Optimum Axle-Load Limits in Oman

Yuichiro Motomura, Louis Berger International, Inc., East Orange, New Jersey

The cost of highway maintenance and construction increases as the axle loading increases, whereas the cost of cargo transport decreases as axle loading increases because fewer trips are needed to transport a given amount of cargo. Each country has its own specific optimum axle-load limit that produces the lowest total cost in highway maintenance and construction and in cargo transport. An analysis was performed, for a developing country, wherein existing axle-load distribution patterns were modified in a specific manner to devise estimated distribution patterns under various axle-load limit alternatives. Subsequent changes in traffic volumes were also estimated. Pavement maintenance and construction requirements were estimated on the basis of total equivalent number of standard axles, for which costs of combined total and relative levels were examined. Some conclusions are (a) that for a given highway the optimum limit exists only for a range of intermediate traffic levels (for the low and high traffic levels, no-limit case always yields the least total cost), (b) that although the total cost may not vary significantly by axle-load limits, public and private sectors share the total cost in considerably different proportion under different axle-load limits, and (c) that an axle-load limit may have significantly different effects on different types of vehicles.

Paved highways are being constructed at a quickening pace in many developing countries, which has made maintenance needs and expenditures increase accordingly.

A phenomenon frequently observed in developing countries is overloading of trucks. The necessity for controlling such axle-loading practices is clear. However, given prevailing economic considerations, the problem is more complex than it may at first seem. On the one hand, if heavier loads are permitted, fewer trucks will be needed and less trips will be required to transport a given amount of cargo. The cost of cargo transport borne by the trucking industry will thus decrease, and, theoretically, if a competitive market exists, the resulting benefit will spread from truckers to shippers and eventually to consumers. On the other hand, heavier loading increases the cost of maintenance or shortens the life of pavement. A subordinate issue here is the allocation of the total cost. Generally, the cost of road maintenance and construction is borne by the public sector, while most direct transportation costs are paid by the private sector. Therefore, the axle-load limit can be a way of allocating expenses between the public and the private sectors.

Each country, with its existing and planned highways, transport and other industries, agricultural and mineral production, and predicted freight volume, has its own specific optimum axle-load limit that results in the lowest total cost in highway maintenance and construction and in cargo transport.

In a study conducted for the government of the Sultanate of Oman, various elements relating to axle-load limitations were considered and recommendations were made. This paper presents an analysis of such limits based on this study. A practical method for analyzing the quantifiable aspect of the problem is presented.

METHOD

Effects of axle-load limit alternatives were identified as changes in the predicted vehicle fleet composition and the axle-load distribution pattern extrapolated from the existing situation. It was assumed that the same amount of total cargo would have to be transported in any case. These estimated axle-load distribution patterns and vehicle fleet compositions were then converted into two separate sets of data: The number of passes of 80-kN (18 000-lbf) standard axles whose effect was equivalent to the effect of actual axle loads on the pavement and traffic volumes for each vehicle type with its average loadings. The maintenance and construction costs were derived from the former; the vehicle operating costs were derived from the latter.

A study period of 20 years was chosen. All highways were assumed to be maintained, on the average, in fair condition throughout the study period. Since automobile and pickup traffic was found to have practically no effect on pavement life, only heavy-vehicle traffic was considered.

Characteristics of Heavy-Vehicle Traffic

Axle-load distribution patterns in Oman were obtained for single and tandem axles for each of three vehicle types. Figures 1 and 2 show these and comparable data for the United States (1) and the United Kingdom (2). It should be noted that axle loadings are substantially higher in Oman than in the other countries, particularly the United States, and that in the United Kingdom tandem axles are regarded as two single axles for commercial vehicles. Table 1 summarizes the characteristics of heavy-vehicle traffic.

Pavement Strength and Maintenance Requirements

The analysis of pavement strength and maintenance requirements was carried out solely on the basis of design parameters by using the method recommended for design purposes in the AASHO Interim Guide for Design of Pavement Structures (3).

The damaging power of axle loads is often expressed in terms of equivalent standard axles of 80 kN (18 000 lbf). The AASHO method calls for applying separate sets of factors to single and tandem axles in order to convert axle loads to equivalent standard axles. Two single axles, each carrying a load W, are treated as causing 40 percent more damage than a tandem axle carrying a load of 2W.

It should be noted that there is some uncertainty concerning the tandem-axle conversion factors. The Transport and Road Research Laboratory has recommended that all axles be considered as single axles on the grounds that empirical results are not conclusive and that the loads of each axle of a tandem axle might differ greatly.

In this study, however, the AASHO method was applied without modification.

Pavement life can be expressed as a function of the structural number (SN) of the pavement; the initial traffic number (ITN), which varies depending on the legal axle load limit; and the traffic growth rate. The difference between the SN that corresponds to the pavement life 10 years beyond the existing pavement life and the SN of existing pavement at the end of its life indicates the required SN for an overlay meant to extend the life of the pavement an additional 10 years. The SN of a pavement at the end of its life is assumed

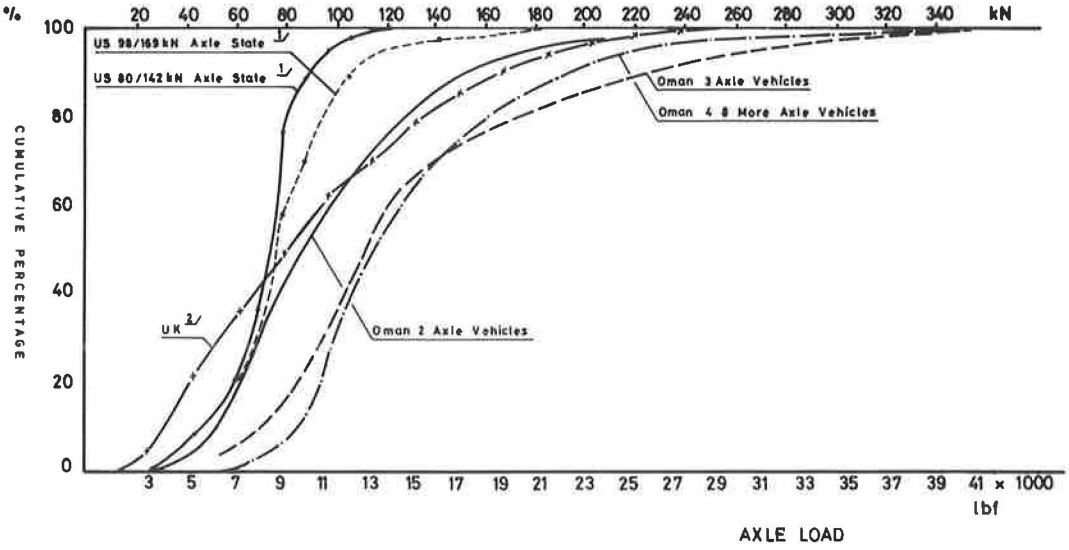


Figure 1. Axle-load distribution for single axles.

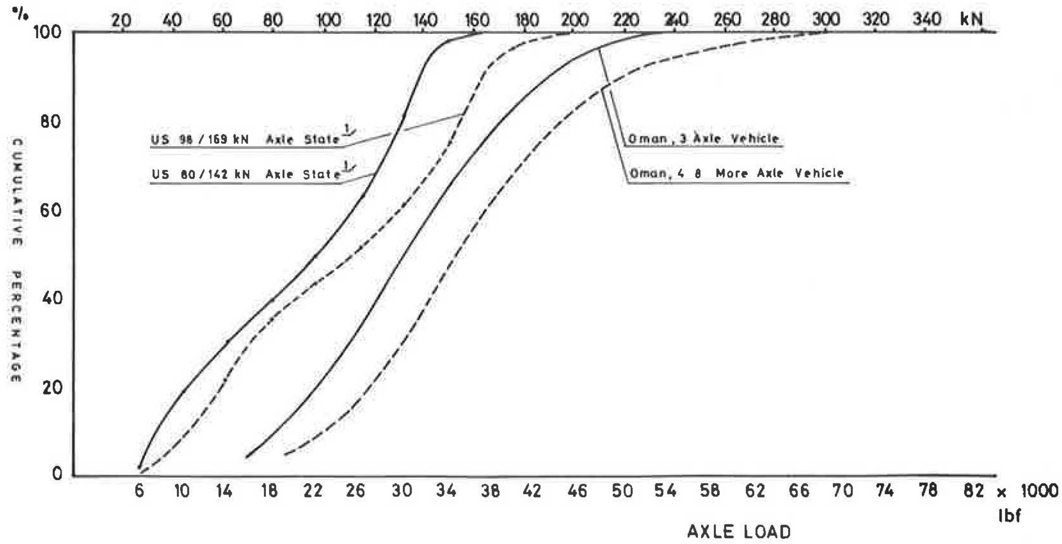


Figure 2. Axle-load distribution for tandem axles.

Table 1. Characteristics of heavy-vehicle traffic in Oman.

	Vehicle Type by No. of Axles		
Characteristic	Two Axles	Three Axles	Four Axles and More
Heavy-vehicle traffic, % of total	68	11	21
Average no. of axles per vehicle			
Single	2	2.13	1.53
Tandem	-	0.43	1.51
Average axle load			
Single, kN	48.0	64.7	66.6
Tandem, kN	-	130.3	158.7
97 percentile axle load			
Single, kN	100.9	146.0	115.6
Tandem, kN	-	216.5	266.5
Average curb weight, t	7.7	12.5	19.6
Average gross weight, t	9.9	19.8	34.8
Average payload, t	3.2	7.3	15.2

Note: 1 kN = 225 lbf; 1 t = 1.1 ton.

to be 80 percent of the SN at the beginning of its life.

The lengths of pavement lives were computed for various parameters. Examples of results were illustrated in Figure 3. Such figures were used to determine overlay thickness as well.

It should be noted that this procedure describes pavement life only from the viewpoint of structural strength. This structural life can be considerably shortened by a factor such as the intrusion of water through neglected cracks. Thus surface treatment, such as seal coating before overlaying, is necessary in order to attain the full structural life. It was assumed in this study that on the average these seal coats would be required two-thirds of the way through a pavement's life.

After an investigation of experiences in other countries that have similar conditions, it was assumed that 40 m^2/km (77 yd^2/mile) of surface would be patched just before the overlay or the seal-coat operation.

It was further assumed that the area needing to be patched annually in the intervening years would be proportional to the cumulative traffic level up to that year. It was assumed that a seal coating would bring the pavement back to such a condition that the area needing patching would increase during the subsequent years until it reaches 40 m^2/km again at the year of overlay. It was assumed that base repair was required in 50 percent of the patch work.

Unit Costs of Pavement Maintenance and Vehicle Operation

The cost of pavement maintenance depends on various

Figure 3. Pavement design life for an interior road.

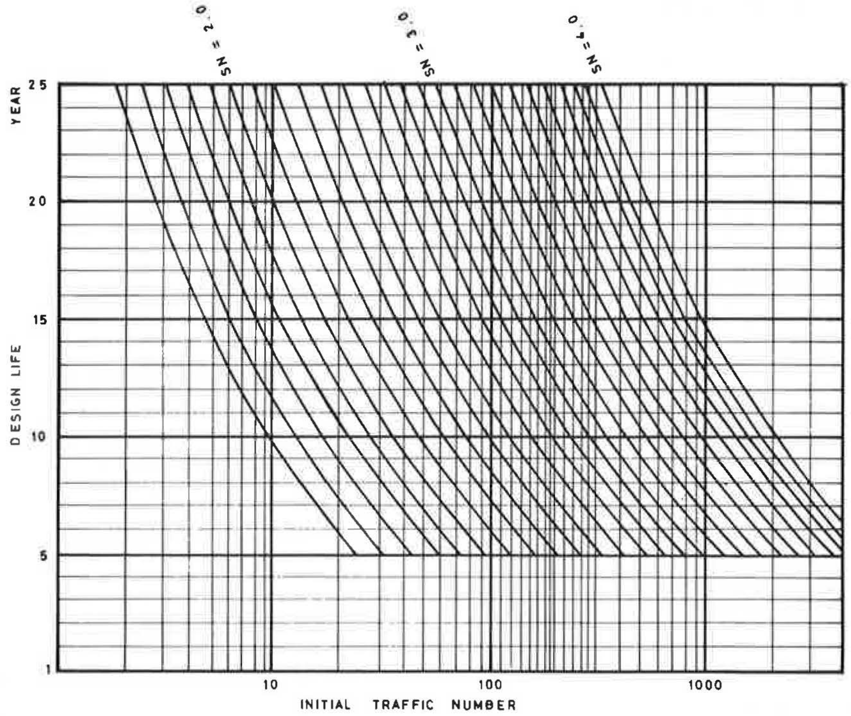


Table 2. Average vehicle characteristics and operating costs.

		Costs per Vehicle Kilometer ($)			Average Load Condition		
Vehicle Type	Operating Speed (km/h)	Fully Loaded	Empty	Load Limit Single/Tandem (kN)	Load Factor	Vehicle Kilometer Costs ($)	Ton-Kilometer Costs ($)
Two axles, capacity 7.2 t	60	0.376	-	78/147	0.327	0.338	0.144
				98/181	0.409	0.342	0.116
				118/216	0.447	0.345	0.107
				137/255	0.447	0.345	0.107
				157/294	0.447	0.345	0.107
				No limit	0.447	0.345	0.107
	70	-	0.319	-	-	0.319	-
Three axles, capacity 12 t	60	0.487	-	78/147	0.189	0.423	0.186
				98/181	0.327	0.433	0.110
				118/216	0.468	0.445	0.079
				137/255	0.577	0.453	0.066
				157/294	0.608	0.456	0.062
				No limit	0.608	0.456	0.062
	70	-	0.407	-	-	0.407	-
Four axles and more, capacity 19 t	50	0.574	-	78/147	0.215	0.501	0.123
				98/181	0.442	0.522	0.062
				118/216	0.640	0.541	0.044
				137/255	0.771	0.553	0.038
				157/294	0.800	0.556	0.037
				No limit	0.800	0.556	0.037
	60	-	0.481	-	-	0.481	-

Note: 1 km/h = 0.6 mph; 1 kN = 225 lbf; 1 km = 0.62 mile; 1 t = 1.1 ton.

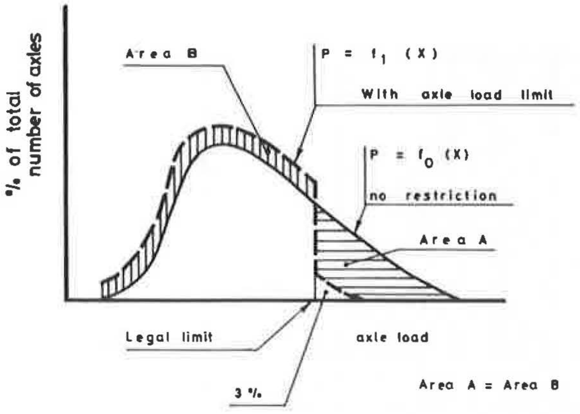
factors. The unit cost of overlay is roughly proportional to its thickness. Average unit costs (1 m^2 = 1.2 yd^2; 1 mm = 0.039 in) of pavement maintenance are shown below.

Maintenance Activity	Cost ($/m²)
Overlay: Supply and lay 40-mm wearing course	7.25
Seal coats: Clean existing surface dressing and add one coat spray and chipping	2.12
Pothole patch and base repair: Cut out existing wearing course and base course and supply and lay base and wearing course (base-course repair is applied to only 50 percent of the total area)	31.9

In the study, the difference in construction costs by axle loading is interpreted as the difference in construction costs of different thicknesses of wearing course on top of the base course and the subbase course with fixed thicknesses. This simplification was possible because available construction methods were very limited in Oman. Thus the procedure for arriving at cost differences by axle-load limit is the same as that applied for overlays except that the life of each new highway is assumed to be 20 years.

Vehicle operating cost items considered were fuel, motor oil, tires and tubes, maintenance, depreciation, interest, insurance, driver's salary, vehicle taxes, and license fee. The latter two are included here as a substitute for the unknown economic cost of administration. Table 2 summarizes the results.

Figure 4. Assumed change in distribution pattern.



EFFECT OF AXLE-LOAD LIMIT ON TRAFFIC

Imposing axle-load limits on vehicle traffic can have many effects, two of which can readily be identified. First (case A), the weight of the individual payload of each truck is reduced, which shifts the axle-load distribution pattern of each vehicle type downward. This shift naturally forces truckers to make more trips in order to haul the same amount of cargo, which in turn increases total traffic volumes of each vehicle type. Second (case B), the use of certain types of vehicles that have more economical advantages is encouraged, while the use of other vehicles is discouraged. This results in a change in traffic composition. The degree of change is very difficult to predict, however, because it cannot be determined by historical records. For the purpose of quantitative analysis in this study, two sets of assumptions were adopted.

Case A

In case A, it was assumed that only the first type of change would occur and that amounts of cargo that could no longer be transported in one trip would be transported by an additional trip by a vehicle of the same type. This is a realistic assumption, considering the strong linkage between commodity types and the kinds of vehicles that transport them.

In the absence of shippers and truckers who possess weighing scales, the most likely change in the axle-load distribution pattern would be the redistribution of excess percentages throughout the range under the limit: Each trucker would try to load the vehicle without exceeding the limit and would sometimes break up a consignment into two vehicle loads. It was assumed that this change in distribution pattern would result in the even redistribution of excess percentages over the entire range under the limit.

It is unrealistic to assume that no operator will violate the limit. A study conducted in the United States reported that 2.9 percent of vehicles sampled had axle loads in excess of the legal limits. In the present study it was assumed that 3 percent of the total number of axles of each type were exceeding the limit.

Figure 4 illustrates the foregoing discussion. If it can be assumed, in addition, that tare weights of each vehicle type will not significantly change, a change in axle load should correspond directly to a change in average payload in each vehicle category. If

$$\bar{x}_{k1} = (1/a)x_{k0} \tag{1}$$

then

$$\bar{w}_1 = (1/a)\bar{w}_0 - w[1 - (1/a)] \tag{2}$$

where

$\bar{x}_{k1}$ and $\bar{x}_{k0}$ = average axle loads of number k axle with and without limit, respectively;
$\bar{w}_1$ and $\bar{w}_0$ = average paylods with and without limit, respectively; and
w = the average vehicle tare weight.

By assumption, the total amount of cargo transported by each type of vehicle remains the same regardless of the limit, so

$$\bar{w}_1 N_1 = \bar{w}_0 N_0 \tag{3}$$

where N_1 and N_0 are the total number of vehicles in this category with and without the limit.

Therefore

$$N_1 = (\bar{w}_0/\bar{w}_1)N_0 \tag{4}$$

Case B

The excess cargo that can no longer be transported by the same number of vehicles in a vehicle category due to an axle-load limit is to be borne by the next larger category. Overloading is probably caused by large consignment sizes, so these excess cargos are likely to be transported by larger vehicles.

Let $\bar{w}_{j0}$ and N_{j0} stand for the average payload and the total number of vehicles, respectively, for the vehicle category j for the case without the axle-load limit. Let $\bar{w}_{j1}$ and N_{j1} be the average payload and the number of vehicles, respectively, for the case with the axle-load limit. The subscript j is in the ascending order of vehicle size.

The $\bar{w}_{j1}$ can be derived from $\bar{w}_{j0}$ and axle-load distribution patterns as shown in the discussion of case A. The N_{j1} can be expressed as follows

Vehicle Category	Total Cargo	Total No. of Vehicles	Excess Cargo
1	$N_{10}\bar{w}_{11}$	N_{10}	$N_{10}(\bar{w}_{10} - \bar{w}_{11})$
2	$N_{20}\bar{w}_{21}$ $+ N_{10}(\bar{w}_{10} - \bar{w}_{11})$	$N_{20} + N_{10}$ $\times [(\bar{w}_{10} - \bar{w}_{11})$ $\div \bar{w}_{21}]$	$N_{20}(\bar{w}_{20} - \bar{w}_{21})$
3	$N_{30}\bar{w}_{30}$ $+ N_{20}(\bar{w}_{20} - \bar{w}_{21})$	$[N_{30}\bar{w}_{30} + N_{20}$ $\times (\bar{w}_{20} - \bar{w}_{21})]$ $\div \bar{w}_{31}$	0

The ratio of total numbers of vehicles with a limit to those without a limit can be expressed as follows: For vehicle category 1 the ratio is 1.0; for category 2 it is $1 + (N_{10}/N_{20})\ [(\bar{w}_{10} - \bar{w}_{11})/\bar{w}_{21}]$; and for category 3 it is $(\bar{w}_{30}/\bar{w}_{31}) + (N_{20}/N_{30})\ [(\bar{w}_{20} - \bar{w}_{21})/\bar{w}_{31}]$.

Five combinations of maximum axle-load limits for single axle and for tandem axle were stipulated: 78/147 kN (17 600/33 000 lbf), 98/181 kN (22 000/41 000 lbf), 117/215 kN (26 000/48 500 lbf), 140/255 kN (31 000/57 000 lbf), and 157/294 kN (35 000/66 000 lbf) (the first number in each pair is for single axles and the second number for tandem axles). Axle loads of single and tandem axles for the same combination give roughly the same AASHO load-equivalency factors.

Axle-load distribution patterns were established for each of the stipulated axle-load limits by modifying the existing patterns in accordance with the method described above. If a limit fell within a range exceeding

Table 3. Traffic increase factors.

Legal Axle-Load Limit Single/Tandem (kN)	Traffic Increase Factor					
	Two Axles		Three Axles		Four Axles and More	
	Case A	Case B	Case A	Case B	Case A	Case B
78/147	1.37	1.0	3.22	3.21	3.72	4.34
98/181	1.09	1.0	1.86	1.40	1.81	2.01
118/216	1.0	1.0	1.30	1.0	1.25	1.32
137/255	1.0	1.0	1.05	1.0	1.04	1.05
157/294	1.0	1.0	1.0	1.0	1.0	1.0
No limit	1.0	1.0	1.0	1.0	1.0	1.0

Note: 1 kN = 225 lbf.

Table 4. Average vehicle operating costs by load limit.

Legal Axle-Load Limit Single/Tandem (kN)	Costs per Vehicle Kilometer ($)		
	Two Axles	Three Axles	Four Axles and More
78/147	0.338	0.423	0.501
98/181	0.342	0.433	0.522
118/216	0.345	0.445	0.541
137/255	0.345	0.453	0.553
157/294	0.345	0.456	0.556
No limit	0.345	0.456	0.556
Empty	0.319	0.407	0.481

Note: 1 kN = 225 lbf; 1 km = 0.62 mile.

Table 5. Average vehicle load-equivalency factors.

Legal Axle-Load Limit Single/Tandem (kN)	Vehicle Load-Equivalency Factor		
	Two Axles	Three Axles	Four Axles and More
78/147	0.518	0.665	0.882
98/181	0.830	1.149	1.686
118/216	1.004	1.927	2.907
137/255	1.004	2.990	4.349
157/294	1.004	3.623	4.841
No limit	1.004	3.623	4.841
Empty	0.118	0.270	0.447

Note: 1 kN = 225 lbf.

the 97 percentile value of the existing distribution, no modification was made, since the limit would not significantly affect the loading pattern.

Theoretically, the loading of a vehicle having both single and tandem axles can be limited by either a single or a tandem axle-load limit. If the load on one of the axles reaches the limit, this is the maximum loading condition regardless of the loads on the other axles. In other words, reducing the payload does not necessarily reduce each axle load to desired limits. To see the degree of discrepancies between reduction factors of single and tandem axles, a comparison was drawn by applying the properties of reference vehicles and average loads. The discrepancies were found to be small. Because of the variety among vehicle dimensions and weights included in each vehicle type, it was decided that axle-load distribution patterns for single and tandem axles developed independently were sufficient for the purposes of this study.

Average load-equivalency factors for each vehicle and axle type for loaded vehicles and for empty vehicles were computed as weighted averages of load-equivalency factors for each load range by percentage distribution of axle loads under each axle-load limit combination.

Load factors were then computed as ratios of average payloads to the capacities of reference vehicles. As noted previously, reduction in average payload causes a corresponding increase in traffic volume needed to transport the same amount of cargo. And, as described before with the equations for the assumed cases A and B, heavy-vehicle traffic increase factors were computed for the traffic of loaded trucks. However, it is unlikely that truckers would find cargo to carry on their return from additional trips necessitated by the load limit in Oman. It has therefore been assumed that empty-vehicle trips would increase by the same proportion.

Operating speeds of fully loaded vehicles adopted in this study were 60 km/h (38 mph) for two- and three-axle vehicles and 50 km/h (31 mph) for vehicles with four and more axles. It was assumed that empty vehicles were operated at speeds 10 km/h (6.3 mph) faster than these speeds. Average vehicle-kilometer costs corresponding to each axle-load limit for each vehicle type were developed by interpolating between fully loaded costs and empty costs by means of load factors already developed (see Table 2).

Tables 3, 4, and 5 show the computational results along with other parameters that characterize operating conditions of each vehicle type under different legal axle-load limits. These parameters were then combined by means of weighting by traffic composition percentages and empty-loaded percentages in order to reach overall averages. To see clearly the effect of axle-load limits, the base of the average load-equivalency factor was set at the level of traffic without the limit.

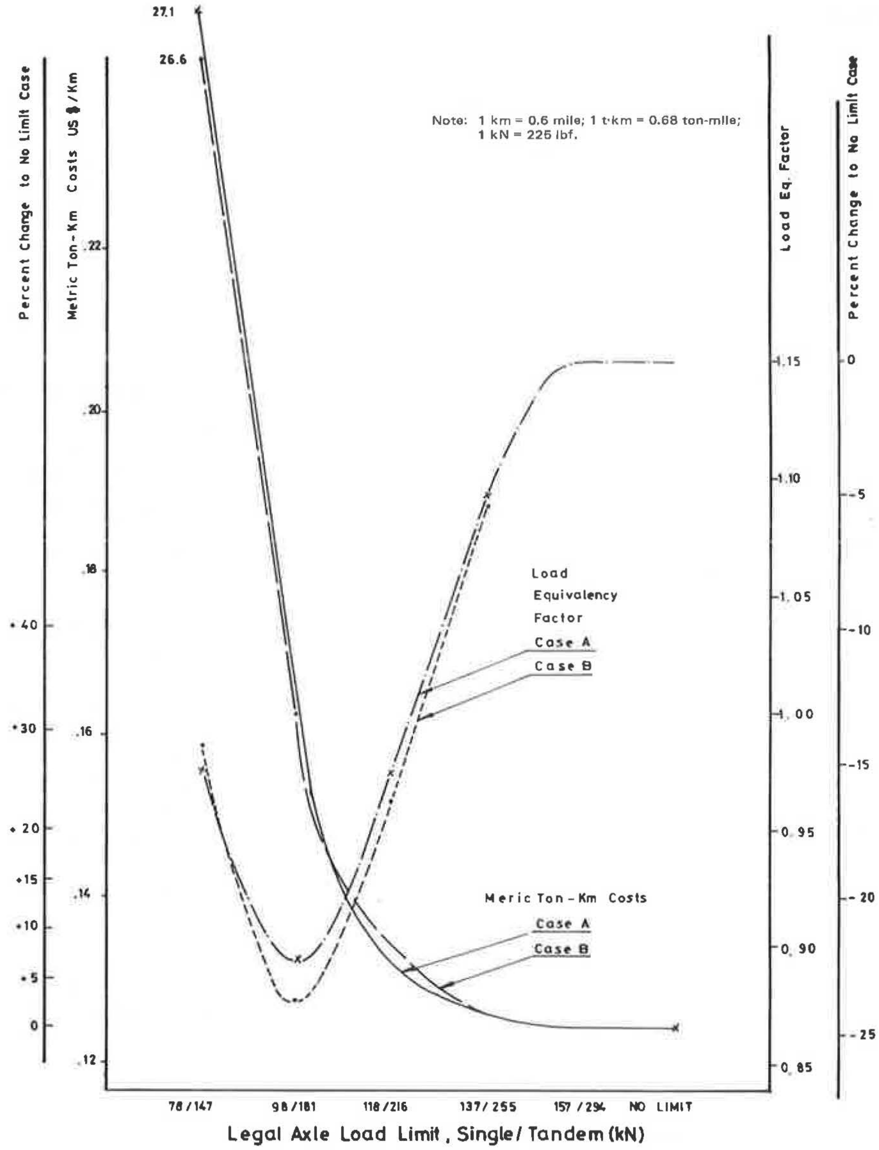
Vehicle Type	Two Axles	Three Axles	Four Axles and More
Percentage of total heavy-vehicle traffic (no limit)	68	11	21
Percentage of loaded vehicles (two-way)	47	50	52

Therefore, the difference in this average load-equivalency factor directly indicates the difference in the aggregate level of the effect that various axle-load limits have on the pavement. Figure 5 illustrates the results for the case of the average empty-loaded percentages.

Overall average metric ton-kilometer costs and average load-equivalency factors for two different assumptions regarding changes in traffic caused by axle-load limit (cases A and B) turned out to be very close. The percentage contribution to the overall value of each vehicle type differs somewhat according to the case in question, but the effects of changes in percentages for each type compensate for each other to yield similar overall values. What actually occurs is somewhere between cases A and B. It was decided, therefore, that average values of the two cases were to be used in further analysis.

It should be noted that the average load-equivalency factors actually applied in estimating the maintenance requirements of each highway link were different from

Figure 5. Overall average costs and load-equivalency factor per vehicle of no-limit case.



the values shown in Figure 5 because of concentration of loaded vehicles in one direction.

Figure 5 suggests that the limits of 78 kN (17 600 lbf) for single axles and 147 kN (33 000 lbf) for tandem axles would result in disproportionately high vehicle operating costs accompanied by an average load-equivalency factor higher than the 98/181-kN (22 000/41 000-lbf) case. This guarantees that the 78/147-kN limit cannot give the minimum total operating and maintenance cost. This phenomenon results primarily from the fact that larger vehicles have heavy axle loads when empty and that their payload must therefore be drastically reduced to meet the very low axle-load limit.

If consignment sizes of excess cargo are such that they are evenly distributed over the range under the load limit, as was assumed in this study, the relative advantage of larger vehicles decreases as the load limit is lowered.

CHARACTERISTICS OF TOTAL SYSTEM PER-KILOMETER COSTS

The costs under consideration are to be incurred over a 20-year period. Because the value of consumption at a future date is lower than the value of consumption of the same amount today, the total costs must be compared in present values, which are the sum of discounted future costs.

General characteristics of system costs were investigated on selected highways. Table 6 shows pavement data pertaining to these highways as well as others in Oman. By definition, total highway user costs are in direct proportion to the traffic level for a given traffic composition. Highway maintenance costs, however, show more complex characteristics. Figure 6 illustrates these relationships.

At very low traffic levels, fewer than 30 heavy vehicles a day, no major improvement work such as overlaying is needed within the 20-year period, resulting in low maintenance costs. As traffic levels grow, however, overlay and seal-coat operations are increasingly needed, but the percentage increase in maintenance costs is lower than the percentage increase in traffic, except at low traffic levels. The major reason for this characteristic is that the percentage increase in the strength of the pavement is more than the percentage increase in the pavement thickness, to

Table 6. Pavement data for existing highways and highways under construction.

Highway	Year Open to Traffic	Total Length (km)	Pavement Width (m)	Pavement Thickness[a] Surface (cm)	Base (cm)	Subbase (cm)	Structural Number	California Bearing Ratio	Assumed Soil Support Value
Muscat-Mutrah (new)	1978	3	14.0	AC 3	AC 16	GR 15	3.75	>30	6.5
Mutrah-Al Bustan	1976	8	7.5	AC3 3.5[b]	AC6 6.5[b]	BS 10[c]	2.17 2.34[b]		6.5
Mutrah-Seeb	1977	50	14.0-14.6	AC 4	AC 11	GR 15	3.13	min. 10	5.0
Seeb-Khatmat Al Malaha	1973-1974	263	7.0	AC 4	AC 8	GR 15	2.66	min. 10	5.0
Spur Shinas	1974	12	7.0	AC 4	AC 8	GR 15	2.66	min. 10	5.0
Mujis-Buraimi	1977	103	7.0	AC 2.5	AC 6	GR 10.5	1.87	min. 20	6.5
Buraimi-Ibri-Tana'am	1976	137	7.5	AC 6	AC 15	-	3.40	-	6.5
Seeb-Nizwa	1976	137	7.0	AC 4	AC11 7[d]	GR15 0.0[d]	3.13 2.27[d]	>30	6.5
Sumail Link	1976	4	7.0	AC 4	AC 11	GR 10	2.27	-	6.5
Bid Bid-Sur	1977	263	7.5	AC 4	AC 12	GR 7.5[e]	1.80	-	6.5
Al Musana'a-Ar Rustaq	1977	35	7.0	AC 5	CR 15	-	1.57	>30	6.5
Nizwa-Ibri	1978-1980	132	7.5	AC 4	AC 11	GR 15	3.13	>30	6.5
Mutrah-Qurayat	1979-1980	85	7.6	AC 3	AC 5	GR 15	1.87	>30	6.5
Al Bustan-Sidab	1979	5	7.6	AC 4	AC 8	GR 15	2.66	>30	6.5

Note: 1 km = 0.62 mile; 1 m = 3.3 ft; 1 cm = 0.39 in.

[a] AC = asphalt concrete, GR = CR = crushed rock, BS = bituminous subbase.
[b] Thickness in mountainous section.
[c] Bituminous subbase course equivalent to gravel 15 cm thick.
[d] Thickness in the last 29-km section.
[e] Subbase was laid for 20 percent of the total length only.

Figure 6. Costs versus traffic level for an interior road.

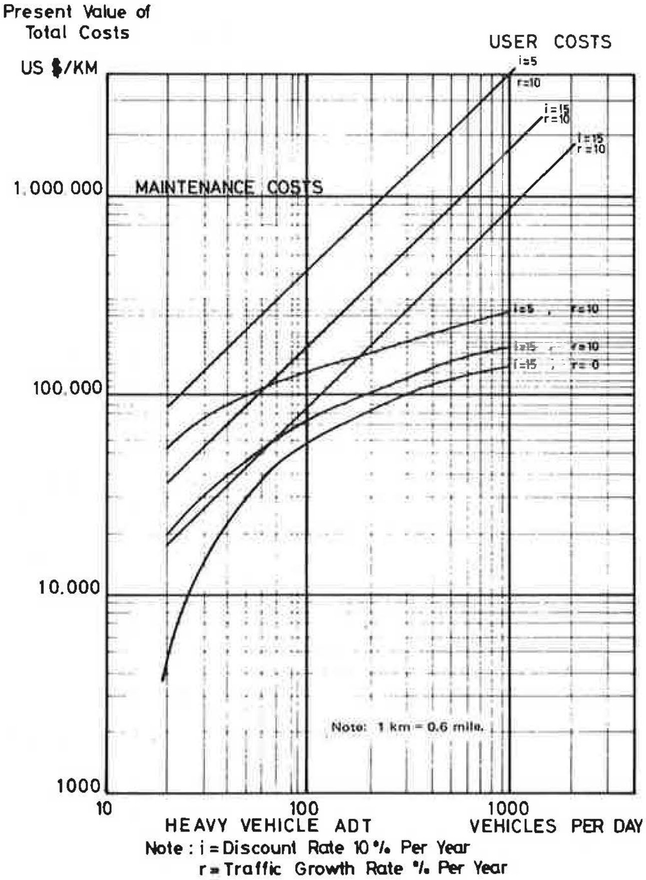
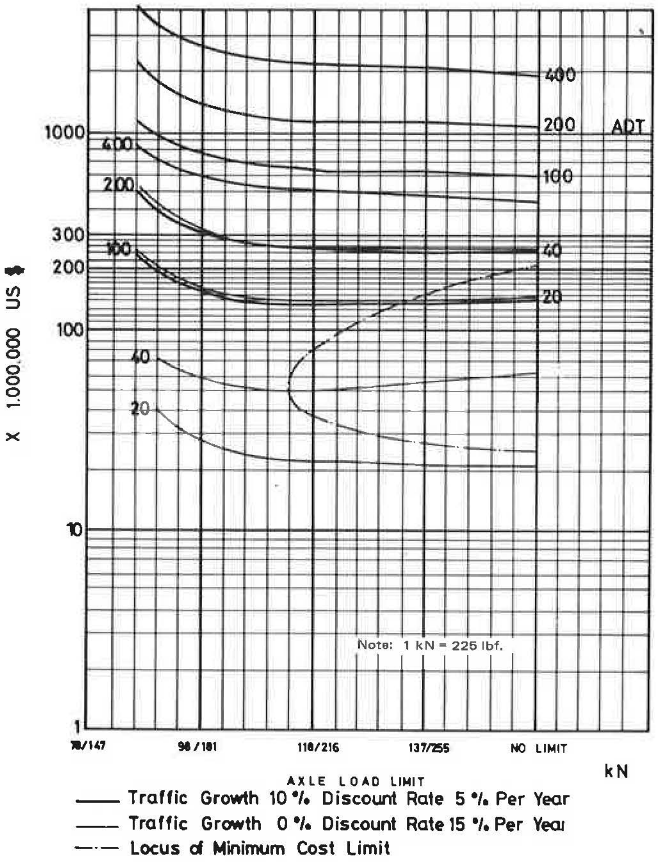


Figure 7. Present value of total system cost and minimum cost limit for an interior road.

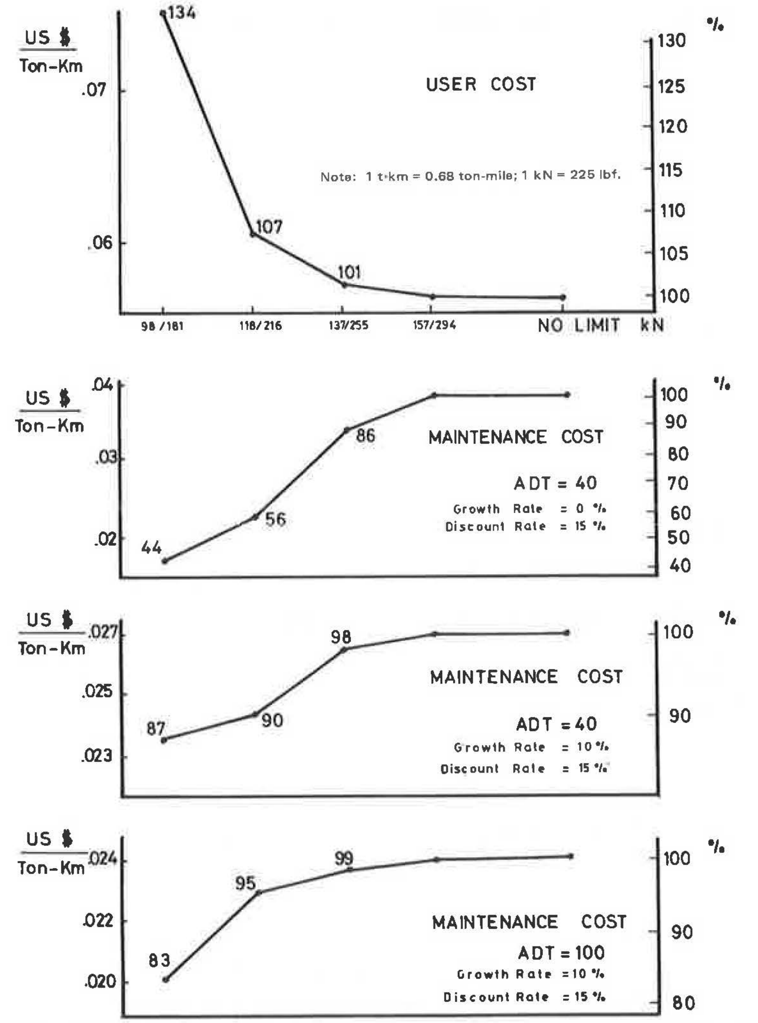


which the overlay cost is closely related. In the range of heavy traffic, more than 200 heavy vehicles a day, the percentage of highway maintenance cost to total cost decreases rapidly as the traffic level increases.

Figure 7 illustrates costs under the presence of axle-load limit for the interior highway. Differences in total cost under different axle-load limits are generally not large. In particular, differences between the 117/215-kN (26 000/48 500-lbf) limit case, the 140/255-kN (31 000/57 000-lbf) limit case, and the no-limit case are so slight (no greater than 6 percent except in the case of 40 initial daily heavy traffic) that they are almost indistinguishable in a graphic presentation such as this one.

It was found for the interior and coastal highways in Oman that, for initial traffic levels higher than 200 heavy vehicles a day, the no-limit case always yields the least present value of total costs. Below the level of 200 heavy vehicles a day, the least-cost limit tends to be at the 117/215-kN limit to the 140/255-kN limit in the

Figure 8. User and maintenance costs changes by axle-load limit for an interior road.



Note: 1 t·km = 0.68 ton-mile; 1 kN = 225 lbf.

Note : Figures beside plotted points indicate percentages to values of no limit case

Table 7. Percentage shares of operator and user costs and percentage changes by axle load.

Share Breakdown	Legal Axle-Load Limit, Single/Tandem (kN)		
	No Limit	137/255	118/216
Traffic growth 0 percent			
Discount rate 15 percent			
Operator cost			
Percent of total	24.3	22.8	19.6
Percent change	0	-6.5	-18.4
User cost			
Percent of total	75.7	77.2	80.4
Percent change	0	+1.5	+7.4
Total Cost			
Percent change	0	-0.5	+1.2
Traffic growth 10 percent			
Discount rate 5 percent			
Operator cost			
Percent of total	13.9	13.1	12.0
Percent change	0	-4.8	-9.4
User cost			
Percent of total	86.1	86.9	88.0
Percent change	0	+1.4	+7.4
Total cost			
Percent change	0	+0.6	+5.1

Note: 1 kN = 225 lbf.

middle range and to show an upward shift in the very low traffic range with little differences, depending on the case.

The total cost for the 98/181-kN (22 000/41 000-lbf) limit was found not to be the minimum in any case and not to be even near the minimum relative to the difference between the least-cost limit and the second-best limit. The line comprising the minimum cost points at various initial traffic levels, or the locus of the minimum cost point, appears to be on the curves shown in Figure 7.

The position of the minimum cost point depends on the relative level of the user cost, which is a decreasing function of the axle-load limit and the maintenance cost, which in turn is an increasing function of the axle-load limit. A comparison was made between differential user and maintenance costs with respect to the axle-load limit. The ratios of differential costs indicated stable minimum point characteristics against unit cost changes of up to 20 percent.

Changes in Shares of Public and Private Sectors

When the 117/215-kN limit is imposed, the share of the maintenance cost incurred mostly by the public sector is reduced by 10 percent in the medium traffic range and 20 percent in the lower traffic range. This reduction is the result of the decrease in the maintenance cost augmented by increases in user costs. Figure 8 shows changes in each total cost component.

Where the 117/215-kN limit is imposed, the user cost would increase by 7 percent, whereas the maintenance cost would decrease by about 35 percent.

System Evaluation

The total system costs were computed for two sets of parameters. Three axle-load limit alternatives were tested: the no-limit case, the 140/255-kN-limit case, and the 117/215-kN-limit case, since a limit less than the latter one would yield a considerably higher total system cost. The highway network of 1493 km (933 miles), including existing highways, highways under construction, and highways to be constructed, was divided into 32 sections. Maintenance and construction costs and user costs were estimated for each section, then added together to obtain total system costs. Table 7 summarizes the results in terms of percentage changes.

CONCLUSIONS

General conclusions drawn from the study are as follows.

1. The axle-load limit that gives the minimum total combined costs of highway maintenance and user costs depends on pavement strength and traffic level. For a given highway, the optimum axle-load limit is no limit for the very low traffic level, a certain value for the intermediate traffic level, and again no limit for the high traffic level.
2. Although the total cost may not vary significantly by axle-load limits, public and private sectors share the total cost in considerably different proportions under different axle-load limits.
3. An axle-load limit may have significantly different effects on different types of vehicles depending on their weight and current loading characteristics. Thus, it may change the relative competitiveness of vehicles and consequently that of vehicle operators.
4. The actual level of the optimum axle-load limit depends a great deal on local conditions of existing pavement strength, present and anticipated traffic, traffic composition, loading practices, and unit costs of pavement maintenance and vehicle operation. The procedure presented in this paper, however, can be applied to any country that has a sufficiently simple highway network and vehicle fleet.

ACKNOWLEDGMENT

The study on which this paper is based was performed for the government of the Sultanate of Oman. The contents of this paper reflect my views, not necessarily those or the policies of the government of the Sultanate of Oman. I wish to thank Derish Wolff, John Whipple, William Howkins, Michael Misaelidis, David Rudge, and Ernesto Arevalo for their help and comments.

REFERENCES

1. R. E. Whiteside and others. Changes in Legal Vehicle Weights and Dimensions: Some Economic Effects on Highways. NCHRP Rept. 141, 1973.
2. Axle Load Distribution on Roads Overseas: Abu Dhabi and Qatar. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Rept. 572, 1973.
3. Interim Guide for Design of Pavement Structures. American Association of State Highway Officials, Washington, DC, 1972.

Publication of this paper sponsored by Committee on Theory of Pavement Design and Committee on Maintenance and Operations Systems.

Evaluation of Patching in Continuously Reinforced Concrete Pavements

Darrell J. Maxey and Michael I. Darter, Department of Civil Engineering, University of Illinois at Urbana-Champaign
Scott A. Smiley, Brown and Root, Inc., Houston, Texas

An evaluation of concrete patching in continuously reinforced concrete pavements (CRCP) located in Illinois was made. Problems in designing and constructing permanent concrete patches were identified; the costs of patching were estimated; and the performance of typical patches was evaluated. Illinois has constructed over 4827 two-lane km (3000 miles) of CRCP, major portions of which are displaying increasing occurrence of distress that requires patching. Patches placed in recent years are performing inadequately. A survey of over 800 CRCP patches showed one-fourth requiring replacement and one-fifth requiring an adjoining patch. Constructing a typical 3x3.7-m (10x12-ft) patch is labor intensive, time consuming, and expensive. Between six and eight people can only place a patch a day at a cost of $1000-1600. The poor performance of many patches can be attributed to inadequate design specifications and poor construction techniques. The information in this paper can be used to improve the design specifications and construction techniques for CRCP patching. Many experimental patches have been placed and are being evaluated.

In this paper, current problems in designing and constructing permanent concrete patches in continuously reinforced concrete pavement (CRCP) are identified. In addition, the costs of patching are estimated, and the performances of typical patches are evaluated. This information can be used to improve future CRCP patches.

Illinois has now constructed nearly 4827 equivalent two-lane km (3000 miles) of CRCP, having begun constructing CRCP as a result of the excellent performance of several experimental sections in both Illinois (e.g., the Vandalia test section in 1947-1948) and other states. The excellent performance was specifically revealed in the low maintenance requirements of the pavement, that is, no joint sealing, corner breaks, blowups, or joint deterioration and very little patching.

However, in recent years CRCP in Illinois and