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Optimal Pavement Management Approach Using Roughness Measurements

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ABSTRACT

Many state highway departments are placing major emphasis on the development of cost-effective procedures for maintaining their existing pavement network. The state of Indiana is in need of a systematic procedure for allocating Interstate resurfacing funds to its pavement network. An optimization procedure for establishing resurfacing priorities at the network level, which can be incorporated in a pavement management system for the state, is described. Roughness measurements, increase in roughness over time, and traffic are the primary factors considered in the optimization scheme. Different types of resurfacing activities are considered in the model. A performance function model was developed to relate resurfacing strategies to the overall reduction in pavement roughness present in the pavement section just before resurfacing. Regression equations based on roughness measurements were also developed in this study for predicting future roughness levels. The optimization model has the capability of considering deficient pavement sections at any point within the specified analysis period. In addition, it has the capability of analyzing the impact of different budget scenarios. The model, in its present format, can predict what pavement section and resurfacing strategy combination should be adopted in order to achieve an optimal resurfacing program in Indiana during the next 5-year period. The application of the optimization model to the Indiana Interstate highway network is discussed in the paper.

The Indiana Department of Highways (IDOH) through the Research and Training Center (R&TC) has been collecting pavement roughness measurements on a continuing basis for the entire highway system since 1979. These data are summarized annually along with other information including average daily traffic (ADT) in one direction, surface type and texture, contract number, length, and last time a major rehabilitation was performed. This information currently forms the basis for most of the decisions about major rehabilitation, primarily for the Interstate system. Although this information is useful in identifying pavement sections that exceed the minimum acceptable values established by the state in any given year, it is not useful in the process of selecting those miles that have the greatest need given a constraint on the amount of money available for major rehabilitation. For an effective management approach, it is necessary to have a mathematical model that can answer questions such as (1,2)

1. Which specific pavement contract sections as well as how many miles of roads should be rehabilitated during a given year or during the time frame specified with available budget?
2. What type of resurfacing strategy should be applied to the pavement contract section selected in order to use the total available budget in the most cost-effective manner?
3. How many additional lane-miles can be improved if the budget is increased by a certain percentage?
4. How much additional budget is required to upgrade the pavement condition of the entire network (or a part of it) to a minimum acceptable level?

In the following paragraphs a systematic procedure, which uses a mathematical model for allocating maintenance and rehabilitation funds to existing pavements within the state of Indiana, is described. The results of applying the mathematical model to the Indiana Interstate highway network are also discussed.

DESCRIPTION OF METHODOLOGY

The methodology used in this study to arrive at the optimal number of resurfacing miles for the Interstate highway network during a given 5-year period is summarized as follows (3):

1. Concrete pavement sections within the Interstate system that have a roughness number greater than 2,000 counts per mile (as measured by the PCA Roadmeter) were identified and selected as input to the optimization model for the first year of the analysis period.
2. Regression models based on roughness measurements were developed for each Interstate route and pavement type combination (3). These models were then used to predict roughness numbers for the next 4 years for those pavement sections that were not identified as deficient during the first year of the analysis period. The development of the regression models is described in detail elsewhere (3).
3. All those pavement sections that exceeded the roughness threshold value during any of these 4 years were identified and selected as input to the optimization model in the year in which they reached the terminal roughness number.
4. Resurfacing activities were then assigned to each contract section selected for the optimization problem on the basis of the current ADT of the facility. A total of three resurfacing activities out of a possible seven were assigned to each pavement section.
5. Percentage reduction in pavement roughness associated with the resurfacing activities assigned to each contract section was estimated using a performance function model developed as part of the study.
6. A growth deterioration factor associated with each pavement section was computed as a ratio of the present roughness and the roughness number of the previous year.
7. Average routine maintenance costs expected during the next 5 calendar years for the resurfacing strategies considered were obtained from findings of a research study conducted at Purdue University by Sharaf and Sinha (4).
8. Unit cost information associated with each resurfacing activity was then used along with the length of each contract section to compute the resurfacing costs of each pavement section considered in the formulation.
9. Budget estimates obtained from IDOH Planning Division for the current year as well as for the last 4 years were then used to estimate the expected budget for the next 4 years of the analysis period (5).
10. The objective function and constraint coefficients were then computed using this information.
11. An optimization program, based on a zero-one integer programming technique, was then used to run the proposed formulation (6,7). The pavement contract sections selected for resurfacing by the optimization program during each year of the analysis period were then tabulated along with the resurfacing activity selected by the program.
12. A sensitivity analysis was then conducted on the model using five different budget scenarios and the results were tabulated in the same manner.

MODEL FORMULATION

The model described in this paper uses the present roughness number of each pavement contract section along with the variable that represents the percentage reduction in roughness number associated with a particular resurfacing strategy and the rate of increase in roughness number for each contract section. The total reduction in roughness number for each pavement section after the application of a particular resurfacing strategy is the new measure of effectiveness. This model, termed roughness reduction model, is

$$\text{Max } Z = \sum_{i=1}^{j} \sum_{j \epsilon A_i} \sum_{k=1}^{nyear} RN_i \, G_{ik} \, RED_j \, x_{ijk} \quad (1)$$

subject to

$$\sum_{i=1}^{n} \sum_{j \epsilon A_i} IF_k \, [L_i \, TRC_j \, (x_{ijk} - x_{ijk-1}) + L_i \, RMC_j \, x_{ijk}] \leqslant B_k \quad (2)$$

$$\sum_{j \epsilon A_i} x_{ijk} \leqslant 1 \qquad \text{for all i and k} \quad (3)$$

$$\sum_{j \epsilon A_i} x_{ijk} > x_{ijk-1} \qquad \text{for all i, k, and } j \epsilon A_i \quad (4)$$

where

RN_i = present roughness number for contract section i;
RED_j = percentage reduction in pavement roughness if resurfacing activity j is selected;
x_{ijk} = 1 if contract section i receives resurfacing activity j in year k and
= 0 otherwise;
L_i = length of contract section i (miles);
TRC_j = total resurfacing cost associated with activity j in 1982-1983 dollars per centerline mile;
RMC_j = annual routine maintenance cost associated with resurfacing activity j in dollars per centerline mile;
$j \epsilon A_i$ = resurfacing activity j that is one of the set of three feasible alternatives for pavement contract section i, A_i;
B_k = available budget for the kth year;
G_{ik} = growth deterioration factor for contract section i in the kth year [RN(k)/RN(k - 1)];
IF_k = inflation factor, $(i + i)^k$;
i = interest rate used, 6 percent;
n = total number of deficient pavement contract sections; and
nyear = number of years in the analysis period.

Equation 1 maximizes reduction in roughness in the entire highway system under consideration. An additional parameter (G_{ik}) is included as part of the objective function coefficient to take into account the annual deterioration rate associated with each contract section. This factor was computed as the ratio of the present roughness number to the roughness number of the previous year.

Equation 2 indicates that the total cost of all rehabilitation projects to be implemented must not exceed the available resurfacing program budget for each of the calendar years in the analysis period.

Equation 3 states that no more than one rehabilitation project can be selected from alternative project types for a contract section in a given year.

Equation 4 ensures that, if a rehabilitation project has been implemented in a previous year, only the routine maintenance task associated with a particular resurfacing activity will be performed in the current year.

The parameter used in the objective function to represent the percentage reduction in pavement roughness (RED_j) was predicted using a performance function model developed as a part of this study.

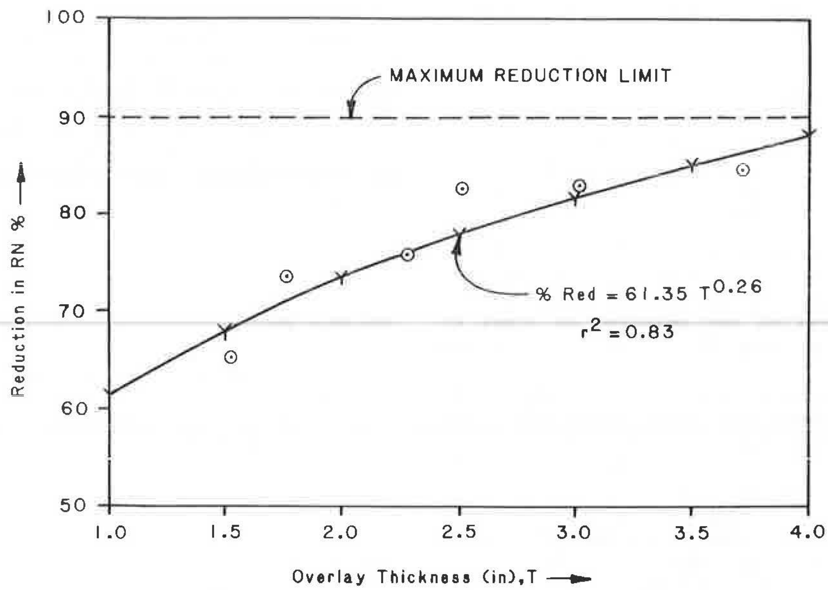

FIGURE 1 Relationship between reduction in roughness and required overlay thickness.

The performance model is shown next and plotted in Figure 1.

$$RED_j = 61.35 \times T_j^{0.26} \quad R^2 = 0.83 \tag{5}$$

where RED_j is the percentage reduction in roughness number after pavement contract section has been resurfaced with activity j and T is the overlay thickness of activity j in inches.

The observations shown in Figure 1 represent the mean reduction in roughness number attributable to the different overlay thicknesses used by IDOH in their entire pavement network.

It should be pointed out that the performance function model is only applicable within the range of thicknesses shown in Figure 1. Any attempt to apply the model above or below this range might give unrealistic results. For example, if the model is applied to a pavement section that has been resurfaced with an equivalent thickness of 5 in., the percentage reduction in roughness number using the model would be 93.2 percent and for 6 in. it would go as high as 97.8 percent. These percentage reduction values might be unrealistic in many cases. Even newly resurfaced pavements have a certain level of roughness, somewhere between 300 and 550 counts per lane-mile.

APPLICATION OF THE MODEL

The Indiana Interstate highway system was used to illustrate the application of the multiyear optimization model. This network consists primarily of jointed reinforced concrete (JRC) and continuously reinforced concrete (CRC) pavements with some segments already resurfaced with asphalt concrete. Because the resurfaced segments were less than 10 years old and the roughness number did not exceed the trigger value established for overlaid pavements, they were not considered for this study. A total of 70 contract sections were initially selected, and an additional 48 sections were selected for subsequent years using the roughness prediction models developed for each Interstate route and pavement type. Only those pavement sections exceeding 2,000 counts per mile as measured by the PCA Roadmeter were considered as input to the optimization problem. Table 1 gives the type of information collected for part of the contract section input to the model.

A total of three resurfacing activities out of seven were assigned to each pavement section input to the model. The criterion used to assign the resurfacing strategy to a particular pavement section was a function of the current traffic of the facility. The ADT ranges and the corresponding feasible resurfacing strategies for this study are given in Table 2. In this study the resurfacing activities considered were primarily the different asphalt concrete overlay thicknesses most commonly used by IDOH as part of their resurfacing program. The percentage reduction in pavement roughness, initial resurfacing cost, and annual pavement routine maintenance cost associated with each feasible resurfacing strategy considered in this study are given in Table 3.

Table 4 gives the input parameters for the optimization model. The pavement contract section was the unit used to represent the decision variables in this study. The section constraints were generated using Equations 2-4 previously defined in this paper. The budget scenarios including the present worth of budget considered in this study are given in Table 5. An interest rate of 6 percent was used to compute the present worth of budget.

The Linear Interactive and Discrete Optimizer (LINDO) computer package was selected to run the optimization program for this study because it is capable of handling a sufficiently large-scale problem (6,7).

DISCUSSION OF RESULTS

Optimal Resurfacing Program

Table 6 gives the results of the application of the roughness reduction optimization model by summarizing the pavement contract sections that were selected for resurfacing under budget scenario 2. An asterisk (*) indicates the calendar year in which a particular resurfacing strategy is to be applied on each pavement contract section. The total number of miles resurfaced in each calendar year and the total

TABLE 1 Information Pertaining to Part of the Pavement Sections Selected as Input to the Model

Route No.	Contract No.	Length (mi)	Surface Type[a]	ADT (vpd)	Age	RN Used	Year Input	Resurfacing Activity a	b	c	d	e	f	g
I-65 N	10232	1.6	261	27,267	7	2059	1986	0	0	1	1	1	0	0
I-65 N	5856	3.2	252	12,686	19	2088	1983	0	0	1	1	1	0	0
I-65 S	10347	1.2	261	27,675	7	2060	1985	0	0	1	1	1	0	0
I-65 S	7714	5.5	253	8,139	13	2052	1986	1	1	1	0	0	0	0
I-65 S	7677	4.4	253	9,543	13	2071	1984	1	1	1	0	0	0	0
I-65 S	7633	5.2	253	8,560	13	2027	1985	1	1	1	0	0	0	0
I-65 S	7624	1.7	253	23,821	13	2029	1986	0	0	1	1	1	0	0
I-65 S	7198	3.3	252	8,100	15	2051	1986	1	1	1	0	0	0	0
I-65 S	6333	1.4	252	15,843	17	2003	1985	0	0	1	1	1	0	0
I-65 S	5969	2.5	252	20,256	19	2077	1984	0	0	1	1	1	0	0
I-65 S	4710	1.4	252	10,700	22	2077	1986	0	0	1	1	1	0	0
I-69 N	7199	5.4	252	11,450	13	2040	1984	0	0	1	1	1	0	0
I-69 N	6930	3.6	252	5,448	17	2012	1984	1	1	1	0	0	0	0
I-69 N	6063	5.1	252	8,088	19	2027	1984	1	1	1	0	0	0	0
I-69 N	6022	3.7	252	7,150	19	2091	1986	1	1	1	0	0	0	0
I-69 N	5995	4.1	252	7,102	20	2006	1985	1	1	1	0	0	0	0
I-69 N	5968	4.0	252	11,149	19	2101	1984	0	0	1	1	1	0	0
I-69 N	5805	4.4	252	11,499	20	2039	1985	0	0	1	1	1	0	0
I-69 S	6930	3.6	252	5,448	17	2099	1986	1	1	1	0	0	0	0
I-69 S	6022	3.7	252	7,150	19	2053	1984	1	1	1	0	0	0	0
I-69 S	5995	4.1	252	7,102	20	2089	1986	1	1	1	0	0	0	0
I-69 S	5968	4.0	252	11,149	19	2080	1984	0	0	1	1	1	0	0
I-70 E	7390	6.6	252	12,462	13	2125	1983	0	0	1	1	1	0	0
I-70 E	7092	5.8	252	12,250	15	2126	1985	0	0	1	1	1	0	0
I-70 E	7091	0.7	252	12,000	14	2135	1983	0	0	1	1	1	0	0
I-70 E	6968	7.3	252	17,140	15	2032	1983	0	0	1	1	1	0	0
I-70 E	6956	3.7	252	20,500	16	2015	1986	0	0	1	1	1	0	0
I-70 W	7390	6.6	252	12,462	13	2072	1986	0	0	1	1	1	0	0
I-70 W	7389	4.8	252	12,500	13	2001	1985	0	0	1	1	1	0	0
I-70 W	7091	0.7	252	12,000	13	2001	1985	0	0	1	1	1	0	0
I-70 W	6968	7.3	252	17,140	15	2068	1986	0	0	1	1	1	0	0
I-70 W	6956	3.7	252	20,500	16	2072	1986	0	0	1	1	1	0	0
I-74 E	6290	6.3	252	3,763	18	2071	1986	1	1	1	0	0	0	0
I-74 E	6269	5.3	252	3,855	15	2118	1985	1	1	1	0	0	0	0
I-74 E	6064	6.0	252	5,212	19	2021	1986	1	1	1	0	0	0	0
I-74 E	5481	5.8	252	6,450	20	2012	1984	1	1	1	0	0	0	0
I-74 E	5434	5.4	252	6,008	20	2052	1983	1	1	1	0	0	0	0
I-74 E	4843	3.5	252	8,000	22	2067	1983	1	1	1	0	0	0	0
I-74 E	4614	7.5	252	5,907	22	2089	1985	1	1	1	0	0	0	0
I-74 E	4507	5.8	252	8,320	23	2019	1984	1	1	1	0	0	0	0
I-465 I[b]	5046	2.5	252	36,458	21	2032	1986	0	0	0	0	1	1	1
I-465 I	4710	3.2	252	23,889	22	2024	1986	0	0	1	1	1	0	0
I-465 O[c]	5969	1.3	252	23,331	19	2027	1985	0	0	1	1	1	0	0
I-465 O	5483	2.9	252	24,110	20	2036	1984	0	0	1	1	1	0	0
I-465 O	5046	2.5	252	36,526	21	2026	1985	0	0	0	0	1	1	1
I-465 O	4710	3.4	252	21,900	22	2029	1985	0	0	1	1	1	0	0
I-465 O	4709	1.2	252	38,117	22	2023	1984	0	0	0	0	1	1	1

[a] The code for type of surface or pavement is: jointed reinforced concrete = 252,261 and continuously reinforced concrete = 253,263.
[b] Inner loop.
[c] Outer loop.

TABLE 2 ADT Values Used To Assign Resurfacing Activities to Pavement Contract Sections Considered in the Model

ADT Range (vpd)	Resurfacing Activity[a] a	b	c	d	e	f	g
<10,000	1	1	1	0	0	0	0
10,000-30,000	0	0	1	1	1	0	0
>30,000	0	0	0	0	1	1	1

[a] Resurfacing activities are: a = 90 lb/yd², b = 175 lb/yd², c = 70 + 135 lb/yd², d = 70 + 220 lb/yd², e = 110 + 220 lb/yd², f = 70 + 135 + 175 lb/yd², and g = 70 + 175 + 175/yd².

number of contracts are also included at the end of the table.

Optimal Number of Miles Resurfaced

Figure 2 shows the pavement resurfacing mile sequence under budget scenario 2. It can be noted that at the beginning of the analysis period about 340 centerline miles were predicted to be deficient and at the end of the 5-year period only 87.2 miles (216.0 - 128.8) were considered deficient and car-

TABLE 3 Percentage Reductions in Roughness, Initial Resurfacing Costs, and Annual Routine Maintenance Costs Used in the Interstate Highway System Formulation

Resurfacing Activity (in.)	Percentage Reduction in Roughness	Resurfacing Cost ($/centerline mile)[a]	Routine Maintenance ($/centerline mile)[a]
a (1)	61.35	310,000	900
b (1.5)	68.17	345,000	765
c (2.0)	73.47	371,000	635
d (2.5)	77.85	393,000	500
e (3.0)	81.63	412,000	365
f (3.5)	84.97	429,000	235
g (4.0)	87.97	445,000	105

[a] Based on two-lane roadway in each direction and 24-ft lanes.

TABLE 4 Input Parameters for Interstate System Optimization Model

Parameter	Calendar Year 1982	1983	1984	1985	1986	Total
Contract sections	70	6	12	13	17	118
Analysis year	1	2	3	4	5	
Decision variables	1,050	72	108	78	51	1,359
Section constraints	1,190	78	108	65	17	1,458
Budget constraints	1	1	1	1	1	5

TABLE 5 Budget Scenarios and Present Worth of Budget Considered in this Study

	Budget Scenarios ($ millions)				
Calendar Year	1	2[a]	3	4	5
1982	17.0	17.0	17.0	17.0	17.0
1983	35.2	32.0	28.0	24.0	19.2
1984	50.6	46.0	41.4	34.5	27.6
1985	66.0	60.0	54.0	45.0	36.0
1986	82.5	75.0	67.5	56.3	45.0
Total budget	251.3	230.0	208.7	176.8	144.8
Present worth	203.8	186.7	169.6	144.1	118.4
Percentage of normal budget	1.1	1.0	0.9	0.75	0.6

[a]Normal level of budget.

ried over to calendar year 1987. Information of this type can also be used to monitor how many centerline miles will be optimally assigned for resurfacing in any calendar year for the budget scenario considered.

Effect of Alternative Budget Scenarios

To investigate the effect of different levels of budget on the effectiveness of resurfacing programs, the roughness reduction model was run with the different budget levels given in Table 5.

Figure 3 shows the effect of the total budget on the optimal number of resurfacing miles and the percentage of deficient mileage resurfaced during the 5-year analysis period.

TABLE 6 Results from Roughness Reduction Model for Budget Scenario 2: Interstate Highway System

Section (coded)	Calendar Year 1982	1983	1984	1985	1986	Resurfacing Activity[a]	Section Length
1			*[b]			e	4.6
2				*		c	5.8
3			*			c	7.1
4	*					c	3.7
5			*			c	6.1
6				*		c	6.4
7		*				e	5.1
8			*			c	6.0
9			*			c	3.7
10			*			c	4.1
11		*				c	4.4
12				*		c	3.6
13			*			c	4.4
14		*				c	3.7
15				*		c	5.1
16			*			c	6.4
17				*		e	6.1
18		*				c	3.7
19		*				e	4.5
20	*					c	2.9
21	*					c	6.2
22			*			c	7.8
23	*					e	5.3
24			*			c	4.1
25					*	c	5.7
26					*	c	5.2
27						n/s[c]	4.4
28				*		c	5.5
29				*		c	4.4
30		*				e	5.8
31	*					e	2.0
32						n/s	4.8
33				*		e	7.3
34		*				e	0.7
35					*	e	6.6
36		*				c	3.5
37					*	c	5.3
38				*		e	6.6
39	*					c	2.7
40					*	c	5.8
41	*					c	2.7
42	*					e	3.2
43			*			e	5.8
44				*		e	4.0
45				*		e	4.4
46	*					c	2.2
47			*			c	3.7
48	*					c	2.7
49			*			c	5.3
50			*			c	3.1
51			*			c	5.3
52				*		c	4.2
53		*				c	1.7
54	*					e	4.4
55					*	e	4.0
56				*		e	5.8
57				*		e	4.5
58		*				e	6.4
59			*			e	5.3
60			*			c	9.2
61		*				c	6.4
62		*				c	6.9
63				*		c	6.4
64	*					c	0.4
65					*	c	9.2
66		*				c	5.3
67		*				e	6.4
68		*				e	4.5
69	*					g	2.5
70					*	e	3.7
71					*	e	1.6
72				*		e	3.2
73					*	c	1.2
74						n/s	5.5
75					*	c	4.4
76				*		c	5.2
77					*	e	1.7
78					*	c	3.3
79				*		c	1.4
80			*			e	2.5
81					*	e	1.4
82					*	d	5.4
83				*		c	3.6
84					*	c	5.1
85					*	c	3.7
86					*	c	4.1
87					*	e	4.0
88				*		e	4.4
89					*	c	3.6
90					*	a	3.7
91					*	c	4.1
92					*	e	4.0
93						n/s	3.3
94						n/s	6.6
95					*	e	5.8
96		*				e	0.7
97						n/s	7.3
98					*	e	3.7
99						n/s	6.6
100					*	c	4.8
101					*	e	0.7
102						n/s	7.3
103						n/s	3.7
104						n/s	6.3
105						n/s	5.3
106						n/s	6.0
107						n/s	5.8
108					*	c	5.4
109					*	c	3.5
110						n/s	7.5
111				*		c	5.8
112					*	g	2.5
113					*	e	3.2
114				*		e	1.3
115				*		e	2.9
116				*		g	2.5
117				*		e	3.4
118				*		g	1.2
Contracts	13	16	18	26	31	104	88.1[d]
Miles	40.9	69.7	94.5	115	126.4	446.5	84.7[e]

[a]See Table 2 for resurfacing activity code.
[b]* = indicates the year the sections would be resurfaced.
[c]n/s = contract section not selected for resurfacing.
[d]Percentage of contracts that would be resurfaced.
[e]Percentage of miles that would be resurfaced.

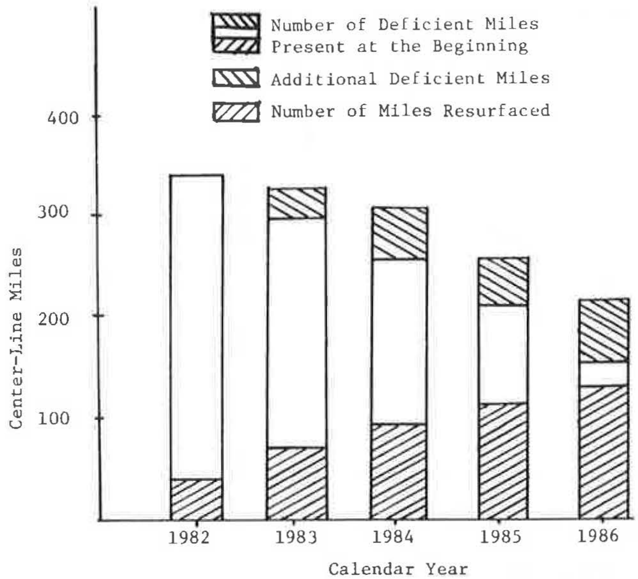

FIGURE 2 Pavement resurfacing mile sequence under budget scenario 2.

According to budget information furnished by IDOH, the total present worth figure of $187 million is the approximate budget expected to be allocated to the Interstate resurfacing program during the 5 years considered. For this amount Indiana can be expected to resurface about 450 Interstate centerline miles during this period of time. This would be equivalent to resurfacing about 85 percent of all the deficient centerline miles during the 5-year analysis period. The graph in Figure 3 also indicates how many additional centerline miles can be resurfaced to improve optimally the overall pavement condition during the next 5 years if the budget available for the Interstate resurfacing program is increased. For example, if the budget is increased 10 percent, the corresponding present worth is about $205 million for the 5 years and the number of centerline miles elected for the optimal resurfacing program is about 480. This is an increase of 30 centerline miles and it represents a program that would resurface about 92 percent of the deficient mileage during the analysis period, an increase in resurfacing miles of 7 percent over the normal budget level.

Rate of Resurfacing per Year

To better understand how the optimization model selects the contract sections for resurfacing under different budget scenarios, Figure 4 is presented. It is interesting to note in this figure how the slope of the mileage curve changes from year to year. In addition, it can be noted that the slopes for different budget scenarios are not the same. This graph indicates that the optimization model selects different sets of deficient contract sections depending on the budget available each year in order to maximize overall reduction in pavement roughness. In other words, if the budget is increased to a higher level, a pavement section selected for resurfacing during a given year under the initial budget scenario may be disregarded for resurfacing during that year and carried over to the next calendar year if another pavement section is encountered that can further improve the objective function in that calendar year.

For example, let us consider the curves corresponding to budget scenarios 1 and 4 in Figure 4. During the first year the number of miles resurfaced using any of the budget scenarios is practically the same because the base year budget was the same for all scenarios. However, during the second year the number of miles resurfaced under the lowest budget scenario 4 was obviously smaller compared to budget scenario 1. The rate of increase in miles of resurfacing was much higher for budget scenario 1 than that for budget scenario 4, as indicated by the slopes. Under budget scenario 4, the model attempted to resurface the most deteriorated sections requiring expensive resurfacing strategies in order to achieve the highest effectiveness, resulting in proportionally fewer resurfaced miles. However, during

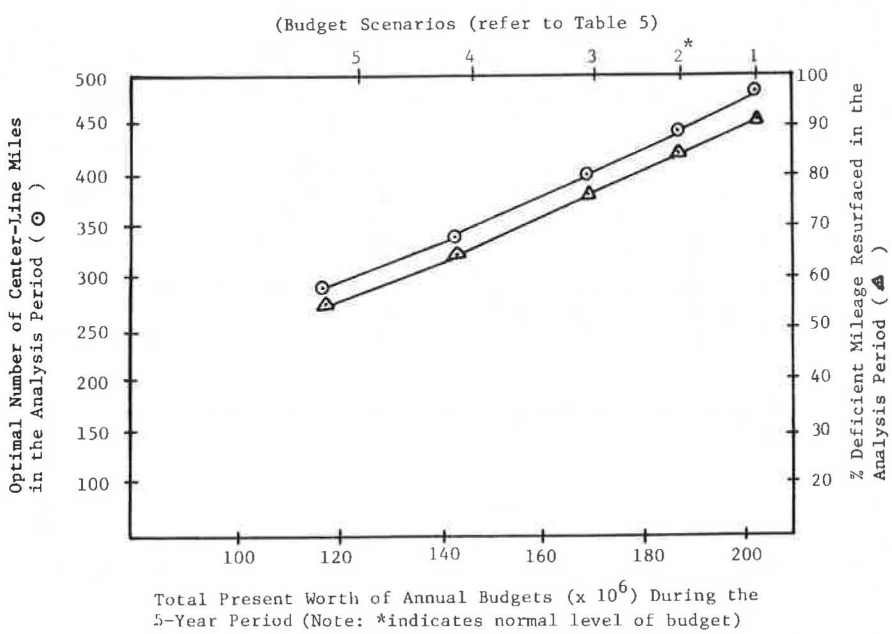

FIGURE 3 Effect of budget level on number of miles resurfaced in Interstate resurfacing program.

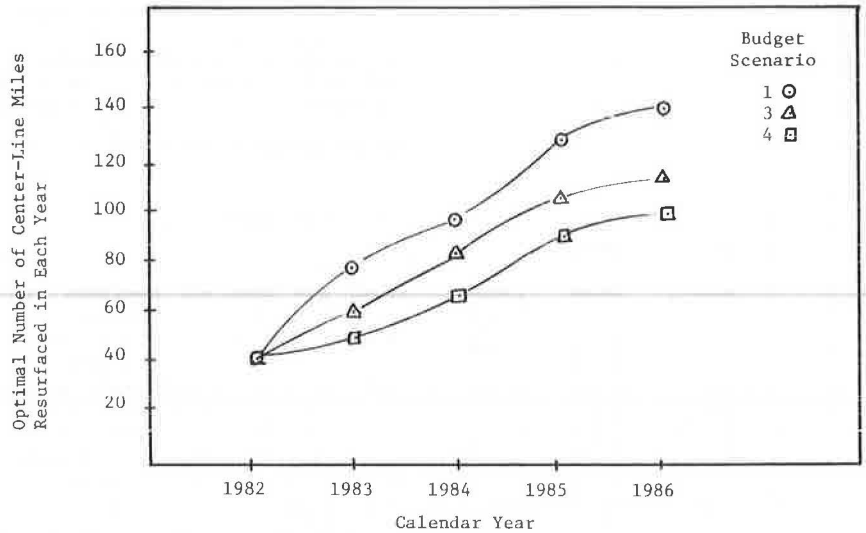

FIGURE 4 Effect of budget scenarios on number of miles resurfaced.

the third and fourth years, because the worst sections already have been resurfaced, the number of resurfaced miles sharply increases under budget scenario 4, as indicated by the steep slopes between 1983 and 1984 as well as between 1984 and 1985.

Optimality of the Solution

The solution achieved by this procedure is not entirely integer optimal but is quite close to the optimal linear programming (LP) solution. Previous research based on the branch and bound technique has shown that only minimal improvements are achieved after the problem has attained at least 97 percent of the optimal LP solution (7). Beyond this level the amount of computer time required to obtain an increase in optimality by even a small amount is disproportionately high. Table 7 gives a summary of the LP and IP solutions obtained from budget sensitivity analysis as well as the percentage of LP optimal. It can be noted that in all cases the first feasible integer solution was at least 97 percent of the optimal LP solution. That the first integer solution obtained was always within 3 percent of the optimum LP solution is also a good indication of the robustness of the formulation developed in this study.

Figure 5 shows the relationship between the percentage of LP optimum and the number of iterations required to achieve this value. In this particular scenario, the execution of the optimization program was stopped after 23,701 iterations when the fifth feasible integer solution was obtained. It can be noted in Figure 5 that the increase in optimality achieved since the first feasible IP solution is minimal compared to the number of iterations required to increase the solution from 99.21 to 99.36 percent. On the basis of the results obtained by the roughness reduction model, it is recommended to terminate the execution of the program if the IP solution obtained is within 3 percent of the optimal LP solution.

Detailed Summary of Results

Tables 8-10 give a detailed summary of the results under budget scenario 2. On the basis of these tables, the following remarks can be made:

1. A total of 103 of 118 contract sections were selected for resurfacing during the 5-year period. This corresponded to about 440 centerline miles out of the 527 mi identified in this study as deficient pavement sections, or about 83.5 percent.
2. More than 90 percent of the available budget was assigned in an optimal manner during the entire 5-year period.
3. Resurfacing activities c and e were the most frequently selected by the optimization routine: 96 of the 103 contract sections selected for resurfacing were assigned one of these two activities. This corresponded to 417.4 mi or approximately 94 percent of the deficient miles considered in this study. In most cases the resurfacing strategy selected by the optimization model was the most expensive of the three feasible rehabilitation strategies for the pavement section in question. Likewise, it was the resurfacing alternative that contributed most to the objective function value.
4. Approximately 10 percent of the budget for

TABLE 7 LP and IP Solutions Obtained from Budget Sensitivity Analysis for Roughness Reduction Model

		Roughness Reduction Model Characteristics					
Present Worth ($ millions)	Budget Scenario	LP (x 10^5)	Iteration	IP (x 10^5)	Iteration	Branch	Percentage of Optimum
203.78	1	15.80	2,497	15.44	6,642	32	97.8
186.71	2	15.40	2,678	15.30	23,701	63	99.4
169.94	3	14.96	2,998	14.75	4,169	23	98.6
144.08	4	14.23	2,681	13.95	5,925	50	98.1
118.44	5	13.37	3,372	13.21	8,283	24	98.8

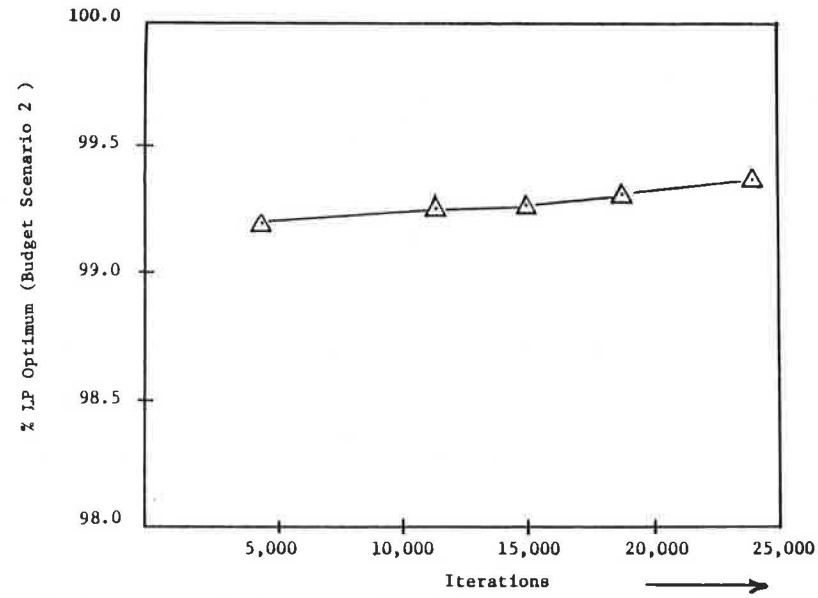

FIGURE 5 Relationship between number of iterations and percentage LP optimum under budget scenario 2.

TABLE 8 Summary of Deficient Centerline Miles, Mileage Resurfaced, Mileage Carried Over, and Budget Spent by Year in the Analysis Period

	Year in the Analysis Period					
Parameter Description	1982	1983	1984	1985	1986	5-Year Total
New sections entered	70	6	12	13	17	118
Total No. of sections present	70	63	60	51	46	
No. of sections selected by model	13	15	22	22	31	103
No. of new miles entered	336.7	26.7	48.4	50.2	64.9	526.9
Total No. of miles present	336.7	324.6	304.4	262.1	216.0	
No. of miles for resurfacing	38.8	68.6	92.5	111.0	128.8	439.7
Percentage of miles for resurfacing	11.5	21.1	30.4	42.4	59.6	83.5
Available budget ($ millions)	17.0	32.0	46.0	60.0	75.0	230.0
Budget spent ($ millions)	16.67	29.0	43.0	53.95	66.22	208.8
Percentage of budget spent	98.04	90.66	93.61	90.11	88.29	90.8
No. of miles carried over	297.9	256.0	211.9	151.1	87.2	
No. of sections carried over	57	48	38	29	15	
No. of new miles entered	336.7	26.7	48.4	50.2	64.9	526.9

the 5-year analysis period was never assigned. It can be recalled that the smallest unit for resurfacing established for this study was the pavement contract section. Therefore, in some cases, during a given calendar year there may be sufficient money left to resurface only a fraction of a set of contract sections. However, this was not done by the optimization routine because it was not feasible to resurface only a part of the contract section. This is a minor point because in reality money assigned to other tasks can be transferred to a related task if there is a need to do so.

TABLE 9 Total Number of Contracts and Miles Resurfaced According to Resurfacing Strategy and Analysis Year

			1982		1983		1984		1985		1986		5-Year Total	
Resurfacing Strategy (coded[a])	Resurfacing Cost ($/clm)[b]	Routine Maintenance ($/clm)	Contract Frequency	Resurfaced Miles	Contract Frequency	Resurfaced Miles	Contract Frequency	Resurfaced Miles	Contract Frequency	Resurfaced Miles	Contract Frequency	Resurfaced Miles	Contract Frequency	Resurfaced Miles
a	310,000	900									3	13.6	3	13.6
b	345,000	765												
c	371,000	635	4	8.8	7	30.4	12	51.0	13	74.7	14	64.6	50	229.5
d	393,000	500												
e	412,000	365	8	27.5	8	38.2	9	40.3	9	36.3	12	45.6	46	187.9
f	429,000	235												
g	445,000	105	1	2.5	—	—	1	1.2	—	—	2	5.0	4	8.7
Total			13	38.8	15	68.6	22	92.5	22	111.0	31	128.8	103	439.7

[a] Refer to Table 2 for resurfacing activity code.
[b] clm = centerline miles.

TABLE 10 Total Pavement Resurfacing Cost and Routine Maintenance Cost Spent According to Resurfacing Strategy and Analysis Year

Resurfacing Strategy (coded)[a]	Resurfacing Cost ($/clm)[b]	Routine Maintenance ($/clm)	1982		1983		1984		1985		1986		5-Year Total	
			TPRC[c] (x 10^6)	TRMC[d] (x 10^3)	TPRC (x 10^6)	TRMC (x 10^3)	TPRC (x 10^6)	TRMC (x 10^3)	TPRC (x 10^6)	TRMC (x 10^3)	TPRC (x 10^6)	TRMC (x 10^3)	TPRC (x 10^6)	TRMC (x 10^3)
a	310,000	900									5.64	16.38	5.64	16.38
b	345,000	765												
c	371,000	635	3.46	5.92	11.28	21.69	22.53	38.57	34.99	59.89	32.07	54.89	104.33	180.96
d	393,000	500												
e	412,000	365	12.01	10.64	17.68	15.67	19.77	17.52	18.88	16.73	25.14	22.27	93.48	82.83
f	429,000	235												
g	445,000	105	1.18	0.28	—	—	0.64	0.15	—	—	2.98	0.70	4.8	1.13
Total			16.65	16.84	28.96	37.36	42.94	56.24	53.87	76.61	65.83	94.24	208.25	281.13
Percentage of budget spent (without TRMC)			97.94		90.5		93.36		89.78		87.78		90.5	
Percentage of budget spent (including TRMC)[e]				98.04		90.66		93.61		90.11		88.29		90.67

[a] Refer to Table 2 for resurfacing activity code.
[b] clm = centerline miles.
[c] TPRC = total pavement resurfacing cost.
[d] TRMC = total routine maintenance cost.
[e] Includes accumulated routine maintenance costs attributed to pavement sections resurfaced in previous years.

SUMMARY

It has been shown how roughness measurements and ADT (as a surrogate of traffic) can be used along with an optimization procedure for establishing resurfacing priorities at the network level during a given 5-year horizon. A more complex model that incorporates the effect of climate and surface condition is described elsewhere (3). These results can be used by highway administrators and decision makers as a guide in making future budget requests and for relating these requests to an overall minimum acceptable level of the entire pavement network during a particular period of time.

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