Impact of Stream Degradation on Bridges and Rural Travel Patterns

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Stream degradation has resulted in significant damage to rural roads and bridges in several areas of the United States. Western Iowa is one region that has been severely affected. In the beginning of the 20th century, many streams throughout Iowa were channelized to reduce flooding and to open more land to farming. Channel straightening accomplished its goal, but led to greater stream flow velocities, causing degradation on stream channels. This widening and deepening of streams resulted in damage to rural roads and bridges. This study evaluates the effects of stream degradation on county bridges and rural travel patterns in western Iowa. A conceptual model for measuring the benefits and costs of reconstructing, maintaining, or closing county bridges is presented, and a budget constraint model is constructed to show how limited funds might be distributed among various bridge projects. This model will be compared with the benefit-cost analysis based on net benefits and the benefit-cost ratio method of allocating funds.

Natural streams are seldom in a true state of equilibrium. If the stream bed continues to lower because more sediment leaves than enters it (throughout a reach or over a considerable length of channel), this nonequilibrium condition is called "degradation" (*1*). Channel degradation also can lead to mass landslides, which result in increased channel widths (*2*).

Stream straightening has been cited as a primary cause of channel degradation in western Iowa. Until the early part of this century, western Iowa streams were meandering natural rivers that overflowed frequently, preventing the conversion of prairies or pastures to cropland and damaging agricultural crops planted in flood plain areas (*1*). From the turn of the century until about 1960, many creeks and rivers throughout Iowa were channelized to achieve better drainage on flood plains and to open bottom lands to farming. Channelization usually accomplished its goal. Most Iowa creek and river flood plains today are productive cropland (Adkins, unpublished data).

Channelization straightened previously meandering streams (*3*), reduced stream lengths, and increased channel grades. However, it also resulted in greater stream flow velocities. Increased run-off into streams had already begun with the conversion of native prairies and forests to cropland. The smooth, straight sides of the new ditches, combined with an increase of gradient, velocity of flow, and the tractive force exerted on the bed and banks of stream channels, contributed to their degradation (*4*). The streams of western Iowa have degraded 1.5 to 5 times their original depth since channelization. This vertical degradation is often accompanied by increases in channel widths of 2 to 4 times original widths (*2*).

Stream degradation is causing significant damage to rural roads and bridges. The deepening and widening of the streams has jeopardized the structural safety of many bridges. The condition of Iowa's rural roads and bridges is deteriorating rapidly, and the funds are not available to maintain and reconstruct them (*5*). Economical stabilization structures to control stream channel degradation and protect roads and bridges are desperately needed. Closing or posting bridges that pose severe safety hazards is a temporary solution, but a procedure for their repair and reconstruction is required in order to ensure the efficient allocation of scarce resources (*6*).

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THE HISTORY OF RURAL ROADS AND BRIDGES

Numerous writers have discussed the deteriorating conditions of the local rural road and bridge system. However, only a few studies (*7–9*) have attempted to identify alternative solutions. Fewer yet have attempted to research the effects of deteriorating roads on travel costs or the benefits of alternative solutions for travelers and for local governments faced with tight budgets.

Nyamaah and Hitzhusen used a circuitry model to estimate the rerouting costs to road users when 15 rural bridges in Ohio were posted or closed (*6*).

Baumel and Schornhorst illustrated the characteristics of local rural roads and bridges in the United States. They proposed several alternative policies to deal with the problem of inadequate funds to rebuild and maintain all the existing county roads and bridges to handle the levels and types of traffic moving on the system (*8*).

Chicoine and Walzer surveyed farmers, township officials, and agricultural and rural business officials in four Midwestern states on a variety of rural road and bridge issues (*9*).

Several studies have suggested a potential cost savings from the abandonment of local rural roads. Baumel et al. were the first to evaluate the impact of local road abandonment on all traffic types using the rural road and bridge system (*10*). In the update and extension of the Baumel study, a benefit-cost analysis was used to examine the effects of alternative investment strategies on local rural roads and bridges (*11*).

No studies have been found that estimate the costs of keeping individual bridges that cross degrading streams. To the authors' knowledge, the current research is the first to address the problem of stream degradation's effects on county road bridges.

METHOD OF ANALYSIS

Benefit-Cost Analysis

The study area for this research includes four streams and road networks in eight counties in western Iowa. The streams studied were McElhaney Creek in Woodbury County, Indian Creek in Pottawattamie, Montgomery, and Mills counties, Keg Creek in Shelby, Pottawattamie, Harrison, and Mills counties, and Willow Creek in

Crawford, Monona, and Harrison counties. These streams were judged to be representative of the many degrading streams in western Iowa. Several have been the subject of previous engineering analyses (*12*).

When the structural integrity of a bridge is compromised because of stream degradation, decisions must be made regarding costs associated with repair, reconstruction, or abandonment. If a bridge is closed, some motorists may have to travel farther to reach their destinations, increasing travel costs. A benefit-cost analysis was used to evaluate the benefits of keeping a bridge versus the costs of maintaining and reconstructing it. Bridges that do not generate positive net benefit to society would become candidates for abandonment. Three categories of costs that were estimated in the benefit-cost analysis were: (a) reconstruction, (b) maintenance, and (c) traffic rerouting.

The net benefit of keeping a bridge in the road system is calculated as

$$NB = TC - (AC_{\mathrm{RC}} + AC_{\mathrm{MC}}) \tag{1}$$

where

NB = net benefit of keeping a bridge in the road network,
TC = the annual traffic rerouting cost,
AC_{RC} = the annualized reconstruction cost, and
AC_{MC} = the annualized maintenance cost.

A positive number of net cost savings indicates a bridge should be reconstructed and kept open. A negative number shows a bridge should not be rebuilt.

Reconstruction Costs

The reconstruction cost is defined as the cost of reconstructing a new bridge or the cost of adding approach spans, or both. The estimated reconstruction costs are based on the length of a bridge needed when reconstruction is carried out or approach spans are added.

Scant published data exists on original straightened stream depths. Most of the original stream straightening records have been discarded by drainage districts and county recorders (*12*). This study relied on the few original stream straightening records that remain in county recorder and engineering offices where the study streams are located. Some original depth data were taken from previous studies (*1,13*). The original channel depths were grouped by size of drainage area. A generalized channel depth was assumed for all drainage areas of similar size on the study streams.

Data on stream depths after channelization were obtained from an Iowa Department of Transportation (Iowa DOT) bridge inventory report. These data were used in a regression to estimate the degradation rate for each stream. Stream depths were estimated at each drainage area interval on each study stream after channelization. The lengths of bridges needed for reconstruction or approach spans were calculated, and reconstruction costs were estimated.

Estimation of Stream Depths The depth of a stream is calculated as

$$D_t = 30.50 - E_t - 1.22 \tag{2}$$

where D_t is the depth of the channel from stream bed to flood plain in meters at time t. The design standard for the distance from the flood plain to the bridge deck is always 1.22 m. The elevation of the bridge deck is 30.50 m at any time for any bridge, and E_t is the stream bed elevation at time t.

The stream bed elevation at time t is estimated by Equation 3.

$$E_t = E_0\, e^{-kt} \tag{3}$$

where

E_0 = stream bed elevation at time of channelization,
t = years since channelization, and
k = rate of degradation.

Estimation of Bridge Length The length of a county bridge was calculated by Equation 4. The bottom width of the stream was assumed to remain constant over time.

$$L_t = 2[m\,(D_t = 1.22)] + BW_t \tag{4}$$

where

L_t = the length of a county bridge at time t,
m = the retained design slope of 2 for county bridges, and
BW_t = the bottom width of the stream at time t.

Costs of Reconstruction and Approach Spans The selected bridges were divided into four groups, A(P), B(P), A(G), and B(G), based on the type of road the bridge serves (paved or gravel) and the year the bridge was built. A and B represent the relative times in which a bridge was built; P represents "paved road"; G represents "gravel road"; and Y_0 denotes the year the bridge was built. The definitions are as follows:

- Group A(P) are bridges on paved roads that were built on or before 1949 ($Y_0 \leq 1949$);
- Group B(P) are bridges on paved roads that were built after 1949 ($Y_0 > 1949$);
- Group A(G) are bridges on gravel roads that were built on or before 1934 ($Y_0 \leq 1934$); and
- Group B(G) are bridges on gravel roads that were built after 1934 ($Y_0 > 1934$).

The reconstruction date is calculated as

$$Y = Y_0 + N \tag{5}$$

where Y is the reconstruction date and N is the life cycle of a county bridge. N is 45 years for paved road bridges and 60 years for gravel road bridges (*11*). Based on Equation 5, bridges in group A(P) and A(G) should be rebuilt on or before 1994. The assumption was made that they will be reconstructed in 1995. Bridges in group B(P) and B(G) should be rebuilt after 1994.

For bridges in group A(P) and A(G), decisions were based on whether they should be rebuilt in 1995. The present value of reconstruction costs includes the present value of the cost of rebuilding a bridge in 1995, plus the present value of the cost of adding approach spans after 1995 until the next reconstruction date. There is no standard length of approach spans. The cost of adding approach spans

is estimated by the additional length of a bridge according to the increasing stream depths every year. The present value of reconstruction costs is estimated by Equation 6.

$$PV_{RC} = \frac{L_{1995}WC}{(1 + i)} + \sum_{t=0}^{N-1} \frac{(L_{1996+t} - L_{1995+t})WC}{(1 + i)^{1995+t-1994}} \tag{6}$$

where

L_{1995+t} = the length of a bridge in meters, t years after 1995,
W = the width of a bridge,
C = the cost of construction per square meter at the bridge deck in dollars, and
i = the long run real interest rate of 4 percent.

Paved road and gravel road bridges are 9.15 and 7.32 m wide, respectively. The reconstruction cost is $\$430/m^2$.

For bridges in group B(P) and B(G), investment decisions were based on whether these bridges should have approach spans added between 1994 and the reconstruction date. A paved road bridge built in 1960 should be reconstructed in 2005; therefore, the cost of adding approach spans from 1994 until 2005 is considered. The cost of adding approach spans is estimated by calculating the difference between the length of a bridge at $t+1$ years after 1994 and the length at t years after 1994. The present value of reconstruction costs is calculated as

$$PV_{RC} = \frac{\sum_{t=0}^{N-1} (L_{1995+t} - L_{1994+t})WC}{(1 + i)^{1995+t-1994}} \tag{7}$$

where N is the number of years in the future in which the reconstruction is required (defined as: the year built + life cycle of a bridge − 1994).

The present value of reconstruction costs is annualized as follows (for all the bridges):

$$AC_{RC} = PV_{RC} \frac{i (1 + i)^N}{(1 + i)^{N-1}} \tag{8}$$

where AC_{RC} is the annualized reconstruction cost over the life cycle of the bridge, and N is the life cycle of a bridge.

When an approach span is added, it becomes part of the original structure, so its life cycle depends on the life cycle of the original structure. Therefore, the life cycle of an approach span is the same as that of a bridge.

Maintenance Costs

For bridges in group A(P) and A(G), the maintenance cost after the bridge is rebuilt in 1995 until the next reconstruction date was estimated as

$$PV_{MC} = \sum_{t=0}^{N} \frac{L_{1995+t}\, WC}{(1 + i)^{1995+t-1994}} \tag{9}$$

where

PV_{MC} = the present value of maintenance cost of a bridge,
C = the cost of maintenance per square meter (3.66 dollars per square meter), and
N = the life cycle of a bridge.

For bridges in group B(P) and B(G), the maintenance cost from 1994 until the next reconstruction date is calculated as

$$PV_{MC} = \frac{\sum_{t=0}^{N} L_{1995+t}\, WC}{(1 + i)^t} \tag{10}$$

where N is the number of years in the future when the reconstruction will be required.

For all bridges in the study area, the present value of maintenance costs was annualized using the following equation:

$$AC_{MC} = PV_{MC} \frac{i (1 + i)^N}{(1 + i)^{N-1}} \tag{11}$$

where AC_{MC} is the annualized maintenance cost and N is the life cycle of a bridge.

Traffic Rerouting Costs

The data base of the streams and roads involved in the study area was input into TransCAD, a Geographic Information System software program that performs transportation analysis. A network model was used to determine the minimum-cost routing from each origin to each destination for each vehicle type. The minimum-cost routings were estimated for household and farm travel. No other commercial traffic occurs on these low-volume rural roads. Because of data limitations, assumptions were made to select origins and destinations. Generally, a node close to the bridge was chosen as the origin. For household travel, the county seat was selected as the destination; for farm traffic and post office traffic, the nearest town was selected as the destination; and for school buses, the nearest town with a school was chosen as the destination.

First, a base solution was run to determine the minimum-cost route with a specific bridge open. Then, a second minimum-cost solution was obtained after a specific bridge was closed. The difference between total travel costs in these two solutions was the estimated cost of traffic rerouting. Equation 12 was used to calculate travel costs.

$$TC = \sum_{d}^{2} \sum_{v}^{5} \sum_{r}^{3} (VC_{rvd} \times M_{rd} \times TP_{vd}) \tag{12}$$

where

TC = total travel cost for 1 year,
VC_{rvd} = the variable cost per kilometer by vehicle type v to destination d on road type r,
M_{rd} = the number of kilometers for each road type r to destination d, and
TP_{vd} = total trips for each type of travel to destination d.

The Data

Rate of Stream Degradation Over Time

Equation 13 was used to estimate the rate of stream degradation over time for each study stream (*2*). This is simply another form of Equation 3.

$$ln(E/E_0) = -kt \quad (13)$$

Assume the year of stream straightening is 1954 for McElhaney Creek, and it is 1920 for all the other study streams (*3*). To estimate the rate of degradation, Equation 13 was regressed on stream bed elevation data obtained from the Iowa DOT bridge inventory report. In the Lohnes model (*2*), k varied by drainage areas. Because of data limitations, k was assumed to be constant over entire streams.

Estimation of Bridge Length

There are 126 county bridges on the four study streams. Among them, 29 bridges were selected for rerouting analysis. Table 1 shows the lengths of the selected bridges at the most recent inspection date, and the estimated lengths at 1994.

Rerouted Bridge Traffic

State highway, county highway, and gravel road variable vehicle operating costs were based on cost estimates drawn from a study by Baumel et al. (*14*). Table 2 shows the variable costs per vehicle kilometer for each type of vehicle in the analysis.

Benefit-Cost Ratio Method

Because the benefit-cost ratio (B/C) method is still widely used by county engineers, it is illustrated in this study and is expressed in Equation 14. Using this method of analysis, any investment alternative that has a $B/C > 1$ is economically feasible. The alternative that has the highest B/C is indicated as the preferred investment (*15*).

$$B/C = \frac{TC}{AC_{RC} + AC_{MC}} \quad (14)$$

Results

The following assumptions were made in this analysis:

- The traveling public attempts to minimize the travel costs from an origin to a destination;

TABLE 1 Estimation of Bridge Length for Each Selected Bridge (in m) 1994

Stream	Bridge	Year built	Length at the latest inspection date	The latest inspection date	Length (1994)
McElhaney	C 213	1984	33.55	1992	33.96
McElhaney	C 274	1950	11.29	1992	11.59
Indian	IC-157	1931	46.06	1991	46.37
Indian	IC-122	1964	32.03	1991	32.35
Indian	IC-160	1965	39.04	1991	39.37
Indian	IC-153	1973	30.50	1991	30.83
Indian	GARF 501	1971	15.25	1989	15.86
Indian	LINC 3201	1941	31.11	1989	31.66
Indian	GR 20	1920	12.20	1992	12.51
Indian	WV 15	1987	30.50	1992	30.73
Indian	WV 13	1900	9.46	1992	9.76
Keg	OAK 0-90	1970	50.33	1991	50.67
Keg	KC-2	1955	43.62	1989	44.17
Keg	HA-1	1958	45.75	1991	46.08
Keg	YO-19	1960	45.75	1991	46.08
Keg	YO-4	1983	24.71	1990	25.01
Keg	WASH 21	1955	21.05	1990	21.66
Keg	S 80 07 210	1940	7.02	1992	7.32
Keg	L 99 07 210	1945	14.03	1992	14.34
Keg	L 99 05 110	1990	10.07	1992	10.37
Keg	L 99 18 110	1954	15.56	1992	15.86
Willow	MAGN 17	1940	45.14	1990	46.06
Willow	LINC 9	1930	50.63	1992	50.94
Willow	LINC 8	1977	58.26	1992	58.56
Willow	LINC 7	1972	21.35	1992	21.66
Willow	S22-1	1979	20.74	1992	21.05
Willow	S12-1	1952	45.75	1992	46.36
Willow	WILLOW 2	1949	15.86	1992	16.47
Willow	WILLOW 4	1961	21.35	1992	21.96

TABLE 2 Estimated Variable Cost per Vehicle Kilometer and Road Type in Dollars per Kilometer (*14*)

	Type of road		
Type of vehicle	State highway	Paved county	Gravel road
Auto/pickup	0.1254	0.1342	0.1742
SA	0.2658	0.2791	0.3881
TA	0.3644	0.3826	0.5321
Semi	0.4156	0.4364	0.6068
TW	0.7019	0.7370	1.0248

- The number of trips from an origin to a destination does not change as because of changes in the road system;
- The routes used to travel from an origin to a destination can change if the road system changes;
- The variable vehicle travel costs are a linear function of distance;
- The U.S. Postal Service serves all residences that have a passable road access;
- School buses provide school transportation to all residences with school-age children; and
- The road maintenance costs and reconstruction costs are functions of bridge length and width, and are independent of traffic levels.

The savings to the traveling public incurred by keeping a bridge in the road system are defined as traffic rerouting savings. The costs to the counties of keeping a bridge in the road system include bridge maintenance and reconstruction costs. Table 3 summarizes the results of the benefit-cost analysis. The bridges in Table 3 are ranked by average daily traffic (ADT) and listed in ascending order. Table 4 shows the results of traffic rerouting.

Low Traffic Volume Bridges

A low-volume bridge is defined as a bridge with an ADT < 20. The first seven bridges in Table 3 are low-volume bridges. They are all gravel road bridges, classified either in group A(G) or B(G). The net benefit of keeping such a bridge in the road network ranged from −\$7,582 to \$2,255. Benefit-cost ratios ranged from 0.11 to 2.55. Three of these bridges (LINC-9, WV-13, and LINC-8) had benefit-cost ratios less than 1, and thus should not be reconstructed.

Bridges LINC-9 and WV-13 belong to group A(G), because they are gravel road bridges built before 1934. LINC-9 was built on Willow Creek in 1930, and WV-13 was built on Indian Creek in 1900; neither has been reconstructed since. Both have an ADT of 10. It was assumed that these 10 ADT bridges serve only as field access roads.

Bridge LINC-9 LINC-9 has a very small annual traffic rerouting cost, not only because of low ADT, but also because the change in total kilometers of the second solution is only 16.79 percent of the total kilometers in the base solution. If this bridge is rebuilt in 1995, the costs of reconstruction and approach spans will be high. Its length was 50.63 m in 1992, making maintenance very costly. Based on the data used in this analysis, LINC-9 should not be reconstructed.

Bridge WV-13 WV-13 has a traffic rerouting cost of more than \$1,000. The annualized reconstruction cost for this bridge is slightly higher than the annual traffic rerouting cost. The maintenance cost is less than one-fourth of that of LINC-9 because WV-13 is a much shorter bridge (9.46 m in 1992).

Bridge LINC-8 All low-volume bridges in group A(G) have annualized reconstruction costs higher than \$1,000 because decisions were based on whether these bridges should be rebuilt in 1995. The low-volume bridges in group B(G) have much lower annualized reconstruction costs because only the cost of adding approach spans is considered. LINC-8 in group B(G) has a negative net benefit because it had a length of 58.26 m in 1992, and therefore had a high maintenance cost.

Low traffic volume bridges tend to have smaller traffic rerouting savings. Some have negative net benefit-cost savings. Bridges with greater benefit-cost ratios should be rebuilt; bridges with ratios less than 1 should not be rebuilt.

Middle Traffic Volume Bridges

Middle-volume bridges are defined as those whose ADT is between 20 and 100. All are gravel road bridges. They are listed in the middle of Table 3, from YO-4 to MAGN-17. Annual traffic rerouting costs ranged from \$1,000 to \$7,000. Annualized reconstruction costs ranged from \$87 to \$743. Annualized maintenance costs are usually several hundred dollars. The benefit-cost ratios varied from 0.33 to 43.85, and the net benefit varied from −\$422 to \$21,364. All selected middle-volume bridges have benefit-cost ratios greater than 1 except WASH-21.

Bridge WASH-21 It was assumed all farm traffic and post office vehicles travel to the nearest town of Persia. In the base solution, the minimum cost route from farms to Persia was over the bridge. The base run route to Persia included 6.02 km of gravel road and 4.60 km of state highway. After the bridge was closed, a vehicle needed only to drive an additional 0.016 km on a gravel road to reach Persia without crossing the bridge. Distance traveled and travel costs increased only slightly in the second solution. For school bus and household traffic, the results were similar. This example shows that change in kilometers is an important factor in measuring traffic rerouting costs.

TABLE 3 Estimated Benefit-Cost Analysis

Stream	County	County bridge code	Average daily traffic	Year built	Group	Annualized reconstruction cost	Annual traffic rerouting cost	Annualized maintenance cost	Net benefit	Benefit cost ratio
Willow	Harrison	LINC 9	10	1930	A(G)	$7,124	$963	$1,420	-$7,582	0.11
Indian	Pottawattamie	WV 13	10	1900	A(G)	1,654	1,550	321	-425	0.78
McElhaney	Woodbury	C 213	10	1984	B(G)	589	2,776	993	1,194	1.75
Willow	Harrison	LINC 8	15	1977	B(G)	595	1,257	1,566	-904	0.58
Indian	Pottawattamie	GR 20	15	1920	A(G)	2017	3,663	394	1,252	1.52
Indian	Montgomery	GARF 501	15	1971	B(G)	635	1,124	431	58	1.05
Indian	Mills	IC-160	15	1965	B(G)	562	3,714	897	2,255	2.55
Keg	Pottawattamie	YO-4	20	1983	B(G)	325	1,655	713	616	1.59
Keg	Shelby	L 99 18 110	20	1954	B(G)	232	1,105	291	582	2.11
Keg	Shelby	L 99 07 210	20	1945	B(G)	149	1,619	172	1,298	5.04
Indian	Pottawattamie	WV 15	20	1987	B(G)	743	3,623	935	1,944	2.16
McElhaney	Woodbury	C 274	20	1950	B(G)	326	2,203	196	1,681	4.22
Willow	Crawford	WILLOW 2	20	1949	B(G)	364	3,195	257	2,574	5.14
Keg	Pottawattamie	KC-2	25	1955	B(G)	213	1,598	802	582	1.57
Indian	Mills	IC-153	25	1973	B(G)	640	5,599	811	4,147	3.86
Willow	Crawford	WILLOW 4	30	1961	B(G)	523	7,054	500	6,032	6.90
Keg	Shelby	S 80 07 210	30	1940	B(G)	87	5,234	56	5,090	36.53
Keg	Pottawattamie	HA-1	35	1958	B(G)	232	4,397	906	3,259	3.86
Indian	Mills	IC-122	40	1964	B(G)	254	3,323	727	2,343	3.39
Willow	Monona	S12-1	45	1952	B(G)	400	4,537	775	3,362	3.86
Keg	Shelby	L 99 05 110	50	1990	B(G)	375	1,649	344	930	2.29
Indian	Montgomery	LINC 3201	55	1941	B(G)	92	3,487	265	3,130	9.77
Keg	Harrison	WASH 21	70	1955	B(G)	229	208	401	-422	0.33
Willow	Harrison	MAGN 17	70	1940	B(G)	155	21,862	344	21,364	43.85
Willow	Harrison	LINC 7	120	1972	B(G)	575	22,315	599	21,141	19.01
Willow	Monona	S22-1	190	1979	B(G)	626	7,556	634	6,295	5.99
Keg	Pottawattamie	YO-19	300	1960	B(P)	268	71,543	1,037	70,238	54.82
Keg	Mills	OAK 0-90	400	1970	B(P)	293	56,729	1,228	55,208	37.30
Indian	Mills	IC-157	580	1931	A(P)	8131	277,028	1,643	267,254	28.34

TABLE 4 Results of Traffic Rerouting

Bridge	Percentage of Change in Kilometers Traveled over Base Solution			Percentage of Change in Travel Costs over Base Solution		
	Household	Farm	Total	Household	Farm	Total
LINC 9	--[a]	16.79	16.79	--	13.14	13.14
WV 13	--	6.47	6.47	--	12.26	12.26
C 213	--	78.09	78.09	--	67.06	67.06
LINC 8	--	8.32	8.32	--	9.76	9.77
GR 20	6.61	41.77	9.89	6.31	43.20	12.32
GARF 501	0.44	45.29	9.02	1.19	32.35	10.04
IC-160	8.25	296.97	14.84	12.13	235.95	22.31
YO-4	6.64	18.20	7.88	4.19	18.32	6.89
L 99 18	-11.41	-1.13	-9.63	3.68	29.25	9.97
L 99 07	9.63	9.56	9.61	11.62	17.93	14.18
WV 15	5.97	17.81	7.53	6.69	19.42	9.14
C 274	3.21	10.98	4.12	5.54	20.22	8.03
WILLOW 2	23.14	0.84	18.65	7.96	12.41	9.11
KC-2	10.44	9.89	10.32	11.58	0.70	8.41
IC-153	11.52	277.64	16.95	12.70	233.88	21.54
WILLOW 4	27.70	14.35	25.20	22.11	12.17	19.78
S 80 07	12.76	46.09	16.50	12.61	37.46	17.10
HA-1	1.65	63.74	8.21	3.30	57.95	13.15
IC-122	-0.39	8.62	0.33	4.47	40.34	8.81
S12-1	0.99	3.26	1.23	4.47	14.94	6.39
L 99 05	-6.90	-17.54	-9.59	6.17	5.48	5.95
LINC 3201	-0.49	35.84	6.95	1.96	19.83	7.46
WASH 21	0.05	0.15	0.10	0.06	0.17	0.19
MAGN 17	25.34	85.02	37.25	49.35	97.73	63.40
LINC 7	9.99	24.28	12.20	12.89	28.66	16.56
S 22-1	2.87	12.10	4.14	1.06	6.38	2.17
YO-19	4.08	55.90	11.52	20.56	30.89	23.33
OAK 0-90	10.47	57.14	12.57	25.30	84.89	29.24
IC-157	25.07	2204.00	43.69	32.67	2580.47	67.44

[a]not applicable.

Bridge L 99 05 110 Table 4 shows that distance driven in the second solution usually increased, but in some cases, it decreased. In the base solution for this bridge, vehicles traveled 1.16 km on gravel roads and 6.83 km on paved county roads per trip. After the bridge was closed, vehicles traveled only 6.58 km on gravel roads, or a reduction of 1.41 km per trip. Because the second solution contains more gravel roads, and the base solution has more paved county roads, the travel cost is lower in the base solution than in the solution without the bridge.

Most of the middle-volume bridges have large benefit-cost savings and should be kept in the road system. Some, however, have low traffic rerouting savings and thus low positive or negative net benefit-cost savings. In addition to ADT, change in kilometers is an important factor in deciding traffic rerouting costs. The type of road is also a factor to be considered.

High Traffic Volume Bridges

High volume traffic bridges are defined as having an ADT $\geq$ 100. The last five bridges in Table 3 are high-volume bridges. The benefit-cost ratios of these bridges ranged from 5.99 to 54.82. YO-19 has the highest benefit-cost ratio among all the selected bridges, and thus should be repaired and rebuilt with priority. Bridges with high traffic volume tend to have significant traffic rerouting savings and large benefit-cost ratios. There also are

significant potential cost savings in keeping these bridges in the road network.

BUDGET CONSTRAINT MODEL IN A LINEAR PROGRAMMING FRAMEWORK

The benefit-cost analysis used in this study implies that every bridge with a positive net benefit should be reconstructed. Budgets available to local governments, however, are limited. Thus, budget constraints play an important role in decision making. In this section, a budget constraint model in a linear programming framework will be introduced to solve the problem.

There are two important classes of mathematical programming problems: linear programming (LP) and integer linear programming (IP). LP can be used when a problem under consideration can be described by a linear objective function to be maximized or minimized, subject to linear constraints, which may be expressed as equalities or inequalities or a combination of the two (*16*). IP problems are essentially the same kind of problem, with one important difference: some or all of the variables are restricted to integral values. IP is called mixed integer programming (MIP) if some decision variables are continuous and some are integer.

Model of Study

A MIP model was developed to maximize the total social benefit subject to the budget constraint of a local government (*17*). This model is presented in Equation 15.

$$\text{Maximize } U = \sum_{j=1}^{n} b_j x_j + f(y)$$

$$\text{Subject to} \sum_{j=1}^{n} c_j x_j + y \leq I, \quad (15)$$

$$y \geq a,$$

$$x_j = 0 \text{ or } 1.$$

where

U = the total social benefit from all the services provided by the local government,

b_j = the present value of benefit from keeping the jth bridge,

c_j = the cost on the jth bridge,

x_j = the status of a bridge ($x_j = 1$ if a bridge is open, or $x_j = 0$ if a bridge is closed),

y = all the other services provided by the local government,

$f(y)$ = the net benefit of all the other services (assume $f(y) = y$),

a = the minimum money on all the other services, and

I = the total budget available.

The Data

There are 378 county bridges in Pottawattamie, Iowa (unpublished data). Among them, 31 have been closed, and approximately one-third have been posted. A posted bridge has a weight limit of less than 36,320 kg. Seven of these bridges were selected for this traffic rerouting study. They are WV-13, GR-20, WV-15 on Indian Creek, and YO-4, KC-2, HA-1, and YO-19 on Keg Creek. Only WV-15, HA-1, and YO-19 have legal weight limits, and the other four are posted. The coefficient b_j is defined as the present value of traffic rerouting cost savings for the jth bridge, and c_j is defined as the amount of money invested in the jth bridge in 1994. Assume that c_j is equal to the sum of the present value of reconstruction and maintenance costs of bridge j, and it will be expended on the jth bridge in 1994. Table 5 shows the present value of benefits and 1994 investment costs of these seven bridges.

For bridges in group A(P) and A(G), the present value of traffic rerouting cost after the bridge is rebuilt in 1995 until the next reconstruction date was estimated by Equation 16:

$$b_j = \sum_{t=0}^{N} \frac{TR_j}{(1 + i)^{1995+t-1994}} \quad (16)$$

where TR_j is the annual traffic rerouting cost of the jth bridge.

For bridges in group B(P) and B(G), the present value of traffic rerouting costs from 1994 until the reconstruction date is calculated by Equation 17:

$$b_j = \frac{\sum_{t=0}^{N} TR_j}{(1 + i)^t} \quad (17)$$

The total county budget I is assumed to be $26 million. The total budget includes $6.9 million of road funds, and $19.1 million for services other than roads, mostly mandated mental health funding. There are three categories of fixed road funds ($5,158,000): engineering and administration, equipment and building maintenance, and road maintenance.

TABLE 5 Present Value of Benefit and 1994 Investment Cost for Selected Bridges in Pottawattamie County

Stream	Bridge	Average daily traffic	Year built	Group	1994 bridge investment cost	Present value of traffic rerouting savings	Present value of net benefit	Ratio of benefit to cost
Indian	WV 13	10	1900	A(G)	$44,682	$35,268	-$9,414	0.79
Indian	GR 20	15	1920	A(G)	54,549	83,346	28,797	1.53
Indian	WV 15	20	1987	B(G)	37,968	82,868	44,900	2.18
Keg	YO-4	20	1983	B(G)	23,502	36,975	13,473	1.57
Keg	KC-2	25	1955	B(G)	22,981	24,017	1,035	1.05
Keg	HA-1	35	1958	B(G)	25,746	71,438	45,692	2.77
Keg	YO-19	300	1960	B(P)	27,031	1,214,998	1,187,967	44.95

The problem was formulated as follows: suppose that money spent on all the other services must be equal to or greater than \$24,258,000, which is the sum of the three items of fixed costs and the non-road use funds. How much of the remaining funds should be expended on these seven bridges?

Results

The model was solved using a computer program in General Algebraic Modeling System (GAMS) (*18*), and the optimal solution was found to be:

$(x_1, x_2, x_3, x_4, x_5, x_6, x_7) = (0, 1, 1, 1, 1, 1, 1)$, with $y = \$25,808,000$, and $U = \$27,322,000$

where $j = 1, 2, \ldots, 7$ represents bridges WV-13, GR-20, WV-15, YO-4, KC-2, HA-1, and YO-19, respectively. The x_j's show that bridge WV-13 should not be reconstructed and repaired, but the other six bridges should be reconstructed and remain open. This is exactly what the benefit-cost ratio indicates. Only WV-13 has a benefit-cost ratio smaller than 1. Thus, if there is sufficient funding to reconstruct and maintain all the bridges, the results from the budget constraint model will be the same as those from the benefit-cost ratio method.

Suppose the federal government requires the local government to spend more money on health and education projects. The money for all the other services will be at least \$25,838,223. Only \$161,777 would be designated for these seven selected bridges. The problem was solved again, and the second optimal solution was found:

$(x_1, x_2, x_3, x_4, x_5, x_6, x_7) = (0, 1, 1, 0, 0, 1, 1)$, with $y = \$25,855,000$, and $U = \$27,307,000$

The results show that bridges WV-13, YO-4, and KC-2 should not be reconstructed. Because the present value of net benefit for WV-13 is negative, the decision variable x_1 in the optimal solution will always be zero. It is not reasonable to invest in something that costs more than it returns. In Table 5, YO-4 has a higher benefit-cost ratio than GR-20. Based on the benefit-cost ratio analysis, YO-4 should be reconstructed before GR-20; however, the second optimal solution shows an opposite decision. The reason is as follows: There is at most \$161,777 available on these seven selected bridges. YO-19, HA-1, and WV-15 are bridges with significantly high benefit-cost ratios, and therefore should be invested in first. After reconstructing and repairing these three bridges, \$71,032 remains. The remaining money is insufficient to invest in the remaining bridges. Only four alternatives remain:

1. The money could be spent on both YO-4 and KC-2,
2. on GR-20 only,
3. on YO-4 only, or
4. on KC-2 only.

Alternative 1 is better than 3 or 4 because the social benefit from 1 is a sum of that from 3 and 4. The social benefit of alternative 2 is \$22,354 more than that of 1. Therefore, 2 is the best choice. After reconstructing GR-20, only \$16,483 is left, which is not enough for either YO-4 or KC-2. This remaining money will be invested in all the other services, or held over for bridges in the next year.

The preceding example shows that the benefit-cost ratio method will not necessarily give the optimal solution. A bridge with a higher benefit-cost ratio will not necessarily have priority over another bridge with a lower benefit-cost ratio. The budget constraint model maximizes the total social benefit of all the services provided by the local government, rather than the benefit of a single bridge.

The benefit-cost analysis implies that projects can be ranked according to net benefits from the highest to the lowest until the money is exhausted. In the case of limited funds, however, this analysis is insufficient to make the best decision. For example, suppose b_j = \$40,000, \$12,000, \$10,000, \$8,000, \$6,000, \$3,000, \$1,500; c_j = \$20,000, \$6,000, \$5,000, \$4,000, \$3,000, \$1,000, \$1,000 for $j = 1, 2, \ldots, 7$; and net benefits are \$20,000, \$6,000, \$4,000, \$5,000, \$3,000, \$2,000, and \$500, respectively. Suppose that the total budget is still \$26,000,000, and $y \geq \$25,980,000$. If selecting by net benefits, the first bridge should be reconstructed because it has the highest net benefit; this is the only bridge that could be invested in with the available money. However, the optimal solution solved by the MIP model is as follows:

$(x_1, x_2, x_3, x_4, x_5, x_6, x_7) = (0, 1, 1, 1, 1, 1, 1)$, with $y = \$25,980,000$, and $U = \$26,020,500$

If bridge x_1 is selected, the MIP analysis indicates that the total social benefit will be \$500 less than if bridges x_2, x_3, x_4, x_5, x_6 and x_7 are reconstructed. Thus, the total social benefit is maximized under the MIP model. This example shows that a combination of small projects may yield greater benefit than a single large project. The examples shown here are very simple. When there are numerous alternative projects with numerous constraints, this budget constraint model with mixed integer programming will be very efficient in providing optimal solutions. Only seven bridges are tested in this model, but there are 347 open bridges in Pottawattamie County. The MIP model would be very useful in allocating funds among all bridges and roads in the county.

The present values of benefits and 1994 investment costs were obtained from only seven bridges in Pottawattamie County. Furthermore, the 1994 investment costs were assumed to be the sum of present value of reconstruction and maintenance costs, which is not true in reality. Therefore, the optimal solutions presented are not actual best solutions, but only a demonstration of how to select a combination of projects that yield the greatest social benefit subject to a budget constraint.

CONCLUSIONS

This study evaluated the impacts of degrading streams on county bridges and rural travel patterns in western Iowa, and developed a method to allocate limited funds to various bridge projects. Benefit-cost analysis was used to evaluate the alternative strategies on affected bridges in the study area. Costs for traffic rerouting, bridge maintenance, and reconstruction were considered. Decisions were made after evaluating the net benefits of a bridge remaining open and the costs of providing the bridge. Only bridges with positive net benefits were recommended for reconstruction. Because the benefit-cost ratio (*B/C*) method is widely used by county engineers, it was illustrated in the study.

The following results were obtained from the benefit-cost analysis:

1. All high volume bridges (ADT ≥ 100) had a positive net benefit;
2. Some low-volume bridges (ADT < 20) should not be reconstructed because of low ADT over the bridges and the maintenance and reconstruction costs to the county exceeded traffic savings to the public;
3. Most middle-volume bridges (20 ≤ ADT < 100) should be rebuilt, but some should not because of the small change in kilometers and high maintenance and reconstruction costs.

The analysis supports the option of abandoning bridges, with a net gain to society.

The benefit-cost analysis indicates that every bridge with a positive net benefit should be reconstructed; however, budgets available to most local governments are limited. A MIP model was developed to maximize the total social benefit of all the county bridges subject to the budget constraint of a local government. The model evaluated all combinations of projects to select the set that yielded the optimal total social benefit under a budget constraint.

If funds are sufficient to rebuild all the bridges, the results from the budget constraint model will be the same as those from the benefit-cost analysis and the benefit-cost ratio method. If funds are insufficient, the net benefits and benefit-cost ratio methods will not necessarily give an optimal solution. A combination of small projects may yield greater benefits than a single large project; a bridge with higher benefit-cost ratio will not necessarily have priority over another bridge with a lower ratio. The budget constraint model will always find the optimal solution that maximizes the total social benefit.

The method presented can be used to estimate the costs of reconstructing bridges on degrading steams. It is useful for any state that borders the Missouri or Mississippi rivers in the United States (i.e., Iowa, Nebraska, Illinois, Tennessee, Arkansas, etc.). It also could be applied to other countries, or areas where degradation affects streams, such as the Yellow River in China. In the absence of degradation, the conventional procedure illustrated in the Baumel study (*11*) should be used to evaluate bridge replacement.

This research is based on limited data. The study demonstrates how to estimate the benefits and costs of reconstructing bridges crossing degrading streams, and how to select a combination of projects whose total social benefit is maximized subject to a budget constraint. The study should be viewed as a demonstration and not as a source of precise estimates for the study bridges. The limitations mentioned should be properly noted in any future study.

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