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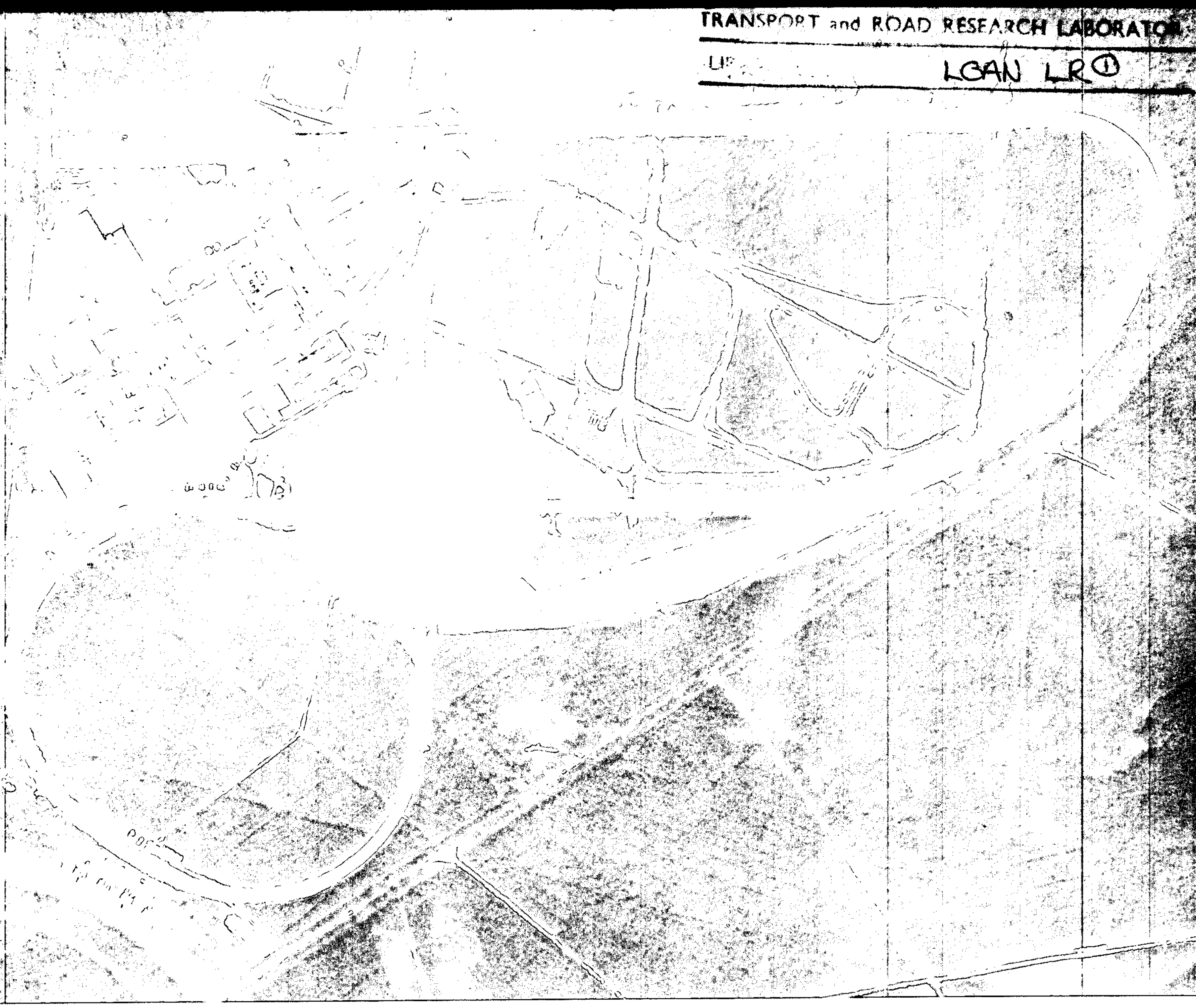

The Kenya maintenance study on unpaved roads: research on deterioration

by

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The work described in this Report forms part of the programme carried out for the Overseas Development Administration, but the views expressed are not necessarily those of the Administration.

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ABSTRACT

This report describes a study of the deterioration of unpaved roads which was undertaken in Kenya. The work formed part of a larger study of the effectiveness of various maintenance strategies on the performance of unpaved roads.

The primary objective of the research described in this report was to provide new and improved deterioration relationships for unpaved roads for use in a computer model for estimating the construction costs, maintenance costs and vehicle operating costs of roads in developing countries.

Experimental test sections were located on the public road network in Kenya and their rates of deterioration were measured and quantified in terms of gravel loss of the wearing course, surface roughness, depth of loose surface material and rut depths. The test sections were monitored for a period of over 2 years. The deterioration of the test sections was related to cumulative traffic, original design standards and construction, maintenance strategy and climate.

1. INTRODUCTION

In developing countries, unpaved roads can account for over 90 per cent of the total road network. In many of these countries, not only are the secondary and feeder roads unpaved, but also a significant proportion of the primary roads.

Unpaved roads can conveniently be categorised as either engineered gravel roads or earth roads.

Engineered gravel roads, as their name implies, are designed and built to an engineering specification. They are normally considered to be 'all weather' roads. Earth roads are built to a wide spectrum of construction standards. These can range from being similar to the engineered gravel road specification, but without an all-weather surfacing, down to the widening of a footpath or a farm track. This report is concerned only with engineered gravel roads.

The maintenance requirements of any unpaved road will depend largely on its original construction standard, the traffic that it carries and the prevailing climate. It follows that roads with different surfacing materials will have different rates of deterioration and that the standard of the maintenance carried out will affect the rate of deterioration.

In 1979, the Overseas Unit of the Transport and Road Research Laboratory (TRRL), in conjunction with the Kenyan Ministry of Transport and Communications (MOTC), initiated a study on the effect of various maintenance inputs on the deterioration rates of unpaved roads in Kenya.

The study was designed to investigate the technical aspects of the maintenance of unpaved roads and was not directly concerned with organisational and management issues.

This Report describes that component of the study concerned with the development of new gravel road deterioration relationships for incorporation into the TRRL road investment model for developing countries[1]. This included an investigation of the time-related weathering of gravel roads which were untrafficked. Other aspects of the study concerned with the development of optimum grading strategies for a range of parameters and equipment are the subject of a separate report[2].

The results of the study, although of direct benefit to Kenya, will also be applicable to many other developing countries.

2. DESIGN OF THE STUDY

2.1 *Background*

Between 1971 and 1974, a joint World Bank/TRRL/MOTC project studied the inter-relationships between construction, maintenance and vehicle operating costs for both paved and unpaved roads[3,4] in Kenya. This resulted in the development of a computer model designed to aid investment decisions within the road sector and which is known as the TRRL Road Investment Model[1]. A model has also been developed on the basis of this work by the World Bank and this is known as the Highway Design and Maintenance Standards Model[5].

The current study required the determination and quantification of relationships between:–

Gravel loss
Surface looseness
Surface roughness
Rut depth
Journey times

and:–

Traffic loading
Climate
Geometry
Camber
Shoulder compaction

Field work started by carrying out an appraisal of the condition of the existing gravel road network in Kenya. Modes of deterioration of the roads were identified and methods of measuring these were developed. Test sections of road were selected and the experimental work and monitoring of road performance commenced. Results were collected over a period of two years. These were then analysed and conclusions drawn.

2.2 *Experimental test sections*

The study was concentrated on three geographical areas of Kenya where the MOTC were carrying out rehabilitation works on large networks of unpaved roads. This rehabilitation programme was part of joint projects between the MOTC and the Canadian (CIDA) and American (USAID) donor agencies. The use of test sections was necessary in order to relate the deterioration rates of unpaved roads to the standard, frequency and type of maintenance, the traffic spectrum, the natural environment and the physical properties of the particular gravel. In addition, the test sections were needed to include variations in geometric design standards in terms of vertical gradient and horizontal curvature. The range of geometric standards studied was based on the results of the initial field appraisal and covered typical geometric standards found in each experimental area. The combination of horizontal and vertical alignments studied is shown in Table 1.

TABLE 1

Geometric framework

		Horizontal curvature		
		Low $< 30^{o}$/km	Medium $30^{o} - 90^{o}$/km	High $> 90^{o}$/km
Vertical gradient	Flat < 1%			
	Intermediate 1 – 3%			
	Steep > 3%			

The annual rainfall on the test sections varied between 500 and 2000 mm per year and, in each experimental area, test sections were duplicated in order that different levels of maintenance could be carried out; all test sections were 300 metres in length. The levels of maintenance chosen were as follows:–

(a) High: graded every six months,

(b) Normal: graded every nine months,

(c) Nil: not graded during the study.

In addition to these levels, it was found possible to include a small number of test sections with maintenance frequencies of three and twelve months. In all cases, normal drainage and roadside maintenance were carried out on a routine basis. On each group of test sections, various maintenance inputs were applied at different frequencies. A typical layout of an experimental site is given in Figure 1.

It was expected that the properties of the gravel wearing course would make a significant contribution to the rate of deterioration. Test sections were therefore chosen to utilise four basic gravel types which were as follows:–

(a) *Lateritic gravels.* These are formed by the accretion of nodules of oxides of iron and aluminium. The test sections in the Bungoma area were all lateritic.

(b) *Quartzitic gravels.* These are rounded gravels derived from the basement rock of the area east of Mount Kenya and were the wearing course materials used on some of the test sections in the Meru area.

(c) *Volcanic gravels.* These are angular gravels derived from the volcanic rocks of the Mount Kenya area and were employed as wearing course materials on other test sections in the Meru area.

(d) *Sandstone gravels.* These are fine grained gravels usually containing quantities of quartz and feldspar found near the Kenya coast. The wearing course materials on the Kaloleni sites were all sandstone in origin.

The location of the experimental test sections is illustrated in Figure 2.

3. MEASUREMENT OF EXPERIMENTAL VARIABLES

3.1 *Gravel loss*

The rate of gravel loss was recorded as the vertical loss in millimetres of material from the road surface. Measurements were made at three monthly intervals and were carried out using optical survey techniques.

In each experimental section, representative grids were selected for the surveys. At 5 metre intervals along a 60 metre length, profiles were taken at 25 cm increments across the road and into the drainage channel. At the side of each test section, concrete monuments were installed parallel to the centre of the grid and approximately 15 metres from the centre line of the road (see Figure 3). An additional bench mark, consisting of a 300 mm square metal plate 10 mm thick, was placed in the road beyond the survey grids at subgrade level to monitor any differential movement between the road structure and the concrete bench marks.

3.2 *Surface looseness*

Loose material on a road will lead to loss of traction which will affect vehicle speeds, journey times and fuel consumption. Consequently, measurements of surface looseness were made immediately before and after any maintenance input on the sections. The surface looseness on the nil maintenance sections was recorded at three monthly intervals. All measurements were carried out at three points: at the beginning and end of the individual grid areas, and also at the end of the section itself.

The measurements were carried out by setting a 1 metre x 0.25 metre metal frame on each wheel track with the 1 metre length placed transversely across the road. All loose material within the frame was then swept into a calibrated cylinder and recorded as the average depth of loose material within the frame. Additional measurements were made to determine the moisture content of the loose material and the CBR value of the top 15 mm of the surface.

3.3 *Surface roughness*

Measurements of surface roughness were made using a 5th wheel towed bump integrator[6,7] supplemented by a vehicle mounted integrator unit. See Plates 1 and 2. The towed bump integrator was pulled by a specially modified Ford Transit van whilst the vehicle mounted unit was installed in a Ford Cortina Mk IV Estate car. The vehicle mounted unit was calibrated periodically against the towed bump integrator unit and a typical calibration curve is illustrated in Figure 4. To ensure that the suspension of the towed unit was not changing with time, this instrument was also calibrated periodically over roads in good structural condition but exhibiting a wide spectrum of roughness levels.

In the study, three measurements of surface roughness were taken in each wheelpath of each test section when using the towed unit and in each direction when using the vehicle mounted unit. Additional measurements were also taken with the towed unit in the centre of the road. The frequency of measurement was related to the various maintenance inputs, but the intervals were never larger than three months.

3.4 *Rut depth*

The rut depth was recorded for each wheel track using a two metre straight edge and a wedge calibrated in millimetres. These recordings were made at the end of each test section and at the beginning and end of each gravel loss survey grid within each test section. In addition, rut depths were also measured from the profiles of the road surface which were plotted as part of the gravel loss assessment. Measurements of rut depth were taken at the same frequency as the surface roughness.

3.5 *Journey times*

Journey time is a useful index of the surface condition of a road. Additionally, value of time is an element of the road user cost and will vary with vehicular type, surface condition and alignment of the road[3]. Measurements were made of the speeds of the everyday traffic that passed over the test sections. This was carried out by placing two observers with synchronised stop-watches at the beginning and end of each test section. These measurements were taken over a 12-hour period from 6.00 am – 6.00 pm, usually before and after any maintenance activity.

3.6 *Traffic volumes*

Classified traffic counts for vehicles travelling in each direction were taken in each group of experimental sections at three monthly intervals during the study. The classification of the traffic is illustrated in Table 2. Site traffic belonging to the construction units were classified separately from the normal traffic flows. The survey periods were for 5 days (6.00 am – 6.00 pm) and 1 night (6.00 pm – 6.00 am). Preliminary surveys had shown that traffic on these rural roads after 6.00 pm was minimal, usually less than 5 per cent of the 24 hour period.

TABLE 2

Vehicle classification

Type of vehicle	Description
Motor cars	This class includes passenger vehicles seating not more than nine persons (including the driver). Estate cars, taxis, and hire cars are generally included but not 'Land-Rover' type vehicles or mini-buses.
Light goods	Goods vehicles of less than 1500 kg unladen weight or vehicles with a payload capacity of less than 760 kg. This class specifically includes 'Land-Rover' type vehicles and mini-buses.
Medium goods	This class includes all 2-axled goods vehicles of more than 1500 kg unladen weight or vehicles with a payload capacity greater than 760 kg. In general medium goods vehicles differ from light goods vehicles in that they have more than one tyre at each end of the rear axle ie twin-tyres.
Heavy goods	This class consists of all goods vehicles with more than two axles.
Buses	This class consists of all regular passenger service vehicles and coaches.

3.7 *Traffic loading*

The traffic loading on each group of test sections was monitored at 4 monthly intervals using the TRRL portable weighbridge[8] together with a digital read-out unit[9]. The surveys were carried out in conjunction with the classified traffic census periods of 5 days and 1 night. They were carried out using procedures and techniques developed by the TRRL and documented in Road Note 40[10].

3.8 *Laboratory testing of materials*

At the beginning of the study and immediately after the unpaved roads had been reconstructed, samples of the gravel both from the roadworks and from the quarry sources were collected and tested. Tests in the laboratory consisted of compaction, plasticity and liquid limit, particle size distribution and linear shrinkage carried out in accordance with procedures described in British Standard 1377/75[11].

3.9 *In-situ testing of materials*

The most frequently used *in-situ* test in the study was the density test carried out at the beginning of the study and both before and after each maintenance operation involving compaction. During initial sampling of the roads, this test also determined the thicknesses of the wearing courses after construction. In addition, *in-situ* CBR tests were carried out on wearing course and subgrade materials.

3.10 *Climate*

The prevailing climate was monitored by setting up weather stations adjacent to each group of experimental sections. Instruments capable of measuring both the volume and intensity of rainfall were installed at each weather station. The measurement of both intensity and volume was necessary to identify any rainstorm which might cause disproportionate damage to the road surface.

3.11 *Road geometry*

On unpaved roads, changes in vehicular behaviour due to the alignment can have an effect on the rate of deterioration of the road. It was therefore necessary for each group of sections to have similar geometry. Test sections were therefore chosen with continuous vertical gradients in one direction and the horizontal geometry of sections in any single group had similar rates of change of curvature as well as total radii of curvature. The geometric and other characteristics of the individual test sections are given in Table 1 of Appendix 2.

4. ANALYSIS AND DISCUSSION OF RESULTS

4.1 *Gravel loss*

4.1.1 *Gravel loss from unpaved roads.* The loss of gravel from the wearing course will eventually lead to permanent damage of the road structure unless remedial treatment is carried out in time. In the past, much of the research on material loss has been carried out in the field of agriculture. Work in the United States of America[12] on soil conservation has found that the mechanism of material loss from agricultural land is defined by the following equation:—

Soil loss = Soil erodibility x Ground slope factor x Rainfall factor

4.1.2 *Soil erodibility.* This is the characteristic of the soil which explains why erosion takes place at different rates, irrespective of usage, when other factors are constant. The erodibility of a soil is to a large extent controlled by its physical properties. The most important properties are the particle size distributions, stability of the grading, plasticity values, organic content, permeability of the structure, mineral content and shape, and the initial compaction of the material.

The ability of a particular soil to resist erosion is sometimes defined in terms of its erodibility factor which expresses the estimated soil loss in metric tonnes per hectare[13]. The rate of erosion does not remain constant but varies with the change of physical state of the soil mass.

4.1.3 *Ground slope.* In highway terms, the effect of ground slope on the soil's ability to resist erosion is largely governed by the road drainage system and, in particular, the longitudinal and transverse alignment. Erosion is frequently manifest in the form of longitudinal gullies along the surface of steep roads with gradients higher than about five per cent and this is especially the case in high rainfall areas. This problem is illustrated in Plate 3 which shows the formation of such gullies on an unpaved road in Kenya. One method for dealing with this problem which is being studied by TRRL is the construction of horizontal transverse drainage systems to remove the rainfall to the side drains as shown in Plate 4.

These drainage systems were installed in 1981 on roads in a mountainous area of Kenya with an average annual rainfall of over 2000 mm. The roads used in this pilot study possessed vertical gradients ranging from 6 to 9 per cent. The performance of this drainage system will be monitored over a further period of 1 to 2 years.

4.1.4 *Rainfall factor.* The rainfall factor is a value used to describe the capacity of localised rainfall to erode soil from an unprotected face. These factors have been developed mainly from studies conducted by the US Agriculture Service for periods of over 40 years. The results of these studies indicate that when other factors are constant, storm soil losses are directly proportional to the product of two rainstorm characteristics.

(a) total kinetic energy of the storm.

(b) its maximum 30 minute intensity.

The parameters of soil erodibility, ground slope and rainfall intensity clearly affect the rate of soil loss, irrespective of whether it is on agricultural land, or on unpaved roads.

4.1.5 *Parametric prediction of gravel loss.* For roads the soil loss equation must also include the effect of traffic on the wearing course material as the interaction between traffic and rainfall contributes significantly to the loss of material from a gravel surfaced road. The study also included the maintenance input as a parameter affecting the rate of gravel loss. The variables investigated in the study were therefore as follows:–

(a) traffic volumes and loading

(b) rainfall volume and intensity

(c) road alignment

(d) gravel type

(e) maintenance input

The gravel loss data from the study was first plotted as a function of the cumulative traffic volume for each test section. The data which was taken from measurements at approximately three monthly intervals showed no significant differences during wet or dry seasons. A selection of results from each of the four gravel types investigated is shown in Figures 5 and 6.

4.1.6 *Comparison of results with those from an earlier study.* Previous studies of gravel loss on unpaved roads by the TRRL[4] had produced an equation for predicting the annual gravel loss for lateritic, quartzitic, volcanic and coral gravels as follows:–

$$GL_A = f\left(\frac{T_A^2}{T_A^2+50}\right)(4.2+0.092T_A+3.50R_L^2+1.88VC) \qquad \text{..... eqn 4.1}$$

where GL_A is the annual gravel loss in millimetres

T_A is the annual traffic in both directions measured in thousands of vehicles

R_L is the annual rainfall measured in metres

VC is the percentage gradient

f is a constant which for;

lateritic gravels	=	0.94
quartzitic gravels	=	1.1
volcanic gravels	=	0.7
coral gravels	=	1.5

Using the relevant values of annual traffic, annual rainfall, vertical gradient and gravel constants in this equation, the predicted annual loss of gravel was evaluated for each test section in the current study. These values were plotted against the actual values obtained in the study and illustrated in Figure 7. It can be seen from this Figure that the annual loss of gravel measured in this study is greater than the predicted annual gravel loss by about 37.5 per cent. To bring the predicted gravel loss into agreement with the actual loss it would be necessary to increase the material constants f in the equation as follows:–

lateritic gravels	0.94 to 1.29	
quartzitic gravels	1.10 to 1.51	
volcanic gravels	0.70 to 0.96	
coral gravels	1.50	(not investigated in the current study)
sandstone gravels	1.38	

The differences between the gravel loss predicted by the original equations and the gravel loss measured in this study can be attributed to the following:–

(a) In the original analysis, the action of rainfall alone in producing gravel loss was calculated theoretically using the results of Wischmeier *et al* [14]. An estimated value of soil erodibility was used which gave a predicted maximum annual gravel loss of 2 mm and it was then assumed that when the traffic volume was zero, the gravel loss would be negligible.

In the current study, two experimental lengths of unpaved road were constructed which were not subjected to traffic. These pilot experiments were designed to study the effect of climate on the deterioration of unpaved roads in isolation from other parameters. One of the variables measured was that of gravel loss over a grid of road area 60 metres by 7 metres. The results of these measurements indicated values of annual gravel loss of 4.3 and 7.5 mm respectively. These figures imply that the eroding effect of rainfall alone is higher than that calculated by either Wischmeier or by using the original TRRL analysis. On exposed roads, the effect of wind erosion, particularly on surfaces that are slightly disturbed by traffic or rainfall could also be significant. The untrafficked test sections were subjected to approximately 0.8 metre of rainfall in the twelve month period. This by itself could account for half the difference between gravel loss predicted from the original equations and the gravel loss measured in this study.

(b) In the original study, the thickness of the wearing courses of the gravel test sections varied from 28 mm to 223 mm, whilst, for the recent study, the variations were contained within a band of 121–165 mm. Although gravel loss can be seen as a loss of the upper surfacing layer, any inherent weaknesses or strengths due to the varying depth of wearing course must influence the resistance of the road to deformation.

(c) Whilst no direct comparisons have been made of speeds over a period of time for the same road, alignments of unpaved roads in Kenya have, in general, greatly improved in the last 7–10 years. In addition, the condition of vehicles on unpaved roads in developing countries has also improved in recent years. Thus, not only are the roads capable of carrying traffic at higher speeds because of improved alignments, but vehicles now also have the ability to travel faster. These increased speeds will have increased the rates of gravel loss.

(d) A contributory factor to the increased loss of gravel is the behavioural changes in road users associated with the introduction of new vehicles. On rural roads in Kenya, the last five years have seen rapid increases in the numbers of 'matatus'. These are light goods vehicles with a nominal load of 1–1½ tonnes, converted to carry up to 40 passengers. On some rural roads, this type of vehicle can account for 30 to 50 per cent of the total traffic. These vehicles, invariably overloaded, are engaged in a highly competitive business which produces very aggressive road user behaviour. The product of overloading, speeding and irregular manoeuvres results in a shearing movement which damages the road surface. In the study, it was not possible to isolate these vehicles from other traffic, so therefore quantification of the damage caused was not possible.

4.1.7 *Results from other countries.* An indication of the range of gravel losses that can occur in practice is illustrated in Figure 8 where the results of studies in a number of different countries are shown[15,16,17,18]. The data from the Kenyan research, both in 1971–74 and 1979–81, refer to test sections with 3 per cent vertical gradient and 1250 mm of annual rainfall. Roads with steeper gradients in wetter areas will have higher losses, whilst the converse will be true of roads with flatter/lower gradients in drier areas.

Figure 8 further illustrates the point that annual gravel loss on unpaved roads will vary between 10 mm and 30 mm per 100 vehicles per day and will be dependent on climate and road alignment. This means that, annually, 70 to 210 cubic metres of gravel will be lost from each kilometre of road per 100 vehicles per day.

4.1.8 *Regravelling requirements.* These rates of gravel loss probably only hold for the first phase of the deterioration cycle lasting possibly for two or three years. They should not be considered to hold over a long period of time. As the wearing course is reduced in thickness, other developments such as the formation of ruts will affect the loss of gravel material. However the rates of loss given above can be used as an aid to the planning for regravelling in the future.

4.2 *Surface looseness*

Previous research has shown that loose material on gravel roads increases fuel consumption for a wide spectrum of vehicles[3].

There are two principal reasons for the presence of loose material on gravel roads. Firstly, it occurs as a direct result of attrition of the road surface by the action of traffic and rainfall. If there is sufficient moisture in the material it will be compacted by traffic, but only in the wheelpaths. If there is insufficient moisture, then the loose dry material will be dispersed across the road by traffic and wind. It can also be due to the maintenance technique of grading material lost to the ditches and shoulders back on to the road.

Most of the test sections in this study were compacted as part of the maintenance input. The data relative to the looseness measurements discussed in this chapter are therefore derived from the nil maintenance sections and the test sections where compaction was not carried out.

The results of the looseness measurements for each gravel type have been plotted as a function of cumulative traffic and are illustrated in Figures 9 and 10.

Although there was a maximum of 10 mm of loose material immediately after grading, the depth reduced rapidly with traffic to a constant level. In the case of the quartzitic gravel, this level was reached after approximately 5000 traffic passes whilst the other gravels took approximately 6000–10 000 traffic passes to reach a similar asymptote. Routine measurements on the compacted sections gave values of less than 1 mm in all cases.

The relationships between depth of loose material against cumulative traffic were found to be the following:

Lateritic gravel

$$DLM = 6.011e^{-0.334T} + 0.5 \qquad \ldots\ldots 4.2$$

Quartzitic gravel

$$DLM = 5.895e^{-0.358T} + 1.0 \qquad \ldots\ldots 4.3$$

Volcanic gravel

$$DLM = 6.748e^{-0.183T} + 1.0 \qquad \ldots\ldots 4.4$$

Sandstone gravel

$$DLM = 6.925e^{-0.187T} + 1.0 \qquad \ldots\ldots 4.5$$

where DLM = depth of loose material in mm

T = cumulative traffic passes in both directions in thousands of vehicles since grading.

4.3 *Surface roughness*

4.3.1 *Surface roughness changes for each gravel type investigated.* The principal index of unpaved road deterioration which affects vehicle operating costs is roughness (surface irregularity). In turn, traffic is the parameter that has the most significant effect on the rate of change of roughness. In the analysis, the roughness of the sections was plotted as a function of traffic. To obtain the best fit of curve for the measurements the data was analysed using polynomial regression techniques. In some cases, as can be seen from Figures 11 and 12, the fit was only marginally better than that obtained using linear regression.

Figures 11 and 12 refer to the experimental sections on which no maintenance was carried out for the period of the study. They were constructed in the three principal research areas of Meru, Bungoma and Kaloleni and consisted of wearing courses made with lateritic, quartzitic, volcanic and sandstone gravels. All the experimental sections were built using the same technique and standard of construction. Each section had a designated wearing course of 150 mm corresponding to the MOTC specification. In practice, the thickness was found to be in the range of 121–165 mm.

In the majority of cases, the correlation between roughness and traffic for each group of test sections is good with regression coefficients higher than 0.93. However, when the results from the individual sections, built with the same gravel type, are plotted together there are apparent differences in the deterioration cycles, particularly in the cases of the quartzitic and sandstone gravels. The main difference in performance of the quartzitic gravels occurs at a traffic level of 15,000 vehicles where there are two significant increases in surface roughness on the lower trafficked roads. These two high readings took place after the heaviest and most intensive rain storm recorded in the study had fallen. This particular storm had an intensity of 40 mm/hour over a period of 1½ hours and was probably responsible for the sudden deterioration of this road.

The two sandstone gravels came from borrow pits 30 kilometres apart, and although of the same geological origin, showed marked differences in their material properties. One of the gravels contained large quantities of mica and feldspar, whilst the other possessed a much coarser particle size distribution. The latter formed the wearing course on the only road monitored in the study that was built by private contractor. Initially, the construction of this road appeared correct in terms of the gravel wearing course thickness, particle size distribution and compaction. However, the subsequent deterioration of the road showed the existence of potholes which had resulted from the presence of oversize material in the wearing course. This oversize material comprised sandstone fragments which had been split by weathering processes into thin flat slabs. Where such material occurred, the compaction could not have been effective and the area would have become a 'soft spot' with the oversize material being exposed and eventually removed by the action of traffic.

Additional analysis of the physical properties of these two gravels was carried out to see if there was any correlation between surface roughness and particle size distribution, but none was found.

The lateritic gravels deteriorated at a slower rate than all the other gravels investigated in the study. After 97,000 traffic passes a roughness of 8000 mm/km was reached which was much lower than the roughness levels obtained with other gravels at lower traffic volumes. The gravel used for the wearing courses came from two large quarries and the materials were very similar in terms of their physical properties. The differences between the various lateritic gravels in their rates of deterioration were thought initially to be due to the differing geometry but no correlation was found between roughness and either vertical gradient or horizontal curvature.

Volcanic gravels deteriorated at a faster rate than any of the other gravels, reaching a roughness level of 8000 mm/km after only 30,000 traffic passes. The three roads built with volcanic gravel wearing courses were constructed to three distinct levels of geometry, but again no correlation was found between the roughness of the sections and their particular geometric standards.

4.3.2 *Comparison with previous TRRL study.* In the previous study conducted by TRRL in 1971–1974, lateritic, volcanic and quartzitic gravels were grouped together and equated to a general deterioration curve of roughness as a function of traffic (see Figure 13). This was due to an absence of nil maintenance sections on volcanic gravel roads and no apparent difference in rates of deterioration between lateritic and quartzitic gravels.

In the current study, nil maintained sections were established on volcanic gravel roads and distinct relationships were found for all four gravels investigated. Although the quartzitic gravels were found to perform better than the volcanic or sandstone gravels, they still deteriorated more quickly than the lateritic gravelled roads.

In the deterioration cycles, there is some evidence in the equations, particularly in the volcanic and lateritic sections, that the rate of change of roughness tends to decrease at the high levels. It was observed during the study that there was a change of behaviour by road users at the higher levels of roughness, particularly on the volcanic gravelled roads which had on average the highest level of roughness recorded. Generally vehicles tended to follow a regular well defined line of travel along a road, the positions of which varied according to the numbers of vehicles using the road and the geometry of the road. For example on roads carrying less than 100 vehicles per day, most of the traffic straddled the centre of the road forming two concentrated wheel paths. On roads with more than 100 vehicles per day, vehicles tended to use their correct lane more often, and usually four separate wheel paths developed. The pattern of behaviour appeared also to be constrained by the horizontal and vertical alignment of the road, especially on roads with radii of curvature greater than ninety degrees per km. On more heavily trafficked roads, the defined wheel paths became more established and deteriorated to a point where much of the traffic, particularly cars and light goods vehicles attempted to travel on smoother and relatively untrafficked parts of the road.

Thus if the measurements of roughness are only taken in the well defined wheel paths, the levels would apparently remain the same because most of the traffic had developed new wheel paths elsewhere on the road. The existing wheel paths then only deteriorate from the effect of rainfall and occasional trafficking. During the study, measurements of roughness were also taken in the middle of the road and, in all cases except on some of the roads on steep alignments, the roughness levels were the lowest here than anywhere else on the road. The towed bump integrator can be used to measure the roughness of individual wheel tracks, but it is not practical to carry out such a monitoring programme with this instrument over a large network of roads.

In the study by the TRRL[3,4] in 1971–1974, the relationship between roughness and traffic was a general one covering lateritic, volcanic and quartzitic gravels, plus a separate relationship for coral gravels based on limited data. Coral gravels were not included in the present study.

The general relationship derived from the original TRRL study indicated a large change in roughness for these gravels after approximately 80,000 traffic passes (see Figure 13). It can be seen that between 80,000 and 100,000 traffic passes, the roughness, in fact, increases by approximately 50 per cent. This is because of the influence of the highest recorded roughness in that study. This single measurement of 14,500 mm/km on one of the lateritic gravel sections has heavily biased the shape of the curve, as the previous highest roughness level recorded was only 9,000 mm/km. More recent investigation of the lateritic section in question has found that the original wearing course was only 65 mm thick as compared to the MOTC specified minimum thickness of 150 mm. Out of the 42 sections in that study, 37 sections had wearing courses substantially thicker than 65 mm. If the single measurement of roughness of 14,500 mm/km had been omitted from the analysis, the change in roughness between 80,000 and 100,000 traffic passes would have been reduced to an increment of approximately 15 per cent rather than 50 per cent. After a trafficking of 100,000 vehicles, the roughness would then be approximately 9,000 mm/km instead of 12,000 mm/km. This compares with a roughness level of approximately 7,500 mm/km for the lateritic gravel in the recent study after 100,000 traffic passes.

The regression equations relating roughness to traffic volume for each of the gravels illustrated in Figures 11 and 12 are:–

Lateritic gravels	$R = 3008 + 22.300T - 0.531T^2 - 0.0033T^3$	..... eqn 4.6
Quartzitic gravels	$R = 3384 + 52.287T + 0.143T^2 + 0.0157T^3$	..... eqn 4.7
Volcanic gravels	$R = 3442 - 2.519T + 8.111T^2 - 0.0934T^3$	..... eqn 4.8
Sandstone gravels	$R = 3505 + 221T - 6.360T^2 + 0.0736T^3$	..... eqn 4.9
	$R = 3545 - 39.1T + 5.060T^2 + 0.149T^3$	..... eqn 4.10

where R = mean roughness in the wheel tracks measured in mm/km by a towed bump integrator towed at 32 km/h

T = Traffic passing the sections in both directions since grading and measured in thousands of vehicles.

4.4 *Rut depth*

4.4.1 *Development of ruts with cumulative traffic.* In the analysis of rut depth, the measurements were plotted as a function of traffic using polynomial techniques and are illustrated in Figures 14 and 15.

On the lateritic gravel sections, the development of ruts was less pronounced than on sections using other gravel types and there was evidence of a reduction in slope or 'flattening' of the curve similar to that obtained with the roughness measurements. The volcanic gravel sections did not have high values of rut depth considering their high levels of roughness. This is attributed to the fact that, on these roads, it was observed that extra wheel paths were being developed as discussed earlier.

The regression equations which have been fitted to the data obtained from the rut depth measurements are as follows:–

Lateritic gravels	$RD = 7.18 - 0.081T + 0.0069T^2 - 0.000036T^3$	..... eqn 4.11
Quartzitic gravels	$RD = 7.49 + 0.171T + 0.014T^2 - 0.00009T^3$	..... eqn 4.12
Volcanic gravels	$RD = 10.11 + 0.314T + 0.00031T^2 + 0.00002T^3$	..... eqn 4.13
Sandstone gravels	$RD = 7.09 + 0.573T - 0.0128T^2 + 0.00024T^3$	..... eqn 4.14

where RD = Rut depth in mm under a 2 metre straight edge

T = Traffic passing the sections in both directions since grading and measured in thousands of vehicles.

4.5 *Journey times*

4.5.1 *Speed measurements over the test sections at the beginning and end of the study.* Measurements of journey times were taken at 6 months intervals for the normal traffic travelling over the test section. The period of measurement was for one day, from 8.00 am to 6.00 pm on groups of test sections. On the roads which carried less than 100 vehicles per day, the measurements were repeated the following day. Typical results of measurements at the beginning and end of the study are illustrated in Table 1 of Appendix 3.

It can be seen from this Table that changes in mean vehicle speed over the period of the study were small. In most cases, there was a slight reduction in speed in response to the deterioration of the road. On one road in Meru which had the highest level of roughness in the study, the reductions in speed were large. Elsewhere, the differences were rarely more than 2 kilometres per hour and, in some cases, there was a small increase in speed. Sample sizes of cars, heavy goods vehicles and buses were small because of the low total number of vehicles using the road but, in the case of the light goods vehicles and medium goods vehicles, the sample size was normally in the range of 50 to 100 vehicles. The small number of cars, buses and heavy vehicles will lead to a high degree of variability in any measurements of speed, although the previous TRRL study[3] found that the road condition had only a small effect on bus speeds. On any particular road, vehicles in each class travelled at a similar speed with usually a small number of vehicles in that class travelling either at very fast speeds or at excessively slow speeds.

4.5.2 *Comparisons with previous studies of vehicle speeds on unpaved roads.* The previous work by TRRL related changes in vehicle speed to changes in road condition in terms of roughness and rut depth. It was found that for roughness changes of 5000 mm/km, the speeds of cars, light goods vehicles, medium and heavy goods vehicles, and buses were reduced by 4.4, 4.8, 3.0 and 1.8 km/h respectively. Rutting of the road surface produced similar results, for example rut depths of 20 mm reduced the speeds of cars and heavy goods vehicles by 3.7 and 5.3 km/h respectively. Changes in roughness of the order of 5000 mm/km and rut depths of 20 mm were only found on the nil maintenance sections in this recent study. With the exception of the road in Meru with the highest roughness level, no large changes in vehicle speed were observed on the test sections, including the nil maintenance sections as the roads deteriorated. The nil maintenance sections were located near test sections which had received maintenance and it is thought that this may have influenced road user behaviour. The axle load surveys showed that up to 80 per cent of the traffic on these roads were regular users. This signified that many of the drivers were familiar with the different features of the road and this may have had considerable influence on the vehicle speed relationship irrespective of the road condition.

4.6 *Traffic loading*

4.6.1 *Axle load survey measurements.* Axle load surveys were carried out at approximately 4 months intervals on each group of roads contained within the study. The surveys lasted for 5 days from 6.00 am until 6.00 pm and for one night from 6.00 pm until 6.00 am. The precise timing of the surveys during the year were related as far as possible to expected changes in the type of goods being transported, such as would result from the harvesting of crops. The main goods transported in the areas of Meru and Bungoma were vegetables, fruit, tea, coffee, sugar and sunflower seeds whilst, in the Kaloleni area, it was sisal, fruit and milk. A high proportion of the traffic flow was composed of passenger carrying 'matatus' as mentioned in section 4.1. In the Meru and Bungoma areas, matatu traffic constituted 30 to 50 per cent of the total flow on the experimental roads. The bulk of the remaining traffic was medium goods vehicles carrying local produce. On the roads in the Kaloleni area which was less densely populated, the number of matatus was substantially less, usually of the order of 15 to 20 per cent of the total flow. On all the experimental roads there were only small numbers of cars, heavy goods vehicles and buses.

The results of the surveys are illustrated in Figures 16 and 17 which show typical axle load distributions for the different experimental roads. It can be seen that the number of axles exceeding the legal limit, which in Kenya is 8 tonnes maximum on a single axle, is minimal and in most cases less than 2 per cent.

Initially, it was planned that the analysis of road condition in terms of roughness and rut depth would be related to cumulative axle loading as well as traffic volumes. The analysis showed however that there was no significant difference if the road condition was plotted as a function of traffic volume or as a function of axle loading. Subsequently, all data relating to road condition has been presented in this report as a function of traffic volume.

4.6.2 *Heavily loaded site vehicles used in road construction.* A common feature of new unpaved roads is that the site construction traffic is invariably heavier than the traffic the road will eventually carry. On the roads built under the aegis of the MOTC/USAID/CIDA rehabilitation programme, the vehicles transporting gravel were usually the International Type C–1954 lorries capable of carrying 8 to 10 tonnes of material. The loading of these three-axled vehicles was strictly controlled and rear axles rarely exceeded 7.2 tonnes. The control by the various organisations was aimed at protecting the suspension of the vehicle under difficult field conditions rather than complying with the legal requirements. Vehicles of this type will exert some additional compaction to the roads when they are new but the major advantage is that they locate softspots and general weak areas in the new construction. This means that remedial treatment can be applied immediately at a time when it is most effective and will prevent, or at least postpone, future problems.

The differences in axle loading between traffic which includes site construction vehicles and the normal traffic are illustrated in Figure 17. Here, results from two axle-load surveys on the Bungoma to Bokoli road are shown. The first survey was carried out soon after completion of the rebuilding of this road when the loaded site vehicles were still travelling over the road to reach the adjacent construction site. The second survey was carried out two months later when there was no site construction traffic. The most notable difference in axle loading was in the range from 6 to 10 tonnes which covered the range normally found for the second and third axle of the heavy lorries hauling gravel. The first survey showed that the road was carrying 2300 tonnes each day whilst the second survey with the normal traffic flow showed that the daily loading was only 900 tonnes.

4.7 *Climate*

4.7.1 *Changes in roughness related to cumulative rainfall for untrafficked roads.* Apart from traffic, other parameters will affect the deterioration rate of the gravel wearing courses. The principal one of these is rainfall.

Pilot experiments were set up in two areas to try to establish the effect of rainfall on the road surface in isolation from other parameters. This was achieved by constructing short lengths of road adjacent to the main test sections investigated in the study. These lengths of road were built to the same standard of construction as the main road and were left untrafficked except when measurements were being taken with the towed bump integrator. To ensure that no traffic would use the road accidentally, the whole area was fenced off and access prevented by the construction of ditches 100 metres from each end of the actual test section of the road. When roughness measurements were being taken, culvert pipes were placed in these ditches and overtopped with gravel over a width of 4 metres. After the measurements had been taken, the gravel was removed, stockpiled and the culverts stored in a nearby school.

The two sections were built with quartzitic and sandstone gravel wearing courses. It had been intended to duplicate these sections in other areas using lateritic and volcanic gravel wearing courses but this was not possible due to problems of land acquisition.

Selection of the precise location of sites for these two experimental roads was governed by the need to look at different levels of rainfall. Annual rainfall figures derived from tables supplied by the Kenya Meteorological Department[19] give average values of 1250 mm and 630 mm over a 5 year period for the areas in which these two roads were constructed. The actual rainfall recorded at the sites during a twelve month period was 711 and 847 mm respectively, which was somewhat different from the average figures.

On the quartzitic gravelled road near Meru, there was an annual increase of roughness of 787 mm/km for a cumulative rainfall of 711 mm. This indicates a ratio of annual roughness increase to rainfall of 1108 mm/km per metre of rainfall. In the Kaloleni area, the roughness increased in the same period by 821 mm/km for a higher rainfall of 847 mm. This gives a ratio of 970 mm/km per metre of rainfall. The increase in roughness at the two test sites plotted as a function of cumulative rainfall is illustrated in Figure 18.

These results mean that, on untrafficked unpaved roads in areas where the annual rainfall is approximately 1 metre, the roughness of the road will increase annually by approximately 970 – 1100 mm/km, regardless of traffic. Rainfall records maintained on the two sites showed that the rainfall intensities were low, with the highest storms recorded during the monitoring period of 10 mm/h. Higher rainfall intensities would have influenced the change in roughness considerably. Therefore, in areas subjected to flash storms, ie near mountains, coastal and lake areas, the annual increases in surface roughness of unpaved roads due to rainfall alone could be much greater.

The equations derived from the regression analysis of the data are as follows:–

Quartzitic gravel

$$R_I = 3303 + 1.117\ R_R \qquad \text{..... eqn 4.16}$$

Regression coefficient $R^2 = 0.83337$

Sandstone gravel

$$R_I = 3550 + 1.021\ R_R \qquad \text{..... eqn 4.17}$$

Regression coefficient $R^2 = 0.90966$

where R_I = roughness in mm/km measured by towed bump integrator

R_R = rainfall in mm.

For the purpose of predicting roughness in terms of rainfall, it is probably adequate to combine these equations to give:–

$$R_I = 3429 + 1.063\ R_R \qquad \text{..... eqn 4.18}$$

Regression coefficient $R^2 = 0.78199$

4.7.2 *Changes in roughness related to cumulative rainfall for trafficked roads.* An attempt was made to separate the effect of traffic from rainfall on the experimental sections by plotting roughness as a function of cumulative rainfall. This is illustrated in Figure 19 where the data is plotted for constant traffic volumes of 8000 vehicles since grading. As can be seen, the data is scattered and, using this form of analysis, there does not appear to be a direct relationship between roughness and traffic. Other levels of traffic volumes were used but no significant relationships were apparent in these cases either. One explanation is that one cannot isolate traffic in this way on unpaved roads as small numbers of overloaded vehicles can cause severe damage to the road if they travel during periods when the road is wet.

The results of the measurements on the untrafficked sections have yielded much needed information on the deterioration of unpaved roads due to rainfall alone. In particular, the relationships found for the untrafficked sections are probably valid for low volume roads carrying less than about 10 vehicles per day.

In order to provide the data to calibrate a better relationship between traffic and rainfall it would be necessary to monitor traffic, rainfall and road condition on a daily basis. The deteriorating effect of traffic could then be weighted according to the rainfall at the time of trafficking. This was not possible with the resources available for this study.

4.8 *Geometry*

4.8.1 *Geometric constraints on deterioration.* It was not found possible in the analysis to isolate the effect of horizontal curvature and vertical gradients on the deterioration of either maintained or non maintained roads.

Horizontal curvature, within the range measured, appeared to have no effect on rates of deterioration. Initially, it had been included in the analysis of gravel loss, but was eventually rejected as it made no significant difference to the results. The most likely influence of this parameter in terms of the deterioration of unpaved roads, would be through its effect on vehicle speeds. Reductions in speed depend more on the frequency and rate of change of curvature rather than the total amount of horizontal curvature.

The effect of longitudinal gradient on deterioration was more noticeable in the latter stages of the study with the development of small gullies along the centre of some of the test sections. In particular, the volcanic sections on steep alignment near Meru were badly affected. This mode of deterioration was not related to any of the maintenance inputs, but occurred as the result of inadequacies in the design of the road. A major problem of unpaved roads built on steep alignments is the efficient removal of surface water to the side drains. As the gradients increase, the problem becomes more acute irrespective of any increase in the crossfall of the road. All the steep volcanic sections were constructed with crossfalls of 4 per cent which would have delayed the formation of gullies but, after a period of eighteen months, these volcanic sections recorded the highest level of gravel loss and rutting of any group of sections monitored in the study, resulting in a significant reduction of the initial crossfall. The nil maintenance section on this steep alignment had a gravel loss of 38.7 mm after eighteen months compared to a gravel loss of 22.2 mm for a nil maintenance volcanic section on flat alignment. The rut depth measured in the centre of the road on the same two sections had values of 53 mm for the steep alignment and 21 mm for the flat alignment. In the latter case, the ruts in the centre of the road were the result of the interaction between the inner wheels of traffic and the gravel wearing course and not as a direct result of erosion by water. Roads on steep alignments with crossfalls less than 4 per cent are common in many developing countries and often display the deterioration illustrated in Plate 3.

The problem of gully erosion along the centre of unpaved roads will be exacerbated as vertical gradients increase above the value of the crossfall. There can only be two solutions to this problem. Either the vertical geometry must be physically reduced by realigning the section of road, or drainage measures, such as those discussed in Chapter 4.1, must be introduced.

4.9 *Road camber*

4.9.1 *Changes in road camber during the study.* At the end of the study most of the test sections had retained an effective camber of over 3 per cent. The only exceptions to this were the nil maintenance sections where the development of ruts and pronounced wheelpaths caused the transverse profiles to take up an irregular shape.

The test sections which had initial cambers of 6 per cent appeared to be in slightly better condition than their 4 per cent counterpart sections with the same maintenance input, but the difference was not significant. It is possible that, if there were differences, they would assert themselves over a longer period of measurement or in a more intensive rainfall area. The higher cambered sections were not found to have correspondingly higher rates of gravel loss.

4.10 *Shoulder compaction*

A frequent problem on both paved and unpaved roads is the deformation of the shoulder which often precipitates the structural failure of the pavement. In many cases, this is the result of vehicles, particularly heavy lorries, standing off the road due to breakdown or overnight stop and sometimes as a result of passing vehicles straying off the edge of the road. It can also occur as a result of water leaving the road surface, but staying on the shoulder because of insufficient crossfall. An objective of the study was to examine whether improved performance of the road could be obtained by applying additional compaction to shoulders during maintenance operations.

During the study, no significant deterioration was found on the shoulders of any test section, whether additional compaction had been applied or not, implying that the additional compaction was unnecessary. However, the numbers of heavy vehicles using the road were low and, when traffic did stop because of mechanical breakdown, it was able to stop on the road itself because of the low traffic intensity.

5. SUMMARY AND CONCLUSIONS

The unit rate of gravel loss found in the study was higher than that predicted by the TRRL road investment model. The total loss of gravel from unpaved roads in developing countries is also increasing annually because of additions to the road network. This problem will become exacerbated as road networks expand and the sources of good road making gravel continue to dwindle. Already, haulage distances of 80 kilometres for gravel exist in Kenya, and in Africa generally haulage distances for material are lengthening.

The study quantified separate deterioration relationships for lateritic, quartzitic, volcanic and sandstone gravels. This was an important improvement on previous studies of gravel roads. The relationships are summarised in Appendix 1. These deterioration relationships will now be combined with the results of research in other countries to produce more general relationships for inclusion in the TRRL road investment model.

The effect of rainfall in isolation from other parameters was found to increase the surface roughness annually by between 970 and 1100 mm/km per metre of rainfall for sandstone and quartzitic gravels.

On well maintained roads the amount of loose material that stayed on the surface was not significant, and is unlikely to influence vehicle operating costs.

Only a small number of vehicles travelling over the test sections were found to be overloaded. Overloaded vehicles did not therefore significantly influence the rate of deterioration.

6. ACKNOWLEDGEMENTS

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1	2	3	4	5	6	7	8
Graded at six months intervals by motor grader, compacted by vibrating roller	Graded at six months intervals by towed grader, compacted by vibrating roller	As section 1 but road built with 6 per cent camber	Nil maintenance	Graded at six months intervals by motor grader, not compacted afterwards	Graded at six months intervals by towed grader, not compacted afterwards	Graded at nine months intervals by motor grader, compacted by vibrating roller	Graded at six months intervals by motor grader, compacted by vibrating roller after adding water

All sections were 300 metres in length separated by transitions of minimum length 25 metres.
In some cases the transitions were much greater because of the geometry of the road.

Fig.1 Bungoma – Mungatsi Road, Site B

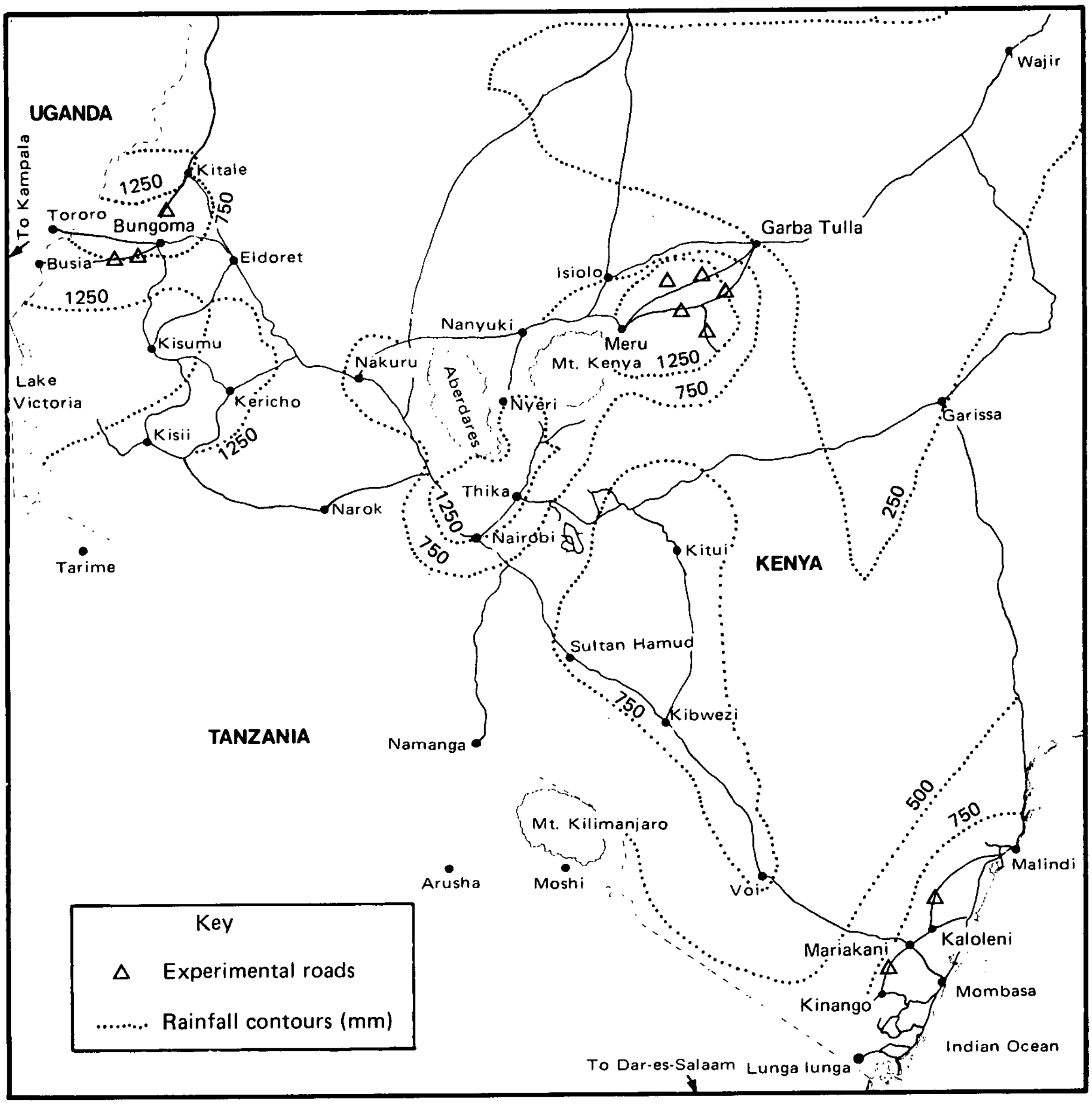


Fig.2 Rainfall map of Kenya showing location of experimental roads

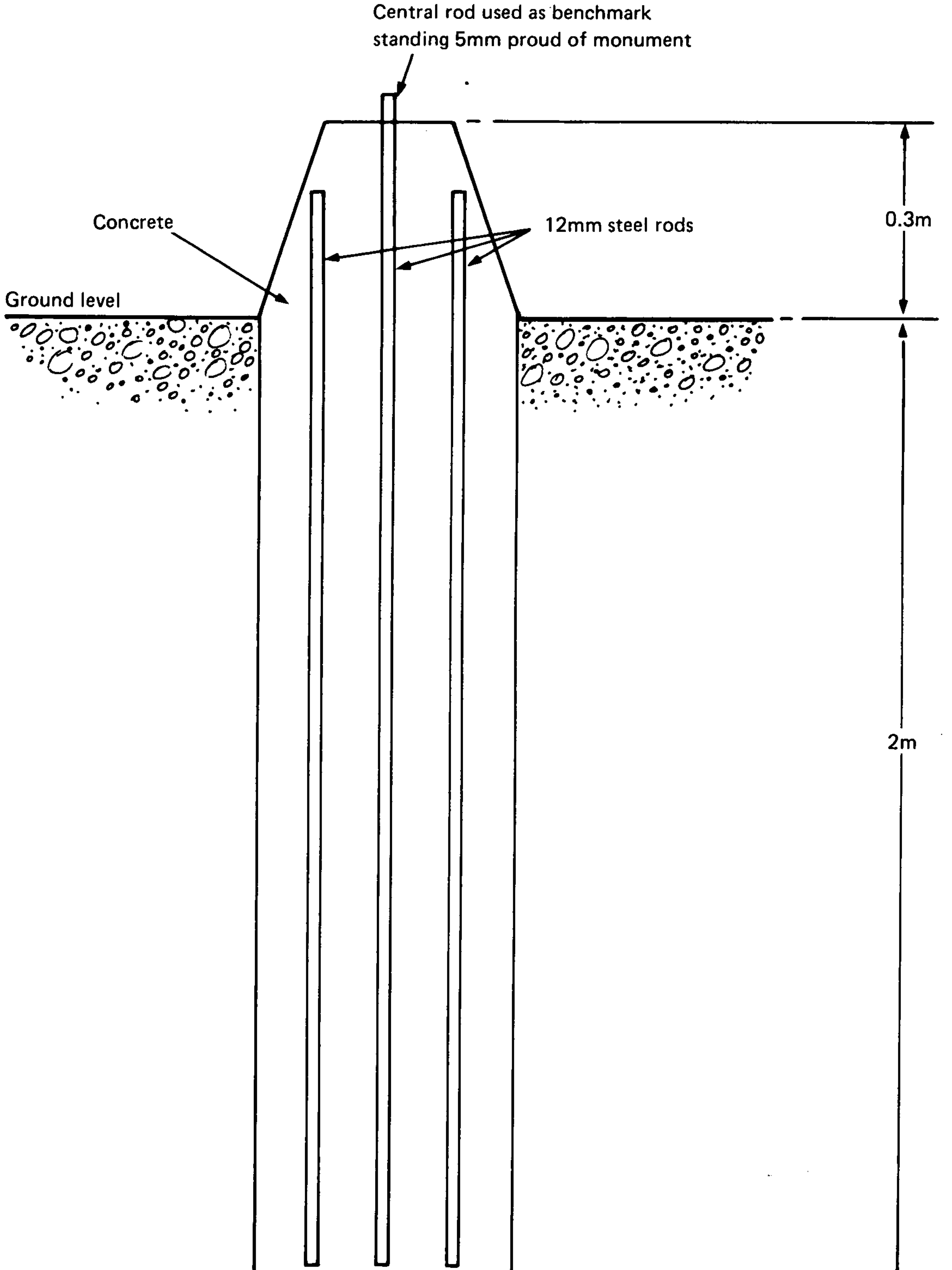


Fig.3 Diagrammatic layout of benchmark monument

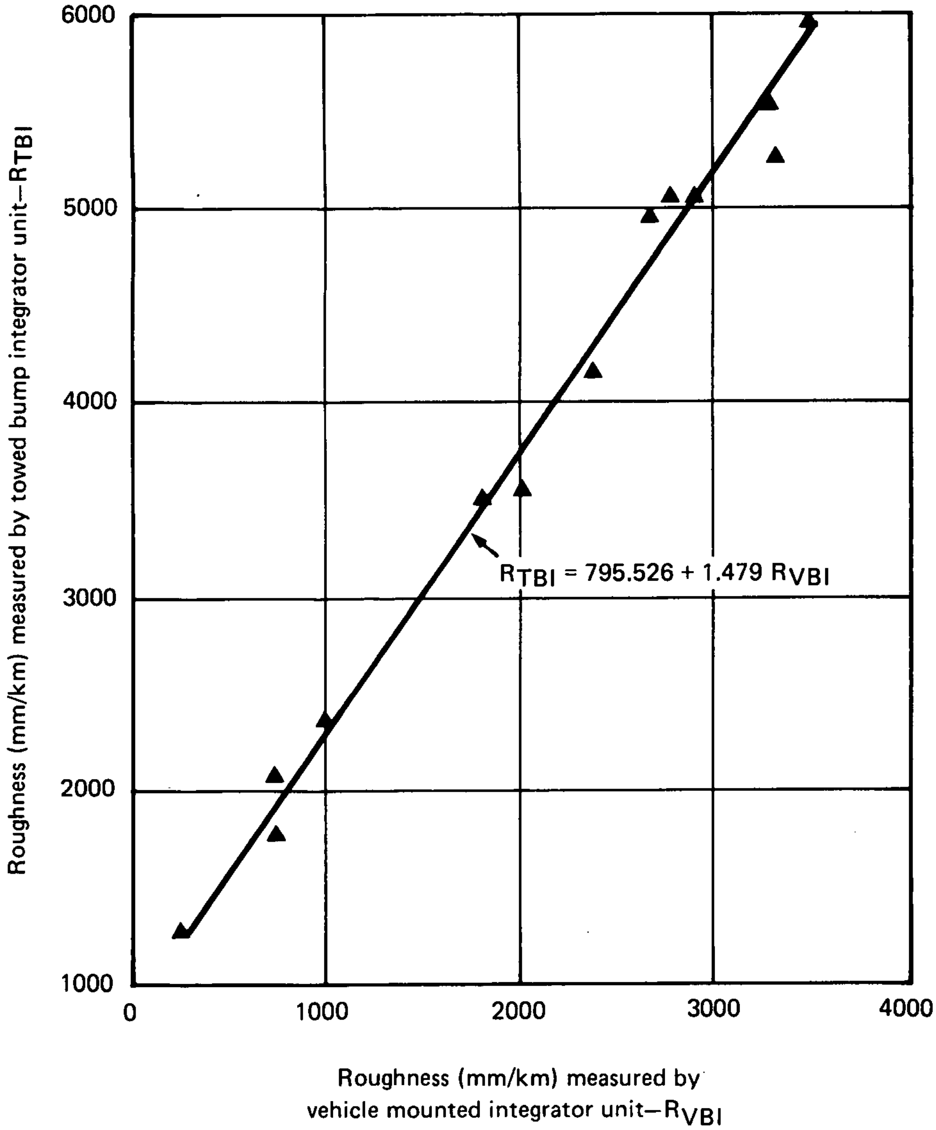


Fig.4 Relationship between towed bump integrator unit and vehicle mounted integrator unit

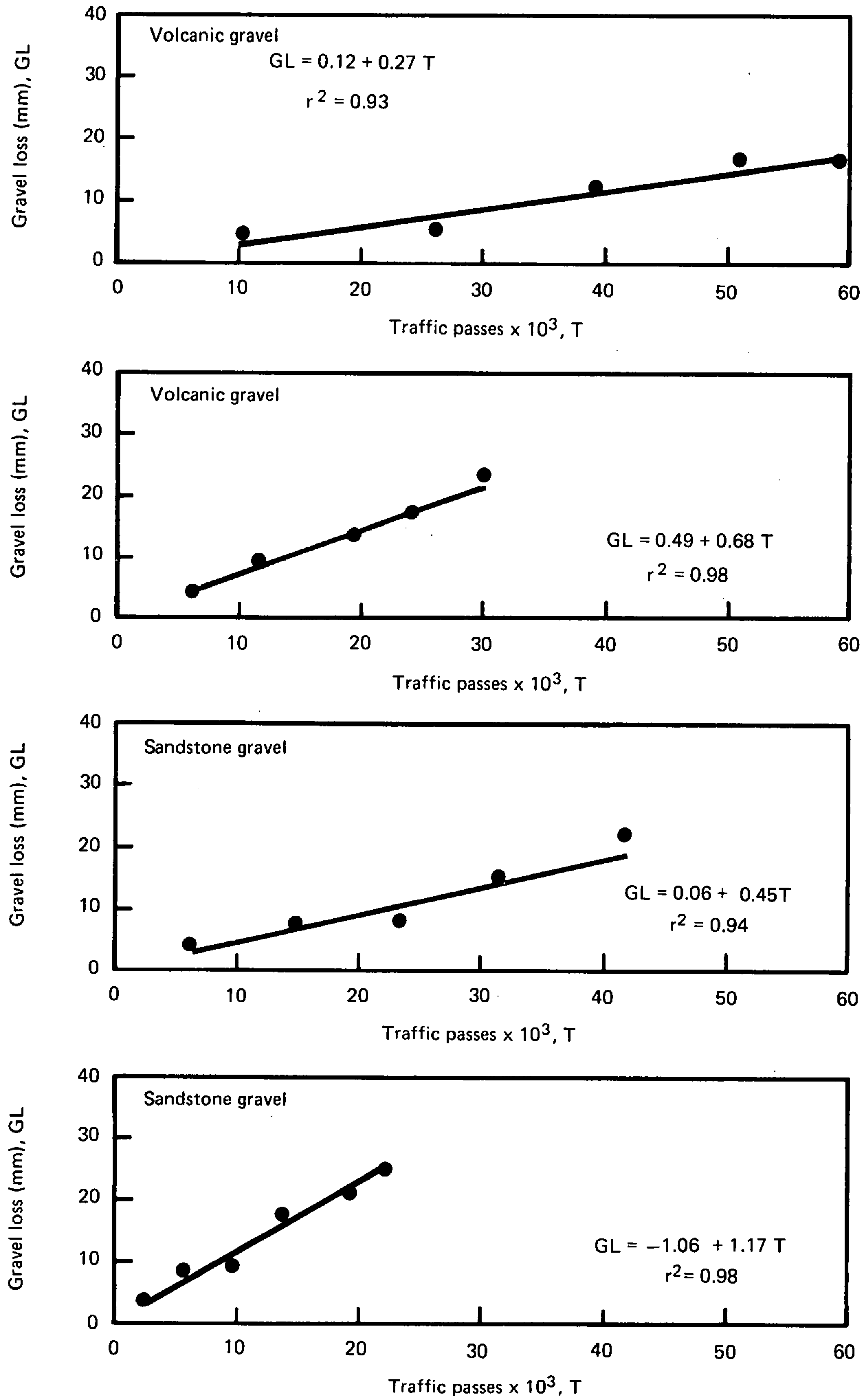


Fig.5 Gravel loss against traffic passes for some volcanic and sandstone gravel roads

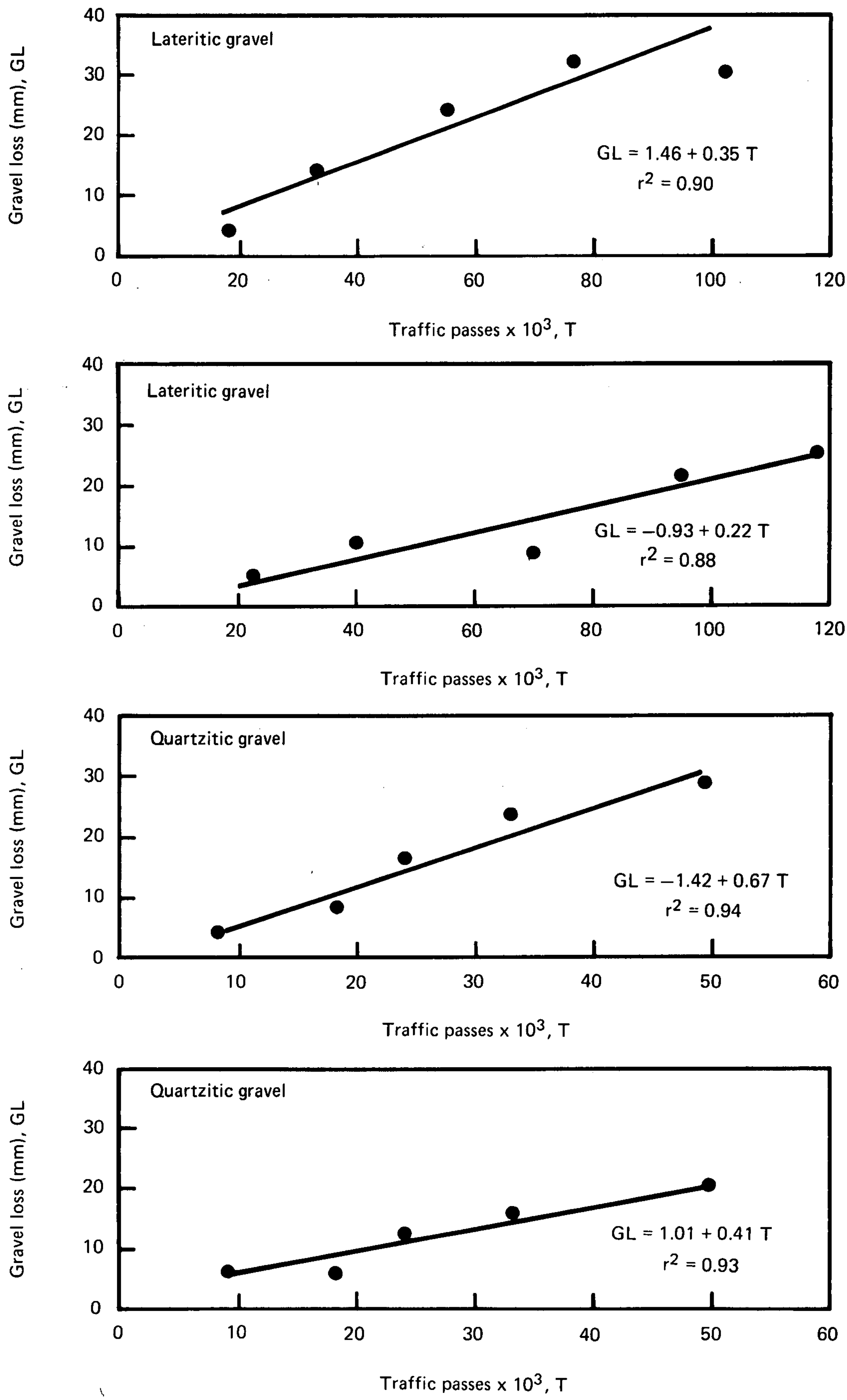


Fig.6 Gravel loss against traffic passes for some lateritic and quartzitic roads

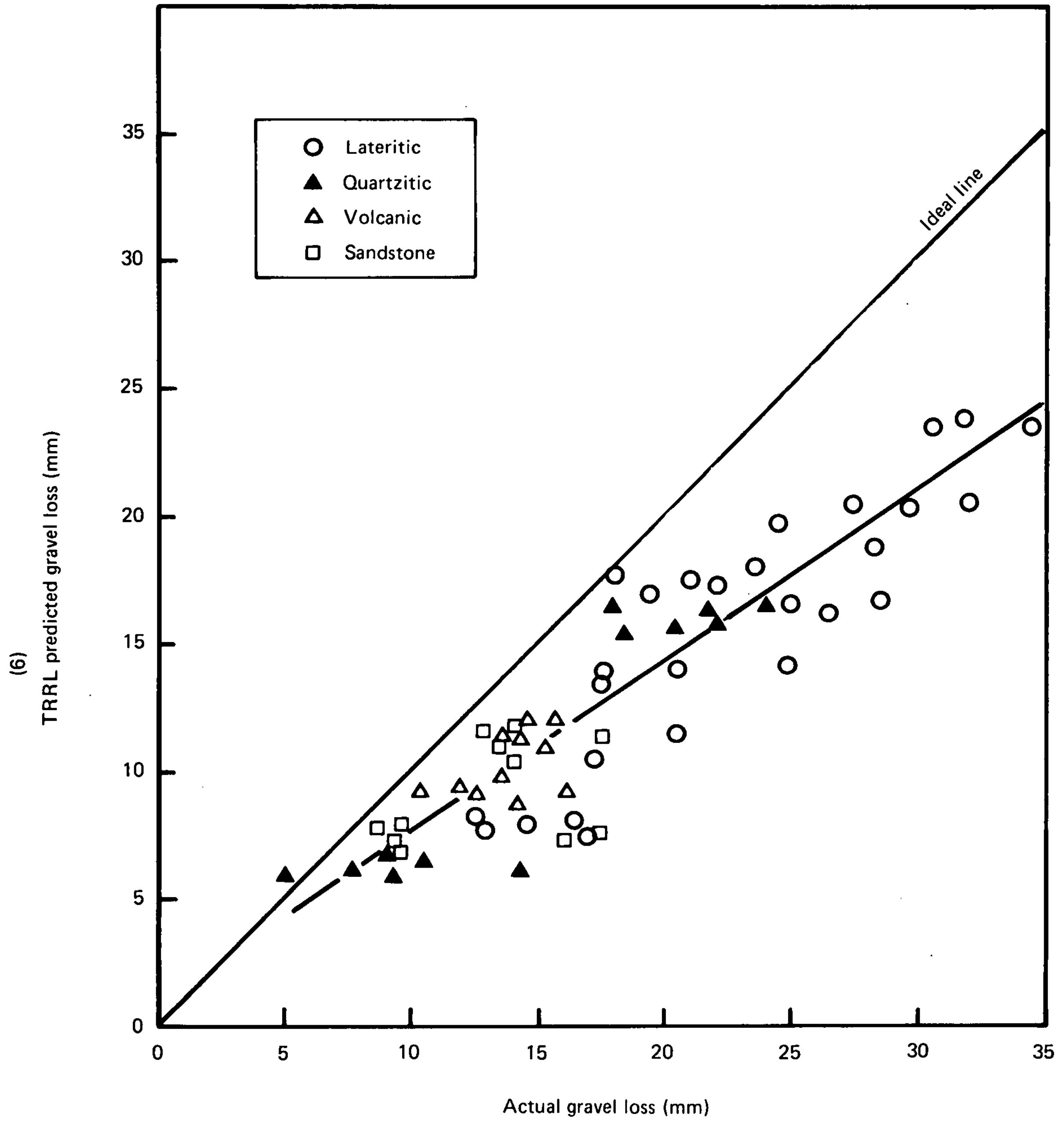


Fig.7 Predicted annual gravel loss against actual gravel loss for roads monitored in this study

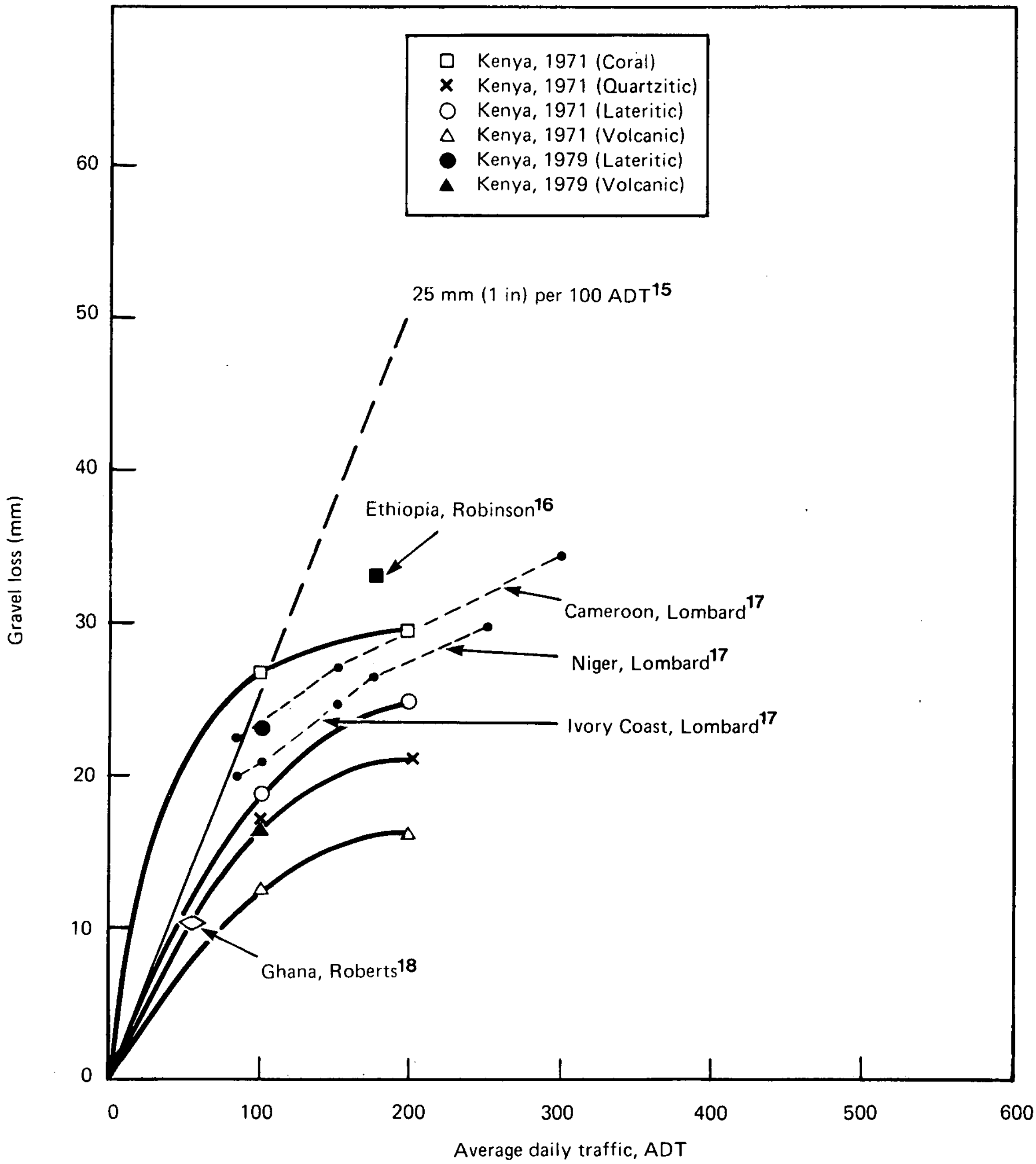


Fig.8 Gravel loss rates for different countries

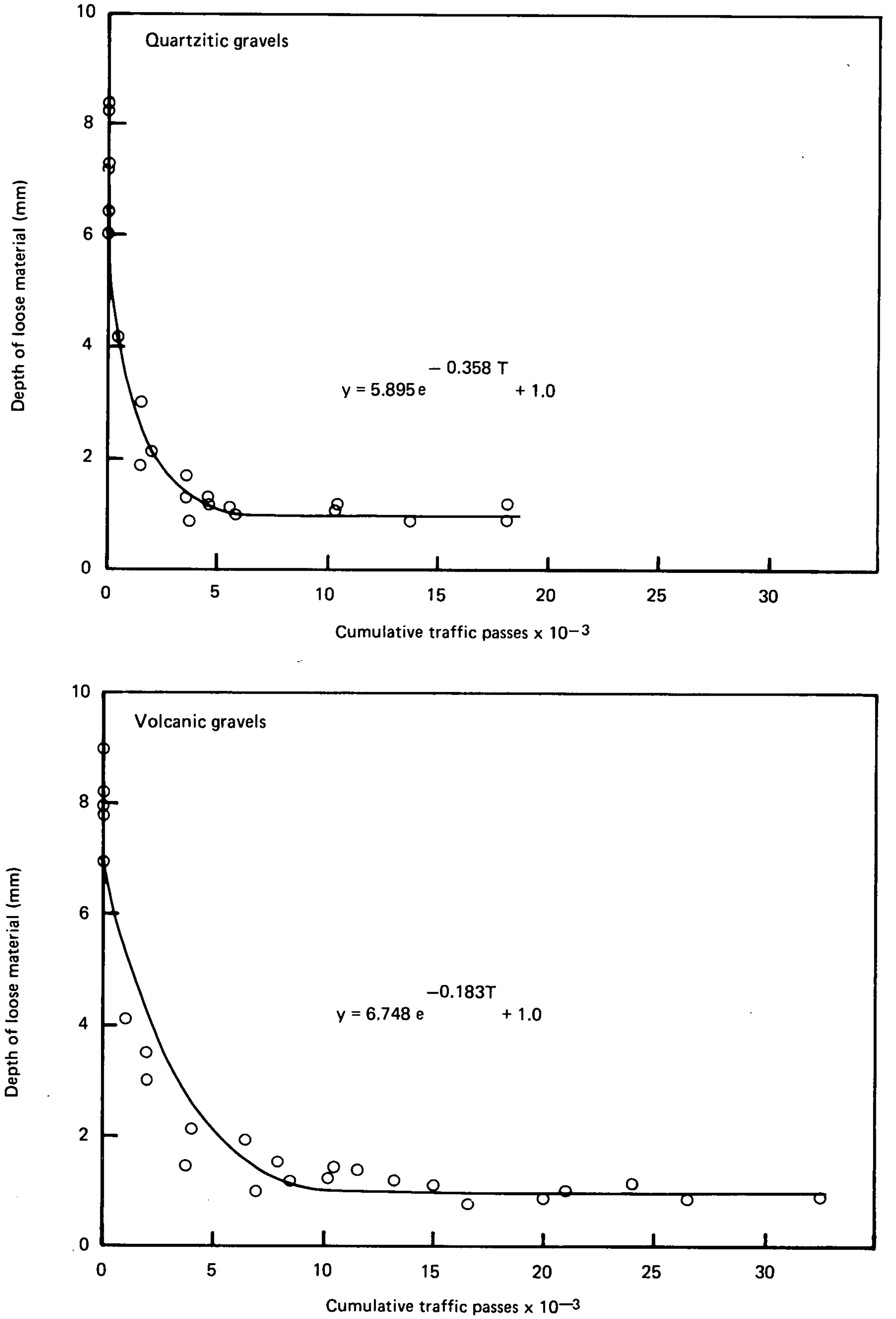


Fig.9 Relationship between depth of loose material and traffic passes for quartzitic and volcanic gravels

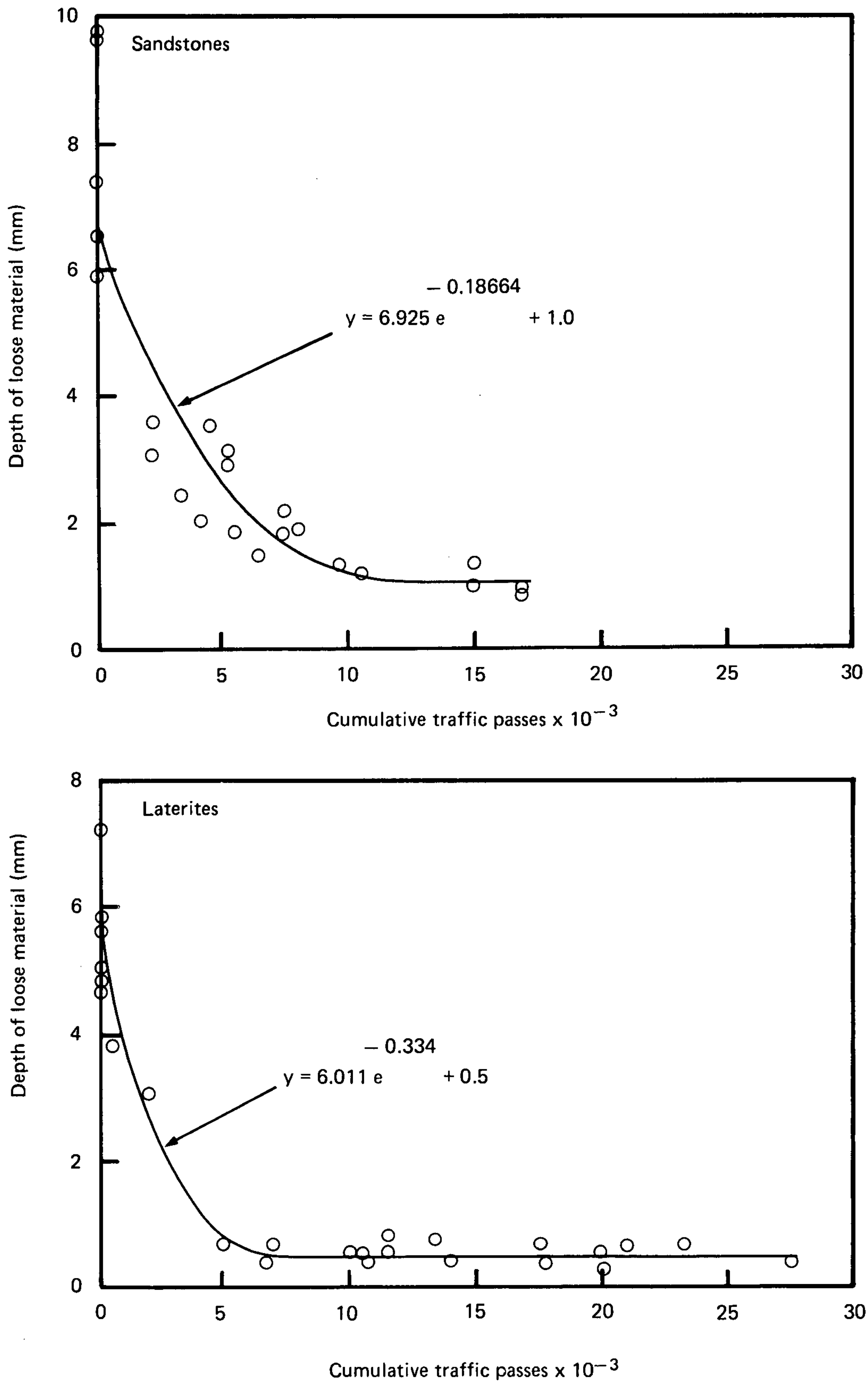
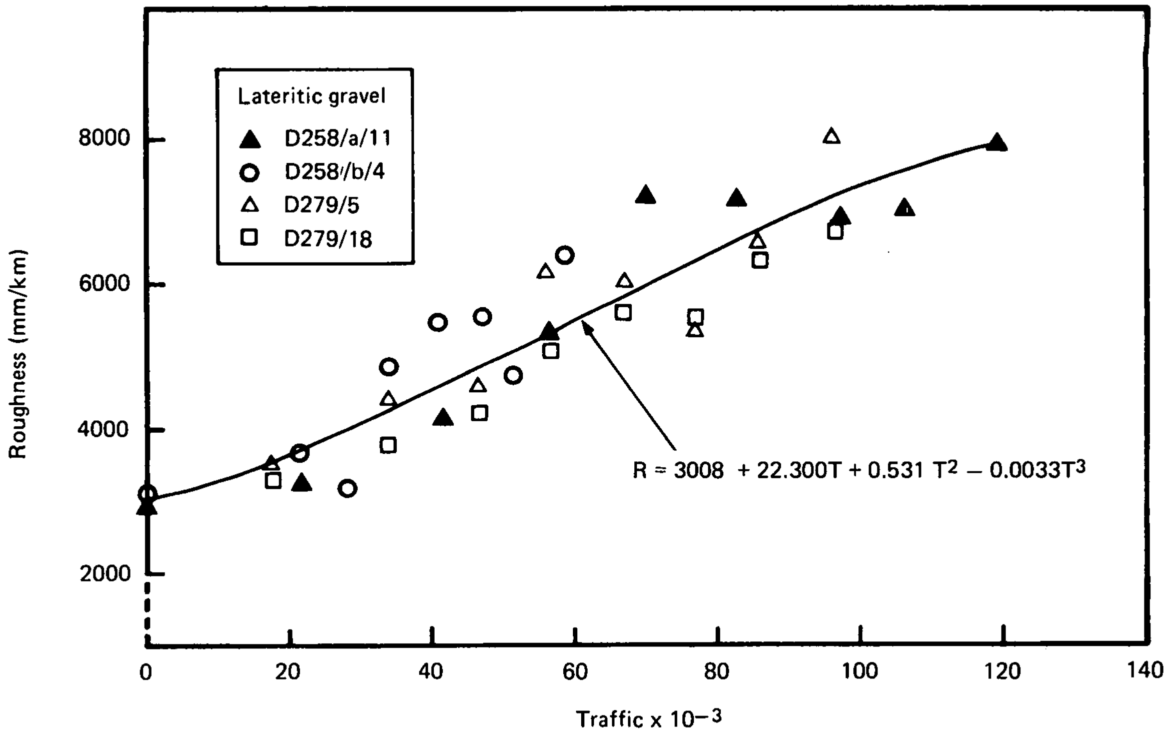


Fig.10 Relationship between depth of loose material and traffic passes for sandstone and lateritic gravels



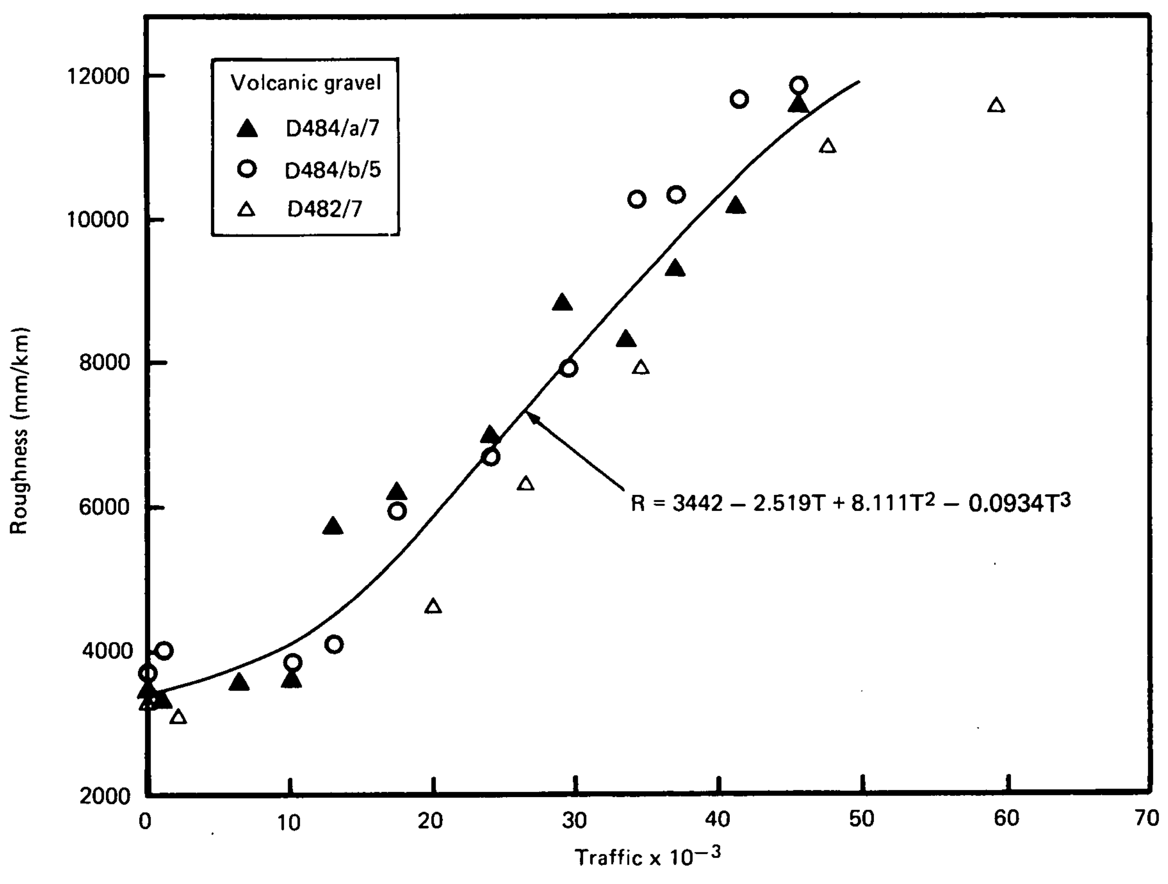
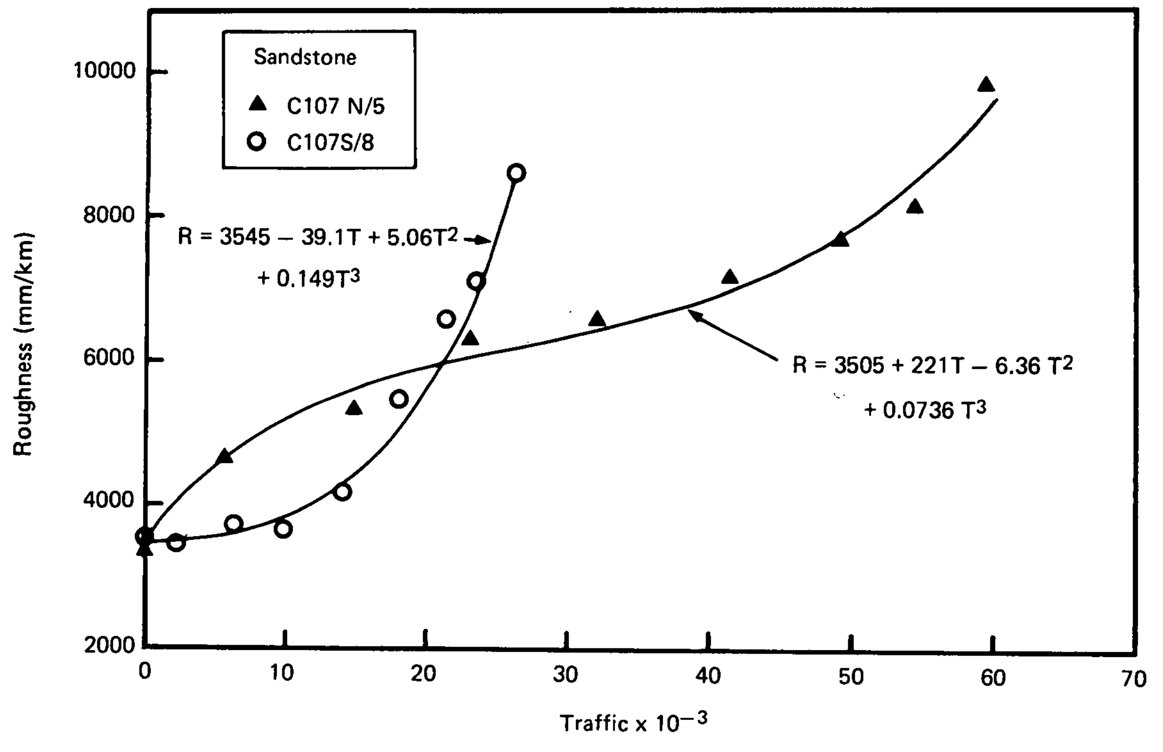


Fig.11 Relationship between roughness and traffic for lateritic and volcanic gravels



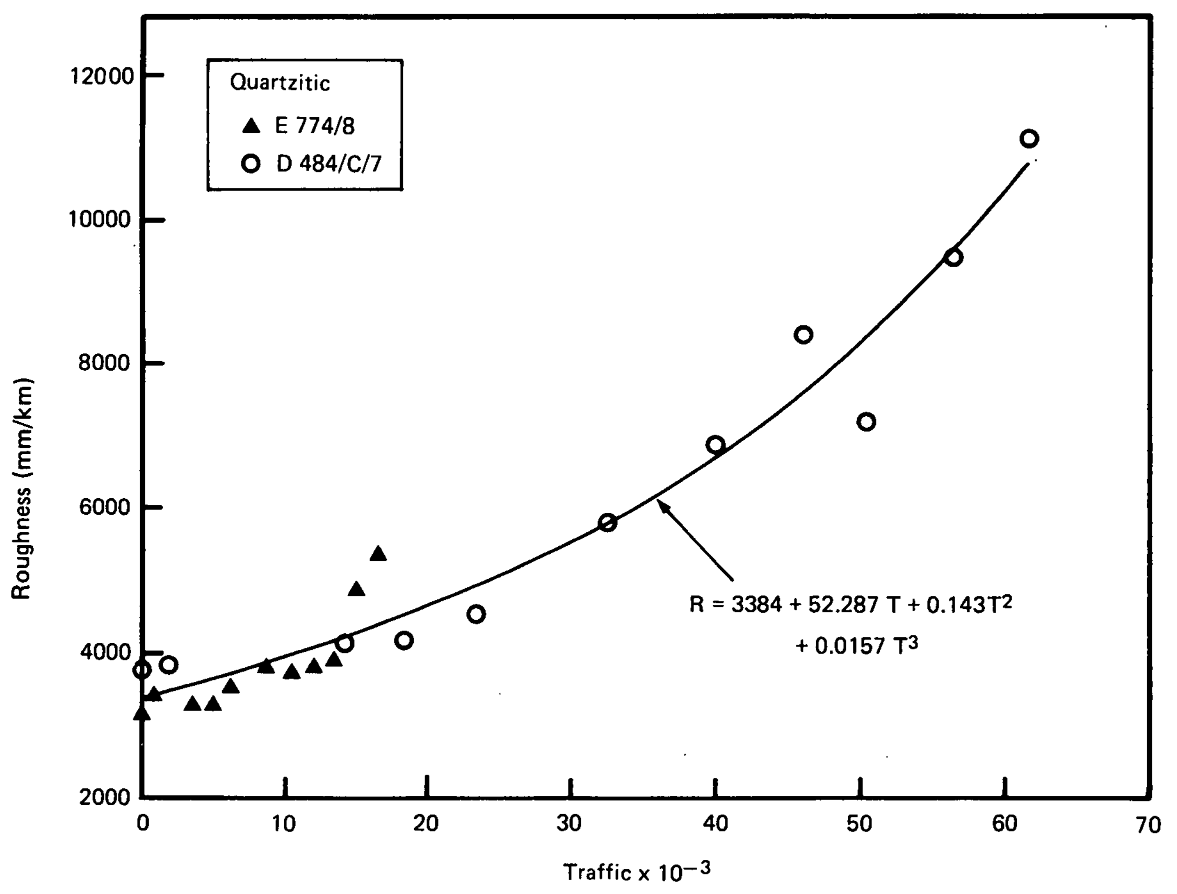


Fig.12 Relationship between roughness and traffic for sandstone and quartzitic gravels

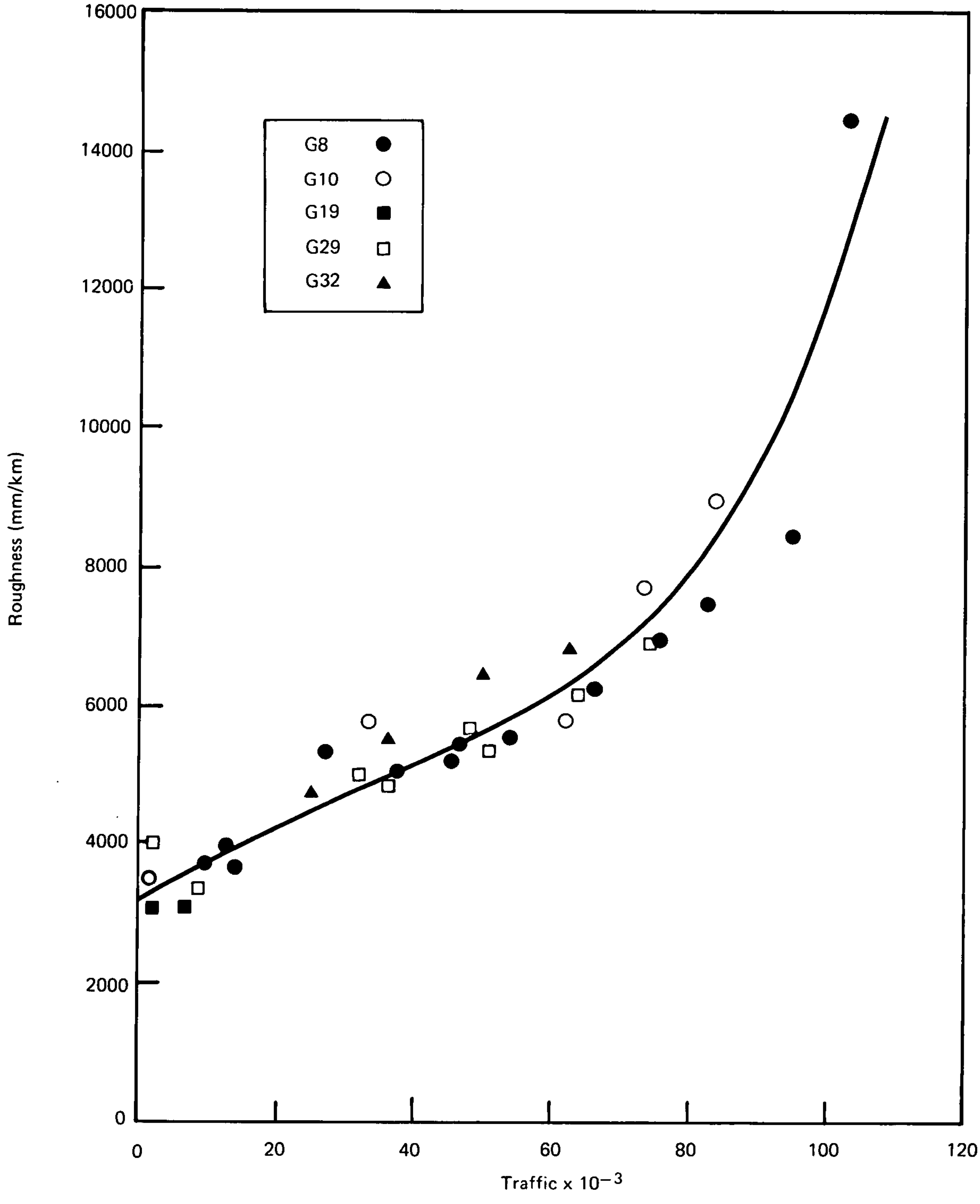


Fig.13 Relationship between roughness and traffic for lateritic, quartzitic and volcanic gravels derived from TRRL study 1971 – 1974

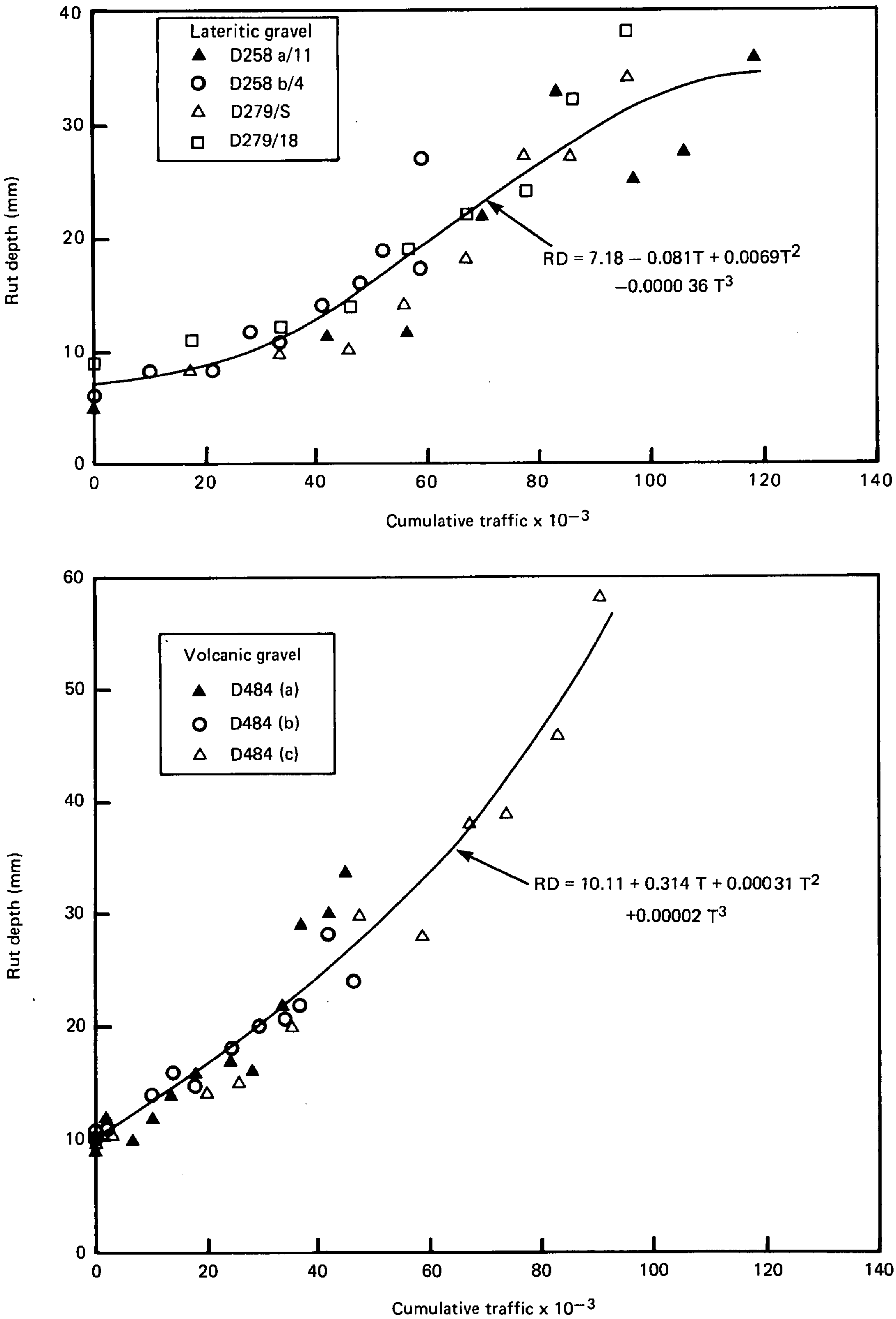


Fig.14 Relationship between rut depth and traffic for lateritic and volcanic gravels

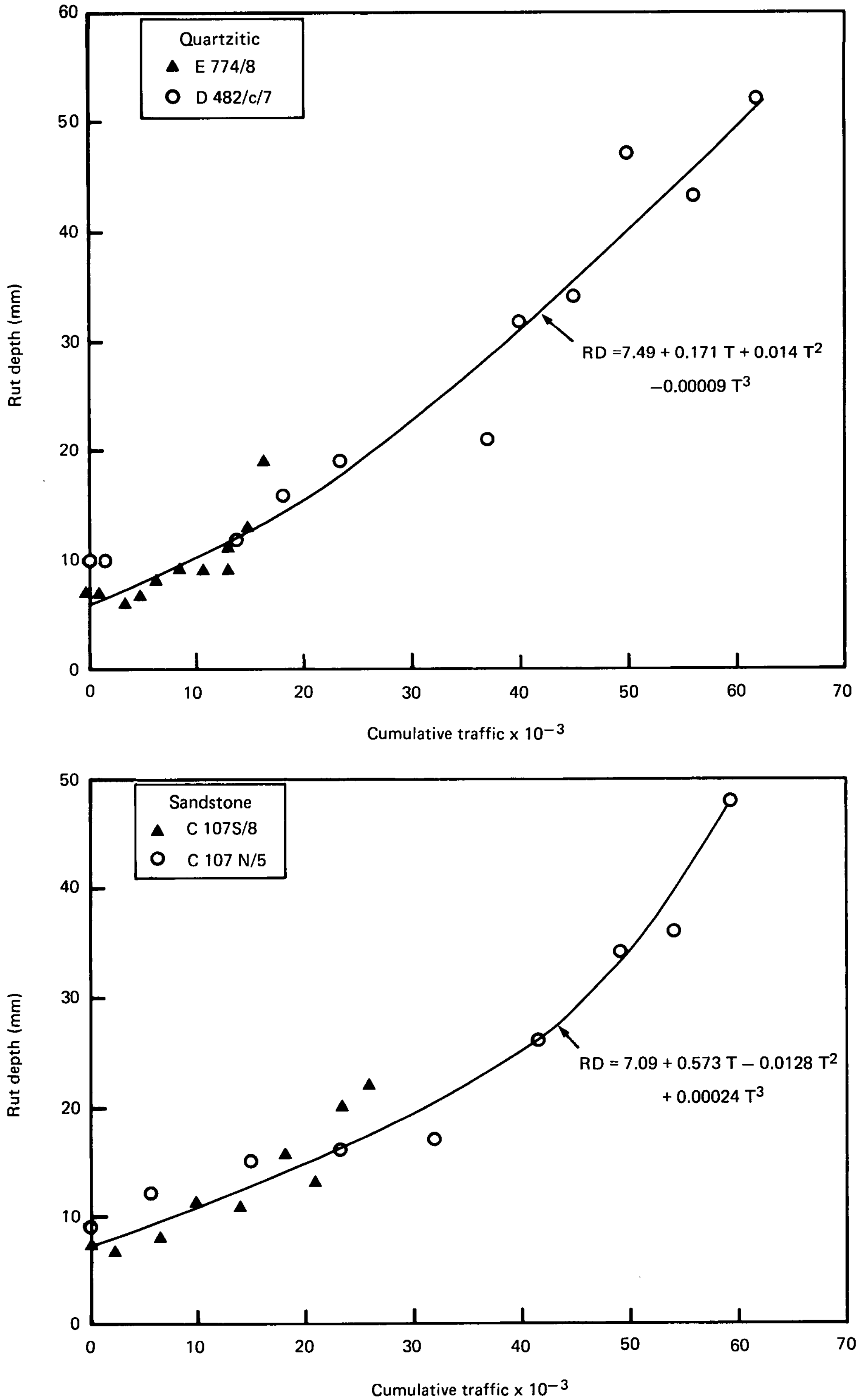


Fig.15 Relationship between rut depth and traffic for quartzitic and sandstone gravels

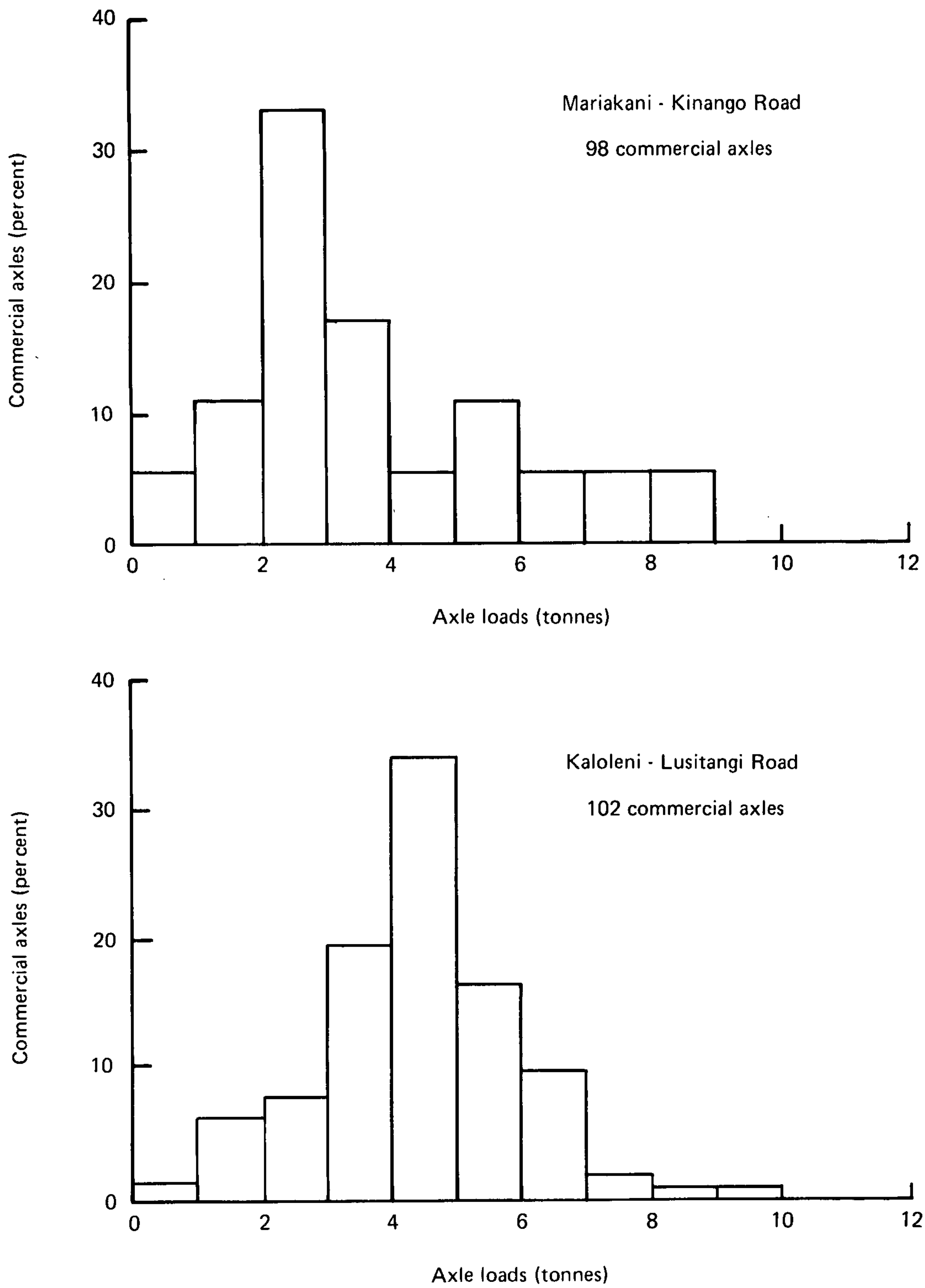
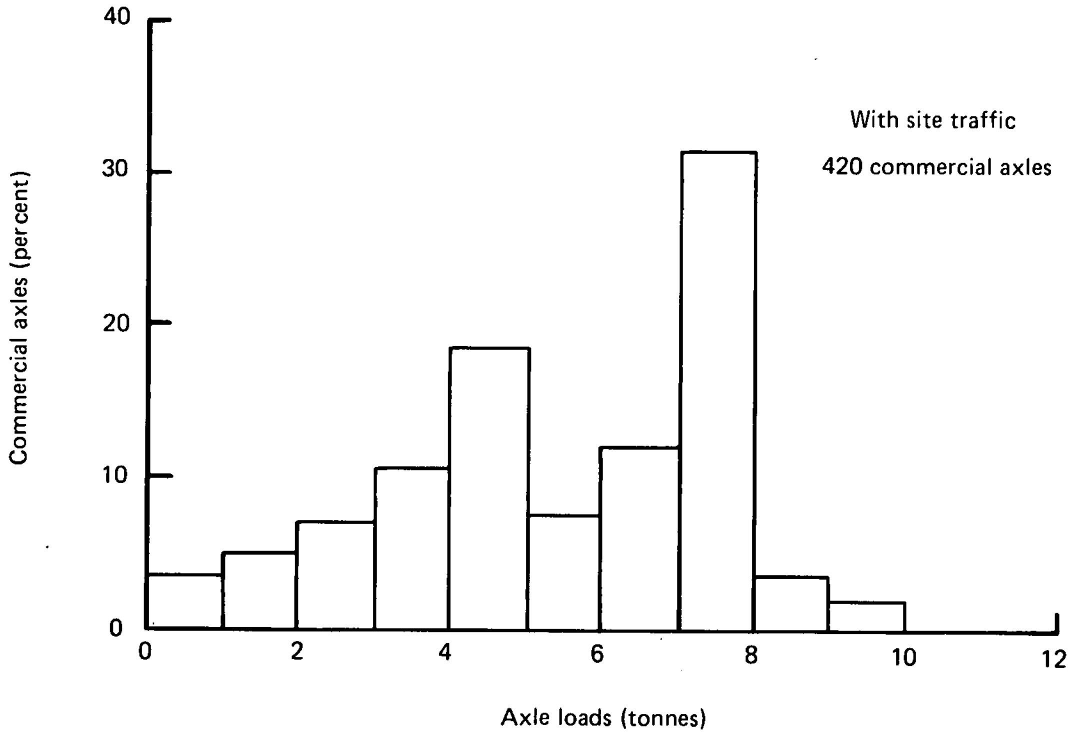


Fig.16 Distribution of axle loads on Kinango Road and Lusitangi Road in Kaloleni area



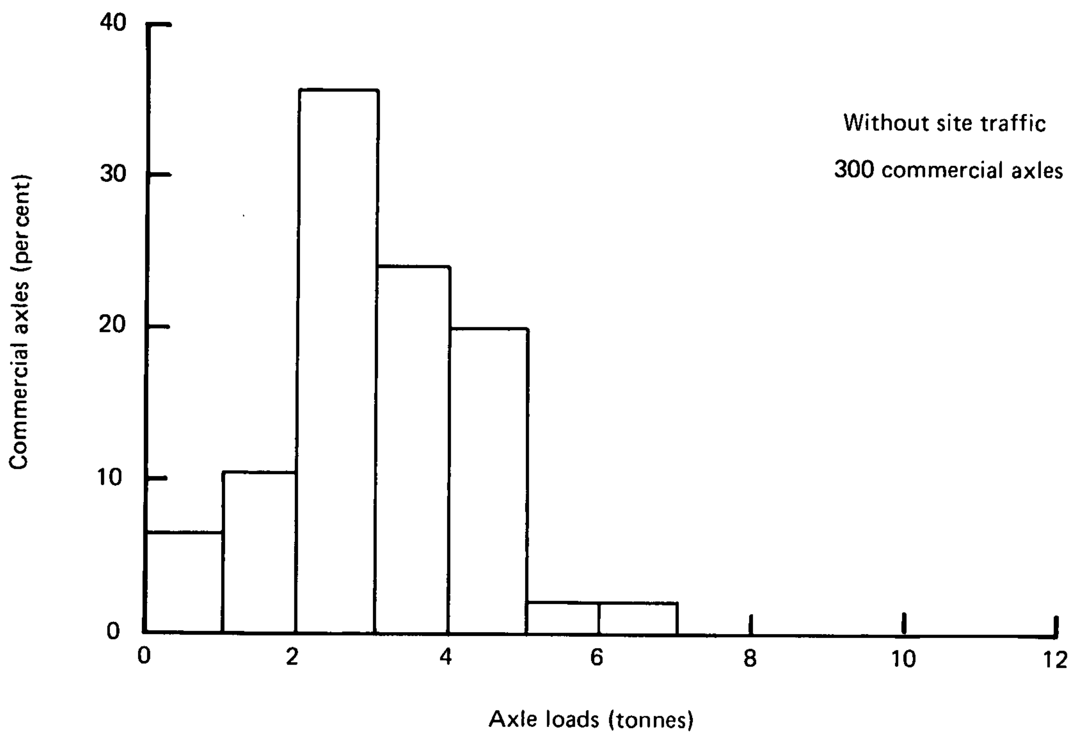


Fig. 17 Distribution of axle loads on Bungoma/Bokoli Road in Bungoma area with and without site traffic

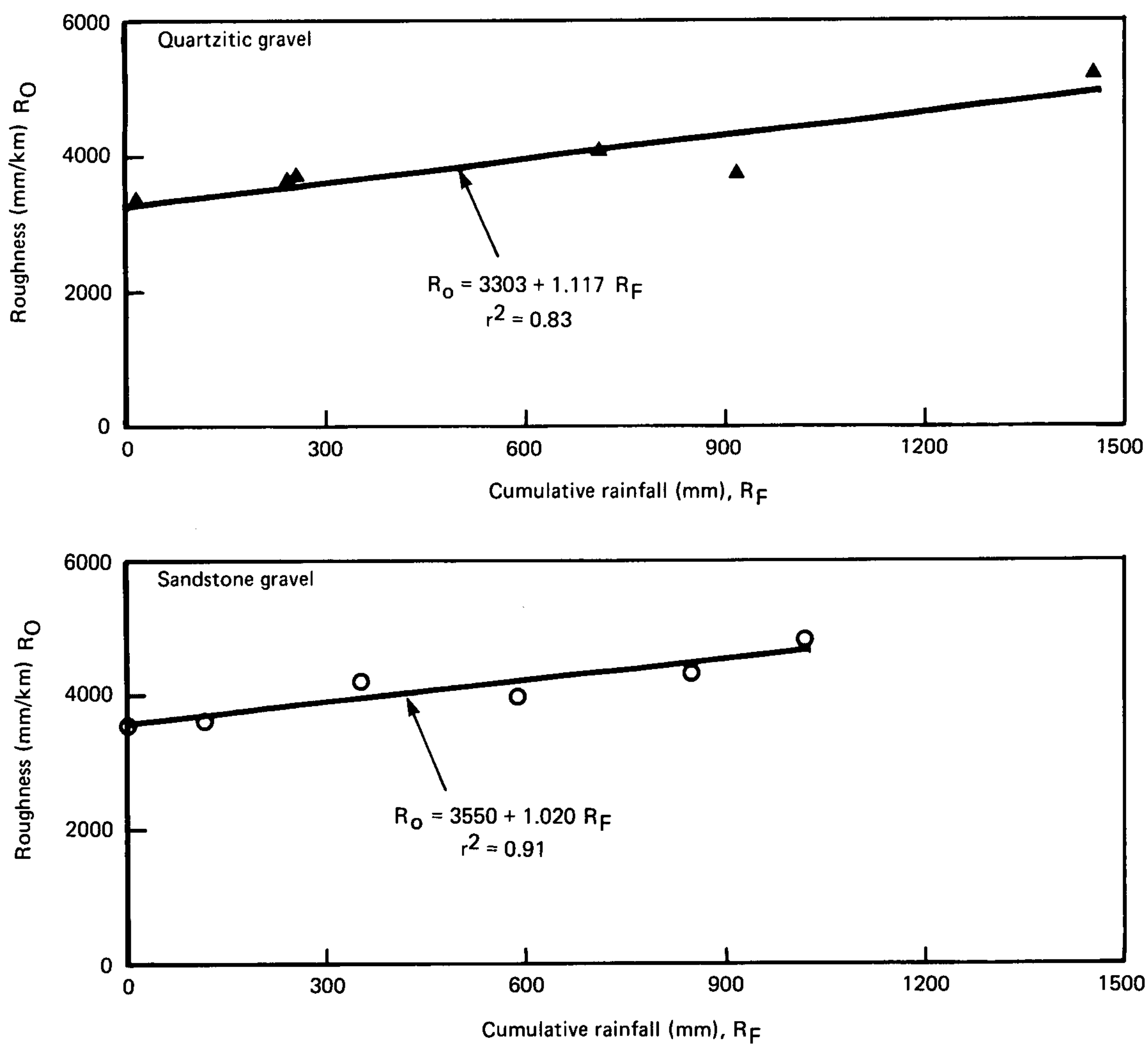


Fig.18 Roughness against cumulative rainfall for non-trafficked roads

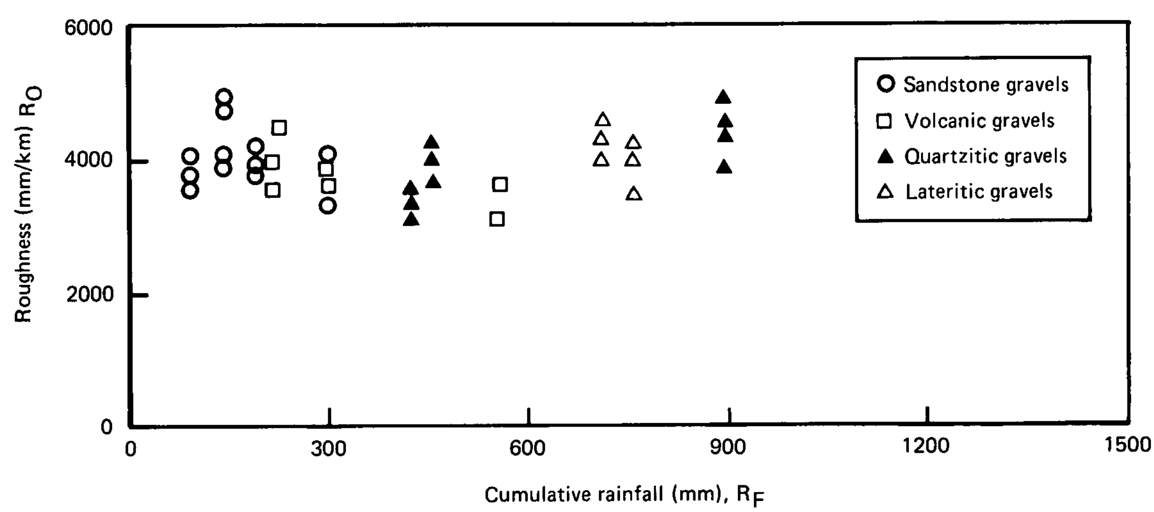
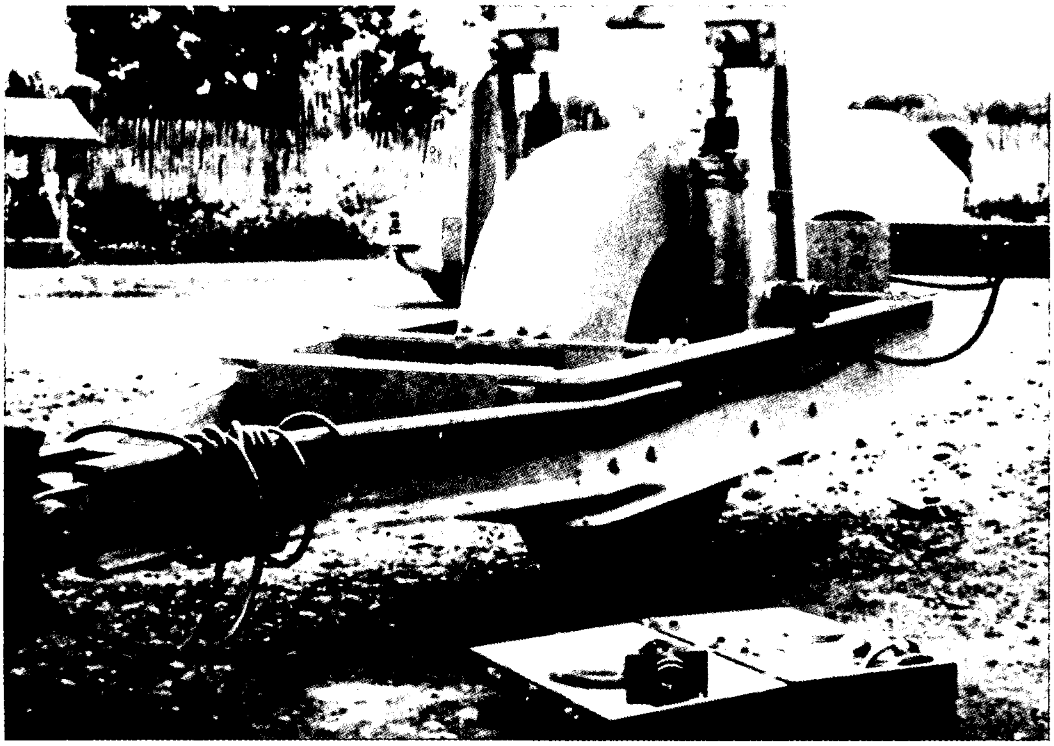
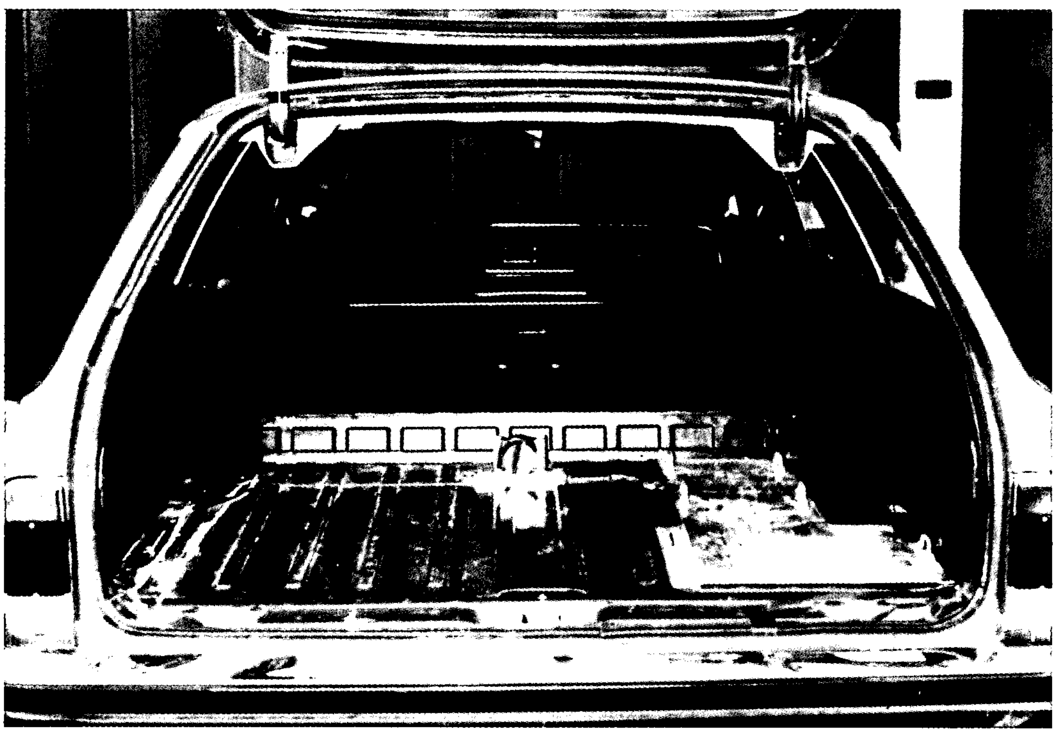


Fig.19 Relationship between roughness and cumulative rainfall for constant traffic volumes



Neg.no. E47/83

Plate 1 Towed bump integrator trailer



Neg.no. E49/83

Plate 2 Vehicle mounted bump integrator in Cortina Estate Car

Neg.no. E46/83

Plate 3 Gully erosion on steep gradient

Neg.no. E46/83

Plate 4 Transverse drainage installations

8. APPENDIX 1

SUMMARY OF THE UNPAVED ROAD DETERIORATION RELATIONSHIPS

1. *Gravel loss*

$$GL_A = f \left(\frac{T_A^2}{T_A^2 + 50} \right) (4.2 + 0.092\,T_A + 3.50\,R_L^2 + 1.88\,VC)$$

f = 1.29 for lateritic gravels
1.51 for quartzitic gravels
0.96 for volcanic gravels
1.38 for sandstone gravels

GL_A = annual gravel loss in mm

T_A = annual traffic volume in both directions measured in thousands of vehicles

R_L = annual rainfall in metres

VC = rise and fall (gradient) given as a percentage.

2. *Surface roughness*

Lateritic gravels

$$R = 3008 + 22.300T - 0.531T^2 - 0.0033T^3$$

Quartzitic gravels

$$R = 3384 + 52.287T + 0.143T^2 + 0.0157T^3$$

Volcanic gravels

$$R = 3442 - 2.519T + 8.111T^2 - 0.0934T^3$$

Sandstone gravels

$$R = 3505 + 221T - 6.360T^2 + 0.0736T^3$$

where R = roughness measured in mm/km by towed bump integrator
and T = cumulative traffic in both directions since grading and measured in thousands of vehicles.

3. *Surface rutting*

Lateritic gravels

$$RD = 7.18 - 0.081T + 0.0069T^2 - 0.000036T^3$$

Quartzitic gravels

$$RD = 7.49 + 0.171T + 0.014T^2 - 0.00009T^3$$

Volcanic gravels

$$RD = 10.11 + 0.314T + 0.00031T^2 + 0.00002T^3$$

Sandstone gravels

$$RD = 7.09 + 0.573T - 0.0128T^2 + 0.00024T^3$$

where RD = rut depth in mm measured under a 2 metre straight-edge
and T = cumulative traffic in both directions since grading and measured in thousands of vehicles.

4. *Surface looseness*

Lateritic gravels

$$DLM = 6.011e^{-0.334T} + 0.5$$

Quartzitic gravels

$$DLM = 5.895e^{-0.358T} + 1.0$$

Volcanic gravels

$$DLM = 6.748e^{-0.183T} + 1.0$$

Sandstone gravels

$$DLM = 6.925e^{-0.187T} + 1.0$$

where DLM = depth of loose material in mm
and T = cumulative traffic in both directions since grading and measured in thousands of vehicles.

9. APPENDIX 2

TABLE 1

Characteristics of experimental sections

Sections area and road	Section no	Rate of rise and fall/km per cent	Horizontal curvature degree/km	Annual rainfall mm	Annual traffic	Gravel type
Bungoma D279	1	0.8	8	940	65700	Lateritic
	2	0.9	10	940	65700	
	3	0.7	10	940	65700	
	4	1.0	14	940	65700	
	5	1.1	11	940	65700	
	6	2.8	19	1170	65700	
	7	2.7	27	1170	65700	
	8	2.3	30	1170	65700	
	9	2.9	16	1170	65700	
	10	3.0	11	1170	65700	
	11	2.4	12	1360	65700	
	12	2.6	15	1360	65700	
	13	2.7	14	1360	65700	
	14	2.8	12	1360	65700	
	15	2.2	10	1690	65700	
	16	2.5	11	1690	65700	
	17	2.7	15	1690	65700	
	18	2.8	12	1690	65700	
Bungoma D258/a	1	1.9	38	910	81760	Lateritic
	2	2.1	33	910	81760	
	3	1.8	28	910	81760	
	4	1.7	25	910	81760	
	5	1.7	25	910	81760	
	6	1.4	21	910	81760	
	7	1.5	29	910	81760	
	8	2.8	35	910	81760	
	9	2.5	40	910	81760	
	10	2.5	45	910	81760	
	11	2.2	34	910	81760	
Bungoma D258/b	1	0.3	5	590	40150	Lateritic
	2	0.3	6	590	40150	
	3	0.2	8	590	40150	
	4	0.2	0	590	40150	
	5	0.2	0	590	40150	
	6	0.2	5	590	40150	
	7	0.2	5	590	40150	
	8	0.3	6	590	40150	

TABLE 1 (continued)

Sections area and road	Section no	Rate of rise and fall/km per cent	Horizontal curvature degree/km	Annual rainfall mm	Annual traffic	Gravel type
Meru E774	1	0.6	10	970	9125	Quartzitic
	2	0.5	8	970	9125	
	3	0.7	8	970	9125	
	4	0.5	15	970	9125	
	5	0.3	10	970	9125	
	6	0.3	9	970	9125	
	7	0.8	17	970	9125	
	8	0.4	7	970	9125	
Meru D482	1	1.0	20	1250	51100	Volcanic
	2	1.3	29	1250	51100	
	3	1.1	29	1250	51100	
	4	1.0	21	1250	51100	
	5	1.3	22	1250	51100	
	6	1.5	21	1250	51100	
	7	1.4	17	1250	51100	
Meru D484/a	1	1.0	83	1250	25550	Volcanic
	2	0.8	79	1250	25550	
	3	1.1	68	1250	25550	
	4	0.9	65	1250	25550	
	5	1.3	84	1250	25550	
	6	1.1	66	1250	25550	
	7	1.0	61	1250	25550	
Meru D484/b	1	2.6	108	1380	25550	Volcanic
	2	2.1	95	1380	25550	
	3	2.5	89	1380	25550	
	4	2.2	109	1380	25550	
	5	2.0	93	1380	25550	
Meru D484/c	1	0.9	9	1380	34675	Quartzitic
	2	0.7	11	1380	34675	
	3	0.6	14	1380	34675	
	4	0.8	12	1380	34675	
	5	0.8	16	1380	34675	
	6	0.7	8	1380	34675	
	7	0.3	8	1380	34675	
	8	0.5	9	1380	34675	
Kaloleni C107/N	1	1.6	28	640	35040	Sandstone
	2	1.1	30	640	35040	
	3	1.5	26	640	35040	
	4	1.8	23	640	35040	
	5	1.5	29	640	35040	

TABLE 1 (continued)

Sections area and road	Section no	Rate of rise and fall/km per cent	Horizontal curvature degree/km	Annual rainfall mm	Annual traffic	Gravel type
Kaloleni C107/S	1	1.1	58	410	15330	Sandstone
	2	1.8	69	410	15330	
	3	1.7	60	410	15330	
	4	1.9	84	410	15330	
	5	1.6	57	410	15330	
	6	1.4	39	410	15330	
	7	1.5	55	410	15330	
	8	1.2	48	410	15330	
Kaloleni D549	1	0.5	8	320	13870	Sandstone
	2	0.7	11	320	13870	
	3	0.6	11	320	13870	
	4	0.8	7	320	13870	
	5	0.8	0	320	13870	
	6	0.8	0	320	13870	
	7	0.4	3	320	13870	
	8	0.3	8	320	13870	
	9	0.3	0	320	13870	
	10	0.5	6	320	13870	
	11	0.3	6	320	13870	
	12	0.7	5	320	13870	
	13	0.5	0	320	13870	
	14	0.5	4	320	13870	

10. APPENDIX 3

TABLE 1

Summary of vehicle speeds over experimental sections

Road no	Section no	Vehicle* class	Beginning of study speed km/h	End of study speed km/h	Difference in speed km/h
D279 Bungoma area	1–5	C	66.7	64.6	–2.1
		LG	54.6	48.7	–5.9
		MG	51.4	51.1	–0.3
		HG	N/A	N/A	–
		B	40.9	40.2	–0.7
	6–7	C	45.7	45.8	+0.1
		LG	48.7	49.3	+0.6
		MG	46.2	45.7	–0.5
		HG	N/A	N/A	–
		B	40.9	38.1	–2.8
	8–12	C	72.2	71.1	–1.1
		LG	59.0	57.6	–1.4
		MG	49.4	47.2	–2.2
		HG	N/A	N/A	–
		B	45.0	42.2	–2.8
	13–17	C	71.1	69.7	–1.4
		LG	58.1	56.6	–1.5
		MG	47.4	47.2	–0.2
		HG	N/A	N/A	–
		B	42.8	41.5	–1.3
	18	C	69.2	67.6	–1.6
		LG	58.1	55.5	–2.6
		MG	47.4	45.3	–1.9
		HG	N/A	N/A	–
		B	40.5	41.5	+1.0
D258(a) Bungoma area	1–7	C	52.9	51.8	–1.1
		LG	56.3	54.1	–2.2
		MG	50.2	47.6	–2.6
		HG	N/A	40.9	–
		B	50.3	50.6	+0.3
	8–10	C	52.9	51.9	–1.0
		LG	55.0	53.9	–1.1
		MG	48.0	47.6	–0.4
		HG	41.9	40.2	–1.7
		B	50.2	51.7	+1.5
	11	C	110.7	112.9	+2.2
		LG	69.2	66.3	–2.9
		MG	66.7	64.4	–2.3
		HG	N/A	N/A	–
		B	61.3	59.9	–1.4

* C = Cars LG = Light goods MG = Medium goods HG = Heavy goods B = Buses

TABLE 1 (continued)

Road no	Section no	Vehicle class	Beginning of study speed km/h	End of study speed km/h	Difference in speed km/h
D258(b) Bungoma area	1–3	C	112.5	112.3	–0.2
		LG	66.7	65.8	–0.9
		MG	65.2	63.9	–1.3
		HG	N/A	N/A	–
		B	58.1	59.8	+1.7
	4	C	104.8	110.6	+5.8
		LG	64.0	61.4	–2.6
		MG	61.5	60.9	–0.6
		HG	N/A	N/A	–
		B	58.1	58.8	+0.7
	5–8	C	108.5	112.3	+3.8
		LG	69.2	65.3	–3.9
		MG	66.7	63.1	–3.6
		HG	N/A	N/A	–
		B	59.9	59.1	–0.8
E774 Meru area	1–3	C	65.1	63.6	–1.5
		LG	62.1	60.1	–2.0
		MG	59.1	58.0	–1.1
		HG	N/A	N/A	–
		B	38.9	39.1	+0.2
	4–7	C	62.1	63.8	+1.7
		LG	61.6	60.2	–1.4
		MG	58.1	58.2	+0.1
		HG	N/A	N/A	–
		B	42.4	42.1	–0.3
	8	C	69.2	64.1	–5.1
		LG	66.7	60.1	–6.6
		MG	61.1	59.3	–1.8
		HG	N/A	N/A	–
		B	42.4	41.9	–0.5
D482 Meru area	1–3	C	47.8	46.3	–1.5
		LG	42.9	46.7	+3.8
		MG	36.7	33.5	–3.2
		HG	N/A	N/A	–
		B	47.8	49.1	+1.3
	4–6	C	48.7	46.8	–1.9
		LG	48.6	46.8	–1.8
		MG	36.7	35.1	–1.6
		HG	N/A	N/A	–
		B	47.8	49.9	+2.1
	7	C	48.7	47.2	–1.5
		LG	48.7	44.9	–3.8
		MG	35.3	34.0	–1.3
		HG	N/A	N/A	–
		B	48.9	48.8	–0.1

TABLE 1 (continued)

Road no	Section no	Vehicle class	Beginning of study speed km/h	End of study speed km/h	Difference in speed km/h
D484(a) Meru area	1–6	C	66.7	65.4	–1.3
		LG	55.3	53.5	–1.8
		MG	43.8	39.6	–4.2
		HG	N/A	N/A	–
		B	42.2	40.9	–1.3
	7	C	64.3	63.2	–1.0
		LG	54.5	52.2	–2.3
		MG	39.1	37.4	–1.7
		HG	N/A	N/A	–
		B	39.1	40.7	+1.6
D484(b) Meru area	1–2	C	48.7	44.1	–4.6
		LG	34.6	31.8	–2.8
		MG	40.9	36.9	–4.0
		HG	N/A	N/A	–
		B	42.9	40.2	–2.7
	3–4	C	47.6	43.8	–3.8
		LG	34.0	30.6	–3.4
		MG	41.9	36.3	–5.6
		HG	N/A	N/A	–
		B	41.9	39.5	–2.4
	5	C	48.7	42.2	–6.5
		LG	36.0	29.0	–7.0
		MG	43.9	33.3	–10.6
		HG	N/A	N/A	–
		B	41.9	39.0	–2.9
D484(c) Meru area	1–4	C	58.1	55.4	–2.7
		LG	64.3	60.6	–3.7
		MG	47.4	47.1	–0.3
		HG	N/A	N/A	–
		B	39.1	40.7	+1.6
	5–8	C	59.1	54.7	–4.4
		LG	58.1	56.9	–1.2
		MG	47.4	48.3	+0.9
		HG	N/A	N/A	–
		B	42.9	41.2	–1.7
C107(S) Kaloleni area	1–4	C	N/A	58.0	–
		LG	58.1	54.5	–3.6
		MG	48.7	46.2	–2.5
		HG	29.0	30.5	+1.5
		B	51.4	48.8	+2.6
	5–7	C	63.0	58.0	–5.0
		LG	57.8	54.5	–3.3
		MG	44.3	47.6	+3.3
		HG	26.9	29.0	+2.1
		B	45.0	47.8	+2.8

TABLE 1 (continued)

Road no	Section no	Vehicle class	Beginning of study speed km/h	End of study speed km/h	Difference in speed km/h
C107(S) continued	8	C	55.9	56.3	+0.4
		LG	54.5	53.5	−1.0
		MG	48.6	47.6	−1.0
		HG	32.7	29.3	−3.4
		B	49.2	46.2	−3.0
C107(N) Kaloleni area	1–4	C	66.7	63.0	−3.7
		LG	58.0	53.5	−4.5
		MG	49.3	48.5	−0.8
		HG	36.0	32.7	−3.3
		B	54.5	52.7	−1.8
	5	C	67.1	63.1	−4.0
		LG	56.3	51.9	−4.4
		MG	48.7	48.0	−0.7
		HG	N/A	31.9	–
		B	50.9	51.9	+1.0

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ABSTRACT

THE KENYA MAINTENANCE STUDY ON UNPAVED ROADS: RESEARCH ON DETERIORATION: *T E Jones:* Department of the Environment Department of Transport, TRRL Laboratory Report 1111: Crowthorne, 1984 (Transport and Road Research Laboratory). This report describes a study of the deterioration of unpaved roads which was undertaken in Kenya. The work formed part of a larger study of the effectiveness of various maintenance strategies on the performance of unpaved roads.

The primary objective of the research described in this report was to provide new and improved deterioration relationships for unpaved roads for use in a computer model for estimating the construction costs, maintenance costs and vehicle operating costs of roads in development countries.

Experimental test sections were located on the public road network in Kenya and their rates of deterioration were measured and quantified in terms of gravel loss of the wearing course, surface roughness, depth of loose surface material and rut depths. The test sections were monitored for a period of over 2 years. The deterioration of the test sections was related to cumulative traffic, original design standards and construction, maintenance strategy and climate.

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