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Natural Rubber in Tyres

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Knowledge of the tasks which the various components of a tyre have to perform is needed to make best use of the properties of NR in tyres and to maintain its position in this field of application.

The present proportions of NR going into tyres are reviewed and the requirements for passenger tyres are examined in detail with special reference to the advantages of oil-extended NR treads in skid and wear resistance. NR-based compounds are the best compromise for winter tyres because of their high wear resistance at low temperatures and superior skid resistance on ice. Like wear, groove cracking can be ameliorated by blending OENR with butadiene rubber.

A similar analysis is carried out for truck tyres where heat build-up makes use of NR in carcasses imperative. The feasibility of oil-extended NR treads for medium-sized truck tyres is demonstrated.

The severe service conditions encountered by off-the-road and aircraft tyres can at present be met only by NR.

Before the last war NR was necessarily used in all parts of the tyre; today compound compositions differ according to the part of the tyre for which they are intended and the application for which the tyre is designed. Although as many as seven different compounds may be used in the building of a tyre, most of the rubber is found in three regions: the tread, the carcass and the sidewalls *(Figure 1)*.

The compounds in the different regions have to meet different physical requirements during the service life of the tyre.

For example, the tread should primarily give good road holding and show a low rate of wear, while the carcass must not fail because of overheating under high-speed running of the tyre and the sidewalls should stand up to repeated flexing without cracking and show adequate resistance to cutting and kerb chafing.

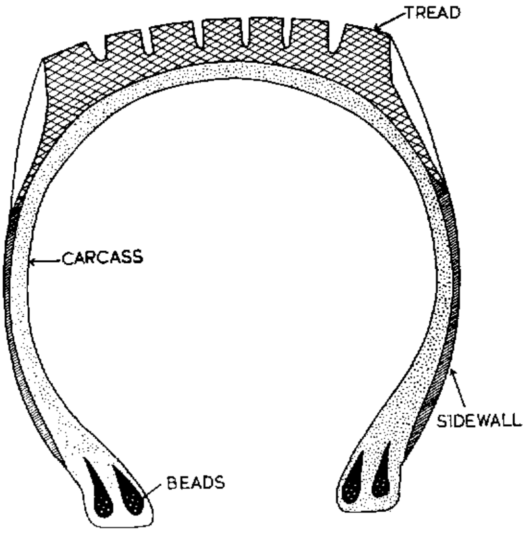

Figure 1. Section of a tyre showing the main parts in a conventional construction.

These requirements are common to all tyres but different applications may in addition demand one property to be particularly outstanding. Thus, a car tyre is often driven to the limit of its road-holding capacity and even a marginal increase in this property would be important to the safety of the driver. In contrast, braking a truck to the maximum braking capacity of the tyres might result in a catastrophic shift of the cargo. Therefore, the efficiency of the brakes of trucks is usually limited to below that of the tyre and hence high braking coefficients of tread compounds are not so important.

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Natural rubber is used in tyres today because it has certain properties which cannot be matched by any other rubber; at the same time it has been replaced from parts of the tyre market because other polymers offer a performance advantage or are sufficiently comparable to allow a change-over for reasons of availability and price. To preserve and strengthen the position of NR in tyres requires a precise knowledge of the technical requirements for each application. The paper surveys the present situation of elastomers in tyres and describes research aimed at consolidating the usage of natural rubber.

RUBBER REQUIREMENTS OF THE TYRE INDUSTRY

The tyre industry forms a section of the wheeled vehicle producing industry. This industry has experienced almost continuous expansion since the last war, as can be seen from *Figure 2*, which shows the growth in passenger car and commercial vehicle production in the world between 1952 and 1964. A similar growth has taken place in the aircraft industry and in 'off-the-road' vehicles like earthmovers and agricultural implements. While the growth rates differ greatly in different regions of the world, the total number of vehicles produced and hence the overall demand for tyres of one kind or another has risen steadily and is still rising. This has demanded a parallel growth of the raw material industries of which, in the tyre field, the rubber-producing industry is the largest. A passenger car tyre contains roughly 8–9 lb of rubber so that, with five tyres as original equipment, every car produced requires about 40–45 lb of rubber for its first set of tyres. Normally two sets of replacement tyres are fitted during its life so that every car produced calls for some 120 – 140 lb of rubber in tyres *in toto*. The corresponding figure for trucks can be derived on the basis that the average truck tyre contains four times as much rubber as the average car tyre, that the average number of tyres per set is eight instead of five and that the number of new replacement tyres is again twice that of the original set (all these assumptions have been deduced from relevant statistics); the value is around 750 – 800 lb. These are conservative figures since no account has been taken of remould tyres. Knowing the number of cars and goods vehicles produced in any year (see *Figure 2*), the world requirement of rubber to supply

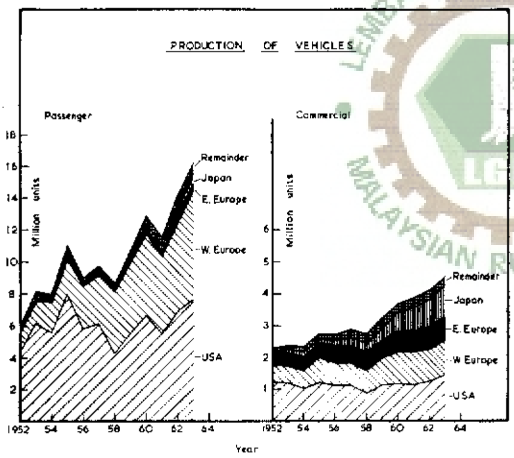

Figure 2. Production of passenger cars and commercial vehicles in various parts of the world between 1952 and 1963.

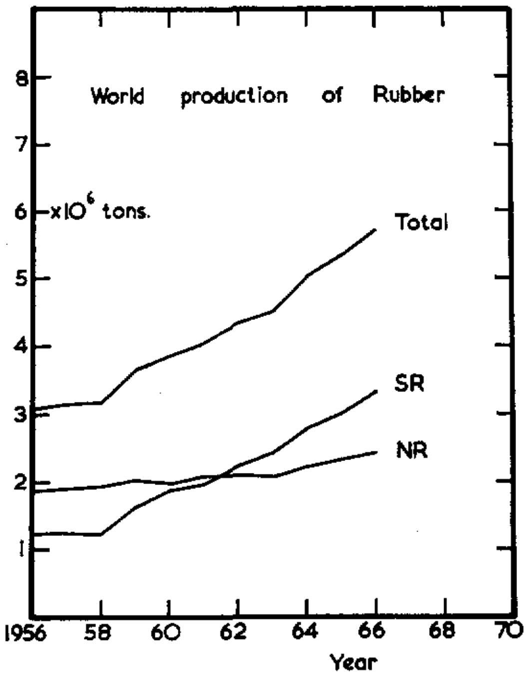

Figure 3. World production of rubber.

these vehicles with tyres can then be estimated —and this estimate approximates to the annual requirements, if the effect of the growth rate on the number of replacement tyres is ignored.

In 1962, for instance, the figure so derived is 2.4 million tons of rubber, while the additional requirement per year because of the growth of the vehicle-producing industry amounts to 100 000 tons per year over the years between 1954 and 1964. How do these material demands compare with the supply? *Figure 3* shows the amounts of natural and synthetic rubber produced over the period 1956–1966. Obviously the total production of NR in 1962 was insufficient to satisfy the demands of these two sections of the tyre industry let alone the demands of the other sections and of the whole area of non-tyre rubber usage. Synthetic rubber (SR) has had to supplement natural rubber just from this supply–demand situation alone and irrespective of any technical factors whatsoever. Further, as the growth rate for supplies of NR has averaged around 50 000 tons annually over the last ten years, its share of the tyre market has necessarily decreased and is likely to continue to do so—again because of the inexorable supply limitation. This changing position is illustrated in *Figure 4*, where the area of the four discs represents the total rubber consumption by the tyre industry in the United Kingdom over four years, selected roughly at equal intervals between 1950 and 1966.

The outer segments divide the area into NR and SR usage, while the inner segments show in each case the section of tyre application in which the rubbers were employed.

In 1950, over 99% of rubber used in the U.K. tyre industry was NR. This decreased to 80% in 1955 but as the total amount of rubber used had at the same time increased by 15%, the tonnage of NR used decreased only slightly. But between 1955 and 1960, the proportion of SR in tyres increased to almost 50%, and as the growth rate of the tyre industry was small, the tonnage of NR used decreased appreciably. From 1961 onwards, however, the proportional share of NR decreased only slightly, less in fact than the relative growth of the industry,

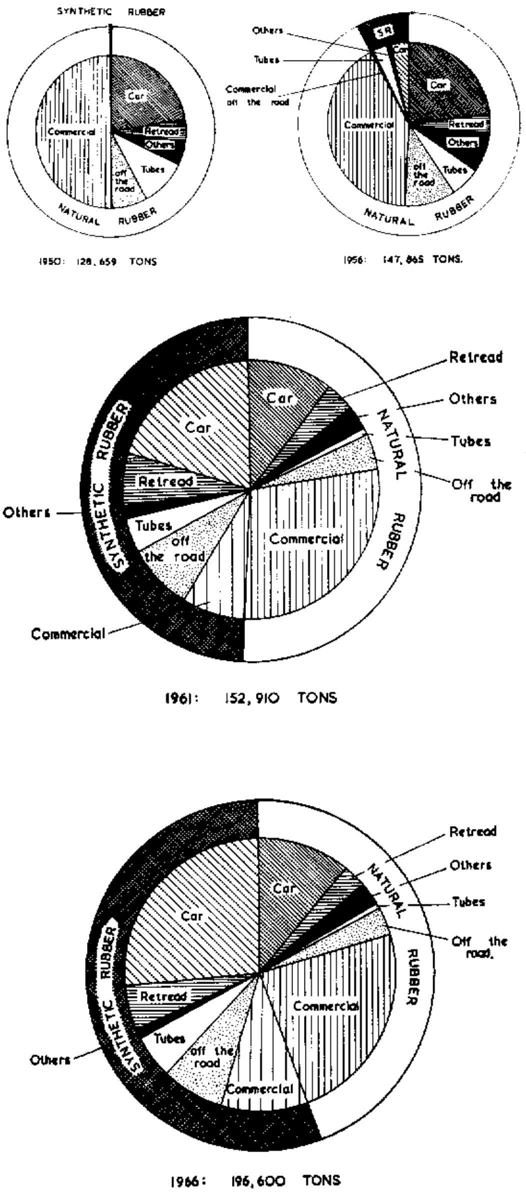

Figure 4. Natural and synthetic rubber used by the tyre industry of the United Kingdom in various sectors of the industry.

so that the weight of NR used increased. This pattern for the U.K. is not parallelled precisely elsewhere, but it exemplifies the general inter-

TABLE 1. CONSUMPTION OF NR BY THE TYRE INDUSTRY AND ITS RELATIVE SHARE OF THE MARKET IN VARIOUS PARTS OF THE WORLD DURING 1960 AND 1967

Year	Consumption*	U.S.A.	Canada	U.K.	France	West Germany	U.S.S.R.	Outside Europe, Socialist Countries and U.S.A.
1960	Amount	323.6	25.1	83	75	75	175†	448†
	% of total	32.5	39.6	53.3	60.7	54.9	–	70.4
1967	Amount	335.3	33.6	84.5	81.6	72‡	285†	570†
	% of total	25.3	29.6	43.2	44.1	37.4	25	48.7

* In '000 long tons † Includes non-tyre useage ‡ Estimated

play of relative and absolute NR/SR uptakes. In the U.S.A., for instance, volume usage of SR in tyres started before 1950 and this is reflected in the present much lower NR/SR ratio, while in some other countries the proportion of NR used remains, today, still considerably larger than that for the U.K.

This can be seen from *Table 1*, which shows the relative share which NR had of the market and the total tonnage of NR used in various parts of the world during the years 1960 and 1967.

Even in the U.S.A. where the NR/SR ratio is lowest the total amount of NR used in tyres has increased during this period, as it did in every other part of the world except West Germany, where however, there was a recession during 1967.

From the inner sectors of the discs in *Figure 4* it is seen that the replacement of NR by SR has not taken place equally in all sections of the tyre industry or uniformly. It occurred first in inner tubes, which are now almost entirely made of synthetic rubber, mainly butyl. In car tyres, the percentage of SR increased rapidly between 1955 and 1961 but has changed much less since then. In truck and bus tyres the replacement of NR has been more gradual and the largest tonnage of NR is now used in this area. Broadly speaking, with the exception of certain agricultural tyres, the larger the tyre the larger the proportion of NR it contains, up to 100%. Clearly, the proportion of big vehicle tyres relative to passenger car tyres will strongly influence a country's NR requirements.

It is insufficient to speak of SR without specifying the kind. Since 1945 a number of synthetic rubbers have been marketed, but only two are used in large quantities in the tyre industry, *viz.*, styrene-butadiene (SBR) and polybutadiene (BR), with polyisoprene (IR) a potential third.

RUBBER COMPOUNDS IN PASSENGER CAR TYRES

Figure 5 shows cross-sections of two typical modern, tubeless passenger car tyres, one cross-ply, the other radial. The main component parts have been marked with the typical proportion of rubber which each contains relative to the total amount of rubber in the tyre. Between 30 and 40% of rubber is found in the tread; a similar amount is in the carcass of the cross-ply or in the carcass and breaker together in the radial-ply construction; the remainder goes

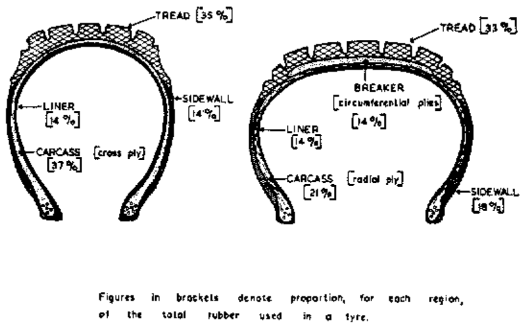

Figure 5. Cross-section of typical cross-ply (left) and radial-ply (right) passenger car tyres. Figures in brackets indicate the fraction of the total amount of rubber used in the various tyre components.

into sidewalls and liners. *Figure 6* shows an analysis of the tread compounds of over 200 passenger car tyres produced in the U.S.A. and Europe between 1964 and 1967. The distribution plots for SBR and BR show pronounced peaks around 75% SBR and 25% BR respectively, indicating that most manufacturers have settled for such a composition with little or no NR as their preferred car tyre tread compound.

A more limited analysis of carcass compounds shows that these are usually made of NR/SBR blends in a proportion which has changed little over the last six years, *viz.*, approximately 60:40 in cross-ply tyres. In radial-ply tyres the corresponding composition was about 70% NR with the remainder either SBR or BR or a blend of these. The breaker compound is usually the same as the carcass compound.

The composition of the sidewall compound depends on the type of tyre. For black sidewall cross-ply tyres, the compounds resemble the tread compounds, *i.e.*, SBR/BR blends, although in some cases triple blends of NR, SBR and BR are used. Sidewall compounds of radial-ply tyres, on the other hand, invariably contain a considerable proportion of NR, the average blend ratio observed being 55 NR, 35 SBR, and 15 BR—with one sidewall compound, however, being entirely NR. Coloured, particularly white, sidewall compounds often contain a considerable proportion of NR even in cross-ply tyres.

Unlike the inner tube, which is almost always made of butyl rubber, the inner liners in tubeless tyres, which replace the inner tube, often contain a considerable proportion of NR.

Tyre compounds contain substances other than rubber, notably carbon black and oil. The segments of the circular disc in *Figure 7(a)* show the volume fractions of the different

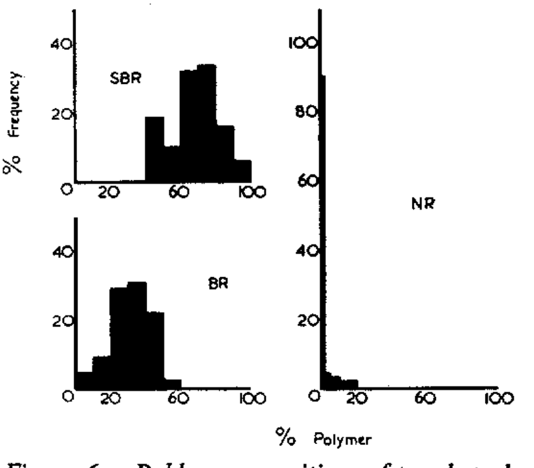

Figure 6. Rubber compositions of tread stocks for car tyres.

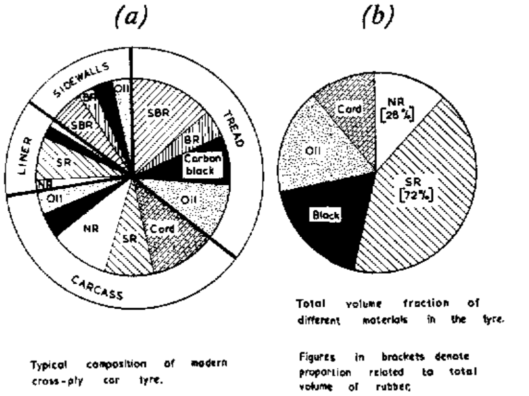

Figure 7. Typical composition of modern cross-ply car tyre (a) and total volume fractions of materials in the tyre (b). (Figures in brackets denote proportion related to total volume of rubber).

materials in the main parts of a typical cross-ply car tyre; this is simplified in *Figure 7(b)* to show just the total volume fractions.

The average car tyre contains about 2.5 lb of NR and hence every car produced requires some 37 lb of NR for its tyres during its life. If the annual production of cars is 20 million vehicles, car tyre production requires some 350 000 tons of NR annually, and this is likely to increase with the increasing proportion of radial-ply tyres.

PERFORMANCE REQUIREMENT OF PASSENGER CAR TYRE COMPOUNDS

Skid Resistance on Wet Roads

Over the past fifteen years an ever increasing emphasis has been placed on the skid resistance of passenger car tyres on wet road surfaces. In the United Kingdom particularly, the combined efforts of research on road surfaces and tyre design have practically doubled the hold between tyres and wet roads. In this improvement, new compounding, different road surfaces, and improved tread pattern have all played their part.

Intensive research into the frictional behaviour of rubbers during the last decade (SCHALLAMACH, 1953; GREENWOOD AND TABOR, 1958; BULGIN *et al.*, 1963; GROSCH, 1963; SABEY AND LUPTON, 1964; GROSCH AND MAYCOCK, 1966) to which N.R.P.R.A. has notably contributed, has shown that the skid behaviour of tread compounds of the same hardness depends on their visco-elastic properties under service conditions.

The hardness is usually maintained at the same level in practical compounds in order to obtain good wear resistance and to prevent other types of failure such as groove cracking. A good empirical relation then exists between the energy absorbed by the rubber in a rebound resilience test, which is proportional to [1-resilience], and the friction coefficient on wet surfaces, as shown in *Figure 8*. The measurements for the correlation obtained at N.R.P.R.A. were carried out at room temperature (GROSCH AND MAYCOCK, 1966) for both skid resistance and resilience. Measurements at the U.K. Road Research Laboratory (R.R.L.)

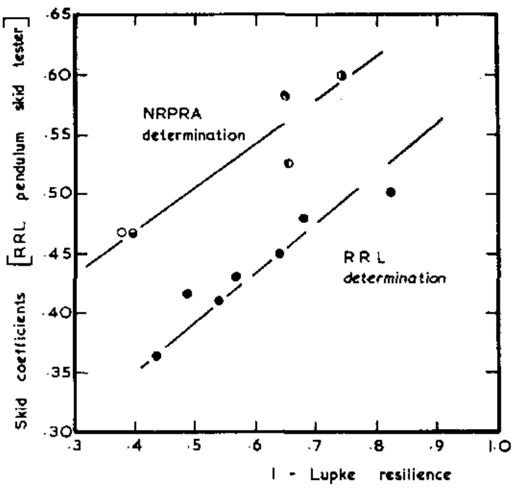

Figure 8. Skid resistance as function of the hysteresis as measured by [1-resilience].

(SABEY AND LUPTON, 1964), on the other hand, were made at 40°C and 0°C respectively to allow for the difference between the effective frequencies at which resilience and pendulum skid measurements are made.

Because of the high resilience of NR, tread compounds based on NR show a lower skid resistance than SBR compounds which have a low resilience. In modern tread compounds the resilience of SBR compounds has been further lowered by oil extension, as is apparent from *Figure 7(a)*. However, for reasons of improving wear and groove cracking resistance, some of the gain in wet skid resistance by oil extension is sometimes sacrificed by blending the SBR with the highly resilient BR. Thus, the typical composition demonstrated in *Figure 7(a)* has become established as an all-round compromise of good wet grip, coupled with a reasonable wear resistance, absence of groove cracking, and not least a sure supply of a rubber at low constant prices.

Recently, it has been shown that large quantities of extending oil can also be added to NR, either during the mixing cycle in the tyre factory as shown by work at N.R.P.R.A. (MOORE *et al.*, 1965; GROSCH *et al.*, 1966), which developed earlier work elsewhere (VAN AMERONGEN AND DE DECKER, 1954; GURNEY, 1961), or on the plantation in the latex stage as demonstrated at the R.R.I.M. (CHIN AND O'CONNELL, 1969). Unlike the oil extension of SBR, where the type of oil has a marked influence on many properties, particularly wear resistance, in NR only the resilience of the compound—which can be lowered drastically by choosing a high viscosity oil or reduced more moderately by choosing a lower viscosity oil—is similarly sensitive. Hence a range of skid resistant properties of NR tread compounds can be obtained by controlled oil extension.

Table 2 shows the skid ratings of five compounds relative to a commercial high skid resistance OESBR control. The tests were carried out with car tyres at the U.K. Road Research Laboratory (GROSCH AND MAYCOCK, 1966). These ratings are averages of tests on four different road surfaces, at ten different speeds, and under two different sliding conditions (completely blocked and partly blocked wheels). This averaging is possible because it has been shown that the relative skid rating of different compounds is insensitive to the above testing variables—this implying that comparative ratings determined under one set of conditions are valid under a wider set.

It is seen that while the wet skid rating of the unextended NR compound is inferior to that of the 'high μ' commercial tyre, oil extension of NR can raise the rating to be virtually the same as that of OESBR. The highly oil-extended compound (55:45) is actually better than the

TABLE 2. AVERAGE SKID RATINGS OF NR-BASED COMPOUNDS ON FOUR SURFACES, TWO TESTING METHODS AND TEN DIFFERENT SPEEDS IN RELATION TO A COMMERCIAL 'HIGH μ' COMPOUND (OESBR)

Surface	Skid rating
Commercial 'high μ compound'	100
NR + 50 HAF	84
OENR 67/33 + 50 HAF	95
OENR 55/45 + 50 HAF	108

TABLE 3. EFFECT OF BLENDING OENR AND OESBR WITH INCREASING AMOUNTS OF BR ON THE SKID RATINGS ON WET SURFACES

Surface	Rating	Surface	Rating
OESBR	100†	OENR	97
OESBR/BR 80/20	95	OENR/BR 80/20	93
OESBR/BR 60/40	88	OENR/BR 60/40	88

*In all cases, ⅓ of rubber was replaced by oil.
†Control.

control but this compound poses handling problems in the factory.

Blending OENR with BR improves groove cracking and wear resistance but reduces wet skid resistance, just as it does in OESBR *(Table 3)*. At the higher BR level the advantage of oil extension on skid resistance is substantially cancelled out both in OESBR and OENR.

Skid Resistance on Ice and Snow

In some countries, good wet skid resistance is the prime requirement; in others, particularly in the northern hemisphere or mountainous areas, good grip on snow and ice can be of the utmost importance during much of the year. Special winter tyres are now made to cope with this situation; they have a bold tread pattern to grip better in snow and steel studs are often used in the tread to give grip on icy roads.

The rubber in the tread in most cases is more or less the same as that for ordinary passenger car tyres *(cf. Figure 9* with *Figure 6)*. Some manufacturers in Scandinavia (where this problem is particularly pressing) depart considerably from this pattern, however, and use mainly NR or blends of NR and BR.

Recent work at N.R.P.R.A. (GROSCH, 1967b) and elsewhere (FRENCH AND PATTON, 1963) has demonstrated that NR compounds can offer much increased skid resistance on icy roads. *Figures 10* and *11* give the skid resistance of NR and SBR and of OENR and OESBR tread compounds at different track temperatures.

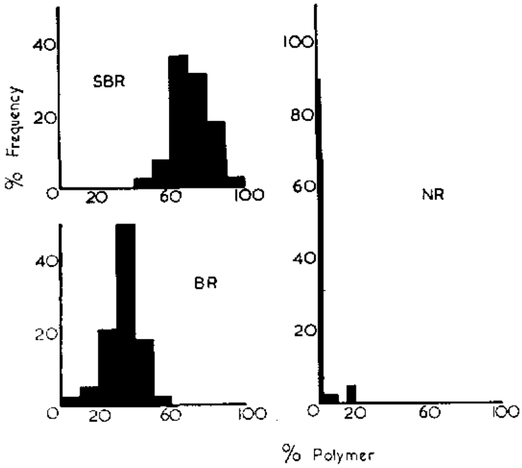

Figure 9. Rubber compositions of tread stocks for winter tyres.

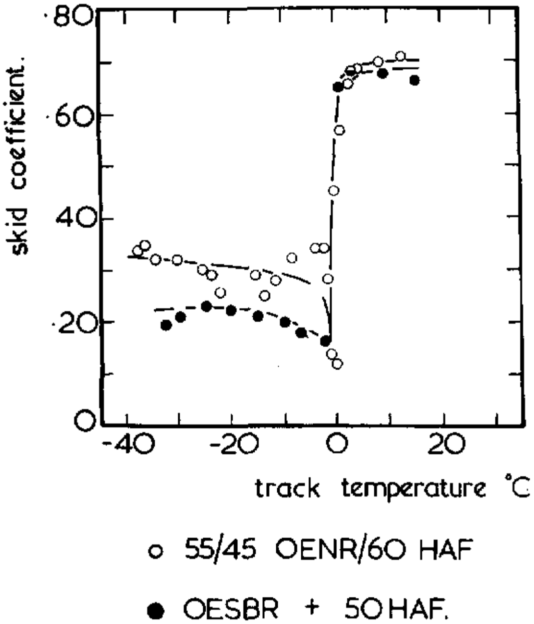

Figure 11. Skid resistance of oil-extended NR and oil-extended SBR tread compounds as function of the track temperature. 55/45 is the rubber/oil ratio.

These data were obtained in the laboratory using a pendulum skid tester, the sample temperature being kept 20°C above the track temperature to simulate winter driving con-

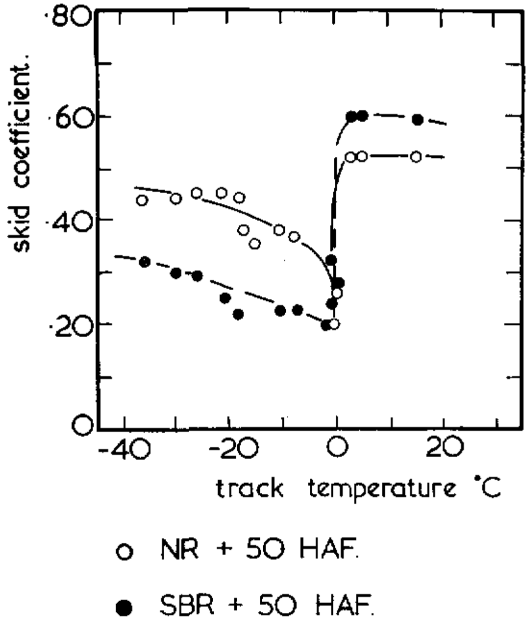

Figure 10. Skid resistance of NR and SBR at different track temperatures. Above 0°C, track is wet; below 0°C, it is icy.

ditions when the temperature of the tyre is also likely to be considerably higher than that of the road surface. Above 0°C the track is wet and SBR has better wet skid resistance than NR *(Figure 10)*. Below 0°C, however, the track is icy and a complete reversal of the compound ranking has taken place, NR having a much superior rating to SBR. In the case of OENR *(Figure 11)* its skid coefficient is similar to that of OESBR at room temperature but, again, is much superior on icy surfaces.

These laboratory findings have been confirmed in road trials with winter tyres in Sweden. The test tyres were fitted to the axle of a two-wheel trailer which was pulled behind a car *(Figure 12)*, the brakes were applied to the trailer wheels while the car was free rolling, and tow-bar pull, deceleration and skid path length were then measured. Skid coefficients and consequently skid ratings relative to a control compound obtained in this way on an icy road surface at ambient temperatures ranging be-

Figure 12. Experimental tyre testing trailer during skid trials in Sweden.

TABLE 4. SKID RATINGS ON SNOW-PACKED ROADS; OENR vs OESBR COMPOUNDS

Base polymer/ BR	25 mile/h		10 mile/h	
	Non-studded	Studded	Non-studded	Studded
OENR vs OESBR	110	120	131	112
OENR/BR (80/20) vs OESBR/BR (80/20)	118	111	138	115

tween −2 and −6°C are shown in *Table 4.* An OENR compound was compared with the corresponding OESBR compound, *i.e.*, oil levels and blend ratios 80/20 of base rubber to BR were the same. The results are clear-cut. At two different approach speeds and both for studded and non-studded tyres, the NR-based compounds are substantially superior to the SBR-based ones. This is so pronounced that the OENR compounds without studs show superior skid resistance to the studded OESBR compound *(Table 5.)* As shown in a second experiment, studding an OENR tyre improved the skid rating still further.

Oil extension increases the *wet* skid resistance of NR tread compounds; it actually lowers the skid resistance on *icy* surfaces. There are thus two choices open to manufacturers. If the tyre is meant to perform exclusively or predominantly on snowy and icy surfaces, unextended NR gives the best skid resistance. In many countries where the winter is neither long nor severe enough for these conditions to apply or where the salting of the major roads ensures that these are wet rather than icy, oil-extended NR offers

TABLE 5. EFFECT OF STUDS ON THE RELATIVE SKID RATING ON SNOW-PACKED ROADS

OESBR	Non-studded	100*
OESBR	Studded	121
OENR	Non-studded	131
OENR	Studded	135

[NR/BR ratio = 100/0] *Control

the better all-round skid performance. It is as good as a synthetic rubber on wet roads, but much superior on icy roads.

Wear of Passenger Tyre Treads

It is often stated boldly that SBR *tread compounds are superior to those based on* NR in wear resistance. However, the more-informed know that not only the absolute loss of tread rubber in a particular test but the comparative rating of different compounds in relation to a control depends on a large number of factors, of which the most important are the severity of the test, the ambient temperature, and the type of road surface, and that such a general statement is misleading.

Intensive research at the N.R.P.R.A. on the very complex phenomena of the wear process (GROSCH AND SCHALLAMACH, 1961) has culminated in the important and simplifying finding that changes in relative wear rating with ambient conditions, including temperature and wetness of the road, and with changes with severity of testing, are due to changes in the surface temperature of the tyre (GROSCH, 1967a). *If the relative wear rating is expressed as function of the tyre surface temperature, results from a wide range of testing conditions fall on a single curve, the shape of which depends only on the compounds tested,* as shown by *Curve A* in *Figure 13* for a NR compound in relation to SBR. Both compounds were oil-extended to the same extent. The curve shows that below a tyre surface temperature of 35°C a NR compound wears better than SBR, while above 35°C the reverse is the case. Similar curves are obtained if non-extended NR is compared with non-extended SBR except that at tyre surface temperatures below 35°C NR becomes more rapidly better than SBR. If oil-extended NR is blended with a small proportion of BR and the same is done with oil-extended SBR, a wear comparison yields *Curve B* in *Figure 13.* Again, the NR compound shows better wear than SBR at low tyre surface temperatures, while at high tyre surface temperatures the OESBR/BR blend is the better one. The curve, however, is flatter, indicating a less pronounced dependence of the wear rating on testing and hence on service conditions. The temperature at which the two compounds show equal wear has been shifted from 35 to 44°C, indicating that the range of conditions under which the OENR/BR blend is superior to the SBR one has been substantially widened.

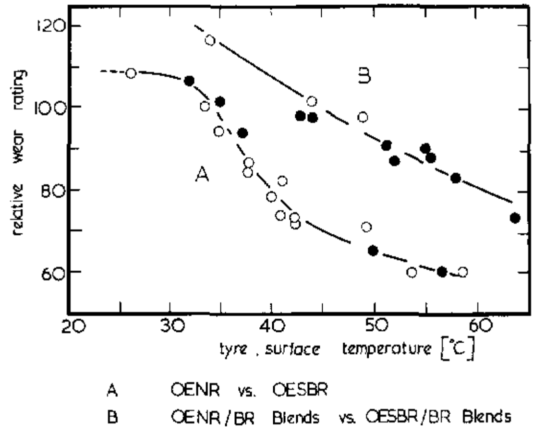

Figure 13. Relative wear ratings obtained over a wide range of testing conditions as function of the tyre surface temperature. Full circles—accelerated trailer tests. Open circles—car tests. (A) OENR vs OESBR. (B) OENR/BR vs OESBR.

This rationalisation in the description of wear testing results allows a prediction of the relative wear rating under a variety of service conditions simply from a knowledge of the tyre surface temperature (t_s) which prevails in service. *Figure 14* shows the t_s values obtained on the N.R.P.R.A. test car over a period of 13 months, during which the car was used in high speed, long distance driving, a condition commonly met in commercial traveller and comparable driving in the U.K. The tyre surface temperature compositely reflects driving habits, ambient temperature, and wetness of the road. A survey carried out on cars commuting to and from place of work revealed a similar curve but the absolute values were lower as shown by the dotted line in *Figure 14.*

Clearly, then, it is patently incorrect to advance the general statement that 'SBR rubber

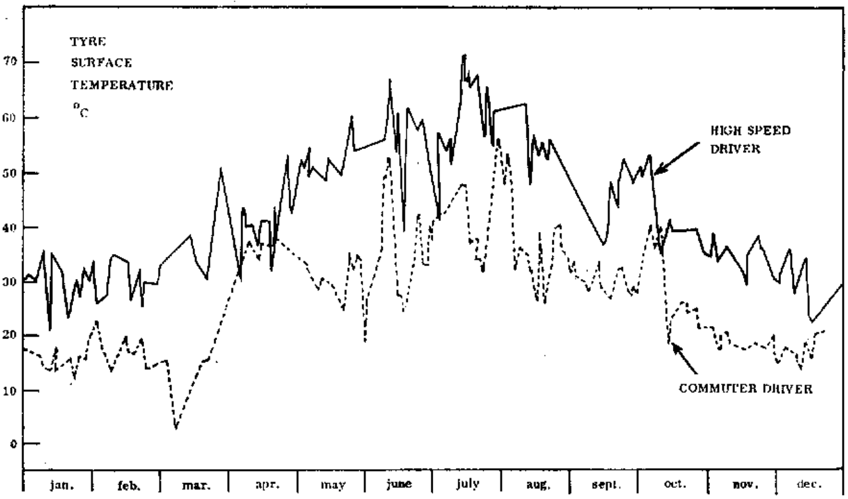

Figure 14. Tyre surface temperatures of passenger cars for fast and slow driving throughout the year in U.K.

tread compounds wear better than natural rubber based ones'. The fact is that there are some conditions where this is the case and there are other conditions where it is certainly not. These conditions are well defined by the tyre surface temperature during service. As another example of Nature's perversity, SBR compounds tend to be better *in this respect* in the tropical NR producing countries, whereas NR compounds have the advantage for a good part of the year in latitudes north of 40°N, where much SBR is produced.

Winter tyres provide the extreme example of NR's value in treads since superior skid performance and superior wear resistance are combined together. There are actually three compounding possibilities to achieve the best compromise for each of three different types of winter tyre use. For use on icy and snowy surfaces alone, unextended NR offers the best performance—it is better than OENR and much superior to OESBR in wear and skid properties. If wet roads have to be reckoned with, OENR offers very good skid resistance and wear resistance on both wet and icy roads. If it is necessary to cater also for a wider range of temperature conditions, as may happen in the U.S.A. or in Central Europe where winter tyres are often used well into the summer or traverse a range of climatic conditions from ice and snow to very warm weather, blending of OENR with BR will ensure the best wear resistance over *all these conditions*, a good skid resistance on wet surfaces and still a superior skid performance on ice and snow, compared with OESBR/BR blends.

It is still common practice for some of the major tyre manufacturing companies to test the wear resistance of their winter tyres in Texas under conditions giving high tyre surface temperatures. It is now clear that these hot conditions are not only inappropriate but that they also give misleading results and are likely to lead to quite erroneous conclusions as to the relative merits of NR and SBR compounds under the conditions prevailing in actual service.

Even in warm climates there are service conditions which result in low tyre surface temperatures, *e.g.*, private car users who employ their cars for short journeys to and from work, family outings, etc. (the user covered by the t_s distribution given by the dotted line in *Figure 14*).

Groove Cracking Resistance

No tyre should fail in any other way than by wear. However, other failure processes are encountered of which groove cracking is a key example. As the name implies, cracks appear at the bottom of the pattern grooves and these grow in number and in length during running of the tyre until they join to form one continuous crack round the circumference. The phenomenon is always said to be more common with NR tread compounds than with SBR although little systematic study has been reported in the literature (SNYDER, 1965).

In N.R.P.R.A. experiments (GROSCH, 1969), eight different tyre compounds were cured to car tyre carcasses (with the co-operation of Pirelli, Milan).

Each tyre was run for 10 000 miles at an average speed of 80 miles per hour on the Italian Autostrada in summer at high ambient temperatures. Every 300 miles the growth of single cracks and the total sum of their lengths was studied. In all cases the cracks grew linearly with distance travelled, and from the measurements on a large number of single cracks, the best straight lines were calculated by means of a computer. The results for five of the compounds measured in the outside grooves are shown in *Figure 15*. Cracks in the OENR compound appeared first, but blending with BR progressively delayed the onset and slowed down the rate of growth. The OESBR/BR compound was best as far as the onset of cracking was concerned but had the fastest rate of growth once cracks had appeared (lines on the right of the *Figure*).

Groove cracking is basically a fatigue phenomenon which occurs because the rubber in the

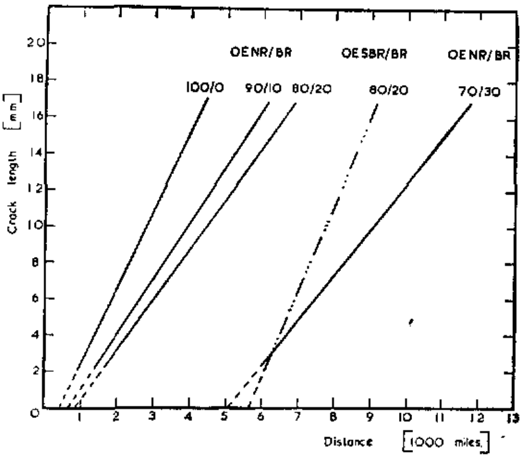

Figure 15. Groove crack growth of different tread compounds as function of distance travelled.

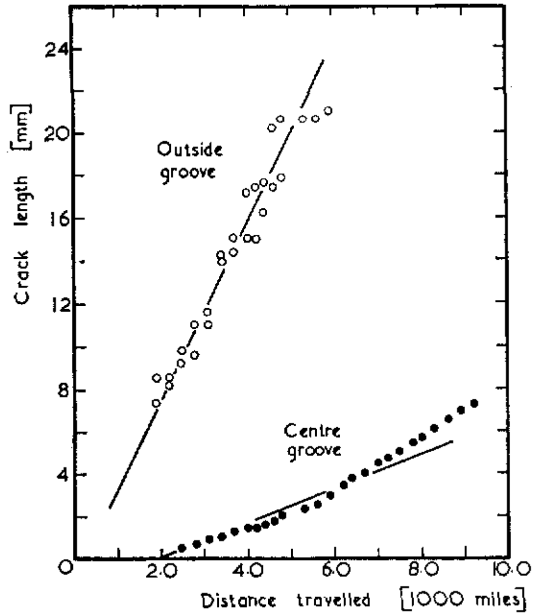

Figure 16. Crack development against distance travelled.

groove undergoes a stress–strain cycle every time it passes through the contact area. Cracks are initiated at microscopic flaws unavoidably introduced during the making of the tyre, and their growth is promoted by chemical changes occurring in service as reflected by observations that cracks appear much earlier and grow much faster in the outside grooves of the tyre than in the centre ones *(Figure 16)*. As the maximum strains are larger in the centre than in the outside grooves exactly the opposite would have been expected if physical processes alone were responsible. However, the average groove temperature was found in the experiments described to be at least 10°C higher in the outside grooves than in the centre grooves. Groove cracking is thus very temperature-sensitive, and laboratory experiments on fatigue resistance have clearly shown that this is primarily associated with changes in the vulcanisate structure which proceed much more rapidly at higher temperatures (CUNNEEN AND RUSSELL, 1969). At the beginning of the test, the network cross-links were polysulphidic but at

TABLE 6. FATIGUE LIFE (1000 CYCLES) OF AN OENR AND OENR/BR COMPOUND UNDER VARIOUS TESTING CONDITIONS

Sample	Temperature °C	W = 3.1 kg/cm²		W = 4.7 kg/cm²		Atmosphere
		OENR	OENR/BR 70/30	OENR	OENR/BR 70/30	
Unmatured	60	1 337	4 608	556	507	N_2
	90	830	2 539	379	129	
Matured*	60	398	571	250	298	
	90	304	561	178	244	
Unmatured	60	605	2 147			O_2
	90	439	974			
Matured	60	587	1 544			
	90	274	465			

* Matured means that the sample has been kept for 120 hours in an inert atmosphere at 100°C before testing commenced.

the end, some 25% had changed to monosulphidic cross-links in the centre grooves and no less than one-half in the outside grooves.

Tread compounds in ring form kept in an inert atmosphere at temperatures and times comparable with the testing conditions of the tyres and then cycled until break had fatigue lives of only $\frac{1}{3}$ of those of similar rings not heat-treated in this way *(Table 6)*. Cycled at two different strain energy values (W), the differences between heat-matured and unmatured rings are pronounced in both cases. However, only at the low strain energy value is the OENR/BR blend much superior to the OENR compound; at the higher energy value, OENR is actually slightly better than the blend. Differences between fatigue lives of rings cycled in N_2 and air are again pronounced but the above reversal in order is not affected.

The conclusions to be drawn from these laboratory experiments in conjunction with the groove cracking trials are:

Because of the steep temperature dependence of the chemical reactions which influence groove cracking (and ring fatigue measurements), even a small drop in the high temperature conditions encountered in Italy are likely to increase the groove cracking resistance of the OENR compounds tested beyond the normal life span of the tyre. In any case, the blending of OENR with BR increases the groove cracking resistance under all conditions *provided* the strain energies in the groove are below a critical value. The latter can be achieved by tyre design.

Sidewall Compounds

Very little NR is found in black sidewalls of *cross-ply* passenger car tyres as performance requirements are not particularly critical. The compound has to protect the carcass from weather influences, from gross damage such as kerb chafing or penetration of sharp objects, and it has to have a good flex-cracking resistance. Compounds, similar to tread compounds, can be used and this simplifies the production process.

In *radial-ply* tyres the performance requirements are greater because the carcass is much thinner and deflections of the sidewalls are larger when passing into the region of the contact area. Strains are also larger during steering when the sidewalls transmit the side forces acting on the tyre to the car. At large strain energies, the fatigue life of a NR compound is superior to SBR or indeed to blends of NR and synthetic rubbers, as shown in *Table 6* for OENR and OENR/BR blends, and hence the use of NR is preferred. The sidewalls of radial-ply tyres are also more prone to chafing and other gross damage because of the larger bulge produced in the contact area and here the high tensile strength of NR compounds is also advantageous.

RUBBER COMPOUNDS IN TRUCK TYRES

Because of the very diverse service conditions ranging from local delivery vans to heavy quarry trucks, the composition of truck tyre compounds differs more than for car tyres. *Figure 17* shows a rubber analysis of treads for small truck tyres from the U.S.A. and Western Europe, of 6 or 8 ply rating, 6.50 — 7.50 with either 16" or 20" rim diameters. In these, the tread compounds differ little from passenger car compounds, consisting essentially of SBR/BR blends which are moderately oil-extended. Some isolated instances show a small proportion of NR. In other parts of the world, notably in regions of colder climate, the NR content is often larger. Sidewall compounds, too, differ little from those in passenger car

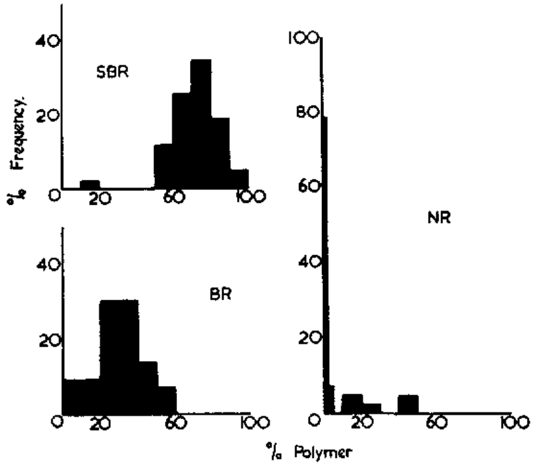

Figure 17. Rubber compositions of tread stocks for small truck tyres.

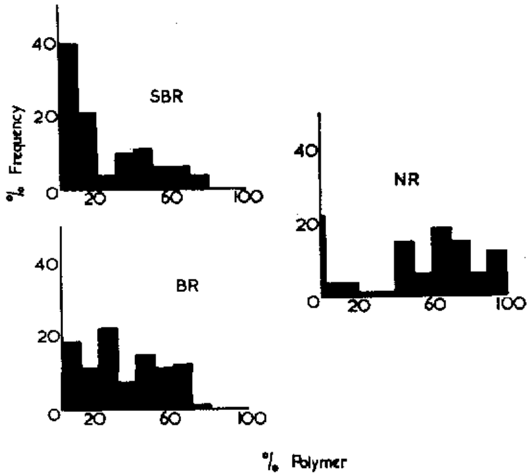

Figure 18. Rubber compositions of tread stocks in large truck tyres.

tyres, but the carcass tends to have a slightly higher proportion of NR.

Figure 18 shows a rubber analysis of large truck tyre treads. In this case, all three of the commonly used rubbers are found in the tread. The distribution of NR shows broadly the outline of a normal distribution with a shallow maximum at about 65% content. If some NR is replaced it is usually by a proportion of BR, and in cases where no NR is employed the compound then consists of a SBR/BR blend. The general trend, however, is towards triple blends of NR, SBR and BR. In 1964–66, 20% were of such composition in the samples examined whereas in 1966–68 the proportion was 53%.

Sidewall compounds again consist mainly of SBR/BR blends. In carcass compounds, however, a large proportion consists of NR in all cases, as can be seen in *Figure 19*. The distribution is normal for NR with a maximum near the 100% level. SBR is used in small quantities and BR is found in isolated cases. The average carcass compound contains about 85% NR and 15% SBR, with black levels similar to those in passenger treads.

Because of the diversity in composition of truck tyres it is difficult to estimate precisely the total NR requirements. A rough estimate, based on the world production of trucks and

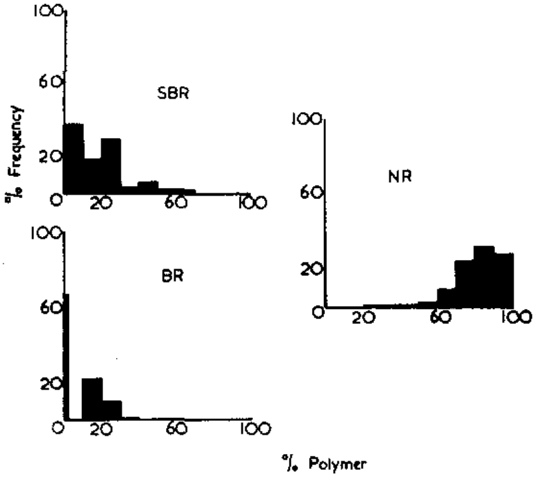

Figure 19. Rubber compositions of carcass stocks for large truck tyres.

the average amount of rubber required per truck given previously, indicated that some 650 000 tons are NR required by the truck tyre industry annually, assuming two-thirds of the total rubber in the tyres is NR *(cf. Figure 4)*.

PERFORMANCE REQUIREMENT OF TRUCK TYRE COMPOUNDS

The dominating quality called for in a truck tyre is a long life under a great variety of operating conditions. High wear resistance coupled with high groove cracking resistance is of major importance. Additionally, heat build-up, with possible failure of the tyre by blow-out or tread separation, intrudes as a serious problem particularly with the large sizes.

Wear of Truck Tyres

Little systematic study of wear of truck tyres is reported in the literature, and the findings reported here are from a current N.R.P.R.A. investigation into the behaviour of oil-extended NR compounds for small truck tyre treads, where OESBR/BR is now much used. A trailer similar to that for passenger tyre wear trials was used except that the tyre size was increased to 7.50–16, 8 ply, with a correspondingly larger load. *Figure 20* shows the relative wear rating of OENR vs OESBR (△) and OENR/BR vs OESBR/BR (○) as a function of the tyre surface temperature. Two rubber/oil ratios, 80/20 and 67/33, were tested, the level of BR (where added) was kept constant at 20 parts to 80 base rubber.

The general behaviour is similar to that of passenger tyres in that at low tyre surface temperatures the NR compounds wear better than the SBR controls while at high tyre surface temperatures the reverse is the case. The effect of oil level is small, again as with passenger car tyres. However, the effect of BR is not as pronounced and a single curve can be drawn through all the points. The scatter is not unreasonable having regard to the compounding and testing variables involved. Data obtained on a lorry (open symbols) and the trailer (full symbols) give equivalent results. The tyre surface temperature at which the OENR compounds are equal to OESBR is 44°C, similar to that for passenger car tyre blends but appreciably higher than that for the OENR/OESBR tyre treads without BR. Whether on average a small truck should have tyres with NR or SBR compounds depends on whether the driving habits produce a higher or lower tyre surface temperature. *Figure 21* shows the

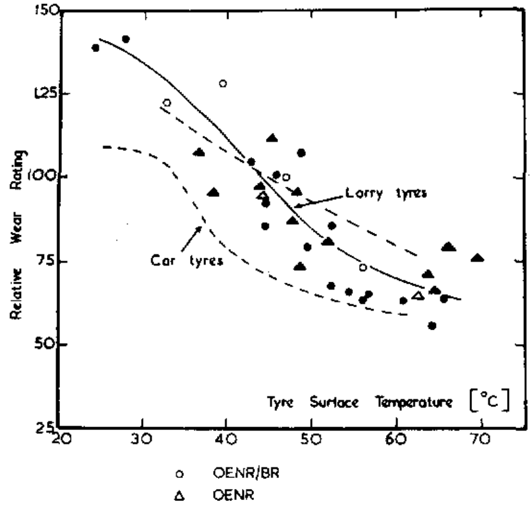

Figure 20. Wear ratings of oil-extended NR in relation to corresponding OESBR tread compounds on small truck tyres (7.50–16) as function of the tyre surface temperatures.

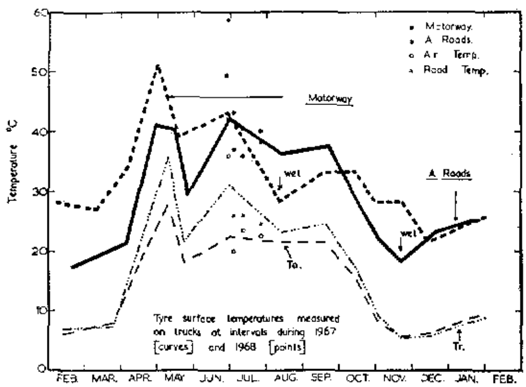

Figure 21. Average tyre surface temperatures of trucks in service in U.K. at different seasons of the year.

average tyre surface temperatures measured at intervals for a large variety of trucks operating over a very wide range of conditions in the U.K. throughout 1967. It is seen that the temperatures are lower than those of passenger car tyres. The conclusion is that OENR compounds have a superior wear resistance to OESBR ones over a wide range of conditions, which are typical of usage in many other parts of the world.

The addition of BR does not appear to improve the wear of NR relative to SBR as it does in passenger tyres. Experimental comparisons of a NR/BR blend with NR and of OENR/BR with OENR have shown that at low tyre surface temperatures the presence of BR does not improve the wear of NR-based compounds, but a progressive improvement appears as the tyre surface temperature rises.

Groove Cracking of Truck Tyre Compounds

Because of the much longer life of truck tyres (100 000 miles is not uncommon), high groove cracking resistance is of the utmost importance. It was demonstrated on car tyres that the addition of BR to a NR compound enhances groove cracking resistance. In the car tyre experiments, cracks appear to be initiated almost entirely at flaws. In truck tyres, an additional mechanism comes often into play. Because of the higher ground pressures, stones tend to get wedged into the groove to produce small cuts which subsequently give rise to cracking. The appearance of cracks under these conditions is then random and independent of the compound, so that their growth rate alone will determine the groove cracking resistance. Under these conditions NR-based compounds outperform SBR compounds, because once a crack has appeared, it grows much more rapidly in SBR compounds than in NR (see *Figure 15*).

Heat Build-up in Truck Tyres

Excessive heat build-up in tyres can lead to spectacular failure of the tyre—blow-out or tread separation. Such heat build-up depends on a number of external factors, such as load on the tyre, inflation pressure, ambient conditions, speed and the duration for which the speed is maintained, and the manufacturer quite rightly is at pains to specify the operating conditions for which his tyres are suitable. Naturally, there has to be (or should be) a substantial margin of safety and this now calls for compounding for high quality in this respect.

Heat build-up in the shoulders of large truck tyres, where it is most serious, has recently been studied by Kainradl (KAINRADL *et al.*, 1966), who investigated the effect of different tread and carcass compounds and the effect of the cords on the equilibrium temperature in the shoulder of these tyres. Some of his results have been summarised in the *Tables 7(a)* and *7(b)*. These bring out the important contribution which the tread makes to the total heat build-up in the shoulder. In *Table 7(a)* NR is compared with two SBR compounds of different black content. In the latter the equilibrium temperature is markedly raised from 80 to 105°C. In *Table 7(b)* NR is compared with a 100% SBR and a SBR/BR blend. Although the latter compound is decidedly better than SBR alone, NR still maintains its marked superiority. The high temperature in the shoulder does not by itself cause failure of a tyre, but the continuous running at high temperature causes chemical changes in the tread and carcass compounds which affect fatigue life as previously revealed.

Here again, for highest quality, the choice is a NR compound blended with BR in order to raise the groove cracking resistance.

TABLE 7(A). HEAT BUILD-UP IN TYRES

Component		Polymer	Black	Contribution to heat build-up in shoulder of tyre, °C		
				I	II	III
Tread compound	I	100 NR	45 HMF	34.6		
	II	40 SBR 1500 60 SBR 1712	45 HAF		60.2	
	III	40 SBR 1500 60 SBR 1712	60 HAF			57.8
Carcass	inner	100 NR	30 SRF	←27.8→		
	outer	100 NR	35 FEF			
Cord				←19.0→		
Total heat build-up			Calculated	81.4	107.0	104.6
			Measured	80	105	105

TABLE 7(B). HEAT BUILD-UP IN TYRES

Component		Polymer	Black	Contribution to heat build-up in shoulder of tyre, °C		
				IV	V	VI
Tread compound	IV	100 NR	55 HAF	26.6		
	V	40 BR + 60 SBR 1712	65 ISAF		53.2	
	VI	100 SBR 1500	70 HAF			69.3
Carcass	inner	100 NR	30 SRF	←34.6→		
	outer	100 NR	45 HAF			
Cord				←19.0→		
Total heat build-up			Calculated	80	106.6	122.7
			Measured	84	108	126

Rib Tearing

When heavily loaded truck tyres are run over uneven surfaces in off-the-road uses or over the kerb stones a large part of the load is momentarily transferred to a single rib of the tread pattern and this produces very large stresses which act to tear out the rib.

Figure 22 shows the fatigue life of samples in ring form as a function of the maximum strain in cycles to break. At low strain energies the OENR/BR blends are much better than the OENR compound(just as SBR is better than NR under these conditions) (LAKE AND LINDLEY, 1964 and 1966), at high strains relevant to rib tearing the reverse is the case. Therefore, if a good groove cracking resistance has to be coupled with a high rib tearing resistance, the proportion of BR has to be kept as low as is

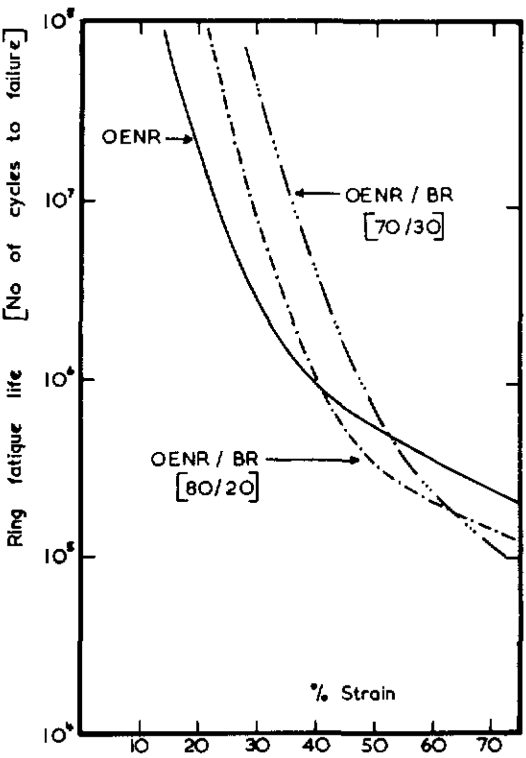

Figure 22. Fatigue life as function of strain.

compatible with satisfactory groove cracking resistance.

PERFORMANCE REQUIREMENTS OF OFF-THE-ROAD AND AIRCRAFT TYRES

Very little need be said about agricultural tyres. Their performance requirements are minimal, subject neither to high speeds nor ground pressures; they usually operate in soft, non-abrasive terrain. Therefore, they can be compounded primarily on a basis of cost.

On the other hand, large earthmover tyres, extensively used in civil engineering projects, operate under arduous conditions. They are dimensioned generously to keep ground pressures reasonably low in order to be able to operate with large loads on soft terrain. This means that the tyres are very thick and since earthmover vehicles often operate at considerable speeds, heat build-up has to be rigorously controlled and here the use of NR is advantageous.

Further, although ground pressures are low if the load is uniformly distributed, they can become very high in rough and rocky terrain when the load may be concentrated on one protruding stone. High cutting resistance is therefore necessary, and the unmatched tensile strength of NR is a determining quality in this regard.

One of the fastest growing industries since World War II has been air transport. *Figure 23* shows the number of take-offs and landings made by commercial aircraft in the U.K. during the years 1952–66 and also the number of passengers carried to take account of the increase in size of aeroplanes. The almost exponential increase in air traffic generates a similar increase in demand for aeroplane tyres and especially of tread rubber since these tyres are retreaded a number of times. At present, aeroplane tyres are made wholly of NR, but efforts at partial replacement by other rubbers (particularly BR) are under way by tyre manufacturers. Here, however, it is supremely important to take full account of performance requirements, for minor economics in raw material cost are irrelevant to the vital function that these tyres have to perform—and which is becoming steadily more demanding. Technical objectivity can be expected to have full reign in this area.

CONCLUSIONS

The tremendous growth in vehicular traffic and the demand this has created for tyres has generated a total requirement for rubber which natural rubber producers cannot satisfy. Large-scale SR production has been inevitable, and so has been the increasing use of SR in numerous applications, including tyres. The sheer necessity of using SR has been a spur to technical innovation and, although developments in tyre construction, non-rubber carcass materials (textiles and steel), and in carbon blacks have played the major part in the great improvement in tyre performance since the second world war, developments in SR have also made a notable contribution. Simply because SR has had to be used, emphasis has been given to the

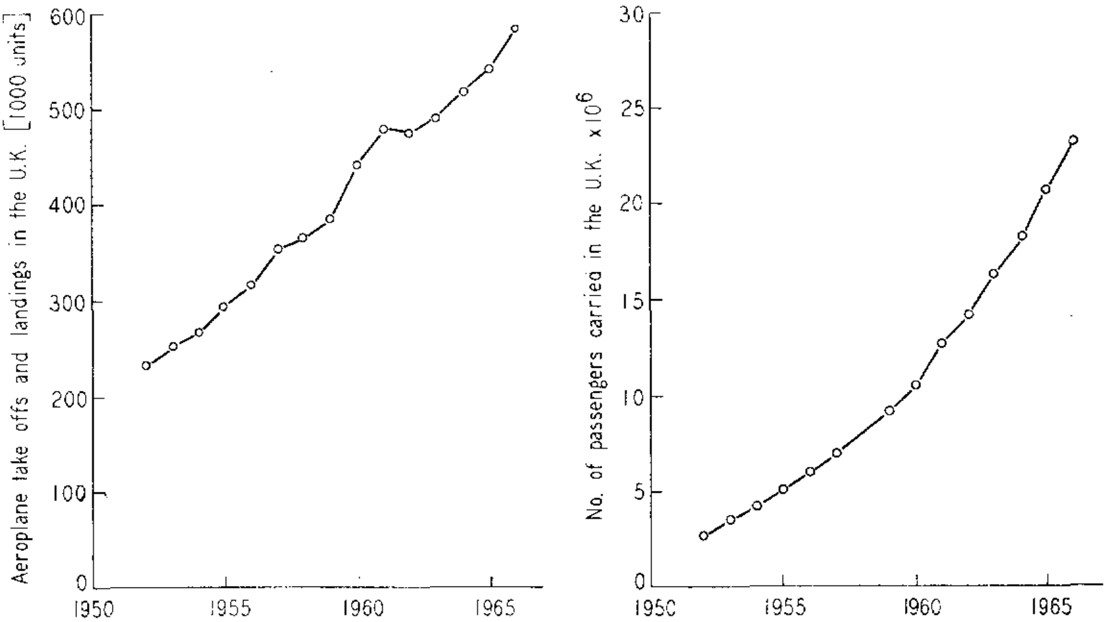

Figure 23. Aeroplane take-offs and landings in the U.K., and number of passengers carried.

particular advantages that it offers and compounding research and application world-wide have been concentrated on exploiting these. Prime examples of better performance thus realised are better skidding resistance on wet roads, better wear at high temperatures, and better resistance to groove cracking.

However, as this paper reveals, compounding developments with NR enable it no less to keep pace with the modern performance requirements in the whole range of tyres. In respect of skid resistance on ice and wet roads, wear at low or moderate temperatures, and groove cracking resistance, practical NR compounds have been devised which match or better SR ones. This, together with recognised merits of NR in respect of low heat build-up, high tensile and tear strength, high flex resistance, superior cord adhesion and green strength properties, makes NR pre-eminent as the most versatile and safe tyre rubber.

Of course NR is not able completely to replace SR on quality grounds in tyres. In particular, often the best use of NR is made in blends with BR, and it appears certain that these and comparable blends will be increasingly valuable. But the view sometimes voiced that any counter-substitution of SR by NR is now *technically* impossible, is not in accord with the scientific facts. Strong and even compelling reasons against such counter-substitution exist (cost, commercial considerations of availability, captive market arrangements, economic nationalism, factory operations, etc.) but not *technical* ones. This contention is reinforced when one remembers that SR has secured its largest outlets in the less arduous and critical tyre uses. Surely, if NR retains its use in whole or in part in the 'heavy duty' applications—aeroplane, earthmover, the bigger truck and bus tyres, and even in radial compared with cross-ply car tyres—it does not make sense to maintain that on *technical* grounds alone, NR cannot be used in greater proportion in some of the lesser demanding sectors.

Although NR producers have reason to be optimistic—more NR is used in tyres today than ever before—it is necessary to stress that this gives no cause for complacency. The pressures which have forced SR substitution so far are stronger today than ever, and purposeful counteraction will be needed by NR interests to consolidate their position in the tyre field and to restrict further substitution to that dictated by supply availability. This counteraction should take three forms. First, ample supplies of NR have to be made available, for today even temporary and minor shortages create an incentive for SR producers to venture over the capital investment barrier. Secondly, recognising that vigorous effort to improve the properties of SR will continue, research must aim at extending the performance limits of NR compounds—particularly in applications where they are entrenched today (carcass compounds and tread compounds in big tyres). Improvements here will undoubtedly depend on a better insight into the nature of the relevant processes and more definitive correction of these than is presently possible. Thirdly, it should be appreciated that performance quality by itself is rarely a decisive acceptance criterion by the consumer—other technical and commercial factors bear heavily on the scales. Thus the value of new presentation NR within the SMR scheme and of the raw rubber quality improvements which can stem from this, coupled with all the factory advantages of easier handling and processing and greater consistency, cannot be over-emphasised. The message in Mr. Bekema's paper to this Conference has to be taken to heart and should be seen as complementary to the substance of this paper. Taken together, the breadth and depth of the improvement in presentation and in end-product quality, of which the work on tyre compounds forms one notable example, will assuredly add to the competitive power of NR.

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