

# Economic Analysis of Axle-Load Limits in Less-Developed Countries

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Overloaded vehicles contribute significantly to the deterioration of road surfaces. Most jurisdictions provide protection against severe pavement deterioration by enacting legislation that limits permissible axle loads. In most cases, axle-load limits are determined without reference to economic viability. Axle-load limits in less developed countries are obtained from experience in developed countries, where axle-load distributions, truck fleet composition, and adherence to regulations may differ significantly. An analysis is presented in which economically viable axle-load limits are established when the additional costs from pavement deterioration due to higher axle-load limits are offset by the benefits from reduced vehicle operating costs. With reference to this criterion, axle-load-distribution data from Abu Dhabi are used to establish economically viable axle-load limits. The dominance of vehicle operating cost savings due to higher limits submerges any additional costs due to pavement deterioration in the analysis. This suggests that economically viable axle-load limits in Abu Dhabi should be set to maximum feasible levels where bridge loading restrictions come into effect. This conclusion is amplified for less developed countries in general by considering sources of additional revenues. These additional revenues would be necessary to restore road serviceability after accelerated pavement deterioration from the application of higher axle loads.

Most jurisdictions provide protection against severe deterioration of road surfaces by enacting legislation that limits permissible axle loads. In general, legislation on maximum allowable axle loads is characterized by a lack of conformity across jurisdictional boundaries. A recent National Cooperative Highway Research Program (NCHRP) study (1) suggests that diverse axle-load requirements in various states in the United States impose additional costs on both trucking operations and road administration. Clearly, there is a need for consistent maximum axle-load guidelines that are both enforceable and economically viable. Economic viability is established when the savings that are realized by reducing pavement deterioration and enhancing service life are sufficient to offset additional hauling and administrative costs. The problem of establishing economically viable axle-load limits is rendered difficult by differences in savings and costs that occur across jurisdictional boundaries.

Experience with axle-load limits in less-developed countries suggests that economically desirable limits differ significantly from those in developed countries despite the fact that, in practice, limits in the former jurisdictions are transferred directly from limits in the latter jurisdictions. Abdel Halim (2) states three conditions that can produce uniquely different responses to axle-load-limit legislation in less-developed countries:

1. Enforcement of legislation may be inadequate.
2. The characteristics of pavement and road network design may vary from those in developed countries.
3. There may be differences in the composition of the truck fleet and in the type of commodities transported.

In this paper, axle-load limits in less-developed countries are assessed solely in terms of truck fleet composition and axle-load distributions. The Transport and Road Research Laboratory (3-5) observed differences in the distribution of axle loads for a number of less-developed and developed countries with varying axle-load limits. In general, the proportion of illegal axle loads in less-devel-

oped countries tended to be higher than in developed countries. Furthermore, most overloaded vehicles were observed to be two-axle trucks in less-developed countries but multiple-axle tractor-trailer combinations in developed countries. This would tend to produce axle-load distributions in less-developed countries that are skewed toward the upper limit.

Axle-load distributions and responses to axle-load-limit legislation in less-developed countries appear to be uniquely different than in developed countries. This suggests that an economically viable limit can be attained if experience in less-developed countries is studied in isolation, since the simple transfer of conclusions from one set of jurisdictions to another can produce significant distortions.

The study presented in this paper has two objectives:

1. To calibrate axle-load-distribution models for several less-developed countries that reflect varying responses to axle-load-limit legislation and
2. To assess the economic benefits and costs of changing axle-load limits in these jurisdictions (a case study of Abu Dhabi is documented to illustrate the economic evaluation).

In general, the framework introduced in this paper should provide guidelines for establishing economically viable axle-load limits in less-developed countries.

## AXLE-LOAD-DISTRIBUTION MODEL

The distribution of axle loads that is applied to the road pavement is a primary cause of surface deterioration and loss of serviceability. Essentially, pavement damage is directly proportional to the magnitude of the axle load and the number of axle passes over the pavement surface. Fossberg (6) expressed the relation between pavement damage and load distribution mathematically as follows:

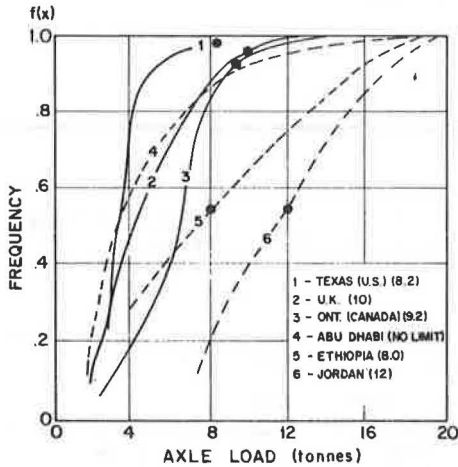
$$e(x) = (X/8.2)^{4.0} \quad (1)$$

where  $e(x)$  is the equivalent damage caused by an axle-load application of  $x$  Mg relative to a standard axle load of 8.2 Mg.

Equation 1 suggests that the damage to the pavement structure caused by the passage of a single axle is proportional to the fourth power of the axle-load application. An increase of 17 percent in the axle load (say, 8.2-9.6 Mg) would double structural damage according to Equation 1 and reduce pavement life by approximately one-third.

To assess the impact of axle-load limits on pavement deterioration, an axle-load-distribution model is required for each jurisdiction. Empirical evidence from several countries suggests a curvilinear relation between cumulative axle-load applications and axle load. Figure 1 shows this relation for six jurisdictions, three less-developed countries, and three developed countries. A gamma density function of the following form is suggested for the relation in Figure 1:

Figure 1. Typical samples of cumulative axle-load distributions.



$$f(x) = \beta(x - \theta) \exp[-\psi(x - \theta)] \quad (2)$$

where

- f(x) = proportion of axle loads with a load value of x Mg,
- $\theta$  = smallest axle load observed in the truck fleet, and
- $\beta, \psi$  = calibration parameters, which vary with limiting legislation and other jurisdictional factors.

Equation 2 implies that, as axle loads approach the upper limit imposed by legislation, fewer passes take place. This condition depends strongly on the level of enforcement of the limiting regulation and the response elicited from the operators. In less-developed countries, a lack of enforcement and a low response rate to legislation may affect higher values for the parameters  $\beta$  and  $\psi$  in Equation 2. Furthermore, the above axle-load-distribution model results in fewer axle passes in the lower range of loads. This is essentially a question of the efficient use of vehicle capacity to reduce individual operating costs.

If  $f(x)dx$  represents the number of axles with a load in the interval  $(x, x + dx)$ , then the total number of axle passes per unit of time can be expressed as

$$F(x) = \int_{\theta}^{x_m} f(x) dx = \int_{\theta}^{x_m} \beta(x - \theta) \exp[-\psi(x - \theta)] dx \quad (3)$$

where  $F(x)$  is the cumulative number of passes up to load  $x$  and  $x_m$  is the axle-load limit. The total payload ( $L$ ) carried by the pavement can be expressed as

$$L(x) = \int_{\theta}^{x_m} \beta(x - \mu)(x - \theta) \exp[-\psi(x - \theta)] \quad (4)$$

where  $\mu$  is the average weight per axle of an empty vehicle. Assuming that  $x_m$  is large and  $\theta$  is small, Equations 3 and 4 become

$$F(\infty) = \beta/\psi^2$$

$$L(\infty) = (\beta/\psi^3)[2 - \psi(x - \theta)]$$

Although the distribution of axle loads  $[f(x)]$  is assumed to vary with axle-load limit ( $x_m$ ), the total payload on the pavement is a function of economic activity in the jurisdiction and is assumed to remain constant for different values of  $x_m$  and  $f(x)$ .

Table 1. Empirical axle-load-distribution expressions for several less developed countries.

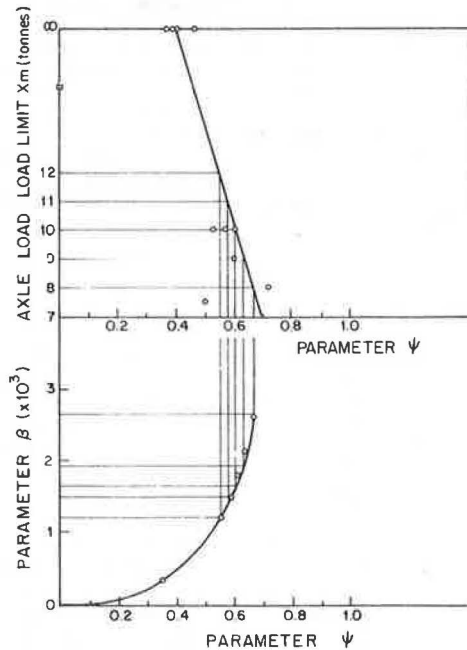
Country	Year	$\Psi$	$\beta^a$	SS/No. of Points	Axle-Load Limit (Mg)
Abu Dhabi	1971	-0.375	141.4	15.9	$\infty$
Qatar	1970	-0.400	160.0	19.0	$\infty$
Jordan	1975	-0.140	30.0	13.2	12
Turkey	1975	-0.325	110.0	7.5	8.2
Ethiopia	1976	-0.220	50.0	6.5	8.0
Kenya <sup>b</sup>	1974	-0.295	92.0	36.0	8.0
Malaysia	1967	-0.500	250.0	4.0	7.0

Note: SS = square root of the residual sum of squares for each expression.

<sup>a</sup>For 1000 axle passes.

<sup>b</sup>Heavy vehicles only.

Figure 2. Calibration parameters  $\beta$  versus  $\psi$  for various axle-load limits.



Several axle-load-distribution expressions were calibrated based on data from seven less-developed countries with different axle-load limits. The results of the calibration exercise are summarized in Table 1. All of the expressions explain a significant proportion of the relation between axle load and axle-load frequency. The mean of the residual sum of squares ranges from a low value of 4.0 for Malaysia to a high value of 36.0 for Kenya. The calibration parameters  $\beta$  and  $\psi$  are statistically significant at the 0.05 level of significance for all of the models. Tests of equivalence between expressions suggested that the calibration parameters are specific within jurisdictions. Obviously, if permissible axle loads have no limit ( $x_m = \infty$ ), operators in these jurisdictions will not be deterred from carrying as much payload as possible to reduce operating costs. This would be reflected in a low value of  $\psi$  and a low value of  $\beta$  in the axle-load-distribution expression for these particular jurisdictions.

Figure 2 shows the relation between the parameters  $\beta$  and  $\psi$  in the axle-load-distribution expressions and the jurisdictional axle-load limit  $x_m$ . Although this relation is based on only 10 observations, Figure 2 suggests that the parameter  $\psi$  decreases with increases in the axle-load limit  $x_m$ . Conversely, the parameter  $\beta$  increases exponentially with increases in  $x_m$ . In general, the fre-

quency of axle passes decreases with axle load. The rate of decrease is particularly significant for higher axle-load limits.

Equations 2-4 can be used to estimate the axle frequency response to varying axle-load limits. The axle-load-distribution expression for Abu Dhabi (1970) as stated in Table 1 can be used to illustrate the procedure. The observed number of axle passes for Abu Dhabi is 2243. Since the axle-load-distribution expression in Table 1 is based on 1000 axle passes, the actual value of  $\beta$  is adjusted by the ratio 2243/1000 to give  $\beta = 315.5$ . The expression of axle-load distribution becomes

$$f(x) = 315.5(x - 0.5) \exp[-0.375(x - 0.5)] \quad \text{for } X_m = \infty \quad (5)$$

Because Abu Dhabi has no axle-load limit on its road network, Equation 5 is calibrated for a value of  $X_m = \infty$  Mg. From Equation 4, the total payload is estimated to be  $L = 8600$  Mg. The smallest observed axle load ( $\theta$ ) and the average weight per axle of an empty vehicle ( $\mu$ ) are assumed to be 0.5 and 2.0 Mg, respectively.

If legislation is enacted that reduces the axle-load limit from  $X_m = \infty$  to  $X_m = 12$  down to 8 Mg, new axle-load distributions would result. The parameters  $\psi$  and  $\beta$  are obtained from Figure 2 for each axle-load limit. The new axle-load distributions are as follows for  $X_m = 8-12$  Mg:

$$f(x) = 2600.0(x - \theta) \exp[-0.67(x - \theta)] \quad X_m = 8 \quad (6a)$$

$$f(x) = 1900.0(x - \theta) \exp[-0.64(x - \theta)] \quad X_m = 9 \quad (6b)$$

$$f(x) = 1600.0(x - \theta) \exp[-0.61(x - \theta)] \quad X_m = 10 \quad (6c)$$

$$f(x) = 1400.0(x - \theta) \exp[-0.58(x - \theta)] \quad X_m = 11 \quad (6d)$$

$$f(x) = 1200.0(x - \theta) \exp[-0.55(x - \theta)] \quad X_m = 12 \quad (6e)$$

Assuming a constant total payload (8600 Mg), the number of axle passes would decrease with higher axle-load limits to 5700, 5292, 4835, 4454, and 4015 axles for  $X_m = 8, 9, 10, 11,$  and  $12$  Mg, respectively. A change in damage to the pavement caused by the axle-load distribution under the new axle-load limit can be obtained. Ultimately, an economic assessment of the legislation is possible based on pavement deterioration and vehicle operating costs.

**ECONOMIC ANALYSIS OF AXLE-LOAD LIMITS**

The purpose of this section of the paper is to assess the economic viability of axle-load-limit legislation based on vehicle operating costs and pavement rehabilitation and maintenance costs. Higher axle-load limits reduce average vehicle operating costs, since operators can consolidate their rolling stock more effectively. On the other hand, higher axle-load limits accelerate the process of pavement deterioration and increase rehabilitation and maintenance costs for the transportation agency. An economically viable program will produce increased rehabilitation and maintenance costs, which are at least offset by savings to vehicle operators. In the subsequent discussion, the various cost components of pavement deterioration due to axle loads are itemized and compared with vehicle operating costs.

**ROAD REHABILITATION AND MAINTENANCE COSTS**

The maintenance of a pavement surface is directed at restoring serviceability at an acceptable standard. Figure 3 shows the relation between serviceability as measured by the present serviceability index

Figure 3. PSI versus SAL repetitions.

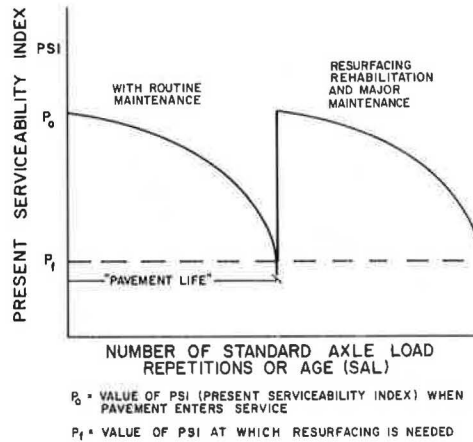
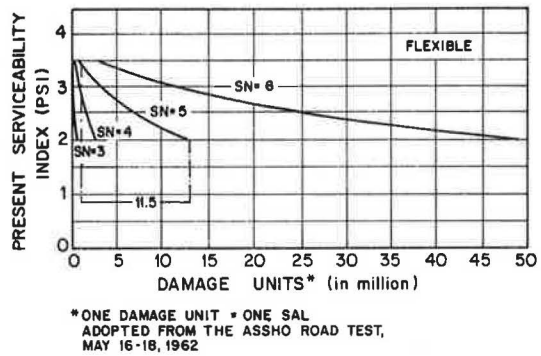


Figure 4. PSI versus DUs for flexible pavements.



(PSI) and the number of standard axle-load repetitions (or age of pavement). The PSI is a rating index established by the American Association of State Highway Officials (AASHO) (7) that reflects the ability of a pavement to serve specific traffic requirements. When the PSI drops below  $P_f$ , major pavement restoration or rehabilitation is required. Rehabilitation involves reconstruction of the pavement layer structure so as to restore serviceability to its original level. Routine maintenance, on the other hand, includes temporary or permanent patching and surface sealing; it is directed at correcting pavement distress when deterioration has not reached a point where rehabilitation is required.

Changes in the axle-load limit will modify rehabilitation and maintenance costs by altering the time stream over which these expenditures are required. Lower axle-load limits enhance the time period over which an acceptable level of serviceability (PSI) can be retained, whereas higher axle-load limits advance the time when rehabilitation is required.

One of the most common methods of relating pavement life to standard axle-load repetitions is provided by the AASHO Road Test (7). Figure 4 shows the relation between PSI and damage units (DUs) for various structural numbers (SNs) for flexible pavements. The DU is a standard unit that reflects the damage caused by the passage of a standard axle (8.2 Mg) on an area of flexible pavement that has a given SN. The SN is an index that reflects the composition of the layered pavement structure:

$$SN = a_1 D_1 + a_2 D_2 + a_3 D_3 \quad (7)$$

where

- $D_1$  = depth of pavement surface,
- $D_2$  = depth of base course, and
- $D_3$  = depth of subbase course.

The most common values for  $a_1$ ,  $a_2$ , and  $a_3$  are 0.44, 0.14, and 0.11, respectively.

Changes in axle-load limits can be expressed in terms of changes in DUs through the AASHO relations in Figure 4. The following example from Abu Dhabi for 1971 can be used to illustrate the procedure.

With an axle-load limit  $X_m = \infty$ , the axle-load distribution is given by Equation 5, which corresponds to 2243 axle passes carrying a total payload of 8600 Mg. A new axle-load limit--say,  $X_m = 9$  Mg--modifies the axle-load-distribution expression to Equation 6b, which yields 5292 axle passes for a constant total payload of 8600 Mg. Similar axle-load-distribution expressions can be obtained for other proposed axle-load limits of  $X_m = 8-12$  Mg. The base PSI is assumed to be 3.5 at the time that the axle-load limit is altered. Major rehabilitation is required when the PSI reaches a value of  $P_f = 2.0$ . The pavement structure is assumed given at  $SN = 5.0$  for all roads in the network. Changes in the service life of the pavement can now be obtained.

By using Equations 1 and 6, the total daily DUs can be estimated from each of the calibrated axle-load distributions: e.g., at  $X_m = \infty$  (no limit),

$$DU_1 = \int_0^{X_m=\infty} e(x)f(x) dx = 3011 \quad (8)$$

where  $e(x)$  is as defined in Equation 1 and  $f(x)$  is the axle-load-distribution Equations 5 and 6a to 6e, respectively.

By using Equation 8 and inserting the respective  $X_m$ , the following DUs are obtained:

$X_m$ (Mg)	DU
12	$DU_2 = 1168$
11	$DU_3 = 1035$
10	$DU_4 = 927$
9	$DU_5 = 837$
8	$DU_6 = 763$

These DU estimates are obtained for a total payload of 8600 Mg/day.

If the payload carried by the pavement is set at 8600 Mg/day, the annual number of DUs before and after the axle-load limit is imposed can be estimated as follows:

$X_m$ (Mg)	Annual DUs
$\infty$	1 099 015
12	426 320
11	377 775
10	338 355
9	305 505
8	278 495

Assuming a base PSI of 3.5 for time  $t = 0$ , the pavement can carry  $11.5 \times 10^6$  DUs before  $PSI = P_f = 2.0$ . If 1 099 015 DUs are applied per year at  $X_m = \infty$ , the pavement life between rehabilitation programs is equal to  $11.5 \times 10^6 / 1\,099\,015 = 10.4$  years. Reducing the axle-load limit to 9 Mg or 305 505 DUs/year will extend the pavement life to  $11.5 \times 10^6 / 305\,505 = 37.6$  years between rehabilitation programs. The pavement rehabilitation periods in years for  $X_m = \infty$  and 12-8 Mg are summarized in Table 2.

Rehabilitation unit costs depend on various factors. They vary proportionally according to the type of overlay and its thickness. These costs vary also from one country to another depending on mate-

Table 2. Annual pavement rehabilitation cost savings.

Axle-Load Limit (Mg)	Rehabilitation Period (years)	Annual Unit Rehabilitation Cost (\$/lane/km)	Annual Savings by Interest Rate Level (\$/lane/km)		
			10 Percent	12 Percent	15 Percent
$\infty$	11	20 000	1079	968	821
		50 000	2698	2420	2053
		75 000	4046	3630	3079
12	28	20 000	149	105	61
		50 000	373	263	153
		75 000	559	394	229
11	32	20 000	99	66	35
		50 000	248	165	88
		75 000	371	248	131
10	35	20 000	74	46	23
		50 000	185	115	58
		75 000	278	172	86
9	38	20 000	45	28	12
		50 000	113	70	30
		75 000	169	105	45
8	43	20 000	35	19	8
		50 000	88	48	20
		75 000	131	71	30

rials, labor, and equipment costs. Motomura's study of axle-load limits in Oman (8) concluded that the cost of 40-mm wearing course/lane/km is about \$25 000. If base course repair is required, then the total cost is as high as \$55 000/lane/km. For the same procedure in Kenya, these costs range from \$12 000 to \$30 000/lane/km, as documented by Robinson and Hide (9). Our analysis includes both values in the range of rehabilitation costs. Oman represents the higher limits, which can be used for Abu Dhabi and Qatar. Kenya represents the lower limits, which can be used for other African countries. Thus, for a 40-mm wearing course the cost ranges from \$12 500 to \$25 000 and for base course repair from \$30 000 to \$55 000/lane/km. All costs are in 1978 U.S. dollars.

Table 2 summarizes the annual savings per lane kilometer for Abu Dhabi from reductions in pavement rehabilitation expenditures. These savings were estimated for axle-load limits of 12-8 Mg. To provide a measure of sensitivity, savings were estimated for interest rates of 10, 15, and 20 percent and unit cost values of \$20 000, \$50 000, and \$75 000/lane/km.

Routine annual maintenance costs were estimated based on the assumption that higher costs would occur under a higher axle-load limit. This assumption seems reasonable since deterioration of the pavement between rehabilitation programs would be accelerated. Estimates of routine annual maintenance were obtained based on the assumption of accelerated deterioration for higher axle-load limits. However, the results of this analysis indicated that routine maintenance costs did not vary appreciably with axle-load limits. Accordingly, routine maintenance has been ignored from the analysis.

Vehicle Operating Costs

Whiteside and others (10) calibrated a model that relates total vehicle operating costs to gross vehicle weight (GVW). The equation is of the following form:

$$CT = 24.8150 + 0.1778W + 0.0047W^2 \quad (9)$$

where CT is total vehicle costs in cents per kilometer and W is GVW in megagrams. The unit cost in Equation 9 includes fuel consumption, maintenance,

driver's wages, wear and tear, overhead, and depreciation costs. This function was calibrated from 1970 U.S. motor carrier data.

Observed vehicle operating costs (1978) for Oman and Kenya are given below:

No. of Axles	Avg GVW (Mg)	Cost (¢/vehicle/km)	
		Oman	Kenya
2	14.4	37.6	33.5
3	20.9	48.7	45.1
4	27.0	57.4	52.2
5	36.0	57.4	54.6
6	42.0	57.4	58.6

For empty vehicles, the following cost data were available from Oman only:

No. of Axles	Cost (¢/vehicle/km)
2	31.93
3	40.74
4	48.11

Unit costs in cents per vehicle per kilometer depend strongly on vehicle type as measured by number of axles. The costs in Equation 9 were updated to 1978 values by using a cost index for pavement management developed by Layton and others (11). The vehicle operating costs given above for Oman and Kenya were used to break the updated cost equation into a vehicle operating cost function for each axle type. The results for Oman and Kenya are given in Table 3.

To illustrate how the aggregate vehicle cost in Equation 9 has been reduced to an axle-specific function for each jurisdiction, consider Equation 10a in Table 3 ( $CT = 26.96 + 0.329 W + 0.0087 W^2$ ). Cost index increases for pavement maintenance for 1970-1978 were 0.6-1.2 (11). Equation 9 is thus updated as follows: Factors 0.1778 and 0.0047 become 0.3290 and 0.0087.

The cost index was applied solely to the weight variable component of the vehicle cost expression so that total vehicle operating costs (CT) could be written as

$$CT = K + 0.329 W + 0.0087 W^2 = 33.5$$

The value of 33.5¢/vehicle/km is taken from the preceding text table on vehicle operating cost for two-axle vehicles in Kenya. Solving for K yields 26.96. The updated two-axle expression for Kenya becomes Equation 10a. The relations between vehicle operating cost and GVW for Oman and Kenya are shown in Figure 5 for five different axle numbers per vehicle. Estimates of unit vehicle operating costs are summarized in Table 4 for various gross load intervals and vehicle types.

To estimate vehicle operating costs for a given

Table 3. Unit vehicle operating cost functions by number of axles for Oman and Kenya.

No. of Axles	Country	Equation	Equation No.
2	Kenya	$CT = 26.96 + 0.329W + 0.0087W^2$	10a
	Oman	$CT = 31.06 + 0.329W + 0.0087W^2$	10b
3	Kenya	$CT = 34.42 + 0.329W + 0.0087W^2$	10c
	Oman	$CT = 38.02 + 0.329W + 0.0087W^2$	10d
4	Kenya	$CT = 36.97 + 0.329W + 0.0087W^2$	10e
	Oman	$CT = 42.17 + 0.329W + 0.0087W^2$	10f
5	Kenya	$CT = 31.48 + 0.329W + 0.0087W^2$	10g
	Oman	$CT = 34.28 + 0.329W + 0.0087W^2$	10h

axle-load distribution, the distribution of GVW must be related to the axle-load distribution. Let the proportion of total gross load carried by vehicles with  $i = 2,3,4...$  axles equal  $a_i$ . GVW can be obtained so that GVW vehicle type  $i = iX_j$ . The total load carried by all axles in the  $j$ th load interval =  $n_jX_j$ . The total number of vehicles with  $i$  axles in the  $j$ th load interval becomes

$$V_j(i) = [n_jX_j(i)a_i/n_iX_j(i)] = n_ja_i/n_i \tag{11}$$

The total number of vehicle trips for each axle-load limit  $X_m$  becomes

$$N(X_m) = \sum_j \sum_i (n_ja_i/n_i) \tag{12}$$

where

$n_j$  = number of axles in interval  $j$  (from Equations 5 and 6),

$n_i$  = number of axles for vehicle type  $i$ ,

$a_i$  = proportion of total gross load carried by vehicles with  $i$  axles, and

$X_j(i)$  = axle load in interval  $j$  for vehicle type  $i$ .

Values of  $V_j(i)$  and  $N(X_m)$  are summarized in Table 5 for axle-load limits  $X_m = \infty$  and 12-8 Mg.

Total vehicle operating costs can be obtained from Table 5. For Abu Dhabi, vehicle operating

Figure 5. Vehicle operating costs versus GVW for Oman and Kenya.

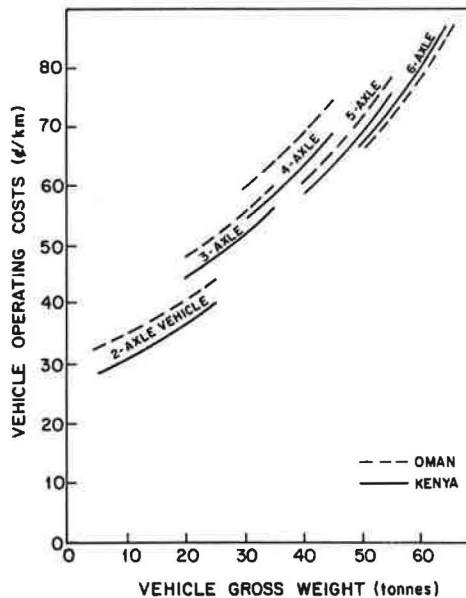


Table 4. Unit vehicle operating costs by vehicle type and load interval.

Axle-Load Interval (Mg)	Cost (¢/km)			
	Two Axles	Three Axles	Four Axles	Five Axles
3	32.1	39.1	43.2	35.4
5	32.9	39.9	44.0	36.1
7	33.8	40.8	44.9	37.0
9	34.7	41.7	45.8	38.0
11	35.7	42.7	46.8	39.0
13	36.8	43.8	47.9	40.0
15	37.0	44.9	49.1	41.2
17	39.2	46.1	50.3	42.4
19	40.5	47.4	51.6	43.7

costs were estimated for various axle-load limits; the results are as follows (costs are given in 1978 U.S. dollars):

Axle-Load Limit (Mg)	Annual Vehicle Operating Cost (\$)
∞	115 600
12	183 200
11	196 500
10	210 200
9	224 800
8	240 000

val and the number of vehicle axles are summarized in Table 6 for axle-load limits  $X_m = \infty$  and 12-8 Mg. Total costs are given below:

Axle-Load Limit (Mg)	Total Cost (\$)	
	Daily	Annual
∞	316.88	115 661.20
12	501.88	183 222.70
11	538.47	196 541.55
10	575.92	210 210.80
9	615.90	224 803.50
8	657.76	240 082.40

Detailed vehicle operating costs by GVW load inter-

In general, vehicle operators would perceive an

Table 5. Daily vehicle passes by load interval for varying axle-load limits.

Axle-Load Limit (Mg)	No. of Axles	Daily Vehicle Passes by Load Interval										$\sum_j V_j (i)$
		3 Mg	5 Mg	7 Mg	9 Mg	11 Mg	13 Mg	15 Mg	17 Mg	19 Mg		
∞	2	256	222	154	95	55	31	17	9	5	844	
	3	17	10	7	4	3	1	1	0	1	39	
	4	7	6	4	3	2	1	1	1	0	25	
	5	5	5	3	2	1	1	1	0	0	18	
12	2	637	395	192	84	35	14	5	1	1	1364	
	3	30	19	9	4	2	0	1	1	0	66	
	4	18	11	5	2	1	0	0	0	0	37	
	5	13	8	4	2	1	1	0	0	0	29	
11	2	721	422	194	80	31	12	5	2	0	1467	
	3	34	20	9	4	1	0	0	0	0	68	
	4	21	12	6	2	1	1	0	0	0	43	
	5	15	9	4	2	1	0	0	0	0	31	
10	2	812	448	194	75	28	10	4	0	0	1571	
	3	38	21	9	4	0	1	0	1	0	74	
	4	23	13	6	2	1	0	0	0	0	45	
	5	17	9	4	2	1	0	0	0	0	33	
9	2	909	473	94	71	25	8	3	1	0	1684	
	3	43	23	9	4	1	1	0	0	0	81	
	4	26	13	5	2	0	0	0	0	0	46	
	5	19	10	4	1	1	0	0	0	0	35	
8	2	1014	498	192	67	22	5	1	0	0	1799	
	3	48	23	9	3	1	2	1	0	0	87	
	4	29	14	5	2	1	0	0	0	0	51	
	5	21	11	4	1	0	0	0	0	0	37	

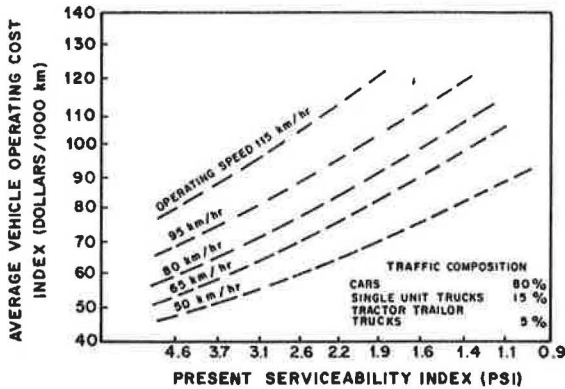
Table 6. Daily vehicle operating costs by load interval for varying axle-load limits.

Axle-Load Limit (Mg)	No. of Axles	Daily Vehicle Operating Cost by Load Interval (\$)										Total
		3 Mg	5 Mg	7 Mg	9 Mg	11 Mg	13 Mg	15 Mg	17 Mg	19 Mg		
∞ <sup>a</sup>	2	82.18	73.04	52.05	32.97	19.64	11.41	6.29	3.53	2.03	283.14	
	3	4.69	3.99	2.86	1.67	1.28	0.44	0.45	-	0.47	15.85	
	4	3.02	2.64	1.80	1.37	0.94	0.48	0.49	0.50	-	11.24	
	5	1.77	1.81	1.11	0.76	0.39	0.40	0.41	-	-	6.65	
12 <sup>b</sup>	2	204.48	129.96	64.90	29.15	12.50	5.15	1.85	0.39	0.41	448.79	
	3	11.73	7.58	3.67	1.67	0.85	-	0.45	0.46	-	26.41	
	4	7.78	4.84	2.25	0.92	0.47	-	-	-	-	16.26	
	5	4.60	2.89	1.48	0.76	0.39	0.40	-	-	-	10.52	
11 <sup>c</sup>	2	231.44	138.44	65.57	27.76	11.07	4.42	1.85	0.78	-	481.32	
	3	13.29	7.98	3.67	1.67	0.43	-	-	-	-	27.04	
	4	9.07	5.28	2.69	0.92	0.47	0.48	-	-	-	18.91	
	5	5.31	3.25	1.48	0.76	0.39	-	-	-	-	11.19	
10 <sup>d</sup>	2	260.65	147.39	65.57	26.03	10.00	3.68	1.48	-	-	514.80	
	3	14.86	8.38	3.67	1.67	-	0.44	-	0.46	-	29.48	
	4	9.94	5.72	2.69	0.92	0.47	-	-	-	-	19.74	
	5	6.02	3.25	1.48	0.76	0.39	-	-	-	-	11.90	
9 <sup>e</sup>	2	291.79	155.62	65.57	24.64	8.93	2.94	1.11	0.39	-	550.99	
	3	16.81	9.18	3.67	1.67	0.43	0.44	-	-	-	32.20	
	4	11.23	5.72	2.25	0.92	-	-	-	-	-	20.12	
	5	6.73	3.61	1.48	0.38	0.39	-	-	-	-	12.59	
8 <sup>f</sup>	2	325.49	163.84	64.90	23.25	7.85	1.84	0.37	-	-	587.54	
	3	18.77	9.18	3.67	1.25	0.43	0.88	0.45	-	-	34.63	
	4	12.53	6.16	2.25	0.92	0.47	-	-	-	-	22.33	
	5	7.43	3.97	1.48	0.38	-	-	-	-	-	13.26	

<sup>a</sup> Daily total = \$316.88, annual cost = \$115 661.20.  
<sup>b</sup> Daily total = \$501.88, annual cost = \$183 222.70.  
<sup>c</sup> Daily total = \$538.47, annual cost = \$196 541.55.

<sup>d</sup> Daily total = \$575.92, annual cost = \$210 210.80.  
<sup>e</sup> Daily total = \$615.90, annual cost = \$224 803.50.  
<sup>f</sup> Daily total = \$657.76, annual cost = \$240 082.40.

Figure 6. Vehicle operating cost index for rural free-flow conditions.



increase in unit costs with increased pavement deterioration. As the pavement surface deteriorates, unit vehicle operating costs increase all other factors assumed to be constant. The unit vehicle operating costs from Equation 10 ignore this time-dependent component and assume that unit costs are a function solely of GVW and number of axles per vehicle. Pavement deterioration is accelerated on roads that have higher axle-load limits. The PSI is a measure of the perception of pavement deterioration by the vehicle operator. Figure 6 (12) shows the relation between average vehicle operating costs and PSI for different operating speeds in Canada and the United States. Figure 6 was used to adjust the unit vehicle operating costs in Equation 10 to account for perceived pavement deterioration.

In general, vehicle operating costs for lower axle-load limits were reduced appreciably. However, the relative magnitude of vehicle operating costs in relation to rehabilitation costs did not change significantly. Vehicle operating costs remained the dominant component in the cost analysis whether unit vehicle operating costs were made dependent on pavement deterioration or were assumed to be constant.

Comparison of reductions in annual road rehabilitation costs (Table 2) with increases in annual vehicle operating costs (from the preceding text table) indicates values several times greater for the latter component. The dominance of vehicle operating costs is unaffected by the assumed interest rate or the unit rehabilitation cost per lane per kilometer. For example, a reduction in axle-load limit from 12 to 8 Mg results in an annual saving in rehabilitation costs of \$428/lane/km based on a \$75 000 unit rehabilitation charge and an interest rate of 10 percent. On the other hand, this reduction in axle-load limit results in an increase in annual vehicle operating costs of approximately \$57 000. Even for an initial axle-load limit reduction of  $X_m = \infty$  to  $X_m = 12$  Mg, increases in annual vehicle operating cost exceed reductions in pavement rehabilitation by approximately \$64 000/lane/km at  $i = 10$  percent.

The dominant nature of vehicle operating costs in relation to pavement rehabilitation costs is the basis of the guidelines for the imposition of an economically viable axle-load limit in less-developed countries. This analysis has considered only the two cost components--rehabilitation costs and vehicle operating costs. Obviously, including other indirect costs such as increase in vehicle operating costs for noncommercial vehicles could modify the results significantly in favor of lower axle-load limits. Nevertheless, in the context of the cost components included in this analysis, the assertion

remains that the most economically viable axle-load limit in less-developed countries is no limit at all.

#### CONCLUSIONS

The dominance of vehicle operating costs in the analysis suggests that road rehabilitation and maintenance expenditures need not be considered in determining an economically viable axle-load limit. It appears that this conclusion is universal regardless of whether the jurisdiction is in a developed economy or a less-developed economy. Clearly, the savings that can be realized by commercial vehicle operators from fewer vehicle trips and greater axle loads more than offset the higher cost of pavement rehabilitation and maintenance.

The implications of the results of this analysis are dramatic. Transportation agencies in developed and less-developed jurisdictions, based solely on the argument of economic efficiency, would be advised to increase the axle-load limit to a level where bridge loading restrictions come into effect.

The underlying concern remains: If no axle-load limit is the most economically viable alternative, why do most jurisdictions persist in imposing lower, less than efficient axle-load limits? The answer to this question lies in three basic factors:

1. The perception of a direct cost by the transportation agency,
2. Budget restrictions and program management, and
3. Joint use of the road facilities by commercial and noncommercial vehicles.

Whereas maintenance and rehabilitation charges are borne directly by the transportation agency and are central to the agency's concerns on axle-load limits, operating costs, although significant, are incidental to the agency. As a result, savings in vehicle operating costs are not considered benefits by the transportation agency in the allocation of road rehabilitation and maintenance funds. Studies on axle-load limits reflect this concern in that vehicle operating costs have been ignored. Ellis and Potocki (3) note that financial savings due to complete enforcement of an axle-load limit in Abu Dhabi and Qatar have not taken account of the extra cost that may be incurred by vehicle operators as a consequence of the reduction in vehicle payload that would be necessary:

The ideal solution would be to minimize total transport costs, i.e., the mix of costs of road construction, maintenance and vehicle operation. In the absence of data and methodology, to effect this ideal solution, it would appear sensible to act in line with other countries and adopt a similar policy of axle-load restraint.

It would appear from our analysis that Abu Dhabi's solution of "no axle-load limit" is closer to the ideal, since the dominant component vehicle operating costs are reduced.

In the absence of an effective benefit-cost guideline for setting axle-load limits, most transportation agencies in both developed countries and less-developed countries rely on budget restrictions. Each year a given sum of money is set aside for rehabilitation and maintenance. This money is obtained from general revenues and may have little relation to pavement restoration needs. If annual rehabilitation and maintenance expenditures exceed the budget, either more money must be set aside or the axle-load limit must be lowered to reduce these expenditures. Jurisdictional axle-load limits are determined, therefore, not by economic viability but

by the availability of funding; higher axle-load levels are tolerated in jurisdictions where money for rehabilitation and maintenance programs is available.

NCHRP Report 198 (1) and reports by Ellis and Potocki (3) and Whiteside and others (10) have recognized that the current practice may not necessarily be economically efficient. It has been suggested that axle-load limits be increased to a more efficient level and a greater share of the cost of pavement rehabilitation and maintenance be paid by operators of commercial vehicles. Ideally, additional charges would be in proportion to applied axle loads. In developed countries, this proposal would be difficult to administer, particularly since a large segment of traffic is noncommercial in nature. Fearing higher surcharges, truck operators themselves have been reluctant to promote the scheme despite, as shown in our analysis, the incidence of significant benefits from reduced vehicle operating costs.

In less-developed countries, three conditions tend to favor an increase in axle-load limits:

1. Commercial traffic constitutes a larger share of total road use.

2. A greater proportion of trucks are double-axle, single-unit vehicles instead of multiple-axle tractor-trailer combinations. This tends to increase axle loads despite lower GVW.

3. The resources required for road rehabilitation and maintenance programs are essentially domestic.

Increased axle-load limits in these jurisdictions would essentially benefit commercial users. Because these users effect the bulk of pavement deterioration, any surcharge to finance maintenance programs is easily justified and recoverable. An arbitrary low axle-load limit in conjunction with a large proportion of double-axle vehicles tends to encourage a greater use of multiple-axle vehicles. In our analysis, truck fleet composition is assumed to be constant, although the cost to a less-developed country of a truck fleet changeover could be significant. The resources required for truck fleet changeover in less-developed countries are essentially imported. On the other hand, few imported resources are required for additional road rehabilitation and maintenance programs. In general, it would be advisable to invite commercial users in less-developed countries to assume a greater share of road restoration programs in exchange for higher

axle-load limits. If they should fail to get the necessary cooperation from commercial users, transportation agencies would be advised to increase current axle-load limits to the levels dictated by available funds.

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