Deterioration of New York State Highway Structures

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The analysis presented here quantifies both the deterioration rate of New York State highway structures and the cost of that deterioration. The data used are from two complete cycles of condition inspections. The condition rating for the entire structure was used to estimate an overall deterioration rate, and the inspector's determination of the quantity of nine types of repairs needed was coupled with unit work costs from maintenance records to estimate the cost of all needed repairs. These backlogged repairs totaled $323 million in 1980 and were increasing at the rate of $39 million per year. This means that maintenance work worth at least an additional $39 million per year must be performed on New York State structures to halt the decline of their condition. A model of structure deterioration was developed from the data and used to predict future costs and condition should the current level of maintenance remain unchanged. It was inferred from the data that the rate of deterioration currently being experienced is considerably higher than that which existed before 1960.

The New York State Department of Transportation (NYSDOT) Highway Maintenance Division has been developing a maintenance management system for a number of years. One part of this system is the Highway Maintenance Information Service (HMIS)--a data base that contains records of all highway maintenance activities, including person hours, equipment hours, and materials expended as well as the quantity of work accomplished for each maintenance task. The Structures Design and Construction Division has developed a detailed inventory file of both state and local structures. In addition to this file, there is a continuing detailed inspection program of all structures; most state structures are inspected by state employees and most local structures by consultants.

Now that these data are available, they can be used to analyze existing maintenance operations in order to determine more-efficient ways of maintaining structures. Thus, the director of highway maintenance requested the Engineering Research and Development Bureau to initiate a research project to analyze existing data and develop a standard methodology by which maintenance operations could be periodically optimized to meet changing conditions. A study proposal for this project, entitled Optimizing Maintenance Quantity Standards for Structures, has been prepared and was recently approved by the Federal Highway Administration (FHWA).

While FHWA was reviewing this study proposal, the maintenance director also requested that some of the summary inspection data be analyzed and that visual aids be prepared to assist in FY 1981-1982 budget preparation. (New York's fiscal year begins April 1.) This work was undertaken as part of the Engineering Research and Development Bureau's Technical Assistance Program, which is meant to address problems that can be handled less formally than can those in the regular research program. It was considered a warm-up for the researchers, who could become familiar with some of the data with which they would be working and at the same time provide the needed information. As it turned out, the amount of data analysis and the information obtained were well beyond original expectations.

DATA ANALYSIS

The data available were summaries of inventory and inspection files for structures maintained by state employees. The total number built each year and the number given each of seven possible condition ratings or general recommendations (referred to hereafter as "ratings," for brevity) were analyzed first. A rating is one of seven values that represents an inspector's overall evaluation of a structure's condition, as follows:

7: Good Condition--few, if any, repairs required;
6: Minor Repairs Required--minor cracks and spalls, bearing adjustments, etc.;
5: Repairs Required--primary structural members and substructure in relatively good condition;
4: Structural Repairs Required--considerable structural reconditioning required;
3: Major Structural Repairs Required--in need of extensive reconditioning (may be posted for less than design load);
2: Poor Condition--serious deterioration of the primary structural members and/or substructure (normally posted for less than original design load); and
1: Very Poor Condition--may be closed to traffic (should be posted for reduced load) and requires major repairs or complete replacement in the very near future.

First, these data were used to plot the age distribution of the structures for 1980. This is shown in Figure 1, in which 6335 structures are represented (7400 structures have been identified as maintained by the state but complete data were not available for all at this time). The data were summed into five-year intervals to reduce the scatter and enhance visual presentation. This distribution is decidedly bimodal. The two peaks are obviously related to historic and economic events that affected not only New York State but the nation as a whole. Although many older structures have been replaced, the remnants of the original trends are still quite apparent.

Growth of automobile and truck use in both the state and the nation led to the first structure-building period, which reached its peak during the Depression, when public works became a nationwide program. The number of new structures declined during World War II, when materials and labor were dedicated to the war effort, and remained low for the decade after the war. The larger peak of recent structures coincides with the next great national road-building program--the Interstate system. Within this perspective, it is reasonable to surmise that the age distribution of New York's structures is likely to be typical of that of other states.

Next, the FY 1979-1980 inspection data were summarized. For each five-year interval, the mean of all ratings for all structures built in that interval was plotted versus the mean age for that group (Figure 2). A rather obvious linear trend appears for structures 15-80 years old. For younger structures, fewer points were available to show the trend, but it could be linear. Thus, two linear regressions, weighted to account for the bimodal age distribution, were calculated for these mean data points. The equations for these regressions for the structures 15-80 years old are shown in Figures 2 and 3. The facts that the trends appear linear and that a definite break shows in the trends are very important, and a complete explanation of their significance follows.

It was originally thought that the cause of the double-slope trend in Figure 2 could have been treatment by inspectors of the rating 7 as a special value, that is, one not retained for long for a new structure. As will be shown here shortly, this is

Figure 1. Structures maintained by New York State (based on 1979-1980 data).

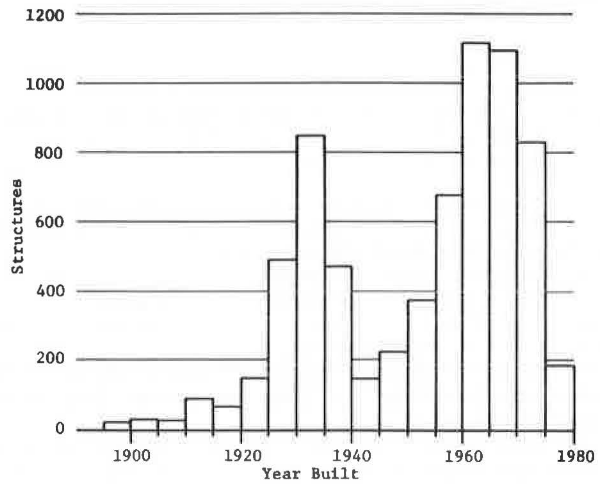


Figure 2. Rating versus age.

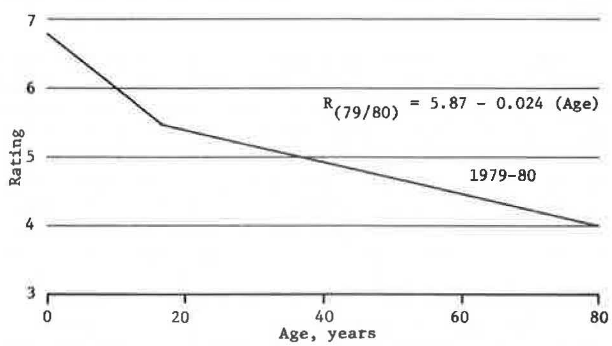
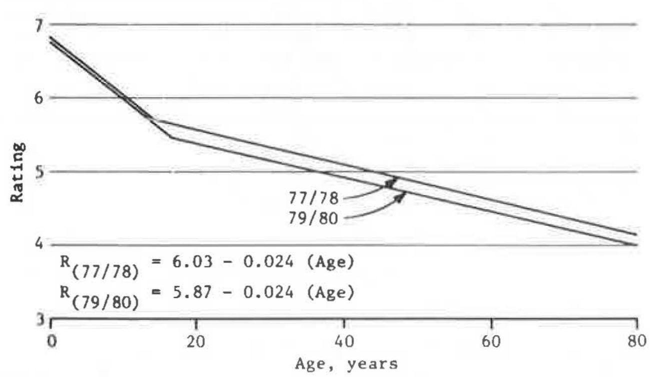


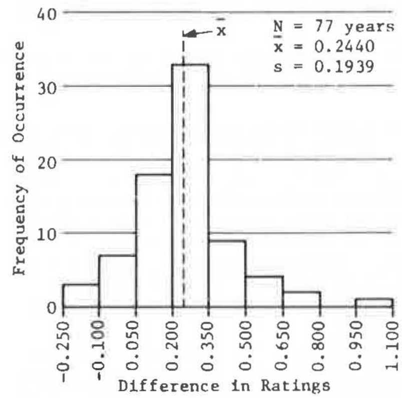
Figure 3. Rating versus age (two-year data).



not the case. Inspectors do not appear to have any bias against the rating 7. This graph could also be interpreted as showing rapid decay of newer structures followed by more-moderate deterioration after they have matured; this also proved incorrect when additional data were analyzed.

Figure 3 shows the regression through the inspection data from FY 1977-1978 with the regression from Figure 2. This fiscal year was chosen because the current inspection schedule requires two years to inspect all structures (only deficient structures rated 3 or less are inspected yearly), and earlier

Figure 4. Rating change between 1978 and 1980 inspections.



data were considered suspect due to inspector retraining during FY 1975-1976.

The fact that there are two distinct and parallel curves for structures more than 15 years old is extremely important. This indicates that a high rate of deterioration is now occurring--one that could not have been taking place for long. An average structure that was 30 years old in 1978 had a rating of 5.31, but two years later, in 1980, its rating was 5.10--an annual deterioration of 0.105. This represents the vertical separation between the curves plus two years down the curve. By taking paired differences between the two sets of data, the average annual deterioration for all structures was computed to be 0.122. This is the value used to predict the future condition of New York's structures, and the distribution of the difference in ratings is shown in Figure 4. (Note that negative values do occur. They are due to significant maintenance rehabilitation that occurred in some data pairs.)

What is shown in these data is the history of all maintenance, rehabilitation, and replacement of structures summed over the past 80 years. The regressions indicate that from 1900 to 1965 all structures on the average declined in condition at the rate of 0.023 rating points per year. Starting about 1965, all structures on the average began to decline in condition at a faster rate.

To translate this deterioration into cost terms, additional data were obtained. In each inspection, the inspector estimates the quantity of work required for each of nine maintenance tasks (known as Repairs Necessary). It was known from past experience that these nine tasks make up about three-fourths of the cost of maintenance. The amount of work required for all structures could be summed for each rating. By searching HMIS, the unit cost for each of these tasks was found. By multiplying the amount of each task required by its unit cost, summing, and then dividing by the number of structures, the average cost of Repairs Necessary for each rating was found to be as follows:

Rating	Avg Cost per Structure ($)
1	214 084
2	220 895
3	211 496
4	109 445
5	44 094
6	13 446
7	3 238

Average costs are plotted versus ratings in Figure 5; the costs have been increased by a factor of 4/3 to include all maintenance costs, not just the nine tasks. This plot is quite important. The cost of Repairs Necessary certainly does not increase linearly with declining condition. More than that, once a structure declines to a rating of 3, it incurs no further Repairs Necessary. This, in essence, implies that as a structure declines below a rating of 3 (at which it is already considered deficient) the amount of work needed to repair it does not increase. Apparently, the urgency of the work increases. This is accentuated by the fact that only about 3 percent of the structures rated 3 are posted for reduced load-carrying capacity, whereas 20 percent of those rated 2 and 100 percent of those rated 1 are so posted. The nonlinear increase of the cost of Repairs Necessary from 7 to 3 (which is nearly a pure exponential increase) argues very strongly in favor of early and preventive maintenance. Relatively modest expenditures to keep a structure at 5 or better will prevent much larger expenditures from being necessary at a future date.

Figure 5. Repairs Necessary costs.

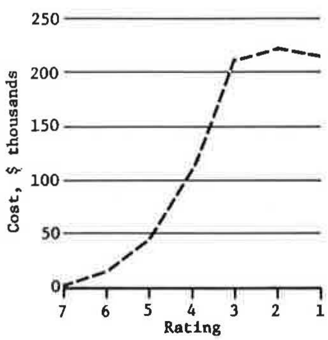


Table 1. Cost of Repairs Necessary in 1980.

Rating	No. of Structures	Avg Repairs Necessary per Structure ($)	Total Repairs Necessary ($)
1	60	217 490	13 049 000
2	170	217 490	36 973 000
3	296	211 496	62 603 000
4	931	109 445	101 893 000
5	1714	44 094	75 577 000
6	2192	13 446	29 474 000
7	972	3 238	3 147 000
Grand total			322 716 000

Table 2. Cost of Repairs Necessary for five-year intervals (1980 inspection data).

Interval	No. of Structures	Mean Rating	Repairs Necessary ($ 000 000s)	Avg Repairs Necessary per Structure ($)
1900-1904	34	3.91	4.1	120 489
1905-1909	30	3.87	3.6	121 142
1910-1914	90	4.13	9.3	103 090
1915-1919	71	4.25	7.0	98 088
1920-1924	156	4.21	16.5	105 700
1925-1929	494	4.55	41.5	83 951
1930-1934	856	4.80	61.5	71 889
1935-1939	477	5.01	28.4	60 680
1940-1944	155	4.92	10.3	66 334
1945-1949	200	5.22	10.0	49 805
1950-1954	307	5.18	17.5	56 982
1955-1959	593	5.35	27.1	45 673
1960-1964	884	5.34	41.7	47 195
1965-1969	1024	5.79	27.8	27 186
1970-1974	777	6.14	14.5	18 704
1975-1979	187	6.58	1.8	9 787

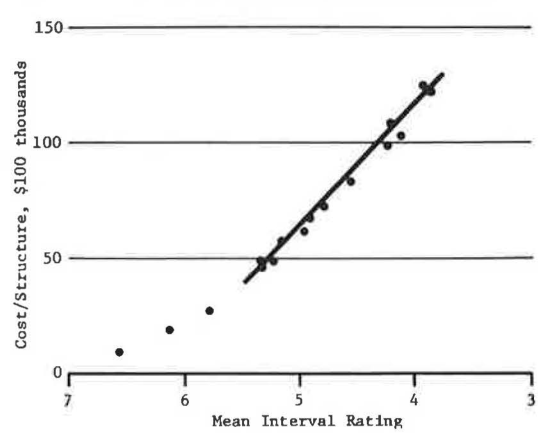
For purposes of calculating total costs of Repairs Necessary, those for each rating can be multiplied by the respective number of structures and summed. Thus, current costs for 1980 were calculated and are given in Table 1. This shows that, for the present condition, the cost of backlogged needed repairs is $323 million.

Because a specific number of structures exist that on the average will incur only $217 500 each in needed repairs when deficient, Repairs Necessary costs that can occur have an upper bound. This bound, when all 6335 structures are rated at 3 or less, has the value of $1378 million. In these terms, the current $323 million cost of needed repairs represents about 23 percent of the maximum.

The current rate at which backlogged repairs are accumulating can be determined by considering each of the five-year intervals as a subset of the whole population that possesses meaningful mean ratings and distributions of ratings about that mean. (Since the smallest interval contains 30 structures--and most contain more than 200--this is a reasonable assumption.) By multiplying the number of structures at each rating within each interval by the respective cost of Repairs Necessary and summing, the total cost for that interval is obtained.

For example, for the interval 1930 through 1934, there are 856 structures with a mean condition rating of 4.80. There are 49 structures rated 7, 223 rated 6, 279 rated 5, 184 rated 4, 73 rated 3, 33 rated 2, and 15 rated 1. The total cost of Repairs Necessary for this interval is calculated to be $61.5 million, or $71 889 per structure. Performing these calculations for each interval yields the data presented in Table 2 and the plot of cost per structure versus mean rating in Figure 6. This plot is obviously linear in the range of 3.8-5.4 (which includes the current mean rating of 5.26 for all structures) and has a slope of $50 458 per structure per change in mean rating. By the chain rule of calculus, this slope can be multiplied by the slope of rating versus time (already found to be -0.122) to get the slope of cost per structure versus time. That slope is $6156 per structure per year. Multiplying by 6335 structures yields the current rate of accumulation of Repairs Necessary--$39 million per year. This is the current yearly cost of deterioration that exceeds what is being corrected by maintenance, rehabilitation, and replacement. It can be

Figure 6. Cost per structure versus mean rating of intervals.



thought of as the amount of debt being incurred yearly, but just for this year. What will happen in the future is something else.

THEORETICAL MODEL

Although the calculations needed to produce these projections are not mathematically complex, the amount of work needed to calculate each point is quite time-consuming. In addition, the points themselves do not provide particularly clear insight into the process taking place. Thus, a theoretical model was sought.

The calculated values of the cost of Repairs Necessary are plotted in Figure 7. The increase in cost of Repairs Necessary results from deterioration of structures. It has already been shown that, as average condition declines, the distribution of structures that have each possible rating shifts to include more deficient structures. There are currently 526 deficient structures and, as previously shown, these structures have already reached their maximum costs and will make no further contributions to the total cost. (The projection conservatively estimates 507 deficient structures.) By 1990, more than 35 percent of the structures will be at their maximum cost. Thus, as accumulated costs increase, the structures available to contribute additional costs diminish. This reduction will halt the exponential rise in Repairs Necessary and eventually cause the rate of increase to decrease, which produces the S-shaped curve in Figure 7. But which S-shaped curve would make a good model?

A probability-curve model was suggested by the shape and is supported by the following analysis of the data. The plot of the average cost of Repairs Necessary versus rating shown in Figure 5 is not a continuous curve because of the discrete nature of the scale. A plot of the slopes of this curve (the derivative) is also discontinuous and looks like a histogram (Figure 8A). This curve, however, is of

Figure 7. Growth of total Repairs Necessary costs.

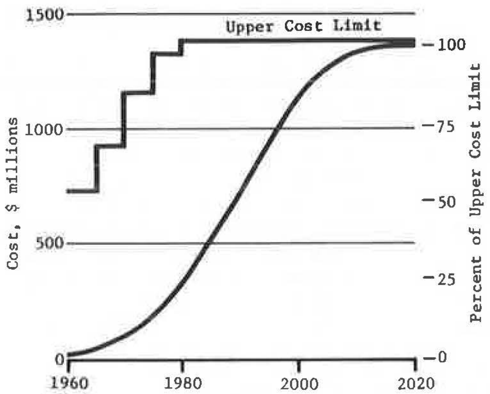


Figure 8. Sample plots.

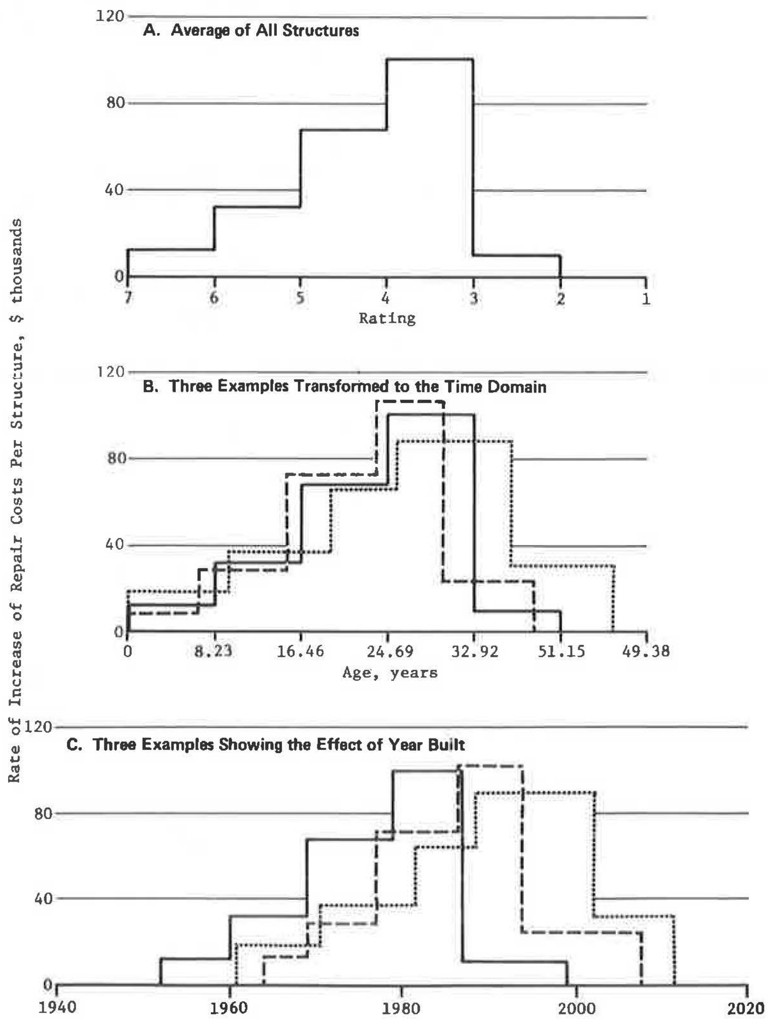


Figure 9. Growth of total Repairs Necessary costs.

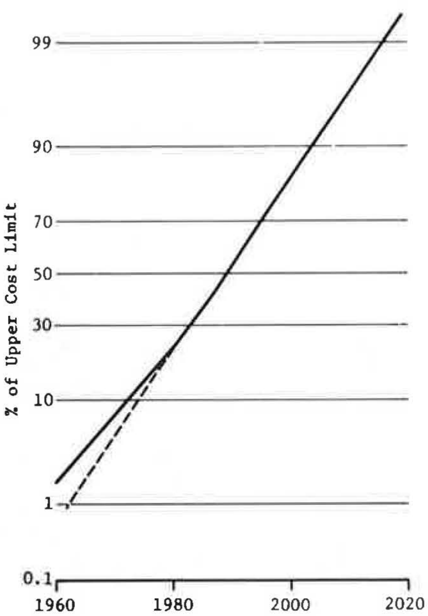
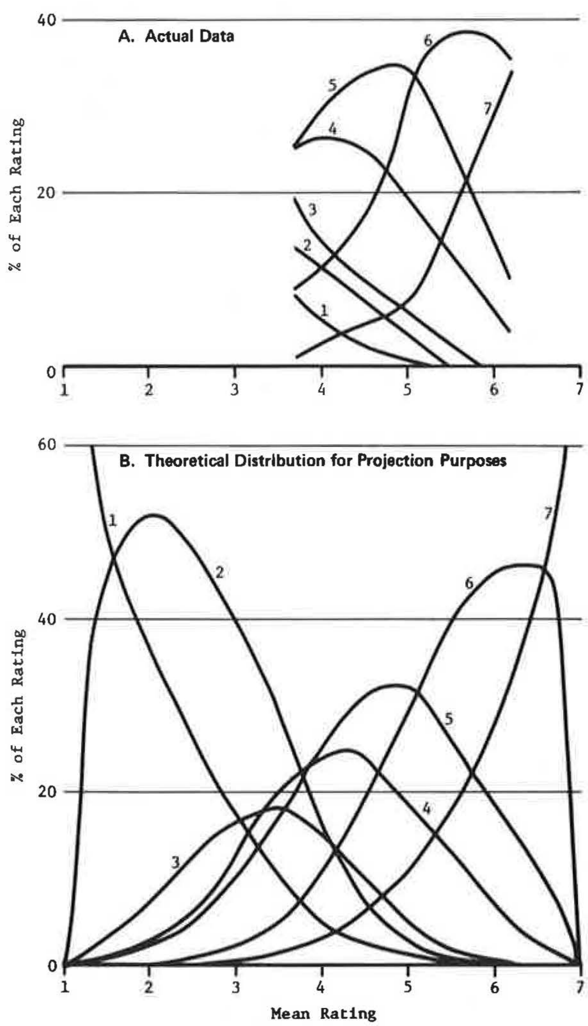


Figure 10. Distribution of ratings versus mean ratings.



no use in its present form because it is an average for all structures and not in the time domain. Three considerations are necessary before the proper curve can be derived:

1. Because this is an average plot, it must necessarily be made up from individual plots of each structure--some higher, some lower, and some with somewhat different shapes. Thus, there would be 6335 individual curves distributed in such a way that the plot in Figure 8A would be the mean.
2. Each of these 6335 plots must be transformed into the time domain. It has already been shown that the average annual deterioration rate is currently 0.122, so it would be possible to replace the rating interval with a time scale; each interval would be 8.23 years (Figure 8B). Since 8.2 years per change of rating is also an average value, it is possible to visualize that each of the 6335 individual curves (which already have different heights) has a different time for a rating-change interval. In fact, the interval need not even be constant throughout the structure's life. Now there are 6335 curves that have different heights and different lengths.
3. Each individual curve can be plotted on a calendar time scale that starts at the year when the structure was built. There are now 6335 curves that have different heights and lengths and start at 80 different times. Three examples are shown in Figure 8C.

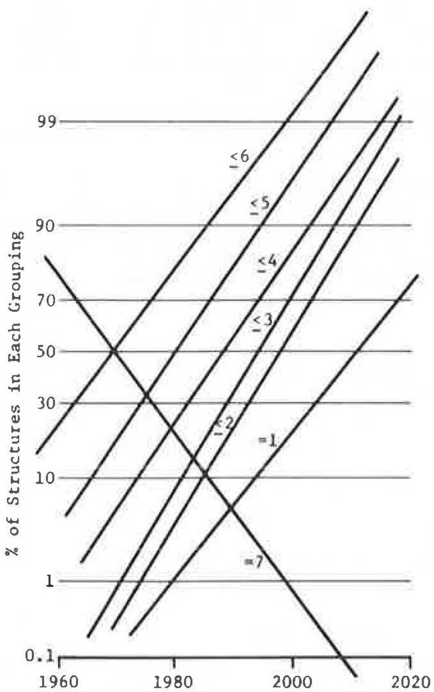
It is reasonable to assume that summing these 6335 curves will yield a normal distribution that represents the rate of increase of the cost of Repairs Necessary. If it does, its integral will be a cumulative probability curve that represents the total cost of Repairs Necessary over time.

Plotting the calculated values of Repairs Necessary on a normal probability yields a straight line that has little error from 1980 to 2010 (Figure 9). This straight line confirms that the data conform closely to a normal distribution within most of their range. This finding is quite significant because it is now possible to use standard statistical tables for simple and accurate calculation of both the accumulated cost and the rate of increase of Repairs Necessary.

A similar type of model was developed for distribution of structural condition. It was considered that decay of a group of structures that had a rating of 7 to a rating of 6 would follow an approximately normal distribution. This type of decay is suggested by Figure 10A. In fact, Figure 10B was derived by just such a model. No matter what the distributional form, the percentage of structures at 6 and below will be 100 percent minus the percentage that remain at 7 and would be symmetrical about the 50 percent level. By the same reasoning, the percentage at 5 and below would be 100 percent minus the percentage at 6 and 7. The data are plotted on a probability scale in Figure 11. They appear as a group of straight lines that have good fit between 5 and 95 percent. The probability model obviously does not apply at very high or low percentages or, more correctly, at the extremes of the rating scale. It would be theoretically neater if they were parallel, but at least they do not intersect within the range of interest. If they did, it would be tantamount to saying that the percentage $\leq$ 6 would be less than the percentage $\leq$ 5, an obviously illogical statement.

Plotting the difference between the straight lines in Figure 11 yields the percentage of structures at each rating over time (Figure 12). This clearly shows that most of the 7's are now gone and the 6's are starting to go, too. By the year 2000, the 3's will be peaking, and the growth of 1's and 2's will be phenomenal (235 per year); only 27 percent will be greater than 3. A full 73 percent (4225 structures) will be rated deficient (not functioning as originally designed). By using the current values of posting structures for reduced load (100 percent of the 1's, 20 percent of the 2's, and 3 percent of the 3's), a plot of the number of posted structures can be derived (Figure 13), which also plots as a straight line on probability paper.

Figure 11. Cumulative grouping of structures that result from the projection.



DISCUSSION OF RESULTS

Predicting Future Deterioration

The present annual rate of 0.122 was assumed to remain constant for the future. Although this rate of decay is disturbing enough, more information can be obtained by predicting the number of structures that will have each of the seven possible ratings at future dates.

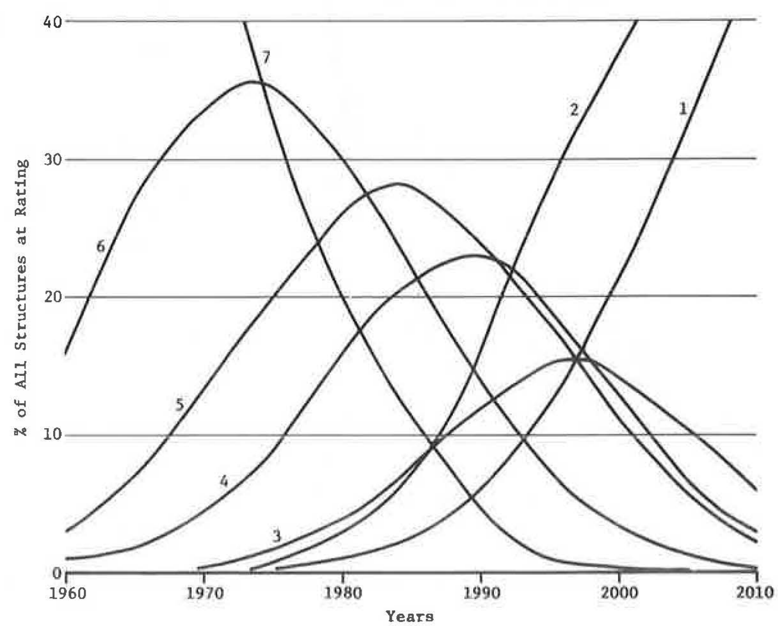
This was done by first analyzing the distributions of ratings for each five-year interval. These data (Figure 10A) indicate the change in the distributions of ratings versus the average rating for an interval. To predict what would occur in the future when the condition would be much worse, it was necessary to extrapolate these data. The resulting distributions are shown in Figure 10B. It was then possible to determine the distribution of ratings for any interval average condition.

To predict the situation in the year 1990, the average rating for each five-year interval was reduced by 1.22, and the distribution of ratings for the new mean was found from Figure 10B. The number of structures for each rating was then calculated by multiplying this distribution by the number of structures in the interval. Then all the intervals were summed, which yielded the total number of structures at each rating in 1990. The results of these calculations are given in Table 3. In line with these projections, the amounts that will be required in 1990 for Repairs Necessary (in millions of dollars) were estimated by rating number to be as follows: 1, 82.4; 2, 233.6; 3, 172.3; 4, 145.7; 5, 68.0; 6, 12.0; and 7, 1.0. This sums to $715.0.

Performing these same calculations for other years yields a graphic picture of what is happening to New York's highway structures. These data are summarized below:

Year	Rating	Repairs Necessary ($000 000)	Annual Rate of Increase ($000 000)
1960	6.96	13.6	4.0
1970	6.25	97.2	14.0
1980	5.33	317.8	31.0

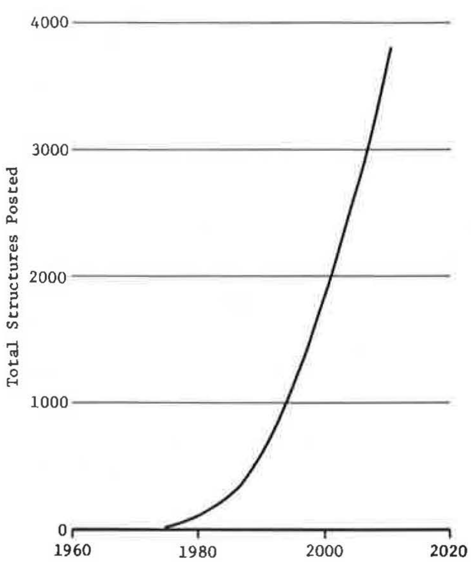
Figure 12. Projected distribution of ratings over time.



Year	Rating	Repairs Necessary ($000 000)	Annual Rate of Increase ($000 000)
1990	4.02	717.3	47.0
2000	2.64	1133.6	32.0
2010	1.67	1327.9	9.0
2020	1.36	1357.8	0.0

Figure 7 showed how the cost of backlogged repairs will increase without even considering inflation. In this decade, the amount will more than double if the same level of maintenance is continued. By the year 2000, it will have more than tripled. The increase of $39 million per year in backlogged repairs calculated for 1980 does not agree with this projection because the curve-fitting process used to extrapolate the data from Figure 10A to get Figure 10B caused considerable smoothing of the data. As seen above, the mean rating for 1980 was overestimated, and the total Repairs Necessary and rate of increase for 1980 were underestimated. All three are errors on the conservative side, so all projections will also be conservative. Total Repairs Necessary are accelerating with time, and the rate of change will peak before 1990. The projection indicates $47 million annually for that peak, but it could be well over $50 million annually.

Figure 13. Projection of structures posted.



As should be expected, as needed repairs are backlogged, the overall system condition declines. The mean rating will reach 3 in less than 20 years.

Significance for Maintenance Management

The calculations just performed are sufficient to explain what is happening to New York's highway structures and to indicate what in general should be done. Since it is only a macroscopic model, it cannot provide detailed answers such as which maintenance activities should have priority for funding. These answers will come only when the research project on quantity standards is successfully completed. Until then, the best judgments of maintenance managers will suffice. These calculations do, however, detail the rules of the game.

The current annual rate of increase of backlogged repair is $39 million and still increasing. The peak of this curve will be reached in 1989 when the annual rate of increase will reach a projected $47 million per year (probably higher). These figures represent the cost of additional repairs beyond those currently taken care of by maintenance forces and rehabilitation by contract.

This means that the deterioration of the overall condition of the state's structures can be stopped today by doing additional repairs equivalent to $39 million at 1979 maintenance unit prices. This additional amount of work will have to be done yearly over the long term. The overall average rating will then stabilize at the current value of 5.26. If action is delayed until 1989, the yearly effort required will be $47 million or more to stabilize the average rating at about 4.20. From then on, it would require progressively less annual expenditure to maintain a progressively worse average condition. Thus, the cost of delay is high.

These calculations give no indication of how the work should be divided between increased Highway Maintenance Division efforts and rehabilitation by contract. The data presented here show that state maintenance forces should be able to rehabilitate an average deficient structure for about $217 500 at 1979 prices. The Structures Design and Construction Division estimated that contract rehabilitation averaged $450 000 per structure at 1977 prices. If we consider inflation between 1977 and 1979, it is apparent that contract rehabilitation costs about three times as much. Thus, the cost of this needed work will range from $39 million annually if it is

Table 3. Projected 1990 distribution of structures.

Interval	Avg Rating	No. of Structures	No. of Structures for Each Rating						
			1	2	3	4	5	6	7
1900-1904	2.74	34	7	15	5	3	3	1	0
1905-1909	2.87	30	6	13	5	3	3	0	0
1910-1914	2.99	90	15	37	14	12	9	2	1
1915-1919	3.12	71	11	27	12	10	9	2	0
1920-1924	3.25	156	21	54	26	26	22	5	2
1925-1929	3.37	494	58	155	86	90	78	21	6
1930-1934	3.50	856	86	240	154	171	150	43	12
1935-1939	3.62	477	42	120	82	100	93	31	9
1940-1944	3.75	155	12	35	26	34	33	12	3
1945-1949	3.88	200	13	39	32	46	46	19	5
1950-1954	4.00	307	15	52	46	74	77	34	9
1955-1959	4.13	593	26	87	82	142	157	77	22
1960-1964	4.25	884	33	108	110	212	248	133	40
1965-1969	4.58	1024	24	69	95	238	319	210	69
1970-1974	5.03	777	9	21	37	145	246	230	89
1975-1979	5.48	187	1	2	3	25	49	74	33
Total		6335	379	1074	815	1331	1542	894	300

all done by state forces to $117 million if it is all done by contract.

If the state fails to meet this challenge, it will soon become evident. On the average, there is one structure for every three miles of roadway. These structures are becoming deficient at a rapid rate. One-half will be deficient by 1994 and 74 percent by 2000. Posting for reduced load lags behind this, but by 2000 nearly one-third will be posted. This means that a posted structure (one unable to carry a large truck safely) will be encountered on the average of every 10 miles. The impact of this on the state's economy will be significant. These findings are summarized for several selected years as follows:

Year	No. Rated 3 or Less	No. Posted	Avg Miles Between Posted Structures
1980	507	109	174
1990	2280	606	31
2000	4688	1838	10
2010	6018	3738	5

Possible Causes of Accelerated Deterioration

The following possible causes of accelerated deterioration were investigated for compatibility with the trends found:

1. Environment: Air pollution is known to attack and damage stone, concrete, steel, etc. However, a serious air pollution problem has existed since well before 1965. In recent years, there has actually been some improvement. This is not compatible with the increasing rate of decay. Thus, acid rain included, the environment is not considered a likely cause.
2. Design and construction: It seemed possible that new designs that incorporate defects and/or poor quality control during construction could lead to increased deterioration. Since structures of all ages are experiencing this accelerated decay, this does not match the trends and was discounted as a probable cause.
3. Dilution of maintenance: An increasing number of structures, inflation, and budget restrictions combine to increase the maintenance workload and make it difficult at best to meet the challenge. The increase in the number of structures is documented in Figure 1, and the building program of the 1960s and early 1970s occurs at the right time to be a possible cause. Serious problems with inflation and budget restrictions are more recent but are at about the right time to take over where the increase in number of structures left off. Thus, dilution of maintenance is considered a possible cause.
4. Snow-and-ice control: In the early 1960s, New York embarked on a bare-pavement policy. This increased the use of chloride chemicals for the purpose of improving safety and traffic operations during and after snow-and-ice storms. It is well known that chlorides damage both portland cement concrete and steel, perhaps more than has been suspected. The timing is right, and it would affect structures of all ages. Thus, it should be considered a possible cause.

These last two possible causes may have combined and compounded the deterioration problem, but at present there is only inference to suggest it. The data analyzed in this paper are insufficient to determine cause. Conclusive data, in fact, may not exist.

CONCLUSIONS

1. New York's structures are experiencing accelerated deterioration. The current rate of decay appears to be five times the historical rate, and this may increase still further.
2. A rapid response to this problem is needed to prevent an unacceptable decline in the condition of structures, with its attendant economic consequences. An annual expenditure of about $39 million ($6150 per structure) by state maintenance forces would halt the decline and hold the structures in their current condition. If done by contract, this work would cost slightly more than $117 million annually ($18 450 per structure).
3. Preventive maintenance applied to structures in good condition appears to be a very cost-effective strategy.

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