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Setting Maintenance Levels for Aggregate Surface Roads

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ABSTRACT

Aggregate surface road maintenance activity frequency guides based on minimizing total maintenance and user costs were developed for Bolivia's national highway department. The guides result from predicting road roughness and simulating the operation of vehicles on the road. Presented are equations that predict road roughness as a function of traffic volume and equations that relate road roughness to vehicle operating costs in Bolivia.

Aggregate surface road ride quality is defined by the service level for surface maintenance activities. Many agencies execute maintenance in response to surface condition. Others base maintenance frequencies on resource availability (e.g., the number of motor graders that are operational).

Responding to condition on the basis of judgment depends on the person controlling the maintenance activity. Because supervisors change and there are a number of different persons controlling maintenance in any jurisdictional area, there will be a lack of uniformity when this approach is used.

When maintenance service levels are based on resource availability, deficient levels may result. It is useful, therefore, to have objective guides to use in establishing service levels and resource requirements.

SETTING MAINTENANCE LEVELS FOR AGGREGATE SURFACE ROADS

One basis for establishing objective guides is to compare the costs of alternatives, not only agency costs but user costs. Evaluating the effect of road condition on user costs has received considerable attention in recent years. The World Bank has encouraged and supported a number of studies worldwide to develop relationships between road surface conditions and user costs (1-4). These relationships allow analyses to be made of the user costs to operate on roads in different condition (5-7).

Vehicle operating costs are influenced by the road's traveling surface. This is where the interaction between the vehicle and the road occurs. Therefore, it is primarily defects in this traveling surface that adversely affect road users.

Maximum benefits to the road user occur when a road is kept in its newly constructed condition. This is not economically practical so a lesser level is always sought. The optimum economic level is determined by comparing the costs to maintain or rehabilitate the road with the costs to users at different levels of deterioration. A level is selected on the basis of a strategy that minimizes total overall costs. This optimum strategy depends on the number and composition of users plus the characteristics of the road and the environment in which the road is situated.

From 1981 through 1983, the Bolivian national highway department, Servicio Nacional de Caminos (SNC), conducted studies to improve their highway maintenance practices. The single most costly maintenance activity performed by SNC is aggregate road surface maintenance. Consequently, objective criteria were developed to set maintenance levels for this work. The criteria proposed for establishing maintenance service levels were to minimize total maintenance and user costs. The maintenance levels were defined by specifying the frequency of surface maintenance activities.

ANALYSIS REQUIREMENTS

The analysis suggested as a basis for establishing maintenance frequencies required that the following information be determined for a road section:

1. Quantitative measurement of road surface condition and the ability to predict this condition,
2. Quantitative measurement of the change in the road surface condition that can be achieved through maintenance or rehabilitation,
3. Cost of any maintenance or rehabilitation,
4. Volume and composition of traffic on the road, and
5. Road user costs to operate on the road for each condition.

Surface Condition

For aggregate surface roads, the condition that most influences the motorist is ride quality, defined by road roughness. A number of different measurement units have been developed to define roughness, most of which relate to the measurement process. However, standard roughness units have not yet been defined.

In the Brazil cost study (3), a series of equations was developed to relate road roughness to vehicle operating costs. The unit of roughness used in those equations was termed quartercar index (QI). These equations were modified to reflect high-altitude vehicle use in Bolivia, and the QI units were adopted as a measure of roughness. The units represent the response of a quartercar (Figure 1) to a road profile. In Brazil QIs were assigned to road calibration sections by

1. Running a GM profilometer over a 300-m road section to get the wheel path profile,
2. Electronically simulating the response of a mathematically defined quartercar to the profilometer-generated profile at a simulated speed of 34 mph, and
3. Defining the response as counts per kilometer (the quartercar simulated a BPR roughometer and generated inches of displacement).

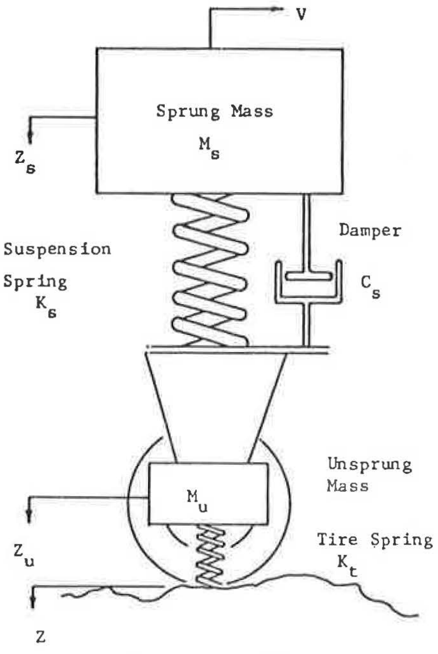

FIGURE 1 Quartercar model.

QI was therefore a dimensionless unit assigned to a road section to define the section's roughness. Twenty such sections made up a calibration course. Maysmeters were run over the calibration course and an equation was established to convert the Maysmeter numbers generated at 300-m sampling intervals to QI units.

Road Roughness Prediction

A study was initiated to evaluate unpaved road performance in Bolivia. A Maysmeter was used to monitor the deterioration of a newly regraveled road with average annual daily traffic (AADT) of 672. The regraveling included watering and rolling. The Maysmeter roughness measurements obtained during March and April 1982 are shown in Figure 2.

Three existing unpaved road roughness prediction equations were examined. The first was the Kenya equation (8) that predicts roughness in millimeters per kilometer and is a function of accumulated traffic:

$$R = 3250 + 84T - 1.62T^2 + 0.016T^3 \tag{1}$$

where R is roughness (mm/km) and T is cumulative traffic volume in both directions that has used road since grading, measured in thousands of vehicle passes.

The second roughness equation was taken from a preliminary Brazil report (9) and is as follows:

$$\begin{aligned}\ln QI = {} & \ln RA + D(0.0070 + 0.000013\,AADT - 0.0036S \\ & - 0.000035RA - 0.00000006\,AADT \times RA \\ & - 0.0136\,W/RAD)\end{aligned} \tag{2}$$

where

ln QI = natural log of roughness in QI units;
ln RA = natural log of roughness following grading in QI units;
D = days since last blading;
AADT = average annual daily traffic in both directions;
S = seasonal variable where dry = 0, wet = 1;
W = road width in meters; and
RAD = curve radius in meters.

The last equation examined was developed at the University of Texas by A. Visser (10). Visser used data from Brazil and developed the following equation:

$$\begin{aligned}\ln QI = {} & \ln RA + D[0.4314 - 0.1705T2 + 0.001159\,NC \\ & + 0.000895\,NT - 0.000227NT * G + S\,(-0.1442 \\ & - 0.0198G + 0.00621\,SV - 0.0142PI \\ & - 0.000617NC)]\end{aligned} \tag{3}$$

where

ln QI = natural log of roughness, in QI units;
ln RA = natural log of roughness following grading, in QI units;
D = number of days since last blading, in hundreds;
T2 = surface-type variable, 1 = clay, 0 = other;

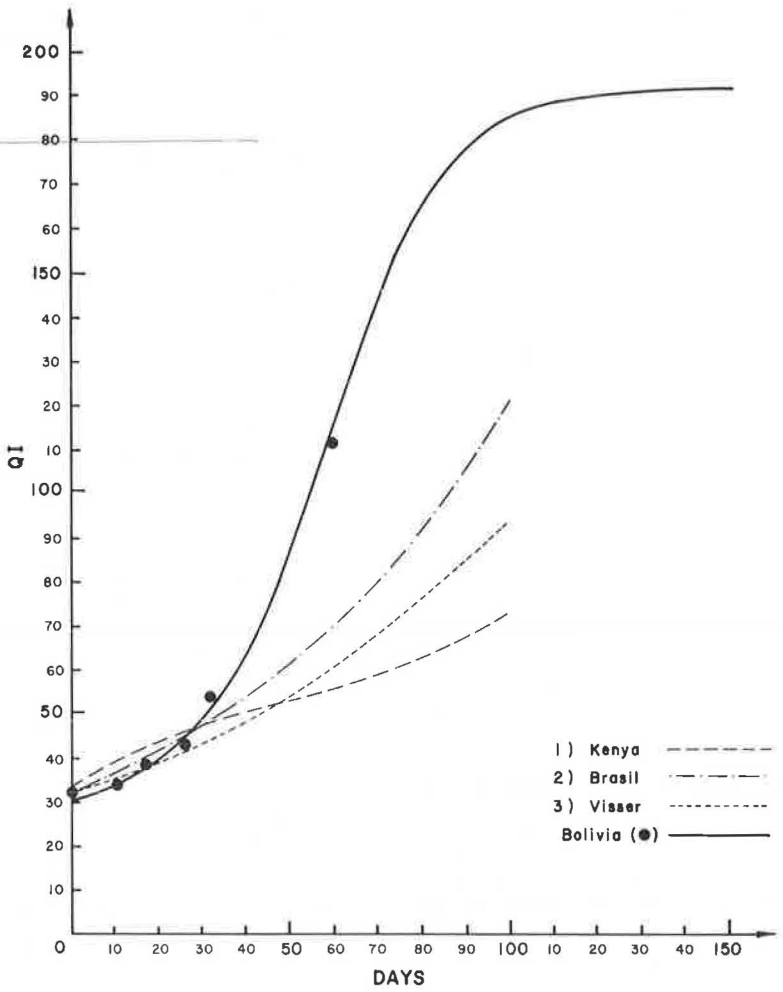

FIGURE 2 Performance curves for Rio Seco-Desaquadero Road.

NC = average daily car and pickup traffic in both directions;
NT = average daily bus and truck traffic in both directions;
G = absolute value of grade, as percentage;
S = seasonal variable where dry = 0, wet = 1;
SV = percentage of surfacing material passing the 0.074-mm sieve; and
PI = plasticity index of surfacing material, as a percentage.

The traffic averaged 672 AADT. This traffic level was used to establish the Kenya road performance prediction shown in Figure 2. The Kenya model predicts roughness in millimeters per kilometer. This was converted to QI units of roughness using an equation established in Brazil for this purpose:

$$QI = 0.0251\ BI^{0.93} \qquad (4)$$

where QI is roughness unit and BI is roughness measured with a bump integrator (mm/km).

For the Brazil and Visser model, the distribution of car, bus, and truck traffic was based on the following established values:

Roughness after blading	QI = 32
Road width	8 m
Radius	1000 m
Average daily traffic	672
Light vehicles	141
Heavy vehicles	531
Plastic index	10%
SV (0.074 material)	10%
Grade	0%
Surface T2	0

Substituting these values into the Brazil and Visser equations produced the curves shown in Figure 2.

The measured deterioration on the Bolivian road, reflected by increasing roughness with time, was compared with predictions based on the three equations identified earlier (i.e., Kenya, Brazil, and Visser). The Bolivian roads became rougher more quickly than predicted using the existing equations. Therefore, a series of studies was made in Bolivia to collect road performance information for roads with different traffic levels.

Roughness Studies

Two different maintenance activities were practiced by the Bolivian National Highway Department (SNC). First, at intervals, motor graders were used to grade the road surface and improve road surface and riding conditions (grade). Second, major surface aggregate replacement and rehabilitation work was performed to rebuild the road surface (rehabilitate).

Aggregate roads with different traffic volumes were selected and sections were established where road roughness was monitored using a Maysmeter. The

Maysmeter was calibrated on a series of calibration sections where a rod and leveling procedure was used to establish a QI measure of roughness for each calibration section. An analysis of the roughness data generated by the Maysmeter produced the following equations:

Performance (roughness) of Road Following Grading

$$QI = 7.922 + 177 \left\{ \left[e^{(AxBxC - 0.78)/1.04} \right] \div \left[3 + e^{(AxBxC - 0.78)/1.04} \right] \right\} \quad (5)$$

where

$A = 5.8$,
$B = D\ (0.0059 + 0.000011\ AADT)$,
$C = (575/AADT)^{0.4175}$,
D = days, and
$AADT$ = average annual daily traffic.

Performance (roughness of road following rehabilitation)

$$QI = 29.189 + 185 \left\{ \left[e^{(AxBxC - 5.47)/2.135} \right] \right\} \div \left[5 + 3^{(AxBxC - 5.47)/2.135} \right] \quad (6)$$

where

$A = 5.2$,
$B = D\ (0.00608 + 0.00001138\ AADT)$,
$C = (575/AADT)^{0.2682}$,
D = days, and
$AADT$ = average annual daily traffic.

Equations 5 and 6 are plotted in Figures 3 and 4 for a range of traffic volumes.

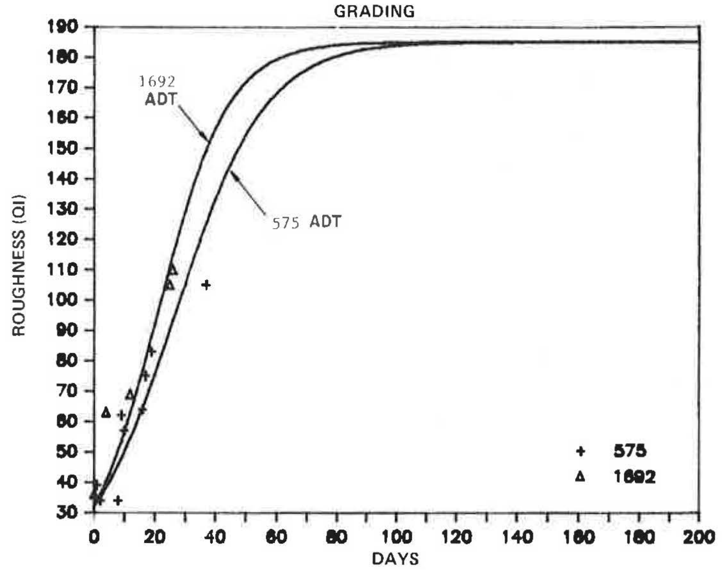

FIGURE 3 Roughness measurements following grading of a gravel road.

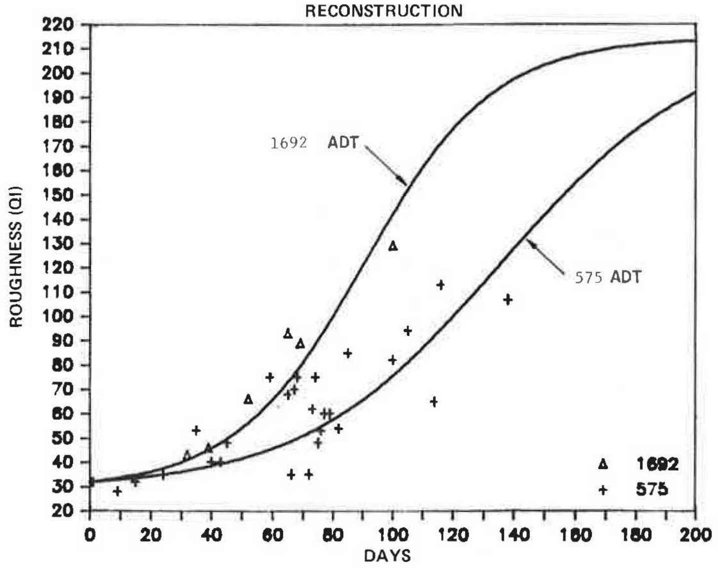

FIGURE 4 Roughness measurements following rehabilitation of a gravel road.

Maintenance Costs

The two aggregate road surface maintenance activities, grading and rehabilitation, were both specified in maintenance performance standards that describe the procedures followed in executing these activities. The standards also provide estimates of the production expected to be achieved and define the labor, equipment, and material requirements per unit of production.

Performance standards were used to calculate the costs of both aggregate surface activities for a base year period (1981). Information available from SNC fiscal records established a maintenance-related administrative charge of 31 percent. Direct maintenance costs were multipled by a factor of 1.31 to accommodate the administrative overhead.

User Costs

Literature studies were made in Bolivia to establish user equations that relate roadway characteristics to vehicle operating costs. Sources ranged from primary studies, such as Winfrey (11), Claffey (12), Bonney and Stevens (2), Hide et al. (1), GEIPOT (3), CRRI (4), De Weille (13), and Zaniewski et al. (14). In addition, users throughout the country were contacted to assess the level of vehicle operating costs they were experiencing on Bolivian roads. The information collected was used to verify existing relationships.

Fuel Consumption

These equations were derived from the Brazil study with adjustments made where necessary to the intercept so that predictions reflected vehicle use in Bolivia. Fuel consumption (FC) is expressed in units of liters/100 km, a unit conventionally used in cost studies.

$$\text{Light vehicle: } \ln(FC) = 5.078 + 0.00141\,QI \qquad (7)$$

$$\text{Bus: } \ln(FC) = 5.675 + 0.00061\,QI \qquad (8)$$

$$\text{Truck: } \ln(FC) = 5.887 + 0.00108\,QI \qquad (9)$$

A range of predictions, for various levels of QI, follows:

QI	50	100	150	200
Light vehicle	172	185	198	213
Bus	300	310	319	329
Truck	380	401	424	447

The percentage increase in fuel consumption on moving from 50 QI to 200 QI is light vehicle, 24 percent; bus, 10 percent; and truck, 18 percent. Worsening surface condition causes a vehicle to alter its speed and these speed changes, together with less efficient engine speeds, cause fuel consumption to rise as the surface deteriorates. Light vehicles travel at higher speeds on good roads so the speed changes are greater. Trucks have heavier loads so the speed changes cause their engines to work harder than do those of buses.

Oil and Grease Consumption

These are small user cost items, often constituting less than 1 percent of total vehicle operating costs. No equations were included for these items.

Parts Consumption

This was based on Brazil equations that were calibrated using Bolivian data. The parts equations developed were:

$$\text{Light vehicle: } PC = [K^{0.302} \exp(6.497 + 0.00426\,QI)]\,0.5 \qquad (10)$$

$$\text{Bus: } PC = [K^{0.485} \exp(5.703 + 0.00323\,QI)]\,0.5 \qquad (11)$$

$$\text{Truck: } PC = (305 + 105.7\,QI)\,0.5 \qquad (12)$$

PC is parts cost per 1000 km in Bolivian pesos at December 1981 prices. K is the vehicle age in 1000-km units. A range of predictions for various levels of QI follows:

	Age	QI			
Class	(K)	50	100	150	200
Light vehicle	150	1,866	2,309	2,853	3,530
Bus	350	3,018	3,547	4,169	4,900
Truck	-	2,795	5,438	8,080	10,723

The percentage increase in parts consumption on moving from 50 to 200 QI is light vehicle, 89 percent; bus, 62 percent; and truck, 384 percent.

Labor Costs

These were also based on equations developed in the Brazil study in which equations predicted labor costs as a function of parts cost and road roughness. The equations are

$$\text{Light vehicle: } LC = \{\exp[3.33 + 0.548 \ln(PC) + 0.00403\,QI]\}\,0.5 \qquad (13)$$

$$\text{Bus: } LC = \{\exp[3.231 + 0.516 \ln(PC) + 0.00514\,QI]\}\,0.5 \qquad (14)$$

$$\text{Truck: } LC = \{\exp[3.396 + 0.519 \ln(PC)]\}\,0.5 \qquad (15)$$

LC is labor cost in Bolivian pesos at December 1981 prices.

A range of predictions for various QI values follows and the PC variable is derived from the parts prediction table.

QI	50	100	150	200
Light vehicle	1,549	2,130	2,925	4,021
Bus	1,461	2,053	2,887	4,056
Truck	1,314	1,856	2,215	2,641

The coefficients on the ln (PC) variable for light vehicles and buses indicate that as parts cost increase, the proportion attributed to labor falls, as long as roughness is constant. When roughness increases, the labor costs for these two vehicle classes start to move upward until they equal or even exceed (at very high roughness) parts cost values.

Tire Consumption

These equations were based on Brazilian data on more than 3,000 tires lives. The dependent variable is tire life in 10 000 km.

Light vehicle:

$$TL = e^{(14.6488 - 0.9432 \ln QI)/10{,}000} \qquad (16)$$

Bus: $TL = 4.181 - 0.00951\ QI$ (17)

Truck: $TL = 3.933 - 0.00951\ QI$ (18)

A range of predictions (in km) for various QI values follows:

QI	50	100	150	200
Light vehicle	57,468	29,888	20,389	15,544
Bus	37,045	32,300	27,545	22,790
Truck	34,575	29,320	25,065	20,310

Depreciation and Interest Costs

The depreciation charge attributable to the characteristics over which the vehicle operates together with the opportunity cost of the capital tied up in vehicle ownership is required in the analysis. Depreciation is based on lifetime kilometer use and the effect of highway characteristics on this life use (15). The effect of roughness and geometry on life utilization was estimated using Brazilian data. A basic vehicle life in kilometers is modified to reflect the reduced lifetime utilization resulting from operation on roads with inferior surfaces or poor geometry. Depreciable lifetime value (initial purchase price less tires and residual value) is divided by the adjusted lifetime kilometers to give a per kilometer depreciation cost.

The interest component requires the estimation of service life in years for each vehicle class. Brazilian data were examined and adjustments made to fit Bolivian conditions. The following values were used:

Depreciation

Lifetime kilometers (based on a QI of 50) are

Light vehicle	380 000
Bus	477 000
Truck	575 000

Lifetime

Lifetime in years and residual values are

Light vehicle	10 years	20 percent
Bus	12 years	12 percent
Truck	12 years	12 percent

Interest

Rate of interest was assumed to be 16 percent in real terms.

Calculations

Depreciation was made a function of lifetime utilization, and lifetime utilization was adjusted for roughness by reducing life mileage 0.1 percent per unit increase in QI. The depreciation and interest equation therefore was

$$D\&I = (.08 \cdot V \cdot 10 + V \cdot RV)/\theta \quad (19)$$

$$\theta = LM/[1+(QI/1{,}000)] \quad (20)$$

where

$D\&I$ = depreciation and interest cost per kilometer,
V = vehicle acquisition cost,
QI = roughness,
LM = life mileage for QI roughness level equal to zero, and
RV = fraction of acquisition cost.

An interest rate on the residual acquisition costs of 16 percent was built into the equation.

Unit Prices

Unit prices were calculated in financial terms at 1981 prices. Maintenance data were already in this form as a result of the unit costs tables developed for labor, equipment, and material used to expand the maintenance performance standards. The user inputs had to reflect a similar cost basis. These data had the added advantage of being rapidly obtainable from vehicle operators and dealers. The user data are

Item	Financial Cost ($ Bolivian)
Gasoline	8 per liter
Diesel	8 per liter
Car tire	2,675
Bus tire	7,750
Truck tire	8,500
Car price	375,000
Bus price	1,125,000
Truck price	800,000
Vehicle Age in Kilometers	
Car	80 000
Bus	300 000

ANALYSIS

The logit equation representing the performance of aggregate surface roads together with the equations relating road roughness to vehicle operating costs were incorporated in a small computer program (RSML). The program allows the unit costs of highway maintenance and vehicle operating consumables to be entered at the beginning of a program run. Output from the program RSML is given in Tables 1-3.

The general methodology built into RSML is as follows:

1. A road section is assumed to be just rehabilitated and its roughness following this activity is defined.
2. The roughness of the road for each succeeding day is predicted.
3. User costs associated with traffic using the road each day, for each roughness condition, are accumulated.
4. User costs are accumulated to some defined roughness threshold (i.e., a level of roughness that will activate a maintenance response).
5. The maintenance sequence specified was two gradings followed by rehabilitation. This made up a complete cycle.
6. Ten cycles are simulated for each roughness threshold and the combined user and maintenance costs for that roughness threshold are determined on an annual basis along with the average cycles per year.
7. The same analysis was performed for a range of roughness thresholds.

In addition, three classes of traffic were defined: light vehicles, buses, and trucks. The percentage of each is given in Tables 1-3. Also given is a factor for administration. The analysis can be run for any traffic volume level and given in Tables 1-3 are AADTs of 100, 300, and 500.

TABLE 1 Annual Agency and User Costs of a Maintenance Cycle Consisting of Rehabilitation of a Gravel Road Followed by Two Gradings for AADT = 100, by Roughness Threshold (maintenance level)

REHABILITATION AND GRADING

** ROAD SURFACE MAINTENANCE LEVELS **

MAX ROUGHNESS	MAINTENANCE COSTS	USER COSTS	CHANGE	TOTAL CHANGE	ANNUAL FREQUENCY	TOTAL COSTS	TOTAL ADJUSTED
35	888532.	355962.	0.	0.	35.3	1244494.	697927.
40	459075.	365177.	9215.	9215.	18.3	824252.	277685.
45	348665.	371111.	5934.	15149.	13.9	719776.	173208.
50	296177.	375325.	4214.	19363.	11.8	671502.	124935.
55	259854.	379352.	4027.	23390.	10.3	639205.	92638.
60	233428.	383207.	3856.	27246.	9.3	616635.	70068.
65	218607.	385957.	2750.	29995.	8.7	604565.	57997.
70	202533.	389355.	3397.	33393.	8.1	591888.	45320.
75	192619.	391896.	2541.	35934.	7.7	584515.	37947.
80	181214.	395145.	3249.	39183.	7.2	576358.	29791.
85	173236.	397833.	2688.	41871.	6.9	571069.	24501.
90	163955.	401289.	3457.	45327.	6.5	565245.	18678.
95	158302.	403692.	2403.	47730.	6.3	561994.	15427.
100	153025.	406138.	2446.	50176.	6.1	559163.	12596.
105	146513.	409393.	3254.	53431.	5.8	555906.	9339.
110	141982.	411925.	2532.	55963.	5.6	553907.	7340.
115	136359.	415300.	3375.	59338.	5.4	551659.	5092.
120	132425.	417901.	2601.	61939.	5.3	550327.	3759.
125	128114.	420918.	3017.	64956.	5.1	549032.	2464.
130	124636.	423561.	2643.	67599.	5.0	548196.	1629.
135	120282.	427078.	3517.	71116.	4.8	547360.	792.
140	116222.	430615.	3537.	74653.	4.6	546836.	269.
145	112427.	434158.	3543.	78196.	4.5	546585.	17.
150	108872.	437696.	3538.	81734.	4.3	546567.	0.
155	105132.	441660.	3965.	85698.	4.2	546792.	225.
160	101267.	446006.	4346.	90044.	4.0	547273.	706.
165	97330.	450718.	4712.	94756.	3.9	548048.	1481.
170	93056.	456148.	5430.	100186.	3.7	549204.	2637.

PERCENT BUSES	.48	AVERAGE DAILY TRAFFIC	100.
PERCENT TRUCKS	.31	COST OF GRADING	7351.
PERCENT AUTOS	.21	COST OF REHABILITATION	42904.
ADMINISTRATIVE OVERHEAD	.31		

TABLE 2 Annual Agency and User Costs of a Maintenance Cycle Consisting of Rehabilitation of a Gravel Road Followed by Two Gradings for AADT = 300, by Roughness Threshold (maintenance level)

REHABILITATION AND GRADING

** ROAD SURFACE MAINTENANCE LEVELS **

MAX ROUGHNESS	MAINTENANCE COSTS	USER COSTS	CHANGE	TOTAL CHANGE	ANNUAL FREQUENCY	TOTAL COSTS	TOTAL ADJUSTED
35	834682.	1064464.	0.	0.	33.2	1899146.	546122.
40	437214.	1090738.	26274.	26274.	17.4	1527952.	174929.
45	335909.	1107902.	17165.	43438.	13.4	1443811.	90788.
50	278227.	1122256.	14354.	57792.	11.1	1400483.	47460.
55	245933.	1134026.	11770.	69562.	9.8	1379959.	26935.
60	222133.	1145171.	11146.	80707.	8.8	1367304.	14281.
65	205556.	1154569.	9397.	90105.	8.2	1360125.	7101.
70	191281.	1164333.	9764.	99869.	7.6	1355614.	2591.
75	178860.	1174450.	10116.	109986.	7.1	1353311.	287.
80	171084.	1181940.	7489.	117476.	6.8	1353024.	0.
85	162026.	1191436.	9496.	126972.	6.4	1353463.	439.
90	154744.	1200030.	8594.	135566.	6.2	1354775.	1751.
95	149698.	1206805.	6775.	142341.	6.0	1356504.	3480.
100	142718.	1216972.	10167.	152508.	5.7	1359690.	6666.
105	137037.	1226131.	9159.	161667.	5.4	1363168.	10145.
110	131792.	1235466.	9335.	171002.	5.2	1367258.	14234.
115	128114.	1242680.	7215.	178216.	5.1	1370794.	17771.
120	123518.	1252238.	9557.	187774.	4.9	1375756.	22732.
125	119240.	1261907.	9669.	197443.	4.7	1381147.	28124.
130	115249.	1271656.	9750.	207192.	4.6	1386905.	33882.
135	111516.	1281463.	9806.	216999.	4.4	1392979.	39955.
140	108018.	1291299.	9837.	226835.	4.3	1399317.	46293.
145	104732.	1301139.	9840.	236675.	4.2	1405871.	52847.
150	100896.	1313350.	12211.	248886.	4.0	1414245.	61222.
155	97330.	1325496.	12146.	261032.	3.9	1422826.	69802.
160	93689.	1338722.	13226.	274258.	3.7	1432411.	79387.
165	89722.	1354049.	15327.	289585.	3.6	1443770.	90747.
170	86077.	1368990.	14941.	304526.	3.4	1455066.	102043.

PERCENT BUSES	.48	AVERAGE DAILY TRAFFIC	300.
PERCENT TRUCKS	.31	COST OF GRADING	7351.
PERCENT AUTOS	.21	COST OF REHABILITATION	42904.
ADMINISTRATIVE OVERHEAD	.31		

TABLE 3 Annual Agency and User Costs of a Maintenance Cycle Consisting of Rehabilitation of a Gravel Road Followed by Two Gradings for AADT = 500, by Roughness Threshold (maintenance level)

REHABILITATION AND GRADING

** ROAD SURFACE MAINTENANCE LEVELS **

MAX ROUGHNESS	MAINTENANCE COSTS	USER COSTS	CHANGE	TOTAL CHANGE	ANNUAL FREQUENCY	TOTAL COSTS	TOTAL ADJUSTED
35	888532.	1772346.	0.	0.	35.3	2660879.	521119.
40	466856.	1814425.	42078.	42078.	18.6	2281281.	141521.
45	357721.	1843030.	28606.	70684.	14.2	2200751.	60991.
50	296177.	1866939.	23909.	94592.	11.8	2163116.	23357.
55	259854.	1888025.	21087.	115679.	10.3	2147879.	8120.
60	235423.	1906078.	18053.	133731.	9.4	2141501.	1741.
65	216886.	1922874.	16796.	150528.	8.6	2139760.	0.
70	202533.	1938325.	15451.	165978.	8.1	2140858.	1098.
75	189962.	1954329.	16005.	181983.	7.6	2144291.	4532.
80	181214.	1967595.	13266.	195249.	7.2	2148809.	9049.
85	172153.	1982367.	14772.	210021.	6.8	2154520.	14761.
90	162985.	1999664.	17297.	227318.	6.5	2162649.	22890.
95	157397.	2011676.	12012.	239329.	6.3	2169073.	29313.
100	150516.	2027504.	15829.	255158.	6.0	2178021.	38261.
105	144971.	2041512.	14008.	269166.	5.8	2186484.	46724.
110	139114.	2057960.	16448.	285614.	5.5	2197074.	57315.
115	135022.	2070655.	12695.	298309.	5.4	2205678.	65918.
120	130543.	2085271.	14616.	312925.	5.2	2215814.	76054.
125	125774.	2102264.	16993.	329918.	5.0	2228038.	88278.
130	121341.	2119388.	17124.	347042.	4.8	2240730.	100970.
135	117712.	2134383.	14995.	362036.	4.7	2252094.	112335.
140	113820.	2151628.	17245.	379281.	4.5	2265448.	125688.
145	110178.	2168870.	17242.	396524.	4.4	2279048.	139288.
150	105940.	2190246.	21376.	417900.	4.2	2296186.	156427.
155	102017.	2211468.	21222.	439122.	4.1	2313485.	173725.
160	98373.	2232435.	20967.	460088.	3.9	2330808.	191048.
165	94009.	2259163.	26728.	486817.	3.7	2353171.	213412.
170	90015.	2285161.	25999.	512815.	3.6	2375176.	235417.

PERCENT BUSES	.48	AVERAGE DAILY TRAFFIC	500.
PERCENT TRUCKS	.31	COST OF GRADING	7351.
PERCENT AUTOS	.21	COST OF REHABILITATION	42904.
ADMINISTRATIVE OVERHEAD	.31		

Figure 5 shows the general simulation procedure for a roughness threshold of QI equal to 110.

Table 3 indicates that eight columns of information were generated for each run. Column 1, "Max Roughness," indicates the level of maintenance in terms of road surface roughness in QI units. The QI numbers 35 through 170 cover the range of roughness thresholds examined.

The column headed "Maintenance Costs" shows the annual road maintenance costs needed to keep the road from exceeding the roughness threshold specified. The column entitled " User Costs" is the annual cost to operate the indicated traffic for the threshold roughness level. The traffic is 500 vehicles per day with a composition of 21 percent light vehicles, 48 percent buses, and 31 percent trucks.

Column 4 is entitled "Change" and shows the user costs associated with moving from one maintenance

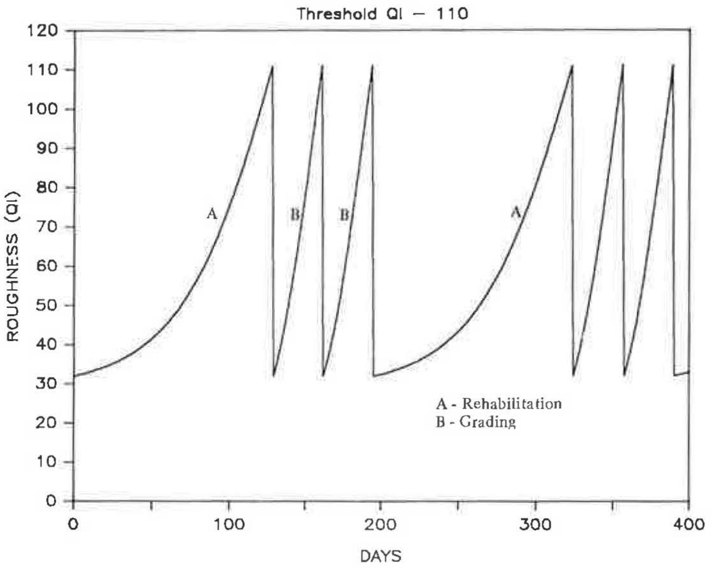

FIGURE 5 Gravel road maintenance activity sequence.

threshold to the next (i.e., allowing the maximum roughness to increase from a QI of 50 to 55 results in a user cost change of 21,087 pesos per year for the composite traffic). The column "Total Change" is the cumulative user costs change from the initial roughness following grading to any roughness threshold. The sixth column is the annual maintenance frequency needed to meet the indicated roughness threshold. The two gradings and one rehabilitation program analyzed reflects the average frequency of the combination (i.e., the 10-cycle frequency divided by 3). The "Total Costs" column is maintenance plus user costs. The last column is titled "Total Adjusted" and was obtained by screening the "Total Costs" column for the minimum total cost and then subtracting this cost from each total costs value. The minimum costs occurred at a roughness threshold of 65 so the value at this point in the "Total Adjusted" column is zero. This is the optimum maintenance level for the traffic composition given with a volume of 500 vehicles per day.

MAINTENANCE SERVICE LEVELS

The objective analysis presented was used to define maintenance service levels in Bolivia. Figure 6 shows the frequency of the grading and rehabilitation cycle studied as a function of traffic volume. The curve was used in a performance budgeting program to generate the annual frequency of grading and rehabilitating aggregate surface roads.

The program RSML was also used to analyze maintenance service levels for grading and rehabilitation separately. The resulting optimum frequencies are shown in Figure 7.

SUMMARY

A procedure has been presented for objectively establishing aggregate road maintenance frequencies in Bolivia. The procedure is based on minimizing total annual maintenance and vehicle operating costs.

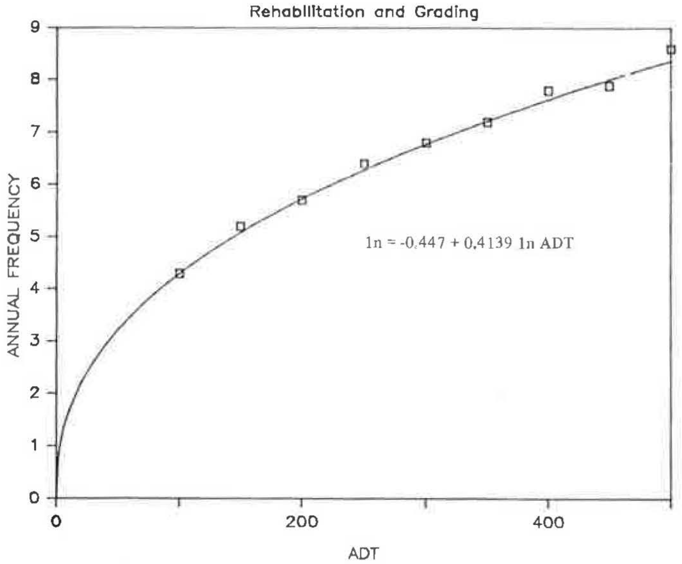

FIGURE 6 Annual frequency of grading and rehabilitation versus ADT.

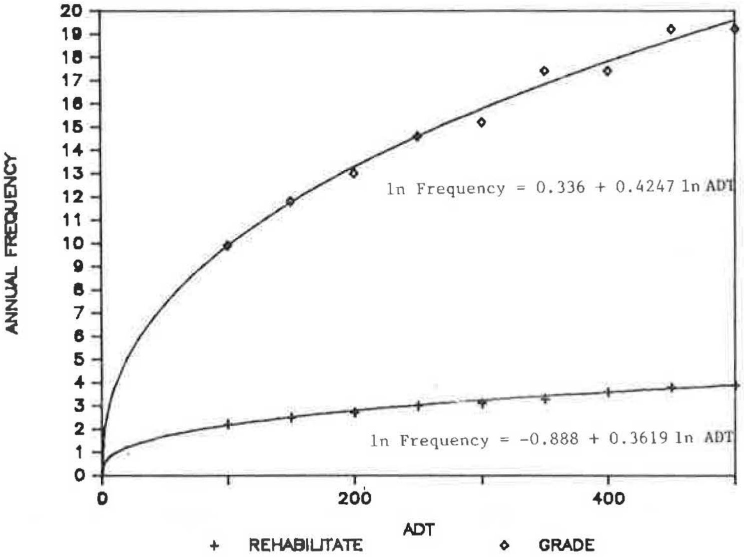

FIGURE 7 Optimum frequencies of grading and rehabilitation.

It requires that road surface conditions (roughness) be predicted over time as a function of traffic. Also needed are equations to relate road roughness to vehicle operating costs. The procedure can be made applicable to any nonpaved road in any country given the appropriate road performance, user costs equations, and grading costs.

ACKNOWLEDGMENT

The República de Bolivia, Ministerio de Transportes, Comunicaciones y Aeronáutica Civil, Servicio Nacional de Caminos (SNC) sponsored the study that provided the basis for this paper. Employees of SNC collected Maysmeter roughness data that were used to develop gravel road performance equations. SNC employees also assisted in assembling the data base that was used to modify the Brazil relationships on roughness to vehicle operating costs that made them applicable to Bolivian driving conditions and vehicle use.

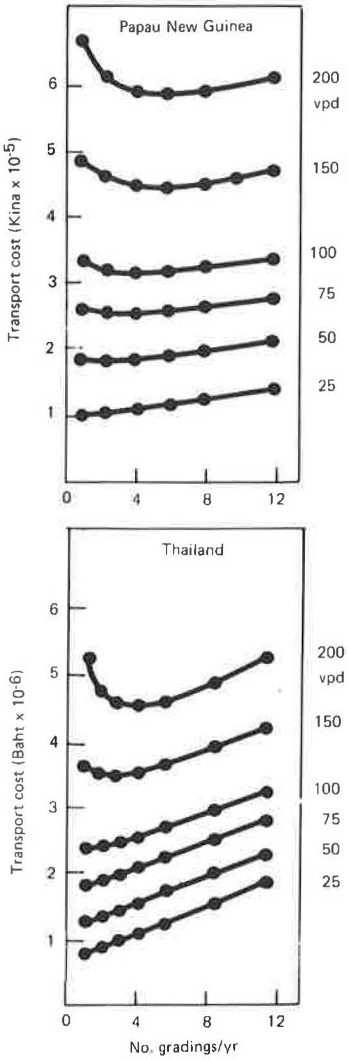

FIGURE 8 Transport cost versus frequency of grading for Papua New Guinea and Thailand.

Discussion

Richard Robinson*

The work described in the paper mirrors studies carried out by the Transport and Road Research Laboratory Overseas Unit in conjunction with Crown Agents in Papua New Guinea and with John Burrow and Partners in Thailand. In both cases, field data were collected and used to determine optimum grading frequencies to minimize the sum of maintenance cost and road user cost for a traffic range of 25 to 200 vehicles per day. The results are plotted in Figure 8.

Figure 9 shows the results from Papua New Guinea and Thailand compared with those of Butler et al. from Bolivia. It is clear that differences in material types, climate, and unit costs in the three

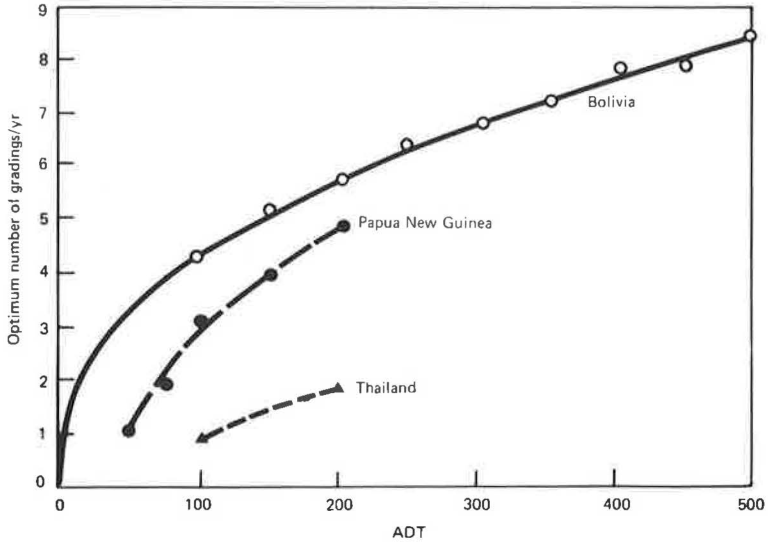

FIGURE 9 Optimum frequency of grading for Papua New Guinea and Thailand compared with that for Bolivia.

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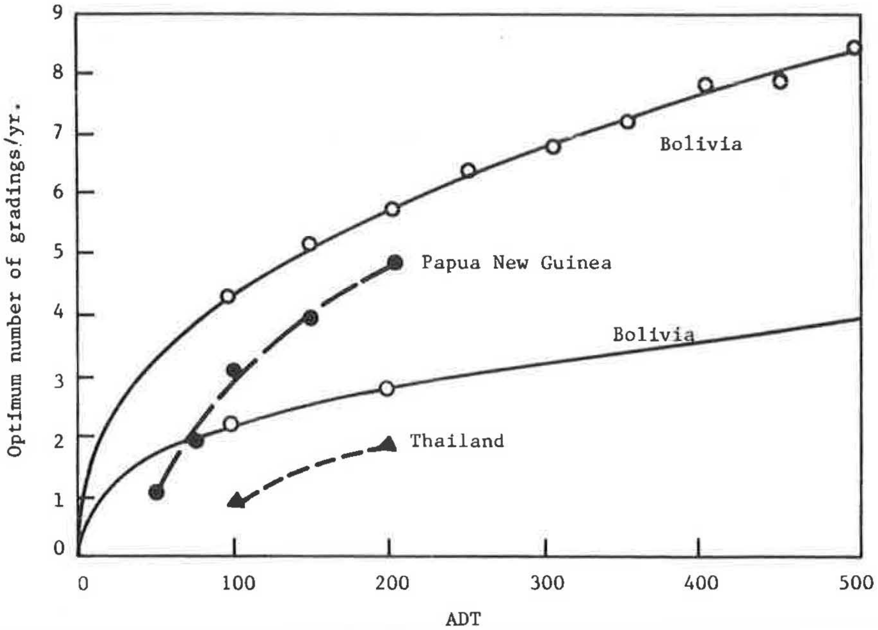

FIGURE 10 Optimum frequency of grading for Papua New Guinea and Thailand compared with that for Bolivia (modification of Figure 9).

countries have resulted in quite different recommendations being made about optimum grading frequencies for each case. This illustrates the danger of assuming that findings from one country will apply elsewhere in the world and emphasizes the need to carry out specific studies for the different conditions found in individual countries.

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Authors' Closure

In our paper equations predicting road roughness in Bolivia and those from Brazil and Kenya were compared. The performance equations were substantially different. This provided the impetus to conduct studies to determine performance equations for Bolivian conditions.

As Robinson suggested, different materials, climate, and unit costs do produce different results and, therefore, we agree with Robinson's note of caution, suggesting the danger of assuming that findings from one country can be applied elsewhere. In regard to Figure 9, if we select rehabilitation as the treatment, we get a curve that falls between his Papua New Guinea and Thailand curves (Figure 10).

Finally, our Bolivian curves reflect a minimum grading frequency of once a year.

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Optimal Rehabilitation Frequencies for Highway Pavements

MICHAEL J. MARKOW and WAYNE S. BALTA

ABSTRACT

The maintenance and rehabilitation of existing, mature facilities are becoming increasingly important components of highway activity. Yet, although the planning, budgeting, evaluation, and management of maintenance and rehabilitation are different from corresponding actions for new construction, comparatively little work has been devoted to the development of planning and management tools intended specifically for repair programs. For a number of reasons, the optimization of maintenance and rehabilitation policy is difficult, and new concepts and analytic approaches need to be formulated to address this problem. Recently, the usefulness of dynamic control theory for optimizing transport investment decisions has been demonstrated. Control theory structures a problem in terms of a dynamic (i.e., time varying) objective function (e.g., maximize total transport-related benefits over time) subject to dynamic constraints (e.g., equations describing changes in pavement condition due to deterioration and repair or variations in traffic levels responding to current pavement condition). The several factors that influence the problem are structured in terms of state variables (over which decision makers have no control, such as traffic, weather, and soil) and control variables (over which decision makers exercise judgment, such as maintenance and rehabilitation policy). Dynamic control theory thus presents an attractive analytical tool for management of highway infrastructure; it encompasses all the key variables of interest, allows technically correct engineering and economic relationships to be expressed in problem formulation, and leads directly and efficiently to solution of optimal maintenance and rehabilitation policy. The tenets of dynamic control theory are described, and a numerical example of the use of dynamic control theory to optimize the overlay frequency on highway pavements in the United States is given.

The maintenance and rehabilitation of existing, mature facilities are becoming increasingly important components of highway activity. However, comparatively little work has been devoted to the development of planning and management tools intended specifically for repair programs. Yet, decisions regarding the planning, budgeting, evaluation, and management of maintenance and rehabilitation are different from corresponding actions for new construction:

1. Planning and managing maintenance and rehabilitation programs require an understanding of concepts underlying facility performance, as opposed to facility design.
2. There is a need to understand the role of