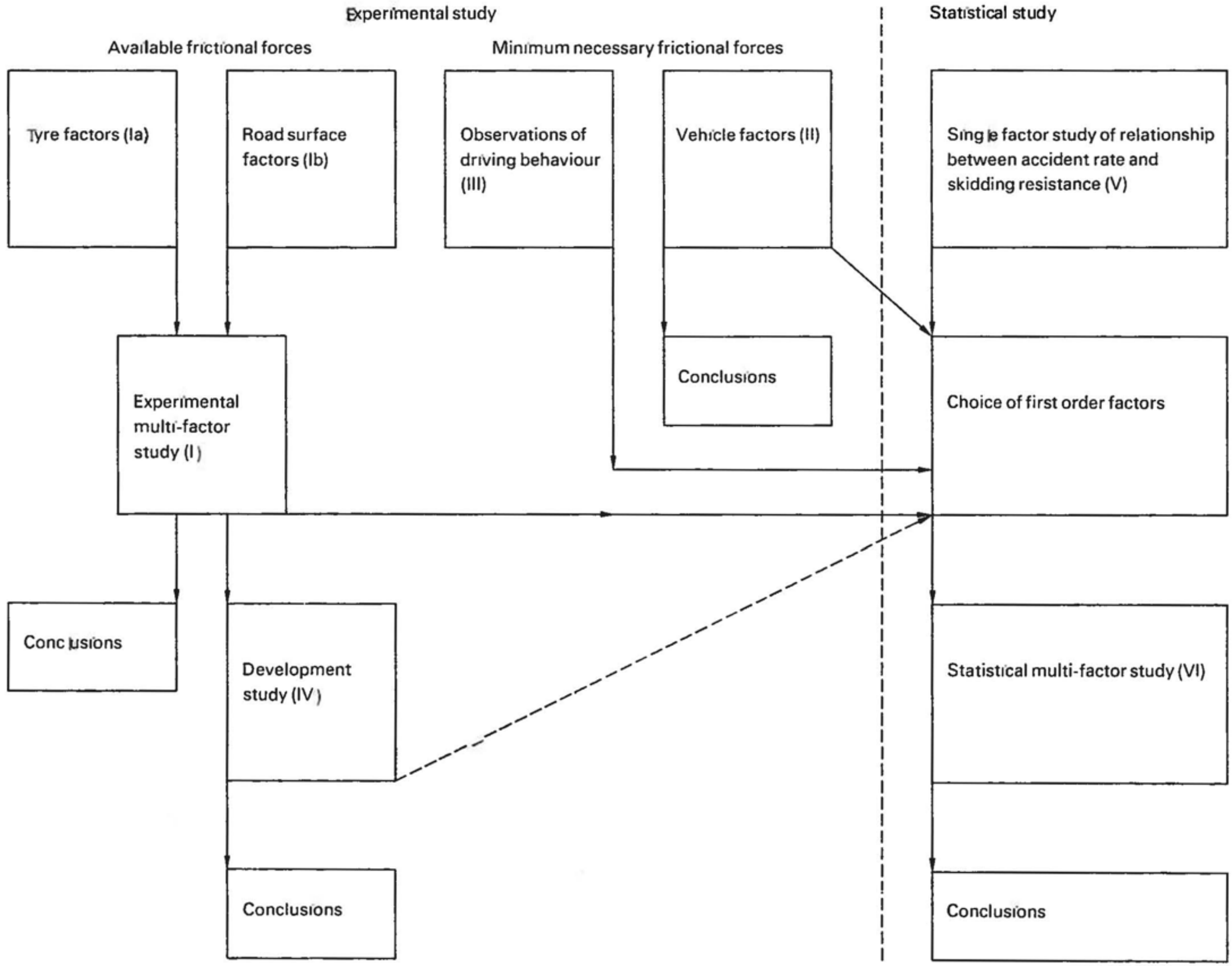

Figure 15. Schematic representation of research programme.

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For the compilation of this report, recourse was had liberally to the following reports and articles obtained by the Working Group on Tyres, Road Surfaces and Skidding Accidents:

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