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FORECASTING PAVEMENT REHABILITATION NEEDS FOR THE ILLINOIS INTERSTATE HIGHWAY SYSTEM

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ABSTRACT

The Illinois Interstate highway network is deteriorating rapidly due to its age and heavy truck loadings. Unfortunately, the funds required for rehabilitation far exceed the available funds. The Illinois Department of Transportation (IDOT) faces many difficult decisions concerning prioritizing rehabilitation projects and anticipating future pavement conditions and rehabilitation needs.

To assist IDOT in making these decisions, three analyses were conducted using the ILLINET pavement network rehabilitation management program. The first of these was an analysis of the accuracy of ILLINET's pavement condition prediction models. The second was an analysis of the remaining life of each of the more than 1200 pavement sections in the Illinois Interstate network. The third was a comparison of the rehabilitation needs predicted by ILLINET to IDOT's latest multi-year program. The results of these analyses are of immediate practical use to IDOT in forecasting pavement rehabilitation needs for individual pavement sections, Interstate routes, and the entire Interstate network.

Key words: Pavement management, network, rehabilitation, programming, prediction.

INTRODUCTION

The Illinois Interstate highway system consists of about 1750 two-directional miles of heavily trafficked multiple-lane pavements which were constructed largely between 1957 and 1980. About one third of these pavements were originally constructed as 10-in [25.4 cm] jointed reinforced concrete pavement (JRCP), and about two thirds were originally constructed as continuously reinforced concrete pavement (CRCP) ranging in thickness from 7 to 10 inches [17.8 to 25.4 cm].

These pavements have performed very well despite Illinois' wet-freeze climate, poor subgrade soils, the prevalence of nondurable aggregates, and an unexpectedly high volume of heavy truck loadings. A recent survival analysis indicates that the mean life (years from construction to first major rehabilitation) of these pavements was about equal to the design life of 20 years, while the mean 18-kip [8.1 metric ton] equivalent single-axle loadings (ESALs) carried was three to four times higher than the design traffic. [1]

The Illinois Interstate system is now deteriorating rapidly due to its age and high volume of heavy truck loadings. As of 1991, about 60 percent of the system had been resurfaced, and much of the rest either is currently in need of rehabilitation or will be within the next ten years. Unfortunately, the funds required for rehabilitation far exceed the available funds. The Illinois Department of Transportation (IDOT) faces many difficult decisions concerning prioritizing rehabilitation projects and anticipating future pavement conditions and rehabilitation needs.

In 1985, IDOT began working together with the University of Illinois to develop the Illinois Pavement Feedback System (IPFS). A major part of the IPFS project has been the development of the IPFS database, which provides IDOT districts and central offices with data on design, construction, traffic, and condition of 1263 Interstate highway sections. Although the IPFS database is neither error-free nor complete, it is sufficiently developed for use in analyses which will provide useful answers to many of IDOT's questions. In addition to the survival analysis mentioned above, other analyses conducted with the IPFS database include assessment of truck traffic growth rates and development of performance prediction models.

Another major component of IPFS is the ILLINET pavement rehabilitation network management program. ILLINET uses data from the IPFS database, decisions trees, performance prediction models, and a variety of project-level and network-level management algorithms to generate feasible rehabilitation strategies (treatments and timing) for each pavement section in the Illinois Interstate network for a period of up to 10 years. The network management algorithm options available in ILLINET include analysis of needs (assuming an unconstrained budget), ranking, benefit-cost ratio, incremental benefit-cost ratio, and long-range optimization. The development of ILLINET and its capabilities are described in References 2 and 3.

Because of the large mileage of Illinois Interstates which will need rehabilitation in the coming years and the expectation that funding for rehabilitation will be inadequate, the Illinois DOT is very concerned about being able to anticipate the potential impact of insufficient rehabilitation funding on the overall condition of the network. Among the specific questions IDOT would like to answer are the following:

- "How accurately can we predict the future condition of individual pavement sections and the future condition of the network as a whole?"
- "How uniform are the various Interstate routes in condition? Is it feasible to manage long corridors of Interstate as units, or must we continue piecemeal rehabilitation of more than a thousand short highway sections?"
- "How well are our rehabilitation needs met by the funds available? What will be the effect of the programmed funding level on the overall condition of the network?"

Three analyses recently conducted to assist IDOT in answering these questions are described in this paper. The first of these was an analysis of the accuracy of ILLINET's pavement condition prediction models. The second was an analysis of the remaining life of each of the 1263 pavement sections in the Illinois Interstate network. The third was a comparison of the rehabilitation needs predicted by ILLINET to IDOT's latest multi-year rehabilitation program. The purpose of these analyses is to demonstrate the practical benefit that a network rehabilitation program with ILLINET's capabilities can provide a state highway agency in quantifying rehabilitation needs and prioritizing rehabilitation projects.

ACCURACY OF PAVEMENT CONDITION PREDICTION MODELS

The Illinois DOT evaluates pavement condition using Condition Rating Survey (CRS) values, which are assigned by panels of expert raters in field inspections conducted in even-numbered years. CRS is the key pavement condition indicator which is used for planning, programming, and scheduling highway pavement improvement projects. Pavements are rated on a 1 to 9 scale, based on the distress observed. The best rating is 9, which is assigned to a newly constructed or resurfaced pavement. For guidance in assigning CRS ratings, panel members consult a manual which illustrates various pavement types and conditions with photographs, accompanied by distress descriptions and CRS ratings.

In general, a pavement whose CRS falls below 6 would be programmed by IDOT for rehabilitation within the next five years. However, many sections have CRS ratings below 6 because their rehabilitation must be deferred due to lack of funds. Some pavements require considerable maintenance to keep the CRS above 5; below this level ride quality is generally very poor, and maintenance needs become more extensive.

CRS Models

ILLINET contains models to predict CRS for the following pavement types:

- Jointed reinforced concrete pavement (JRCP)
- Continuously reinforced concrete pavement (CRCP)
- Asphalt concrete overlay of JRCP (JROL) and CRCP (CROL)

Each predictive model was developed from in-service pavement condition data. After considerable evaluation of different possible model forms, the following functional form was selected for the CRS models:

$$CRS = 9 - a * THICK^{b} * AGE^{c} * CESAL^{d} \tag{1}$$

This nonlinear model form may also be expressed in the following linear form by logarithmic transformation:

$$\log_{10}(9 - CRS) = a + b*\log_{10}THICK + c*\log_{10}AGE + d*\log_{10}CESAL \tag{2}$$

where CRS = panel Condition Survey Rating (1-9)

THICK = slab thickness for JRCP or CRCP, overlay thickness for AC overlay

AGE = years since construction or overlay

CESAL = accumulated million ESALs in outer lane since construction or overlay

a, b, c, d = constants for each pavement type (see Table 1)

CRS Model Calibration

Within a certain climatic range (i.e., Illinois conditions), pavements of a certain type and design can be expected to exhibit a general trend in condition as a function of time and traffic loadings. However, even pavements of a single type and design can exhibit highly variable performance. Therefore, the prediction model must be calibrated to the observed condition of a specific section in order to accurately predict the performance of that section.

In other words, if the actual current condition of a given section differs from the CRS predicted by the model (as it almost certainly will, since the model describes the mean performance of all sections of that pavement type), then the prediction curve must be adjusted to match the actual value. If this calibration is not done, future conditions predicted by the model for that section will not be reasonable.

Two different methods for prediction model calibration are available. The first method basically involves shifting the prediction curve upward or downward so that it passes through and extrapolates from the actual known pavement condition (e.g., CRS). The extrapolated curve is parallel to (thus, predicts the same rate of deterioration as) the mean curve. This approach inherently assumes that the data on age and past accumulated traffic are accurate but that the specific section's performance differs from the predicted mean performance.

The second calibration method uses the actual current condition (e.g., CRS) and the current annual traffic level to "backcast" values for the age and/or past accumulated traffic inputs which will predict a condition level matching the actual value. This method, which shifts the mean curve horizontally forward or backward until it passes through the actual known condition level, is particularly appropriate when the accuracy of the age or past traffic data is questionable.

This latter calibration method is currently used in ILLINET due to the uncertainty associated with estimating accumulated ESALs. The current annual ESALs in the outer traffic lane may be estimated more reliably from current or recent counts of the average daily traffic (ADT), single-unit trucks (SU), and multiple-unit trucks (MU). A direct relationship is assumed to exist between pavement age, annual ESALs (ESALPYR), and cumulative ESALs:

$$CESAL = AGE * ESALPYR \tag{3}$$

The CRS model for a given pavement type may be calibrated to the current condition of any given section of that type in any year by calculating the following two calibration constants:

$$C_1 = \left[\frac{9 - CRS}{a * THICK^b * ESALPYR^d} \right]^{\frac{1}{c + d}} \tag{4}$$

$$C_2 = C_1 * ESALPYR \tag{5}$$

Once the model has been calibrated to the current condition of the section, the condition of the section in any future year may be predicted as a function of the change in the age of the pavement in years (ΔYEAR) and the change in millions of accumulated ESALs (ΔCESAL) over that time period:

$$CRS_{future} = 9 - a * THICK^{b} * (C_1 + \Delta YEAR)^{c} * (C_2 + \Delta CESAL)^{d}$$

The increase in millions of accumulated ESALs over some future time period is computed using the current annual ESALs (ESALPYR), the length of time (ΔYEAR), and an assumed annual ESAL growth rate. A compound growth rate of 6 percent is used as a default in ILLINET, though this value may be changed at the user's discretion.

Accuracy of CRS Prediction for Pavements Without D Cracking

The first step in assessing the accuracy of the CRS prediction models was a comparison of the 1992 CRS values predicted by the models with the actual 1992 CRS values assigned by the expert rating panels. This was done using CRS history, pavement design, and traffic information retrieved for each of the 1263 Interstate sections in the IPFS database.

For each section, the appropriate model for the pavement type was calibrated to the actual 1990 CRS, and the CRS was projected from that point assuming a 6 percent compound growth rate in ESALs. This comparison showed that the models predicted the CRS well from 1990 to 1992 for bare JRCP, bare CRCP, AC-overlaid JRCP, and AC-overlaid CRCP without D cracking. These results are illustrated in Figure 1.

To assess how many years into the future the CRS models could predict accurately, the comparison of predicted and actual 1992 CRS values was repeated with models calibrated to 1988 CRS data, and then to 1986 CRS data. Sections which were rehabilitated between the starting year and 1992 were excluded from the analysis. The results for pavements without D cracking indicate that the models' predictive accuracy is good even for six years into the future. Analysis of the models' accuracy for longer time periods could be done, but there is a limitation: the predicted and actual CRS values can only be compared for sections which do not receive any rehabilitation during the time period considered. For periods of eight years or more, the number of sections available for use in the analysis becomes considerably smaller.

Accuracy of CRS Prediction for Pavements With D Cracking

The drop in CRS from 1990 to 1992 was generally greater for D-cracked pavements than the models predicted. When the CRS models were developed in 1986, a D cracking variable was not included, primarily because the D cracking data contained in the IPFS database at that time was not considered sufficiently reliable.

In 1991, a thorough review of the D cracking data in the database was conducted, using distress survey results, materials records, and previous research results. This review was done in order to conduct survival analyses of bare and resurfaced concrete pavements in Illinois with and without D cracking. [4] One finding of the survival analysis was that both bare and overlaid pavements without D cracking lasted longer and carried more truck traffic than D-cracked pavements of the same type and thickness. The mean life (age and accumulated ESALs) was 20 to 50 percent higher for non-D-cracked pavements than for D-cracked pavements of the same type and thickness.

To account for the more rapid deterioration of D-cracked pavements, an analysis was conducted to determine an appropriate adjustment to apply to the predicted rate of loss in CRS. This was done for four pavement categories (bare JRCP, bare CRCP, AC-overlaid JRCP, and AC-overlaid CRCP, all with D cracking) by comparing predicted to actual 1992 CRS, using CRS data sets from 1990, 1988, and 1986. The following adjustment factors were found to give the best fit over the time ranges considered:

Adjustment Factor	Pavement Category
1.2	Bare JRCP
1.2	AC-overlaid JRCP
1.2	AC-overlaid CRCP
1.5	Bare CRCP

An alternative to applying these adjustment factors to the rate of CRS loss for D-cracked pavements would be to repeat the regression of the CRS models with an additional term for D cracking. However, the use of adjustment factors may be preferable because IDOT personnel will be able to modify the factors as needed in future years to maintain good fit of predicted to actual CRS, without having to conduct nonlinear regression analyses to modify the CRS models themselves.

REMAINING LIFE ANALYSIS

ILLINET was also used to predict the remaining life of each section of the Illinois Interstate network. The purposes of this analysis were to assess the overall health of the network and to examine the variability in remaining lives of pavements along the various Interstate routes. This knowledge would be useful to the Illinois DOT in assessing the feasibility of identifying corridors of multiple sections which could be brought up to uniform condition and subsequently managed as units in terms of future rehabilitation decisions.

Selection of Critical CRS

The "remaining life" of each Interstate section, defined as the number of years from 1993 until the section reached a CRS of 6.0, was predicted using the CRS models, calibrated to the 1992 CRS and adjusted for D cracking as described before, and assuming a 6 percent compound ESAL growth rate. This analysis was then repeated using a CRS of 5.1, which IDOT personnel felt might represent more realistically the level at which a pavement was likely to be rehabilitated (considering the typical budget limitations), even though CRS of 6.0 was the level at which rehabilitation would be desirable. Of course, the estimate of remaining life depends on the critical CRS selected.

Effect of Maintenance on CRS Prediction

The prediction of years remaining to CRS of 6.0 is reasonable in most cases; however, the prediction to lower CRS levels for any given section is highly dependent upon the level of maintenance applied. Many sections of Interstate highway receive extensive maintenance in order to keep the pavement in service until rehabilitation can be done. The CRS histories of such sections fluctuate between about 5 and 6 for several years, despite a previous steady decline from 9 to about 6. Of course it is difficult to predict accurately the rate of deterioration for such sections.

Remaining Life of Interstate Routes

The results of the remaining life analysis were plotted by Interstate route and direction. The results for portions of I-55 and I-70 are shown in Figures 2 and 3 as examples. The heights of the bars indicate the remaining life in years, and the widths of the bars indicate the relative lengths of each section. The numbers on the horizontal axis indicate the beginning mileposts of the sections, rounded to the nearest mile.

Some Interstate routes show reasonable uniformity in remaining life, while others show large variations. I-55 is an example of a route with large variations in remaining life. The non-overlaid pavement sections represented in Figure 2 range in age from about 15 to 30 years, and the overlays on some sections range in age from about 3 to 12 years. About half of the sections have D cracking, and thus have shorter predicted remaining lives than sections of similar design and traffic which do not have D cracking. Some large differences in remaining life by direction are also evident for some sections.

Among the routes with more uniform remaining life, some have fairly long remaining lives and others have fairly short remaining lives. I-70 is an example of route with uniformly short remaining life: the sections illustrated by Figure 3 are primarily 8-in [20.3 cm] CRCP with some 10-in [25.4 cm] JRCP, constructed between 1960 and 1972. Nearly all of these pavements have D cracking, which combined with the heavy truck traffic on I-70, has resulted in considerable deterioration of the concrete. All of these sections have been overlaid at least once since 1980 and some have been overlaid three times. It is understandably discouraging to Illinois DOT planners and district engineers to contemplate the future rehabilitation needs of such a long stretch of a heavily trafficked Interstate, which despite frequent rehabilitation and nearly constant maintenance, has only a few more years of remaining life.

Future Analyses of Remaining Life by IDOT

The remaining life analysis capability was added to the ILLINET program so that in future years, this analysis can be repeated easily by IDOT personnel, for the entire network or specific routes. The user only needs to select an ESAL growth rate and a critical CRS. The standard keyboard "page up" and "page down" keys are used to move through the Interstate route graphs displayed on the computer screen, and once a printer has been selected, the "shift" and "print screen" keys are used to print the displayed graph.

ANALYSIS OF REHABILITATION NEEDS VERSUS IDOT PROGRAMMING

The third analysis conducted was a comparison of the rehabilitation needs predicted by ILLINET and IDOT's proposed multi-year rehabilitation program. This analysis has actually been conducted four times: first with IDOT's improvement program for fiscal years 1991 to 1995, then for 1992 to 1996, 1993 to 1997, and most recently with the 1994-1998 program.

Proposed Highway Improvement Program

The multi-year program itemizes IDOT's proposed expenditures for Interstate highways, state highways, and other facilities in several areas, including pavement rehabilitation, bridge rehabilitation or replacement, major highway construction, and safety improvements. The programmed expenditures considered in this analysis were those for resurfacing and reconstruction of Interstate pavement sections. Programmed expenditures for patching, interchange reconstruction, and bridge reconstruction were excluded.

Rehabilitation Needs Analysis with ILLINET

One of several pavement network management algorithms programmed in ILLINET is the needs algorithm, which estimates the rehabilitation needs for up to ten years into the future, assuming no yearly budget constraint. Every section in the network whose condition falls below a user-defined minimum CRS is a candidate for rehabilitation. The type of rehabilitation is determined by selection of one of several available options for project-level rehabilitation. [2] For this analysis, the needs algorithm was run using a single thickness of asphalt resurfacing as the sole rehabilitation strategy. In fact, the rehabilitation type is not significant to this analysis, the purpose of which is to predict the timing of rehabilitation, not the cost. The analysis was run for three critical CRS levels: 6.0, 5.5, and 5.1.

Comparison of Rehabilitation Needs with Program by Route

The sections with rehabilitation needs identified by ILLINET and the sections programmed for rehabilitation by IDOT were graphically displayed by Interstate route and direction. A comparison for a portion of I-55 is shown in Figure 4 as an example. For each direction, the sections needing rehabilitation according to ILLINET are represented by the bars above the line representing the route, and the sections actually programmed by IDOT for rehabilitation are represented by the bars below the line. The numbers next to the bars indicate the beginning and ending mileposts, followed in parentheses by the year that rehabilitation is needed or programmed.

A summary of the mileage of rehabilitation needs identified by ILLINET and the programmed rehabilitation mileage is provided in Table 2. This summary indicates that the rehabilitation work programmed by IDOT with the anticipated available funds is only about 60 percent (939 miles versus 1570 miles [1502 versus 2512 km]) of the needs identified by ILLINET to keep all sections of the Interstate above a CRS of 6. If additional funding is not available, a large percentage of Interstate sections are predicted to fall below a CRS of 6.0 over the next five years. If the funds available for rehabilitation continue to fall short of the amount required to keep the pavements in acceptable condition, the backlog of deficient pavements will continue to grow. This will result in substantial maintenance expenditures and probably more costly rehabilitations as well. Of course, what constitutes an acceptable pavement or a deficient pavement depends on the target CRS level selected.

At a critical CRS of 5.5, the ratio is about 96 percent (939 versus 975 miles [1502 versus 1560 km]), and at a critical CRS of 5.1, the programmed mileage exceeds the needs indicated by ILLINET by about 39 percent (939 versus 676 miles [1502 versus 1082 km]). These results suggest that the rehabilitation funds programmed over the next five years should be sufficient to keep nearly all sections of the Interstate network above a CRS of 5.5 over that time period.

Limitations of the Needs Algorithm

ILLINET's needs algorithm was used in this analysis to identify projects which will reach the selected critical CRS and determine the total mileage of these projects. This algorithm was run using resurfacing as the single rehabilitation strategy. Hypothetically, the budget for rehabilitation is unlimited, so a section is resurfaced as soon as it reaches the critical CRS. This algorithm, particularly when run with a single rehabilitation strategy, does not necessarily develop the optimum rehabilitation plan for the network.

Indeed, what is an "optimum" plan depends on what benefit one chooses to maximize, or what cost one chooses to minimize. The needs algorithm basically seeks to eliminate the mileage of deficient pavements. It may do this in a manner which is not the most cost-effective for particular sections or for the network as a whole. For example, a severely deteriorated pavement which continues to deteriorate rapidly probably should not be resurfaced every few years; some longer-lasting rehabilitation strategy would be more cost-effective. Other analyses conducted for this research study and described in a separate paper indicate that very different network rehabilitation programs may be developed depending on the network-level management algorithm selected. [5] For example, in another analysis conducted using ILLINET, the incremental benefit-cost ratio algorithm produced a network rehabilitation program with the same total cost (in millions of dollars) as the needs algorithm, but with a 50 percent improvement over the needs analysis in vehicle-miles travelled on good pavements. This is because the incremental benefit-cost algorithm may pick more costly rehabilitation strategies for some sections if they are more cost-effective for the network as a whole, and also will favor rehabilitation of higher-volume routes, since the benefit which it seeks to maximize is vehicle-miles travelled on good roads.

Future Program-Versus-Needs Analyses by IDOT

The capability to compare IDOT's multi-year improvement program with the results of the needs analysis was added to the ILLINET program so that in future years, this analysis can be repeated easily by IDOT personnel, for the entire network or specific routes. The multi-year program of pavement rehabilitation and reconstruction projects simply needs to be entered in an ASCII input file with route, direction, and beginning and ending milepost data. The user only has to select an ESAL growth rate and a critical CRS.

CONCLUSIONS

The Illinois Interstate highway network is deteriorating rapidly due to its age and heavy truck loadings. Unfortunately, the funds required for rehabilitation far exceed the available funds. The Illinois Department of Transportation (IDOT) faces many difficult decisions concerning prioritizing rehabilitation projects and anticipating future pavement conditions and rehabilitation needs.

To assist IDOT in making these decisions, three analyses were conducted using the ILLINET pavement network rehabilitation management program. The first of these was an analysis of the accuracy of ILLINET's pavement condition prediction models. The second was an analysis of the remaining life of each of the more than 1200 pavement sections in the Illinois Interstate network. The third was a comparison of the rehabilitation needs predicted by ILLINET to IDOT's multi-year program.

The analysis of the CRS prediction models showed that future pavement conditions could be predicted with acceptable accuracy for several years into the future. The rate of deterioration for bare and overlaid concrete pavements with D cracking, which is more rapid than for pavements without D cracking, could be more accurately predicted using adjustment factors determined in this analysis. However, the effect of maintenance on pavement condition is difficult to predict.

The analysis of the remaining life of the Interstate routes demonstrated considerable variability along some routes, and more uniform remaining life along others. This type of information is needed to assess the feasibility of identifying corridors of entire routes or major components of routes which could be brought up to uniform condition and subsequently managed as units in terms of future rehabilitation decisions.

The comparison of rehabilitation needs indicated by the ILLINET software to IDOT's multi-year improvement program demonstrated that for any selected critical CRS level, a section-by-section and route-by-route comparison could be made of rehabilitation needs and rehabilitation funding. In this analysis, the IDOT program met only about 60 percent of the indicated needs when the critical CRS was set at a level below which IDOT personnel generally consider rehabilitation desirable. What constitutes an acceptable or a deficient pavement obviously depends on the critical CRS selected. However, even when rehabilitation costs are deferred due to budget limitations, maintenance costs continue to accrue and increase greatly as the pavement deteriorates.

The purpose of these analyses is to demonstrate the practical benefit that a network rehabilitation program with ILLINET's capabilities can provide a state highway agency in quantifying rehabilitation needs and prioritizing rehabilitation projects. The graphical displays and graphical printed outputs are useful in communicating the analysis results to central office and district personnel responsible for rehabilitation planning and programming.

The ILLINET software has also been modified to facilitate these analyses being repeated in the future by IDOT personnel. This represents another step in development of the Illinois Pavement Feedback System: after development of the database, after retrieval of data for specific analysis demonstrations, after demonstrating the practical value of the analysis results, user-friendly tools to do those analyses should be put into the hands of the IDOT planners and engineers responsible for pavement rehabilitation decision-making. A reliable and accessible database, reliable performance prediction models, and the tools required to do the analyses needed to support decisions are the essential elements of a dynamic feedback system for continuously improved pavement performance and efficient, cost-effective pavement network management.

ACKNOWLEDGMENTS

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Table 1. Constants for CRS prediction models.

log10 a

MODEL	CRS MODEL CONSTANTS			
	a	b	c	d
JROL, CROL	~~-0.1646~~ -0.1175	~~-0.0957~~ -0.1458	~~0.6124~~ 0.5732	~~0.1293~~ 0.1431
JRCP	2.0251	-2.7359	0.3800	0.6212
CRCP	1.0910	-1.3121	0.1849	0.2634
FLEX	1.456	-1.8720	0.5488	0.3385

Table 2. Summary of rehabilitation needs versus rehabilitation program.

District	ILLINET Needs			IDOT Programmed Miles	Total Miles Analyzed
	CRS = 6.0	CRS = 5.5	CRS = 5.1		
1	237.17	170.31	153.14	153.81	412.59
2	160.10	114.71	51.55	95.46	320.10
3	196.55	123.85	93.73	117.73	476.63
4	122.83	91.09	72.90	107.27	207.26
5	256.03	146.81	112.90	172.49	510.82
6	106.01	43.57	32.78	62.54	246.56
7	263.95	143.98	113.28	131.63	405.93
8	117.78	86.77	37.62	37.62	352.16
9	110.17	53.82	7.91	7.91	229.88
Total	1570.59	974.91	675.81	939.23	3161.93

Notes:

1. All miles are one-directional.

2. Ratio of miles programmed by miles needed (for critical CRS = 6.0) is 939.23 / 1570.59 = 0.60, or 60 percent.

3. District 2 has one resurfacing project programmed on I-180 (mileposts 5.43 to 9.76, both directions), which was not included in this comparison because I-180 is not currently in the IPFS database.

4. Only resurfacing and reconstruction projects programmed for 1994-1998 were considered in this comparison. Patching, interchange reconstruction, bridge reconstruction, etc. were excluded. Some projects let for bids recently may not be included. The latest bid letting information available was December 1992.

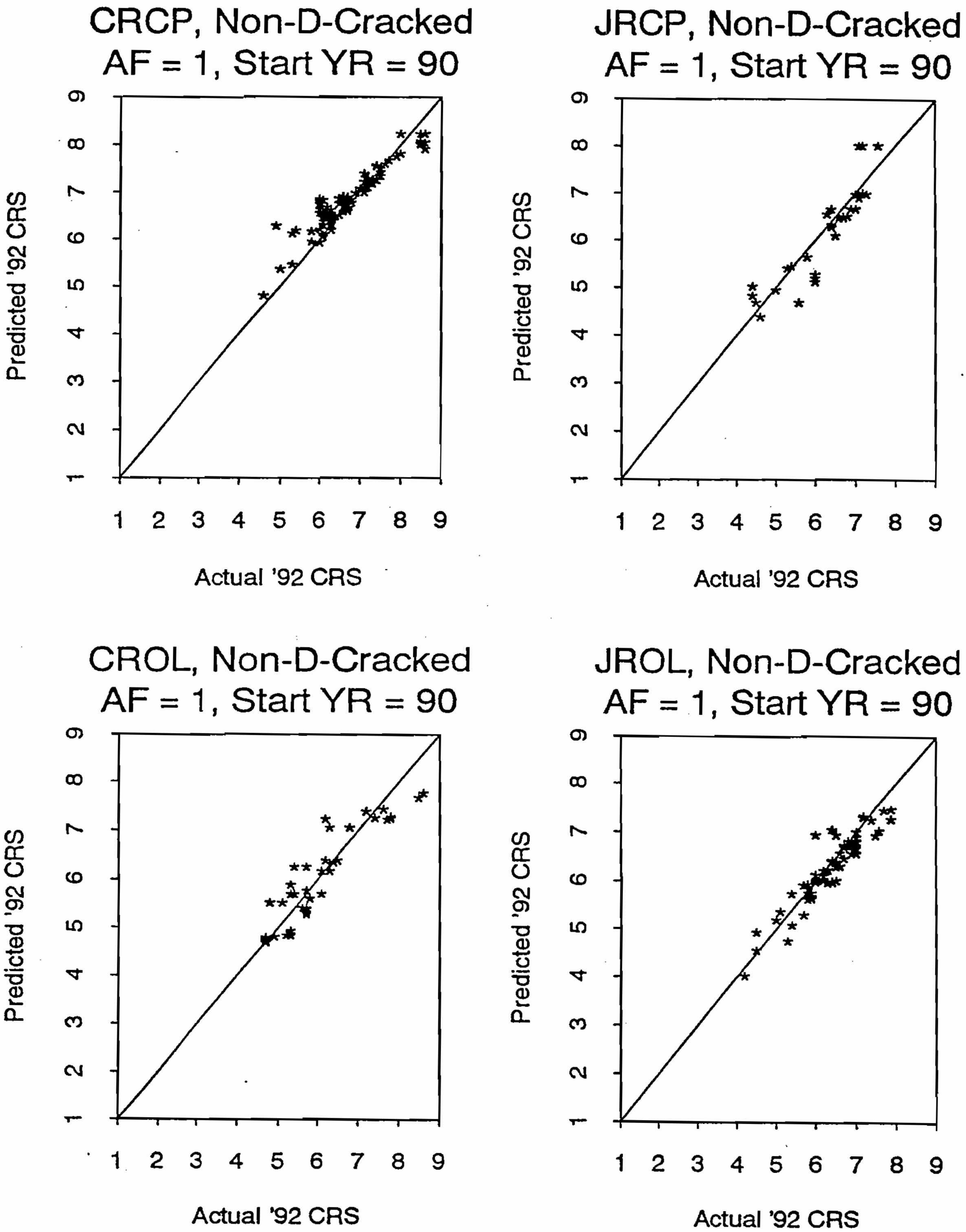
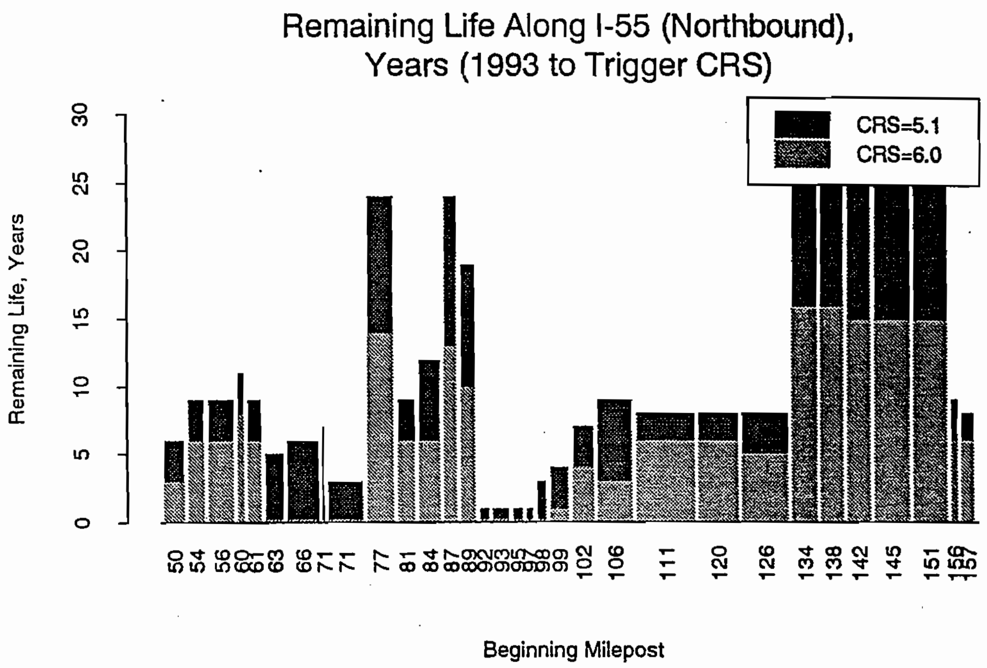


Figure 1. Predicted versus actual 1992 CRS for non-D-cracked pavements.



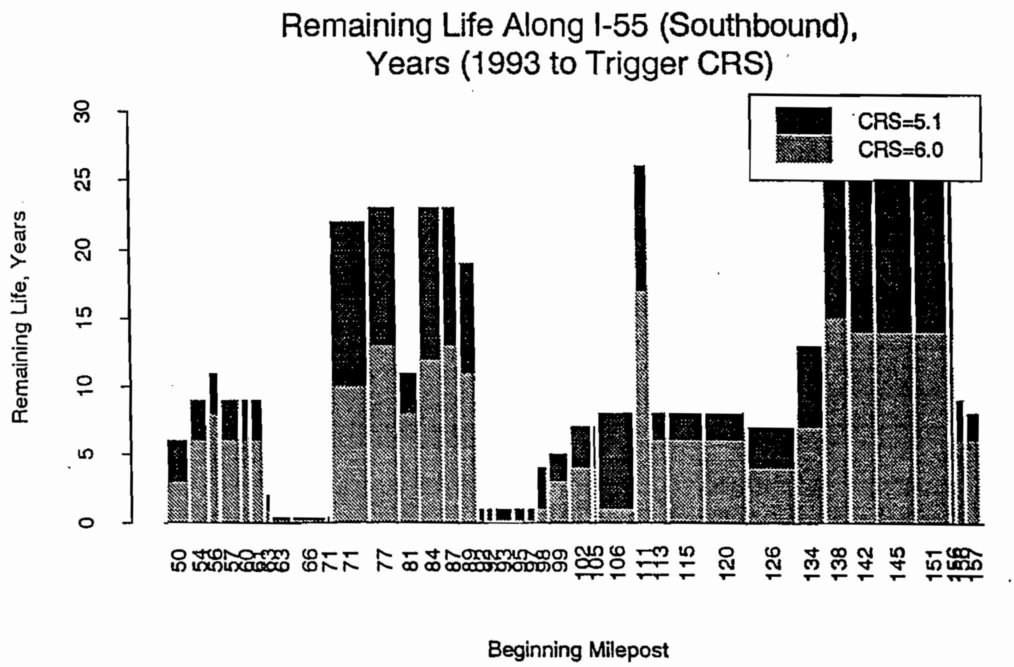
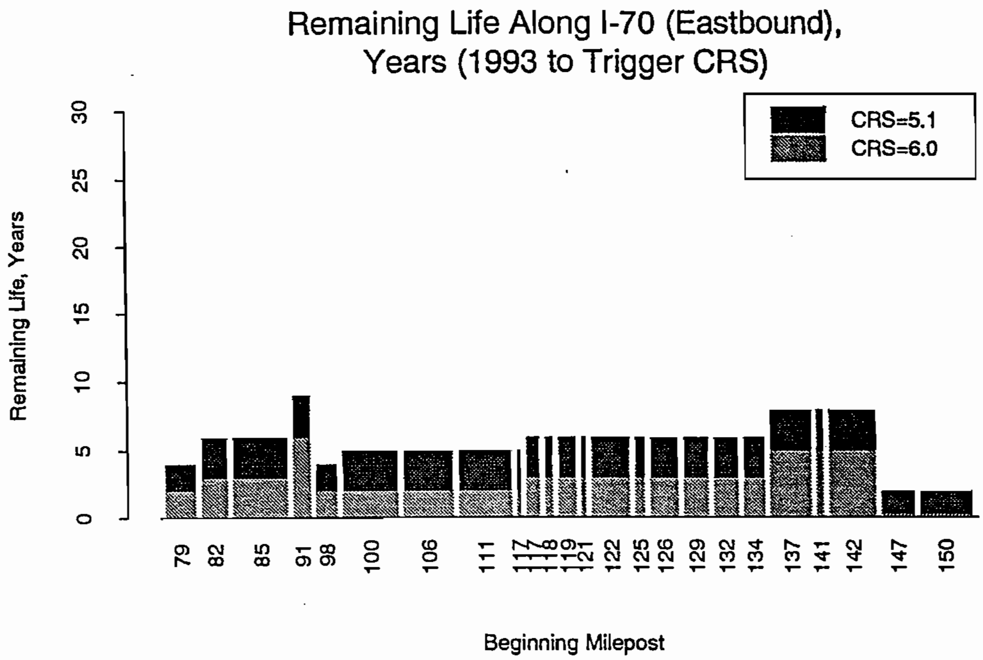


Figure 2. Remaining life of pavement sections along portion of Interstate 55.



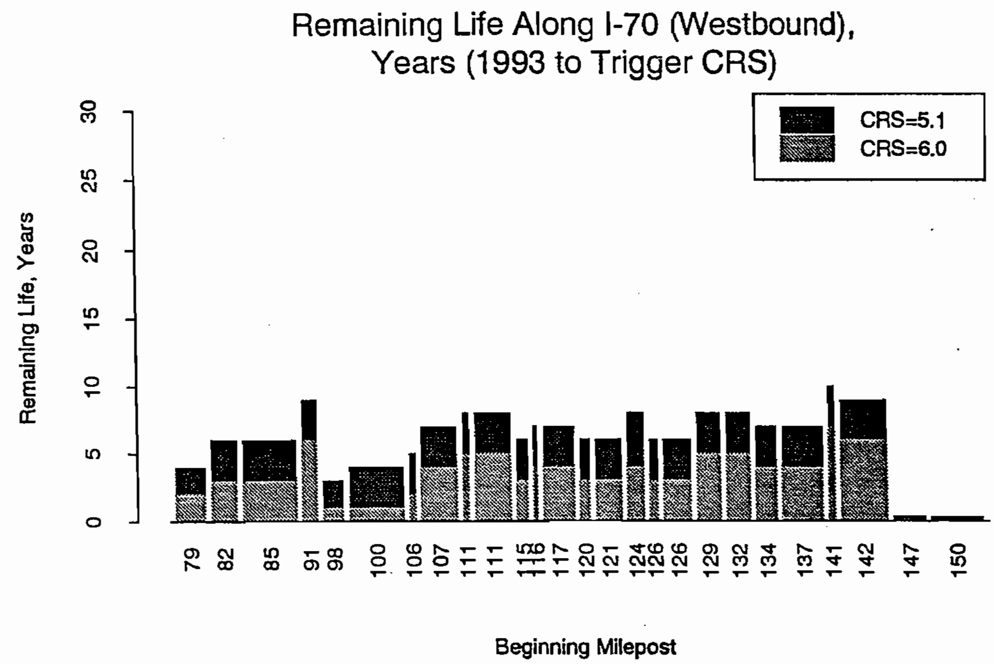
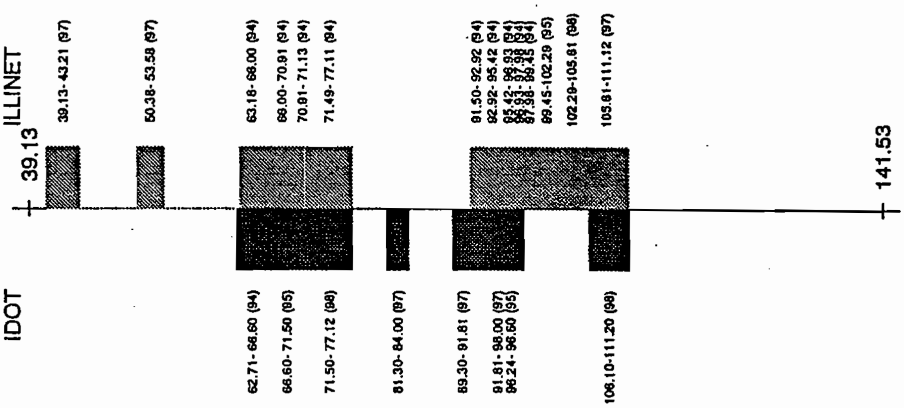


Figure 3. Remaining life of pavement sections along portion of Interstate 70.

ILLINET CRS=6.0 Needs vs. IDOT Programming '94-'98
District 6, Along I-55 (Northbound)



ILLINET CRS=6.0 Needs vs. IDOT Programming '94-'98
District 6, Along I-55 (Southbound)

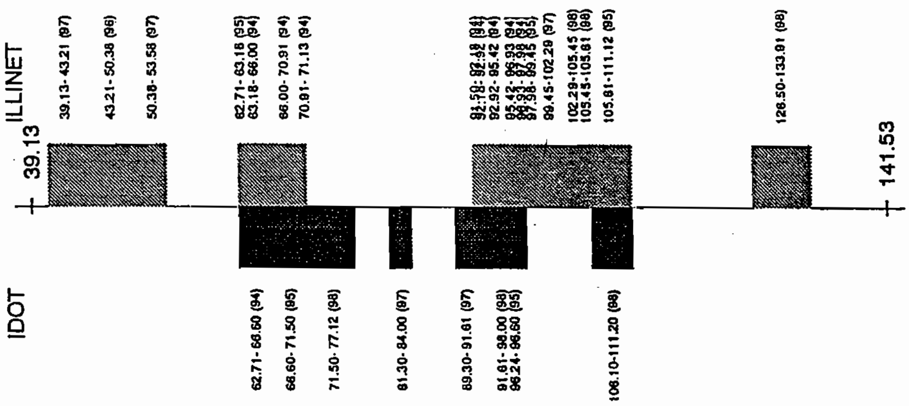


Figure 4. Rehabilitation needs (from ILLINET) versus rehabilitation programmed (from IDOT 1994-1998 program) for portion of Interstate 55.

ment type, functional group, and climatic zone as previously described. It is assumed that pavements within the same group more or less follow the same performance pattern. Thus, predictive models need only be developed for a few groups of conditions, as opposed to many different types of pavement design, functional system, climatic region, and rehabilitation type.

DEVELOPMENT OF PERFORMANCE PREDICTION MODELS

After considerable review of different regression techniques, it was decided that nonlinear regression should not be used to develop predictive models for the HPMS because of the high possibility of having many errors in the data base. Several trials using nonlinear regression produced unacceptable models largely due to including some bad data points in the analysis. Therefore, the following steps were adopted to develop predictive models:

1. A feasible general present serviceability rating (PSR) loss model form was assumed including variables based on engineering knowledge and available data bases.
2. Least-median-squares, or "robust," regression was performed to identify the potential outliers by using this assumed model form (*3,4*).
3. After screening out possible outliers, traditional least-squares regression was then used to obtain the regression coefficients and summary statistics.

Because it cannot be guaranteed a priori that the assumed functional form is valid, the analysis must proceed iteratively so that a more meaningful and reliable model can be developed. An alternating conditional expectations algorithm (*5*) was also applied to find other possible transformations of each explanatory variable to maximize the squared multiple correlation coefficient (R^2) for the next trial.

A new statistical package named S-PLUS, which has been widely used by statisticians for data analysis (*6–8*), was selected because of the availability of these techniques. S-PLUS is very strong in its graphics, data exploration tools, and flexibility but weak in data base management as compared with the most well-known and widely used statistical package, SAS (*9*). As a result, SAS was used primarily for data retrieval and data summary whereas S-PLUS was used for most of the modeling processes.

Attempts To Develop Models Directly from HPMS Data Base

Five sets of the HPMS data base in 1982, 1984, 1986, 1988, and 1989 were first retrieved from magnetic tapes (*1*) and downloaded to a personal computer (PC) for further analysis. To obtain the needed history of the HPMS pavement performance, the data were merged by their unique identification number, that is, sample number (Item 24) and sample subdivision (Item 25).

Initially, major research efforts were focused on developing predictive models directly from the HPMS data base using data from 1984 to 1989. Several feasible model forms were used to develop the performance prediction models. Robust regression successfully identified portions of the data base as potential outliers, which after deletion improved the regression dramatically. However, the regression models were still not adequate for implementation. This attempt was unsuccessful because of problems with the HPMS data base, such as missing data, highly variable performance histories, and apparent errors in many important data elements.

Alternative Data Bases for Model Development

Owing to the difficulties in developing prediction models directly from the HPMS data base, other accessible data bases were considered for developing PSR prediction models for each of the five major pavement types. They include the pavement management data base from the Illinois Department of Transportation, the Illinois portions of the NCHRP Project 1-19 data base (*10*), the original AASHO Road Test data (DS 7322) (*11*), and some additional data from the extended road test (1962–1974) (*12,13*).

The Illinois pavement management data base contains detailed information about pavement inventories, materials, distress surveys, condition rating surveys, maintenance and rehabilitation records, and traffic data. The most recent data (March 1991)—which contain six condition rating surveys, in 1981, 1982, 1984, 1986, 1988, and 1990—were obtained to construct data bases for CRCP and composite pavements.

The NCHRP Project 1-19 data base, which contains some existing Illinois Interstate JRCP pavements and sections from the original and the extended AASHO Road Test for JRCP, was used to construct a JRCP data base. The JPCP data base was constructed from the original and the extended AASHO Road Tests. The serviceability records of flexible pavements of the original AASHO Road Test at 22-week (or 11-index-day) intervals were obtained to create the data base for flexible pavement.

Proposed Predictive Model Form

After considerable evaluations of different model forms including linear, logarithm, and other simplified forms, the following functional form was chosen to develop the proposed HPMS predictive models for all five major pavement types:

$$PSR = PSR_I - a * STR^b * AGE^c * CESAL^d \quad (1)$$

where

- PSR_I = initial value of PSR at construction (4.5 used in analysis);
- STR = existing pavement structure: structural number for flexible pavement, total AC overlay thickness for composite pavements (in.), and slab thickness for concrete pavements (in.) (1 in. = 25.4 mm);
- AGE = age of pavement since construction or major rehabilitation (overlay) (years); and
- CESAL = cumulative 18-kip equivalent single-axle loads (ESALs) applied to pavement in the heaviest traffic lane (millions).

From: " Simplified Pavement Performance Models", by Ying-Haur Lee, A. Mohseni, M. I. Darter, TRR 1397 pp7-14. 1993

This nonlinear model form is also an implicit linear model since after transformation it becomes

$$\log_{10}(PSR_I - PSR) = \log_{10}a + b * \log_{10}STR + c * \log_{10}AGE + d * \log_{10}CESAL \quad (2)$$

This nonlinear model form permits a realistic consideration of age, traffic, and pavement structure on the prediction of PSR. Subsequent model development has shown that this equation form fits all of the pavement types reasonably well.

Note that the structural number is reported as an indicator of pavement structure for both flexible and composite pavements in the HPMS data base so that the AASHTO FLEX equation could be used to predict performance. However, composite pavements perform dramatically different from flexible pavements due to different failure modes. It is believed that the AC overlay thickness rather than the structural number or the underlying concrete slab thickness is the dominating factor in the performance of composite pavements. Thus, overlay thickness was used in the model development. The questionable determination of structural number for composite pavements is no longer needed in the HPMS data base since no adequate guidelines are available.

Summary of Proposed Predictive Models

The regression coefficients and summary statistics of each predictive model for all five major pavement types are summarized in Table 1. The standard error of estimates (*SEE*) as provided in the table is also a very good indicator of the accuracy of the prediction of the loss of PSR (ΔPSR). The number of potential outliers identified and then excluded from the model are also indicated by parentheses in the table. For example, 31 out of 553 data points were deleted from the FLEX model.

The statistics of the CRCP model are not very good as expected, since both D-cracked and non-D-cracked pavements from the Illinois Interstate highways were all included in the data base to develop this model. This model can be improved after more D-cracking information is collected in the HPMS data base.

To check the adequacy of each proposed model, the predicted ΔPSR values were plotted against the actual values as shown in Figures 1 through 5. Several sensitivity analyses of the variables included in each model were also performed and found to be very reasonable (*14*). In general, the PSR curves of FLEX, COMP, and CRCP are in a concave shape or have more rapid loss of PSR early. The PSR curves of JPCP and JRCP are in a convex shape or have more rapid loss of PSR later.

APPLICATION OF PROPOSED MODELS TO HPMS

Calibration of Models to Existing Pavement Conditions

On the basis of the proposed predictive models, a fixed family of curves could be developed for different pavement structures. Unfortunately, both age and cumulative ESALs are not available in the HPMS data base. Therefore, it is necessary to obtain the best estimates of pavement age and cumulative ESALs through knowledge of only the current annual ESALs and the current year condition of an existing pavement structure in the HPMS data base.

Assume that there is a direct relationship between pavement age and cumulative ESALs:

$$CESAL = AGE * ESALPYR \quad (3)$$

where ESALPYR is current yearly ESALs in millions.

TABLE 1 Summary of Proposed Predictive Models

	Model				
	FLEX	COMP	JPCP	JRCP	CRCP
$\log_{10}a$	1.1550	-0.4185	0.5104	1.7241	0.7900
b	-1.8720	-0.1458	-1.7701	-2.7359	-1.3121
c	0.3499	0.5732	1.0713	0.3800	0.1849
d	0.3385	0.1431	0.2493	0.6212	0.2634
R^2	0.52	0.58	0.79	0.57	0.37
SEE	0.45	0.38	0.26	0.40	0.31
N	522 (31)	509 (0)	117 (3)	254 (21)	1204 (65)

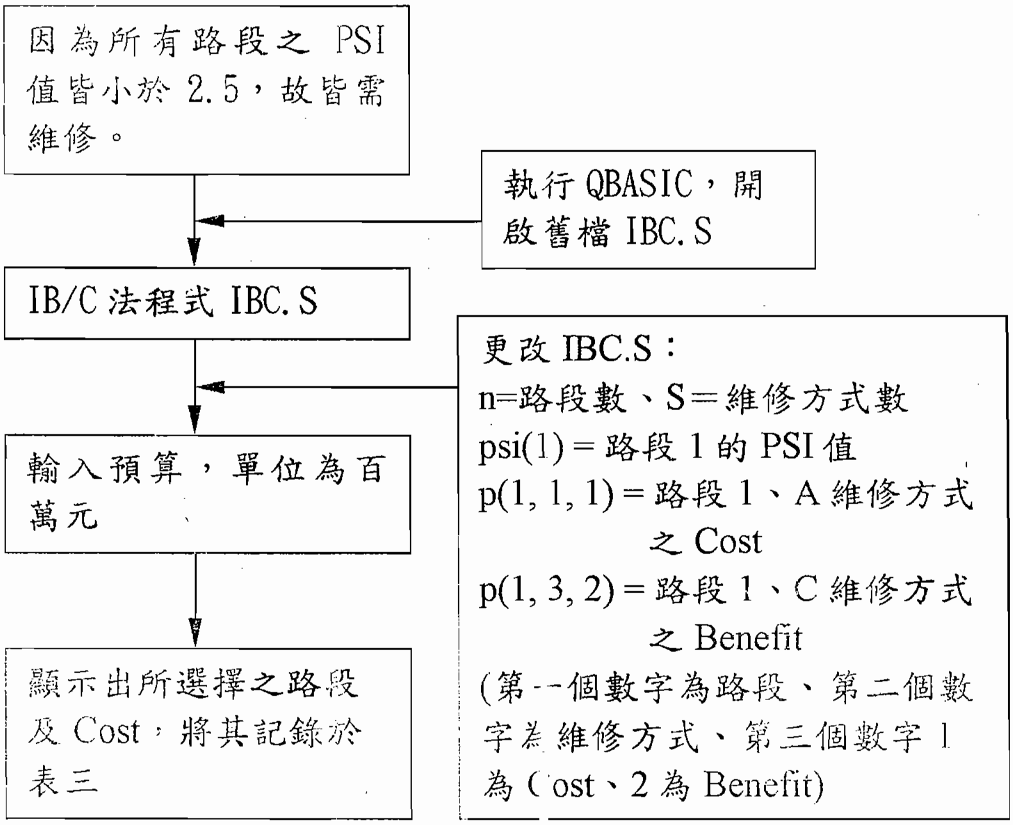
一、假設某一鋪面路網有十個路段，可考慮三種維修方式（A, B, C），在某一分析期間期PSI 值、維修成本、與預期效益如表一：

（a） 假設可接受之 PSI 門檻值為 2.5，在可運用的經費為五百萬與一千萬元的條件下，請利用先前建立之 IB/C 法程式分析不同之最佳化路網維修方式與經費運用情形，並比較在不同 Benefit 之差異為何？

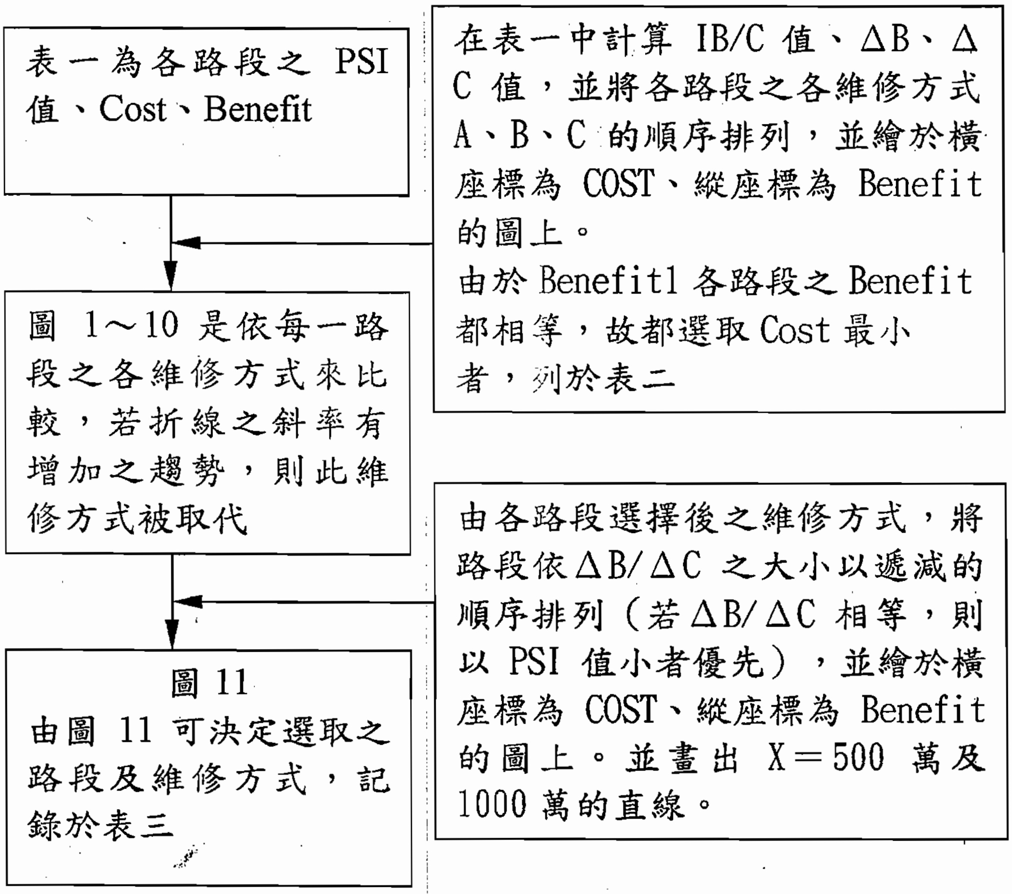
（b） 請以試算表或手算方式驗算上題結果之正確性。

（c） 請利用 LINDO 程式，將上述問題以 LIP 問題求解，並比較其與 IB/C 結果之差異。

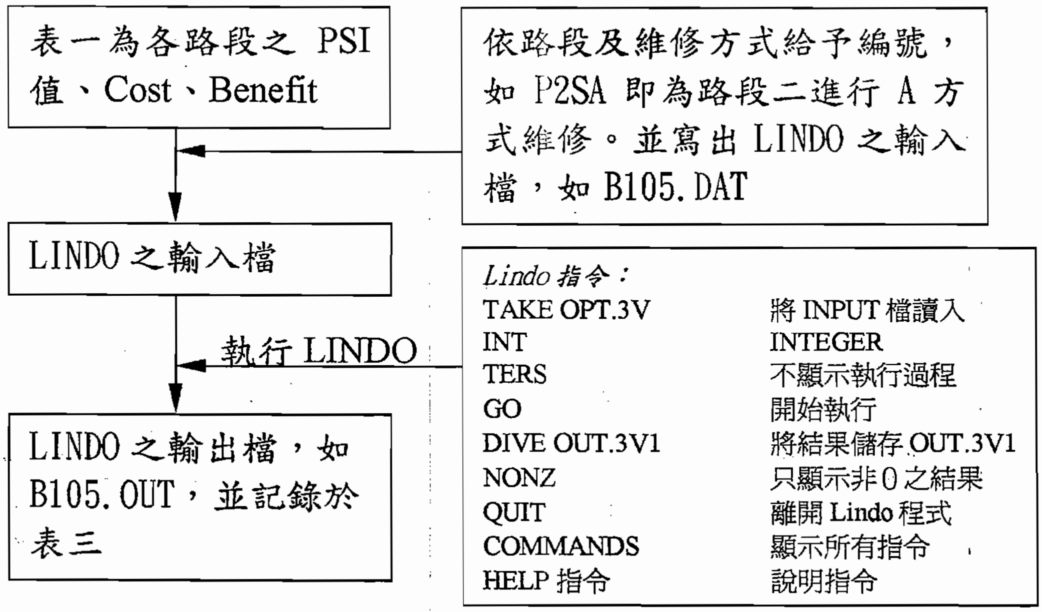
（a）IB/C 法程式分析



（b）試算表



（c）LINDO 程式



Projects	PSI	Cost,百萬元	Benefit1, VMT (1000延車英哩)	Benefit2, Added Life (Years)	IB_1/C	IB_2/C	Selected IB2/C	DC	DB2
1-A	2.2	0.5	30	3	60.0	6.0			
1-B	2.2	0.7	30	5	0.0	10.0	7.143	0.7	5
1-C	2.2	1.5	30	10	0.0	6.3	6.250	0.8	5
2-A	2.0	0.6	45	3	75.0	5.0			
2-B	2.0	0.9	45	5	0.0	6.7	5.556	0.9	5
2-C	2.0	2.5	45	10	0.0	3.1	3.125	1.6	5
3-A	1.8	0.4	20	3	50.0	7.5	7.500	0.4	3
3-B	1.8	0.8	20	5	0.0	5.0	5.000	0.4	2
3-C	1.8	1.9	20	10	0.0	4.5	4.545	1.1	5
4-A	2.4	0.3	22	3	73.3	10.0	10.000	0.3	3
4-B	2.4	0.5	22	5	0.0	10.0	10.000	0.2	2
4-C	2.4	1.2	22	10	0.0	7.1	7.143	0.7	5
5-A	2.1	0.5	35	3	70.0	6.0			
5-B	2.1	0.8	35	5	0.0	6.7	6.250	0.8	5
5-C	2.1	1.3	35	8	0.0	6.0	6.000	0.5	3
6-A	2.0	0.6	42	3	70.0	5.0	5.000	0.6	3
6-B	2.0	1.1	42	5	0.0	4.0	4.000	0.5	2
6-C	2.0	2.1	42	8	0.0	3.0	3.000	1.0	3
7-A	1.7	0.7	24	3	34.3	4.3			
7-B	1.7	1.0	24	5	0.0	6.7	5.000	1.0	5
7-C	1.7	2.0	24	8	0.0	3.0	3.000	1.0	3
8-A	2.1	0.5	28	3	56.0	6.0			
8-B	2.1	0.7	28	5	0.0	10.0	7.143	0.7	5
8-C	2.1	1.2	28	8	0.0	6.0	6.000	0.5	3
9-A	1.9	0.6	20	3	33.3	5.0			
9-B	1.9	0.8	20	5	0.0	10.0	6.250	0.8	5
9-C	1.9	1.7	20	8	0.0	3.3	3.333	0.9	3
10-A	2.2	0.7	25	3	35.7	4.3			
10-B	2.2	0.9	25	5	0.0	10.0	5.556	0.9	5
10-C	2.2	1.6	25	8	0.0	4.3	4.286	0.7	3

表一

以Benefit1爲選擇條件，僅最低Cost被選取
優先順序爲

Projects	Cost,百萬元	Benefit1	IB_1/C	累計Cost
2-A	0.6	45	75.0	0.6
4-A	0.3	22	73.3	0.9
5-A	0.5	35	70.0	1.4
6-A	0.6	42	70.0	2.0
1-A	0.5	30	60.0	2.5
8-A	0.5	28	56.0	3.0
3-A	0.4	20	50.0	3.4
10-A	0.7	25	35.7	4.1
7-A	0.7	24	34.3	4.8
9-A	0.6	20	33.3	5.4

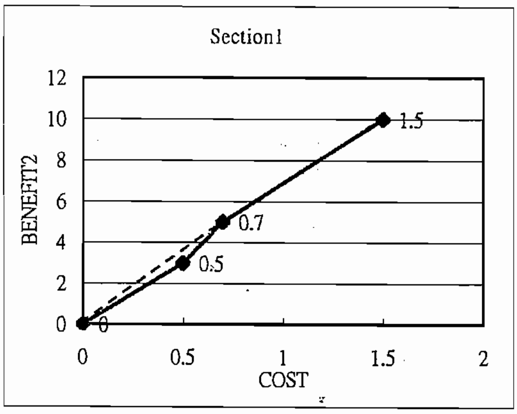
表二

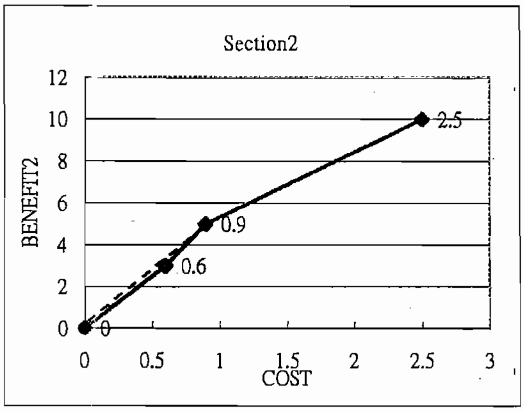
在五百萬的條件下，選擇2-A、4-A、5-A、6-A、1-A、8-A、3-A、10-A、7-A
在一千萬的條件下，選擇2-A、4-A、5-A、6-A、1-A、8-A、3-A、10-A、7-A、9-A

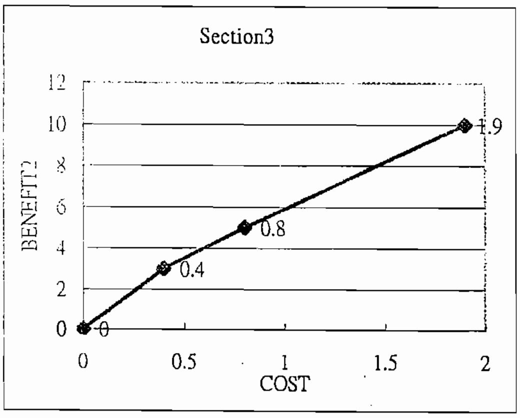
Benefit1(VMT)		
Budget=500萬		
	IBC程式	2A、4A、6A、5A、1A、8A、3A、10A、7A
	手算	2A、4A、6A、5A、1A、8A、3A、10A、7A
	LINDO	1A、2A、3A、4A、5A、6A、7A、8A、10A
Budget=1000萬		
	IBC程式	2A、4A、6A、5A、1A、8A、3A、10A、7A、9A
	手算	2A、4A、6A、5A、1A、8A、3A、10A、7A、9A
	LINDO	1A、2A、3A、4A、5A、6A、7A、8A、9A、10A
Benefit2(LIFE)		
Budget=500萬		
	IBC程式	3A、8B、1B、4C、9B、5B
	手算	3A、8B、1B、4C、9B、5B
	LINDO	1C、3B、4C、8B、9B
Budget=1000萬		
	IBC程式	4C、9B、1C、5C、8C、2B、10B、7B、3B
	手算	4C、9B、1C、5C、8C、2B、10B、7B、3B
	LINDO	1C、2B、3A、4C、5C、6A、7B、8C、9B、10B

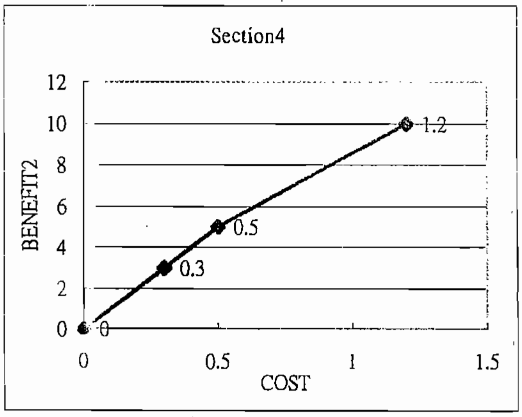
表三

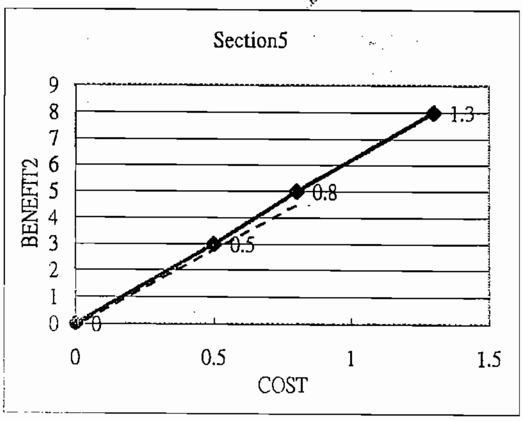
以Benefit2爲選擇條件

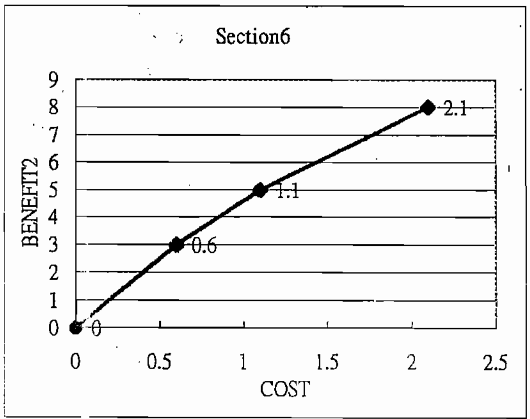


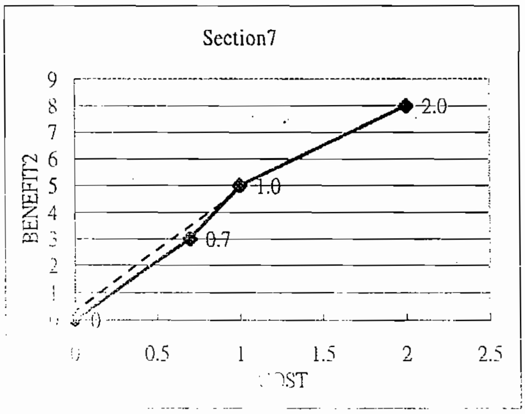


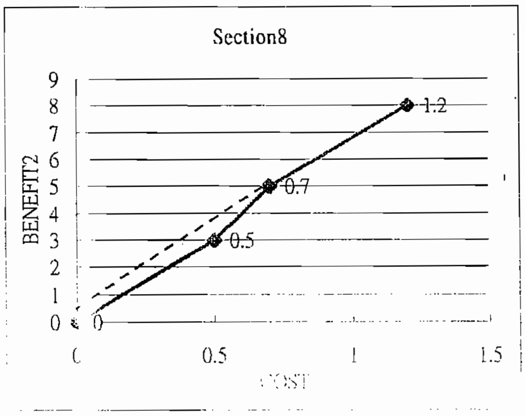


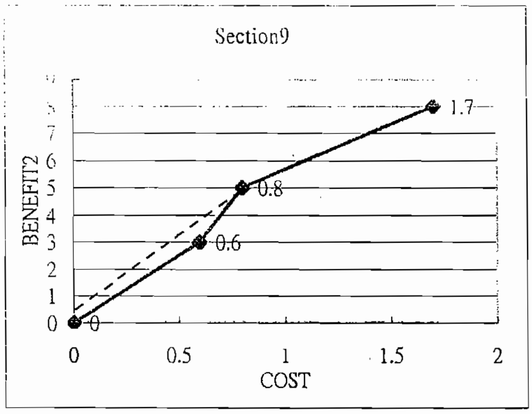


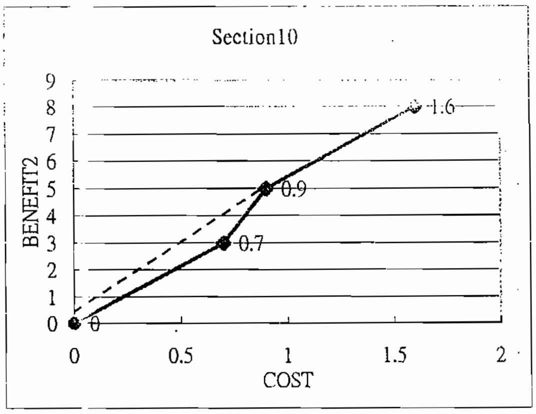






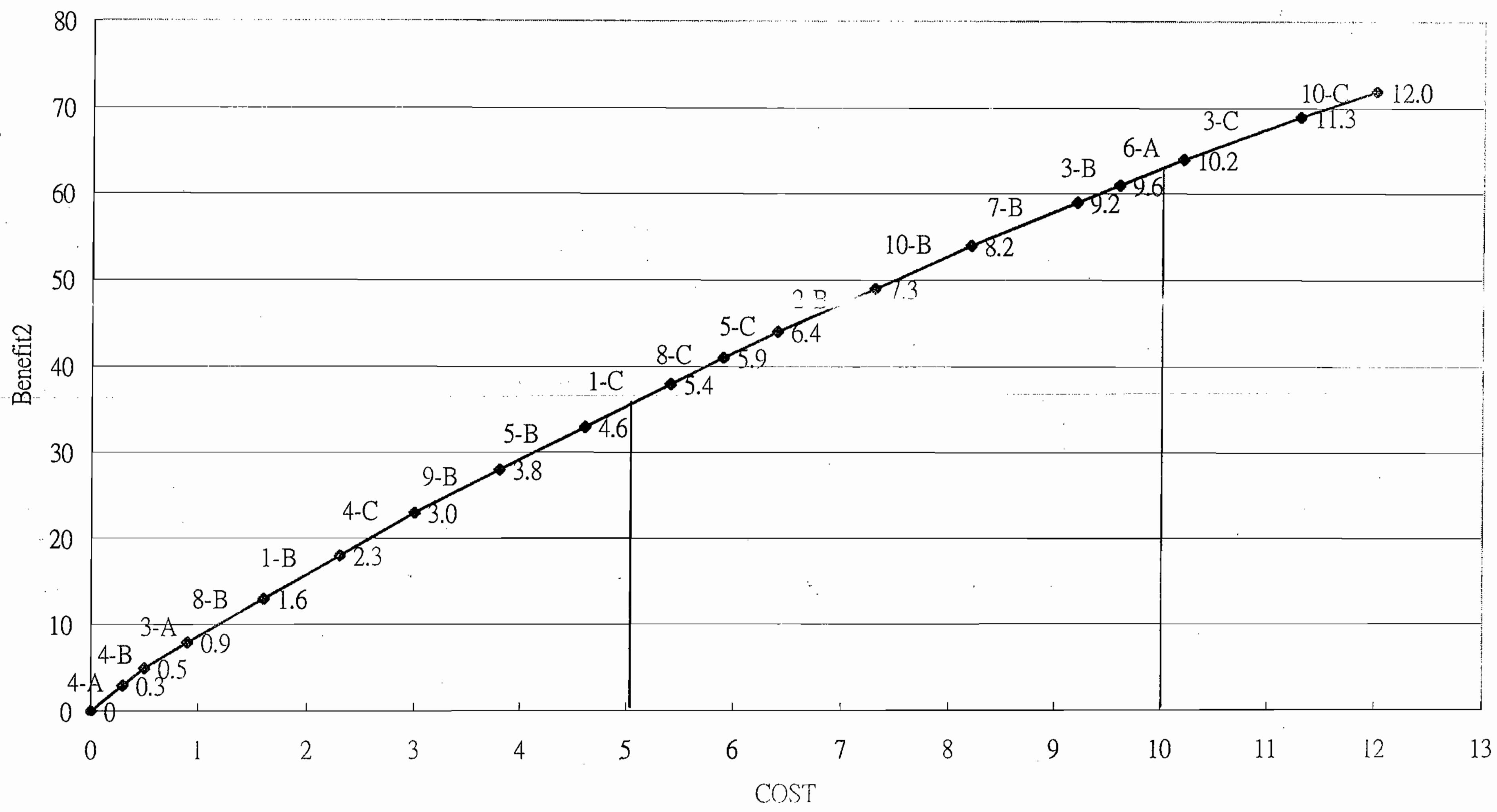






優先順序爲**4-A、4-B、3-A、8-B、1-B、4-C、9-B、5-B、1-C、8-C、5-C、2-B、**10-B、6-A、3-B、7-B、3-C、10-C、6-B、9-C、2-C、7-C、6-C

圖11 Benefit2



```
CLS

TYPE total
  number AS INTEGER
  cost AS SINGLE
  slope AS SINGLE
END TYPE

n = 10: s = 3

DIM psi(n)
DIM ss(n, s)
DIM p(n, s, 2)
DIM yes(n)
DIM rehab(n)
DIM tt(n * s) AS total
DIM change AS total

psi(1) = 2.2: psi(2) = 2
psi(3) = 1.8: psi(4) = 2.4
psi(5) = 2.1: psi(6) = 2
psi(7) = 1.7: psi(8) = 2.1
psi(9) = 1.9: psi(10) = 2.2

p(1, 1, 1) = .5: p(1, 1, 2) = 3
p(1, 2, 1) = .7: p(1, 2, 2) = 5
p(1, 3, 1) = 1.5: p(1, 3, 2) = 10
p(2, 1, 1) = .6: p(2, 1, 2) = 3
p(2, 2, 1) = .9: p(2, 2, 2) = 5
p(2, 3, 1) = 2.5: p(2, 3, 2) = 10
p(3, 1, 1) = .4: p(3, 1, 2) = 3
p(3, 2, 1) = .8: p(3, 2, 2) = 5
p(3, 3, 1) = 1.9: p(3, 3, 2) = 10
p(4, 1, 1) = .3: p(4, 1, 2) = 3
p(4, 2, 1) = .5: p(4, 2, 2) = 5
p(4, 3, 1) = 1.2: p(4, 3, 2) = 10
p(5, 1, 1) = .5: p(5, 1, 2) = 3
p(5, 2, 1) = .8: p(5, 2, 2) = 5
p(5, 3, 1) = 1.3: p(5, 3, 2) = 8
p(6, 1, 1) = .6: p(6, 1, 2) = 3
p(6, 2, 1) = 1.1: p(6, 2, 2) = 5
p(6, 3, 1) = 2.1: p(6, 3, 2) = 8
p(7, 1, 1) = .7: p(7, 1, 2) = 3
p(7, 2, 1) = 1: p(7, 2, 2) = 5
p(7, 3, 1) = 2: p(7, 3, 2) = 8
p(8, 1, 1) = .5: p(8, 1, 2) = 3
p(8, 2, 1) = .7: p(8, 2, 2) = 5
p(8, 3, 1) = 1.2: p(8, 3, 2) = 8
p(9, 1, 1) = .6: p(9, 1, 2) = 3
p(9, 2, 1) = .8: p(9, 2, 2) = 5
p(9, 3, 1) = 1.7: p(9, 3, 2) = 8
p(10, 1, 1) = .7: p(10, 1, 2) = 3
p(10, 2, 1) = .9: p(10, 2, 2) = 5
p(10, 3, 1) = 1.6: p(10, 3, 2) = 8


nn = 0

FOR i = 1 TO n: IF psi(i) >= 2.5 THEN ss = 0 ELSE ss = s
FOR j = 1 TO ss
```

(表 九-1)

```
 IF j = 1 THEN
  nn = nn + 1: tt(nn).number = i * 100 + j
  tt(nn).cost = p(i, j, 1): c = p(i, j, 2) / p(i, j, 1)
  tt(nn).slope = c
 ELSE
  a = p(i, j, 1) - p(i, j - 1, 1): b = p(i, j, 2) - p(i, j - 1, 2)
  b = b / a
   IF b <= c AND b > 0 THEN
    nn = nn + 1: tt(nn).number = i * 100 + j
    tt(nn).cost = a: tt(nn).slope = b: c = b
   ELSEIF b > 0 AND b > c THEN
    tt(nn).number = i * 100 + j
    tt(nn).cost = p(i, j, 1): c = p(i, j, 2) / p(i, j, 1)
    tt(nn).slope = c
   END IF
 END IF
NEXT: NEXT

FOR i = 1 TO nn
change = tt(i)
PRINT change.number, change.cost, change.slope
NEXT

FOR i = 1 TO nn - 1
FOR j = i + 1 TO nn
IF tt(j).slope > tt(i).slope THEN
  change = tt(i): tt(i) = tt(j): tt(j) = change
ELSEIF tt(j).slope = tt(i).slope THEN
  ai = INT(tt(i).number / 100): aj = INT(tt(j).number / 100)
  IF psi(ai) > psi(aj) THEN
     change = tt(i): tt(i) = tt(j): tt(j) = change
  END IF
END IF
NEXT: NEXT

PRINT : PRINT
FOR i = 1 TO nn
change = tt(i)
PRINT change.number, change.cost, change.slope
NEXT

INPUT "Budget="; money
tmoney = 0
FOR i = 1 TO nn
a = INT(tt(i).number / 100): b = (tt(i).number MOD 100)
tmoney = tmoney + tt(i).cost
IF tmoney <= money THEN yes(a) = b: rehab(a) = p(a, b, 1)
NEXT

PRINT
FOR i = 1 TO n
PRINT "Section "; i; "=>"; yes(i); "  Rehab Cost="; rehab(i)
NEXT

totalcost = 0
FOR i = 1 TO n
totalcost = totalcost + rehab(i)
NEXT

PRINT : PRINT "Total Rehab Cost="; totalcost
```

(表 九-2)

利用Lindo分析B2，經費500萬及1000萬所得結果

利用Lindo分析B2，經費500萬所得結果

OBJECTIVE FUNCTION VALUE

1) 35.0000000

VARIABLE	VALUE	REDUCED COST
P1C	1.000000	-10.000000
P3B	1.000000	-5.000000
P4C	1.000000	-10.000000
P8B	1.000000	-5.000000
P9B	1.000000	-5.000000
P20	1.000000	.000000
P50	1.000000	.000000
P60	1.000000	.000000
P70	1.000000	.000000
P100	1.000000	.000000

ROW SLACK OR SURPLUS DUAL PRICES

NO. ITERATIONS= 429
BRANCHES= 53 DETERM.= 1.000E 0

****

利用分析B2，經費1000萬所得結果

OBJECTIVE FUNCTION VALUE

1) 62.0000000

VARIABLE	VALUE	REDUCED COST
P1C	1.000000	-10.000000
P2B	1.000000	-5.000000
P3A	1.000000	-3.000000
P4C	1.000000	-10.000000
P5C	1.000000	-8.000000
P6A	1.000000	-3.000000
P7B	1.000000	-5.000000
P8C	1.000000	-8.000000
P9B	1.000000	-5.000000
P10B	1.000000	-5.000000

ROW SLACK OR SURPLUS DUAL PRICES

NO. ITERATIONS= 103
BRANCHES= 8 DETERM.= 1.000E 0

LP OPTIMUM FOUND AT STEP 20
OBJECTIVE VALUE = 291.000000

（表 七）