Correlation between Road Wear of Tires and Computer Road Wear Simulation using Laboratory Abrasion Data.

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Abstract
Any laboratory abrasion method has to take account of the well known fact that the ranking and wear rating of tire tread compounds depend strongly on the testing conditions.
The severity of road tests, particularly when carried out with customer vehicles is not well defined. Any result obtained in this way is a spot reading which contains no information about its general validity.
A road wear computer program was designed which is able to simulate a very wide range of road wear testing severities and the effect which they have on achievable mileage and wear rating of tread compounds. The program uses the laboratory abrasion test system designed to be used with the Laboratory Abrasion Tester designated as LAT 100.
It is shown that good agreement is obtained with actual road test results not only for the rating of compounds but also for the achieved mileages.

Introduction

The road testing of tire tread compounds for wear is an expensive operation in compound development. Most tests have only a very limited information content; they are spot readings without any indication of the scope of its validity or application to other operating conditions. With the development of the laboratory abrasion testing system LAT 100 by VMI Holland BV it is possible to determine the wear resistance of a tread compound over a wide range of severities, yielding both absolute abrasion data as well as the behavior relative to a known reference compound at a small fraction of the cost of a road test. The system been described previously (1). It will be reviewed briefly here in order to establish the basis for the main purpose of the paper which is to show that it is possible to obtain not only valid tread wear ratings but also tire mileages using laboratory abrasion data in a road test simulation program. The main part of the paper discusses the tire wear mechanism in road use and identifies the main variables which contribute to tire wear. If the boundary conditions of the road test are chosen correctly it is possible not only to simulate passenger - but also truck tire tests. Simulation test ratings from laboratory abrasion measurements compare well with actual road test results obtained during a Brite Euram Program of the European Union to assist small tire retreaders to ensure and improve the quality of their products.

The laboratory testing method.

Figure 1 shows a diagrammatic view of the apparatus employed and figure 2 shows a picture of the LAT 100 abrasion apparatus. The rubber sample wheel runs under a set slip angle and

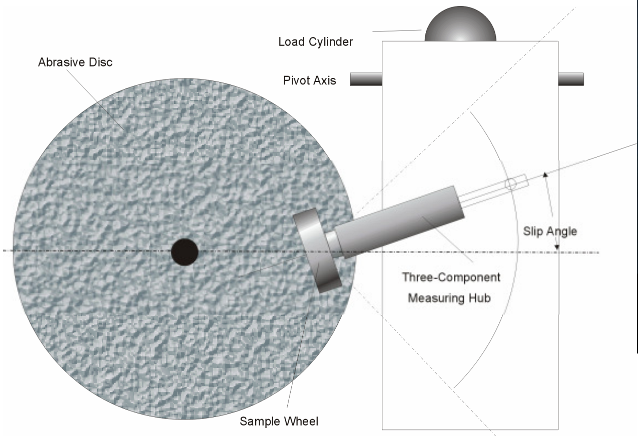


Figure 1: Diagrammatic Arrangment of Testing Apparatus


figure2: The laboratory traction- and abrasion tester LAT 100

load on the flat side of an abrasive disk at a given speed. Slip angle, load and speed can be varied over a wide range. The abrasive disks used are made of high grade Alumina, with different grain size. A mixture of magnesium oxide powder and Alumina (grain size 120) is fed between track and sample to avoid smearing of the sample due to thermal-oxidative degradation of the rubber during the abrasion process (2, 3). During the experiment, the side force generated on the test wheel by the slip angle is monitored.

In order to be able to cover a wide range of experimental conditions which are necessary to reflect the complex abrasion behaviour of compounds, an experimental design is required. The one employed has been worked out on two basic conclusions that have emerged from extensive abrasion research:

a. Abrasion is a function of the energy dissipation in the contact area of the slipping sample wheel.

This can be expressed mathematically by

$$A = A_{vo} \cdot \left\{ \frac{U}{U_{vo}} \right\}^n \qquad (1)$$

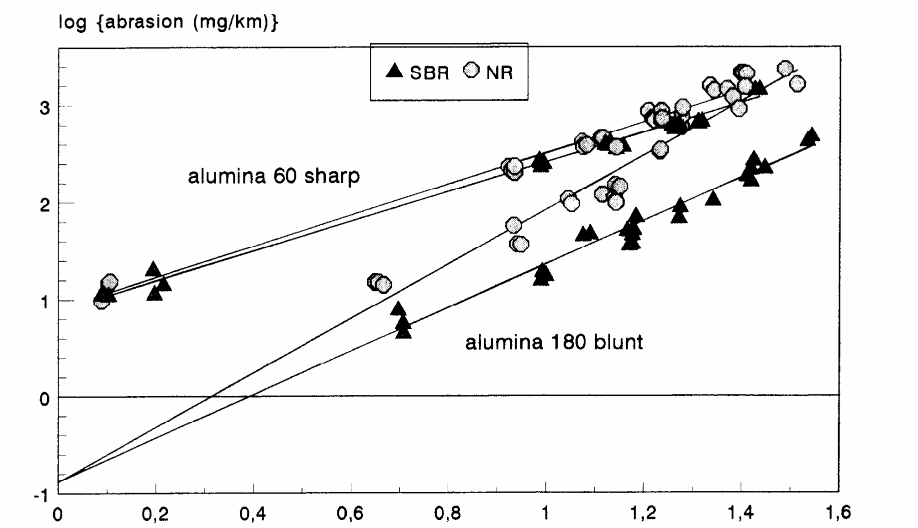
where A_{vo} is the abradability (abrasion loss/unit energy dissipation) of the compound at the reference energy U_{vo} (in the present case 1 kJ/km). and at the experimentally set speed. The power index depends on the tread compound and the sharpness of the abrasive disk.

The energy dissipation U in a slipping wheel is given by (4)

$$U = F \cdot \sin\alpha \text{ (kJ/km)} \qquad (2)$$

Since the side force F at a given slip angle and load is measured directly in the present set up the energy dissipation is known. Plotting the log (abrasion loss per km) as function of the log (energy dissipation), obtained by different settings of slip angle and load always gives straight line graphs as shown in figure 3. The slopes of these lines (power index n of equation (2))

Figure 3: Log Abrasion Loss vs log Energy Dissipation on Two Surfaces of Different Sharpness: NR vs SBR Tread Speed: 19 km/h



depend on the rubber compound and the sharpness of the abrasive track. This can result in cross-over between the ranking of compounds.

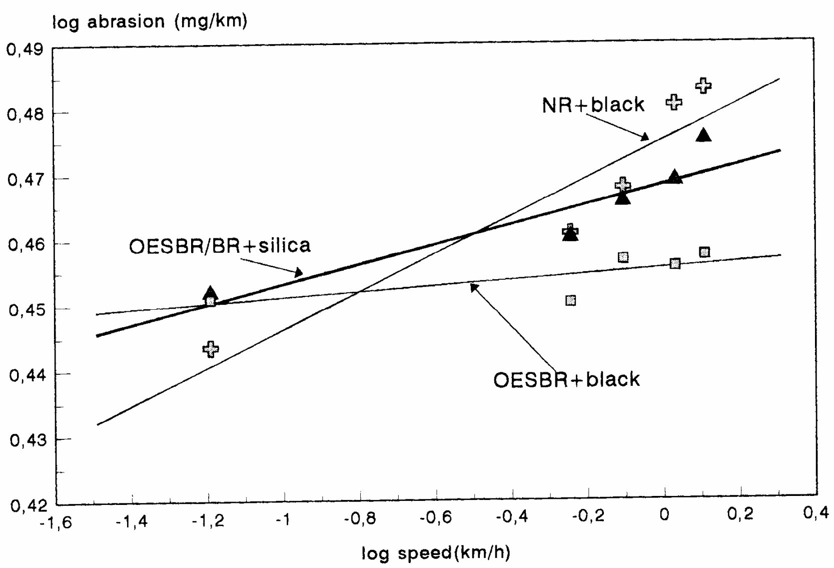
b. The abrasion at a given energy dissipation (set slip angle and load) depends on the speed of the abrasive disk in the contact area as shown in figure 4.

Again straight line graphs are obtained when plotting log (abrasion) against log (speed). This behaviour can be described by

$$A = A_{Uo} \cdot \left\{ \frac{v}{v_{uo}} \right\}^m \qquad (3)$$

where v= forward speed in the contact area, A_{Uo} is the abradability at the reference speed v_{Uo} (in the present case 1 km/h) and the experimentally set energy dissipation level (slip angle and

Figure 4: Log abrasion vs log (forward speed) of three tread compounds; corundum 60; slip angle 15°; Load: 57 N



load). These lines, too, show cross over effects, indicating that compounds can reverse their ranking with speed at a constant energy dissipation as shown in figure 4 for three tread compounds based on different rubbers and fillers.

These equations can be combined on a linear basis if logarithmic quantities, as indicated by square brackets, are used

$$[A] = a + b_1[U] + b_2[v] + b_3[U][v] \qquad (4)$$

where $[A]$= log (abrasion), $[U]$ = log(energy) and $[v]$ = log(speed)

The product term of $[U][v]$ allows for an interaction between energy and speed on abrasion, which can develop because both change the surface temperature of the sample in the contact area when the energy dissipation or the speed are changed. This has obviously a strong effect on abrasion (5).

In order to evaluate the four coefficients of equation 4 at least four different testing conditions are required, two different energy settings i.e. slip angle and/or load and two speed settings, both on a logarithmic scale. Because of the inherent variation of abrasion, repeat measurements are necessary and more than four testing conditions in the testing scheme are desirable. The scheme uses log energy- and log speed values within a range from 0 to 1.6 for both variables. This corresponds to a factor of about 40 for speed and energy and because of the non linear dependence of abrasion on these variables a volume loss range of about 1 to

2000. The extreme points of the range are not practicable for actual experimental conditions. The setting for highest energy and speed produces an abrasion volume loss which is hardly ever produced in tire wear although it can be realised. The lowest setting produces very low abrasion loss rates. It takes too long a time to obtain a reasonable weight loss of the sample. Hence some extrapolation is necessary to cover all possible testing conditions within that energy and speed range.

Using the coefficients obtained by a multiple regression analysis from the abrasion data of the experimental design, abrasion losses and compound ratings are calculated and presented in tabular form to cover the above range of energies and speeds. These are best estimates obtained from the limited number of the selected testing conditions. The more repeat measurements and the more testing conditions are used the better the estimates. A typical set of ratings for four compounds for which also road test ratings were available is shown in table I (3). It is seen that compound 1 is poorer than the reference over almost the whole range of

Table I: Ratings of Four Compounds as Function of log Energy and log Speed together with Road Test Ratings

road test rating	log U	compound 1			log vf					
		0	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
	0	51.8	57.5	63.8	70.7	78.5	87.1	96.7	**107.3**	**119.0**
	0.2	58.9	63.2	67.9	73.0	78.4	84.3	90.6	97.3	**104.6**
	0.4	66.9	69.6	72.4	75.4	78.4	81.6	84.9	88.3	91.9
87	0.6	76.0	76.6	77.2	77.8	78.3	78.9	79.5	80.1	80.7
	0.8	86.4	84.3	82.3	80.3	78.3	76.4	74.5	72.7	70.9
	1	98.3	92.8	87.7	82.8	78.2	73.9	69.8	66.0	62.3
	1.2	**111.7**	**102.2**	93.5	85.5	78.2	71.5	65.4	59.9	54.8
	1.4	**127.0**	**112.5**	99.6	88.2	78.1	69.2	61.3	54.3	48.1
	1.6	**144.3**	**123.8**	**106.2**	91.1	78.1	67.0	57.5	49.3	42.3
100		**compound 2 = 100**								
		compound 3								
	log U	0	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
	0	91.9	**105.0**	**120.1**	**137.3**	**157.0**	**179.5**	**205.2**	**234.7**	**268.3**
	0.2	97.9	**106.7**	**116.3**	**126.7**	**138.1**	**150.4**	**163.9**	**178.6**	**194.6**
	0.4	**104.4**	**108.4**	**112.6**	**116.9**	**121.4**	**126.1**	**130.9**	**135.9**	**141.1**
107	0.6	**111.3**	**110.2**	**109.0**	**107.9**	**106.8**	**105.6**	**104.5**	**103.5**	**102.4**
	0.8	**118.7**	**111.9**	**105.6**	99.5	93.9	88.5	83.5	78.7	74.2
	1	**126.6**	**113.7**	**102.2**	91.9	82.6	74.2	66.7	59.9	53.9
	1.2	**134.9**	**115.6**	99.0	84.8	72.6	62.2	53.2	45.6	39.1
	1.4	**143.9**	**117.4**	95.8	78.2	63.8	52.1	42.5	34.7	28.3
	1.6	**153.4**	**119.3**	92.8	72.2	56.1	43.7	34.0	26.4	20.5
		compound 4								
	0	0	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
	0	68.1	88.0	**113.7**	**147.0**	**190.0**	**245.5**	**317.3**	**410.1**	**530.0**
	0.2	75.1	92.5	**114.0**	**140.4**	**172.8**	**212.9**	**262.2**	**322.8**	**397.6**
	0.4	82.9	97.3	**114.2**	**134.0**	**157.3**	**184.6**	**216.6**	**254.2**	**298.3**
170	0.6	91.5	**102.3**	**114.4**	**127.9**	**143.1**	**160.0**	**178.9**	**200.1**	**223.8**
	0.8	**101.0**	**107.6**	**114.6**	**122.2**	**130.2**	**138.7**	**147.8**	**157.5**	**167.9**
	1	**111.4**	**113.1**	**114.9**	**116.6**	**118.4**	**120.3**	**122.1**	**124.0**	**125.9**
	1.2	**122.9**	**118.9**	**115.1**	**111.4**	**107.8**	**104.3**	**100.9**	97.6	94.5
	1.4	**135.6**	**125.1**	**115.3**	**106.3**	98.0	90.4	83.4	76.9	70.9
	1.6	**149.7**	**131.5**	**115.5**	**101.5**	89.2	78.4	68.9	60.5	53.2

testing conditions whilst compound 3 is only better over a limited range and compound 4 is better over most testing conditions.

If a set of road test results are available, as is the case here a correlation analysis can be carried out between the road test ratings and the laboratory ratings for each of the testing conditions corresponding to one box of the each of the compound tables in table I. This is shown in table II. Three quantities are obtained:

Table II: Correlation between laboratory ratings of compounds of table I on alumina 180 and road test ratings

					log vf				
	log U	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
ordinate intercept	0.2	75	16	18	35	49	61	69	75
	0.4	49	-9	-2	18	36	50	60	68
	0.6	6	-46	-31	-5	**17.41**	34.25	47	56
	0.8	-60	-105	-74	-36	-6.86	**14.30**	30	41
	1	-143	-198	-130	-63	-21	7	25	38
	1.2	-202	-310	-148	-30	27	56	73	83
	1.4	-191	-301	-33	76	109	121	126	129
	1.6	-130	-113	97	142	148	147	145	143
					log vf				
	log U	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
regression coefficient	0.2	0.45	1.01	0.91	0.68	0.50	0.37	0.28	0.21
	0.4	0.71	1.26	1.12	0.87	0.67	0.51	0.40	0.32
	0.6	1.12	1.63	1.44	1.15	**0.90**	0.72	0.59	0.48
	0.8	1.73	2.20	1.90	1.52	1.23	**1.01**	0.85	0.73
	1	2.47	3.10	2.50	1.88	1.47	1.21	1.03	0.90
	1.2	2.93	4.17	2.73	1.59	1.03	0.73	0.55	0.43
	1.4	2.72	4.04	1.57	0.46	0.09	-0.07	-0.15	-0.19
	1.6	2.11	2.20	0.20	-0.30	-0.41	-0.43	-0.44	-0.43
					log v				
	log U	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
correlation coefficent	0.2	0.211	0.637	0.840	0.926	0.964	0.982	0.991	0.995
	0.4	0.298	0.686	0.867	0.943	0.975	0.990	0.997	0.999
	0.6	0.411	0.748	0.897	0.957	**0.981**	0.991	0.995	0.996
	0.8	0.553	0.828	0.927	0.953	0.959	**0.958**	0.956	0.955
	1	0.708	0.924	0.929	0.880	0.836	0.804	0.781	0.766
	1.2	0.821	0.993	0.808	0.616	0.491	0.408	0.349	0.304
	1.4	0.837	0.883	0.456	0.186	0.045	-0.042	-0.101	-0.146
	1.6	0.774	0.566	0.073	-0.152	-0.259	-0.321	-0.363	-0.392

The correlation coefficient, the regression coefficient which is the slope of the straight line graph between road and laboratory ratings and the intercept of the ordinate. Clearly if the correlation coefficient is 1 all points lie on a straight line. The regression coefficient, however is also important. If it is nearly 1 the laboratory- and road rating are both of the same magnitude, if it is smaller than 1 and the laboratory rating as shown on the x-axis, the spread of the compounds between lowest and highest rating is larger in the laboratory than on the road and the reverse is true if the regression coefficient is larger than 1. The table indicates at which single testing condition a high correlation would have been achieved.. This condition could be used in future for quality control tests of compounds used under similar road conditions as those for which the correlation was obtained. However, it must be remembered that the correlation holds in most cases only for a very narrow range of road testing conditions i.e. the actual conditions of the road test in question.

The factors contributing to road tire wear.

Generally a road test is judged primarily by the severity of wear, defined by the absolute loss in tread height per unit distance of a reference tire and tread compound, which in Europe is usually expressed as mm/1000 km. This severity has itself a large number of contributing factors, which not only influence the absolute wear but also the rating of compounds in different ways. This definition of severity is, therefore; insufficient to describe a road test uniquely.

A broad based classification divides the wear contributing factors into three sub-groups:

Tire- and vehicle independent factors (road, weather)

Vehicle driving factors

Tire factors.

Road surface and weather condition influences

The first group is made up of Road surface texture and weather conditions.

Weather conditions depend on the season of the year, local rainfall cycles and the geographical location of the road test.

Weather conditions, including rain, influence the tire wear of compounds primarily through their influence on the contact temperature between tire and road.

The road surface texture is usually not well defined in ordinary road testing. Because of the large distances involved to achieve a sufficient amount of wear for measurement a variety of different surface textures or structures is experienced, unless the wear tests are carried out on a well defined test track. In addition, the sharpness or micro-texture of a road surface changes with the weather conditions. Traffic increasingly polishes the surface during dry periods and rain etches the surface and dissolves small particles out of the road aggregate sharpening the micro texture of the surface. There is therefore a continuous process of polishing and sharpening going on with time.

If a wear test takes several weeks to carry out, which is usually the case, it is reasonable to assume that a sufficiently large number of road sections of different texture have been encountered and also for the season an average weather condition has prevailed. Its influence on severity would therefore be reasonably constant and to some extent repeatable. It would still depend on the season of the year, rainfall and on the geographical location.

Driving factors

The group of vehicle driving factors includes

Steering forces

Driving and braking forces

Driving speed

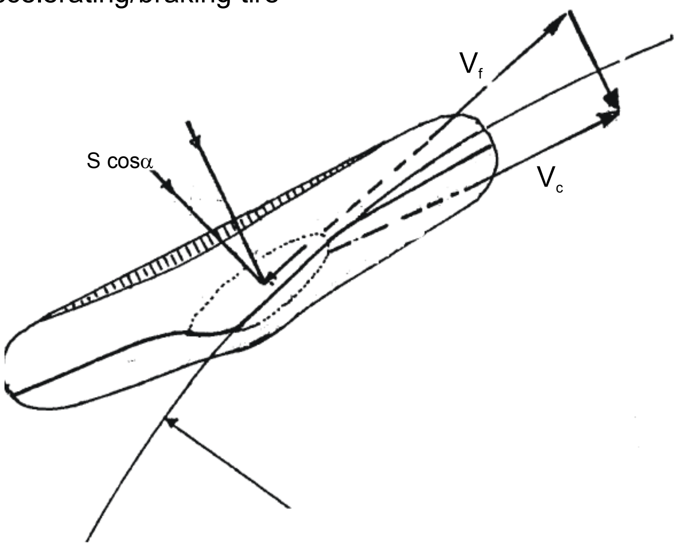
Tire load

This group has a large influence on tire life and also on compound rating. Forces are transmitted between tire and road through the frictional contact. These forces distort the tire and lead to slip and partial sliding in the contact area. Figure 5 shows the forces and speeds acting on a tire during cornering. Slip $\vec{s}$ is defined by

$$\vec{s} = \frac{\vec{v}_f - \vec{v}_c}{|v_f|} \qquad (5)$$

where v_f is the hub speed of the wheel in relation to the road and v_c is the circumferential speed in the contact area. The vector difference between forward speed and circumferential speed is called the slip speed.

Figure 5 Force- and speed components on a cornering- and accelerating/braking tire



During steering the vehicle around a corner, the plane of the wheel makes an angle α with the tangent of the cornering curve and side slip s occurs which becomes

$$s = \sin\alpha \qquad (6)$$

where α is the slip angle

During braking or accelerating the forces on the tire act in the plane of the wheel and lead to circumferential slip which is given by

$$s = 1 - \frac{v_c}{v_f} \qquad (7)$$

The maximum force which can be transmitted is limited by the coefficient of friction. Principally both force components and slip on the tire can be measured during driving using accelerometers and the ABS sensor system.

Slip leads to energy losses which are partly turned into heat and partly into wear. This energy consumption is the major cause for the wear of the tire. (There is a much smaller energy consumption and wear process due to the flattening of the tire in the contact area. The resulting stresses add up to zero but they lead to slip and energy losses, which may be termed the contact rolling resistance.). The energy loss is given by

$U_s = F_s \cdot \sin\alpha$ for side forces F_s and

$U_c = F_c \cdot \frac{s}{1-s}$ for circumferential forces F_c.

If both force components act simultaneously on the tire the energy consumption is the sum of the two components.

It is principally possible to monitor both force and slip during a road test and hence to calculate he energy loss in the contact area throughout a road wear test. This results in a precise picture of the severity of the test. In practice, this is rarely done because it is still expensive.

If only one of the factors is being measured it is necessary to take recourse to a tire model to calculate the other (or obtain it experimentally by a tire force slip characteristic at the correct load and inflation pressure.). In the present paper the simplest model, the so called brush model devised by Schallamach and Turner [4] is used.

Apart from forces on the tire, the wear is influenced by the speed of the tire. There are two reasons for this. First, the power consumed and hence the temperature generated in the contact area is a function of the speed, actually the sliding speed at the rear of the contact area. Second, the visco-elastic properties of the tread compound influence the capability of the compound to absorb energy. They depend on the deformation frequency, as well as the temperature in the contact area during sliding. In particular, the tearing energy which governs the cut growth and fatigue resistance of compounds and hence is also a basic parameter of the abrasion process, is strongly influenced by the deformation frequency, which itself is a function of sliding speed and road surface structure, and prevailing ambient temperature [6, 7 ,8].

The influence of the tire construction on wear.

A driver taking a car around a given curve at a given speed will have to set the slip angle of the tire such that the resulting side force will exactly balance the centrifugal force. Hence this event is force controlled as indeed are all other situations when driving a car on the road. The required slip angle to obtain the correct force depends on the cornering stiffness of the tire. Similarly, the circumferential slip produced when accelerating or braking depends on the circumferential slip stiffness of the tire.
For small slips the force - slip relation is given by

$$s_s = \frac{F_s}{K_s} \qquad (10) \qquad \text{and}$$

$$s_c = \frac{F_c}{K_c} \qquad (11) \qquad \text{for circumferential slip}$$

where K is the stiffness of the tire to slip at the origin of the force slip curve and differs for cornering slip and circumferential slip respectively. At large slips the limiting force F is given by the frictional force F

$$F = \mu \cdot L \qquad (12)$$

where L is the tire load and μ is the friction coefficient.
When this force is reached complete sliding sets in and the force acts opposite to the instantaneous velocity of the wheel i.e. control of the vehicle is lost. This situation is not normally encountered in road wear tests.
Hence two measurable quantities determine the force-slip behavior of any tire (and also that of the small test wheel of the laboratory abrasion apparatus), its slip stiffness K (with components K_s and K_c) and its coefficient of friction μ.
In case of small slip values, which are more relevant for tire wear than large ones, the energy dissipated is then given by

$$U_s = \frac{F_s^2}{K_s} \quad \text{and} \quad U_c = \frac{F_c^2}{K_c} \quad \text{respectively} \qquad (13)$$

The tire force-slip stiffnesses have essentially two components: The carcass and belt construction including also the inflation pressure and the tread stiffness which is influenced by the tread pattern design and the shear modulus of the compound. Particularly the tread depth and the shear modulus of the tread compound are major contributors to the shear stiffness of the tread. Carcass and tread act like springs in series. Their stiffness should, therefore, be as nearly equal as possible since the weaker one takes most of the deformation. The higher the cornering stiffness the smaller the required slip angle to obtain the desired force. This means also that there is less energy consumed in the contact area since under force controlled conditions the energy consumption is inversely proportional to the cornering stiffness of the tire as shown above. The same holds also for circumferential forces and is responsible for the higher wear resistance of the radial tire compared with the old diagonal tire construction.

A Model for a tire wear road test.

In the absence of instrumented test cars it is possible to obtain an insight into forces , slips and slip speeds which occur when a car is driven over a sufficiently long test route by simulating different driving situations using a computer program. The program, which is part of the software packet supplied with the LAT 100, divides the route into a large number of segments over which forces and the speed can be assumed to remain constant.

Cornering accelerations are determined by the radii of the curves occurring along the route and the speed with which the car is driven through them. Braking and driving accelerations occur when speeds are reduced or increased and when hills are climbed or descended. In addition a circumferential force is required to overcome the wind- and rolling resistance of the car, including the rolling resistance of the tires.

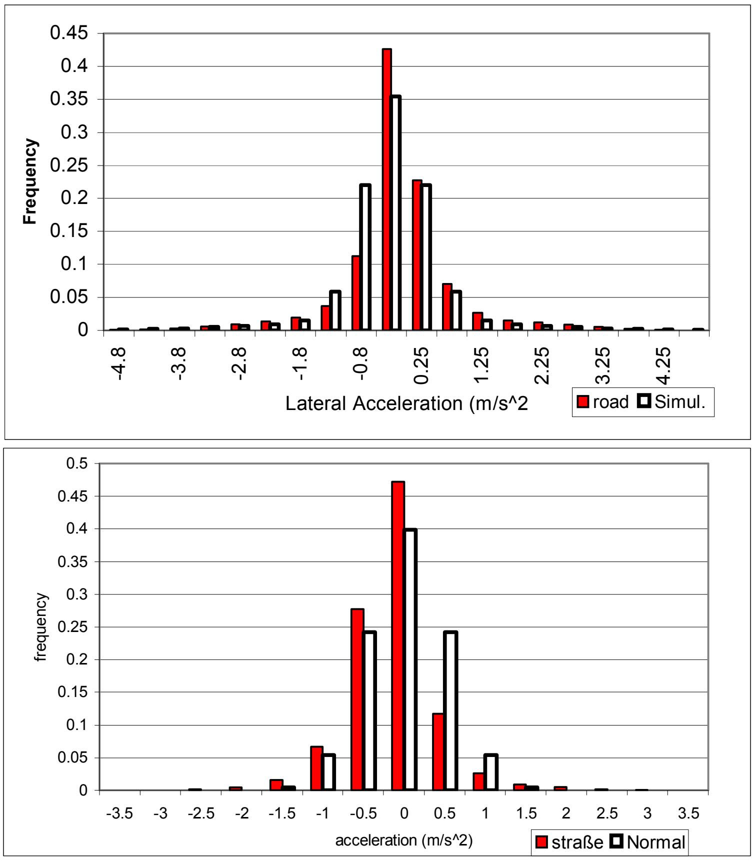
Differences between the tires on the left and on the right are likely to be small (unequally distributed loads and load transfer during cornering, braking or acceleration) and these small differences are averaged out along the test route so that they can be can neglected i.e. the model reduces to a two-tire-model.

Differences between front and rear, however, are important because of differences in load and because the non-driving axle is subject to side- and braking forces only whilst the driving axle has in addition also to take driving forces (acceleration wind- and rolling resistance) .

Separate models are therefore necessary for driven and non-driven axle positions. With this in mind it is possible to use the forces and speeds on a single tire with the acting mass given by the load which it carries.

It will be further assumed that the accelerations due to cornering and braking/driving are

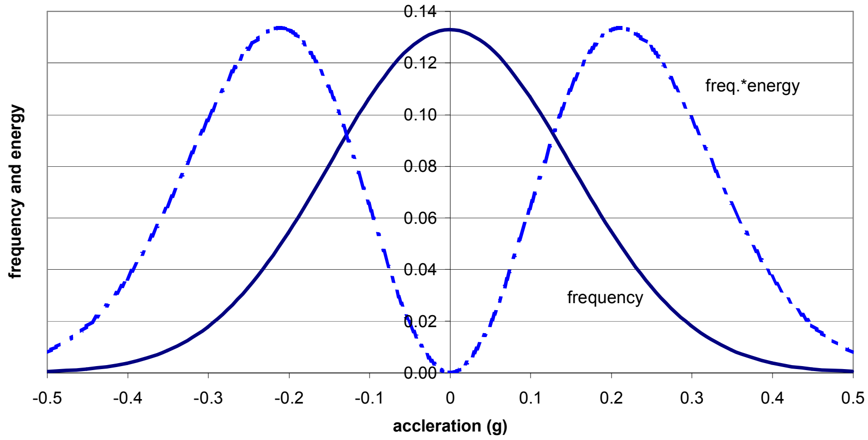
Figure 6: Comparison of Actual Acceleraation Distribution Functions with Normal Ones



normally distributed around zero. They are defined by their standard deviation σ. If it is also assumed that the occurrence of the maximum acceleration during driving is 3σ (99.9% of all occurrences), a measure is found for the driving severity due to applied forces. That such an assumption is close to reality is shown in figure 6, which compares actual acceleration measurements during a road test with a normal distribution function for lateral and longitudinal accelerations.

Figure 7 shows a normal distribution of the cornering acceleration during a test simulation.

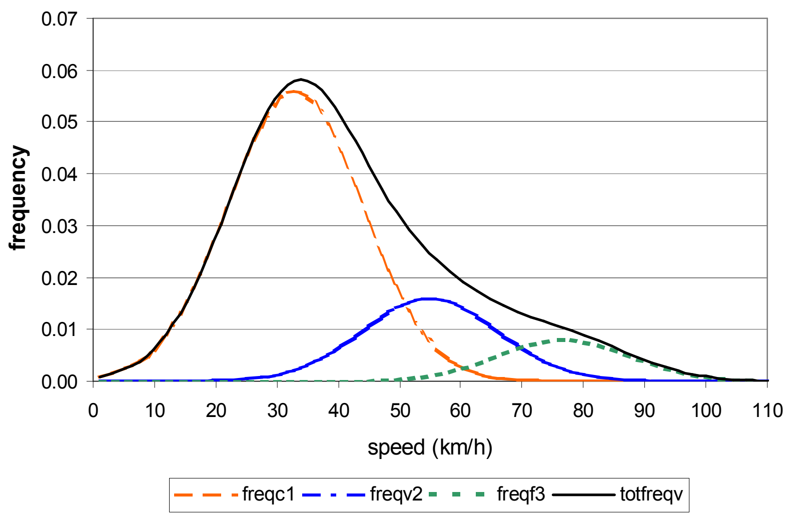
Figure 7: Frequency and energy consumption for normally distributed accelerations



Also shown is the consumed energy multiplied by the frequency of its occurrence for a given tire stiffness and load (normalized to fit the scale). This is zero at straight driving, because there is no side force and it becomes zero again at very large accelerations because of their low or near zero occurrence.

Driving speeds are not expected to be normally distributed. Even under rigorous test driving conditions on a prescribed track, there are likely to be several peaks following the lay-out of the track. Under normal conditions about three peaks of preferred speeds are expected to occur: one for town traffic, one for cross-country traffic and one for motorway (freeway) traffic. In the model described here the total distribution is made up of three normal distributions around three peaks. Each single distribution has a width of 6σ, the total reaching from zero to a maximum speed of 10σ which is fixed by the maximum speed likely to occur. The positions of the peaks along the speed axis are fixed at 3σ, 5σ and 7σ. This makes the probability at zero speed and maximum speed of 10σ practically zero (0.001exactly) the heights of the peaks can be changed. They are given as fractions of 1 and must add up to 1.

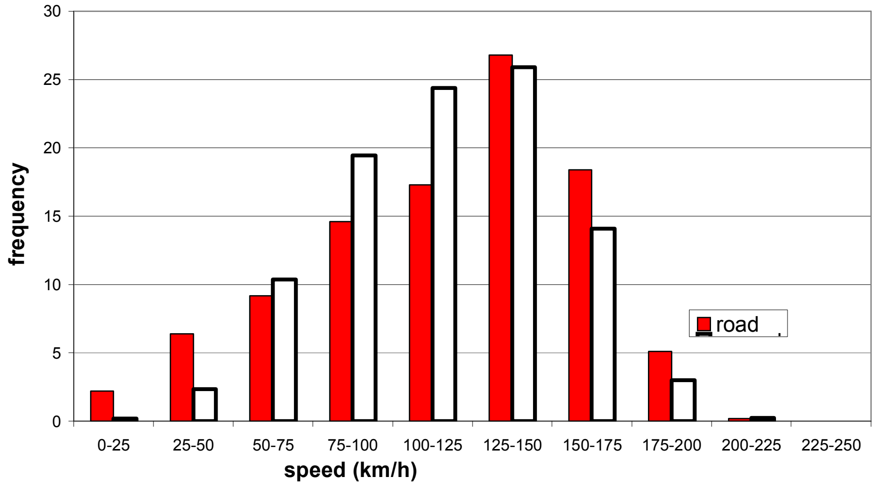
figure 8: Example of Speed Distribution for a Track Tire Test



An example is shown in figure 8 for a truck tire test. The distribution is an example. Its exact shape depends on the prescribed testing conditions of maximum speed and the ratios of town, country and motorway driving. Figure 9 is an actually measured distribution. The shown simulation was obtained by two superimposed normal distributions i.e. the height of the third was taken to be zero.

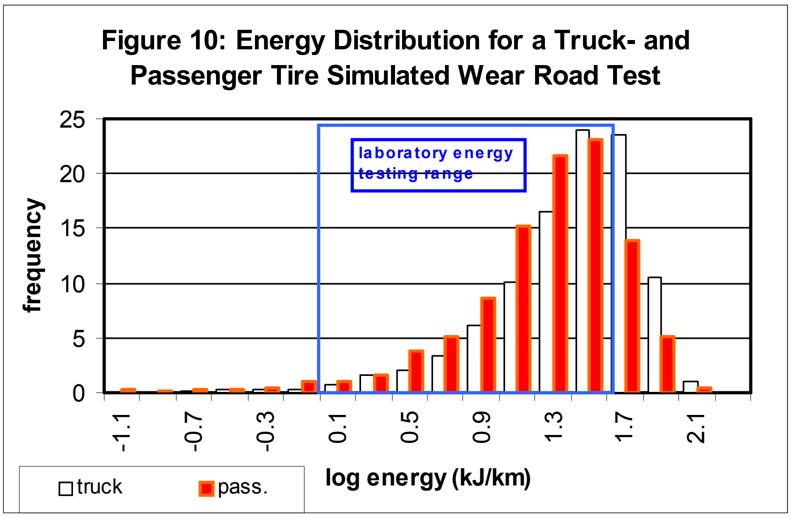
In general, also tire loads are likely to vary during a road test. They may be kept constant for highly controlled tests as they would be carried out for tire- or vehicle development but generally loads will change during the life of a tire and will influence its life. This is particularly the case when testing truck tires on fleet trucks. For this purpose, again three

Figure 9: Comparison betw. Speed Distribution of Road Test with superposed Normal Distribution



superposed normal distributions are used with fixed positions between a minimum and a maximum load. The minimum load is taken as the load when the truck is empty or in case of cars when the car is only occupied by the driver. The full load is taken as the maximum permissible tire load. The interval corresponds again to 10 times the standard deviation σ of a single normal distribution and the positions are again fixed at 3, 5 and 7σ. Their height can be varied in ratios of 1 which have to add up to 1. They have principally a similar shape as the speed distribution example of figure 8.

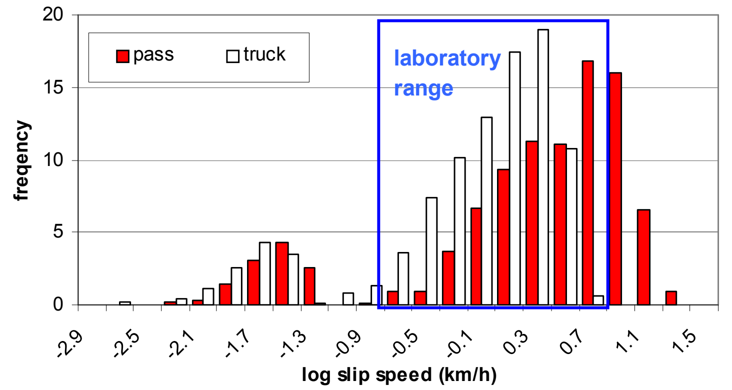
The mass acting on the tire through the load it carries, multiplied with the accelerations, and the driving forces to overcome wind- and rolling resistance determine the slip for a given tire construction and hence the energy consumption in the contact area of the tire. Since loads, cornering- and fore and aft accelerations are distributed this will lead to a complex



distribution of energy consumption in the contact area. Figure 10 shows such an energy distribution for a passenger tire and the same for a truck tire both with given load-, acceleration- and speed distributions. It is interesting to note that the magnitude of the dissipated energies is not very different in the two cases. The reason is that accelerations are likely to be lower for truck tires and the tire slip stiffness is much larger than for passenger tires so that the slip in the contact area is smaller although the forces are larger. The actual values lie between 1 and 70 kJ/km in both cases. This is in the range of the laboratory experimental range from 1 to 40 kJ/km

Similarly the slip speeds depend on the driving speed distribution and the slip in the contact

Figure 11: Slip Speed Distribution in a Simulated Tire Wear Road Test



area i.e. on the forces on the tire and the slip stiffness of the tire. Figure 11 show slip speed distributions for a passenger car tire- and a truck tire road test respectively. It is obvious that the slip speeds are much lower than the driving speeds. They are naturally somewhat higher for passenger tire road tests than for truck tire ones but do not differ very much from slip speeds in the laboratory abrasion test which range from about 0.2 km/h to about 10 km/h.

Tire wear in a road test simulation using laboratory abrasion data.

Having calculated the slip speeds and the energies dissipated in the contact area of a tire on the road it requires only the calculation of the abrasion loss per km multiplied by the frequency with which the energy-speed combination occurs to obtain the contribution to the total weighted average volume loss/km over the whole test route. The abrasion is calculated using the multiple regression equation (4) shown above with the parameters for the different compounds.

As an example table III shows a road test simulation on the driving axle with the four compounds which are discussed above for which ratings for a road test were known. The road test conditions were not specified except that it was a controlled road test and it is assumed

Table III: Road test simulation of a driven tire with abrasion results on alumina 180 with compounds of table I

Tire size	205/ 60R 15

cornering stiffness (N/rad)	45000	tire cross-section ratio	0.6
circumf. slip stiffness (N/slip)	90000	net/gros of pattern	0.7
frction coefficient	1	pattern width/ tire width	0.76
tire load (N)	4500	pattern depth (mm)	8
rolling resistance (N)	45		
cw coefficient	0.3		
maximum speed (km/h)	170		

compound	Vol/km	km/mm	tire life (km)	Rating	Rating fr, road
max cornering acceleration (g) 0.2; max fore and aft acceleration (g) 0.2					
1	12.2	17563	112404	**80**	87
2	9.8	21929	140348	**100**	100
3	10.9	19617	125549	**89**	107
4	5.4	39566	253224	**180**	170
max cornering acceleration (g) 0.3; max fore and aft acceleration (g) 0.3					
1	49.0	4386	28072	**86**	87
2	42.0	5120	32766	**100**	100
3	41.1	5231	33477	**102**	107
4	25.5	8439	54008	**165**	170
max cornering acceleration (g) 0.35; max fore and aft acceleration (g) 0.35					
1	83.7	2566	16420	**88**	87
2	73.9	2906	18600	**100**	100
3	69.7	3080	19711	**106**	107
4	46.0	4671	29896	**161**	170

that this was done at a constant load. The maximum acceleration components were adjusted to obtain the best correlation between the actual road ratings and the simulated ones.
It is seen that a close correlation is obtained for maximum acceleration components of 0.35g. The corresponding tire life is as would be expected from professional road test drivers.

The simulation under the assumption of equal energy consumption gives legitimate results provided the tires and compounds have approximately the same stiffness, since the tires in road use run under equal force conditions and not under equal energy. As is shown above, the energy dissipation in the contact area is inversely proportional to the stiffness at small slip angles
For the same tire construction this still assumes that all compounds have the same shear stiffness. This is not generally the case. An estimation of the shear stiffness of the compounds is obtained from the side force measurements at a small slip angle and high speed which is part of the abrasion evaluation. Differences in compound shear modulus for an otherwise equal tire and pattern design modify the cornering- and circumferential slip stiffness of the

tire. This is allowed for in the model on the basis that carcass and tread act like two springs in series which leads to the following relation

$$K_s = K_{so} \cdot \frac{2\upsilon}{1+\upsilon} \qquad (14)$$

where K_{so} is the cornering stiffness of the control tire
and ν is the relative side force stiffness of the compound to the control as measured in the abrasion experiment at a small slip angle. A similar relation holds for the circumferential slip stiffness K_c.

$$K_c = K_{co} \cdot \frac{2\upsilon}{1+\upsilon} \qquad (15)$$

where K_{co} is the circumferential slip stiffness of the control tire.
It is presumed, of course, that tires of the same compound are mounted on all positions so that there is no interaction between tires of different stiffness.

table IV: Influence of tire stiffnesses on tire life and compound rating in a simulated tire test

tire size:	205/ 65R 15
Laboratory surface	alumina 24

tire construction influence	kso(N/rad)=		**pattern influences**	pattern width/tire width =	0.78
	kco(N/sl)=			cross-section ratio =	0.65
	friction coefficient =	1.1		Net/gros =	0.7
				pattern depth (mm) =	8

driving influence	max. corn accel.(g)=	0.2		
	max longitudinal accel.(g)=	0.2		
	smallest tire load(N)=	3200		
	largest tire load(N)=	4900		
		low	med	high
	3-load distr. ratio=	0.2	0.5	0.3
	max vehicle speed(km/h)=	160		
		low	med	high
	3-speed distr. ratios.=	0.2	0.3	0.5

vehicle influence	rol. resistance coef.=	0.01
	cw=	0.3
	Proj vehicle cross-sect.(m^2	2.5

kso(N/rad)=	**45000**
kco(N/sk)=	**90000**

compond	Vol/km	km/mm	tire life (km)	Rating
1	88.1	2584	**16537**	**100.0**
2	89.1	2555	**16353**	**98.9**
3	68.0	3349	**21432**	**129.6**

kso(N/rad)=	**60000**
kco(N/sk)=	**120000**

compond	Vol/km	km/mm	tire life (km)	Rating
1	49.4	4609	**29496**	**100.0**
2	55.0	4136	**26469**	**89.7**
3	37.9	6003	**38416**	**130.2**

Table IV shows a road simulation in which all influences have been kept constant except for the tire stiffness. The rating of the compounds is effected but much more important, the tire life is significantly increased when going from the softer to the stiffer tire construction.

The effect of the friction coefficient is small because in tire wear the slips are small i.e. the sliding zone of the contact area is small compared to the adhesional zone and sliding friction is a minor part of the total force. The driving effects which are the major variables in road tests are going to be discussed in conjunction with road test ratings on truck tires

Truck Tire Test Simulation: A the Comparison of Compound Ratings with actual road Data

During a Brite Euram project of the European Union to assist small tire re-treaders to ensure and improve their product quality, laboratory abrasion test methods were compared with actual road data. H Monepenny discussed the results comparing road test ratings with the standard DIN and Akron abrasion test (9). The author et al. described the correlation between road ratings and laboratory abrasion data (10). Now, the abrasion data will be used to demonstrate that it is also possible to simulate these road tests and obtain thereby both correlations with road data and reasonable tire lives.
Two groups of re-treading compounds were used to make tires and place them on commercial

Table V: Road Wear Ratings of the Re-treading Compounds

A: whole tires

Compound	Road test conditions			
	rear drive tipper	front drive tipper	tractor units	rigids
1(NR/SBR)	100	100	100	100
2 (NR/BR)	113	105	127	126
3 (SBR/BR)	113	-	110	119

B: Triple Section Tires

Compound	Road test conditions			Total average of all tires
	rear drive tipper	front drive tipper	tractor units	
1(NR/SBR)	100	100	100	100
2 (NR/BR)	127	114	112	118
3 (SBR/BR)	113	-	110	113

C: Seven Filler Compounds based on 80 SBR/20 BR on Tri-section Tyres

Compound	Road test conditions			
	rear drive tipper	front drive tipper	tractor units	average
1	100	100	100	100
2	103	105	104	104
3	102	104	95	100
4	95	94	92	94
6	98	101	101	100
7	104	105	107	105
8	108	106	102	105

vehicles in several European countries. Table V shows the road wear ratings obtained for the compounds employed: (a) three re-trading compounds based on different polymer combinations, NR/SBR, NR/BR and SBR/BR and (b) seven compounds using the same polymer formulation but different filler types. All compounds were re-treaded on the same

type of new carcass of tire size 11 R 22.5 with the same tread pattern. All tires were tested on the rear driven axles of trucks. Two types of tire were produced: Tires with one compound over the whole tread and tires with three compounds divided into equal sections around the tire. When tires with one compound were placed two experimental tires were put on one side of the axle and two control tires on the other. For the triple section tires, one section was always the control compound, the other two were experimental compounds. Whilst the filler compounds had nearly the same stiffness, the three basic polymer compounds differed considerably in stiffness. This is of importance when comparing road test rating with ratings obtained in a road test simulation based on laboratory abrasion measurements.
The axle of the vehicle sustains the force necessary to corner, accelerate or brake the vehicle.

If tires with different stiffness are mounted on the same axle the common force produces an average slip condition which is the same for all tires on the axle. The stiffer tire runs at a larger slip than would be required if all tires on the axle were of that compound whilst the softer tire runs at a smaller slip than would be required to sustain the imposed force. The stiffer tire therefore abrades more than it should whilst the softer one benefits.
When discussing the road test simulations with the laboratory abrasion data of the above

Table VI: Ti Test Conditions for the Following Test Simulations

tire size:	275/ 80R 22.5	
Laboratory surfac		alumina 120

tire	kso(N/rad)=	175000	pattern width/tire width =		0.82
parameter	kco(N/sl)=	325000	Net/gros =		0.72
	friction coefficient =	1.1	cross-section ratio =		0.8
			pattern depth (mm) =		16
vehicle	rol. resistance coef.=	0.01			
parameter	cw=	0.9			
	Proj vehicle cross-sect.(m^2	5			
	max. corn accel.(g)=	0	smallest tire load(N)=		13500
driving	max longitudinal accel.(g)=	0	largest tire load(N)=		27500
parameter	max vehicle speed(km/h)=	80			
	3-load distr. ratio=	0.25	0.3	0.45	
	3-speed distr. ratios.=	0.3	0.4	0.3	

compounds, the variables which were kept constant for all tests are shown in table VI and will not be shown again in the tables for the results in order to improve clarity.

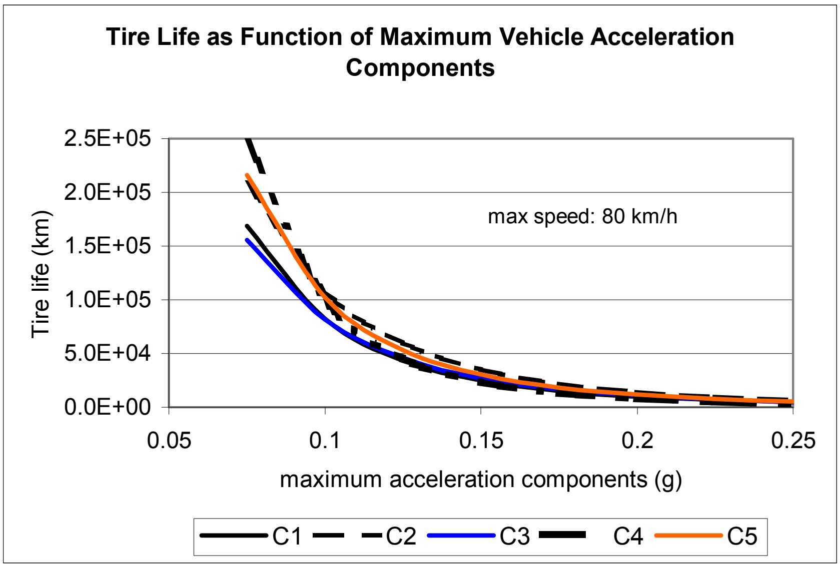
Table VII shows the results of a group of simulation tests based on the laboratory abrasion of five polymer compounds on an Alumina 120 surface as function of the maximum acceleration components which determine the shape of the distribution functions during the

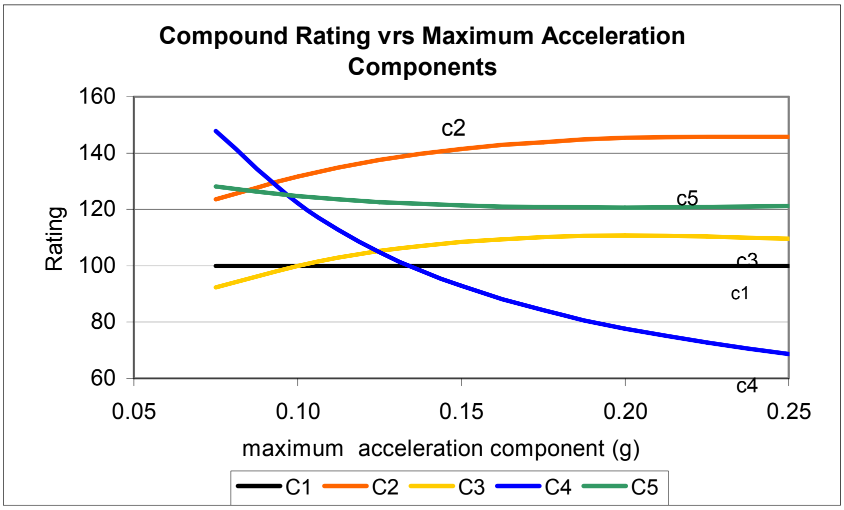
Table VII: Tire Lives and Compound Ratings as Function of Maximum Acceleration Components in simulated Road Tests with Equal tire stiffness (same energy dissipation)

		comp.	Vol/km	km/mm	tire life(km)	Rating
		1	44.1	11708	168593	**100.0**
max. corn accel.(g)=	**0.075**	2	35.7	14457	208188	**123.5**
max longitudinal accel.(g)	**0.075**	3	47.8	10796	155464	**92.2**
		4	29.8	17304	249173	**147.8**
		5	34.4	14998	215976	**128.1**
		1	298.9	1726	24853	**100.0**
max. corn accel.(g)=	**0.15**	2	211.3	2441	35150	**141.4**
max longitudinal accel.(g)	**0.15**	3	275.5	1873	26967	**108.5**
		4	321.8	1603	23088	**92.9**
		5	246.2	2095	30167	**121.4**
		1	1671.4	309	4444	**100.0**
max. corn accel.(g)=	**0.25**	2	1145.9	450	6483	**145.9**
max longitudinal accel.(g)	**0.25**	3	1526.0	338	4868	**109.5**
		4	2431.7	212	3055	**68.7**
		5	1379.6	374	5385	**121.2**

test and which is the major contribution to the severity of the test. They were varied between

Figure 12: Tire Lives and Compound Ratings as Function of Maximum Acceleration Components in simulated Road Tests with Equal tire stiffness (same energy dissipation)





0.075 g and .25 g, the two extreme ones and the center one are shown in the table. All other variables were kept constant according to table VI.. Of the five compounds listed, three i.e. c1, c3 and c5 were used in road tests. Compounds 4 and 5 differed only in the mixing process. Tire lives and compound ratings are also shown as graphs in figure 12 as function of the maximum acceleration. It is seen that the expected tire life is very strongly influenced, but also the rating of the compounds depends on the maximum acceleration as seen from the graphic representation of the results.

Table VIII compares the results of road test simulations with constant boundary conditions,

Table VIII: Road Simulation under constant conditions (table VI) using laboratory abrasion data but comparing the results of a road tire test simulation under equal force, equal energy and equal slip conditions

	comp.	Vol/km	km/mm	tire life(km)	Rating	average road rating
	1	298.9	1726	24853	**100.0**	**100**
	2	192.1	2686	38674	155.6	
equal force	3	287.7	1793	25818	**103.9**	**118**
	4	256.3	2013	28981	116.6	
	5	217.5	2372	34154	**137.4**	**113**
	1	298.9	1726	24853	**100.0**	**100**
equal	2	211.3	2441	35150	141.4	
energy	3	275.5	1873	26967	**108.5**	**118**
	4	321.8	1603	23088	92.9	
	5	246.2	2095	30167	**121.4**	**113**
	1	298.9	1726	24853	**100.0**	**100**
	2	233.0	2214	31887	128.3	
equal slip	3	260.5	1980	28516	**114.7**	**118**
	4	396.7	1301	18728	75.4	
	5	277.6	1859	26764	**107.7**	**113**

first under equal force conditions, second under equal energy dissipation conditions i. e in the simulation differences of stiffness which influence the energy dissipation are neglected, third under imposed slip conditions, i. e. compounds are tested under the same slip distributions which come about when tires of different stiffness are mounted on the same axle or multi-section tires are used in the road test. In this case the axle adjusts to an average slip condition supporting the force acting on it.

The simulation model calculates compound ratings R_U under equal energy conditions. If ratings R_f under equal force conditions are to be compared the cornering and circumferential slip stiffness in relation to the control are estimated using equation (15). The ratings are then modified according to

$$R_f = R_u \left[\frac{K_{exp}}{K_{control}} \right] \qquad (16)$$

where $K_{control}$ is the slip stiffness of the control tire and K_{exp} is the slip stiffness of the experimental tire (in the simulation model both cornering- and circumferential components are taken into consideration).

Under equal slip conditions the energy dissipation of a slipping wheel is proportional to the stiffness of the wheel and hence the wear rating R_s is estimated as

$$R_s = R_u \left[\frac{K_{control}}{K_{exp.}} \right] \qquad (17)$$

i. e. the influence of stiffness ratio reverses.

In this table the average ratings obtained in the actual road tests are also shown. It is seen that the ranking and a good correlation between ratings is only obtained when comparing the results under the equal slip conditions. This is not surprising since either multi-section tires were used or if whole tread tires were mounted experimental and control tires were always mounted on the same axle

Table IX compares the ratings for the three polymer based compounds obtained on laboratory

Table IX: Tire Lives and Compound Ratings on two Different Alumina Surfaces
Comparison of simulated Road Tests with Road Tire ratings
Equal slip condition (multi-tires and different tires on same axle)

three polmaer based compounds

	comp.	Vol/km	km/mm	tire life(km)	Rating	aver. road rating
Alumina 120	1	298.9	1726	24853	**100.0**	**100**
	3	260.5	1980	28516	**114.7**	**118**
	5	277.6	1859	26764	**107.7**	**113**
Alumina 24	1	408.1	1264	18201	**100.0**	**100**
	3	329.0	1568	22581	**124.1**	**118**
	5	379.3	1360	19585	**107.6**	**113**

four filler compounds on Alumina 120

	comp.	Vol/km	km/mm	tire life(km)	Rating	aver. road rating
Alumina 120	1	329.1	1567	22571	**100.0**	**100**
	4	388.2	1329	19134	**84.8**	**94**
	6	317.7	1624	23379	**103.6**	**100**
	7	314.4	1641	23628	**104.7**	**105**

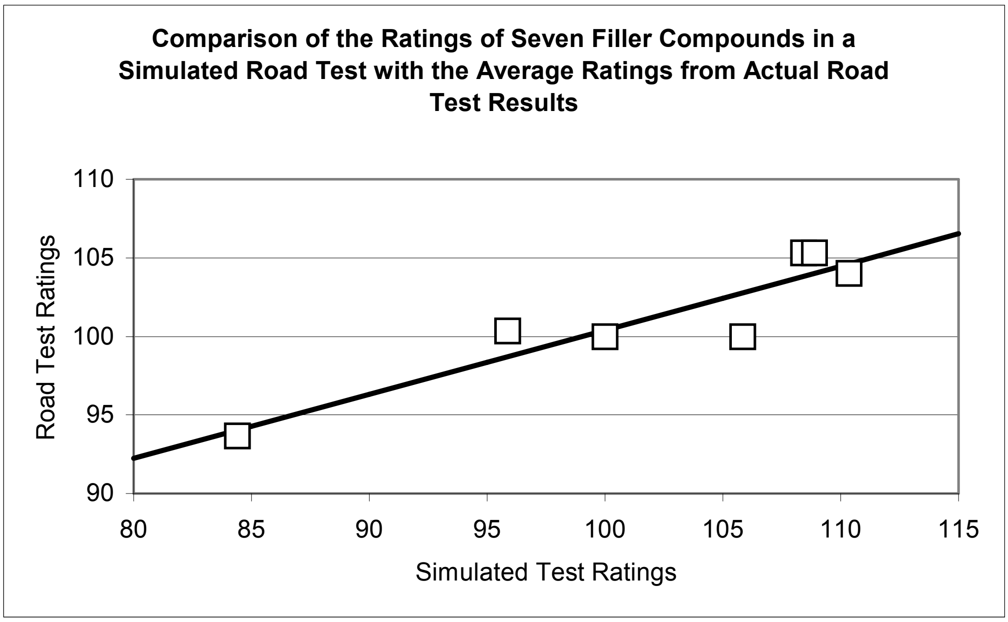
abrasive surfaces Alumina 120 and Alumina 24 with the road ratings. Also shown are ratings of four filler based compounds obtained on Alumina 120 with road ratings.

Finally all seven filler compounds were run in the laboratory on Alumina 24. The comparison with road ratings is shown in table X and graphically in figure 13 below.

It is remarkable that good ranking of the compounds is achieved in all cases with practically the same simulated testing condition. Since virtually nothing is known about load, speed, and acceleration distributions it must be assumed that the averages over a large umber of similar truck units produce finally a reasonably well defined average testing condition. Of the actually achieved tire lives no accurate record was kept, but they were between 20000 and

table X: Simulated Road Test Results with the Laboratory Abras Results of Seven Filler Compounds on Alumina 24

comp.	Vol/km	km/mm	tire life(km)	Rating	av. Road
1	203.7	2532	36466	100.0	100
2	184.6	2794	40237	110.3	104
3	212.5	2428	34958	95.9	100
4	241.4	2137	30775	84.4	94
6	192.4	2680	38598	105.8	100
7	187.9	2745	39535	108.4	105
8	187.1	2758	39710	108.9	105



30000 km which again is of the same order as the tire lives predicted from simulated road tests.

Summary and Conclusions

The laboratory abrasion method using the LAT 100 and a testing scheme of at least four but preferably more (up to nine), testing conditions involving as variables slip and speed makes it possible to describe the abrasion loss by an equation that relates abrasion to energy dissipation and speed . In this way a wide range of testing conditions is covered by interpolation and extrapolation.

Although only a small test wheel is involved, the energies and slip speeds in the contact area are close to those expected for the contact area of actual tires. This occurs because tires are very stiff and produce small slips and hence also a low energy dissipation, whilst the soft test wheel produces only a small force but runs under much larger slip angles. This similar range of energy dissipation between tires and laboratory sample wheel raises the hope of a direct link between tire wear and laboratory abrasion. A computer simulation program was therefore established, taking account of the major influences in road wear and using distribution functions to reproduce the large range of variables encountered during a road test.

Using the equations obtained from laboratory abrasion experiments in the program produces tire lives which are close to practical experience. This alone is encouraging that the major variables have been identified correctly. The paper shows that also the ratings of compounds reflect those of the practical road test.

Since no calibration factors are used between laboratory abrasion and road test results, it may be concluded that the average surface encountered during normal driving behaves much like the Alumina surfaces used in the laboratory.

The advantage of the simulation is that the influence of a very large number of variables on the rating and life of a tire can be studied in a very short time: – The program takes about a minute to run through the simulation of about 20000 different driving situations. These variables do not only include driving factors but also tire construction features and vehicle parameters which influence the major parameters of the abrasion process namely energy dissipation in the contact area and slip speed.

It may well be that some calibration between laboratory- and road surfaces is required if mileages are to be guaranteed but a major purpose is surely, to get a clear insight in the wear mechanisms of tires and the likely performance of compounds in a short time at very low cost compared with actual road tests.

Acknowledgements

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