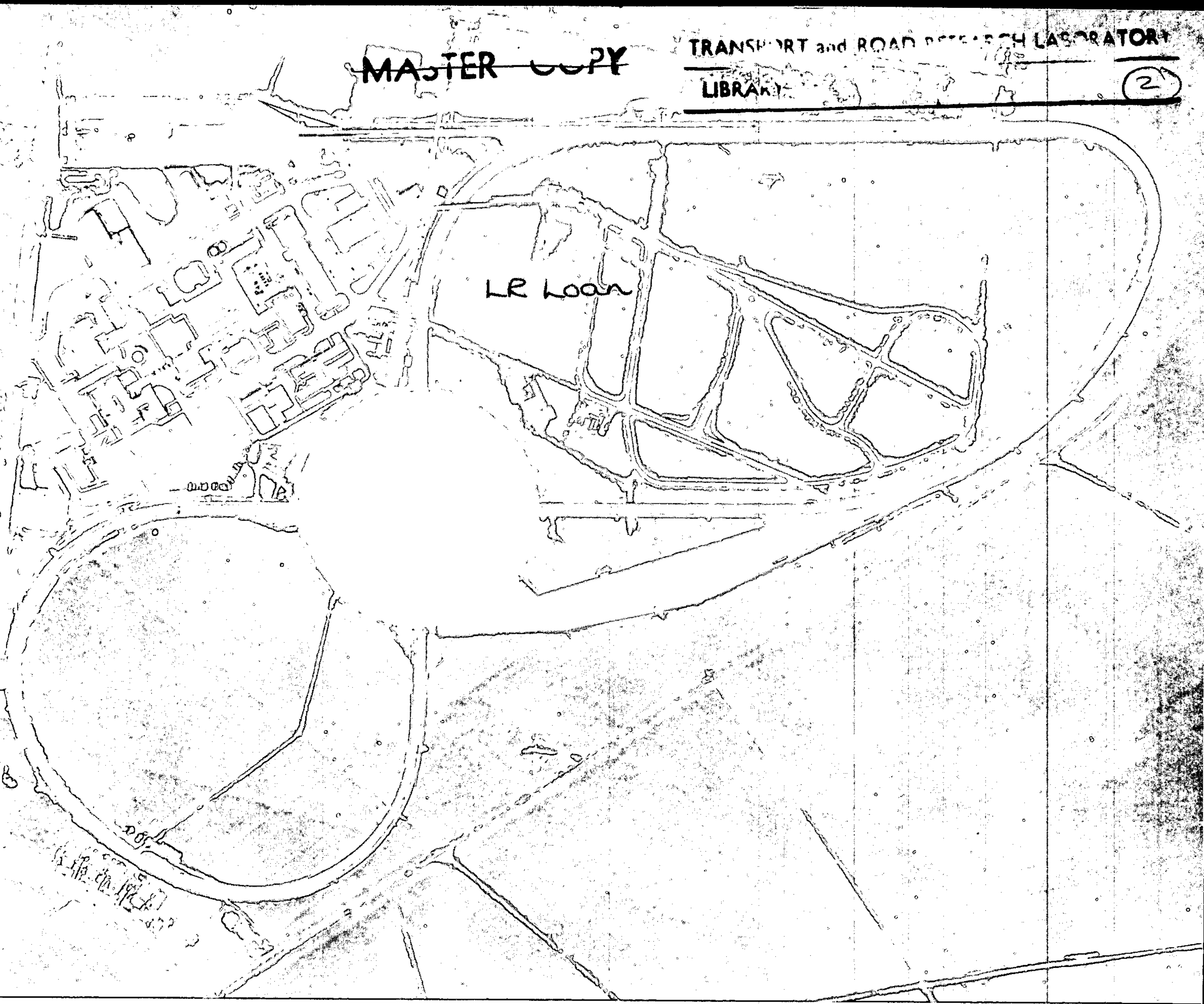
TRRL Laboratory Report 1002

TRANSPORT and ROAD RESEARCH LABORATORY

DEPARTMENT of the ENVIRONMENT DEPARTMENT of TRANSPORT



Optimum axle loads of commercial vehicles in developing countries

by

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

Overseas Unit
Transport and Road Research Laboratory
Crowthorne, Berkshire
1981
ISSN 0305–1293

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ABSTRACT

The Road Transport Investment Model for developing countries has been used to examine the effects of different axle loading characteristics on the total costs of road transport. It is shown that the sum of vehicle operating costs, road construction costs and road maintenance and rehabilitation costs for a two lane highway initially decrease rapidly as the axle load of the most heavily loaded vehicles increases and passes through a shallow minimum at the optimum axle load.

The value of this optimum axle load was found to be strongly dependent on the total freight tonnages carried by the heavily loaded vehicles, the load condition of these vehicles on the return trip, the exponent of the pavement damage – axle load relationship, and the relative prices of the major components of road transport cost. The optimum axle load was found to be virtually independent of the road alignment and strength of the subgrade, but the road construction and strengthening policy and the composition of the vehicle fleet had a small but significant effect on its value.

It is shown that under most conditions there exists a traffic level above which the optimum axle load is above the current legal limits in force in most developing countries.

The total road transport costs were usually found to be relatively insensitive to axle load in the region of the minimum total transport cost, changes in axle loads of 10 per cent producing changes in the transport costs of less than 1 per cent.

1. INTRODUCTION

The cost of operating a road transport system consists of two main components, namely the cost of operating the fleet of vehicles using the roads and the cost of constructing and maintaining the roads themselves. The cost of transporting a particular tonnage of freight decreases quite rapidly as the amount of freight which each vehicle carries increases. On the other hand the cost of providing and maintaining the roads increases as vehicle axle loads increase. The magnitude of these component costs and their variation with axle load ensures that under most circumstances the total cost of operating the transport system initially decreases as axle load increases but passes through a minimum value at the optimum axle load before increasing again. Most developing countries spend a large proportion of their scarce resources on road transport. It is therefore particularly desirable in such countries that the road transport system should operate under conditions which minimise the total cost. This report discusses the relationship between axle load and road transport costs in developing countries and considers the 'optimum' axle load at which the total road transport costs are minimised.

The legal limits for axle loads in industrialised countries have increased slowly over the last few decades, but until relatively recently the economic justification for changes in these legal limits has not been examined very closely. Formerly the basic data were not available to enable either the cost of operating the vehicle fleet to be calculated or the estimation of the additional pavement damage caused by the heavier axle loads to be made. This has been partly rectified as a result of the AASHO Road Test in which the damaging effect of different axle loads on a variety of pavement structures was quantified[1]. In addition several major studies[2,3] of the factors which influence the cost of operating vehicles have been made and it is now possible to conduct incremental analyses to show the economic effects of increases in axle loads. Studies of this kind have been made in several industrialised countries[4,5] with the conclusion that from a purely economic point of view, increases in present legal axle load limits are justified under a wide variety of conditions. For example in a study completed about ten years ago in the United States of America[5] it was found that if legal axle weight limits throughout the country were increased to 11.8 tonnes on a single axle and 20.0 tonnes on a tandem axle on all federal-aid highways the total benefit-cost ratio would be 12:1. To quote a recent report[6] 'The magnitude of these figures was so startling and so contrary to the expectations of highway officials that they were not readily accepted. A subsequent sensitivity analysis and assessment of the calculations indicated that the benefit-cost ratios were of such a magnitude as to be insensitive to any reasonable combination of possible errors'.

The legal limits for axle loads in developing countries differ widely from country to country ranging from 4 tonnes to 13 tonnes on a single axle and from 8 tonnes to 20 tonnes on a tandem axle. Indeed some countries have no legal limit on axle loads at all. To some extent these limits reflect the different environmental and social conditions of each country but economic analyses have rarely, if ever, been used to justify them.

In many developing countries vehicles are often loaded above the legal load limits. In axle load surveys carried out in various countries[7,8], it has been found that up to 70 per cent of commercial vehicles are overloaded in this way, a typical figure being about 30 per cent. Not only are the number of vehicles which are overloaded large but the magnitude of the overloading is high. For example it has been shown that on one trunk road in Kenya the *average* equivalence factor for commercial vehicles is over five times the value which would be obtained if the vehicles were loaded to the current legal limits. Although the damaging effect of these heavily loaded vehicles on the pavement has been appreciated the overall economic consequence of operating heavy vehicles with high axle loads has rarely been examined. In particular the relationship between the optimum axle load, the legal axle load limits and the spectrum of observed axle loads has not been studied in detail for a developing country.

Recognising the magnitude of the benefits which can arise from operating the road transport system under conditions which give rise to a minimum total cost, some developing countries are now attempting to rationalise the operation of their road transport system. An important step in this process is the selection of legal limits for axle loads. This report illustrates how the Road Transport Investment Model[9] can be used to calculate the costs and benefits associated with different axle loads. The main factors which affect the value of the optimum axle load are identified and the sensitivity of the optimum to changes in these factors is examined. It is shown that under most conditions higher legal axle load limits than are currently in force in most developing countries are justified for a given vehicle fleet and the magnitude of the benefits which would be forgone if existing legal limits were genuinely enforced is very large indeed. This conclusion applies whether new road construction or the strengthening of an existing road network is considered.

2. METHOD OF ANALYSIS

2.1 Introduction

To appreciate the relative importance of the variables which affect the optimum axle load for a trunk road in a developing country and the interactions between them, the actual situation was initially simplified. As the analysis proceeded these simplifications were removed until finally an example of a complete analysis for a trunk road in a developing country is presented. No attempt has been made to conduct an analysis for the road network of an entire country for the reasons outlined in Section 6.1.

Initially it was assumed that all the freight is transported by a fleet consisting of one type of vehicle and that all the vehicles are loaded to the particular axle load under consideration. The total transport costs for this simplified situation were then calculated for a particular total freight tonnage carried over a fifteen year analysis period. The calculations were then repeated for different axle loads to determine the minimum total costs and the corresponding optimum axle load. This complete series of calculations was then repeated for different total freight tonnage ranging from 0.5 to 10.0 million tonnes. Further analyses were then performed to show how the minimum total costs and optimum axle loads depend on the other variables discussed below. The calculations themselves were all performed using the Road Transport Investment Model for developing countries (RTIM) which is described in detail elsewhere[9,10].

2.2 Factors included in the analysis

The analysis was designed to show how the optimum axle load depends on the following principal factors.

1) Total freight tonnage carried.
2) Terrain and road alignment.
3) Subgrade strength.
4) Pavement damage relationship.
5) Relative prices of the major components of road transport costs.
6) Vehicle wastage or wear rates.
7) Stage construction policy for the pavement.
8) Type of vehicle and axle configuration.
9) Vehicle load condition.
10) Road maintenance policy.

2.3 Method of computation – main series

The computational procedure is outlined in Figure 1. In this section of the report the ranges of the various parameters included in the analysis are described.

The main series of calculations is defined by loops 1 and 2 in Figure 1. At the beginning of loop 1 the vehicle type or types have already been chosen and once the freight tonnage and rear axle load have also been selected the total number of vehicle trips can be calculated (Section 2.4.7). It was assumed throughout this study that the growth rate of traffic (or freight) was constant at 5 per cent per year. Using this assumption the first year average daily traffic was calculated as required by the model input. Next the pavement was designed, according to the selected construction policy, using established pavement design procedures as described in Section 3.1. Finally the Road Transport Investment Model was run to obtain the road construction costs, vehicle operating costs and road maintenance costs. The rear axle load of the vehicles was then changed keeping the total freight tonnage constant and the sequence of operations repeated. For tandem axles the total rear axle load on the pair of axles was varied from 6 tonnes up to 32 tonnes and for single axles from 4 tonnes up to 16 tonnes. The sequence of loop 1 was then repeated for different total freight tonnages (loop 2) and the results plotted as a series of graphs showing, for each freight tonnage, the dependence on rear axle load of

a) Vehicle operating costs.
b) Road construction and maintenance costs.
c) Total transport costs.

Graphs of this kind were produced for the complete range of the variables discussed in the following sections.

The model input data are summarised in Appendix 1.

2.4 Method of computation – subsidiary series

2.4.1 Terrain and subgrade. Three types of terrain were selected namely flat, rolling and hilly and three values of subgrade strength, defined by CBR values of 3, 7 and 15 per cent. The vertical alignment of the roads in the three terrain areas is shown in Appendix 1.

The only costs which are of interest in this analysis are those which depend on the load imposed by the main load-bearing axles of the vehicles. Thus the principal effect of the road alignment is on the vehicle operating costs which depend in a complex manner on vehicle weight and road geometry. The subgrade strength directly influences the structural design of the pavement which is extremely dependent on the axle loads imposed. The costs of the additional earthworks associated with the rolling and hilly terrain are independent of axle load.

2.4.2 Pavement damage relationship. The structural damage to a pavement caused by static wheel loads is given by an empirical equation of the following form:

$$(\text{Pavement damage}) \ \alpha \ (\text{Axle load})^n$$

The value of the exponent, n, is generally taken to be about 4.5 but there is considerable uncertainty as to its exact value under different conditions. A partial reanalysis of the AASHO Road Test[1] is given in Reference 11 where it is shown that n can vary from 2.4 up to 6.6 under extreme conditions.

It was concluded that for heavy wheel loads on roads of medium or high strength, as measured by the structural number, the value of n was in the range 3.2–5.6. In this study a value of 4.5 has been used for most of the calculations but a value of 6.0 has also been used to examine the sensitivity of the results to the value of this exponent.

2.4.3 Price structure. Both the vehicle operating costs and pavement structural costs are strongly dependent on the cost of products derived from crude oil. In recent years these costs have risen rapidly in real terms hence the sensitivity of the value of the optimum axle load to the price structure, in particular the price of petrol and bitumen, has been examined. Only two alternatives were studied namely the prices which applied in Kenya two years before and one year after the large rise in the price of crude oil which took place in 1974. Details of the prices used in the analysis are contained in Appendix 1.

2.4.4 Vehicle wastage. Vehicle operating cost data were collected for the fleet of vehicles operating in Kenya as part of the study which lead to the production of the Road Transport Investment Model[3]. In Kenya, as in most developing countries, vehicles are often heavily overloaded hence the vehicle operating costs which were obtained included data from vehicles which were habitually operated in this state. However data on the average working lives of vehicles were not obtained directly from the operators hence it was not possible to identify the dependence, if any, of this factor on vehicle load. To study the effect of reducing the average life of vehicles the vehicle wastage equations in the model were changed to reduce the average life by 25 per cent, thus increasing the vehicle operating costs.

2.4.5 Construction policy. Two types of road construction policy were used. In the first policy the road was designed to carry the total traffic throughout the fifteen year analysis period without the need for additional pavement strengthening. In the second policy the road was designed to carry the traffic expected during the analysis period assuming that the axle load limit was 8 tonnes on a single axle and 16 tonnes on a tandem axle. In these calculations as the axle load increased the total traffic load expressed in equivalent standard axles also increased although the number of vehicle trips needed to transport a given freight tonnage decreased. Thus the road needed strengthening at least once during the analysis period. Strengthening overlays were applied whenever the road reached a 'failure' condition.

Road 'failure' is defined in RTIM by a critical level of roughness and since roughness has a considerable influence on vehicle operating costs it was important to ensure that in all runs of the model for which a particular maintenance policy was in use all vehicles experienced the same average roughness values. This was achieved by choosing the design thickness of the road or the thickness of strengthening overlays in such a way that the pavement reached the 'failure' condition at the end of the analysis period. This method also ensured that the residual economic value of the road at the end of the analysis period was always the same and therefore did not need to be calculated.

2.4.6 Type of vehicle. Various types of vehicle were used in the analysis together with mixed vehicle fleets. The characteristics of these vehicles are based on the results of several axle load surveys conducted in Kenya[7]. Classifications of vehicles based on axle configuration and unladen weight were used to define typical vehicles, details of which are given in Appendix 2. For each type of vehicle the relationship between axle load and payload and between axle load and pavement damage expressed in equivalent standard axles are known from the survey data. Using the first of these relationships the payload can be found for any given axle load and hence the total number of vehicle trips required to carry the selected freight tonnage can be found. Using this result the second relationship can be used to calculate the total number of standard axles for which the road must be designed.

2.4.7 Vehicle load condition. The average cost of transporting each tonne of freight depends on the level of vehicle utilisation. For vehicles which are of interest in this study, namely those able to make use of the maximum allowed axle load, two extreme conditions were examined. In the first condition, here called the full load condition, the vehicles were fully loaded in both the outward and return directions. In the second or half-load condition the vehicles were fully loaded in one direction and empty in the other.

2.4.8 Road maintenance policy. The options in the model allow different road patching and surface dressing policies to be adopted. The effect of these different policies on the total costs was negligible in comparison with the different costs of the stage construction policies and is not discussed further.

3. ROAD CONSTRUCTION COSTS

3.1 Pavement design

The relationship between the modified structural number of a pavement and its traffic carrying capacity which is used in the model is an extension of Road Note 31[12,13]. The total thickness of pavement is always less than that recommended in the design curves of Road Note 29[14] but the thickness difference is almost constant hence both design curves give the same variation in thickness, and therefore construction costs, with axle load. The road structure assumed consists of a cement stabilised sub-base, a crushed stone base and a bituminous surfacing.

Comparisons of thickness design charts has shown that the defined terminal condition of a road has a major influence on the recommended pavement thicknesses. Thus although a design based on Road Note 29 does not alter the variation in pavement costs with axle load it does affect the vehicle operating costs through the influence of road surface condition and could therefore affect the optimum axle load. By ensuring that the average roughness experienced by all vehicles in a series of model runs is always the same, the effect of roughness on vehicle operating costs is also the same and therefore not dependent on axle load. This is guaranteed by ensuring that the road reaches the terminal condition at the end of the analysis period.

It can be shown from most pavement design charts that the traffic carrying capacity of a road is related to the structural number[1] by an equation of the form:

Traffic Carrying Capacity α (Structural Number)^{m}

The value of the parameter 'm' obtained from the AASHTO design charts[15], which recommend larger values of structural number than most design charts in current use, is approximately 6.3; for other design charts 'm' is greater than 6.3. In general for a low traffic design (less than 2.5 million standard axles) the value of 'm' is greater than for a high traffic design. In the design chart used here 'm' varies from 10.0 for low traffic to about 7.5 for high traffic (more than 10.0 million standard axles). If this equation is considered together with the pavement damage equation above it can be seen that an increase in structural number of 15 per cent increases the traffic carrying capacity by about 200 per cent. This is equivalent to an increase in single axle load from 8.0 tonnes to just over 10.0 tonnes even assuming the number of vehicle trips remains unaltered. A 15 per cent increase in structural number is also equivalent to an increase in pavement costs of about 15 per cent (Section 3.2) and an increase in total construction costs of considerably less than this. This example illustrates the extreme importance of the power indices in the above equations. Unfortunately the only systematic study of the relative damaging effects of different axle loads was undertaken during the AASHO Road Test. The conclusions of this study have been criticised for a variety of reasons but principally because (a) the test was conducted on only one type of subgrade, (b) much of the pavement deterioration occurred during the spring thaw making it difficult to isolate the deterioration which took place during the dry, warm periods of the year and (c) the study was an accelerated test leading to road failure within two years. Nevertheless this is the only full scale study from which it has been possible to derive a relationship between axle load and pavement deterioration and therefore the results are widely used.

In this study the traffic has been defined by the equivalent number of standard axles calculated by using either the standard 4.5 power law approximation to Liddle's original equation developed during the AASHO Road Test or by using a 6.0 power law as described in Section 2.4.2 above.

3.2 Construction costs

The unit costs used in the construction submodel of RTIM are shown in Appendix 1. The results of the model runs show that the cost of construction is linearly dependent on the structural number provided the structural number, SN, is above the lower limiting value SN_0. The costs can be expressed as follows:

$$\text{Costs} = a + (b \times SN), \quad SN > SN_0$$

where the constant 'a' depends principally on the vertical geometry and therefore the quantity of earthworks but not on SN, the constant 'b' is independent of vertical geometry and SN_0 is the value of SN which is required for the lowest traffic levels.

3.2.1 Partially loaded vehicles. Figure 2 shows the cost of constructing a road in rolling terrain on a subgrade with a design CBR of 3 per cent as a function of traffic. The curve indicates that the marginal cost of construction decreases quite quickly as the design traffic increases. The importance of this becomes apparent when the traffic which does not increase its axle load in accordance with the increasing limits is taken into account. Generally throughout this study it has been assumed that all the vehicles make full use of the axle load limits imposed. Certainly the results of axle load surveys in developing countries has shown that overloading above the legal limits is so frequent and of such a magnitude that virtually all pavement damage is often attributable to these vehicles. The effect of vehicles which do not make use of the axle load limits under consideration is twofold. The effect on the total vehicle operating costs as axle load increases is constant since no changes take place to these vehicles but the effect on pavement construction costs is not constant. The graph shows that when the axle load limit is low and the total construction costs are also low the marginal cost of design for the partly loaded vehicles is high whereas when the axle load limit is raised the total construction costs are also raised but the marginal cost of design for the partly loaded vehicles decreases. The effect of this on the relationship between road construction costs and axle load is to flatten the rising curve and thereby to increase the optimum axle load.

3.2.2 Increasing axle load. The results of a series of runs of the model showing the relationship between construction costs, axle load, and total freight tonnage are shown in Figure 3. The effect of the different terrain categories is simply to raise or lower the cost curves by fixed amounts depending on the differences in the fixed earthworks costs.

3.3 Stage construction costs

The relationship between the cost of structural overlays and traffic is similar in shape to Figure 2. An example of such a relationship is shown in Figure 4 for a road with an initial structural number of 3.05. The costs shown are the sum of normal maintenance costs and overlay costs. Indicated on the graph are the points corresponding to various thicknesses of overlay and the number of overlays which have been applied during the analysis period. Various alternative policies are possible within the constraints of the assumptions. Whenever the number of overlays required is greater than one there are always policies available which require thicker but less frequent overlays. These policies will usually be more expensive as a result of the discount procedure built into the model.

The maintenance costs themselves excluding the cost of overlays are small and many of the component costs of maintenance are independent of axle load. The costs of patching failed areas of pavement and the costs of surface dressing are calculated in the model and included in the total cost summations but are not analysed in detail.

4. VEHICLE OPERATING COSTS

4.1 Introduction

The estimation of vehicle operating costs within the model is based on the results of studies carried out in Kenya, Ethiopia and elsewhere[9,13]. Data were collected in terms of quantities rather than prices so that the model user is able to apply up to date prices in his calculations.

Two sets of input cost data were used in this study. These are summarised in Appendix 1 and apply to Kenyan conditions.

4.2 General results

Tables 1 and 2 show typical vehicle operating cost components. Table 1 shows that although the price of fuel increased by more than 100 per cent between 1972 and 1975 the total costs increased by 63 per cent. In this example the proportion of total costs attributable to fuel thereby increased from 10.0 per cent to 12.4 per cent. Table 2 illustrates how sensitive the costs per tonne payload are to the axle load selected. Detailed comparisons of the vehicle operating cost components obtained using the model with the results of other studies have been discussed elsewhere[3].

TABLE 1

Effect of price structure on vehicle operating costs
(Prices expressed in Kenyan shillings per km)

Vehicle type	3 axle	Road roughness	3,000 mm/km
Unladen weight	7.5 tonnes	Annual kilometrage	75,000
BHP	177		

Load condition Payload (tonnes)	Full 11.6		Full 11.6		Full 16.3	Half 16.3
	1972	%	1975	%	1975	1975
Fuel	0.34	10.0	0.69	12.4	0.77	0.54
Oil	0.02	0.6	0.04	0.7	0.04	0.04
Spares	0.71	20.8	1.26	22.7	1.26	1.26
Maintenance	0.41	12.0	0.54	9.7	0.54	0.54
Tyres	0.33	9.7	0.49	8.8	0.61	0.39
Depreciation	0.21	6.2	0.43	7.7	0.43	0.43
Interest	0.11	3.2	0.20	3.6	0.20	0.20
Crew wages	0.60	17.6	0.80	14.4	0.80	0.80
Overheads	0.68	20.0	1.11	20.0	1.16	1.05
Total	3.41		5.55		5.80	5.25
Total/tonne km	0.294		0.469		0.356	0.644

TABLE 2

Typical vehicle operating costs
(1975 prices expressed in Kenyan shillings per km)

Vehicle type Unladen weight BHP	2 axle 5.5 tonnes 150		Road roughness Annual kilometrage		3000 mm/km 75,000	
Rear axle (tonnes) Payload (tonnes)	5.0 2.0	7.0 5.0	9.0 7.4	10.0 8.8	11.0 10.0	12.0 11.2
Fuel	0.39	0.50	0.57	0.60	0.63	0.65
Oil	0.04	0.04	0.04	0.04	0.04	0.04
Spares	1.16	1.16	1.16	1.16	1.16	1.16
Maintenance	0.54	0.54	0.54	0.54	0.54	0.54
Tyres	0.19	0.27	0.33	0.37	0.40	0.43
Depreciation	0.39	0.39	0.39	0.39	0.39	0.39
Interest	0.19	0.19	0.19	0.19	0.19	0.19
Crew wages	0.80	0.80	0.80	0.80	0.80	0.80
Overheads	0.93	0.97	1.00	1.01	1.03	1.05
TOTAL	4.63	4.86	4.97	5.10	5.13	5.25
TOTAL/TONNE	2.31	0.972	0.672	0.580	0.513	0.469

Vehicle type Unladen weight BHP	3 axle 7.5 tonnes 177		Road roughness Annual kilometrage		3000 mm/km 75,000	
Rear axle (tonnes) Payload (tonnes)	10.0 6.8	14.0 11.6	18.0 16.3	20.0 18.7	22.0 21.1	24.0 23.5
Fuel	0.59	0.69	0.77	0.81	0.85	0.88
Oil	0.04	0.04	0.04	0.04	0.04	0.04
Spares	1.26	1.26	1.26	1.26	1.26	1.26
Maintenance	0.54	0.54	0.54	0.54	0.54	0.54
Tyres	0.37	0.49	0.61	0.67	0.73	0.80
Depreciation	0.43	0.43	0.43	0.43	0.43	0.43
Interest	0.20	0.20	0.20	0.20	0.20	0.20
Crew wagea	0.80	0.80	0.80	0.80	0.80	0.80
Overheads	1.05	1.11	1.16	1.19	1.21	1.23
TOTAL	5.27	5.55	5.80	5.93	6.05	6.17
TOTAL/TONNE	0.775	0.479	0.356	0.317	0.287	0.263

Vehicle type Unladen weight BHP	3 axle + 2 axle trailer 12.0 tonnes 177		Road roughness Annual kilometrage		3000 mm/km 75,000	
Rear axle (tonnes) Payload (tonnes)	10.0 12.3	14.0 21.1	18.0 29.8	20.0 34.2	22.0 38.6	24.0 43.0
Fuel	0.78	0.91	1.02	1.07	1.11	1.16
Oil	0.04	0.04	0.04	0.04	0.04	0.04
Spares	1.57	1.57	1.57	1.57	1.57	1.57
Maintenance	0.54	0.54	0.54	0.54	0.54	0.54
Tyres	0.62	0.85	1.07	1.19	1.30	1.41
Depreciation	0.53	0.53	0.53	0.53	0.53	0.53
Interest	0.25	0.25	0.25	0.25	0.25	0.25
Crew wages	0.80	0.80	0.80	0.80	0.80	0.80
Overheads	1.29	1.37	1.46	1.50	1.54	1.58
TOTAL	6.43	6.87	7.28	7.49	7.69	7.89
TOTAL/TONNE	0.523	0.326	0.244	0.219	0.199	0.183

4.2.1 Vehicle wastage. Vehicle wastage is taken into account in the model as part of depreciation costs. Table 1 shows that depreciation costs are less than 8 per cent of total vehicle operating costs and hence total costs are not very sensitive to this factor. The difference in vehicle operating costs when the high wastage equations were used was always less than 2 per cent and made no significant difference to the resulting optimum axle load.

4.2.2 Vehicle load factor. Table 2 indicates that for the example shown vehicle operating costs per tonne of payload for the half load condition are increased by about 80 per cent over the full load condition. This figure increases to nearly 100 per cent for low values of axle load, as might be expected.

4.3 Total vehicle operating costs

The dependence of total vehicle operating costs per tonne kilometre on gross vehicle weight is illustrated for three types of vehicle in Figure 5. These costs are total running costs plus standing charges for the vehicle in question but do not include costs associated with loading and unloading. It is assumed that these latter costs are dependent only on payload and can therefore be expressed as an extra cost per tonne. Naturally this will vary for different types of cargo but for any particular cargo it is assumed constant and therefore cannot affect the optimum axle load.

Detailed comparisons with vehicle operating costs obtained in other studies have proved difficult for several reasons. Firstly the operating conditions in developed countries where all the comprehensive studies have taken place are quite different. For example the cost components which are of interest in this study, namely those which depend on vehicle load condition, represent a completely different proportion of total running costs. Furthermore there are no other studies in which the relationship between these costs, expressed in terms of costs per vehicle kilometre, and vehicle load condition has been isolated. Costs are usually expressed as average costs per tonne kilometre for different types of vehicles obtained under average load conditions. The decrease in costs with gross vehicle weight therefore represents a mixture of effects. First of all the decrease in costs per tonne is attributable to the increased load factor even though the average trip cost is assumed to be the same. Secondly as the gross vehicle weight increases so generally does the size of vehicle used in the calculations. Thus the basic relationship between the cost of a vehicle-kilometre and the payload (or gross vehicle weight) for a particular type of vehicle cannot be obtained. A further major disadvantage of other studies is that costs are usually obtained in money terms with the result that they are soon out of date. In the Road Transport Investment Model quantities are used where possible for all the components of vehicle operating costs. Thus different price structures can be used to assess the effects of, for example, the rise in price of any component cost. Finally it is not always clear in reports of other studies which of the component costs have been included and which excluded from the total vehicle operating costs. In particular the treatment of interest charges, depreciation and crew wages often varies from author to author.

Despite these difficulties a comparison between a sample of the vehicle operating costs used in this study and several other studies is shown in Figure 6. The data have all been normalised to the vehicle operating costs obtained for a vehicle of 14 tonnes gross vehicle weight. The data for this figure were obtained from Figure 5 by drawing a smooth curve through the lowest sections of the three separate curves representing the 2-axled vehicle, the 3-axled vehicle and the 5-axled vehicle trailer combination in the full load condition. This is the same approach used by the other authors and represents a sensible choice of vehicle by the vehicle operators. It would be expected that since many operators in developing countries overload their vehicles the change over between vehicle sizes would take place further along the gross vehicle weight scale resulting in lower costs per tonne payload in comparison with the studies conducted in Sweden[16] and the USA[2]. This is confirmed in Figure 6.

5. TOTAL TRANSPORT COSTS

5.1 New road construction

In this series of runs of the model the road was assumed to be designed and constructed to carry the total traffic expected during the design life at various axle loads and freight tonnages without the need for any structural strengthening. Thus surface dressings and other normal maintenance costs were included but overlays were not required.

A typical set of results is shown in Figure 7. In the AASHO Road Test the highest tandem axle load used to determine the axle load – pavement damage relationship was about 22 tonnes. Extrapolation of the base data much beyond this is unreliable. In addition it is apparent from the histograms shown in Appendix 2 that although a 24 tonne load on a dual-dual tandem axle is the value below which 95 per cent of axle loads lie there are many individual axles on both the 2-axled vehicles and on vehicles and trailers with a single-dual tandem which exceeds 12 tonnes. The 95 percentile appears to be about 16 tonnes for a single axle. This would correspond to 24 tonnes on the single-dual tandem axle provided the dual wheeled axle carried two-thirds of the load and the single wheeled axle one-third, as would be expected for a properly designed axle. Thus 24 tonnes appears to be the 95 percentile for both types of tandem axle and 16 tonnes for a single axle. Few vehicles included in the vehicle operating cost study[3] exceeded these limits. All results for tandem axle loads above 24 tonnes must therefore be considered an extrapolation of both the vehicle operating cost data and the pavement damage data. For this reason graphical results are always shown as broken lines above 24 tonnes.

5.1.1 Minimum total transport costs. The results in Figure 7 show that for each freight tonnage the total transport costs initially decrease very rapidly as axle load increases, pass through a very shallow minimum and then increase slowly thereafter. Over a wide range of axle loads the total costs are relatively insensitive to axle load. This pattern applies to all total cost curves discussed in this report. However the axle load at which the minimum occurs depends very strongly on the total freight tonnage carried by the fully loaded vehicles.

The insensitivity of the total costs to axle load in the region of the minimum is an important factor to be considered when policy decisions about legal limits and enforcement are being made. As a measure of this insensitivity the axle load at which total costs are 2½ per cent higher than the minimum has been plotted in Figure 7. In this example an increase in costs of 2½ per cent is equivalent to a decrease in tandem axle load of between 5 and 6 tonnes, ie a decrease of between 17 and 33 per cent in the axle load as total freight tonnage varies from 10 down to 0.5 million tonnes.

Figure 7 has been plotted for a particular fleet of vehicles using 1972 prices on a new road in rolling terrain constructed on a subgrade of CBR 3 per cent. The lowest freight tonnage (0.5 million) corresponds to an initial daily traffic of about 10 fully loaded vehicles per day in each direction. The optimum axle load for this tonnage agrees reasonably well with the current legal limit in many developing countries. However for any higher levels of freight tonnage carried on fully loaded vehicles the optimum rises appreciably. In addition the effect of additional freight carried on vehicles which are not loaded to the axle load limit is to increase the optimum axle load as discussed in Section 3.2.1 above.

The relationship between the optimum tandem axle load and freight tonnage is summarised in Figure 8.

5.1.2 Terrain and subgrade. The optimum tandem axle loads for each freight tonnage were found to be almost independent of the vertical alignment of the road. No differences were distinguishable between flat and rolling terrain but the values for hilly terrain were about 0.5 tonnes lower for low freight tonnages.

Similarly the effect of subgrade strength was small, the curves representing subgrades of CBR value 3, 7 and 15 per cent all falling within 0.5 tonnes of each other. The only likely exception to this general result occurs if the design charts which are used to determine the thickness of the pavement layers do not require a continuously increasing thickness as traffic loading increases. Some design charts recommend a fixed design for a considerable range of traffic loads thereby providing a slight overdesign for traffic at the low end of the range and possibly a slight underdesign for traffic at the high end. Under these circumstances the pavement costs do not increase continuously with axle load and unique minima in the total cost curves do not always exist. In this study the pavement design thicknesses always increase continuously with traffic loading[13].

5.1.3 Vehicle load condition. The model runs described above were all for vehicles fully loaded in both directions. The other extreme condition in which vehicles are empty on the return trip has a significant effect on the minima in the cost curves. The relationship between the optimum axle load associated with these minima and freight tonnage is shown in Figure 8. The optima are always higher than for the full load condition, the difference varying from 2.0 tonnes at a total freight tonnage of 0.5 million to over 6.0 tonnes at freight tonnages greater than 3.0 million. However for tonnages greater than 1.5 million the tandem axle optima are always above 24 tonnes and therefore in the area of data extrapolation.

5.1.4 Vehicles with high pavement damage factors. Vehicles with tandem axles consisting of one dual wheeled axle and one single wheeled axle have been shown to be particularly damaging to the roads (Appendix 2). Such a vehicle does more than three times as much damage to the road as a similarly loaded vehicle with two dual wheeled axles making up the tandem set. Unfortunately vehicles of this type are very common in East Africa. Figure 8 shows that the optimum tandem axle load for a fleet of vehicles of this type is between 2 and 4 tonnes less than that for vehicles with dual wheels on both axles.

5.1.5 Pavement damage relationship. The effect of changing the pavement damage-axle load relationship from a 4.5 to a 6.0 power law is also shown in Figure 8. The optimum tandem axle load is about 1 tonne less than obtained using the 4.5 power law at low freight tonnages but this difference increases to more than 6 tonnes as the tonnage increases to 10.0 million.

5.2 Existing roads with strengthening overlays

In this series of runs the roads were designed assuming that the total freight tonnage was carried on 3-axle vehicles whose tandem axle load was 16.0 tonnes. As the axle load increased for each tonnage, overlays were applied to the road as described in Section 2.4.5. The cost of the original road construction was therefore identical for each axle load and did not affect the optimum axle load.

Typical results are shown in Figure 9 and the relationship between the optimum tandem axle load and the freight tonnage is shown in Figure 10. It can be seen that the optima are between 1 and 2 tonnes lower than obtained for the new road construction policy. This difference is not significant in view of the insensitivity of total costs to axle loads near the minima.

5.2.1 Price structure. The model runs were repeated using 1975 prices thus enabling the effect of prices before and after the oil crisis to be determined. The prices used are shown in Appendix 1. The relationship between the optimum axle loads and freight tonnage is shown in Figure 10. The minima in the total cost curves are less shallow than before, the difference in tandem axle load between the optima and the axle load corresponding to an increase in the minimum costs of 2.5 per cent being between 2 and 3 tonnes instead of between 4 and 5 tonnes. The optima themselves are also between 1 and 3 tonnes lower than obtained using 1972 prices.

5.3 An example of mixed traffic on an existing road

The results of the axle load survey on the main A109 trunk road in Kenya are shown in Appendix 2. A series of model runs was made using a mixed fleet of vehicles similar to the fleet operating on this road. The actual pavement details were also used as input together with an overlay policy designed to allow the road to reach failure after fifteen years. A growth rate of 5 per cent for traffic and a discount rate of 12 per cent (appropriate in 1975) were used as before. It was assumed that the vehicles were all loaded so that the main load bearing axle for each type of vehicle and trailer always carried the selected axle load as in the previous examples. The axle load which most closely resembles the average operating conditions encountered in practice is about 19 tonnes on a tandem axle but this varies with each vehicle type. The runs were made using 1975 prices.

The cost curves are shown in Figure 11 for different total freight tonnages carried in one direction. The actual tonnage on the road is close to 20 million tonnes[7]. The optimum tandem axle load is well above 24 tonnes. The optimum axle load for lower freight tonnages have been plotted in Figure 10 where it can be seen that they lie close to the line for 3-axled vehicles with the 1975 price structure.

The total costs for vehicles in the half load condition show that the minima for all tonnages greater than 5.0 million are greater than 24 tonnes.

5.4 Discussion

The results described here indicate that for any combination of variables there is a freight tonnage above which the optimum tandem axle load exceeds 24 tonnes. For any reasonable combination of variables (Section 2.2) this tonnage is likely to be between 5 and 10 million tonnes transported in one direction during a 15 year period provided it is carried by fully loaded vehicles which are also able to make a return trip in the fully loaded condition. This tonnage is equivalent to an initial daily traffic flow of less than 100 fully loaded vehicles in each direction. The existence of other vehicles which are not fully loaded increases the optimum axle load and consequently decreases the traffic level of fully loaded vehicles at which the above statement is true. In addition if the vehicles are only partially loaded on the return trip the optimum axle load rises further implying that at even lower traffic levels the optimum tandem axle load exceeds 24 tonnes. In Kenya under conditions where the optimum is clearly greater than 24 tonnes its dependence on the factors considered here is unimportant because vehicle operators are unable or unwilling to exceed this weight with their current fleet of vehicles; 24 tonnes on a tandem axle is the value below which 95 per cent of all tandem axle loads lie.

Under conditions where the optimum is below 24 tonnes, the optimum is found to be independent of terrain or subgrade and relatively independent of whether the road is designed initially to carry the full load or is initially designed to carry a lower load with subsequent strengthening. It is extremely dependent on whether the vehicles can be fully loaded on both the outward and return trips and also on the total tonnage actually carried. However unless the number of fully loaded vehicles falls below about 5 per day the optimum is unlikely to be below the relatively common legal limits of 8 tonnes on a single axle and 16 tonnes on a tandem axle.

Under most conditions it appears that the total operating costs are insensitive to axle load near to the optimum. Thus costs increase only by 2.5 per cent as the axle load is reduced below the optimum by 3 or 4 tonnes.

Comparison with the work of other authors is difficult because conditions vary so much from country to country, however it is interesting to note that from Brinck's comprehensive study[16] for Swedish conditions using a 6.5 metre wide highway, a traffic growth of 6 per cent and a 20 year design life, the freight tonnage at which a tandem axle load of 24 tonnes or more becomes justifiable is about 4.5 million tonnes carried on the fully loaded vehicles. Brinck's results are shown in Figure 10. The relationship between optimum axle load and tonnage is steeper than obtained here but leads to the same conclusions for heavily trafficked roads. Results obtained by Motomura[17] for the Sultanate of Oman showed that under almost all conditions the optimum tandem axle load was greater than 24 tonnes. The only exceptions occurred at low traffic levels (less than 100 heavy vehicles per day) under conditions of no traffic growth coupled with high discount rates. Under conditions of more realistic traffic growth it was found that the optimum tandem axle load was greater than 24 tonnes even when the number of heavy vehicles per day fell below 20. The report[17] uses 1978 prices but does not give a detailed breakdown of all component costs. It must be assumed that in Oman the cost of oil based products such as bitumen and petroleum is low with the result that the optimum axle load is high in comparison with most countries.

In almost all other studies which have considered the effects of changing axle load limits the calculations have been done on an incremental basis. Generally the results confirm that increases in vehicle axle load limits are justified economically and that quite large increases in load are beneficial for a heavily trafficked network[5,18,19,20].

6. OTHER COSTS

6.1 Introduction

There are two classes of costs which cannot be included in the Road Transport Investment Model and which therefore have to be considered separately. First of all there are those costs which although quantifiable cannot be generalised sufficiently precisely for inclusion in the model. These costs include all major structures such as bridges and major culverts. Secondly there are those costs which are difficult or impossible to quantify and include the social costs of transport such as air pollution, accidents, traffic delays and noise.

This report is concerned primarily with the dependence of the optimum axle load on those factors which can be included in the model. The report would, however, be incomplete without some discussion of these other costs, some of which are not very dependent on the axle load and hence have little or no influence on the optimum.

These additional costs must all be included if a complete cost-benefit analysis for a countrywide road network or even a principal trunk road is attempted. Table 3 summarises all the important factors which need to be included in such an analysis. The probable response of vehicle operators and freight shippers to changes in axle load limits, levels of enforcement, taxes and duties and related legislation need to be determined before a full analysis can proceed. Vehicle operations other than the long distance haulage considered in this report need to be included and this will require a study of the operating characteristics of the whole vehicle fleet. A summary of the incremental cost benefit analysis necessary for a developed country is given in Reference 2 and a summary of the additional problems encountered in developing countries has been given by Fossberg[21]. Some of these factors are discussed in this section with particular reference to the likely effect on the optimum axle load. It should be borne in mind throughout this section that only those vehicles which are loaded to the specified limit have any major influence on the optimum axle load.

TABLE 3

Principal factors to be included in a complete cost-benefit analysis of the effects of changing vehicle axle loading practice

1.	Changes in taxation, licensing, duties and other revenue collection by Government
2.	Cost of enforcement
3.	Cost of operating vehicles
4.	Changes in loading practice of vehicles
5.	Changes in operators choice of vehicle
6.	Changes in the number of vehicle trips
7.	Change in total freight costs and transport charges
8.	Impact on other transport modes due to change in modal split
9.	Additional cost of new highway construction including bridges
10.	Additional cost of road strengthening including bridges
11.	Additional cost of road and bridge maintenance
12.	Changes in the timing of the construction of additional highway capacity
13.	Additional cost of road realignment
14.	Changes in traffic accidents
15.	Changes in noise and vehicle induced vibrations
16.	Changes in levels of air pollution
17.	Changes in the price and availability of goods
18.	Changes in travel time due to the impact of heavy vehicles on traffic operations

6.2 Bridges

Bridges respond differently to loads depending mainly on the dimensions of the structure, the strength of the materials used in fabrication, the type of bridge and the basic design. For any increase in axle loads or gross vehicle weights some bridges will require strengthening whereas others will not. For some of the former category strengthening will be found to be economically unjustified and complete reconstruction will be necessary. A method of calculating these costs has been proposed in Reference 2 but each bridge has to be treated separately and generalisations are not possible. In a case study completed for Sweden[16] Brinck has estimated that the cost of constructing bridges to carry vehicles with a 24 tonne tandem axle load is about 26 per cent higher than for a 16 tonne load. He does not, however, calculate the cost of strengthening existing bridges. With an average of one 28 metre span bridge for every 10 kilometres of highway Brinck estimates that bridge construction costs are about 12 per cent of road construction costs. The incremental cost of bridges designed for the higher axle load therefore makes a small but significant difference to total transport costs and therefore to the optimum axle load. In those developing countries with a much lower density of bridges than Sweden the incremental cost of bridge strengthening and construction will make little difference to the optimum axle load. For those countries with a high density of bridges the calculation of the optimum axle load is not possible until a complete study of all the bridges has been made.

6.3 Accidents

The effect of increases in axle loads on the number and severity of road accidents is controversial and difficult to assess from published data even for industrialised countries. In the United Kingdom the involvement rate (accidents per kilometre travelled) for heavy goods vehicles in serious accidents is similar to that for cars but the severity of accidents is greater[22]. The causes of those accidents are difficult to determine but it is likely that the dimensions and mass of the vehicle and its mode of use are factors. The effect on accident rates of increasing vehicle axle loads is unknown, but for the same freight tonnage transported accident involvement may increase as a result of increases in vehicle weight. This will be offset by a reduction in the number of kilometres travelled. The operating conditions in developing countries are so different from industrialised countries that even broad generalisations are not possible. Vehicle maintenance is much poorer, vehicle testing often non existent, restrictions on driving hours are not enforced or are non existent, training of drivers is less effective and road conditions are very different. Detailed accident studies are necessary before a relationship between accidents and vehicle axle loading can be established.

6.4 Air pollution

In the USA transportation causes serious air pollution giving rise to nearly all the carbon monoxide and about half of the nitrous oxides and hydrocarbons present as pollutants in the air. Diesel engines have been shown to be considerably cleaner than petrol engines in all respects except in the emission of particles of unburnt carbon (smoke)[23]. These particles, while smelling unpleasant and being visually obvious, are less of a health hazard than the other pollutants. The dependence of the quantity of pollutants on vehicle load condition is unknown but possible incremental increases caused by increases in axle load are likely to be offset by the reduction in vehicle trips necessary to carry the same amount of freight.

6.5 Noise and vibration

Both the level of noise and the vibrations caused to structures near the road by heavy vehicles are likely to increase with axle load but as with pollution this is offset by the decrease in vehicle trips. Neither noise nor vibrations are important in the context of most developing countries where population densities in rural areas are generally low.

7. SUMMARY

The Road Transport Investment Model[9] has been used to show that for a typical developing country the sum of vehicle operating costs and road construction, maintenance and strengthening costs for a two lane highway decrease rapidly as the axle load of the fully loaded vehicles increases, passes through a relatively shallow minimum value at the optimum axle load, and then increases gradually thereafter.

The value of the optimum tandem axle load was found to be virtually independent of the vertical alignment of the road and the strength of the subgrade. The choice of road construction and strengthening policy and the composition of the vehicle fleet had a small effect on the optimum tandem axle load; the variations considered here making less than 3 tonnes difference in the optimum provided that tandem axles consisting of one dual wheeled axle and one single wheeled axle are treated as two single axles for the purpose of defining the axle load limits.

The most important variables which influenced the optimum axle load, listed in order of importance, were found to be the total freight tonnage carried by the fully loaded vehicles, the load conditions of these vehicles on the return trip, the exponent of the pavement damage-axle load relationship and the relative price of the major components of road transport cost.

For total freight movements of less than one million tonnes transported in one direction over 15 years by fully loaded vehicles the optimum axle load is close to or below the common tandem axle legal limit of 16.0 tonnes which is found in many countries. However under most conditions there exists a freight tonnage above which the optimum tandem axle load exceeds the 95 percentile found in Kenya of 24 tonnes. This tonnage is generally less than 10.0 million tonnes, a figure which is equivalent to an initial average daily traffic of about 100 heavy vehicles making full use of the 24 tonne tandem axle load. The effect of additional vehicles which are not fully loaded is to increase the value of the optimum axle load still further and thus to reduce the average daily traffic of the fully loaded vehicles at which the optimum tandem axle load exceeds 24 tonnes.

The minimum in the total cost curves is such that quite large decreases in the axle load of the fully loaded vehicles below the optimum increases the total transport costs only by small amounts. For example decreases in tandem axle loads of 3 or 4 tonnes usually increase the total costs by less than 2.5 per cent.

Finally the report shows how the Road Transport Investment Model can be used for a complete cost-benefit analysis of a proposed change in axle load limits for a developing country and indicates the data which need to be obtained for the calculations to be completed successfully.

8. ACKNOWLEDGEMENTS

This study was carried out by the Overseas Unit (Head of Unit: J N Bulman) of the Transport and Road Research Laboratory, United Kingdom.

Much of the work described in this report was carried out in conjunction with the Kenyan Ministry of Works. The author is indebted to the Engineer in Chief, Ministry of Works and his staff without whose consistent cooperation the work could not have been successful.

9. REFERENCES

1. HIGHWAY RESEARCH BOARD. The AASHO Road Test. Report 5. Pavement Research. *Highway Research Board Special Report 61E.* Washington DC, 1962 (National Research Council).

2. STEVENS, H. Line haul trucking costs upgraded, 1964. *Highway Research Record No. 127.* Washington DC, 1966 (National Research Council).

3. HIDE, H, S W ABAYNAYAKA, I SAYER and R WYATT. The Kenya Road Transport Cost Study: research on vehicle operating costs. *Department of the Environment, TRRL Report* LR 672. Crowthorne, 1975 (Transport and Road Research Laboratory).

4. BRINCK, C E. Benefits of increased axle loads. *Proceedings 94.* Stockholm, 1968 (The National Road Research Institute, Sweden).

5. WHITESIDE, R E, TING Y CHU, J C COSBY, R L WHITAKER and R WINFREY. Changes in legal vehicle weights and dimensions: some economic effects on highways. *National Cooperative Highway Research Program Report 141.* Washington DC, 1973 (National Research Council).

6. FREITAS, M D and M L REISS. Safety performance of large trucks in the United States of America. *Symposium on Heavy Freight Vehicles and their Effects 1977.* Pan's, 1977 (Organisation for Economic Cooperation and Development), pp 67–82.

7. JONES, T E. Axle loads on paved roads in Kenya. *Department of the Environment Department of Transport, TRRL Report* LR 763. Crowthorne, 1977 (Transport and Road Research Laboratory).

8. ELLIS, C I. Axle load distribution on roads overseas. Survey on roads in West Malaysia 1967. *Ministry of Transport, RRL Report* LR 187. Crowthorne, 1968 (Road Research Laboratory).

9. ROBINSON, R, H HIDE, J W HODGES, S W ABAYNAYAKA and J ROLT. A road transport investment model for developing countries. *Department of the Environment, TRRL Report* LR 674. Crowthorne, 1975 (Transport and Road Research Laboratory).

10. ROBINSON, R. Road transport investment model: draft user manual. *Department of the Environment, TRRL Report* SR 224 UC. Crowthorne, 1976 (Transport and Road Research Laboratory).

11. ADDIS, R R and R A WHITMARSH. Relative damaging power of wheel loads in mixed traffic on pavements of different strengths. *Department of the Environment Department of Transport, TRRL Report* LR 979. Crowthorne, 1981 (Transport and Road Research Laboratory).

12. TRANSPORT AND ROAD RESEARCH LABORATORY. A guide to the structural design of bitumen-surfaced roads in tropical and sub-tropical countries. *Department of the Environment Department of Transport, Road Note* No. 31. London, 1977 (H M Stationery Office).

13. ROLT, J and S W ABAYNAYAKA. Revision 1 of the Road Transport Investment Model. *Department of the Environment, TRRL Report* SR 246. Crowthorne, 1976 (Transport and Road Research Laboratory).

14. TRANSPORT AND ROAD RESEARCH LABORATORY. A guide to the structural design of pavements for new roads. *Department of the Environment, Road Note* No. 29. London, 1970 (H M Stationery Office).

15. AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS. AASHTO interim guide for the design of pavement structures 1972. Washington DC, 1974 (American Association of State Highway and Transportation Officials).

16. BRINCK, C E. Optimum axle loads. *Proceedings 92.* Stockholm, 1966 (The National Road Research Institute, Sweden).

17. YUICHIRO MOTOMURA. Optimum axle load limit. *The 58th Annual Meeting of the Transportation Research Board 1979.* Washington DC, 1980 (National Research Council).

18. SHEEDY, J P M. The implications in relation to road pavements of increasing the permitted single axle load from 10 tons to 13 tons (12.8 tons). *The National Institute for Physical Planning and Construction Research* RC 81. Dublin, 1971 (The National Institute for Physical Planning and Construction Research).

19. PHANG, W A. Vehicle weight regulation and the effects of increased loadings on pavements. *Department of Highways Ontario Report* RR 151. Ontario, 1969 (Department of Highways Ontario, Canada).

20. FRY, A T, G R EASTON, I R KER, J McL STEVENSON and J R WEBBER. A Study of the Economics of Road Vehicle Limits. *National Association of Australian State Road Authorities.* Sydney, 1975 (National Association of Australian State Road Authorities).

21. FOSSBERG, P E. Road freight transport problems with special reference to developing countries. *Symposium on Heavy Freight Vehicles and their Effects 1977.* Paris, 1977 (Organisation for Economic Cooperation and Development).

22. NEILSON, I D, R N KEMP and H A WILKINS. Accidents involving heavy goods vehicles in Great Britain; frequencies and design aspects. *Department of the Environment Department of Transport, TRRL Report* SR 470. Crowthorne, 1979 (Transport and Road Research Laboratory).

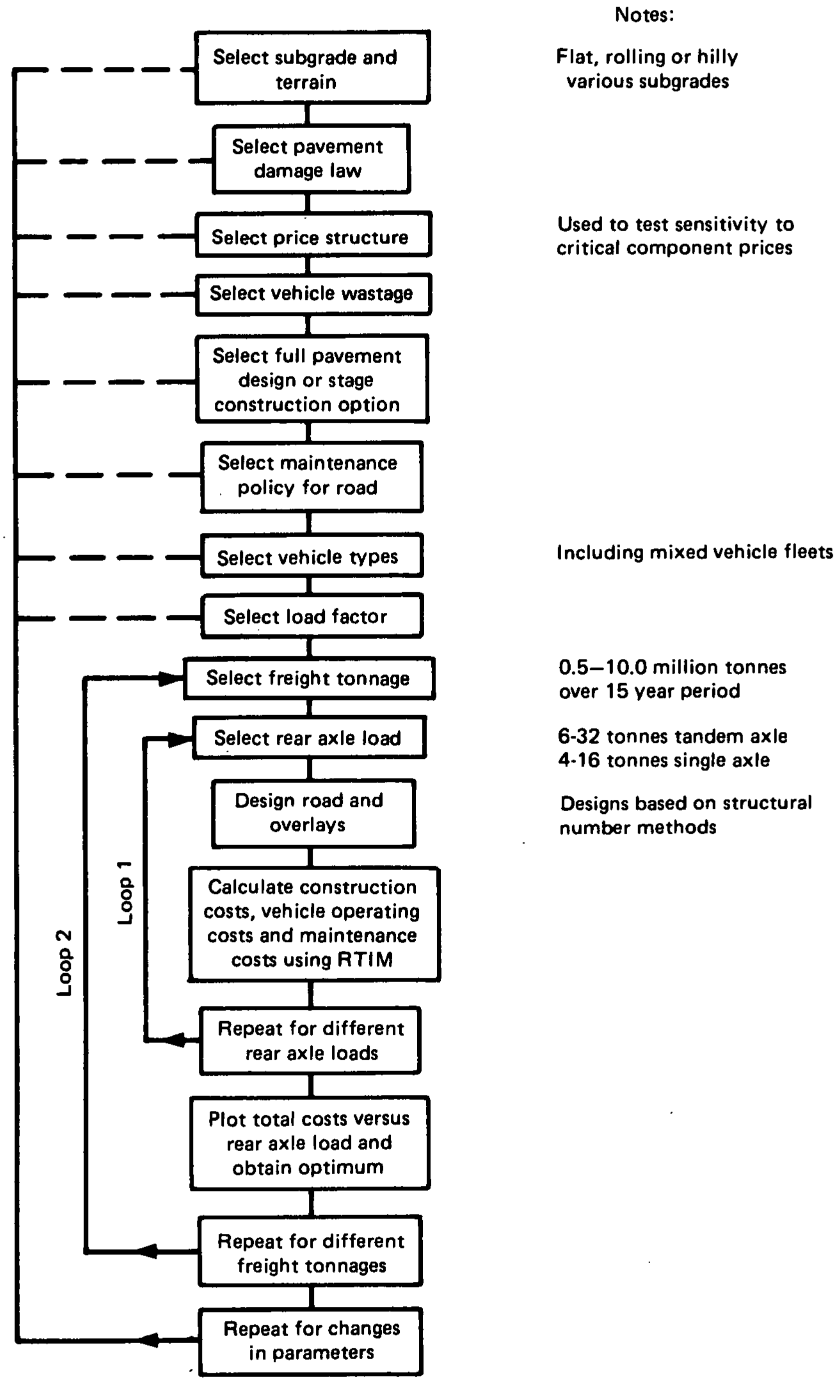

Fig. 1 Method of analysis

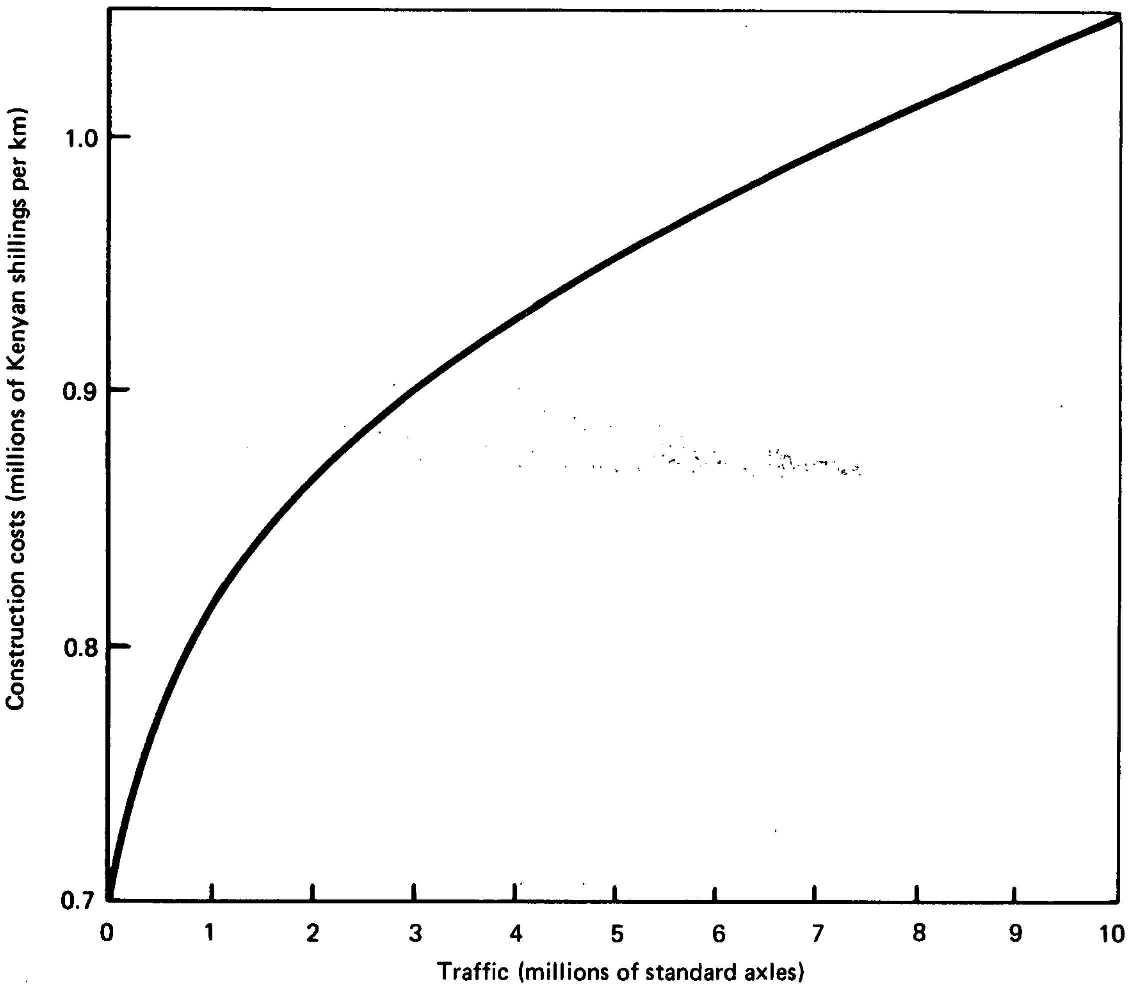

Fig. 2 The cost of a new road in rolling terrain as a function of traffic (1972 prices)

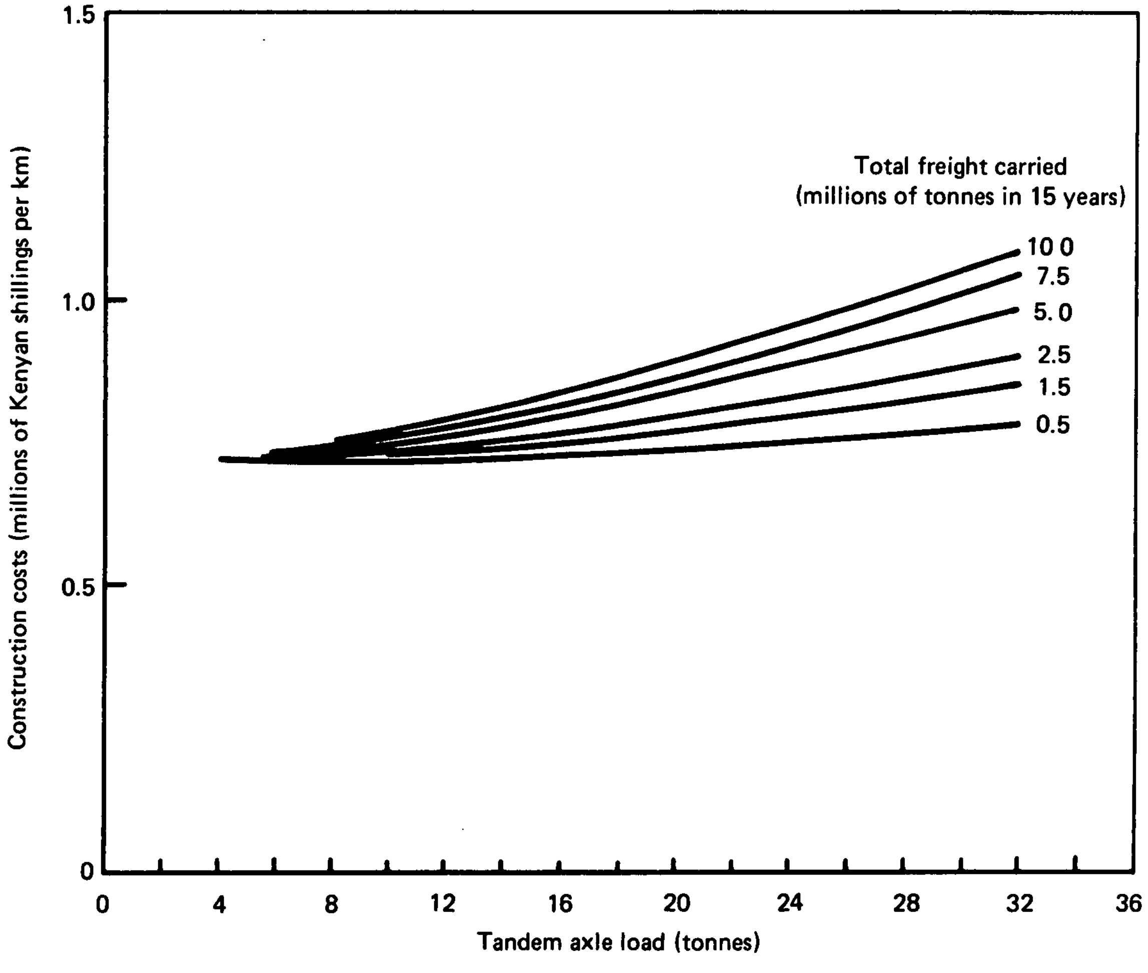

Fig. 3 Pavement construction costs for a new road in rolling terrain as a function of axle load and freight tonnage

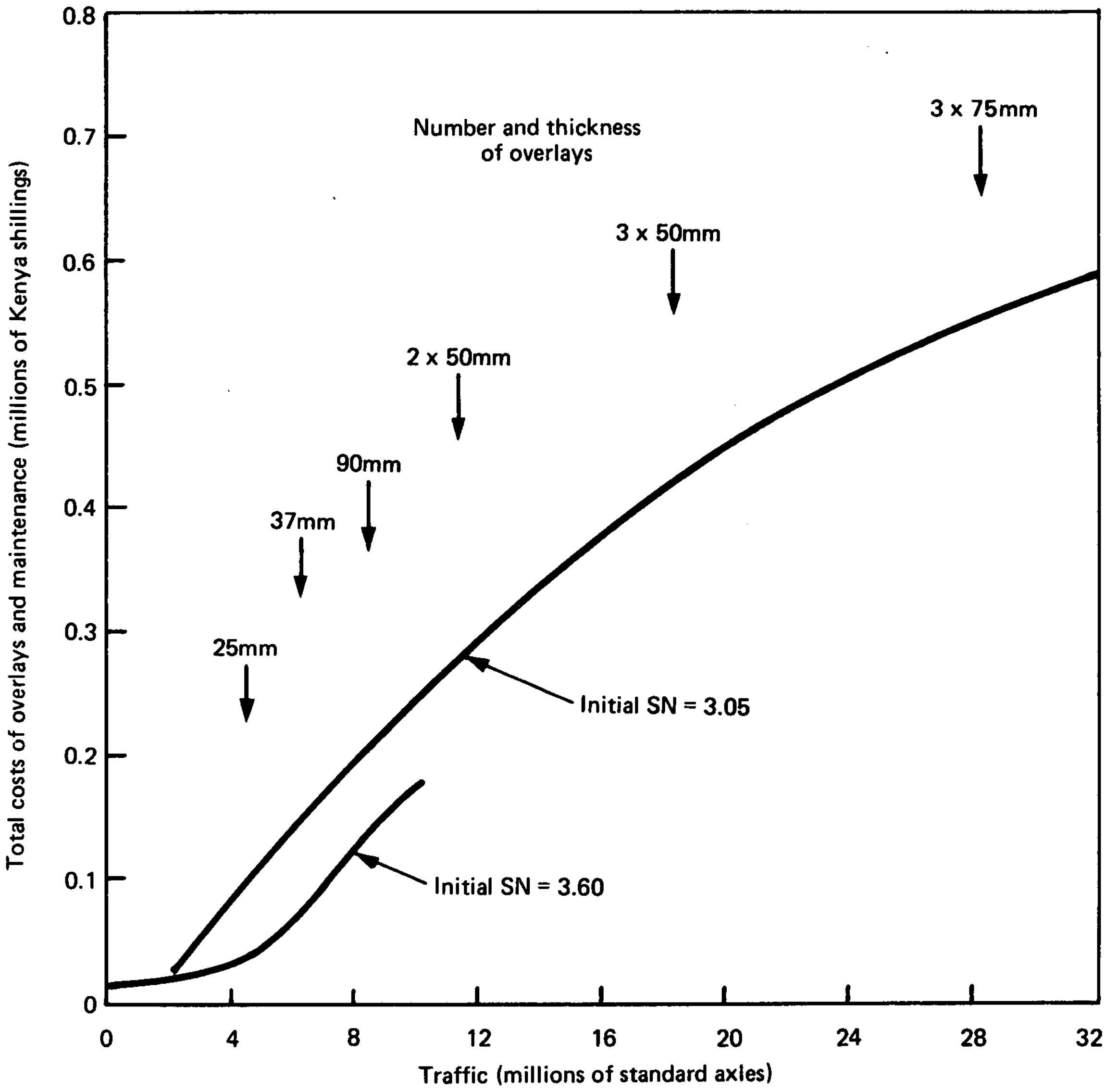

Fig. 4 Total costs of overlays and maintenance as a function of traffic (1975 prices)

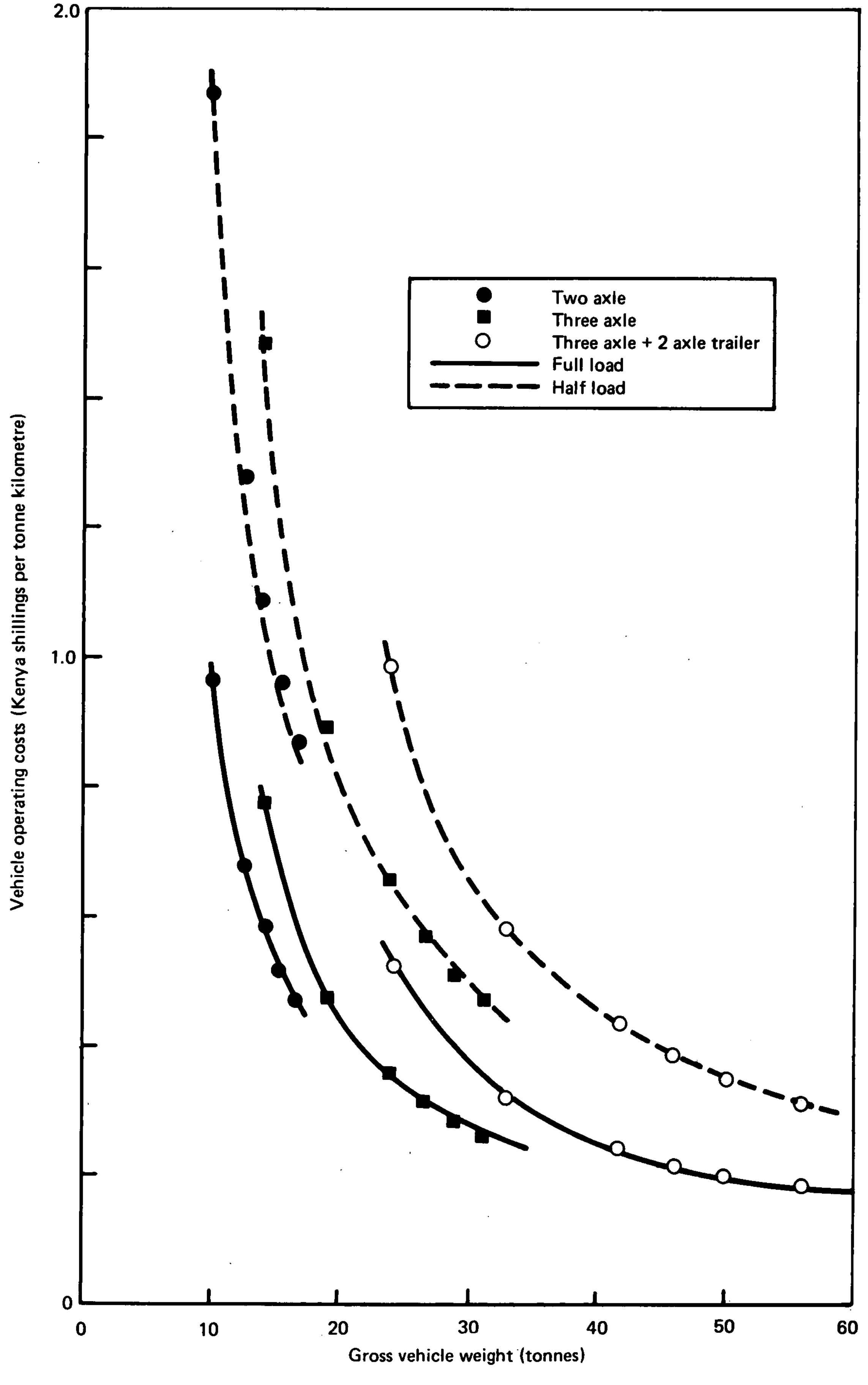

Fig. 5 Vehicle operating costs as a function of gross vehicle weight for three types of vehicle (1975 prices)

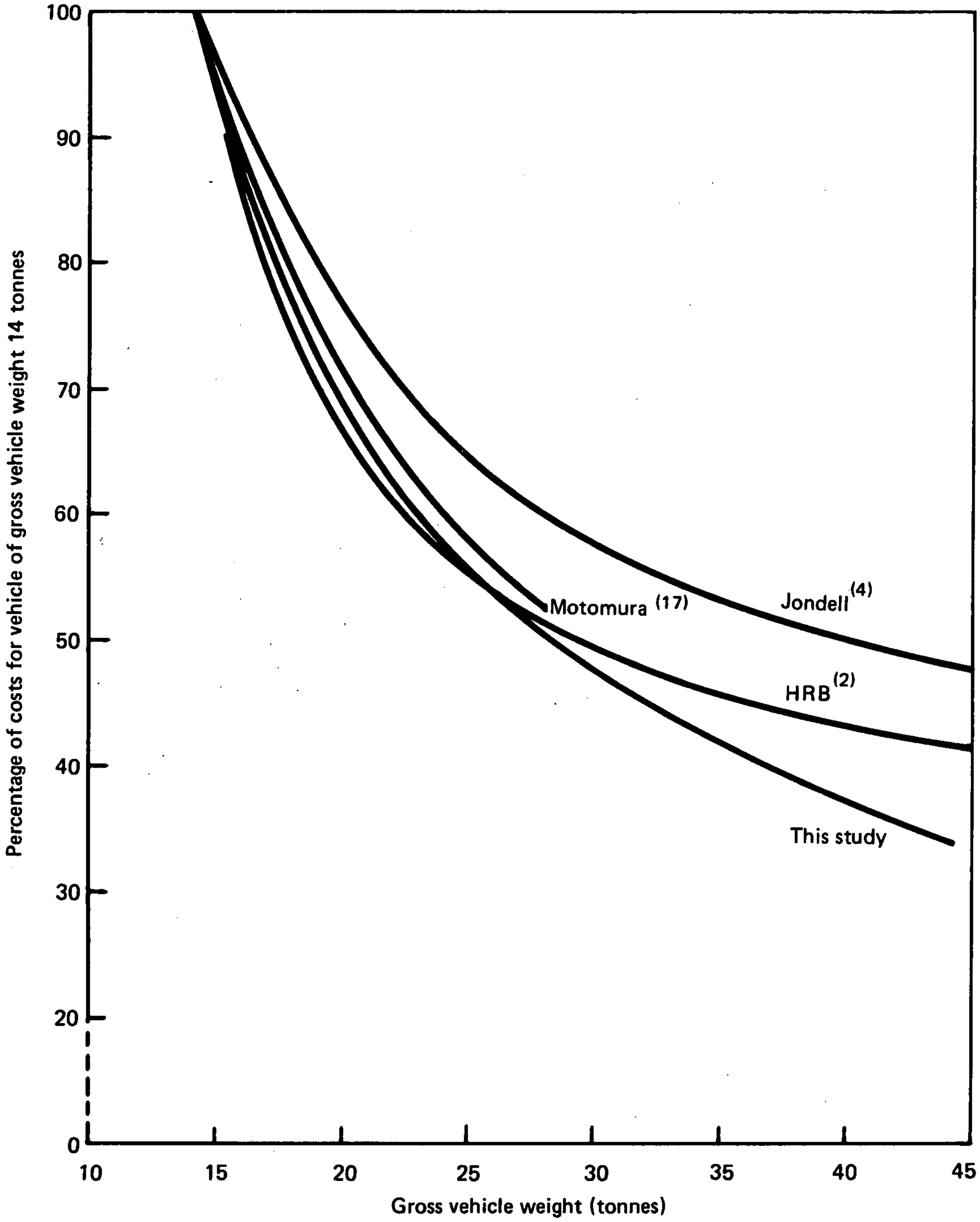

Fig. 6 Comparison of vehicle operating costs

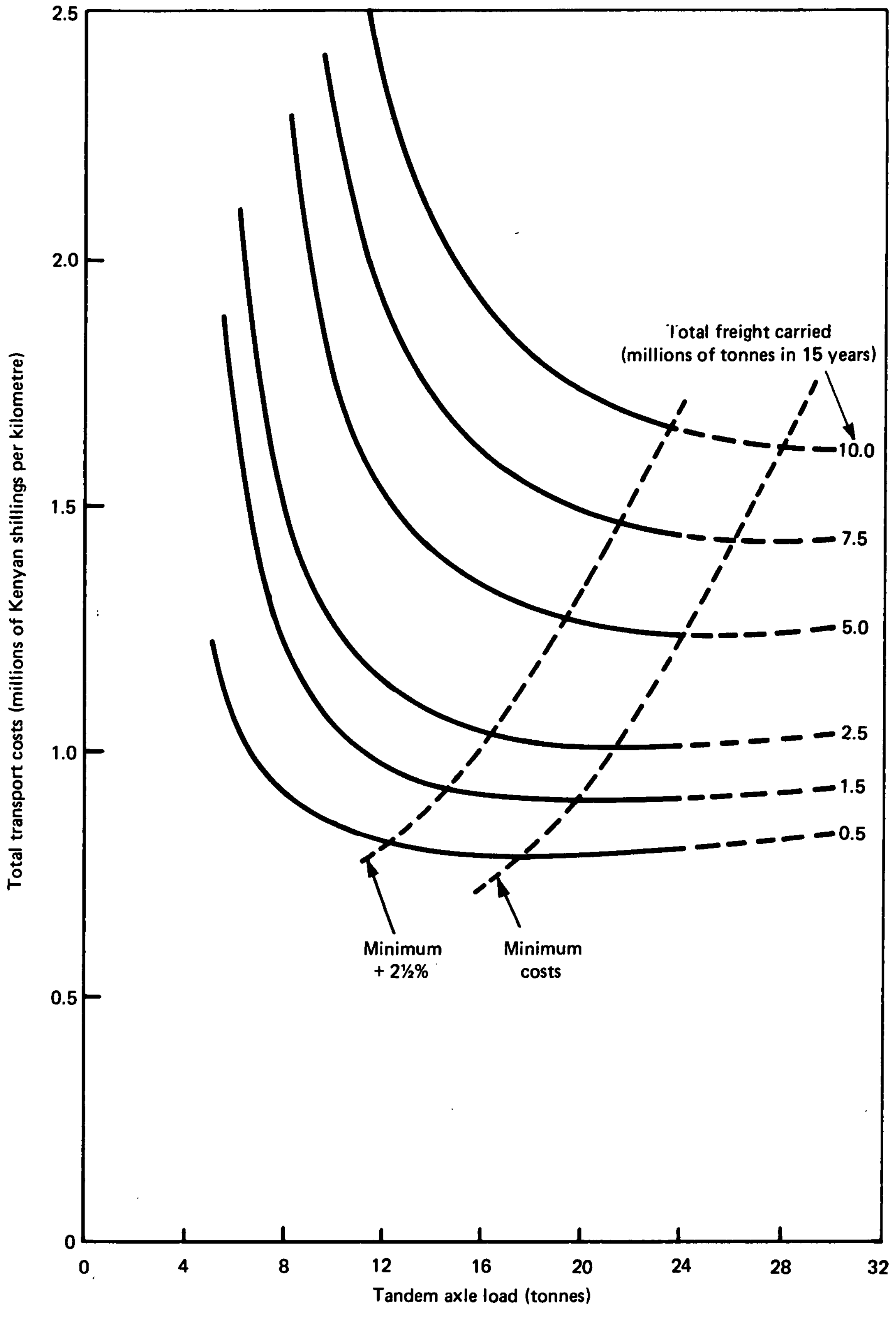

Fig. 7 Total transport costs for a fleet of 3-axled vehicles on a new road under full load conditions using 1972 prices

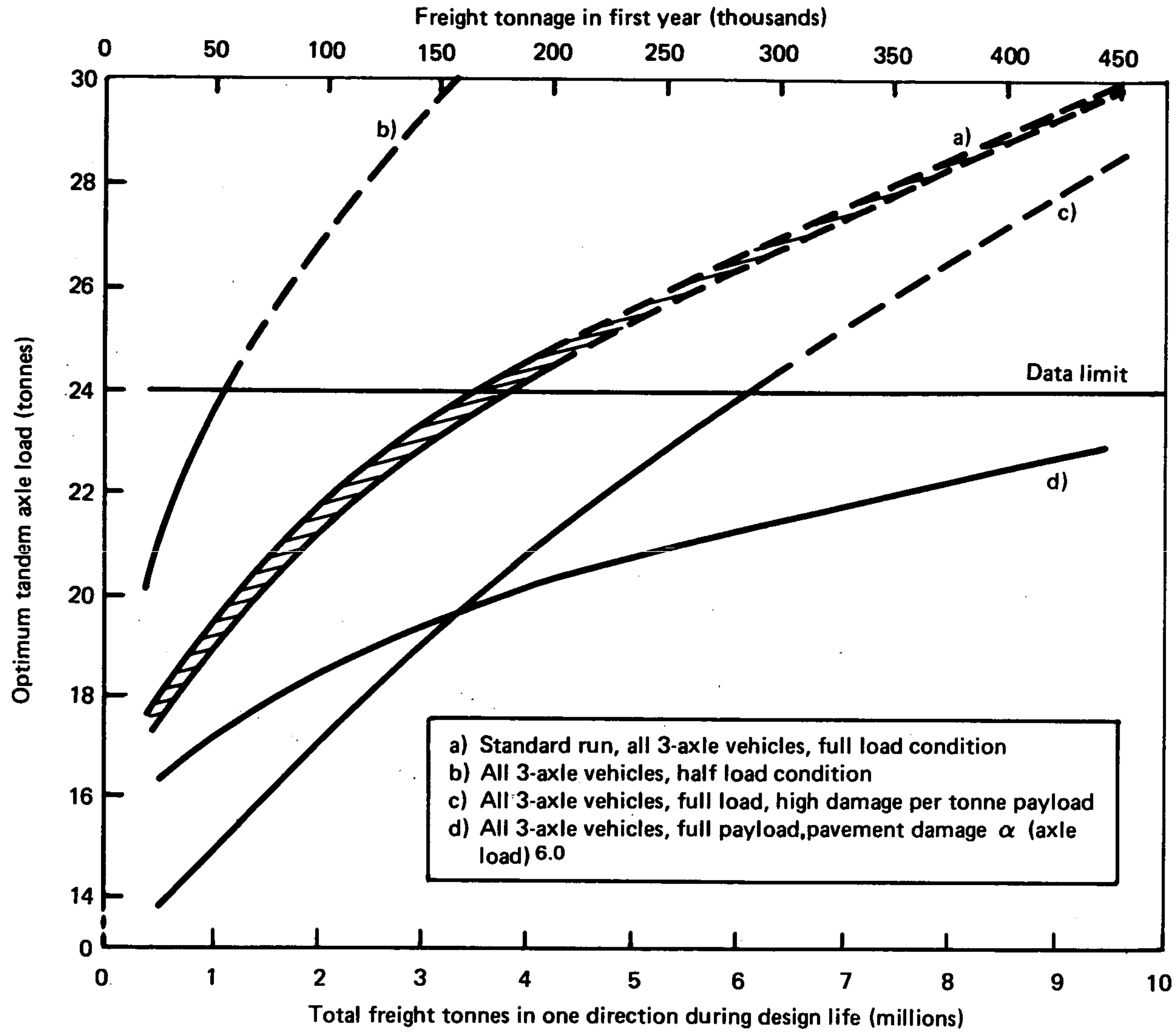

Fig. 8 Relationship between optimum axle load and total freight tonnage for a new road policy under various assumptions

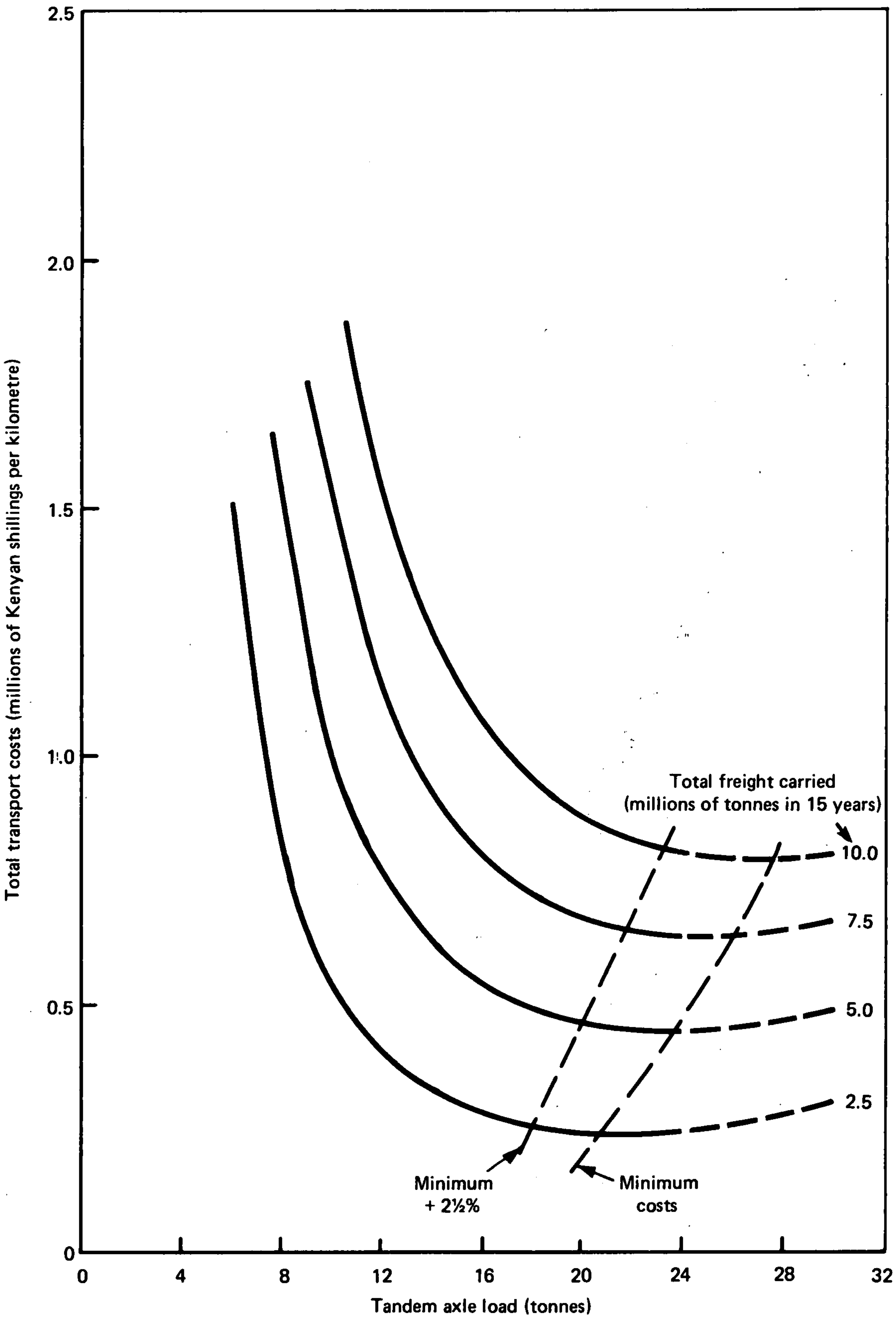

Fig. 9 Total transport costs for a fleet of 3-axled vehicles on an existing road strengthened with overlays under full load conditions using 1972 prices

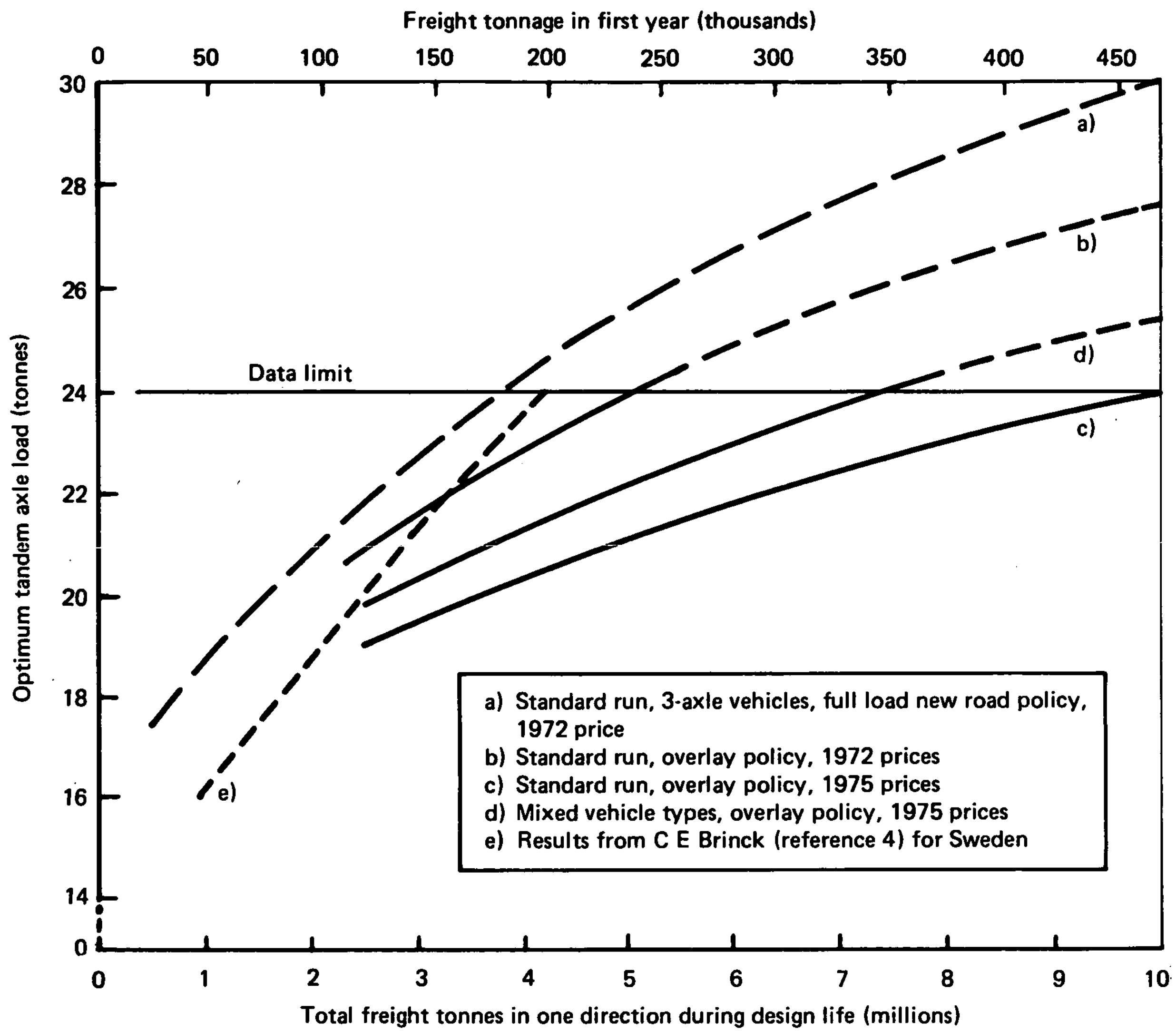

Fig. 10 Relationship between optimum tandem axle load and total freight tonnage for an existing road with overlay policy under various assumptions

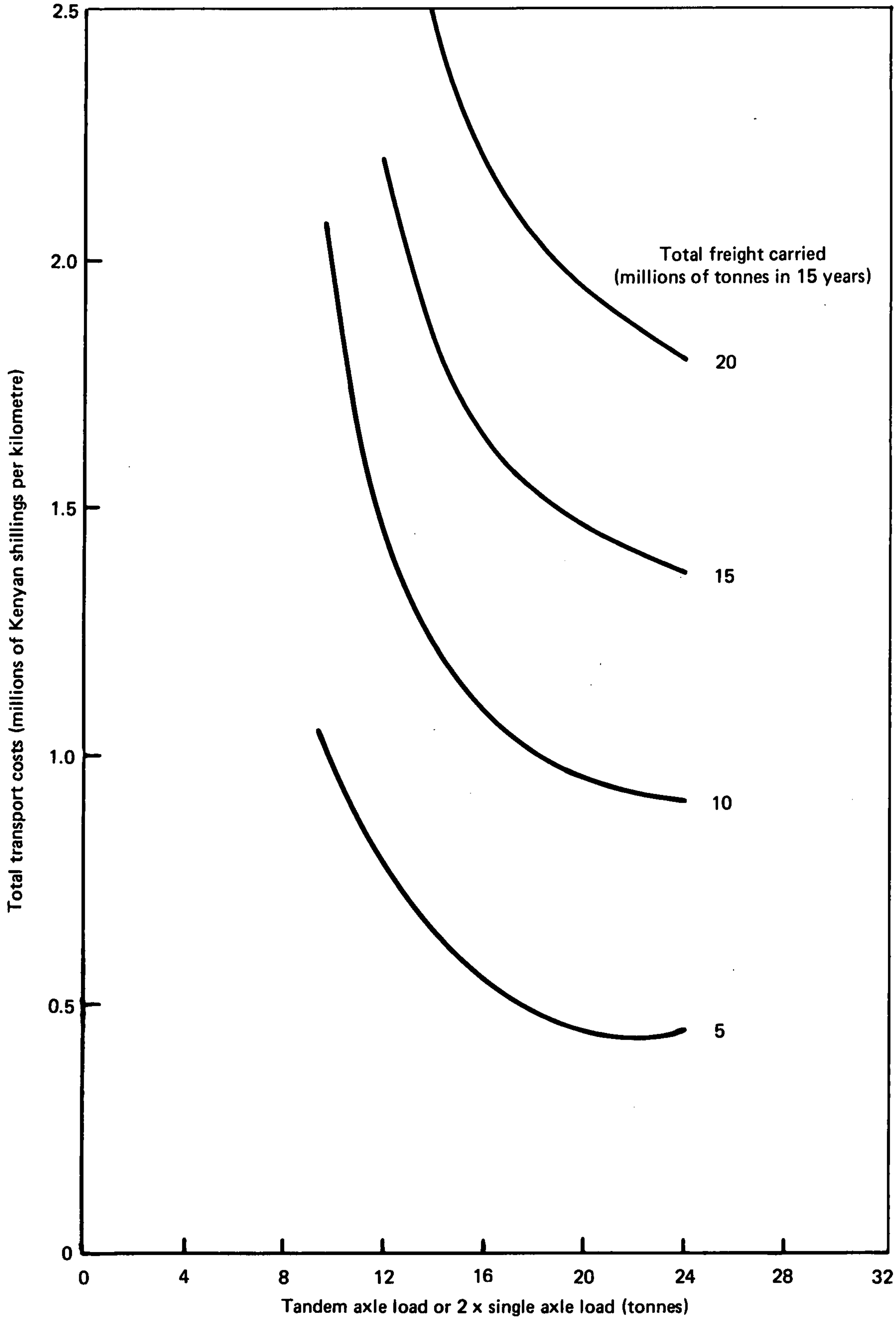

Fig. 11 Total transport costs as a function of axle load for a mixed vehicle fleet, overlay policy, full load conditions using 1975 prices.

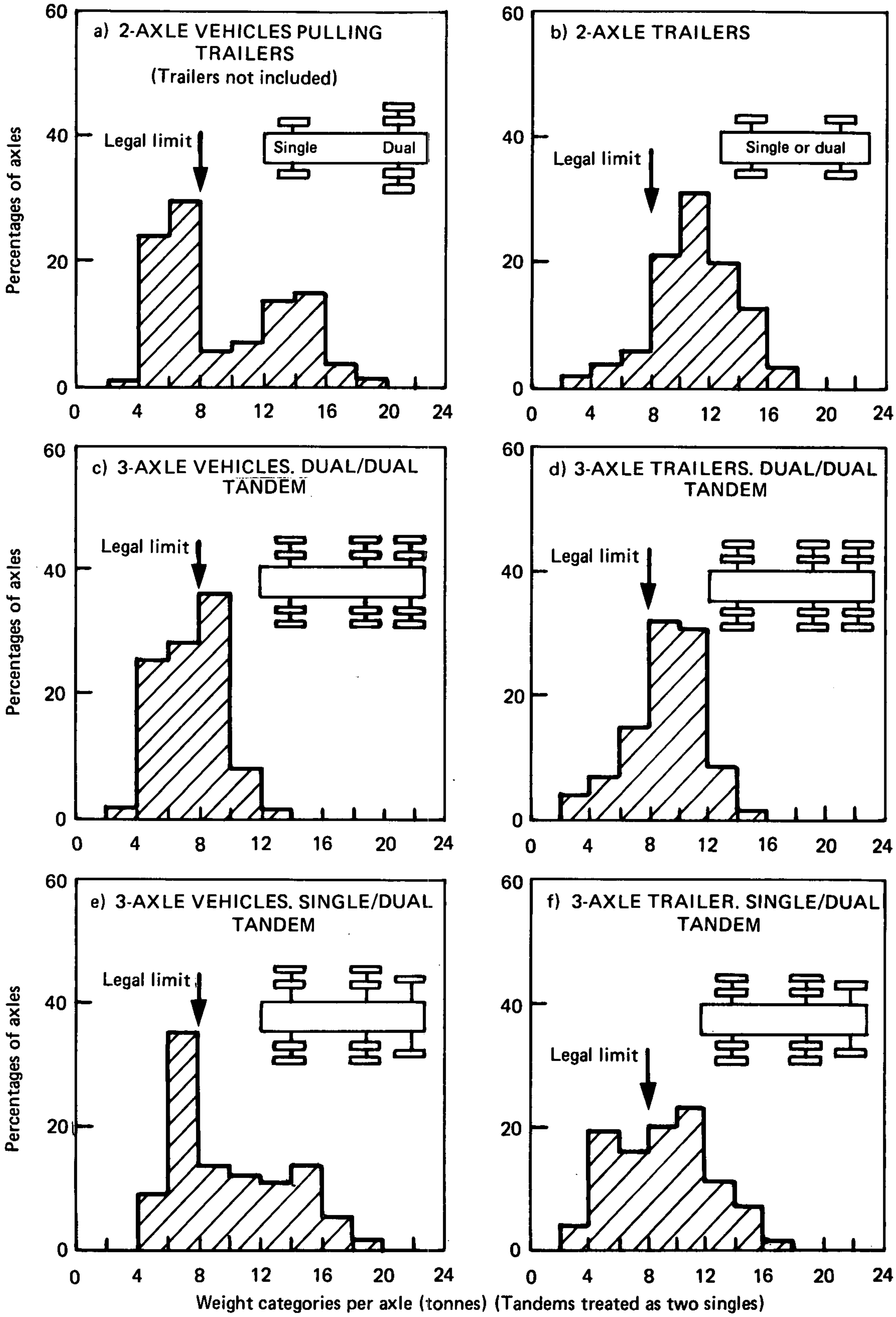

Fig. 12 Results of weighing survey

10. APPENDIX 1

INPUT DATA FOR MODEL

The original input data were based on the costs derived for the Yala–Busia road in Kenya described in Appendix 1 of Reference 9. These are summarised below. The new prices are based on a survey of prices in Nairobi in 1975 and are also shown.

1. Road cross section

Carriageway width	=	7.00 metres
Carriageway slope	=	1 in 40.00
Shoulder width	=	2.50 metres
Shoulder slope	=	1 in 10.00
Cut slope	=	1 in 1.00
Fill slope	=	1 in 3.00
Ditch depth	=	1.00 metres
Ditch bottom width	=	2.50 metres
Ditch bottom slope	=	1 in 0.00
Ditch side slope	=	1 in 1.50
Clearing width	=	20.00 metres

2. Road alignment

Road type	Total rise (m/km)	Total fall (m/km)	Curvature degrees/km
Level road	3.2	2.8	15
Rolling road	25.5	5.4	75
Hilly road	34.0	17.0	150

3. The costs of earthworks, culverts and headwalls are independent of axle load and are therefore not reproduced here.

4. Pavement costs (Kenyan shillings)

	1972	1975
Improved subgrade per cubic metre	15.5	20.0
Stabilised sub-base per cubic metre	71.1	90.0
Crushed stone base per cubic metre	122.4	159.7
Surface dressing per square metre	11.1	16.8
Asphaltic concrete per cubic metre	260	525
Shoulder gravel per cubic metre	21.3	25.0

			1972	1975
5.	Maintenance costs (Kenyan shillings)			
	Materials loaded			
	Liquid bitumen at source	Per litre	0.80	1.00
	Surface dressing stone at source	Per cu m	78.00	90.00
	Base patch material on site	Per cu m	1.50	3.00
	Surface patch mix on site	Per cu m	71.00	175.00
	Water at source	Per cu m	1.25	1.50
	Diesel fuel delivered	Per litre	1.16	1.84
	Labour (Kenyan shillings per hour)			
	Common labour		1.60	1.90
	Truck driver		2.40	3.00
	Plant operator		4.00	5.00
	Foreman		6.00	8.60
	Plant hire (Kenyan shillings per hour)			
	4500 litre self propelled bitumen distributor		20.0	40.00
	0.25 tonne vibrating roller		5.0	10.00
	Grader (3.7m blade)		34.3	70.00
	10 tonne self propelled roller		20.0	40.00
	Tractor mower (1.8m wide)		15.0	25.00
	Water truck (6 cu metres)		15.0	25.00
	Tipper truck (4 cu metres)		18.00	35.00
6.	Vehicle costs (Kenyan shillings)			
	Petrol per litre		1.10	2.65
	Diesel per litre		0.90	1.84
	Lubricants per litre		4.70	9.20
	Maintenance labour per hour		30.00	40.00
	Tyres		1500.0	2200.0
	Crew wages per hour		9.50	12.00
	Vehicle type A (purchase price in Kenyan shillings) BHP = 150 ULW = 5.5 tonnes		–	234000
	Vehicle type B (purchase price in Kenyan shillings) BHP = 177 ULW = 7.5 tonnes		142000	253000
	Vehicle type C (purchase price in Kenyan shillings) BHP = 177 ULW = 12.0 tonnes		–	317000
	Vehicle type D (purchase price in Kenyan shillings) BHP = 177 ULW = 12.5 tonnes		–	357000

All heavy vehicles travel 75 000 kilometres per year and the crews work for 5 000 hours per year.

7. Maintenance package units

Light (surface) patching
0.25 tonne vibrating roller
Tipper truck(4 cu metres)
6 labourers
1 foreman
Productivity of unit is 19 sq m/hr

Heavy (base) patching
0.25 tonne vibrating roller
Tipper truck(4 cu metres)
7 labourers
1 foreman
Productivity of unit is 3 cu m/hr

Surface dressing
4500 litre self propelled bitumen distributor
10 tonne self propelled roller
Tipper truck (4 cu metres)
23 labourers
1 foreman
Productivity of unit is 1600 sq m/hr

Mowing of shoulders
Tractor mower (1.8m wide)
1 labourer
0 foreman
Productivity of unit is 5000 sq m/hr

Grading of shoulders
Grader (3.7m blade)
1 labourer
0 foreman
Productivity of unit is 7000 sq m/hr

Drainage maintenance
Tipper truck (4 cu metres)
10 labourers
1 foreman
Productivity of unit is 10 cu m/hr

11. APPENDIX 2

VEHICLE LOADING CHARACTERISTICS

The loading characteristics of the majority of the vehicles used in this study were taken from axle load surveys conducted in Kenya during 1972-1974[7]. Figure 12 shows the results of surveys at one site on the A109 trunk road from Mombasa to Nairobi. The results are for the heavily loaded direction which is towards Nairobi. A more detailed examination of the histograms shows that there is a sharp cut off as axle load increases. For each type of vehicle or trailer the highest 5 per cent of axle loads spans less than 1.5 tonnes. The axle loads below which 95 per cent of all values lie for each type of axle configuration are given below.

a) 2-axled vehicles – 16 tonnes
b) 2-axled trailers – 14.5 tonnes
c) 3-axled vehicles (dual-dual tandem) – 10 tonnes per axle or 20 tonnes per tandem set
d) 3-axled vehicles (single-dual tandem) – 16 tonnes per dual axle or 24 tonnes per tandem set
e) 3-axled trailers (dual-dual tandem) – 12 tonnes per axle or 24 tonnes per tandem set
f) 3-axled trailers (single-dual tandem) – 14 tonnes per dual axle or 21 tonnes per tandem set

A more detailed analysis of the surveys is shown in Tables 4 and 5. From these tables the payload, pavement damage and main load carrying axle weight for all vehicles used in the study can be obtained by interpolation.

TABLE 4

Characteristics of 3-axled vehicles and trailers

	Unladen weight (tonnes)	Payload (tonnes)	Rear axle load (tonnes)	Equivalent standard axles	
				Dual-dual axle	Single-dual axle
Vehicles	6.5	6	8.9	0.15	0.30
		10	12.3	0.60	1.3
		14	15.7	1.7	4.1
		18	19.0	4.0	10.0
		22	22.2	8.1	21
		26	25.4	14	39
		30	28.6	25	68
	7.5	6	9.0	0.16	0.31
		10	12.6	0.71	1.4
		14	16.1	2.0	4.6
		18	19.5	4.6	11.4
		22	22.8	9.2	24
		26	26.0	17	43
		30	29.1	28	75
	8.5	6	10.3	0.30	0.58
		10	13.7	0.98	2.2
		14	17.0	2.5	5.9
		18	20.3	5.3	13.7
		22	23.6	10.7	28
		26	26.8	19	51
		30	30.0	32	86
	10.0	6	11.8	0.51	1.1
		10	15.1	1.48	3.4
		14	18.5	3.6	8.9
		18	21.7	7.4	19
		22	25.0	13.8	37
		26	28.1	23	63
		30	31.3	38	103
Trailers	5.0	8.3	10.0	0.19	0.42
		13.6	14.0	0.85	1.92
		19.0	18.0	2.7	6.0
		21.7	20.0	4.3	9.7
		24.3	22.0	6.6	14.9
		27.0	24.0	9.8	22

TABLE 5

Characteristics of 2-axled vehicles and trailers

	Unladen weight (tonnes)	Payload (tonnes)	Rear axle load (tonnes)	Equivalent standard axles
Vehicles	5.0	4.00	6.0	0.26
		6.65	8.0	0.92
		9.25	10.0	2.5
		11.75	12.0	5.6
		14.20	14.0	11.3
		16.55	16.0	20
		18.80	18.0	35
		20.90	20.0	55
Trailers	4.5	5.5	5.0	0.22
		9.5	7.0	1.00
		13.5	9.0	3.1
		15.5	10.0	5.0
		17.5	11.0	7.7
		19.5	12.0	11.3

(1461) Dd8041301 1,400 8/81 HPLtd So'ton G1915
PRINTED IN ENGLAND

ABSTRACT

Optimum axle loads of commercial vehicles in developing countries: J ROLT PhD MInst HE: Department of the Environment Department of Transport, TRRL Laboratory Report 1002: Crowthorne, 1981 (Transport and Road Research Laboratory). The Road Transport Investment Model for developing countries has been used to examine the effects of different axle loading characteristics on the total costs of road transport. It is shown that the sum of vehicle operating costs, road construction costs and road maintenance and rehabilitation costs for a two lane highway initially decrease rapidly as the axle load of the most heavily loaded vehicles increases and passes through a shallow minimum at the optimum axle load.

The value of this optimum axle load was found to be strongly dependent on the total freight tonnages carried by the heavily loaded vehicles, the load condition of these vehicles on the return trip, the exponent of the pavement damage – axle load relationship, and the relative prices of the major components of road transport cost. The optimum axle load was found to be virtually independent of the road alignment and strength of the subgrade, but the road construction and strengthening policy and the composition of the vehicle fleet had a small but significant effect on its value.

It is shown that under most conditions there exists a traffic level above which the optimum axle load is above the current legal limits in force in most developing countries.

The total road transport costs were usually found to be relatively insensitive to axle load in the region of the minimum total transport cost, changes in axle loads of 10 per cent producing changes in the transport costs of less than 1 per cent.

ISSN 0305–1293

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