Optimization of Long-Range Major Rehabilitation of Airfield Pavements

DAVID H. ARTMAN, JR., JUDITH S. LIEBMAN, AND MICHAEL I. DARTER

A procedure has been developed to optimize the planning for major rehabilitative measures for airfield pavements. The procedure is divided into two parts. First, at the project level, an optimum long-range pavement rehabilitative plan is developed for each individual pavement feature (project) of the airfield for each of several levels of funding. The optimum rehabilitative alternative is selected by maximizing the pavement performance as defined by the weighted pavement condition index (PCI) versus time curve. The decision process is modeled by using dynamic programming. The second part of the analysis steps up to the network level of optimization. The criteria for selecting the set of projects is done by maximizing the pavements' performance weighted by the relative value of each project in the network. The rehabilitative projects are selected by using Toyoda's heuristic for 0-1 integer linear programming. The results of the airfield analysis are the selection and timing of major rehabilitative activities. The consequence of many funding levels and any directed work are also determined. Lastly, the pavement engineer can justify an optimum level of funding for long-range planning purposes. The methodology can also be applied directly to highways, roads, and city streets to provide long-range plans for better pavement management.

The U.S. Air Force has long recognized the need for effective airfield pavement management. This need led to the extensive effort contracted to the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL). The work at CERL produced several pavement management aids [e.g., Pavement Condition Index (PCI), Airfield Pavement Management System (APMS), and PAVER]. These aids provided U.S. Air Force pavement engineers with extensive data storage and retrieval plus data manipulative and presentation capabilities. By using these aids pavement engineers interactively develop and compare alternative plans for maintenance and rehabilitation of their airfield. These plans are based on the current use and performance of the airfield pavement feature. Inexperienced engineers can draw on the many years of valuable pavement engineering experience built into the system as they design projects; experienced pavement engineers use the system as a tool for extensive analysis and detailed comparison. The systems greatly enhance an engineer's abilities for comparing many more alternative designs objectively.

Yet, with all this enhanced capability, engineers have still been constrained in that all efforts in designing and comparing alternatives are directed at the present condition of the pavement. When asked what the best plan for the pavements is for the next 20 years, engineers have to rely on their previous manual techniques, their engineering judgment, and their experiences.

Not only are long-range planning capabilities limited to current decision making for each pavement section, but engineers cannot optimize these types of long-range plans at the network level (for an entire airfield or group of airfields). Since optimization of the expenditure of funds for the network of pavement sections over a specified period of time cannot be achieved, pavement engineers cannot be assured of getting the maximum performance of the entire network for a specified level of funding.

The work described in this paper is addressed to

1. Optimize the selection and timing of major rehabilitative measures over a specified period of time at a given funding level for individual pavement features (the project level) and

2. Optimize the selection of these measures at the network level, also with limited funding and for a specified time period.

Simply put, with a limited amount of money, the objective is to let the air force maintain its pavements in the best condition possible and to predict the performance of the pavement network given a limited amount of money.

AIRFIELD PAVEMENT FEATURE OPTIMIZATION--PROJECT LEVEL

U.S. Air Force bases are divided into separate pavement sections, called features. The number of features per base can be as low as 50 or as high as 200. Each feature is a unique element of the airfield and has its own construction and maintenance history, current traffic use, and relative need or importance for aircraft operations. In order to optimize the rehabilitation of the entire network of features, the first task must be to develop strategies for each individual feature as input into the overall network analysis. Each of these individual analyses is an optimization problem in itself, which consists of selecting possible rehabilitative measures, timing their occurrence within a fixed funding limit, and concurrently maximizing the performance of the feature.

Performance Criteria

One of the initial developments by CERL for the U.S. Air Force was PCI (1,2). Well-established in the air force as the standard measure of airfield pavement distress, PCI is an objectively derived value from 0 to 100, highly correlated to the engineering judgment of many air force pavement engineers. The engineers based their subjective rating on their experiences in airfield pavement maintenance and the standards levied on them by aircraft operations (Figure 1). Some states are using PCI for airfield pavement rating (Illinois) on civilian airports.

In addition to the basic index, the PCI scale also has a relative utility. The utility of the PCI is the relative value of a particular unit point of PCI to another unit point of PCI elsewhere on the scale. To illustrate, the value of raising the PCI of a particular pavement feature from 50 to 60 is very different from that of raising the PCI from 90 to 100. With utility, this change or difference in value up and down the PCI scale can be evaluated (Figure 2). As the PCI gets larger, the utility of the unit PCI point diminishes.

The performance measure of a particular feature over time is defined as the area under the utility weighted PCI versus time plot [Figure 3 (3)]. The area is called the nonmonetary benefit or performance of a particular rehabilitation policy for the analysis period. The larger this area, the better the structural performance of the pavement section.

Part of CERL's work included the development of a PCI prediction model. The current models (4) predict the future PCI of a particular pavement feature within a range acceptable to the U.S. Air Force for use in planning, programming, and budgeting. These

Figure 1. Summary of steps for PCI determination.

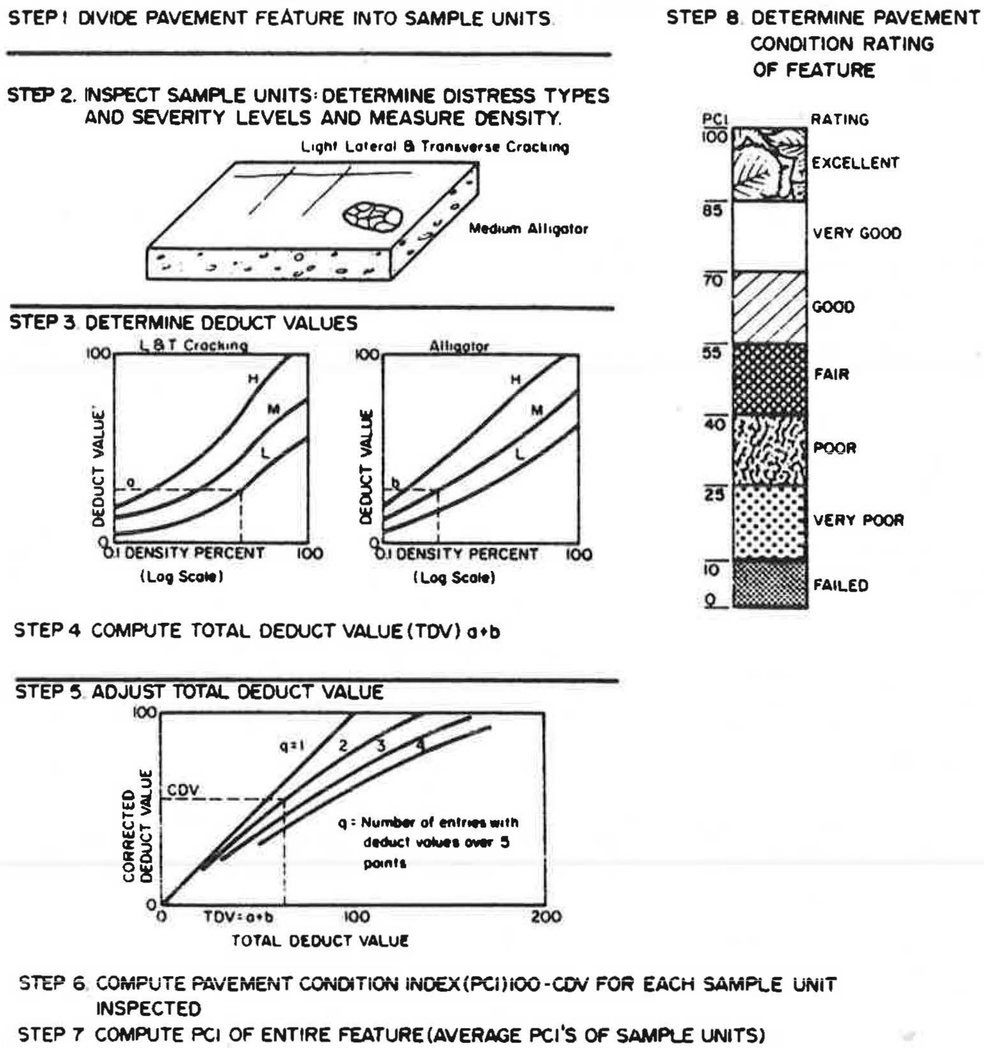


Figure 2. Utility weighted PCU versus time curve.

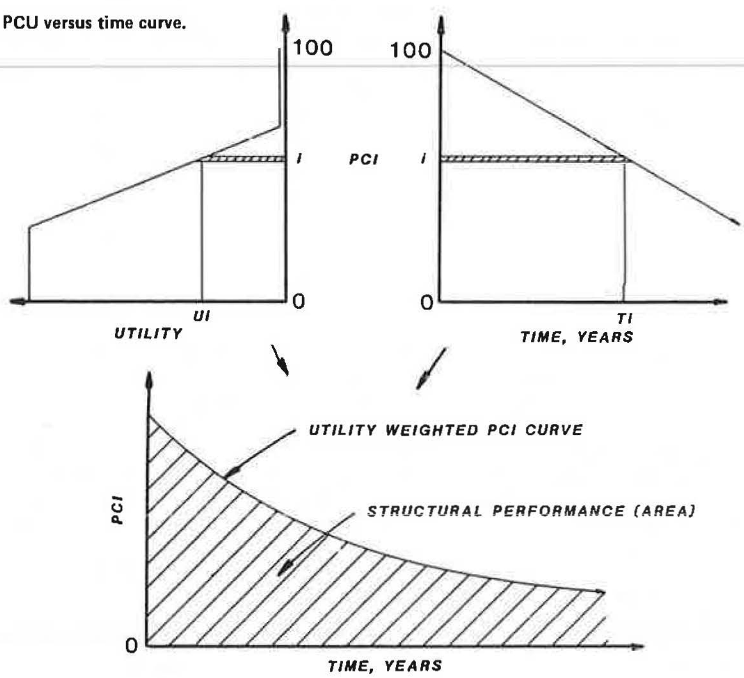


Figure 3. Performance of rehabilitative activity.

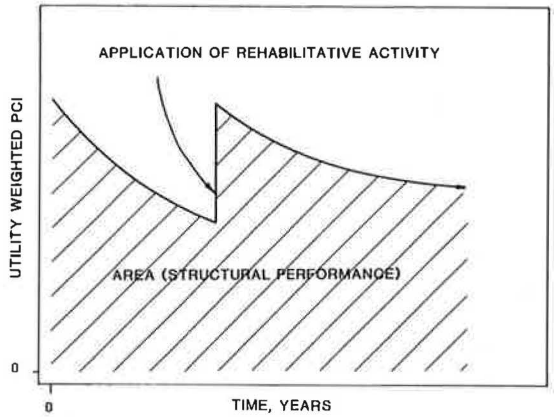
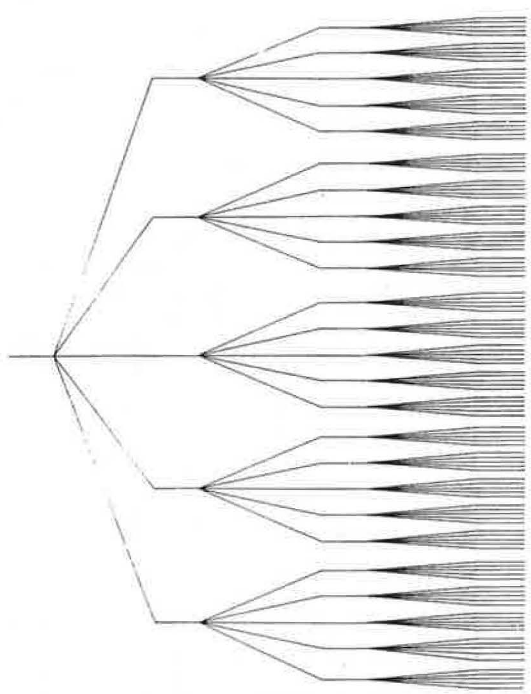


Figure 4. Decision tree of project decision process.



models lend themselves to the prediction of major rehabilitative activities (overlays and reconstruction) and their timing in light of the level of routine maintenance the air force was using during the development of the models.

Feature Decision Process

The decision process for selecting the best rehabilitative activity and its timing for a particular feature becomes an extensive decision tree when expanded over a period of time (20 years). If the decision process included 5 possible alternatives and were considered every 2 years for a period of 20 years, the number of possible combinations of decisions would be 5^{10}. Figure 4 depicts the complexity of the decision tree over just 3 decision periods.

With such a large number of possible combinations of decisions, even the most efficient computer in existence would take more than 10 days to enumerate all possible decision paths. However, because of the nature of this decision process, an algorithm called dynamic programming can be used to determine the optimal rehabilitative policy in a reasonable amount of computer time without enumerating all possibilities.

The term dynamic programming, first used by Bellman, denotes a mathematical method to solve a multistage decision process (5). When properly applied, dynamic programming reduces the problem size and still guarantees an optimal or best solution within the bounds of the models used. In this case, the 5^{10} possible combinations of decisions over 20 years reduces to 5 x 5 x 10 possible combinations of decisions for the same period.

The decision process of pavement rehabilitation at the feature (project) level is modeled as a series of staged decisions (every 2 years for 20 years). At each stage (decision point) all the feasible decisions (e.g., routine maintenance, reconstruction, and overlays) are applied to each entering state (previous combination of possible decisions). Only the decision that gives each of the entering states its maximum benefit or performance (area under the utility weighted PCI versus time plot) over the next decision period (2 years) is retained and passed on to the next stage (decision point). Figure 5 is the dynamic programming flow chart for the decision process in this procedure. This property of the dynamic programming algorithm permits reduction of the decision tree to a feasible size for computer solution. This is illustrated in Figure 6, with the dynamic programming methods applied to the decision tree shown in Figure 4.

Dynamic Programming Inputs

Basic pavement and aircraft data are necessary inputs into the dynamic programming algorithm. Those data are readily available at each U.S. Air Force base either in the form of reports (condition survey reports or pavement evaluation reports) or drawings (master plans). Reconstruction designs for each feature (project) are standard designs from current U.S. Air Force manuals. These designs are functions of the structural parameters of the existing feature (obtained from reports and drawings) and current (or anticipated) aircraft use. Costs for either reconstruction or overlays are based on current average pricing used for planning purposes. As these alternatives are selected as future decisions, their costs are adjusted for inflation.

Dynamic Programming Execution

The current dynamic programming algorithm averages approximately 3 central processing seconds on a CDC Cyber 175 computer for each feature (project) in the network. One feature (project) at a time, the input data are read in and the long-range rehabilitative plans are developed until all the features in the network have been analyzed.

The program is operated in an interactive mode and the feature information is read from a data input file. The results of all the features are output into a single data file.

Dynamic Programming Results

The output from the dynamic programming algorithm is a series of long-range rehabilitation policies for different levels of funding. The first policy is always the routine maintenance policy. That policy reflects the resulting performance (area under the utility weighted PCI versus time plot over 20 years) and distress condition if only routine maintenance

Figure 5. Dynamic programming model flow chart.

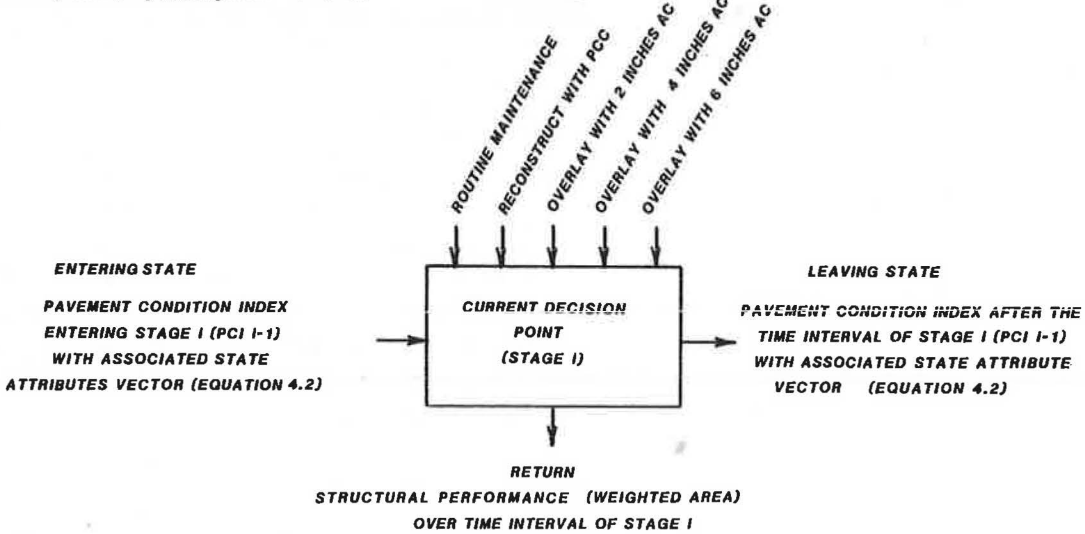
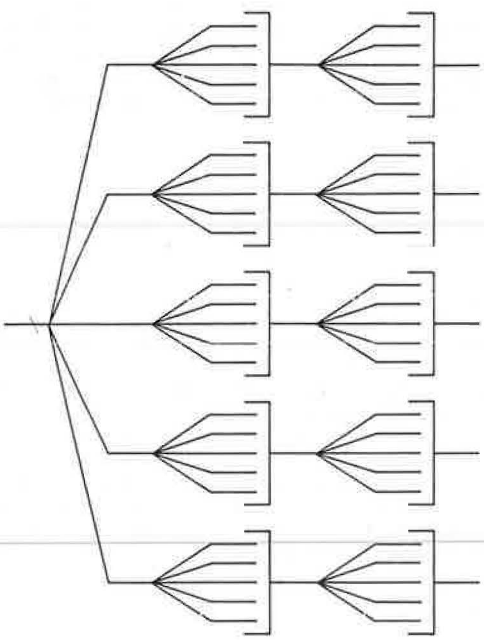


Figure 6. Dynamic programming method applied to project-level decision process.



is applied over the analysis period (20 years). Even though no expenditure of funds for major rehabilitation is made over the period, a benefit (performance) is still obtained. The other policies reflect rehabilitative plans that maximize the performance over the analysis period for different levels of funding. At each level of funding the optimal plan provides the type and timing of major rehabilitation for a feature.

Major rehabilitative activities include

1. Routine maintenance,
2. Reconstruction with portland cement concrete (PCC),
3. Overlay with 2 in. of asphalt concrete (AC),
4. Overlay with 4 in. of AC, and
5. Overlay with 6 in. of AC.

In addition, the output provides the increments of performance and the features' PCI as a function of time over the analysis period.

AIRFIELD OPTIMIZATION--NETWORK LEVEL

Air force airfield pavement networks suitable for network optimization can be defined in several ways. First, a network that encompasses all the airfields in the entire U.S. Air Force inventory would include several hundred airfields around the world. Another network could be defined to include only those air force bases within a single major air command [e.g., Strategic Air Command (SAC), Military Airlift Command (MAC), Tactical Air Command (TAC), or U.S. Air Forces in Europe (USAFE)]. This division of U.S. Air Force airfields would entail sizes from 6 to 20 airfields/network. Funds are allocated at both the air force and command levels for airfield pavement rehabilitation; therefore, either of these would be a logical division for network funding optimization. A third logical network level is the individual airfield itself. If the network is defined at the single airfield level, each base has the opportunity to plan long-range strategies that reflect its specific needs. The base engineers are the most familiar with their unique pavement problems and specific operational needs and are responsible for the performance of their airfield pavements; therefore, the airfield level of network optimization is also very important.

This paper addresses the airfield network optimization; however, the methods developed and explained here are directly applicable to higher levels (command and air force) of optimization. The objective of airfield network optimization is similar to individual feature (project-level) optimization: Within given funding restraints, maximize the total network performance over the analysis period.

Performance Criteria

The criteria used in optimizing the expenditure of limited funds can take several forms at the network level. First, the same criteria used at the feature-level optimization can be reflected at the network level. For all the feature plans submitted to the network optimization, maximization of the summation of the performance (area under the utility weighted PCI versus time plot) for all the selected feature plans, constrained by a limited funding level, is a feasible criterion. With this method engineers can obtain the maximum performance (per the defined criterion) of their networks for a specified level of funding.

However, obtaining the maximum performance (as previously defined) regardless of the value or need of a particular pavement section to the aircraft operations of an airfield might not provide the best pavement system over the analysis period. This is because all the features in an airfield have a relative worth as compared with each other for supporting the aircraft operations. For example, the taxiway used by B-52 bombers standing strategic alert has a higher value than the taxiway used for access to an engine test cell. The primary runway that supports fighter operations has a higher value than the ladder taxiway of an adjacent auxiliary runway. To keep the engine test cell taxiway or the auxiliary runway ladder taxiway in tip top shape but allow the alert bomber taxiway and primary fighter runway to deteriorate to high distress levels just because this might be easier or cheaper would not be in the best interest of the users. Hence, relative feature value must be incorporated when optimizing at the network level.

The relative value of a particular feature can be broken down as a function of the following variables:

1. Pavement type (e.g., runway, taxiway),
2. Pavement need (e.g., primary, secondary),
3. User aircraft type (e.g., bomber, fighter, cargo),
4. User aircraft mission (e.g., alert, training, operational), and
5. Number of user aircraft by type and mission.

Together these variables describe the relative worth of one particular pavement feature versus another. The features being compared can be on the same airfield or different airfields around the world. Table 1 gives the complete breakdown of each category. The relative numerical value assigned to each element is also included. These weights have been estimated based on 6 years of experience in air force pavement management, but they should be validated before implementation.

The worth of a single feature can be calculated by

$$\text{Worth} = \sum_{i=1}^{n} N_i*(PT_i + PN_i + AT_i + AM_i) \quad (1)$$

where

N_i = number of user aircraft by type and mission,
PT_i = pavement type coefficient for user aircraft,
PN_i = pavement need coefficient for user aircraft,
AT_i = user aircraft type coefficient,
AM_i = user aircraft mission coefficient,
i = counter of different user aircraft types, and
n = number of different aircraft types that use feature.

All the information necessary for the worth calculation is readily available at each U.S. Air Force base. If the relative worth of a single feature becomes the criterion used at the network level for optimizing the expenditure of funds, then the pavement engineer can maximize the user's needs. In this case the limited funds are spent without regard to getting the most pavement structural benefit for the expenditure. Because different long-range rehabilitative plans from the same feature have the same feature worth to the total network system, the network optimization will choose the cheapest rehabilitative plans within the specified network funds. As

Table 1. Relative weights of total feature worth calculation.

Characteristic				
Feature	Relative Weight	Criteria	Relative Weight Within Criteria	Relative Weight[a]
Aircraft mission	10	Alert	100	1,000
		Operational	50	500
		Training	10	100
Pavement need	5	Primary	100	500
		Secondary	20	100
		Auxiliary	5	25
		Transient	2	10
		None	1	5
Pavement type	2.5	Runway	100	250
		Taxiway	30	75
		Apron	10	25
Aircraft type	0.5	Bomber	100	50
		Command	50	25
		Tanker	30	15
		Cargo	20	10
		Fighter	10	5
		Transport	8	4
		Reconnaissant	6	3
		Trainer	4	2
		Experimental	2	1

[a]Product of characteristic and criteria weights.

discussed, criteria might not always be in the best interest of the pavement structure.

These two optimizing criteria represent the extreme limits, ranging from do the best for the pavement to do the best for the user. The correct optimization criteria rest somewhere in between. For the work in this paper, the features' total benefit is weighted by the features' worth parameter.

Optimization at the network level with the feature-worth weighted performance of each long-range rehabilitative plan takes into consideration both the importance of the feature to the user and the effect of the plan on the performance of the pavement. These are the criteria used in the examples in this paper.

Network Decision Process

The decision process for optimizing the selection of long-range plans can be modeled very simply as a 0-1 integer linear programming problem. The integer program algorithm selects the plans (one plan per feature) that provide the largest summation of feature worth and plan performance product. The problem is formulated as

$$\text{Maximize: } \sum_i \sum_j P_{ij}*FW_i*PP_{ij}$$

such that

$$\sum_i \sum_j P_{ij}*C_{ij} \leq \text{network funding limit}$$

and

$$\sum_i P_{ij} \leq 1 \quad \text{for all } j \text{ (limits one selected plan per feature)}$$

where

FW_i = feature worth of ith feature,
PP_{ij} = plan performance of jth policy of ith feature,
C_{ij} = cost of jth policy of ith feature, and
P_{ij} = jth policy of ith feature (the decision variables), equals 1 if selected or 0 if not selected.

Integer Program Inputs

For optimizing at the network level, the required inputs for all the long-range rehabilitative plans are

1. Cost of rehabilitative plan for each feature,
2. Performance of the rehabilitative plan,
3. Relative worth of the plan's feature, and
4. Funding limit for network expenditure.

All the inputs are either set by the pavement engineer at the time of execution or are output from the dynamic programming algorithm. Also, in addition to setting the funding limit at the time of execution, pavement engineers can choose the optimizing criteria. Choices for optimizing criteria (objective function) include

1. Structural performance of individual feature plans (area under utility weighted PCI versus time plot),
2. Relative feature worth (function of user aircraft type and mission plus type and need of feature to the user aircraft), and
3. Structural performance weighted by relative feature worth (performance times worth).

Integer Program Solution

Solutions to integer programming problems normally require checking (either directly or indirectly) every possible combination of solutions. Small problems (in our case a small problem is 10 features with 3 or 4 plans or long-range strategies each) are easily solvable on most computers. But, as the size of the problem approaches an air force base network with possibly 100 features with 3 to 4 plans each,

Figure 7. Selected project listing example.

SELECTED PROJECT LISTING

NETWORK OPTIMIZATION

DECISION LEGEND

R/M = ROUTINE MAINTENANCE
R/C = RECONSTRUCT
O/L2 = OVERLAY WITH 2" AC
O/L4 = OVERLAY WITH 4" AC
O/L6 = OVERLAY WITH 6" AC

NETWORK DESCRIPTION: EXAMPLE PROBLEM WITH OPTIMIZED WITH TFW*PERFORMANCE

NETWORK SPENDING LIMIT(PRESENT WORTH): 250000

AMOUNT SPENT(PRESENT WORTH): 246746

OBJECTIVE FUNCTION VALUE: 327956890

BASE	FEATURE	TOTAL COST	BENEFIT	WORTH
EXAMPLE	R03A	185435	2214	48170

TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
PCI	80	78	76	74	72	70	98	96	95	93	91
DECISION	R/M	R/M	R/M	R/M	R/M	O/L4	R/M	R/M	R/M	R/M	R/M
COST($)	0	0	0	0	0	185435	0	0	0	0	0

BASE	FEATURE	TOTAL COST	BENEFIT	WORTH
EXAMPLE	T01A	23512	2049	41170

TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
PCI	60	57	96	92	88	84	80	76	71	66	61
DECISION	R/M	O/L2	R/M	R/M	R/M	R/M	R/M	R/M	R/M	R/M	R/M
COST($)	0	23512	0	0	0	0	0	0	0	0	0

BASE	FEATURE	TOTAL COST	BENEFIT	WORTH
EXAMPLE	T03C	17951	2035	22810

TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
PCI	75	73	71	68	95	89	84	79	74	68	63
DECISION	R/M	R/M	R/M	O/L2	R/M	R/M	R/M	R/M	R/M	R/M	R/M
COST($)	0	0	0	17951	0	0	0	0	0	0	0

BASE	FEATURE	TOTAL COST	BENEFIT	WORTH
EXAMPLE	T05A	19848	2199	41170

TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
PCI	75	73	70	68	97	95	92	89	86	84	81
DECISION	R/M	R/M	R/M	O/L2	R/M	R/M	R/M	R/M	R/M	R/M	R/M
COST($)	0	0	0	19848	0	0	0	0	0	0	0

evaluation of each and every possible combination becomes infeasible. The number of possible combinations of network solutions exceeds 3^{20} with just 20 features and 3 plans per feature.

Total or implicit enumeration is infeasible; therefore, a heuristic must be used to solve the resulting large integer program optimization. A heuristic procedure (providing good but not necessarily optimal solutions) developed by Toyoda (6) has been used by Ahmed (7), and Phillips and Lytton (8) for their procedures in allocating state highway resources during a single period. This same procedure by Toyoda can be used for selecting the optimal set of policies developed for long-range rehabilitation. The procedure uses an effective gradient search to select the best feature plans. For the sample problems solved in this research the heuristic solved for more than 90 percent of the objective function value when compared with solving for a global solution by using normal linear programming.

Integer Program Execution and Results

The current integer programming algorithm uses 20 to 40 central processing seconds to solve each level of expenditure at the network level on a CDC Cyber 175 computer (for 10 features, averaging 3 plans each). The program is rerun for different levels of expenditure, which results in the optimal set of feature plans for each level of expenditure.

The output from the integer programming heuristic is a listing of selected feature plans giving the maximum objective function within the network funding limit. Each set of feature plans represents the best group of long-range rehabilitative plans at selected budget levels, and also strives to serve the user and pavement structure in the best way possible.

Analysis Results

On completion of both the feature- (project) and network-level optimizations, the output data are summarized and presented in a user-readable format. Three tables are formed for each level of funding at the network optimization level:

1. Selected project listing,
2. Features without project listing, and
3. Network summary.

Selected Project Listing

The selected project listing is a summary of all the long-range rehabilitative feature plans selected by the network optimization. Each listing represents the optimal group of plans that does not exceed the specified funding limit. The listing provides the amount of money spent out of the amount allotted plus a summary description of each selected long-range plan.

Figure 7 is a typical example of the selected project listing. After identifying the airfield and feature of the selected long-range plan, the total cost of the plan (present worth dollars), total benefit (performance, area under utility weighted PCI versus time plot), and total feature worth (relative value of feature to aircraft operations, function of aircraft mission and type, plus pavement type and need) are shown. The predicted PCI, selected decisions, and costs (present worth) are given as a function of time (years) from the present. The information is repeated for each selected long-range plan as shown in Figure 4. A separate listing is developed for each specified limit of network funding.

Features Without Projects

The features without projects listing (Figure 8) summarizes all the features in the network that did not receive funding for any of their long-range rehabilitative plans. Each feature is identified with its total benefit (performance) and relative value, plus the PCI as a function of time for the analysis period. Note that because an air force airfield pavement is considered in poor condition when its PCI reaches 40, the features that fall in this category during the analysis period (this case 20 years) are flagged and their PCIs are asterisked. Again, a separate listing is generated for each specified level of network funding.

Figure 8. Features without projects example.

FEATURES WITHOUT PROJECTS

NETWORK DESCRIPTION: EXAMPLE PROBLEM WITH OPTIMIZED WITH TFW*PERFORMANCE

NETWORK SPENDING LIMIT(PRESENT WORTH): 250000

AMOUNT SPENT(PRESENT WORTH): 246746

FEATURES FALLING BELOW PCI OF 40 ARE FLAGGED AND PCI'S ARE ASTERISKED

	BASE	FEATURE	BENEFIT	REL VALUE	PCI BY YEAR										
					0	2	4	6	8	10	12	14	16	18	20
<40	*EXAMPLE*	R01A	1127	48170	65	62	58	54	50	45	41	36*	31*	26*	21*
	EXAMPLE	R02C	1654	48170	75	73	71	68	66	64	62	60	58	55	53
<40	*EXAMPLE*	T02A	1128	41170	65	62	58	54	50	45	41	36*	31*	26*	21*
	EXAMPLE	T04C	2032	22810	85	84	82	81	80	78	77	76	75	73	72
	EXAMPLE	A01B	2007	16420	85	84	82	81	79	78	76	75	73	71	70
<40	*EXAMPLE*	A02B	1089	22750	60	57	53	50	46	43	39*	36*	32*	29*	25*

Figure 9. Network summary example.

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* NETWORK SUMMARY *
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NETWORK DESCRIPTION: EXAMPLE PROBLEM WITH OPTIMIZED WITH TFW*PERFORMANCE

NETWORK SPENDING LIMIT(PRESENT WORTH): 250000

AMOUNT SPENT(PRESENT WORTH): 246746

TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
PCI(WEIGHTED)	71	69	71	68	71	67	68	65	62	58	55
COST(PRESENT WORTH)MILLIONS	0.00	.02	0.00	.04	0.00	.19	0.00	0.00	0.00	0.00	0.00
ACCUM COST,MILLIONS	0.00	.02	.02	.06	.06	.25	.25	.25	.25	.25	.25
NEW FEATURES W/PCI<=40	0	0	0	0	0	0	1	2	0	0	0
POOR FEATURES(PCI<=40)	0	0	0	0	0	0	1	3	3	3	3
BENEFIT	0	1844	1887	1817	1910	1827	1823	1736	1650	1565	1475
ACCUM BENEFIT	0	1844	3731	5548	7458	9285	11108	12844	14494	16059	17534

Network Summary

The last product of the network optimization procedure is the network summary. For each specified limit of funding the summary lists the following as a function of time:

1. Weighted network mean PCI,
2. Cost of rehabilitation (present worth),
3. Accumulated cost of rehabilitation,
4. New features that become poor (PCI = 40),
5. Total number of poor features in network,
6. Total summed benefits (performance) of all features, and
7. Accumulated summed feature benefits.

Figure 9 is a typical example of a network summary listing. The network PCI is the average of all features weighted by the relative worth of each feature. The cost is the amount of money spent in present worth values at each interval of time in the analysis period. The new features with PCI less than or equal to 40 represent the number of features that became poor during the respective decision points (time intervals) in the analysis period. The poor features listing gives the total number of features that have a PCI less than or equal to 40. The benefit is the increment of benefit or performance (area under utility weighted PCI versus time plot) summed for all the features for the individual time increments of the analysis period. Accumulated benefit is the summation of the individual time increment network benefits.

SAMPLE AIRFIELD APPLICATION

A small sample airfield was analyzed with this procedure. The sample airfield has only 10 features so the size of the problem does not hinder understanding the decision process (Figure 10). The inputs for each feature were extracted from real U.S. Air Force base features subjected to light load aircraft. All the feature data were run through the dynamic programming algorithm and these results were input into the Toyoda network analysis programs. All reports were generated for funding levels between $0 and $3 million present worth (at $250,000 intervals). The resulting objective function values are plotted in Figure 11.

Figure 10. Layout of example airfield.

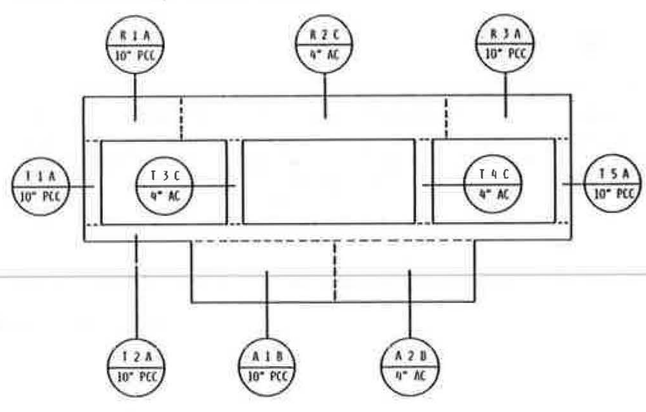
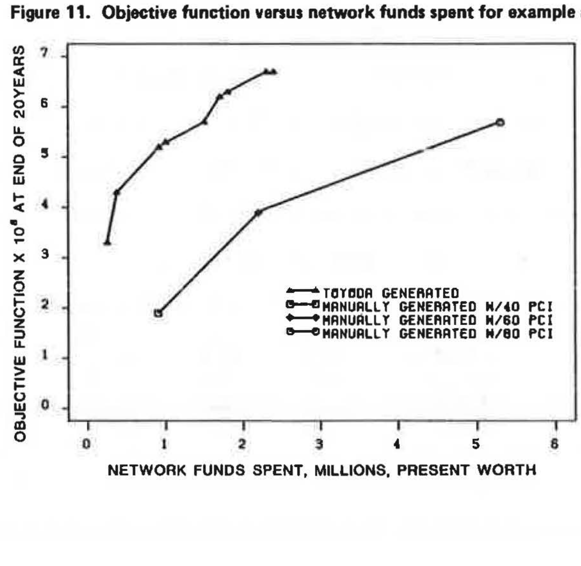


Figure 11. Objective function versus network funds spent for example airfield.



As a comparison, the same sample airfield was managed manually. By using three different condition levels (PCIs of 40, 60, and 80) a separate network analysis was completed. An activity (2-in. asphalt overlay) was scheduled for any feature on the sample airfield when its condition reached the preestablished minimum condition level (40, 60, or 80 PCI). The analyses were carried out for 20 years (the same as for the Toyoda analyses). For each of the three analyses, the objective function value was calculated and also plotted on Figure 11. Note that in each case, for the same amount of money spent, the methods developed in this research nearly double the objective function values obtained manually. Or, from another perspective, for any level of the objective function, the cost of the optimally selected projects was less than half the cost of the manually selected methods to achieve the same objective function.

Examination and comparison of the results (which feature activities were scheduled at various funding levels) for both methods revealed several reasons for the vast differences illustrated in Figure 11:

1. Activity assignment was optimized at the project level for the method derived in this research,
2. Manual network analysis selected projects regardless of the relative value of a feature to the user, and
3. Manual analysis does not take into consideration the structural benefit (performance) of a selected activity schedule (project).

This small example illustrates the value of the program developed in this research: it provides substantially better ways of spending the same money and maintaining an established condition for a reduced amount of money.

Figure 12. Terminal PCI at 20 years versus network funds spent, McClellan Air Force Base.

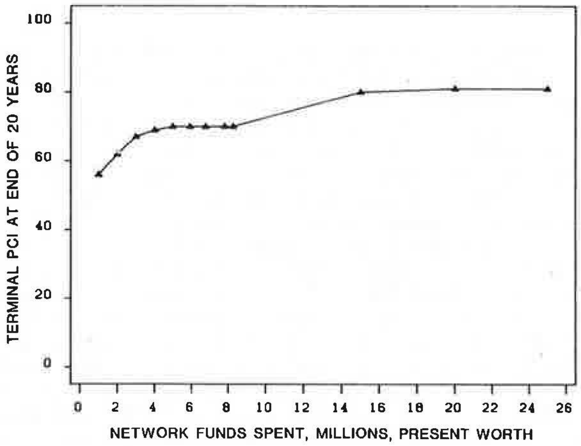


Figure 13. Network performance at 20 years versus network funds spent, McClellan Air Force Base.

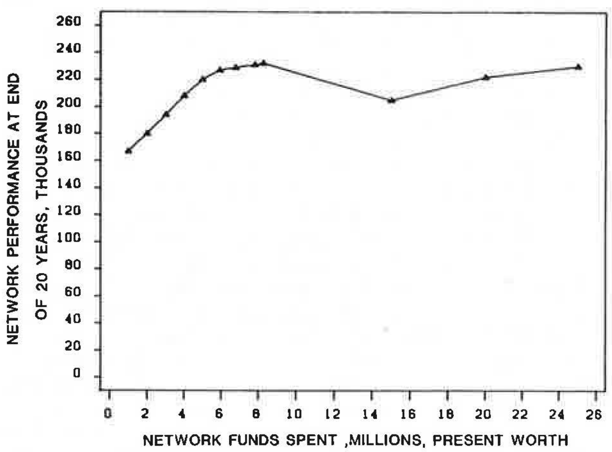
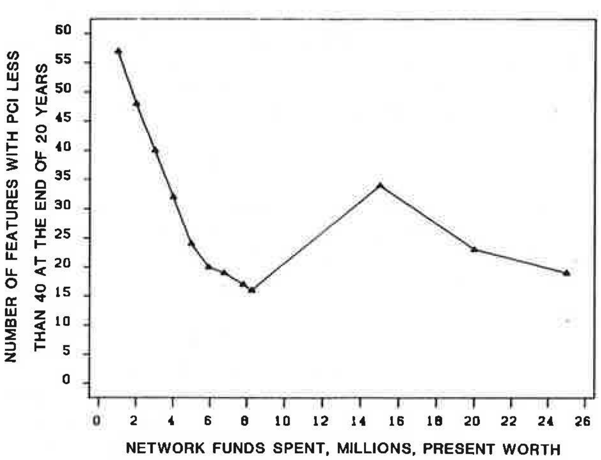


Figure 14. Number of features that have PCI less than 40 at end of 20 years versus network funds spent, McClellan Air Force Base.



EXAMPLE NETWORK ANALYSIS

To illustrate the use of the programs developed, a U.S. Air Force base was selected, analyzed, and is presented as an example. The selected U.S. Air Force base is in California and serves all sizes of aircraft in the inventory. The airfield has 113 features, a mixture of both flexible and rigid pavements.

All of the airfield's features were loaded into the feature analysis dynamic programming algorithm. The resulting optimized long-range feature plans were automatically processed into a condensed data file and input into the network optimization program. The network was optimized for funding levels from \$0 to \$25 million (present worth). Reports were generated at all funding levels and used for the following discussion.

Pavement engineers can use the reports generated from the example described to show justification for increased funding or consequences of decreased funding of the long-range rehabilitative plans for their airfield. They can modify their analysis and make additional runs to compensate for directed work (ordered independent of the analysis). This modified analysis can show the consequence of the directed work on the network airfield. Figure 12 is a plot of the network PCI at the end of the analysis period as a function of network funding level. At approximately \$5 million (present worth), the terminal network PCI reaches an asymptotic value close to 70. Figure 13 plots the network structural performance at the end of the analysis period. Note that it also reaches an asymptotic value at approximately \$5 or \$6 million. Figure 14 shows the number of features that fall below a PCI of 40 by the end of the analysis period as a function of network funding level. The amount of decrease of the total number of features in this category remains constant until approximately \$5 million. At this point and beyond, additional monies are spent in previously funded features due to their relative value to the user. Figure 15 depicts the network objective function versus network funds spent. It is a smooth continuous curve as expected and reaches an asymptotic value of about $6 million.

With these findings air force pavement engineers can not only show justification for adjustments to a proposed plan of the long-range rehabilitative measures for an airfield, but they now have justification for setting the approximate optimum level of network funding for the analysis period. Looking at Figure 16, in this case $5 or $6 million present worth would maintain the airfield at a level most advantageous to both the sustained performance of the pavement structures and the sustained normal operations of aircraft.

Figure 15. Objective function versus network funds spent, McClellan Air Force Base.

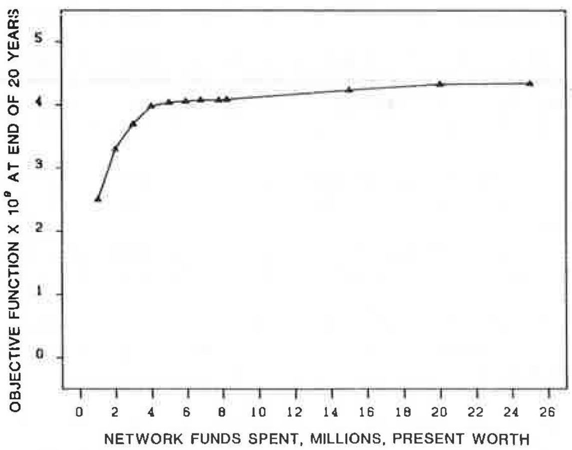


Figure 16. Network consequences versus network funds spent, McClellan Air Force Base.

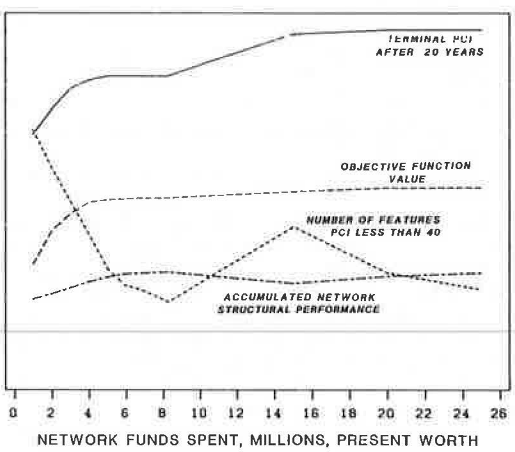
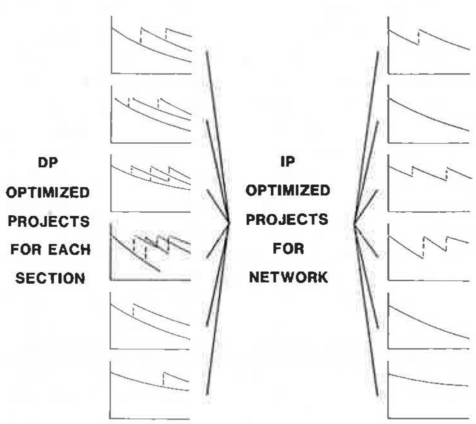


Figure 17. Graphical presentation of entire decision process.



SUMMARY

The programs and procedures developed during the course of the research described in this paper focus on the long-range planning of only major rehabilitative measures (routine maintenance, reconstruction, and overlays) of military airfields. The dynamic and integer programming procedures make it possible to solve large decision processes far beyond the abilities and comprehension of pavement engineers. This approach provides pavement engineers with the resources to consider many different alternative plans and rationally select the series of major rehabilitative measures that maximize the performance of the pavement structure (area under the utility weighted PCI versus time curve). The engineers now can comprehensively consider the possible decisions available for implementation as rehabilitative measures and can identify the unique plan that is best for each pavement feature at a specified funding level.

After developing the optimal long-range feature plans, airfield pavement engineers can use this information for the basis of long-range planning. Figure 17 shows the process from generating optimal projects for many features to selecting the best of these projects at the network level.

In the case of the example, the pavement system to be planned for was defined as a single airfield with 113 features with the dynamic program developing approximately 3 long-range feature plans each. The Toyoda algorithm was used to select among these feature plans. Air force pavement engineers can develop an optimal long-range plan for all the features of an airfield at specified funding levels.

Reports generated by this procedure of feature-level and network-level optimization describe what work is to be done and when to schedule it for all the features in the network. They reveal the consequence of this work not only on the features with planned projects, but also the impact on those features without any scheduled work. When directed to accomplish work not scheduled, the engineer can show the consequence of such work on the system as a whole and, if still directed, can reoptimize the use of the remainder of the funds. The report listings summarize the results of the long-range plan with respect to total network composite parameters of condition, cost, and performance. Furthermore, all of this information is generated at each funding level to be considered. Further details of this study may be found elsewhere (9).

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Development and Implementation of Alberta's Pavement Information and Needs System

M.A. KARAN, T.J. CHRISTISON, A. CHEETHAM, AND G. BERDAHL

Alberta Transportation initiated a project in November 1980 to develop and implement a pavement management system (PMS) for the province of Alberta, Canada. A comprehensive project plan was developed in the first phase of the project, which commenced in November 1980 and was completed in January 1981. Carried out as a preplanning project, the first phase identified six successive stages for the overall total PMS development and implementation project. Stage 1 of the project, the development and implementation of a pavement information and needs system (PINS), was initiated in May 1981 and scheduled to be completed in September 1982. A major element of PINS is a set of models that predict performance and various data processing and analysis components that take the individual field meansurements; calculate the performance measures in terms of pavement quality index, riding comfort index, structural adequacy index, and visual condition index; apply the performance prediction models; and identify both current and future needs. The major features of the PINS system and how the system fits into Alberta's overall PMS development and implementation are described. Specific attention is given to the details of performance prediction modeling and development of a pavement quality index concept.

Alberta Transportation is responsible for the management of a large network of provincial highways that consists of approximately 7,000 miles of paved primary highways and about 2,000 miles of paved secondary roads. In addition, approximately 200 miles of new pavement are added to the highway system annually. This represents a substantial investment of many millions of dollars. To preserve this investment and maintain an acceptable level of serviceability for the total highway network, an additional investment of approximately $50 million is required annually for the maintenance and rehabilitation of deteriorating highway sections.

The department's engineers and administrators are concerned that the rehabilitation and maintenance programs make the best possible use of available funds on an overall basis as well as ensure an equitable allocation between the regions in the province. To establish an objectively based rehabilitation program several questions must be answered:

1. What is the current status of the network?
2. What are the expected needs during the programming period?
3. What rehabilitation alternatives can be considered for sections that require action within the programming period?
4. What are the performance and cost implications associated with the possible rehabilitation alternatives?
5. What is the effect of delaying or advancing a rehabilitation project within the programming period?
6. What are the effects of maintenance on the rehabilitation alternative selection?
7. What is the optimum total program of work for each year in the programming period based on the previous questions for a given level of funding?
8. What are the effects of the funding level used on the network as a whole?
9. What level of funding is required to maintain or increase the average serviceability of the network during the programming period?

Pavement management is the process by which answers to these questions can be obtained; Alberta Transportation initiated a project in November 1980 to develop and implement a pavement management system (PMS) for the province of Alberta.

A comprehensive plan was developed in the first phase of the project, which started in November 1980 and was completed in January 1981 (1). Carried out as a preplanning project, the first phase identified six successive stages for the overall total PMS development and implementation project. These stages, which are briefly summarized in Figure 1, were designed specifically for Alberta Transportation's needs and requirements considering its goals and objectives, organizational structure, current