SCHOOL OF
CIVIL ENGINEERING

INDIANA

DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-85/18

Final Report

ENERGY CONSERVATION AND COST SAVINGS
RELATED TO HIGHWAY ROUTINE MAINTENANCE

Mitsuru Saito
Essam A. Sharaf
Kumares C. Sinha

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Final Report

ENERGY CONSERVATION AND COST SAVINGS RELATED TO
HIGHWAY ROUTINE MAINTENANCE: FINAL REPORT

TO: Harold L. Michael, Director
Joint Highway Research Project

FROM: Kumares C. Sinha, Research Engineer
Joint Highway Research Project

October 9, 1985
Revised July 10, 1986
Project: C-36-67L
File: 9-11-12

Attached is the Final Report on the HPR Part II Study entitled, "Energy Conservation and Cost Savings Related to Highway Routine Maintenance". This final report covers the entire study with particular emphasis on Tasks 2, 3 and 4 dealing with optimization procedure and development of energy conservation guidelines. The research in the final phase of the study was conducted by Mitsuru Saito under my direction.

This report is forwarded for review, comment and acceptance by the IDOH and FHWA as fulfillment of the objectives of the research.

Respectfully Submitted,

Kumares C. Sinha
Research Engineer

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Final Report

ENERGY CONSERVATION AND COST SAVINGS RELATED TO

HIGHWAY ROUTINE MAINTENANCE

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in cooperation with the

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and the

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Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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16. Abstract This research was conducted in three phases. The first two phases were presented in two interim reports. This report includes a summary of the first two phases and a detailed discussion of the final phase. The final phase of the study focused on a trend analysis of energy use in routine maintenance and development of an optimization approach that can be used to determine the optimal assignment of various equipment types to different activities. The use of the approach was illustrated through an example application. A set of energy conservation guidelines was then outlined for possible implementation.					
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CHAPTER 1

INTRODUCTION

General Background

The nationwide highway maintenance resource costs, including labor, material and equipment, have significantly risen in recent years and the upward trend seems to continue, as shown in Figure 1.1. Revenues, however, have not kept up with the cost increase. With the constrained revenue situation, maintenance budget of many highway agencies has become increasingly limited. For example, in Indiana, while total highway revenue remained stable, disbursement for maintenance and operation considerably declined during the past several years, as shown in Figure 1.2.

To prolong the service life of existing highway pavements and to defer expensive major projects, the importance of routine maintenance is critical. However, the increased need for routine maintenance has placed a challenge for state highway agencies, because routine maintenance activities do not receive any federal aid and states must carry out the task through state generated revenues. Increased federal aid for major projects in recent years requires increased matching funds from state sources, and thus if there are no additional funds from state revenues, less funds will be available for routine maintenance. Consequently, routine maintenance productivity is receiving a considerable attention from highway agencies at all levels of government.

Routine maintenance is a fuel intensive work, as shown in Figure 1.3. In fiscal year 1984, Indiana Department of Highways (IDOH) spent an estimated amount of \$46.8 million in 1982 dollars for maintenance field activities.

Figure 1.1 Cost Indices of Highway Maintenance and Operation
In the United States

Figure 1.2. State Highway Revenues and Disbursements for Highways in Indiana in Million Dollars

Figure 1.3 Estimated Shares of Three Major Cost Components for Routine Maintenance in FY1984 (in 1982 Dollars)

About 12% of this cost was estimated to have been spent for fuel to operate equipment units assigned to routine maintenance. Also, approximately 35% of the total maintenance cost was spent for materials. Depending on the snowfall of the year, the share of fuel cost becomes one-third to one-fourth of the material cost when fuel is considered as a part of material.

Routine maintenance consists of various activities and requires different types of equipment. It was found that fuel use is dependent on the interaction of activity and equipment types. In order to plan effective energy conservation programs, it is first necessary to identify trends of fuel use by maintenance activities and equipment and to determine which components of highway routine maintenance have high fuel consumption rates. Efforts can then first be directed to major fuel consuming activity-equipment combinations.

Scope of the Study

This is the third and final report of a study entitled "Energy Conservation and Cost Savings Related to Highway Routine Maintenance." The first interim report [1] discussed the results of a field survey aimed at the identification of fuel consumption by various types of equipment used in highway routine maintenance activities conducted by IDOH. It presented two basic groups of results: (1) fuel consumption rates for all possible activity-equipment combinations as well as total fuel consumed per production unit of each activity; and (2) the effect of factors such as location (subdistrict), highway type, and season on fuel consumption. A summary of the first phase of the study is presented in Chapter 2.

The second interim report [2] presented an indepth analysis of pavement routine maintenance costs. Based on a series of statistical analyses, cost prediction models were developed for various pavement related maintenance activities. It was found that an increased execution of crack sealing in fall may reduce the amount of shallow patching on the same highway sections in the following spring. The tradeoff equations developed were used to estimate the extent of fuel consumption that can be expected due to a program of increased sealing and thus reducing the need for post-winter patching. A summary of the second phase of the study is included in Chapter 3.

The findings of the last phase of the study are presented in Chapters 4, 5 and 6. Chapter 4 discusses the results of the trend analysis on fuel consumption by various maintenance activities and equipment types in order to identify major fuel consuming activities and equipment. Chapter 5 includes the development of a fuel use optimization model and its application. In Chapter 6, a set of broad guidelines is discussed that can be used in the conservation of fuel in highway routine maintenance. Chapter 7 presents conclusions and recommendations of the study.

CHAPTER 2

DATA COLLECTION AND ANALYSIS OF FUEL CONSUMPTION RATES

This chapter provides a summary of the first phase of the study. This phase involved data collection and analysis of fuel consumption rates for various equipment types used in different routine maintenance activities. A more detailed description of this phase of the study is given in Reference 1.

Motor fuel should be treated as a special resource that needs to be effectively controlled. A careful management of motor fuel cannot be undertaken, however, without detailed information regarding equipment utilization and associated fuel consumption. Available information does not provide either the degree of variability of fuel consumption between different equipment types, or the variability of fuel consumption for the same equipment when used in different maintenance activities. Furthermore, the current information of equipment utilization in the IDOH is presented in terms of number of hours or number of miles an equipment is used. These measures are not detailed enough for maintenance management unless other supporting rates of consumption are developed. Such rates as miles per gallon (mpg) or gallons per hour (gph) are necessary not only to recognize the amount of fuel consumed, but also to identify the degree of use of a particular equipment. This information can then be used to formulate strategies that can achieve improved equipment utilization and thus can save energy and maintenance costs. The results obtained can also be of use to the IDOH in programming of routine maintenance activities.

Data Collection Procedure

Although the primary objective of the first phase of the study was to develop new standards for maintenance equipment fuel consumption, it was decided to consider also the calculation of unit costs for the other two resources, material (other than motor fuel) and labor. This was done for two reasons: (i) to update the current material and labor standards, if necessary; and (ii) to determine the share of fuel cost in the total cost of undertaking a routine maintenance activity.

Field data were collected in the present study using the existing system of maintenance data recording of the IDOH with some modifications. The current data recording system consists of filing work records on a card called a crew day card. Each time a crew performs an activity all necessary information is recorded on a crew day card. Information recorded on such cards includes: (i) routine maintenance activity type; (ii) location where the activity was performed; (iii) date; (iv) number of crew members and corresponding man-hours; (v) equipment used and corresponding miles or hours; (vi) materials used and corresponding quantities; and (vii) total accomplishment (production units).

Six subdistricts were chosen within the six districts of the IDOH for field data collection. The location of these subdistricts is shown in Figure 2.1. The current data recording system of the IDOH does not include any information about the amount of fuel consumed by different equipment types. To provide fuel use data for this study, the subdistrict managers were instructed to fill each equipment with fuel before and after each job. The difference was to be recorded on the same crew day card with other associated activity data.

Figure 2.1. Locations of Subdistricts Included in the Study

To avoid bias toward a specific period of the year, the data collection was spread over the entire fiscal year 1981-1982. The year was divided into four basic work seasons: fall, winter, spring, and summer. During a particular season, the data were collected over an extended period. For example, the fall data were collected for about six weeks during October and November, 1981, the winter data in a period of eight to ten weeks between December, 1981 and April, 1982, the spring data in a period of six weeks between April and May, 1982, and the summer data in a period of six weeks between May and July, 1982. By spreading the sample data over the entire fiscal year, it was ensured that those activities with seasonal peaks would be appropriately represented. For instance, about 50% of the total production units of shallow patching activity is accomplished in the spring season, while machine mowing is concentrated in the summer.

The data were screened and about 15% of the total sample size was excluded for one or more of the following reasons: (i) more than one activity reported on the same crew day card; (ii) missing information, such as number of gallons consumed by one or more equipment; or (iii) when obvious recording mistakes were detected.

Table 2.1 shows the different routine maintenance activities included in the maintenance management system of the IDOH, along with their code numbers and units of measure. The list of equipment types used in maintenance activities is shown in Table 2.2 along with the code numbers.

Table 2.1 Routine Maintenance Activities Included in the Study

Code No.	Activity Name	Work Category *	Unit of Measure
I. Roadway and Shoulder			
201	Shallow patching	UL	Tons of mix
202	Deep patching	UL	Tons of mix
203	Premix leveling	V	Tons of mix
204	Full width shoulder seal	L	Foot miles
205	Seal coating	L	Lane miles
206	Sealing longitudinal cracks & joints	L	Linear miles
207	Sealing cracks	L	Lane miles
209	Cutting relief joints	L	Linear feet
210	Spot repair of unpaved shoulders	UL	Tons of aggregate
211	Blading shoulders	L	Shoulder miles
212	Clipping unpaved shoulders	L	Shoulder miles
213	Reconditioning unpaved shoulders	V	Shoulder miles
214	Joint and bump burning	V	Bumps removed
219	Others	V	Man-hours
II. Roadside			
221	Machine mowing	UL	Swath miles
222	Brush cutting	V	Man-hours
223	Herbicide cutting	UL	Man-hours
224	Seeding and/or fertilizing	L	Man-hours
225	Topping, trimming or removal of long trees	UL	Trees
226	Stump removal	UL	Stumps
227	Spot mowing and hand trimming	UL	Man-hours
228	Right-of-way fence repair	V	Linear feet
229	Others	V	Man-hours
III. Drainage			
231	Clean and reshape ditches	L	Linear feet
232	Inspect minor drainage structures	L	Structures
233	Pipe replacement	L	Locations
234	Motor patrol ditching	L	Ditch mile
235	Cleaning minor drainage structures	UL	Structures
239	Others	V	Man-hours
IV. Bridges			
241	Hand cleaning bridges	L	Decks cleaned
243	Bridge repair	UL	Man-hours
244	Flushing bridges	L	Decks flushed
245	Patching bridges	UL	square feet
249	Others	V	Man-hours

Table 2.1 Routine Maintenance Activities Included in the Study
(continued)

Code No.	activity Name	Work Category *	Unit of Measure
V. Traffic Control			
251	Subdistrict sign maintenance	UL	Man-hours
257	Paint pavement messages and special markings	UL	Man-hours
258	Guardrail maintenance	UL	Linear feet
259	Others	V	Man-hours
VI. Winter and Emergency			
261	Emergency maintenance	UL	Man-hours
263	Snow and ice removal	UL	Man-hours
265	Stockpiling winter materials	UL	Man-hours
266	Winter night patrol	UL	Man-hours
269	Others	UL	Man-hours
VII. Public Service			
271	Rest area and lift bridge attendant	OH	Man-hours
272	Roadside park, rest area, and weigh station maintenance	OH	Man-hours
273	Work of Department of Natural Resources	OH	Man-hours
274	Work for state institutions	OH	Man-hours
275	Full width litter pickup	UL	R.O.W. Pass-miles
276	Spot litter pickup	UL	Man-hours
277	Roadway cleaning	V	Man-hours
279	Others	OH	Man-hours
VIII. Others			
281	Equipment repairs and maintenance	OH	Man-hours
283	Buildings and grounds maintenance	OH	Man-hours
284	Materials handling and storage	OH	Man-hours
287	Detour maintenance	UL	Man-hours
289	Other support activities	OH	Man-hours
291	Special maintenance	V	Man-hours
295	Special maintenance	V	Man-hours
296	Special maintenance	V	Man-hours
112	Field maintenance supervision	OH	Man-hours
117	Training	OH	Man-hours
120	Standby time	OH	Man-hours
900	Leave	OH	Man-hours

* Work Category: UL = Unlimited category
V = Variable category

L = Limited category
OH = Overhead category

Table 2.2 List of Equipment Used in Routine Maintenance Activities

Code No.	Equipment Type	Code No.	Equipment Type
1	Pickup truck	41	Paint machine
2	Pickup crew cab	42	Tractor truck
3	Aerial basket truck	43	Tractor mower
4	Flatbed truck	44	Compressor
5	Water truck	45	Mixer
6	Bucket truck	46	Squeegee cart
7	Distributor	47	Flashing arrow board
8	Utility truck	48	Porta patcher
9	Dump truck	49	Jeep
10	Do-all truck	50	Lowboy trailer
11	Catch basin cleaner	51	Trailer
12	Compactor	52	Pavement cutter
13	Tar kettle	53	Chemical spreader
14	Premix storage trailer	54	Maintainer
15	Burner unit	55	Back blade
16	Paver	56	Berm drag
17	Widener	57	Undeck body
18	Jack hammer	58	Broom tractor
19	Portable roller	59	Weed eater
20	Roller	60	Rotor tiller
21	Street sweeper	61	Rack truck
22	Broom	62	Pole truck
23	Backhoe	64	Gradall
24	Excavator	65	Pavement breaker
25	Grader	66	Semi trailer
26	Loader	67	Dozer
27	Snow blow	68	Whocker
28	Chip spreader	69	Crawler
29	Salt spreader	70	Vermeer cutter
30	Underbody scraper	71	Ave-all
31	Brush chipper	72	Sewer jet
32	Stump cutter	73	Crane
33	Auger/driver	74	Stake truck
34	Lawn mower	75	Generator
35	Hand mower	76	Port line marker
36	Chain saw	77	Van
37	Concrete saw	78	Sewer vector
38	Pavement cutter	79	Vermeer trailer
39	Hydro-seeder		
40	Weed sprayer		

Results of the Data Analysis

Calculation of Fuel Consumption Rates and Costs

In this group, fuel consumption rates and costs were computed along with the ratio of fuel cost to total cost or to material cost. Total cost of an activity was defined as the sum of labor, material (other than fuel), and fuel (equipment) costs. Although the IDOH already has good standards (unit costs) for both labor and material (other than fuel), it was decided to determine these unit costs on the basis of the field sample data collected in this study. This way the current rates can be further checked and a uniform and unbiased set of cost data can be developed for the computation of ratios of fuel cost to other resource costs.

Cost Computation Procedure

The general form of cost calculation of an activity is given by:

$$T_k = \sum_i \sum_j f_{ijk} * R_{ijk} * C_{ij} \quad (2.1)$$

where,

T_k = total cost in dollars per production unit of the k^{th} activity;

f_{ijk} = usage factor of the j^{th} element of the i^{th} resource when used in accomplishing the k^{th} activity;

R_{ijk} = rate of consumption of the j^{th} element of the i^{th} resource required to produce one unit of the k^{th} activity;

C_{ij} = unit cost of the j^{th} element of the i^{th} resource.

The usage factor, f_{ijk} , is calculated as

$$f_{ijk} = \frac{n_{ijk}}{N_k} \quad (2.2)$$

where,

n_{ijk} = total number of jobs observed using the j^{th} element of
of i^{th} resource in the k^{th} activity;

N_k = total number of jobs in the k^{th} activity.

Finally, the consumption rate, R_{ijk} , is obtained from

$$R_{ijk} = \frac{U_{ijk}}{P_k} \quad (2.3)$$

where,

U_{ijk} = total number of units of the j^{th} element in the i^{th}
resource when used in the k^{th} activity;

P_k = total number of units produced of the k^{th} activity.

The computational procedure can best be illustrated by an example. Consider Activity 201 (shallow patching). The computations of labor, material, and fuel costs for this activity are presented in Table 2.3.

The usage factor (f_{ijk} , Equation 2.2) represents the frequency of use of certain resource element. For example, the usage factor of the first element ($j=1$) of the first resource ($i=1$), namely maintenance worker IV, is 5.0. This means that in the 342 jobs of activity 201 (shallow patching) there was a total of about 1710 maintenance workers of category IV, resulting in an average of 5.0. Similarly, in the 342 jobs where activity 201 was conducted (in the sample), a total of 311 dump trucks was used; the corresponding usage factor is therefore 0.91 for the 6th element (dump truck) in the 3rd resource (equipment).

Rate of consumption is the average number of units of a certain resource element required to produce one production unit of an activity (R_{ijk} , Equation

Table 2.3. Cost Calculation Example (for Shallow Patching Activity).

Resource	i	Element	j	f _{ij}	R _{ij}	C _{ij}	Total Cost
Labor	1	Maintenance Worker IV	1	5.0	2.23 m.hr/Prod. Unit	\$5.67 / m.hr.	\$77.77 Labor Cost per Production Unit.
	1	" " III	2	1.0	2.23 m.hr/Prod. Unit	\$6.52 / m.hr.	
Materials	2	Aggreg. or backfill	1	0.02	1.00 tons/Prod. Unit	4.10 / ton	\$27.30 Material Cost per Production Unit.
	2	Seal Cover Aggreg.	2	0.02	0.30 tons/ "	3.00 / ton	
	2	Bit. Material	3	0.30	7.77 gallons/ "	0.78 / gallon	
	2	Bit. Mix	4	0.50	1.00 tons/ "	25.50 / ton	
Equipment	2	Salvage Bit. Mix	5	0.50	1.00 tons/ "	25.50 / ton	\$9.32 Fuel Cost per Production Unit.
	3	Pickup Truck	1	0.10	3.66 gallons/ "	1.05 / gallon	
	3	Pickup Crew Cab	2	1.10	2.69 "	"	
	3	Flatbed Truck	3	0.06	3.27 "	"	
	3	Distributor	4	0.02	2.53 "	"	
	3	Utility Truck	5	0.01	4.22 "	"	
	3	Dump Truck	6	0.91	4.78 "	"	
	3	Do-all Truck	7	0.12	3.71 "	"	
	3	Compactor	8	0.10	0.19 "	"	
	3	Tar Kettle	9	0.06	0.00 "	"	
	3	Premix Storage Trailer	10	0.49	0.00 "	"	
	3	Roller	11	0.05	0.60 "	"	
	3	Loader	12	0.03	1.66 "	"	
	3	Air Compressor	13	0.01	2.17 "	"	
	3	Flashing Arrow Board	14	0.18	1.14 "	"	
	3	Porta Patcher	15	0.09	0.00 "	"	
	3	Stake Truck	16	0.01	7.14 "	"	

\$114.39 Total Cost per Production Unit.

2.3). For example, to calculate the consumption rate of fuel for a dump truck when used in activity 201, the total number of gallons consumed by all dump trucks in the 342 jobs of this activity (U_{ijk} , Equation 2.3) was calculated and found to be equal to 3640.4 gallons. On the other hand, the total number of activity 201 units produced in the 342 jobs was found to be 1180 tons of mix (P_k , Equation 2.3). Thus, by applying Equation 2.3, the average fuel consumption rate of a dump truck when used in activity 201 is about 4.78 gallons.

Application of Equation 2.1 in this example results in a total cost of \$114.39 per production unit of Activity 201 (1981-1982 unit costs). The fuel cost per production unit is \$9.32 and the total materials cost (including fuel) per production unit is \$36.62. Therefore, the motor fuel cost, as a single material item, represents about 25% of the total material costs, and nearly 8% of the total cost for shallow patching activity.

The above calculations were repeated for all other activities considered in this study. A summary of the results is given in Table 2.4. In addition, Table 2.4 provides a comparison between different activities in terms of fuel and material (other than fuel) costs per man-hour. Man-hour was chosen as the unit for this comparison because it is common in all activities. On this basis, the high fuel consuming activities could be divided into 3 groups: (i) activities with high degree of equipment involvement in their operations such as Activities 203, 204, 205, 212, 213, 226, and 231 (refer to Table 2.1 for activity names); (ii) winter activities such as 263, 265, and 266; and activities which involve long distance driving such as 284 and 289.

Table 2.4 Summary of Resource Costs¹

Activity Number	Av. Fuel Cost Per Prod. Unit	Av. Material Cost Per Prod. Unit	Av. Labor Cost Per Prod. Unit	Ave. Total Cost Per Prod. Unit	Av. Man-Hours Per Prod. Unit	Av. Fuel Cost Per Man-Hour	Av. Material Cost Per Man-Hour
201	9.32	27.3	77.77	114.39	13.39	0.70	2.04
202	8.88	25.98	31.77	66.63	5.32	1.67	4.88
203	5.30	26.84	13.93	46.07	2.31	2.30	11.64
204	8.16	77.56	19.65	105.37	3.16	2.58	24.51
205	89.74	1435.41	158.32	1683.47	25.49	3.52	56.30
206	8.25	56.00	49.72	113.97	7.99	1.03	7.01
207	24.41	114.64	166.85	305.90	28.72	0.85	3.99
209	0.55	2.14	2.67	5.36	0.44	1.24	4.87
210	2.26	4.10	7.55	13.91	1.30	1.74	3.16
211	2.80	0	12.49	15.29	2.10	1.34	0
212	55.51	0	147.00	202.51	23.86	2.33	0
213	63.43	305.86	162.45	531.45	26.67	2.38	11.47
214	2.24	1.09	25.15	28.48	4.18	0.53	0.26
219	0.56	3.10	5.85	9.51	1.00	0.56	3.10
221	1.95	0	6.65	8.60	1.13	1.73	0
222	0.78	0	5.99	6.77	1.00	0.78	0
223	0.88	15.65	5.95	22.48	1.00	0.88	15.65
224	0.23	7.03	5.95	13.21	1.00	0.23	7.03
225	21.69	0	106.48	128.17	17.37	1.25	0
226	5.30	0	14.08	19.38	2.37	2.24	0
227	0.80	0	5.95	6.75	1.00	0.80	0
228	0.17	1.24	1.13	2.54	0.19	0.87	6.45
229	1.48	0	5.93	7.41	1.00	1.48	0
231	0.24	0.03	0.58	0.85	0.10	2.49	0.31
232	0.27	0	3.72	3.99	0.61	0.45	0
233	65.20	749.41	365.81	1180.42	61.27	1.06	12.23
234	82.13	0	349.50	431.63	57.20	1.44	0
235	4.06	0	24.05	28.11	4.03	1.01	0
239	0.86	3.82	5.88	10.56	1.00	0.86	3.82
241	5.69	0	46.60	52.29	7.93	0.72	0
243	0.62	2.10	6.10	8.82	1.00	0.62	2.10
244	2.31	0	20.50	22.81	3.42	0.67	0
245	1.01	0.49	5.43	6.93	0.92	1.10	0.53
249	0.62	11.09	5.85	17.56	1.00	0.62	11.09
251	1.09	5.10	6.20	12.39	1.00	1.09	5.10
257	0.79	2.82	6.00	9.61	1.00	0.79	2.82
258	0.92	6.20	7.13	14.25	1.21	0.76	5.11
259	1.21	0	5.92	7.13	1.00	1.21	0
261	1.83	1.00	6.10	8.93	1.00	1.83	1.00
263	5.25	22.46	6.50	34.21	1.00	5.25	22.46
265	2.01	0	5.76	7.77	1.00	2.01	0
266	3.58	0	5.67	9.25	1.00	3.58	0
269	0.81	0.23	5.84	6.88	1.00	0.81	0.23
271	0.98	0	5.40	6.38	1.00	0.98	0
272	0.98	0	5.67	6.65	1.00	0.98	0
273	0.65	4.88	6.00	11.53	1.00	0.65	4.88
274	0.65	2.17	5.89	8.71	1.00	0.65	2.17
275	2.59	0	17.95	20.54	3.17	0.82	0
276	0.98	0	5.67	6.65	1.00	0.98	0
277	0.80	0	6.17	6.97	1.00	0.80	0
279	1.98	0	5.67	7.65	1.00	1.98	0
281	0	0	6.00	6.00	1.00	0	0
283	1.64	0	6.00	7.64	1.00	1.64	0
284	3.73	0	5.95	9.68	1.00	3.73	0
287	1.08	0	6.10	7.18	1.00	1.08	0
289	2.86	0	6.10	8.96	1.00	2.86	0
291	1.86	30.80	6.30	38.96	1.00	1.86	30.80
295	0.63	9.56	6.30	16.49	1.00	0.63	9.56
296	1.64	14.90	6.30	22.84	1.00	1.64	14.90
112	0	0	8.00	8.00	1.00	0	0
117	0	0	6.00	6.00	1.00	0	0
120	0	0	6.00	6.00	1.00	0	0
900	0	0	5.50	5.50	1.00	0	0

1. All costs are based on 1981-1982 prices.
2. Refer to Table 2.1 for activity names.

Factors Affecting Fuel Consumption

Two major factors that affect fuel consumption rates in maintenance activities are: (i) frequency of use of individual equipment; and (ii) consumption rate of individual equipment. The effect of highway type and of season on each of these factors was also considered.

Equipment Frequency of Use

The usage factors (f_{ijk} , Equation 2.1) for all activity-equipment combinations were computed. Several cases were studied to determine whether the frequencies of equipment use on Interstate System (IS) differ from those on Other State Highways (OSH). A close examination of the usage factors developed from the field data indicated that frequency of use of an equipment was independent of highway type.

The next analysis of equipment usage was carried out to examine the variation between subdistricts. In fact, a significant variation by subdistrict was noted in more than 50% of the activities. However, for the purpose of illustration, we consider here five most frequently undertaken activities. These activities are 201, 221, 231, 251, and 276 (refer to Table 2.1 for activity names). For each activity we chose the most frequently used equipment (highest usage factor). The results concerning the usage factors for the different cases considered are illustrated in Figures 2.2 through 2.6.

It is obvious from these figures that the frequency of use of an equipment can vary significantly from one subdistrict to another. Consequently, the individual values for each subdistrict can also differ considerably from the total average. To illustrate, consider the case of Activity 201, as shown in Figure 2.2. The usage factor for a dump truck in subdistrict number 1 (refer to Figure 2.1 for subdistrict locations) is 1.20, whereas it is 0.42

Figure 2.2. Usage Factors for Dump Truck - Shallow Patching Combination (by Subdistrict)

Figure 2.3. Usage Factors for Tractor Truck - Machine Mowing Combination (by Subdistrict)

Figure 2.4. Usage Factors for Dump Truck - Cleaning and Reshaping Ditches Combination (by Subdistrict)

* Refer to Figure 2.1 for subdistrict name and location.

Figure 2.5. Usage Factors for Utility Truck - Sign Maintenance Combination (by Subdistrict)

Figure 2.6. Usage Factors for Pickup Truck - Spot Litter Pickup Combination (by Subdistrict)

* Refer to Figure 2.1 for subdistrict name and location.

for subdistrict 4 and 1.50 for subdistrict 6. Similar results can be seen for the other four cases, as presented in Figures 2.2 through 2.6. There are also other numerous cases that indicate a variation between subdistricts in their degree of equipment usage frequency. This fact should be kept in mind in the evaluation process, as this variation can greatly affect the total number of gallons per production unit of an activity.

The last factor that was investigated is the season (time of year when an activity was performed). The same activity-equipment combinations used in the previous analysis (Figures 2.2 through 2.6) were utilized in the present analysis.

The main conclusion arrived at in this analysis is that equipment usage factors vary in many cases from season to season. This is primarily because the availability of an equipment for a given activity is limited by the competition between several activities being undertaken during the same season. For example, considering Activity 201 (shallow patching), the usage factor of a dump truck is less in winter than in summer (see Figure 2.7). This difference can be attributed to the fact that during the winter months the use of the available dump trucks for snow removal and ice control is given higher priority over other activities. The variation in other equipment usage factors by season is illustrated in Figures 2.8 through 2.11.

Rates of Equipment Fuel Consumption

Rate of fuel consumption of an equipment when used in an activity is defined as the number of gallons consumed by this equipment to accomplish one production unit of the activity. The summation of these rates for all equipment used in an activity will result in the overall rate of fuel consumption

Figure 2.7. Usage Factor for Dump Truck - Shallow Patching Combination (by Season)

Figure 2.8. Usage Factors for Tractor Truck - Machine Mowing Combination (by Season)

Figure 2.9. Usage Factors for Dump Truck - Clean and Reshape Ditches Combination (by Season)

Figure 2.10. Usage Factors for Utility Truck - Sign Maintenance Combination (by Season)

Figure 2.11. Usage Factors for Pickup Truck - Spot Litter Pickup Combination (by Season)

for the particular activity.

Consumption rates of an equipment usually vary from activity to activity. This is usually so because of the difference in the nature of work conducted by the same equipment in different activities. A good factor to analyze such differences is the equipment operational rates related to fuel consumption, such as miles per gallon (mpg) or gallon per hour (gph). For example, in Figure 2.12 are shown the operational rates for a dump truck when used in different activities, while Figure 2.13 shows similar results for a loader. The two equipment types, dump truck, and loader, are discussed here as examples; however, the available data would allow an analysis of this pattern of variation for any other equipment types.

It is obvious that an assumption of equal operational rates for a maintenance equipment in different activities can be misleading. To illustrate, consider Figure 2.13 where the loader operational rates are shown. In Activity 202 (deep patching), 0.94 gallons per hour is the operational rate, contrasted to 2.67 and 2.13 gallons per hour for Activities 212 and 234, respectively. It is clear that the work conducted by a loader in Activity 202 is much simpler than that performed in Activity 212 or 234, where more gallons per hour are consumed. Similarly, a dump truck (Figure 2.12) would show more miles per gallon in those activities that have less idling.

The first analysis on operational rates of fuel consumption was to examine if these rates differed by type of highway. A relatively small number of data observations was available for jobs done on Interstates. This is because the number of units accomplished in most activities on the Interstate system is much less than that carried out on Other State Highways system

Figure 2.12 Fuel Consumption Rates (Miles Per Gallon for a Dump Truck.

* Refer to Table 2.1 for activity names.

Figure 2.13. Fuel Consumption Rates (Gallons Per Hour) for a Loader.

*Refer to Table 2.1 for activity names.

(OSH). This can be confirmed by the fact that only 10% of the total routine maintenance expenditures in 1981-1982 was on the Interstate system.

The limited available data for the Interstate system did not cover all activity-equipment-highway type combinations. Only 20 separate statistical tests were therefore applied. Each test is defined by the season, activity number, subdistrict number and equipment number. A list of these tests is shown in Table 2.5. The reason for considering the above elements in defining each test is to eliminate the effect of factors other than highway type. So, in each test the operational rates of an equipment type in both Interstate and Other State Highways were statistically compared, and the results are reported in the last column in Table 2.5. A "Yes" means that average values of operational rates in the two systems is significantly different at a level of confidence of 90% or 95%. To illustrate, consider Test 15. This test was to compare the output rates (mpg) of a dump truck (Equipment 2.9) for shallow patching (Activity 201) on Interstate and Other State Highways within Subdistrict 5, performed in spring season. It was found that average operational rates on the two highway systems are significantly different. It is clear that the general trend is a higher rate of fuel consumption on Interstate systems. Out of 20 tests, 17 tests indicated a significant difference between the two highway systems with a higher fuel consumption rate for the Interstate system.

It should be noted that the results are based on a relatively small number of Interstate observations and not all activities were covered by the comparison tests. However, the results point out the importance of a careful study of the management units (subdistricts) that have a large portion of Interstate mileage in their highway system. These subdistricts may need to

Table 2.5. Tests to Compare Operational Rates of Fuel Consumption in Interstate and Other State Highway Systems.

Test Number	Season	Activity Number ¹	Subdistrict Number ²	Equipment Number ³	Rate	Consumption Rate		Test Significance ⁶
						Interstate	Other State Highway	
1	Fall	207	2	1	mpg ⁴	3.02	4.49	Yes
2	Fall	207	2	2	mpg	3.59	4.83	Yes
3	Fall	207	2	9	mpg	0.84	1.86	Yes
4	Fall	207	2	44	gph ⁵	1.80	1.50	Yes
5	Fall	251	1	8	mpg	7.89	8.80	Yes
6	Fall	276	1	9	mpg	3.49	4.37	Yes
7	Fall	276	2	1	mpg	8.29	7.69	No
8	Fall	276	5	1	mpg	9.50	10.41	Yes
9	Fall	276	5	9	mpg	4.13	5.12	Yes
10	Fall	277	5	1	mpg	11.02	12.22	Yes
11	Fall	277	5	2	mpg	6.33	6.48	No
12	Winter	207	2	2	mpg	3.70	5.58	Yes
13	Winter	207	2	9	mpg	2.30	2.81	Yes
14	Spring	201	1	2	mpg	4.03	5.46	Yes
15	Spring	201	5	9	mpg	2.07	2.91	Yes
16	Spring	222	5	36	gph	0.46	0.50	No
17	Spring	241	5	1	mpg	6.74	5.70	Yes
18	Spring	275	5	9	mpg	2.60	3.65	Yes
19	Spring	277	5	44	gph	2.17	2.88	Yes
20	Spring	279	5	9	mpg	3.05	4.85	Yes

1 Refer to Table 2.1 for activity names

2 Refer to Figure 2.1 for subdistrict names and locations

3 Refer to Table 2.2 for equipment types

4 Miles per gallon

5 Gallons per hour

6 Yes: The averages are significantly different (at 90% to 95% levels of confidence)

No: The averages are not significantly different (at 90% to 95% levels of confidence)

use more fuel in their operations than those with low amount of Interstate mileage because of the precautionary work necessary to ensure safety.

The second analysis was carried out to investigate the effect of the time of year (season) on equipment fuel consumption rates. This is the effect of season on the number of miles per gallon or gallons per hour consumed by an equipment when used in an activity. The approach adopted in this analysis was identical to that of the previous analysis. Statistical comparison tests were employed to determine if the equipment operational rates were actually affected by the season. Each test is defined by activity, subdistrict, equipment, and season. A total of 138 tests were applied in this analysis. A list of these tests is given in Table 2.6. Tests 1 through 42 were used to compare fall and winter seasons, Tests 43 through 96 to compare fall and spring, Tests 97 through 129 to compare fall and summer, and Tests 130 through 138 to compare spring and summer. For example, consider Test 10. This test was used to compare the miles per gallon consumed by a dump truck in the fall and winter seasons for Activity 207 performed in Subdistrict 2. The test indicated that the average fuel consumption rates of a dump truck during these two seasons for crack sealing are significantly different, with a higher fuel consumption rate in winter.

In comparing the fall versus winter seasons, 31 out of 42 tests showed a significant difference between the two seasons (indicated by "Yes" at the last column in Table 2.6), with higher rates of consumption in winter, at a confidence level of 90% or 95%. Stated differently, less miles per gallon or higher gallons per hour can be expected when an equipment is used to perform a particular activity in winter than in fall.

Table 2.6. Comparative Tests for Seasonal Variations

Test No.	Activity No. 1	Subdistrict No. 2	Equipment No. 3	Consumption Rate	Average Fuel Consumption				Test Significance ⁶
					Fall	Winter	Spring	Summer	
1	201	2	2	mpg ⁴	8.26	7.29			Yes
2	201	2	9	mpg	3.01	2.97			No
3	201	4	2	mpg	8.78	6.23			Yes
4	201	4	9	mpg	3.98	2.84			Yes
5	201	6	2	mpg	8.65	5.89			Yes
6	201	6	9	mpg	3.40	2.57			Yes
7	201	6	47	gph ⁵	1.08	0.35			Yes
8	207	2	1	mpg	4.24	2.00			Yes
9	207	2	2	mpg	5.34	4.68			No
10	207	2	9	mpg	2.73	1.67			Yes
11	210	2	1	mpg	8.02	8.31			No
12	211	2	10	mpg	2.40	2.37			No
13	225	2	2	mpg	8.93	7.00			Yes
14	225	2	9	mpg	3.57	3.33			No
15	232	2	1	mpg	7.59	6.94			Yes
16	235	6	1	mpg	11.31	7.94			Yes
17	239	2	1	mpg	8.83	4.44			Yes
18	251	2	8	mpg	8.24	8.38			No
19	251	4	8	mpg	6.44	6.44			No
20	251	6	8	mpg	8.92	8.00			Yes
21	261	4	1	mpg	8.90	4.91			Yes
22	261	4	9	mpg	4.29	2.42			Yes
23	261	6	1	mpg	13.67	12.05			Yes
24	265	2	26	gph	1.25	2.04			Yes
25	265	4	26	gph	1.58	4.30			Yes
26	276	2	1	mpg	9.38	7.78			Yes
27	276	2	9	mpg	5.91	4.31			Yes
28	276	4	1	mpg	12.09	11.13			No
29	276	4	2	mpg	9.56	6.47			Yes
30	276	6	1	mpg	15.27	12.94			Yes
31	276	6	2	mpg	15.10	13.41			Yes
32	276	2	1	mpg	7.78	9.38			No
33	276	2	9	mpg	5.91	4.31			Yes
34	284	6	1	mpg	11.60	12.40			No
35	284	6	26	gph	1.42	1.30			Yes

Table 2.6. Comparative Tests for Seasonal Variations
(continued)

Test No.	Activity No.	Subdistrict No.	Equipment No.	Consumption Rate	Average Fuel Consumption				Test Significance
					Fall	Winter	Spring	Summer	
36	289	2	1	mpg ⁴	11.67	9.60			Yes
37	289	2	9	mpg	5.20	4.81			No
38	289	2	25	gph	1.67	3.00			Yes
39	289	4	9	mpg	5.00	3.35			Yes
40	289	4	10	mpg	3.76	3.33			Yes
41	289	6	8	mpg	6.62	3.00			Yes
42	289	6	9	mpg	5.36	4.67			Yes
43	201	1	2	mpg	8.18		5.54		Yes
44	201	1	9	mpg	4.01		2.84		Yes
45	201	1	10	mpg	3.93		3.14		Yes
46	201	1	12	gph	0.40		0.40		No
47	201	2	2	mpg	7.50		7.29		No
48	201	2	9	mpg	2.97		2.62		Yes
49	201	2	10	mpg	3.35		2.62		Yes
50	201	4	1	mpg	10.38		9.91		No
51	201	4	2	mpg	8.78		6.27		Yes
52	201	4	4	mpg	7.46		5.27		Yes
53	201	4	9	mpg	3.98		2.95		Yes
54	201	5	2	mpg	8.75		7.98		Yes
55	201	5	9	mpg	4.18		4.74		No
56	201	6	2	mpg	8.65		7.96		Yes
57	201	6	9	mpg	3.40		3.30		No
58	201	6	10	mpg	2.85		2.78		No
59	207	4	2	mpg	8.54		5.44		Yes
60	207	4	7	mpg	3.56		2.43		Yes
61	207	4	9	mpg	2.76		2.65		No
62	207	4	44	gph	2.62		3.19		Yes
63	211	5	1	mpg	7.49		7.39		No
64	211	5	25	gph	1.90		1.99		Yes
65	222	5	2	mpg	9.71		8.06		Yes
66	222	5	9	mpg	4.74		3.37		Yes
67	222	5	36	gph	0.24		0.46		Yes
68	231	5	1	mpg	7.77		7.70		No
69	231	5	9	mpg	2.42		1.77		Yes
70	233	5	2	mpg	9.17		7.96		Yes
71	233	5	9	mpg	3.66		3.21		No

Table 2.6. Comparative Tests for Seasonal Variations
(continued)

Test No.	Activity No.	Subdistrict No.	Equipment No.	Consumption Rate	Average Fuel Consumption				Test Significance
					Fall	Winter	Spring	Summer	
72	233	5	23	gph	1.50		1.70		Yes
73	251	4	8	mpg	6.44		5.37		Yes
74	251	5	8	mpg	8.84		8.10		Yes
75	261	5	9	mpg	3.28		2.39		Yes
76	269	5	2	mpg	13.16		9.42		Yes
77	269	5	9	mpg	4.60		3.60		Yes
78	269	5	53	mpg	3.33		2.40		Yes
79	272	5	2	mpg	11.45		8.31		Yes
80	272	5	9	mpg	5.31		3.61		Yes
81	275	5	9	mpg	3.91		2.24		Yes
82	276	4	2	mpg	9.60		9.00		Yes
83	276	4	9	mpg	5.00		4.70		No
84	276	5	1	mpg	10.05		9.40		Yes
85	276	5	9	mpg	4.79		3.77		Yes
86	277	4	2	mpg	6.43		5.41		Yes
87	277	4	9	mpg	2.61		1.53		Yes
88	277	4	26	gph	1.67		3.00		Yes
89	277	5	1	mpg	11.54		7.08		Yes
90	277	5	2	mpg	11.85		6.40		Yes
91	284	4	7	mpg	4.21		3.15		Yes
92	284	4	9	mpg	3.63		3.53		No
93	289	4	9	mpg	5.00		4.30		No
94	289	4	10	mpg	3.76		1.19		Yes
95	289	4	74	mpg	10.22		8.11		Yes
96	289	5	42	mpg	3.44		3.66		No
97	201	1	2	mpg	8.18			6.65	Yes
98	201	1	9	mpg	4.01			3.85	No
99	201	1	10	mpg	3.93			3.48	No
100	201	1	12	gph	0.40			0.33	No
101	201	2	2	mpg	7.29			9.07	Yes
102	201	2	9	mpg	2.97			2.93	No
103	201	4	2	mpg	8.78			6.81	Yes
104	201	4	9	mpg	3.98			3.99	No
105	202	1	2	mpg	4.43			2.63	Yes
106	206	1	9	mpg	7.35			3.56	Yes
107	206	4	9	mpg	3.54			2.76	No
108	206	4	44	gph	0.90			1.57	Yes
109	210	1	2	mpg	4.50			7.16	No

Table 2.6. Comparative Tests for Seasonal Varia
(continued)

Test No.	Activity No.	Subdistrict No.	Equipment No.	Consumption Rate	Average Fuel Consumption				Test Significance
					Fall	Winter	Spring	Summer	
110	210	1	9	mpg	2.06			3.75	No
111	210	1	10	mpg	2.99			3.48	No
112	221	1	2	mpg	9.27			7.14	Yes
113	221	1	42	gph	1.28			1.21	No
114	221	1	59	gph	0.20			0.27	No
115	221	6	2	mpg	11.24			9.16	Yes
116	221	6	42	gph	1.15			1.22	No
117	222	4	2	mpg	8.87			7.34	No
118	222	4	36	gph	.13			0.29	Yes
119	227	4	1	mpg	7.80			2.03	Yes
120	251	4	8	mpg	6.44			6.63	No
121	257	4	8	mpg	9.56			7.45	No
122	276	4	1	mpg	12.09			16.66	Yes
123	277	4	2	mpg	6.43			3.90	Yes
124	277	4	9	mpg	2.61			1.49	Yes
125	284	4	9	mpg	3.63			3.89	No
126	289	4	2	mpg	9.36			12.00	Yes
127	289	4	9	mpg	5.00			5.00	No
128	289	4	10	mpg	3.76			3.66	No
129	289	4	77	mpg	14.2			15.61	No
130	231	4	1	mpg			2.75	7.67	Yes
131	231	4	2	mpg			3.81	7.22	Yes
132	231	4	9	mpg			2.25	3.61	Yes
133	231	4	24	gph			6.40	8.94	Yes
134	239	4	9	mpg			3.44	2.83	Yes
135	251	4	8	mpg			5.37	6.00	Yes
136	277	4	2	mpg			5.41	3.90	Yes
137	277	4	9	mpg			1.53	1.49	No
138	284	4	9	mpg			3.53	3.89	No

- 1 Refer to Table 2.1 for activity names
- 2 Refer to Figure 2.1 for subdistrict names and locations
- 3 Refer to Table 2.2 for equipment types
- 4 Miles per gallon
- 5 Gallons per hour
- 6 Yes: Test is significant at 90% or 95% confidence level.
No : Test is not significant at 90% or 95% confidence level.

Fifty-four tests were applied to compare fall and spring. Out of the 54 tests, 40 tests indicated a significantly higher fuel consumption rate in spring than in fall.

For the comparison between fall and summer, 19 out of 33 tests showed no significant difference between the two seasons, 9 tests indicated a higher consumption rate in summer, and 5 tests indicated a higher rate in fall. Consequently, no clear trend could be established for this group. The last comparison was between spring and summer. Seven tests out of 9 indicated a higher fuel consumption rate in spring than in summer.

Reviewing the results of the four test groups, it can be concluded that the rate of fuel consumption by an equipment fleet is higher in the winter and spring seasons than in fall and summer. However, the degree of that difference may vary between activities. A general conclusion is that for the comparison of the consumption rates, a year can be divided into two basic periods, the first including winter and spring seasons, and the second including fall and summer seasons. Jobs executed in the winter and spring seasons were observed to consume more fuel than those performed in the fall and summer seasons. Furthermore, fuel consumption rates are affected by highway type. More fuel consumption can be expected for jobs carried out on Interstate system than for jobs on Other State Highway system.

Chapter Conclusions

This chapter presented the results of the field study conducted to identify fuel consumption rates of various equipment types used in state highway routine maintenance activities in Indiana. Based on the findings of the field survey, the following conclusions can be made:

1. Motor fuel was the most expensive single material used in routine maintenance activities in 1981-82. It is estimated that about 12% to 13% of the costs for maintenance field activities can be assigned to fuel only. Considering the material costs, 26% to 27% can be attributed to fuel.
2. Routine maintenance activities in winter and emergency group consumed about 43% of the total fuel use. The next highest consumption took place in activities in roadway and shoulder group, where about 19% of total fuel was consumed.
3. A major contributing activity in total fuel consumption in routine maintenance is snow removal and ice control. In 1981-82 about 38% of the total fuel used in routine maintenance was consumed in this activity.
4. The frequency of equipment use was found to be significantly different by location (subdistrict) in at least 50% of the total number of activities. Also, the frequency of use was found to be considerably different from season to season. On the other hand, no significant difference was detected in the frequency of equipment use between Interstate and Other State Highway maintenance activities.
5. The assumption of a standard fuel consumption rate for a given equipment type was found to be arbitrary. It was observed that the majority of equipment types have considerably different rates of fuel consumption when used in different activities.
6. Although only a few observations were obtained from the Interstate system, it was found that there is a general trend of a higher fuel consumption rate in jobs done on Interstate system than those done on Other

State Highway system.

7. In general, more fuel is consumed in jobs done in winter and spring than in those done in summer and fall.

CHAPTER 3

ENERGY SAVINGS RESULTING FROM INCREASED PREVENTIVE MAINTENANCE

Introduction

This chapter is based on the second phase of the study that involved an examination of pavement routine maintenance cost analysis. Here a particular emphasis is placed on the development of tradeoff relationships between pavement routine maintenance activities and the application of these relationships in estimating the savings in direct fuel use in pavement maintenance. Two major pavement routine maintenance activities were considered: patching (corrective maintenance) and sealing (preventive maintenance). The results showed that the higher the sealing level applied before winter, the lesser was the patching level required after winter. The models took into consideration different highway classes, pavement types and geographic locations. The application example presented assesses possible cost savings in terms of savings in direct fuel consumption by a maintenance equipment fleet. A more detailed description of this phase of the study is given in Reference 2.

Tradeoff in Highway Programming

The tradeoff concept is a central issue in highway system analysis including Pavement Management Systems (PMS), Maintenance Management Systems (MMS), and other related areas. A tradeoff relation can be viewed as a means to know how much of an alternative has to be sacrificed in order to gain something of another alternative.

In highway programming, tradeoff relations can be used to split the available funds among different options at several levels. At the first level, tradeoffs may be used to determine the split of total available funds

between state roads and other local roads followed by, at the second level, tradeoff relations that can determine portions of available funds to be allocated to specific highway classes (e.g. Interstates and Other State Highways of the state roads). At the third level, tradeoffs may be used to distribute available funds between major maintenance activities (Federally funded activities) and routine maintenance activities (state funded activities). Finally, at the fourth level, tradeoffs may be used to split available funds among specific maintenance actions, for example, resurfacing, rehabilitation, and reconstruction as major maintenance actions; and crack sealing, pothole patching, and so on as routine maintenance activities. Of the above four levels, the last one is the most significant for a Pavement Management System (PMS) as well as for a Maintenance Management System (MMS). This is because the last level deals with the allocation of funds to specific maintenance treatments.

This chapter addresses the tradeoff relations involving two pavement routine maintenance activities, namely, patching (corrective maintenance) and sealing (preventive maintenance). Total pavement routine maintenance needs are first identified through a set of prediction models followed by tradeoff relations indicating the split of total need among patching and sealing activities. Finally, an example is presented showing the use of the tradeoff models to assess possible cost savings in terms of savings in direct fuel consumption.

Data Base

The state highway system of Indiana is divided into two categories: Interstate and Other State Highways (OSH). In this study, the two highway systems were further subdivided by geographic location (climatic zones) and by

pavement type. Two geographic locations, north and south, were included to reflect the major climatic differences in Indiana. The pavement types considered were: flexible pavement, rigid pavement, and resurfaced pavement. All data collection and analysis were conducted in terms of 820 sections where a section is defined as the portion of a highway within county limits.

For each of the 820 sections, four major groups of information were summarized: traffic, pavement characteristics, climatic zone, and pavement maintenance records. Traffic information included average annual daily traffic (ADT), percent of trucks, and the equivalent axle load (EAL). Pavement characteristics included pavement type, layer thickness(es), and age. Climatic zones included geographical areas with similar climate in terms of snowfall, rainfall, temperature difference and so on. Finally, pavement maintenance records included total production units, total man-hours, and types and quantities of materials. Pavement maintenance information was summarized for each highway section by activity and by fiscal year. The details of the development of this data base are given in Reference 2. An important feature of the study was that it used only those data that are routinely collected by the Indiana Department of Highways [IDOH].

Model Description

In Indiana, rigid pavement is the major type on the Interstate system (about 70% of total Interstate lane-miles), while flexible pavement and resurfaced pavement are the major pavement types on the OSH system (about 90% of total OSH lane-miles). The three categories constitute about 85% of the total lane-miles of state highway system in Indiana. Consequently, enough number of homogeneous sections of the same pavement type and other characteristics were found in these categories resulting in 26 sections of Interstate rigid, 213

sections of OSH flexible, and 84 for OSH resurfaced. There were only a limited number of homogeneous sections in other pavement categories (five sections for Interstate flexible, eight sections for Interstate resurfaced and five sections for OSH rigid), and most of these sections were found to be located in the southern part. These limitations were considered in the statistical analysis described in Reference 2.

The general form of the total pavement routine maintenance cost prediction model is given in Equation 3.1. The model parameters are presented in Table 3.1.

$$\text{Log}_{10} (\text{TC}) = m \text{Log}_{10} (\Sigma \text{EAL}) + n \text{Log}_{10} (\Sigma \text{EAL}) * (Z) \quad (3.1)$$

where,

TC = total pavement maintenance cost in \$/lane-mile/year;

ΣEAL = accumulated equivalent axle load applications during
the entire age of the pavement section (in thousands);

Z = dummy variable representing the location of the section.
(North or South)

The term $\Sigma \text{EAL} * Z$ was introduced to measure the effect of the interaction between traffic level and climatic zone.

Tradeoff Relations Between Patching and Sealing Activities

Cost models were developed for individual maintenance activity groups, namely patching and sealing. The patching group included shallow patching and deep patching. The sealing group included sealing longitudinal cracks and joints, and sealing cracks. Patching and sealing activities comprise about

Table 3.1. Parameters for the Pavement Routine Maintenance Cost Estimation Models
Presented in Equation 3.1.

Model Parameters	Pavement Category						
	Interstate				OSH		
	Flexible	Rigid	Resurfaced	Flexible	Rigid	Resurfaced	
m	0.610	0.530	0.590	0.974	0.681	0.850	
n	0.000	0.032	0.000	0.240	0.000	0.040	
R ²	0.870	0.890	0.810	0.850	0.870	0.800	

85% of the total pavement maintenance cost in Indiana and there is a high correlation between patching and sealing performed in the same fiscal year. The results of a detailed correlation analysis performed on the portions of total cost allocated to patching versus those allocated to sealing for different highway categories and fiscal years resulted in a correlation value as high as -0.65 as shown in Figure 3.1. The scheduling of different maintenance activities in a fiscal year (July-June) adds a particular characteristic to the correlation between patching and sealing. This is because sealing activities usually precede patching activities within a fiscal year. Sealing activities take place in the late summer through fall, while patching usually takes place during the spring season after the winter. Although there might be some variation in scheduling of these activities, the majority of sealing and patching jobs occur during the periods mentioned.

A high correlation between patching and sealing in a fiscal year is in fact a one-way correlation that indicates that the amount of patching done in a year is generally dependent upon the extent of sealing performed before the winter. However, the sealing activity does not depend on patching activity.

The general type of regression models for patching and sealing follows the form presented in Equations 3.2 and 3.3.

$$PS = a * \text{Log}_{10} (\Sigma EAL) + b \text{Log}_{10} (\Sigma EAL) * Z \quad (3.2)$$

$$PP = c * \log_{10} (\Sigma EAL) + d \log_{10} (\Sigma EAL) * Z + e * PS \quad (3.3)$$

where,

PS = percent of total pavement maintenance cost allocated
to sealing group;

PP = percent of total pavement maintenance cost allocated

Based on the percentages of total cost allocated to sealing and patching activities.

Figure 3.1 Correlation Analysis of Sealing and Patching Activities.

to patching group.

The model parameters for the six pavement categories are given in Table 3.2. The models indicate that although an increased traffic level requires an increased level of pavement maintenance (patching and sealing), the rate of increase in the share of patching cost as traffic level increases is higher than that in the share of sealing cost. Furthermore, it can be concluded that patching level (amount of patching activities taking place after winter) is negatively affected by the level of sealing (amount of sealing activities taking place before winter). That is, as more cracks are sealed before winter, less patching is required after winter, primarily because of less potholes.

An Example of the Use of Tradeoff Models

The purpose of this section is to present one of the applications of the tradeoff models. The example involves an assessment of cost savings in highway pavement routine maintenance in terms of direct fuel consumption. The example given here considers the energy cost savings associated with the tradeoff between preventive maintenance (sealing) and corrective maintenance (patching).

Equation 3.3, discussed earlier, established that the extent of patching under a given traffic level is a function of the extent of sealing performed in the same fiscal year. The implication of this equation is that a higher level of pre-winter preventive maintenance (sealing) can reduce the extent of post-winter corrective or repair maintenance (patching). At the same time, it was found that direct fuel consumption in terms of gallons per dollar spent in sealing group activities is less than in patching group activities [1]. Con-

Table 3.2. Parameters for Estimating Percent of Total Cost
in Patching and Sealing Activities (Equations 3.2 and 3.3).

Activity	Model Parameters	Pavement Category					
		Interstate			OSH		
		Flexible	Rigid	Resurfaced	Flexible	Rigid	Resurfaced
Sealing	a	0.185	0.098	0.115	0.220	0.108	0.196
	b	0.000	-0.015	0.000	-0.074	0.000	-0.062
	R ²	0.870	0.810	0.91	0.780	0.820	0.810
Patching	c	0.182	0.206	0.186	0.346	0.150	0.228
	d	0.000	-0.023	0.000	0.025	0.000	0.011
	e	-0.670	-0.998	-0.621	-0.786	-0.135	-0.550
	R ²	0.830	0.950	0.850	0.890	0.920	0.840

sequently, an increased level of sealing activities would not only reduce the need for subsequent patching activities and thus improving the overall pavement serviceability, but it would also cause savings in the direct fuel consumption in pavement routine maintenance.

In this example, five scenarios were considered: increasing sealing level by 5%, 10%, 15%, 20% and 25%. For each of these scenarios, total fuel consumption in terms of gallons/lane-mile/year was calculated and then compared to the current level of energy consumption to estimate the amount of energy saved. With an increase in sealing activities, the fuel consumption for sealing would increase. However, the increase in sealing activity would reduce the level of patching and the corresponding decrease in fuel consumption would more than offset the increase in fuel consumption due to the increased level of sealing. The result would be a net savings in fuel consumption by the maintenance equipment fleet. In the following paragraphs a detailed explanation of the procedure to estimate energy savings at different traffic levels is presented.

First, fuel consumption rates in terms of gallons per dollar spent in both patching and sealing groups were developed to avoid the difference in production units of the two groups, on the basis of results of the first phase of the study. A summary of the resulting rates is presented in Table 3.3. It can be seen in Table 3.3 that energy consumption levels of the patching group are consistently higher than those of the sealing group.

Energy savings were then calculated for all highway categories under different traffic levels. For illustration, the case of Interstate rigid pavement in the southern zone can be considered. Assuming a traffic level (accu-

Table 3.3. Energy Consumption Rates for Sealing and Patching Groups

Highway Category	Energy Consumption Rates (Gallons/Dollar)			
	South		North	
	Patching	Sealing	Patching	Sealing
Interstate, Flexible	0.091	0.070	N.A.	N.A.
Interstate, Rigid	0.094	0.065	0.091	0.063
Interstate, Resurfaced	0.096	0.066	N.A.	N.A.
OSH, Flexible	0.088	0.056	0.096	0.059
OSH, Rigid	0.092	0.065	N.A.	N.A.
OSH, Resurfaced	0.088	0.065	0.089	0.066

culated EAL) of 20,000,000, the computations are presented below:

- a. From Equation 3.1 with appropriate parameters for Interstate rigid pavement, total pavement maintenance cost = 190.35 \$/lane-mile/year
- b. From Equation 3.2 with appropriate parameters for Interstate rigid pavement, percent allocated to sealing = 42.15%
- c. From Equation 3.4 with appropriate parameters for Interstate rigid pavement, percent allocated to patching = 46.54%
- d. Sealing cost = $0.4215 * 190.35 = 80.23$ \$/lane-mile/year
- e. Patching cost = $0.4654 * 190.35 = 88.58$ \$/lane-mile/year
- f. From Table 3.3, fuel consumption rates are:

0.094 gallons/\$ of patching, and

0.065 gallons/\$ of sealing.

Energy consumed in sealing = $80.23 * 0.065 = 5.22$ gallons/lane-mile/year

Energy consumed in patching = $88.58 * 0.094 = 8.33$ gallons/lane-mile/year

Total energy consumption = 13.55 gallons/lane-mile/year

- g. For a 15% increase in sealing activity, the percent of total pavement maintenance cost allocated to sealing is 48.47%
- h. From Equation 3.4 with appropriate parameters for Interstate rigid pavement, the corresponding patching percent is 40.23%
- i. Repeating steps (d) through (f) the new total energy consumption is 13.19

gallons/lane-mile/year resulting in a savings of 0.35 gallons/lane-mile/year due to a 15% increase in the current level of sealing.

The above computations were repeated for all highway categories for each of the five levels of sealing activity. The resulting fuel consumption savings for the major three highway categories, Interstate rigid pavement, OSH flexible pavement, and OSH resurfaced pavement, are presented in Figures 3.2 through 3.4, respectively.

The information summarized in Figures 3.2 through 3.4 was then utilized to estimate expected total energy savings for the state highway department of Indiana under the five options of increasing sealing level. For example, considering Interstate rigid pavement in the north, with an average traffic level of 25,000,000 accumulated EAL, a savings of 0.15 gallon/lane-mile/year can be expected with 5% increase in sealing level. This is equivalent to about 0.85% reduction from the current level. Similar computations were done for all other highway categories under the average traffic level and the corresponding percent reductions in energy consumption were calculated. These reduction rates were then weighted by the percent of total lane-miles of each highway category. The resulting weighted value was taken as the average percent reduction in energy consumption for the entire state highway system. Under 5% increase in sealing level, it was estimated that the average reduction in energy consumption would be about 0.82%. The corresponding reduction rates were 1.64%, 2.5%, 3.3% and 4.1% with an increase in sealing level of 10%, 15%, 20% and 25%, respectively. With an estimated 0.7 million gallons of direct fuel consumption by equipment fleet in pavement maintenance activities [1], the expected savings in motor fuel consumption can be 5740, 11,480, 17,220,

Figure 3.2 Energy Savings Due to Increase in Sealing Level for Interstate

Figure 3.3 Energy Savings Due to Increase in Sealing Level for OSH Flexible Pavement.

Figure 3.4 Energy Savings Due to Increase in Sealing Level for OSH Resurfaced Pavement.

22,960 and 28,700 gallons under the five levels of increase in sealing activity group, respectively.

All computations so far considered a fuel price of \$1.05 per gallon as paid by the IDOH in 1982. A sensitivity analysis was conducted to assess the impact of fuel price ranging from \$0.75 to \$2.00/gallon. The results are shown in Figure 3.5. It can be noted that the economic impact of increased level of sealing is more pronounced at higher price ranges.

It should be mentioned here that the energy savings are only the direct benefits of increasing the sealing level. However, there are several indirect benefits associated with an increased program of preventive maintenance of sealing. With an increase in the level of sealing, the required corrective maintenance of patching is reduced indicating a lower level of pavement damages, such as potholes. A lower level of pavement damages would improve traffic safety and provide a higher level of service to highway users with less vehicle operating cost.

Chapter Conclusions

Based on the findings of this phase of the study, the following major conclusions can be made:

1. There is a definite tradeoff relation between the amount of sealing (preventive routine maintenance) and that of patching (corrective maintenance). This tradeoff relation is negative in nature indicating that the higher the sealing level applied before winter, the less pavement repair is (patching) required after winter.
2. A direct cost savings in terms of reduction in fuel consumption by rou-

Figure 3.5 Cost Savings Due to Increase in Sealing Level
for the Entire State Highway System

tine maintenance equipment fleet could be achieved by increasing the level of sealing activity.

3. The developed tradeoff relations indicated that the level of service and effectiveness of the routine maintenance dollars could be increased through increasing sealing level which in turn results in a reduction in the required pavement repair (less patching).

CHAPTER 4

TRENDS OF FUEL USE IN ROUTINE MAINTENANCE

Introduction

There are various types of equipment used in performing different maintenance activities. In planning for energy conservation in maintenance, it is necessary to concentrate on those activities and equipment types that consume the most fuel. The purpose of this chapter is to describe the results of a trend analysis to determine whether there exist definite trends in the consumption of fuel by activity type and by equipment type, and to identify the elements of routine maintenance that should be the prime targets of fuel conservation efforts. The trend analysis was conducted on the basis of routine maintenance accomplishment records of three consecutive years, 1982, 1983 and 1984. The accomplishment data were converted to fuel use estimates by using the appropriate consumption rates presented in Reference 1.

Estimation of Share of Fuel Consumption

by Activity and by Equipment Type

In this analysis, 63 activity types and 79 equipment types were evaluated. Activity types were grouped into eight major maintenance areas, as shown in Table 2.1. A list of equipment types has been given in Table 2.2. Three types of fuel use values were used in the trend analysis: (i) fuel share by equipment type for an individual activity, (ii) fuel share by activity type in total fuel consumption, and (iii) fuel share by equipment type in total fuel consumption.

Fuel Share by Equipment Type for Each Activity

Share of fuel consumption by equipment type in total fuel consumption for an activity was calculated by the following formula. This value indicates how much a particular equipment type contributes to the total fuel consumed for completing one production unit of an activity.

$$S_{ij} = F_{ij} * \frac{R_{ij}}{T_i} * 100 \quad (4.1)$$

where,

S_i = Share of equipment type j in the total fuel
consumption of activity i, in percent

F_{ij} = Usage factor of equipment type j when used in
activity i

R_{ij} = Consumption rate (gallons per production unit)
of equipment type j when used in activity i

T_i = Consumption rate (gallons per production unit)
of activity i

Usage factors can be defined as the number of units of an equipment type used to perform a given activity in one working day. The values of F_{ij} , R_{ij} and T_i were available from field survey data conducted in the first phase of the study [1].

Fuel Consumption by Activity Type

Share of fuel consumption by activity type in total fuel consumption was computed as shown below.

$$A_i = 100 * P_i * T_i / \sum_{i=1}^n P_i * T_i \quad (4.2)$$

where,

A_i = Share of activity type i in total fuel
consumption for all activities, in percent

P_i = Total units of production of activity i

T_i = Consumption rate (gallons per production unit)
of activity i

n = Total number of activity types

Fuel Consumption by Equipment Type

Using Equations 4.1 and 4.2, the fuel share by equipment type in the total annual fuel consumption was computed, as shown below:

$$E_j = \sum_{i=1}^n S_{ij} * A_i / 100 \quad (4.3)$$

where,

E_j = Share of an equipment type j in the total
fuel consumption for all activities, in percent

S_{ij} = Share of equipment type j in the total fuel
consumption of activity i, in percent

A_i = Share of activity type i in the total fuel
consumption for all activities, in percent

n = Total number of activities

Data Base and Assumptions

The unit usage factors developed in the first phase of the study [1] were used as input to the present analysis on the assumption that the average usage of equipment units remained the same over the last few years. This assumption is valid as long as the field work practices of the maintenance crews did not change. Also used were annual maintenance accomplishment record kept by the Indiana Department of Highways [4]. The accomplishment records of three consecutive fiscal years, 1982, 1983, and 1984, were used in this trend analysis. In Table 4.1 is shown a portion of the output of fuel consumption information for various equipment types for each activity for FY 1984.

Results of Trend Analysis

A reasonably stable trend of fuel consumption was found among equipment types during the fiscal years 1982, 1983, and 1984. Annually, approximately 4.0 to 5.5 million gallons of fuel were consumed by maintenance equipment units used for field activities only. This value does not account for the fuel used by field maintenance supervision. Currently, maintenance supervision is not recorded on daily report cards called the crew day cards.

In Figure 4.1 is presented the estimated annual fuel consumption by snow and ice removal activity and by all other activities. While the fuel consumed by all other maintenance activities remained the same, the fuel used in snow and ice removal showed a wide variation, as this activity is entirely dependent on weather. On the average, about 3.5 million gallons of the total annual fuel consumption were used for regular maintenance activities whereas the rest was spent for snow and ice removal. A mere reduction of one percent of the fuel used for regular activities, therefore, would save about 35,000

Table 4.1 Fuel Share by Activity and by Equipment Type for FY84

Activity 201	7.00 %	233135 gallons															
Equipment No.	1	2	4	7	8	9	10	12	13	14	20	26	44	47	48	74	
Fuel Share (%)	4.17	33.70	2.23	0.58	0.48	40.54	5.07	0.22	0.	0.	0.03	0.57	0.25	2.34	0.	0.81	
Activity 202	1.36 %	45319 gallons															
Equipment No.	1	2	8	9	10	12	13	14	20	23	26	42	44	47	48	50	
Fuel Share (%)	1.07	0.84	0.65	74.35	0.48	1.74	0.	0.	0.87	3.62	4.35	10.14	1.86	0.	0.	0.	
Activity 203	1.15 %	38273 gallons															
Equipment No.	1	2	7	9	10	13	14	16	20	25	26	42	47	50	51		
Fuel Share (%)	0.50	12.37	11.44	64.30	5.72	0.	0.	0.	1.68	2.24	1.66	0.	0.	0.	0.		
Activity 204	1.53 %	51045 gallons															
Equipment No.	1	2	7	9	13	26											
Fuel Share (%)	1.29	2.84	6.72	84.88	0.	4.26											
Activity 205	3.58 %	119281 gallons															
Equipment No.	1	2	7	9	13	26											
Fuel Share (%)	1.29	2.84	6.72	84.88	0.	4.26											
Activity 206	0.74 %	24516 gallons															
Equipment No.	1	2	4	7	9	10	13	44	47								
Fuel Share (%)	29.57	0.90	0.75	7.61	50.96	7.04	0.	3.17	0.								
Activity 207	5.11 %	170383 gallons															
Equipment No.	1	2	7	9	10	13	26	42	44	47							
Fuel Share (%)	6.58	14.91	6.68	46.78	16.04	0.	0.30	0.18	5.24	3.28							
Activity 209	0.37 %	12407 gallons															
Equipment No.	1	2	9	10	14	47	50	51	52								
Fuel Share (%)	6.92	12.31	53.85	4.23	0.	0.	0.	0.	23.08								
Activity 210	3.07 %	102224 gallons															
Equipment No.	1	2	9	10	12	14	20	25	26	27	47	53					
Fuel Share (%)	7.33	9.04	21.63	47.01	0.	0.	1.07	0.59	0.11	12.31	0.	0.93					

Table 4.1 Fuel Share by Activity and by Equipment Type for FY84
(continued)

Activity 211	1.23 %	40820 gallons													
Equipment No.	1	2	9	10	20	22	25	27	30	42	47	54	55	56	57
Fuel Share (%)	11.14	5.64	31.93	3.42	0.	0.	19.13	10.00	0.56	11.25	0.	7.11	0.	0.	0.
Activity 212	3.54 %	117878 gallons													
Equipment No.	1	2	9	22	25	26	42	50	58						
Fuel Share (%)	6.95	4.67	64.96	0.	12.49	5.23	2.36	0.	3.35						
Activity 213	0.89 %	29573 gallons													
Equipment No.	2	9	10	26											
Fuel Share (%)	6.27	82.79	7.57	3.37											
Activity 214	0.69 %	23111 gallons													
Equipment No.	1	2	9	10	13	15	25	26	47	54					
Fuel Share (%)	33.62	15.77	13.15	15.87	0.	7.06	4.63	6.41	0.94	2.32					
Activity 219	0.40 %	13169 gallons													
Equipment No.	1	2	9	10	13	37									
Fuel Share (%)	22.64	9.43	37.74	25.66	0.	4.53									
Activity 221	3.81 %	126949 gallons													
Equipment No.	1	2	9	10	26	34	42	59							
Fuel Share (%)	3.20	28.80	8.30	0.59	0.	0.	58.07	0.89							
Activity 222	1.16 %	38686 gallons													
Equipment No.	1	2	4	6	9	23	26	31	36						
Fuel Share (%)	6.62	23.88	2.05	0.85	53.26	3.26	1.12	5.26	4.32						
Activity 223	0.69 %	22869 gallons													
Equipment No.	1	2	40												
Fuel Share (%)	49.29	28.10	22.86												
Activity 224	0.01 %	359 gallons													
Equipment No.	1	40	60												
Fuel Share (%)	72.73	27.27	0.												
Activity 225	1.34 %	44663 gallons													
Equipment No.	1	2	3	4	9	10	26	31	32	36	61				
Fuel Share (%)	3.55	15.13	16.92	0.90	49.25	0.	8.74	1.01	0.52	3.99	0.				

Table 4.1 Fuel Share by Activity and by Equipment Type for FY84
(continued)

[illegible]

Table 4.1 Fuel Share by Activity and by Equipment Type for FY84
(continued)

Activity 241	26258 gallons										
Equipment No.	1	2	4	9	44						
Fuel Share (%)	28.79	14.13	2.35	15.10	39.48						
Activity 243	3418 gallons										
Equipment No.	1	2	8	9	23	44	45	74	75		
Fuel Share (%)	63.00	10.05	2.92	17.05	0.47	4.05	0.22	1.80	0.45		
Activity 244	8471 gallons										
Equipment No.	1	2	5	9	40						
Fuel Share (%)	51.84	17.17	3.43	18.24	9.10						
Activity 245	19394 gallons										
Equipment No.	1	2	9	10	37	44	45	47	48	65	
Fuel Share (%)	7.58	30.32	48.63	3.37	0.84	3.37	0.84	5.05	0.	0.	
Activity 249	2997 gallons										
Equipment No.	1	2	8	9	23	44	45	74	75		
Fuel Share (%)	63.00	10.05	2.92	17.05	0.47	4.05	0.22	1.80	0.45		
Activity 251	103883 gallons										
Equipment No.	1	2	8								
Fuel Share (%)	18.35	2.03	79.77								
Activity 257	14076 gallons										
Equipment No.	1	2	8	44	51	76					
Fuel Share (%)	32.11	4.29	48.16	15.47	0.	0.					
Activity 258	28426 gallons										
Equipment No.	1	2	9								
Fuel Share (%)	79.55	10.66	9.75								
Activity 259	8494 gallons										
Equipment No.	1	8									
Fuel Share (%)	5.26	94.95									
Activity 261	25216 gallons										
Equipment No.	1	2	8	9	10	21	26	27	36	44	53
Fuel Share (%)	50.79	1.97	4.30	33.00	0.	0.57	0.39	0.	1.46	0.07	1.33
											74
											6.29

Table 4.1 Fuel Share by Activity and by Equipment Type for FY84
(continued)

[illegible]

Table 4.1 Fuel Share by Activity and by Equipment Type for FY84
(continued)

[illegible]

Figure 4.1 Estimated Fuel Consumption by Snow & Ice Removal (Act. 263)
and All Other Activities

gallons of fuel or approximately 36,750 dollars each year with the price of fuel being \$1.05 per gallon. The fuel cost savings can range from \$26,250 to \$70,000 each year with the fuel price ranging from \$0.75 to \$2.00 per gallon, respectively.

Fuel Consumption By Maintenance Activity

The trend in fuel consumption by activity group and by activity type was analyzed to find what specific activities or groups must be targeted to achieve the highest return in energy conservation efforts. The three activity groupings used for maintenance management purpose are:

- Highway Class (Class 1 = interstate highways, and Class 2 = other state highways)
- Four maintenance work categories
- Eight major activity areas

The results of the analysis are discussed in the following sections.

Highway Class

Figure 4.2 shows the shares of fuel consumption by highway class. The split of fuel consumption between the two highway classes remained stable. In fiscal year 1984, approximately, 13.5% of the estimated total annual fuel consumption excluding snow and ice removal was for maintenance activities on interstate highways. About 0.40 million gallons of fuel was used for maintaining interstate highways. On the other hand, 2.94 million gallons of fuel was spent for the maintenance of other state highways. Therefore, the marginal reduction of fuel use by managing maintenance activities on other state

Figure 4.2 Estimated Fuel Consumption In Routine Maintenance
by Highway Class *

highways is much more substantial than the fuel savings in maintenance of interstates. For example, 1% reduction in fuel consumption in interstate would amount to about 4,000 gallons, while 1% reduction of fuel consumption in maintenance of other state highways would amount to about 29,400 gallons.

The split in the amount of fuel consumption between interstate and other state highways is much greater than the split in the total mileage of these two classes. Interstate comprises 8.9% of the total state highway mileage in Indiana with a total mileage of 1,102 miles. The other state highways cover a total mileage of 11,245 miles. The difference was caused by high fuel consumption rates per mile by maintenance activity type on interstate highways. On the average, interstate highways required 340 to 350 gallons/mile/year of fuel for maintenance, whereas other state highways required 250 to 260 gallons/mile/year. The interstate maintenance thus needed a 26% extra fuel consumption per mile. It is reasonable to have such a difference because interstate highways are multi-lane facilities and their maintenance require more equipment units due to the variety of tasks expected to be done. Also, access to job sites on interstate highways is constrained by limited entrances and exits, requiring longer traveling time to haul material, equipment, and labor.

Work Category

Routine maintenance work categories represent the importance and ranking of the routine maintenance activities, as stated below [5].

1. Limited activities - include activities for which quantities can be established and firmly observed to.

2. Unlimited activities - include activities which are to be performed when needed and in the amount required to correct the deficiency.
3. Overhead activities such as rest area attendant, standby time, training, and maintenance field supervision.
4. Variable activities - include activities where the amount of work is not urgently needed each year. The planned work is desirable but it is not critical if all of the planned work is not completed during any one year.

Of the 63 activities considered in the study, 14 activities are in the limited category, 22 activities in the unlimited category, 14 activities in the variable category, and the remaining 13 activities in the overhead category. Actual accomplishments of the limited activities were found to be significantly different from the planned accomplishments at some subdistricts. Variations between the actual and planned accomplishments were more frequent among the activities in the unlimited category. The amount of work done in these two categories greatly affects the amount of fuel consumption. Therefore, an improvement in the procedure to assess needs of specific maintenance activities is desirable if energy conservation programs are directed to these activities.

Activities of the overhead category consist mostly of public service and "other" maintenance areas. These activities are not directly related to the performance of the highway. Activities in the variable category deal with minor maintenance work that are left out from the activities of the limited or

unlimited categories. Therefore, fuel consumption by this category can be reduced if the activities in the limited and unlimited categories are better managed.

Figure 4.3 illustrates the three year trend of fuel consumption by maintenance category. During the study period, the amount of fuel used for the limited category increased. However, the fuel consumption of the unlimited work decreased as if it had reflected the increase of the activities in the limited category. Figure 4.3 shows that about two-thirds of the estimated total annual fuel consumption is due to these two categories. Consequently, the activities included in these categories should be carefully evaluated as to their potential for fuel savings. When a sudden fuel saving measure has to be undertaken, activities in the variable category can be reduced or postponed, if activities in the limited and unlimited categories are better managed.

Major Activity Areas

A substantial portion of the total maintenance cost can be attributed to the roadway and shoulder area (Area I), followed by the "others" area (Area VIII), as shown in Figure 4.4 (a). Total cost was broken down into fuel, material, and labor costs. All costs were computed using the 1982 unit cost data. As far as fuel consumption is concerned, the pavement and shoulder (Area I), drainage (Area III), and "other" (Area VIII) maintenance areas consumed most of the fuel needed in maintenance work (Figure 4.4(b)). In reality, the "other" maintenance area would require more fuel than the amount shown here because the fuel used for field maintenance supervision is not currently recorded in crew day cards.

Figure 4.3 Fuel Consumption by Routine Maintenance Work Category *

Figure 4.4 Maintenance Cost Splits Among Eight Major Activity Groups
(Excludes Snow & Ice Removal)

(a) Total Cost

(b) Fuel Cost

(c) Material Cost

The roadway and shoulder area accounts for most of the materials cost (Figure 4.4 (c)). Although this study deals only with direct energy use, a substantial part of the materials used in highway routine maintenance involves petroleum products. Therefore, an improvement in the use of quality of materials should provide opportunities to conserve the overall energy use including indirect energy. In any event, a good management of the first three areas - roadway and shoulder, roadside, and drainage - can greatly contribute to energy conservation.

Fuel Consumption by Activity

Fuel consumption by activity shows a tendency of being concentrated on a few activities every year, as shown in Figure 4.5. Most of the activities considered in the study used less than 2% of the total fuel consumption excluding snow and ice removal. Activities with more than 3% of the total fuel consumption except the fuel used for snow and ice removal were identified as dominant activities, and they are listed in Table 4.2. These activities account for approximately 65% of the total fuel consumption excluding snow and ice removal and supervision.

The roadway and shoulder maintenance area has several maintenance activities that require a substantial amount of fuel. They are shallow patching (201), seal coating (205), crack sealing (207), spot repair of unpaved shoulders (210), and clipping unpaved shoulders (212). These activities represent the most common types of maintenance work and any energy conservation effort should thus start with them.

Among the regular activities, the cleaning and reshaping of ditches singly stands out from other activities for its high fuel consumption level.

Figure 4.5 Estimated Annual Fuel Use by Activity (FY1984)

Figure 4.5 Estimated Annual Fuel Use by Activity (FY1984) (continued)

Table 4.2 Major Fuel Consuming Activities
(FY1984 Statewide Total)

Maintenance Area	Activity Code	Description	Fuel Consumed (1,000 gallons)	Share (%)
I	201	Shallow patching	233.1	7.00
	205	Seal coating	119.3	3.58
	207	Sealing cracks	170.4	5.11
	210	Spot repair of unpaved shoulders	102.2	3.07
	212	Clipping unpaved shoulders	117.9	3.54
II	221	Machine mowing	126.9	3.81
III	231	Clean and reshape ditches	451.7	13.56
	235	Cleaning minor drainage structures	90.2	2.71
V	251	Subdistrict sign maintenance	103.9	3.12
VII	271	Rest area and lift bridge attendant	161.8	4.86
VIII	283	Buildings and grounds maintenance	200.3	6.01
	284	Materials handling and storage	134.0	4.02
	289	Other support activites	160.7	4.82
Total			2,172.4	65.21

Note: Activity 263 (snow and ice removal) was excluded from the share computation.

Major equipment types used for this activity are the dump truck and excavator. About 60% of the fuel used for this activity is due to dump trucks and about 30% due to excavators. Field observations indicate that minimization of idle time and reduction of hauling distance to dump the excavated earth are two main areas that can cause a major reduction in fuel consumption for this activity.

In the area of roadside maintenance, machine mowing (221) dominates the fuel use. Mowing is done periodically during the growing season and it is not directly related to roadway performance. However, mowing may be necessary for public safety and aesthetics.

Fuel consumption for bridge maintenance is comparatively very low. During FY 1984, about 60.5 thousand gallons of estimated amount of fuel was used, accounting for only about 2% of the total fuel consumption for that year. The potential for fuel saving in this area, therefore, is not that great.

In the area of traffic control related maintenance, the subdistrict sign maintenance (activity 251) uses up about 70% of the fuel consumed for this maintenance area. About 80% of the fuel consumed for subdistrict sign maintenance is due to the use of utility trucks.

In the public service area, the rest area and lift bridge attendant work uses about 45% of the fuel consumed for this maintenance area. The litter pickup work is the second highest fuel consuming activity and uses about 25% of the total fuel consumed. Pickups, pickup crew cabs, and dump trucks are equipment types most frequently used for these activities.

In the "others" maintenance area, the buildings and grounds maintenance,

materials handling and storage, and other support activities use about 90% of the total fuel in this area. The majority of these maintenance activities is for picking and hauling supplies and materials and transferring equipment.

Fuel Consumption By Equipment Type

A variety of equipment types are used for routine maintenance activities, as shown in Table 4.3. First, the demand level for a particular equipment type by various activities was identified. Then, dominant equipment types were singled out and amounts of their fuel use were examined. In this study, equipment types with more than 1% of the total fuel consumption, excluding the fuel used for snow and ice removal, were considered as dominant equipment types.

The majority of equipment types are used for less than ten different activity types, as shown in Table 4.3. Some equipment types, such as water truck or catch basin cleaner, are used in specific activities and their low shares in fuel consumption reflect their limited use. The equipment types that were used by more than 20 activities included only five types: pickup truck, pickup crew cab, dump truck, do-all truck, and loader. These equipment types consumed most of the total fuel in each of the three years considered in the study.

Table 4.4 shows the result of fuel share computation by equipment type for fiscal year 1984. For the three study years, similar trends were observed. Table 4.5 shows a list of the equipment types using more than 1% of the total annual fuel consumption excluding snow and ice removal along with their demand levels. Altogether they account for about 95% of the total fuel consumed. Their fuel use shares were found to remain stable over the three

Table 4.3 List of Equipment Used in Routine Maintenance Activities and Their Level of Demand

Code	Equipment type	Level	Code	Equipment type	Level
1	Pickup truck	A	41	Paint machine	*
2	Pickup crew cab	A	42	Tractor truck	E
3	Aerial basket truck	F	43	Tractor mower	*
4	Flatbed truck	E	44	Compressor	E
5	Water truck	F	45	Mixer	F
6	Bucket truck	F	46	Squeegee cart	*
7	Distributor	E	47	Flashing arrow board	E
8	Utility truck	E	48	Porta patcher	F
9	Dump truck	A	49	Jeep	F
10	Do-all truck	D	50	Lowboy trailer	F
11	Catch basin cleaner	F	51	Trailer	E
12	Compactor	F	52	Pavement cutter	F
13	Tar kettle	E	53	Chemical spreader	F
14	Premix storage trailer	F	54	Maintainer	F
15	Burner unit	F	55	Back blade	F
16	Paver	F	56	Berm drag	F
17	Widener	*	57	Undeck body	F
18	Jack hammer	*	58	Broom tractor	F
19	Portable roller	*	59	Weed eater	F
20	Roller	E	60	Rotor tiller	F
21	Street sweeper	F	61	Rack truck	F
22	Broom	F	62	Tilt cab	F
23	Backhoe	E	63	Pole truck	F
24	Excavator	F	64	Gradall	F
25	Grader	E	65	Pavement breaker	F
26	Loader	D	66	Semi trailer	F
27	Snow blow	F	67	Dozer	F
28	Chip spreader	F	68	Whocker	F
29	Salt spreader	*	69	Crawler	*
30	Underbody scraper	F	70	Vermeer cutter	F
31	Brush chipper	F	71	Ave all	F
32	Stump cutter	F	72	Sewer jet	F
33	Auger/driver	*	73	Crane	F
34	Lawn mower	F	74	Stake truck	F
35	Hand mower	F	75	Generator	F
36	Chain saw	F	76	Port line marker	F
37	Concrete saw	F	77	Van	F
38	Pavement cutter	*	78	Sewer vector	*
39	Hydro-seeder	*	79	Vermeer trailer	*
40	Weed sprayer	F			

Demand Level:

A = Used by 50 or more activity types

B = Used by 40 to 50 activity types

C = Used by 30 to 40 activity types

D = Used by 20 to 30 activity types

E = Used by 10 to 20 activity types

F = Used by 10 or less activity types

* = Not appeared in the field data

Table 4.4 Fuel Share by Equipment Type for FY84

Equipment No.	Equipment Type	Fuel Share in %	In gallons
1	Pickup truck	9.80	326523
2	Pickup crew cab	11.12	370433
3	Aerial basket truck	0.23	7555
4	Flat bed truck	1.02	33829
5	Water truck	0.01	291
6	Bucket truck	0.01	329
7	Distributor	2.42	80730
8	Utility truck	3.83	127711
9	Dump truck	44.45	1480750
10	Do-all truck	4.95	164903
11	Catch basin cleaner	0.76	25439
12	Compacter	0.04	1406
13	Tar kettle	0.	0
14	Premix storage trailer	0.	0
15	Burner unit	0.05	1632
16	Paver	0.	0
17	Widener	0.	0
18	Jack hammer	0.	0
19	Portable roller	0.	0
20	Roller	0.13	4250
21	Street sweeper	0.02	714
22	Broom	0.	0
23	Backhoe	0.54	17862
24	Excavator	4.19	139679
25	Grader	2.07	68840
26	Loader	4.05	135084
27	Snow blow	0.50	16663
28	Chip spreader	0.	0
29	Salt spreader	0.	0
30	Underbody scraper	0.01	230
31	Brush chipper	0.47	15702
32	Stump cutter	0.03	991
33	Auger driver	0.	0
34	Lawn mower	0.	0
35	Hand mower	0.00	73
36	Chain saw	0.12	3928
37	Concrete saw	0.02	760
38	Pavement cutter	0.	0
39	Hydro-seeder	0.	0
40	Wood sprayer	0.19	6398
41	Paint machine	0.	0
42	Tractor truck	4.37	145526
43	Tractor mower	0.	0
44	Compressor	1.05	35049
45	Mixer	0.01	177
46	Squeeze cart	0.	0
47	Flushing arrow board	0.39	13106
48	Porta patcher	0.	0
49	Jeep	0.11	378
50	Lowboy trailer	0.	0
51	Trailer	0.	0
52	Pavement cutter	0.09	2863
53	Chemical spreader	0.41	13708
54	Maintainer	0.10	3436
55	Back blade	0.	0
56	Berm drag	0.	0
57	Undeck body	0.	0
58	Broom tractor	0.17	5693
59	Weed eater	0.06	2021
60	Rotor tiller	0.	0
61	Rack truck	0.	0
62	Tilt cab	0.03	1100
63	Pole truck	0.01	266
64	Gradall	1.44	47890
65	Pavement breaker	0.	0
66	Semi trailer	0.	0
67	Dozer	0.51	16989
68	Whacker	0.	0
69	Crawler	0.	0
70	Vermeer cutter	0.01	242
71	Ave all	0.	0
72	Sewer jet	0.03	663
73	Crane	0.02	612
74	Stake truck	0.26	8622
75	Generator	0.00	29
76	Port line marker	0.	0
77	Vin	0.21	6988
78	Sewer vector	0.	0
79	Vermeer trailer	0.	0

Total Fuel Consumption = 3,338,061 gallons

Table 4.5 Major Fuel Consuming Equipment Types
(FY1984 Statewide Total)

Equipment Code	Equipment Type	Share in Percent	Demand Level *	Remarks
1	Pickup truck	9.8%	A	Interchangeable
2	Pickup crewcab	11.1%	A	Interchangeable
4	Flatbed truck	1.0%	E	0.7% for Act. 271 (Rest area & lift bridge attendant)
7	Distributor	2.4%	E	Not interchangeable
8	Utility truck	3.8%	E	2.6% for Act. 251 (Subdistrict sign maintenance), Interchangeable
9	Dump truck	44.4%	A	Interchangeable
10	Do-all truck	5.0%	D	Interchangeable
24	Excavator	4.2%	F	4.1% for Act. 231 (Clean & reshape ditches), Not interchangeable
25	Grader	2.1%	E	Not interchangeable
26	Loader	4.1%	D	Not interchangeable
42	Tractor truck	4.4%	E	2.2% for Act. 221 (Machine mowing), Not interchangeable
44	Compressor	1.1%	E	Not interchangeable
64	Gradall	1.4%	F	1.1% for Act. 283 (Buildings & grounds maintenance)

		Total =	94.9%	

* See Table 4.3 for explanation

study years. Therefore, if a better management of equipment fleet is considered as a means to conserve energy, these thirteen types are the ones that should be included first. Table 4.5 suggests that interchangeable equipment types are mostly hauling equipment, such as dump trucks and pickup trucks. Dump trucks alone account for about 45% of the total annual fuel used for all routine maintenance activities excluding snow removal and ice removal.

Chapter Conclusions

The trend analysis discussed in this chapter was used to identify components of highway routine maintenance where energy conservation efforts can be directed. The analysis sorted out thirteen dominant activities out of sixty-three different activity types. These activities are mainly in road and shoulder, roadside, and drainage maintenance groups.

The analysis also identified the critical equipment types. Of seventy-nine equipment types included in the study, thirteen types were found to be critical with respect to energy conservation. These types accounted for about 95% of the total fuel consumed in FY 1984. The four most fuel consuming equipment types were pickup truck, pickup crew cab, dump truck, and do-all truck, using about 70% of the total fuel consumption every year.

By carefully managing the dominant activities and critical equipment types, highway agencies would be able to better control the fuel consumption in highway routine maintenance. In order to implement such a program, however, it is desirable that equipment use and fuel consumption data be regularly recorded and monitored.

CHAPTER 5

FORMULATION AND APPLICATION OF OPTIMIZATION MODEL

Introduction

Highway maintenance consists of a variety of activities requiring many different types of equipment. These activities are both labor and fuel intensive. Fuel consumed by maintenance equipment may account for as much as one-third of the total material cost and about one-tenth of the total maintenance cost. In the first phase of the study it was found that equipment types are interchangeably used to do the same task and that fuel consumption rates are substantially different among different equipment types [1]. Consequently, equipment management tools that can enable a better control of fuel consumption are important elements of maintenance management. Optimization techniques can be applied to the problem of assigning different equipment types to various maintenance activities such that total fuel consumption can be minimized.

Mathematical modeling techniques are being applied to pavement management [6,7,8,9,10]. However, the application of mathematical optimization techniques to highway routine maintenance has long been considered to be infeasible because of the wide variation in the characteristics of routine maintenance activities and because of many uncertain elements such as weather and difficulty in accurately assessing maintenance needs.

Simulation is another operations research technique that can be applied to routine maintenance activities. A project level simulation model of roadside mowing was developed in the early 70s [11]. Later, a highway maintenance

simulation model was developed for the Louisiana Department of Highways [12,13,14]. Besides these two simulation models, however, there have not been serious efforts in this area.

As the specific objective of the present study was to maximize energy conservation, an approach focusing on the equipment assignment component of the overall maintenance scheduling process was needed. A linear programming technique was applied to develop a mathematical model for determining the optimal equipment assignment to minimize total fuel consumption. An example application is discussed to demonstrate the feasibility of incorporating this equipment assignment technique into the current activity scheduling process.

Optimization Methodology

The concept of the optimization model developed in the study is based on the interchangeability of equipment types for performing particular tasks of each activity. Equipment types which would use less fuel should be assigned as much as possible such that the total fuel consumption could be minimized. The field survey data collected in the first phase of the study [1] and subsequent field observations indicated that different equipment types are used to perform the same tasks. For example, pickup crew cabs and dump trucks are interchangeably used in rest area maintenance. Similarly, for hauling purposes, pickup trucks, pickup crew cabs, dump trucks, and do-all trucks have also been found to be interchangeably used. However, the fuel usage rates of these equipment types vary considerably. Furthermore, the same equipment type, when used in different activities, has different fuel usage rates. It is possible, therefore, to optimize the equipment assignment so that total fuel consumption in performing various activities is minimized.

A trend analysis on fuel use described in Chapter 4 indicated that pickup trucks, pickup crew cabs, dump trucks, and do-all trucks use about 70% of the total fuel consumed in all routine maintenance activities excluding the snow and ice removal work. Therefore, the consideration of only these equipment types can result in a substantial amount of fuel savings.

Decision Variable

The optimization model approaches the problem of fuel savings on an aggregated basis. The decision variable used in the model is the number of equipment days of a particular type to be used for an activity. This optimal value can then be taken as the target value of equipment days to be assigned to the activities. The variable of equipment days was used as an aggregate measure, because there are daily fluctuations in equipment scheduling due to such factors as the amount of accomplishment, equipment availability, labor availability and weather conditions. Specific scheduling of targeted total equipment days to actual job sites can be best dealt with by experienced schedulers. Scheduling equipment units while making efforts to conform to targeted values resembles the activity scheduling procedure currently used by subdistricts of the Indiana Department of Highways for preparing the bi-weekly activity plan [15].

Model Development

The optimization model developed in the present study has two types of constraints: (i) planned accomplishments of activities and (ii) the equipment availability. Both constraints are expressed in equipment days. A data base containing equipment usage, fuel usage, productivity, and equipment breakdown data is provided as input. A schematic diagram showing the components of the

model is presented in Figure 5.1.

First, planned accomplishments of all maintenance activities are set and activities which are considered in the model are selected from the activity list. A set of equipment types of interest is then selected. The availability of selected equipment types is expressed in equipment days. Total available equipment days of a particular equipment type are computed by simply multiplying the number of units of the equipment type by the number of working days available during the analysis period. From the total available equipment days, the number of equipment days that are expected to be lost due to mechanical breakdowns and the number of equipment days necessary to perform other activities which are not considered in the model must be subtracted. The remaining equipment days for each selected equipment type, then, form equipment availability constraints.

After the equipment-activity combinations are identified, interchangeable equipment types are grouped within each activity. Only equipment types which are interchangeable for a specific task are grouped. If a particular equipment must be used to perform a task, then constraints are appropriately formulated to indicate this requirement. Equipment usage factor of each equipment within an interchangeable equipment group is provided as input and the resulting sum of equipment usage rates is considered as a combined equipment usage factor. Equipment usage factor is defined as the average number of equipment units of a particular type used to complete a scheduled amount of an activity in one working day. The combined equipment usage factor reflects the actual need of equipment for an activity. For example, if pickup truck and pickup crew cab are used interchangeably in shallow patching, and if pickup truck's usage factor is 0.5 and pickup crew cab's usage factor is 0.7, the combined

Figure 5.1. Maintenance Equipment Assignment Technique

usage factor of this interchangeable equipment group will be 1.2. This means that for every 100 working days of shallow patching, 120 units of either pickup trucks or pickup crew cabs, or a combination of these two types will be needed. Combined equipment usage factors are used to compute conversion factors called K-values, which translate the amount of accomplishment for an activity to the number of equipment days necessary to complete the activity by a particular equipment within a given analysis period. The resulting equipment days, then, form equipment requirement constraints.

After these constraints are determined, the objective function can be formulated. Each coefficient of the decision variable in the model is computed by multiplying a combined usage factor, fuel usage rate of an equipment used for an activity, and a conversion factor K-value.

Model Formulation

The formulation of the Maintenance Equipment Assignment Technique (MEAT) using linear programming is discussed below. The objective function is to minimize the total number of gallons of fuel consumed in performing a set of scheduled maintenance activities.

$$\text{Minimize } \sum_i \sum_j R_{i,j} \times U_{i,j(\ell)} \times K_{i,j(\ell)} \times Y_{i,j} \quad (5.1)$$

Subject to the following constraints:

- a. Demand Constraints - All scheduled activities must be performed.

$$\sum_j Y_{i,j} \geq D_{i(\ell)} \quad \text{for all } i \quad (5.2)$$

- b. Capacity Constraints - Total number of equipment days assigned to any

equipment type must not exceed the number of equipment days available.

$$\sum_i Y_{i,j} \leq C_j \quad \text{for all } j \quad (5.3)$$

c. Non-negativity Constraints - All variables must be greater than or equal to zero.

$$Y_{i,j} \geq 0 \quad \text{for all } i,j \quad (5.4)$$

where,

$Y_{i,j}$ = Number of equipment days of equipment j assigned to activity i ,

$R_{i,j}$ = Fuel consumed by one unit of equipment j in accomplishing one production unit of activity i ,

$U_{i,j(\ell)}$ = Combined usage factor of equipment j in interchangeable equipment group ℓ when used in activity i ,

N_i = Scheduled level of accomplishment of activity i ,

$D_{i(\ell)}$ = Number of equipment days required to perform the scheduled accomplishment (N_i) of an activity i by equipment j in interchangeable equipment group ℓ ,

C_j = Number of available equipment days of equipment type j ,

$K_{i,j(\ell)}$ = Units of accomplishment of activity i by equipment j in interchangeable equipment group ℓ .

$D_{i(\ell)}$ is computed as follows:

$$D_{i(\ell)} = \frac{N_i}{K_{i,j(\ell)}} \quad (5.5)$$

It should be noted that the equipment types which are interchangeable have the

same K-value.

Procedure to Estimate K-Values

The K-value can be interpreted as the capacity of one unit of a given equipment type to perform a particular task in one work day called crew day. This value is stated in terms of the production unit of the activity in which the equipment is used. Thus, the K-value is expressed in units of accomplishment per equipment per crew day.

For example, a K-value of 1.1 for dump trucks when used in crack sealing activity indicates that 1.1 lane miles of crack sealing can be accomplished on the average by one dump truck per crew day. The use of K-values allows the consideration of different units of measurement into one common ground for the decision variables employed - equipment days. K-values are used for translating the information on scheduled production units of different activities into equipment days necessary to complete the scheduled levels. The resulting equipment days are then used as work demand constraints in the optimization model. K-values are also used to transform the optimal solutions given in equipment days back into original units of production of each activity so that fuel consumption can be computed by using available fuel usage rates given in gallons per production unit. K-values are computed by the following formula:

$$K_{ij(\ell)} = \frac{P_i}{\sum_{j \in \ell} F_{ij}} \quad (5.6)$$

where $K_{ij(\ell)}$ = K-value for equipment type j in

interchangeable equipment group ℓ for activity i,

P_i = Production per crew day for activity i,

F_{ij} = Usage factor of equipment j when used in activity i,

$\sum_{j \in \ell} F_{ij}$ = Combined usage factor for equipment type j
in interchangeable equipment group ℓ when used
in activity i.

The combined usage factor indicates how many equipment units would be required to perform a certain amount of accomplishments per crew day if only one type of equipment were used.

Model Output

The unit of decision variables is given in equipment days. For example $Y_{207,1}$ is the number of equipment days allowed for equipment number 1, pickup truck, to be used for activity 207, crack sealing. The model minimizes the total amount of fuel consumed by activity-equipment combinations considered. Therefore, the optimization model may indicate that some activities would receive more than or less than the amount of equipment days for certain equipment types than normally used for those activities. If the results appear to be grossly misrepresented or far from reality, equipment grouping needs to be reconsidered and constraints adjusted to reflect any corresponding changes.

In actual scheduling, once an equipment unit is assigned to an activity, this equipment unit is not available for other activities for the entire day. The average number of equipment units to be assigned to do one activity during one crew day can be computed by dividing the values for decision variables by proper crew days scheduled. Therefore, if one decision variable has 200 equipment days for a particular equipment and 100 crew days are scheduled, the usage factor will be 2.0.

Application of the Model

The model can be used at any level of management, state, district, sub-district or even at the unit level. An example problem applied to the subdistrict level was used to test the applicability of the model. The fuel use resulting from the optimal equipment assignment were compared with the actual fuel use estimated for the subdistrict. The application example was developed by using the routine maintenance accomplishment data [4], equipment use data [1] and equipment availability data compiled during the study.

Description of the Example Subdistrict

The Fowler subdistrict was selected for the analysis. It is typical of most of the subdistricts in Indiana, where much of the highway mileage is non-interstate. This example subdistrict was one of the six subdistricts where the field survey on equipment and fuel use was conducted in the first phase of the study discussed in Chapter 2.

Description of Maintenance Demand

In Table 5.1 are given the 1984 actual accomplishments of the subdistrict for the thirteen major fuel consuming maintenance activities. These accomplishment amounts were used in the example problem as demand constraints. Activity 271 on interstate is a major fuel consuming activity, while other activities on interstate are not so significant in fuel consumption. On the other hand, most of the activities on other state highways consume a considerable amount of fuel. Therefore, in the example problem Activity 271 on interstate and twelve activities on other state highways were considered.

Table 5.1. Actual Accomplishments of 13 Major Activities and Estimated Fuel Consumption during FY 1984 for the Fowler Subdistrict

Activity Code	Activity Name	Unit of Measurement	Fuel Use * (gal/unit)	INT			OSH			ALL		
				Actual Accompl. ** (units)	Estimated Fuel Use (gallons)	Actual Accompl. ** (units)	Actual Accompl. ** (units)	Estimated Fuel Use (gallons)	Actual Accompl. ** (units)	Estimated Fuel Use (gallons)	Actual Accompl. ** (units)	Estimated Fuel Use (gallons)
201	Shallow patching	Tons of mix	8.78	113	990	814	7,150	928	8,150			
205	Seal coating	Lane miles	85.14	-	-	95	8,090	95	8,090			
207	Sealing cracks	Lane miles	23.27	-	-	186	4,330	186	4,330			
210	Spot repair of unpaved shoulders	Tons of aggregate	2.15	36	80	655	1,410	691	1,490			
212	Clipping unpaved shoulders	Shoulder miles	52.86	-	-	75	3,960	75	3,960			
221	Machine mowing	Swath miles	1.35	-	-	2,177	2,940	2,177	2,940			
231	Clean & reshape drainage structures	Linear feet	0.22	140	30	41,426	9,110	41,566	9,140			
235	Cleaning minor drainage structures	# of structures	3.81	32	120	361	1,380	393	1,500			
251	Subdistrict sign maintenance	Man-hours	1.02	638	650	2,306	2,350	2,944	3,000			
271	Rest area and lift bridge attendant	Man-hours	0.93	11,740	10,920	-	-	11,740	10,920			
283	Buildings and ground maintenance	Man-hours	1.52	-	-	4,170	6,340	4,170	6,340			
284	Material handling and storage	Man-hours	3.52	-	-	2,153	7,580	2,153	7,580			
289	Other support activities	Man-hours	2.69	-	-	3,742	10,070	3,742	10,070			

* Source: Reference 1

** Source: Reference 4

Equipment Availability

Table 5.2 shows how equipment availability constraints were derived. In this example problem, five hauling equipment types were considered. First, four major equipment types, pickup truck, pickup crew cab, dump truck, and do-all truck, were selected. Utility trucks were then added because pickup trucks and pickup crew cabs can often do the same work as utility trucks when used for sign maintenance. During FY 84, the example subdistrict had 11 pickup trucks, 6 pickup crew cabs, one utility truck, 20 dump trucks, and 7 do-all trucks. To compute the number of available equipment days of each equipment type, 250 working days or crew days per year were used. The value for annual available equipment days was adjusted for possible mechanical breakdowns. The statewide average breakdown rates were used since the existing equipment management system does not provide equipment breakdown rates by equipment type by subdistrict. In case the actual equipment days computed from usage factors [1] for the subdistrict exceeded the values estimated, the equipment availability was set equal to the actual equipment days assigned.

Next, the equipment days used for activities not included in the optimization model were subtracted. It was also necessary to subtract equipment days used in supervision of field activities by the superintendent and three unit foremen, because this activity (Activity 112) is not recorded on crew day cards. It was assumed that supervisory personnel use one pickup each working day. The remaining equipment days then become constraints to the optimization model.

Computation of K-Values

The computation of K-values is a key element of the maintenance equipment

Table 5.2. Estimated Available Equipment Days of Five Equipment Types
for the 13 Activities Included in the Model: FY1984
Fowler Subdistrict Data

Equipment No. & Name	1 Pickup truck	2 Pickup crew cab	8 Utility truck	9 Dump truck	10 Do-all truck
=====					
* Equipment availability					
No. of equipment	11	6	1	20	7
No. of total equipment days available (a)	2,750	1,500	250	5,000	1,750
Breakdown rate (b)	12%	4%	2%	16%	12%
=====					
Remaining equipment days available	2,420	1,440	245	4,200	1,540
=====					
* Equipment days used for activities other than 13 activities included in the model					
Interstate (INT)	76	93	37	469	10
Other State Highways (OSH)	404	224	69	2,016	57
=====					
INT + OSH	480	317	106	2,485	67
Supervision (c)	1,000	-	-	-	-
=====					
Total excluded	1,480	317	106	2,485	67
=====					
* Equipment days available for 13 activities included in the model	940	1,123	139	1,715	1,473
=====					

a) 250 working days/year

b) Statewide average equipment breakdown rates were used

c) 1-superintendent and 3-unit foremen are assumed to use 1 pickup
truck each day to supervise field maintenance activities

assignment technique. In the first phase of the study equipment usage factors were developed for all equipment and activity combinations. The usage factor indicates how often a particular equipment is used for an activity. For example, a usage factor 1.10 indicates that 110 units of this equipment type are used in 100 crew days of this activity, or 110 equipment days are assigned for 100 crew days of this activity. This means more than one unit are used in some of the crew days.

A comparison of computed usage factors, field survey data (crew day cards), and the field operations handbook [15] shows which equipment types can be interchanged. For example, for Activity 207, crack sealing, the equipment usage factors for dump truck (#9) and do-all trucks (#10) are 1.77 and 0.57, respectively, as shown in Table 5.3. Dump trucks are used in crack sealing to spread cover aggregate (usually sand) over the bituminous material applied to cracks. Do-all trucks can substitute for dump trucks to do the same work. Since these two types are used for the same purpose, they form an interchangeable group for this particular activity (207), and the usage factor of this group is the summation of the usage factors of dump trucks and do-all trucks. For the example analysis, the combined usage factor then becomes 2.34. This value is reasonable as the handbook for foremen [15] estimates two dump trucks for each crack sealing activity.

This basic idea of a trade-off between equipment types was used to estimate other combined usage factors. Table 5.3 lists the thirteen activities and equipment usage factors for the five major hauling equipment types. Basically, pickup trucks and pickup crew cabs were treated as interchangeable, and dump trucks and do-all trucks were taken as interchangeable. Where equipment

Table 5.3. Individual Equipment Usage Factors and Combined Usage Factors

Activity Code	Usage Factors *				Combined Usage Factors for Interchangeable Equipment Types					
	#1	#2	#8	#9	#10	#1+#2	#9+#10	#1+#2+#9+#10	#1+#2+#8	#9 only
201	0.10	1.10	-	0.91	0.12	1.20	1.03	-	-	-
205	1.00	1.00	-	9.00	-	2.00	-	-	-	9.00
207	0.53	1.13	-	1.77	0.57	1.66	2.34	-	-	-
210	0.75	0.36	-	0.50	1.33	1.11	1.83	-	-	-
212	0.85	0.60	-	3.35	-	1.45	-	-	-	3.35
221	0.12	0.81	-	0.07	0.01	-	-	1.01	-	-
231	0.51	0.86	-	2.56	-	1.37	-	-	-	2.56
235	0.74	0.35	-	0.17	0.04	-	-	1.30	-	-
251	0.18	0.03	0.79	-	-	-	-	-	1.00	-
271	-	0.75	-	0.75	-	-	-	-	1.50	-
283	0.37	0.37	-	1.05	-	0.74	-	-	-	1.05
284	0.09	0.02	-	1.23	0.14	0.11 (Omitted)	1.37	-	-	-
289	0.19	0.14	-	0.70	0.14	0.33	0.84	-	-	-
Equipment Types: #1 - Pickup truck #8 - Utility truck #10 - Do-all truck										
#2 - Pickup crew cab #9 - Dump truck										

* Source: Reference 1

types are not interchangeable, constraints were constructed accordingly. In case of sign maintenance, pickup trucks, pickup crew cabs, and utility trucks can be interchanged. For activity 271, rest area maintenance and lift bridge attendant, pickup crew cabs and dump trucks can be interchanged.

After the combined usage factors for the equipment types needed for different activities were determined, K-values were computed. Table 5.4 lists the annual average accomplishments per crew day for the 13 activities in the Fowler subdistrict during the fiscal year 1984. The K-value is obtained by dividing the average accomplishment per day with the combined usage factor as shown in Table 5.4. The dimension of K-value is therefore the accomplished production units per equipment unit per crew day. Figure 5.2 shows which equipment types were considered to be interchangeable to do various activities.

Estimated Fuel Consumption

The objective function of the optimization model is to minimize total fuel consumption by equipment types to accomplish the needed maintenance work. The model is run for unconstrained and constrained cases in terms of equipment availability. The unconstrained case refers to the situation where optimal equipment assignment was derived without considering the equipment availability at the subdistrict level, while the constrained case considers the actual equipment availability. The optimal levels of fuel consumption calculated under both cases were compared with estimated actual fuel consumption. Table 5.5 gives fuel consumption rates of equipment types for different activities included as input to the optimization model. The estimates of actual fuel consumed by various equipment types were computed using these rates. Table 5.6 shows the fuel consumption for the activities included in the model for

Table 5.4. Estimated Capacity of Equipment Types - K-Value

Act. Code	Accomp. per Day	Unit of Measure	Combined Usage Factors (no. of equipment/crewday)										K-Values (production/equipment/crewday)														
			1					2					8					9					10				
			Pickup truck	Pickup crew cab	Utility truck	Dump truck	Do-all truck	Pickup truck	Pickup crew cab	Utility truck	Dump truck	Do-all truck	Pickup truck	Pickup crew cab	Utility truck	Dump truck	Do-all truck	Pickup truck	Pickup crew cab	Utility truck	Dump truck	Do-all truck					
201	3.79	tons of aggregate	1.20	1.20	-	-	1.03	1.03	1.03	1.03	3.16	3.16	-	-	3.68	3.68	3.68	3.68	3.68	3.68							
205	8.64	lane miles	2.00	2.00	-	-	9.00	-	-	-	4.32	4.32	-	-	0.96	-	-	-	-	-							
207	2.51	lane miles	1.66	1.66	-	-	2.34	2.34	2.34	2.34	1.51	1.51	-	-	1.07	1.07	1.07	1.07	1.07	1.07							
210	26.20	tons of aggregate	1.11	1.11	-	-	1.83	1.83	1.83	1.83	23.60	23.60	-	-	14.32	14.32	14.32	14.32	14.32	14.32							
212	3.13	shoulder miles	1.45	1.45	-	-	3.35	-	-	-	2.16	2.16	-	-	0.93	-	-	-	-	-							
221	22.21	swath miles (b)	1.01	1.01	-	-	1.01	1.01	1.01	1.01	21.99	21.99	-	-	21.99	21.99	21.99	21.99	21.99	21.99							
231	881.40	linear feet	1.37	1.37	-	-	2.56	-	-	-	643.36	643.36	-	-	344.3	-	-	-	-	-							
235	20.06	structures	1.30	1.30	-	-	1.30	1.30	1.30	1.30	15.43	15.43	-	-	15.43	15.43	15.43	15.43	15.43	15.43							
251	15.07	man-hours	1.00	1.00	1.00	-	-	-	-	-	15.07	15.07	15.07	-	-	-	-	-	-	-							
271	16.00	man-hours	-	1.50	-	-	1.50	-	-	-	-	10.67	-	-	10.67	-	-	10.67	-	-							
283	32.00	man-hours	0.74	0.74	-	-	1.05	-	-	-	43.24	43.24	-	-	30.48	-	-	30.48	-	-							
284	16.19	man-hours	-	-	-	-	1.37	1.37	1.37	1.37	-	-	-	-	11.81	11.81	11.81	11.81	11.81	11.81							
289	12.23	man-hours	0.33	0.33	-	-	0.84	0.84	0.84	0.84	37.06	37.06	-	-	14.56	14.56	14.56	14.56	14.56	14.56							

* Estimated from crewday cards and IDOH's accomplishment records (MM-113): Reference 4

Figure 5.2. Combinations of Equipment Types Considered to Be Interchangeable for the Example Subdistrict

Activity Code	Activity Name	Equipment Type				
		#1	#2	#8	#9	#10
201	Shallow patching	▨	▨		▩	▩
205	Seal coating	▨	▨		░	
207	Sealing cracks	▨	▨		▩	▩
210	Spot repair of unpaved shoulders	▨	▨		▩	▩
212	Clipping unpaved shoulders	▨	▨		░	
221	Machine mowing	▩	▩		▩	▩
231	Clean & reshape drainage structures	▨	▨		░	
235	Clean minor drainage structures	▩	▩		▩	▩
251	Subdistrict sign maintenance	▩	▩	▩		
271	Rest area & lift bridge attendant		▩		▩	
283	Buildings & ground maintenance	▨	▨		░	
284	Material handling & storage				▩	▩
289	Other support activities	▨	▨		▩	▩

- ▨ Pickup truck & Pickup crew cab (#1 & #2)
- ▩ Dump truck & Do-all truck (#9 & #10)
- ▩ Pickup truck, Pickup crew cab, Dump truck, & Do-all truck (#1, #2, #9, & #10)
- ▩ Pickup crew cab & Dump truck (#2 & #9)
- ▩ Pickup truck, Pickup crew cab, & Utility truck (#1, #2, & #8)
- ░ Dump truck only (#9)

Table 5.5. Fuel Consumption Rates of Five Equipment Types for Different Activities Included in the Optimization Model

(gallons per production unit/ miles per gallon)

Activity Code	Activity Name	Unit of Measurement	#1 Pickup truck	#2 Pickup crew cab	#8 Utility truck	#9 Dump truck	#10 Do-all truck
201	Shallow patching	Tons of mix	3.66/ 7.35	2.69/ 6.67	-	4.78/ 3.17	3.71/ 3.08
205	Seal coating	Lane miles	1.10/ 9.00	2.42/ 4.40	-	8.03/ 4.14	-
207	Sealing cracks	Lane miles	2.89/ 4.33	3.07/ 5.75	-	6.15/ 2.17	6.55/ 2.36
210	Spot repair of unpaved shoulders	Tons of aggregate	0.21/ 8.24	0.54/ 5.27	-	0.93/ 2.74	0.76/ 6.20
212	Clipping unpaved shoulders	Shoulder miles	4.32/ 7.31	4.11/ 8.05	-	10.25/ 2.95	-
221	Machine mowing	Swath miles	0.36/ 7.10	0.48/ 7.92	-	1.60/ 4.30	0.80/ 2.88
231	Clean & reshape drainage structures	Linear feet	0.01/ 6.68	0.02/ 6.82	-	0.05/ 2.84	-
235	Cleaning minor drainage structures	# of structures	1.28/ 7.88	0.92/ 7.50	-	7.20/ 3.39	1.92/ 6.83
251	Subdistrict sign maintenance	Man-hours	1.04/10.69	0.69/ 9.03	1.03/ 7.62	-	-
271	Rest area and lift bridge attendant	Man-hours	-	0.21/ 9.36	-	0.76/ 4.17	-
283	Buildings and ground maintenance	Man-hours	0.27/10.45	0.16/ 7.45	-	0.43/ 3.35	-
284	Material handling and storage	Man-hours	-	-	-	1.35/ 3.84	1.54/ 3.80
289	Other support activities	Man-hours	0.68/11.53	0.62/ 8.69	-	1.37/ 4.68	2.00/ 3.52

Source: Reference 1

Table 5.6. Fuel Consumed by Five Major Hauling Equipment Types for the 13 Major Activities in the Fowler Subdistrict

Activity Types	Fuel Use by Equipment Type and Activity in Percentages *										Total Fuel Used by All Equipment Types **			Fuel Used by the Five Equipment Types		
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Total	INT	OSH	INT	OSH	(gallons)
201	4.17	33.76	-	-	44.33	5.07	92.5	-	-	-	7,150	-	-	-	-	6,614
205	1.29	2.84	-	-	84.88	-	89.6	-	-	-	8,090	-	-	-	-	7,200
207	6.58	14.91	-	-	46.78	16.04	84.3	-	-	-	4,330	-	-	-	-	3,650
210	7.33	9.14	-	-	21.63	47.01	85.6	-	-	-	1,410	-	-	-	-	1,199
212	6.95	4.67	-	-	64.96	-	76.6	-	-	-	3,960	-	-	-	-	3,033
221	3.20	28.80	-	-	8.33	0.59	40.9	-	-	-	2,940	-	-	-	-	1,202
231	2.32	7.82	-	-	58.12	-	68.3	-	-	-	9,110	-	-	-	-	6,225
235	24.86	8.45	-	-	32.13	2.02	67.5	-	-	-	1,380	-	-	-	-	932
251	18.35	2.03	79.77	-	-	-	100.0	-	-	-	2,350	-	-	-	-	2,350
271	-	16.94	-	-	61.24	-	78.2	-	-	-	10,920	-	-	-	-	8,539
283	6.57	3.89	-	-	29.70	-	40.2	-	-	-	6,340	-	-	-	-	2,549
284	-	-	-	-	47.17	6.13	53.3	-	-	-	7,580	-	-	-	-	4,040
289	4.80	3.23	-	-	35.65	10.41	54.1	-	-	-	10,070	-	-	-	-	5,448
											Total	8,539	44,442			
											Grand Total = 52,981 gallons					

the example subdistrict in FY 84.

Summary of Results

The LINDO (Linear, Interactive and Discrete Optimization) computer program developed at the University of Chicago [16] was used to solve the example problem. Results of the optimization efforts are summarized in Tables 5.7 through 5.9, and are discussed below.

Constrained Problem

Table 5.7 shows a comparison of optimal equipment assignments resulting from the model and the actual equipment use derived from the field data [1]. For the constrained case the disposable equipment days given in Table 5.2 formed the equipment availability constraints. It can be seen that there is a difference between the actual equipment use and optimal equipment use. For example, in the case of crack sealing activity, the optimal assignment was to use only pickup trucks and dump trucks instead of pickup trucks, pickup crew cabs, dump trucks, and do-all trucks as used in the actual assignment.

The estimated actual fuel consumption by the equipment-activity combinations included in the model was 52,981 gallons (Table 5.6), whereas the fuel consumption for the optimal equipment assignment was 46,411 gallons (Table 5.8), resulting in a 12.4% reduction from the actual equipment use. This reduction is substantial because the fuel consumed by the activities considered in the model accounts for only about 65% of the total fuel consumed in routine maintenance at the state level. Therefore, if other activities were included in the model, the estimation of the amount of fuel saved would increase even if the percentage reduction might remain the same. A simple

Table 5.7. Actual Equipment Assignment vs. Optimal Equipment Assignment

Actual *															
Equipment Types						Optimal - Constrained					Optimal - Unconstrained				
Activity	#1	#2	#8	#9	#10	#1	#2	#8	#9	#10	#1	#2	#8	#9	#10
201	22	237	-	196	26	258	0	-	0	221	0	258	-	0	221
205	11	11	-	99	-	22	0	-	99	-	22	0	-	99	-
207	39	84	-	131	42	123	0	-	174	0	123	0	-	174	0
210	19	9	-	13	33	28	0	-	0	46	28	0	-	0	46
212	20	14	-	80	-	35	0	-	81	-	0	35	-	81	-
221	12	79	-	7	1	99	0	-	0	0	99	0	-	0	0
231	24	40	-	120	-	64	0	-	120	-	64	0	-	120	-
235	13	6	-	3	1	1	23	-	0	0	0	24	-	0	0
251	28	5	121	0	-	14	0	139	0	-	0	153	0	0	-
271	-	550	-	550	-	-	1,100	-	0	-	-	1,100	-	0	-
283	48	48	-	137	-	96	0	-	137	-	0	96	-	137	-
284	12	3	-	164	19	0	0	-	182	0	0	0	-	182	0
289	58	43	-	214	43	101	0	-	257	0	0	101	-	257	0
Total	306	1,126	121	1,715	165	841	1,123	139	1,050	267	336	1,767	0	1,050	266

Equipment types:	#1 - Pickup truck #2 - Pickup crewcab	#8 - Utility truck #9 - Dump truck	#10 - Do-all truck
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Equipment types: #1 - Pickup truck #2 - Pickup crew cab #8 - Utility truck #9 - Dump truck #10 - Do-all truck

* Computed using the data found in References 1 and 4

multiplication of the number of subdistricts (37 subdistricts in Indiana) to the reduction of this example can mean a savings of approximately 243,000 gallons of fuel every year. This could amount to about \$182,250 to \$486,000 of fuel cost savings every year if the fuel prices ranged from \$0.75 to \$2.00 per gallon. Table 5.8 also shows which activities would use less or more fuel in the optimal case than the actual assignment. It appears that the total annual fuel consumption of Activity 271 could have been reduced to about half of the current fuel requirement.

Table 5.9 shows the available equipment days and the equipment days used for each type of equipment for both the actual equipment assignment and the optimal equipment assignment. It is evident that the model can determine the critical equipment types as well as the redundant equipment types. This information can help determine which equipment types need to be added or to be decreased from the current fleet. For example, the most critical equipment type for this subdistrict is pickup crew cab. Other four types considered in the model are abundant for this subdistrict for carrying out regular maintenance activities. The number of do-all trucks greatly exceeds the actual demand. The reason for this abundance is, however, that most do-all trucks are kept for the snow and ice removal work in winter, and the model did not include this emergency activity.

Unconstrained Problem

In order to check how much fuel could be saved if all equipment needed were available, an unconstrained case was analyzed. In Table 5.7 was also shown the equipment assignment obtained by the unconstrained version of the model. The unconstrained equipment assignment is somewhat different from both

Table 5.8. Fuel Consumed by Each Activity Under Three Equipment Assignment Scenarios

Activity Number	Actual Equipment Assignment	Optimal Assignment for Constrained Case	Optimal Assignment for Unconstrained Case
	gallons	gallons	gallons
201	6,614	6,686 (+72)	5,738 (-876)
205	7,200	7,078 (-122)	7,078 (-122)
207	3,650	3,568 (-82)	3,564 (-86)
210	1,199	1,062 (-137)	1,063 (-136)
212	3,033	3,043 (+10)	3,020 (-13)
221	1,020	792 (-410)	792 (-410)
231	6,225	5,827 (-398)	5,827 (-398)
235	932	437 (-495)	432 (-500)
251	2,350	2,377 (+27)	1,591 (-759)
271	8,539	3,697 (-4,842)	3,697 (-4,842)
283	2,549	2,715 (+166)	2,376 (-173)
284	4,040	3,981 (-59)	3,981 (-59)
289	5,448	5,148 (-300)	5,073 (-375)
Total	52,981	46,411	44,236

Table 5.9. Equipment Days Used by Each Equipment Type Under Three Equipment Assignment Scenarios

Equip. No.	Equipment Type	Available Equipment Days	Equipment Days Used		
			Actual Assignment	Optimal Assignment	
				Constrained	Unconstrained
1	Pickup truck	940	306	841	336
2	Pickup crew cab	1,123	634	1,123	1,767
3	Utility truck	139	121	139	0
9	Dump truck	1,715	1,715	1,050	1,050
10	Do-all truck	1,473	166	267	266

the actual and constrained assignments. The fuel consumption for the unconstrained optimal assignment resulted in 44,256 gallons, as shown in Table 5.8. There could be as much as 16.5% reduction from the estimated actual fuel consumption. However, since there was only one critical equipment type, the pickup crew cab, the difference of total fuel consumption between the constrained and unconstrained assignments was only about 5% for this subdistrict.

Sensitivity Analysis

A sensitivity analysis was conducted by examining the results of the constrained and unconstrained versions of the optimization program for the example subdistrict. The objective of this analysis was to determine explicitly the impact of each type of equipment on the overall fuel consumption. Figure 5.3 shows the reduction in fuel consumption per unit of pickup crew cab added. In this case, only the number of pickup crew cabs was increased and the number of units of other equipment types were kept the same, since adding other vehicles would not produce any extra fuel savings for the example subdistrict. Figure 5.3 clearly illustrates that adding extra pickup crew cabs to the current fleet would help conserve fuel, but the marginal fuel savings would dramatically decrease after one or two equipment units are added to the current fleet. If available from other subdistricts, borrowing one or two pickup crew cabs would be a possibility to help reduce a substantial amount of fuel use.

Importance of the Input Data

The validity of the results of the optimization technique developed in this study is largely dependent upon the accuracy of the input data. Three types of information are critical: (i) equipment usage factors, (ii) fuel

Figure 5.3. Number of Available Pickup Crew Cabs (Equipment No.2) vs.
Total Fuel Consumption by the 13 Major Activities
Included in the Model

consumption rates, and (iii) interchangeability of equipment types.

Currently, usage factors obtained from the field survey [1] are average usage factors of six subdistricts selected for the survey. They may not necessarily reflect the equipment usage pattern of a particular subdistrict. Also, the field survey was conducted in FY 82, while the example problem was for FY 84. It is suggested that field data should be collected periodically to update the usage factors.

Fuel consumption rates are probably the most important input data affecting the accuracy of the results. Fuel consumption rates of all equipment types are given in gallons per production unit. These rates are greatly affected by the condition of job sites even within each activity. Hauling distance and the manner by which equipment units are used can also substantially affect the fuel requirement for one unit of production. Fuel consumption rates now available are average values for six subdistricts used for the field survey [1]. In order to increase the accuracy of the results for a particular subdistrict, it is recommended that each subdistrict monitor fuel consumption rates for its own fleet.

Interchangeability of equipment can be found by reviewing crew day cards and by field observation. In the example problem, the interchangeability observed during the field survey was considered. Any changes in equipment interchangeability can be evaluated by examining updated equipment usage factors.

The only data that are not currently recorded in crew day cards are fuel consumption data. If the fuel consumption data are kept current, IDOH would be in a better position to keep a close control of its fuel conservation programs.

Suggested Implementation of Optimization Results

The optimization model discussed in this chapter gives the number of equipment days of an equipment type that would be assigned to a particular maintenance activity in order to minimize total fuel consumption. Equipment scheduling according to the optimization results should, however, follow the existing activity scheduling procedure.

The current activity scheduling procedure is discussed in the Handbook for Foremen [15]. The optimal equipment assignment procedure would not interfere with the process of overall routine maintenance programming process [15,17], which eventually produces the Work Calendar (Report MM-109), as shown in Figure 5.4. The Work Calendar lists standard crew size, road class, work control category, annual planned crew days, and planned crew days per month for all work activities that should be carried out in a subdistrict during a fiscal year.

At subdistricts, the Semi-Monthly Schedule, which lists the work to be done during the next two week period, is prepared from the Work Calendar, Maintenance Needed Lists and Maintenance Needed Reports. The Work Calendar is the major guide for scheduling activities. Individual activities for the coming two weeks are scheduled using supporting information from the other two reports mentioned above. The semi-monthly schedules are prepared for the units by the General Foreman and approved by the Superintendent. The schedule also describes the activities and locations to which crews are to be assigned unless emergency work requires other work be to done. When emergency work is

Figure 5.4. Example of IDOH Activity Scheduling

REPORT MM-109	INDIANA DEPARTMENT OF HIGHWAYS															PAGE 14
DATE PREPARED 06/01/84	DIVISION OF MAINTENANCE															
	MAINTENANCE MANAGEMENT SYSTEM															
	MAINTENANCE WORK CALENDAR															
	FISCAL YEAR 84-85															
DISTRICT 1	SOUTHERN DISTRICT 3 FOWLER															
MAINTENANCE	CREW	ROAD	WORK	ANNUAL	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
WORK ACTIVITY	SIZE	CLASS	CONTROL	CREW	PLANNED CREW DAYS PER MONTH											
NAME	CATEGORY DAYS															
204 FULL WIDTH SHOULDER SEAL 20	INT	LIM	1	1												
204 FULL WIDTH SHOULDER SEAL 20	OSH	LIM	3	3												
ACTIVITY TOTAL			4	4												
205 SEAL CRACKING	21	OSH	LIM	9		9										
206 SEAL LONG CRACK/JNT	9	INT	LIM	4									4			
206 SEAL LONG CRACK/JNT	9	OSH	LIM	11					7	4						
ACTIVITY TOTAL			15	15					7	4			4			
207 SEALING CRACKS	11	OSH	LIM	59		6	16	16	10	7	2					
209 CUT-RELIEF JOINTS	6	OSH	LIM	3				3								
211 BLADE MOWING	3	OSH	LIM	8												
212 CLIP UNPAVED SELDR	8	OSH	LIM	20	12	6										2
224 SEEDING-FERTILIZING	3	INT	LIM	1											1	
224 SEEDING-FERTILIZING	3	OSH	LIM	1											1	
ACTIVITY TOTAL			2	2											2	
231 CLEAN-RESHAPE CUTCH	7	INT	LIM	3	3											
231 CLEAN-RESHAPE CUTCH	7	OSH	LIM	58	7	5	12	12	6	3					6	7
ACTIVITY TOTAL			61	61	10	5	12	12	6	3					6	7
232 INSPECT MIN ORN STR	2	INT	LIM	2						2						
232 INSPECT MIN ORN STR	2	OSH	LIM	25						3	5	5	7	5		
ACTIVITY TOTAL			27	27						5	5	5	7	5		
233 PIPE REPLACEMENT	8	OSH	LIM	9	3			6								
234 MUDCE PATCH/DITCH	9	OSH	LIM	4		4										
241 HAND CLEAN BRIDGES	5	INT	LIM	7											4	
241 HAND CLEAN BRIDGES	5	OSH	LIM	17										17		
ACTIVITY TOTAL			24	24										20		4
244 FLOUSHING BRIDGES	4	INT	LIM	6											6	
244 FLOUSHING BRIDGES	4	OSH	LIM	8											8	
ACTIVITY TOTAL			14	14											14	
203 PREMIX LEVELING	11	OSH	VAR	5	3											2

completed, work assignments will then return to the priority activities on the schedule. According to the given priority, the general foreman and sometimes the unit foreman assign work, workers and equipment in the morning of a work-day.

As the decision variable of the optimization model is given by the number of equipment days of a particular equipment to be used, the scheduling personnel, most probably the unit foreman, can use these values as target values for equipment scheduling. The task for the scheduler would be to follow the given equipment assignment guideline as close as possible. The scheduler would keep records showing how many equipment days are left for the next activity. Also, equipment days of substituting equipment types should also be recorded. The basic principle is to attempt to schedule equipment types which would use less fuel as long as the substituting equipment can do the same work.

Let us consider the shallow patching activity. The Handbook for Foremen [15] recommends one unit of pickup-crew cab for this activity. From the field data collected during the study, it is known that a pickup truck can be a substitute equipment. Therefore, these two equipment types can be considered as an interchangeable equipment group. Suppose that the optimization model indicates that the optimal equipment days of pickup truck and pickup-crew cab to be assigned to shallow patching activities for the entire year in a particular subdistrict are 50 and 70, respectively. These values can be used by the scheduler of routine maintenance work in advance as target values. The scheduler would attempt to assign equipment units to shallow patching activities so that these target values would not be exceeded over the period. For that, every time a shallow patching activity is scheduled, the scheduler will have to keep track of the equipment days of use of pickup truck and pickup-

crew cab. However, when many activities need to be done in a short period, equipment units are to be assigned first to dominantly fuel consuming activities, such as shallow patching and crack sealing.

Chapter Conclusions

The example discussed in this chapter demonstrated the usefulness and applicability of the maintenance equipment assignment technique (MEAT) developed in the study. The technique allocates equipment to various maintenance activities within the given constraints of resources and maintenance requirements. As the optimization routine considers the equipment assignment problem on a macroscopic scale, the results are not affected by fluctuations in equipment use due to various conditions pertinent to equipment scheduling, such as weather and equipment breakdowns. The technique is capable of dealing with a large number of activities and a variety of equipment types provided that there is an interchangeability of certain equipment types.

CHAPTER 6

DEVELOPMENT OF GUIDELINES

Introduction

The purpose of this chapter is to present a set of guidelines that can be used to conserve fuel and reduce cost in highway routine maintenance. The guidelines are broad in their framework and can be applied to any element of the routine maintenance system. However, the dominant activities and equipment types should be considered first. There are two major approaches that can be followed to achieve the goal of fuel savings, as shown in Figure 6.1. Equipment management is a direct approach where fuel use can be specifically considered, whereas in maintenance management fuel savings can be considered indirectly through other objectives.

Approaches to Fuel Conservation

A summary of possible strategies is given below and detail discussions are presented in subsequent sections.

A. Equipment Management

1. Equipment types should be identified in terms of their fuel consumption rates. Equipment types with lesser fuel consumption rate should be assigned first as long as they are available and compatible to do the required task.
2. Equipment should be used efficiently by reducing hauling distance, loading time and idling time. Also, equipment units scheduled should be commensurate with the type and amount of particular maintenance activities.

Figure 6.1 Approaches to Energy Conservation Related to Routine Maintenance

3. Dieselization of dominant fuel consuming equipment units should be continued.

B. Maintenance Management

1. Increased attention should be given to preventative maintenance.
2. Planned accomplishments of activities in the limited category should be firmly adhered to.
3. Procedures for assessing maintenance needs should be improved so that an appropriate equipment assignment can be planned.
4. The information provided by the routine maintenance management information system should be kept up to date so that the three basic resources, fuel, material and labor, can be optimally utilized.
5. Quality of maintenance work, especially that in the roadway and shoulder area, should be evaluated and improved so that the effectiveness of maintenance activities can be increased resulting in less frequent work.

Equipment Management

Equipment use and dieselization of maintenance equipment are two major areas through which fuel conservation can be accomplished.

Equipment Use

Approaches in this group are the most direct ones for fuel conservation. The three approaches suggested are discussed below with reasons for their selection.

Better Assignment of Equipment Types

The mathematical optimization model presented in Chapter 5 is one tool to accomplish this task with the objective of minimizing fuel use. As long as the substitution of equipment types is feasible to do the same task, equipment with less fuel consumption should be used. Only five dominant fuel consuming equipment are considered in the model, namely pickup, pickup crewcab, utility truck, dump truck and do-all truck, because they consume most of the fuel used in routine maintenance in Indiana and they can be interchanged in most cases.

From the field survey it was found that pickups and pickup crewcabs were interchanged and that often dump trucks and do-all trucks, and sometimes flatbed trucks as well, were interchanged to do the same job. Fuel consumption rates of these vehicles are different when used in different activities. By assigning equipment first to the most important activities in terms of minimizing fuel consumption, it may be possible to achieve a substantial annual reduction in fuel consumption.

Efficient Use of Equipment

The need for an efficient use of equipment has been stressed in the construction area [18,19,20]. The same is true in the routine maintenance area. The fuel use trend analysis conducted in the study identified that hauling equipment are the ones where the highest fuel savings can be expected. These vehicles, therefore, should be managed first.

Three major factors exist in routine maintenance that affect fuel use. They are hauling distance, loading time, and waiting time. As for hauling distance, supervisors need to make efforts to find sites to dispose the exca-

vated material close to the job site. Also, major equipment other than hauling equipment, such as mowing tractors and excavators, may be left at or near job sites if the same work continues for more than one day. This practice is currently followed by the IDOH and it should be continued.

Loading time largely depends on the capacity of other equipment, such as excavators, that load the hauling vehicle. Sometimes the loading is done while equipment units are in motion. However, if loading is done at a stationary position, it may be better to turn the engine off during loading in order to save fuel.

Probably controlling idling time is the most promising area for fuel conservation. Idling time is related to waiting time which is affected by the capacity of loading equipment and hauling distance. It may be difficult to completely eliminate idling time. However, field observations showed that idling time can be considerably reduced. For example, at one ditch reshaping site, it was observed that each dump truck waited for about 15 minutes before being loaded. During that period the engine of the truck was kept turned on and the driver remained in the operator's seat. The amount of time spent in hauling, loading, and waiting during the same field visit was observed to be, on the average, 30 minutes, 10 minutes, and 15 minutes, respectively.

Idling can also occur with equipment other than hauling vehicles. When the number of hauling vehicles are inadequate, the other major equipment such as excavators will have idling time. Therefore, the relation of hauling distance, loading time, and waiting time needs to be evaluated for major loaders, excavators, and graders before they are scheduled, based on the requirement of the job site. On one occasion during the field visit, it was observed that

only one dump truck was scheduled to haul the excavated material since the other dump truck was used to carry fill material. This arrangement caused a long idling time for the backhoe.

Selection of Proper Equipment

Equipment to be scheduled should be commensurable with the tasks to be performed. FHWA's continuous efforts to optimize maintenance activities by using the principles of value engineering point out the importance of assigning proper equipment which are commensurable with the nature of maintenance [21,22,23,24,25].

The field survey data also showed that a pickup truck or crewcab, or dump truck was sent to carry out similar types of sign maintenance work. In most cases, pickup trucks are quite satisfactory to carry out the task assigned for sign maintenance. Also, some subdistricts use pickup trucks or crewcabs instead of dump trucks to carry bituminous mix. If a pickup truck or pickup crewcab can do the same job because of the small amount of material to be carried, it can replace dump trucks.

Type of Fuel Used

Dieselization of some units of major equipment types has just begun at IDOH (Figure 6.2). Dieselizing hauling vehicles can produce a significant reduction in fuel use because the past studies showed that diesel equipment units are more fuel efficient than gasoline units [26,27].

One field supervisor mentioned that mowing tractors with diesel engine have had less troubles than gasoline powered tractors. Since it is not yet known whether dieselized units are superior than gasoline powered units in

Figure 6.2 Annual Consumption of Fuel by All Equipment *

terms of total maintenance cost, the historical data including fuel consumption and maintenance costs should be maintained for an overall evaluation of dieselized equipment. Nevertheless, when fuel reduction is considered to be the prime target, diesel powered equipment surpass gasoline powered equipment.

Maintenance Management

The following three areas in Maintenance Management can be considered: (i) maintenance policy, (ii) maintenance planning, and (iii) maintenance practice. These three areas are discussed here with possible guidelines that can help conserve energy. In this respect the thirteen major activities should be considered first. In fiscal year 1984 these thirteen activities accounted for 65.8% of the total fuel, 58.0% of the total material, and 43.4% of the total labor costs expended for all field activities except the snow and ice removal, as shown in Figure 6.3. Figure 6.3 also shows what must be first evaluated to achieve energy and cost savings related to maintenance. For example, the use of material is concentrated in pavement related maintenance activities. Because these materials are primarily petroleum products, management of these activities would not only reduce direct energy consumption, but also achieve overall conservation of petroleum products.

Maintenance Policy

Two guidelines are offered in the policy aspect of maintenance management. They include the increase in preventive type maintenance and the firm adherence to planned accomplishments, especially with regard to the activities in the "limited" maintenance category.

Figure 6.3. Shares of Fuel, Material, and Labor Cost in Unit Costs
of 13 Major Fuel Consuming Activities in FY 1984

Increase in Preventive Maintenance

As for activities in the roadway and shoulder maintenance, grouping of preventive and remedial type of activities can be made. In the second phase of the study, it was estimated how much fuel can be saved by increasing the amount of crack sealing and subsequently reducing the amount of patching. The maintenance cost analysis showed that highway sections which received more crack sealing in fall required less shallow patching in the following spring. A careful evaluation should be made of the optimal level of preventive maintenance that can maximize the cost and energy savings without jeopardizing the level of maintenance service and motorist safety.

In FY 1984 one-third of the 37 subdistricts of IDOH did not complete their planned accomplishments for crack sealing by more than 10%. If these subdistricts had completed the plan, IDOH might have saved as much as 10,000 gallons of fuel that year according to the prediction models developed in the study and discussed in Chapter 3.

Adherence to Planned Accomplishments

Routine maintenance data show that there are substantial differences between the planned and actual accomplishments. This phenomenon is found not only among activities of lower priority but also among activities of higher priority, such as those in the limited category. In order to implement an effective fuel conservation program, it is essential that planned accomplishments be completed within a reasonable level of variation.

Adherence to planned accomplishments can also mean overall energy and cost savings in the long run. Deferring maintenance would cause further deterioration of highways and consequently would require more elaborate maintenance in the future. This would result in additional costs and energy

use.

Table 6.1 compares percent accomplishment rates of shallow patching and crack sealing of the subdistricts in Indiana in fiscal year 1984. In order to avoid bias caused by the existence of interstates in some of the subdistricts, only the data for other state highways (OSH) were used for the comparison. Crack sealing is in the limited category, whereas shallow patching is in the unlimited category.

The table shows that 10 of the 37 subdistricts fell short of the planned accomplishment of crack sealing by more than 10% in fiscal year 1984. Two subdistricts completed only one-third of the planned accomplishments. These ratios become worse in the case of the unlimited category. As for shallow patching, 27 of the 37 subdistricts did not complete planned accomplishments by more than 10%. The average percent accomplishment of these 27 subdistricts was 65%.

Crack sealing and shallow patching are the two major activities of roadway and shoulder maintenance. In order to prevent further deterioration by falling short of the planned accomplishments, a maintenance policy which sets a minimum value of percent accomplishment may be established wherever possible. Those activities which have man-hours as production units encounter difficulty in setting such a criterion unless production units can be given in objective measurement units other than man-hours. Therefore, activities in the roadway and shoulder area can be the best candidates for establishing such policies. This process should help identify what maintenance activities have the highest priority and where fuel should be allocated when an emergency curtail in fuel use is to be effected.

Table 6.1. Comparison of Planned Accomplishment with Actual Accomplishment
for Activity 201 & Activity 207 (OSH in FY1984 only)

Dist.	Subdistrict	Act. 201-Shallow Patching (Unlimited Category)			Act. 207-Crack Sealing (Limited Category)		
		Planned (Tons of Mix)	Actual	%	Planned (Lane Miles)	Actual	%
1	1 Terre Haute	1,125	1,048	93	144	128	89*
	2 Crawfordsville	450	243	54*	117	76	65*
	3 Fowler	840	814	97	171	186	109
	4 Frankfort	405	342	85*	135	156	116
	5 Greencastle	830	521	63*	132	104	79*
	6 Veedersburg	550	680	124	147	148	101
2	1 Warsaw	1,285	700	55*	168	170	102
	2 Goshen	1,515	933	62*	147	157	107
	3 Fort Wayne	1,020	912	89*	129	158	122
	4 Angola	1,255	605	48*	117	90	77*
	5 Wabash	1,550	1,073	69*	192	209	109
	6 Bluffton	875	921	105	135	142	106
3	1 Indianapolis	585	424	73*	168	51	31*
	2 Greenfield	500	422	84*	159	112	71*
	3 Centerville	950	515	54*	144	158	110
	4 Anderson	333	306	92	114	39	34*
	5 Tipton	745	380	51*	180	185	103
	6 Ridgeville	780	572	73*	141	142	101
4	1 LaPorte	830	569	69*	159	206	130
	2 Monticello	935	858	92	138	142	103
	3 Plymouth	1,500	1,877	125	189	199	105
	4 Rensselaer	835	633	76*	129	123	96
	5 Valparaiso	855	573	67*	156	177	114
	6 Winamac	1,305	1,135	87*	138	151	110
	7 Gary	1,095	1,026	94	129	102	79*
5	1 Aurora	1,190	663	56*	147	113	77*
	2 Bloomington	850	658	77*	144	162	113
	3 Columbus	650	283	44*	132	186	141
	4 New Albany	975	688	71*	141	150	107
	5 Madison	500	172	34*	168	235	140
	6 Seymour	1,405	904	64*	165	227	138
6	1 Linton	675	402	60*	246	276	112
	2 Dale	505	336	67*	258	304	118
	3 Evansville	500	337	67*	273	219	80*
	4 Paoli	525	342	65*	267	300	113
	5 Branchville	500	450	90	177	223	126
	6 Petersburg	440	430	98	267	271	102

Note: * - Subdisrict with the actual accomplishment less than the planned accomplishment by more than 10%.

Maintenance Planning

The importance of adhering to planned accomplishments was stressed in the preceding section. Such policy is meaningful only when the planned accomplishments truly reflect actual needs of maintenance. Where the difference between the planned and actual accomplishments is too large, there can be two possible reasons. One of them is that the procedure for assessing maintenance may not be satisfactory. The other is that subdistricts may not be careful in meeting the plan they set up.

A study on the assessment of routine maintenance needs currently underway at Purdue should provide the essential information necessary to develop procedures for better estimating routine maintenance needs. Once an improved assessment procedure is established, the next step is to supervise subdistricts so that they would complete at least the minimum percent accomplishment requirements which can be set as part of the maintenance policies.

Where true needs are correctly assessed and deficiencies are corrected in due time, the estimate of fuel use can be accurately made and the implementation of appropriate measures for fuel conservation can be effective. Furthermore, priorities of various maintenance work may be taken into account and the amount of low priority activities can be reduced when an emergency fuel reduction program has to be implemented.

Work Practices

There are two areas in work practices that can be considered. Their objectives are indirectly related to energy conservation. However, consideration of these areas can, in the long run, contribute to the reduction of

overall fuel use in routine maintenance.

Increase in Productivity

A statistical analysis conducted in the study showed that some subdistricts have chronically low productivity. Routine maintenance consists of three components, fuel, material, and labor. As shown in Figure 6.2, labor is a very vital part in maintaining productivity. Excess labor can be used for completing other maintenance activities. A careful use of labor resource should help complete more important activities as they were planned and should contribute to overall cost savings.

A comparison of average productivity of shallow patching and crack sealing was made to identify the productivity levels of the 37 subdistricts, using the data of fiscal years 1982, 1983, and 1984. To reduce the data to a common ground, production/worker/crewday was also used. Table 6.2 shows a comparison of production/crewday, workers/crewday, and production/worker/day for shallow patching and crack sealing among the 37 subdistricts. In this study, subdistricts with production rate less than the rate which is one standard deviation minus the state average, was considered as low productivity subdistricts. It can be seen in Table 6.2 that in 1984 there were several subdistricts that had low productivity in either sealing or patching or both activities.

A two-way ANOVA (analysis of variance) was run to see whether the difference of productivity among the subdistricts was significant. Annual averages of production/crewday and production/worker/crewday of the fiscal years 1982, 1983, and 1984 were used. Since there was only one value (annual average productivity data) per each treatment combination ("year" and "subdistrict"), the Tukey One Degree of Freedom Test [28,29] was used to estimate the interaction

Table 6.2. Comparison of Average Productivity of Shallow Patching and Crack Sealing among Subdistricts (OSH only)

Dist.	Subdistrict	Act. 201-Shallow Patching (Tons of Mix)			Act. 207-Crack Sealing (Lane Miles)		
		Production/ Crewday	Workers/ Crewday	Production/ Worker/Day	Production/ Crewday	Workers/ Crewday	Production/ Worker/Day
1	1 Terre Haute	4.70 **	6.00 **	0.78	2.58	7.56 *	0.35 **
	2 Crawfordville	2.96 *	5.65	0.52 *	2.19	9.02	0.24 *
	3 Fowler	4.73 **	5.55	0.85	2.29 *	8.60 *	0.27 *
	4 Frankfort	3.55	5.48	0.65	2.65	9.29	0.28
	5 Greencastle	2.90 *	5.93 **	0.49 *	2.69	9.00	0.30
	6 Veedersburg	4.53	5.50	0.82	2.90	10.52 **	0.28
2	1 Warsaw	4.10	5.50	0.74	2.17 *	9.71	0.22 *
	2 Goshen	5.08 **	5.02	1.03 **	2.89	9.89	0.29
	3 Fort Wayne	4.96 **	5.46	0.91	3.09	9.27	0.33
	4 Angola	3.83	4.18 *	0.92 **	3.03	9.10	0.33
	5 Wabash	3.95	5.20	0.76	2.70	9.58	0.28
	6 Bluffton	4.31	5.98 **	0.72	3.01	8.76	0.34
3	1 Indianapolis	3.06 *	5.43	0.56 *	2.90	10.50 **	0.28
	2 Greenfield	4.00	5.94 **	0.67	2.37 *	9.63	0.25 *
	3 Centerville	3.99	6.13 **	0.65	2.65	11.22 **	0.24 *
	4 Anderson	2.43 *	5.95 **	0.41 *	2.50 *	9.87	0.25 *
	5 Tipton	3.36	5.56	0.60	2.82	8.29 *	0.34
	6 Ridgeville	3.91	4.62 *	0.85	1.99 *	7.83 *	0.25 *
4	1 LaPorte	3.79	5.16	0.73	2.78	10.46 **	0.27 *
	2 Monticello	3.90	4.91	0.79	3.42 **	10.37 **	0.33
	3 Plymouth	4.34	4.93	0.84	2.80	9.83	0.29
	4 Rensselaer	4.35	5.28	0.82	2.94	9.50	0.31
	5 Valparaiso	4.99 **	5.19	0.96	3.06	9.73	0.31
	6 Winamac	4.61 **	5.09	0.90	3.28 **	11.56	0.29
	7 Gary	4.03	5.51	0.73	2.81	9.98	0.28
5	1 Aurora	3.16	4.04 *	0.76	2.52	8.95	0.28
	2 Bloomington	5.51 *	4.16 *	1.32	3.13	10.54 **	0.29
	3 Columbus	2.54 *	4.80	0.52 *	3.42 **	9.16	0.37 **
	4 New Albany	3.91	4.60 *	0.85	3.09	9.80	0.32
	5 Madison	2.89 *	5.08	0.57	3.03	9.77	0.31
	6 Seymour	4.29	4.71 *	0.92 **	3.30 **	8.61 *	0.38 **
6	1 Linton	3.11 *	5.64	0.55 *	3.63 **	9.55	0.38 **
	2 Dale	3.18	5.62	0.56 *	3.26	8.77	0.37 **
	3 Evansville	3.80	5.61	0.68	3.25	8.97	0.37 **
	4 Paoli	3.53	5.28	0.67	3.36 **	9.60	0.35 **
	5 Branchville	3.95	6.12 **	0.65	3.34 **	9.46	0.35 **
	6 Petersburg	3.42	5.20	0.66	2.93	8.32 *	0.35 **
State Average		3.88	5.29	0.74	2.89	9.48	0.31
Standard Deviation		0.73	0.54	0.18	0.39	0.86	0.04

Note: * - Lower than or on the border of one standard deviation minus the state average.

** - Higher than or on the border of one standard deviation plus the state average.

of year with subdistrict.

The interaction of year with subdistrict was significant at a 5% significance level for shallow patching. The data transformation was attempted. It was found that common logarithm ($\log_{10}$) would be most effective to reduce the interaction effect. After transformation, the interaction remained significant for the production/crewday data, but its effect was reduced. The year factor for production/worker/day became insignificant at a 5% significance level after the transformation. The difference of productivity among the subdistricts was strongly significant before and after the transformation. It can be said that productivity of shallow patching was statistically different among the subdistricts. As for the productivity of crack sealing, the year factor and the interaction of year with subdistrict were not significant at a 5% significance level, but the subdistrict factor remained statistically significant.

The statistical analysis showed that a subdistrict with a high production/crewday did not always have a high production/worker/crewday. Therefore, scattergrams of these two factors were made for shallow patching and crack sealing, as shown in Figures 6.3 and 6.4, respectively. These scattergrams indicate that an increase in the number of workers/crewday per activity does not necessarily increase production/crewday.

Quality Control

The issue of productivity improvement also brings up the question of quality control. Field observations conducted during the study revealed strong needs for quality control. Procedures for proper repair works are discussed in manuals such as those published by the Asphalt Institute [30].

Figure 6.4 Average Production/Crewday vs. Workers/Crewday of Shallow
Patching (37 Subdistricts for FY82, 83, &84)

Figure 6.5 Average Production/Crewday vs. Workers/Crewday of Crack
Sealing (37 Subdistricts for FY82, 83, & 84)

However, in the field these standard procedures are not always fully followed. Diversions from the standard may be caused due to a lack of equipment, lack of personnel, or lack of training. If the standard procedure for maintenance is closely followed, it may require more time and the productivity per day may become lower than the current level. However, repairs of better quality should eventually reduce overall maintenance needs in the future.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR IMPLEMENTATION

The study was conducted in three phases. In the first phase a field survey was performed to identify fuel consumption rates of various equipment types when used in different routine maintenance activities. The survey included a detailed data collection program in FY 1982 in six subdistricts of the Indiana Department of Highways (IDOH). Based on the analysis of the field data, the following conclusions were made:

1. Motor fuel is the most expensive single material used in routine maintenance.
2. Snow and ice removal is the single major fuel consuming activity. However, this activity is entirely weather dependent and it cannot be controlled in the same manner as other activities.
3. For various reasons, frequency of equipment use is significantly different from subdistrict to subdistrict for most activities.
4. Frequency of equipment use is considerably different from season to season.
5. The assumption of a standard fuel consumption rate for equipment types can be grossly erroneous.
6. Appropriate fuel use information should be incorporated in maintenance data recording system.

The second phase of the study focused on pavement maintenance. A data base was prepared utilizing the IDOH routine maintenance records from fiscal years 1980 through 1983, traffic data, road life information, and climatic information. A set of pavement maintenance cost prediction models was developed for both the total cost and the cost for patching and scaling groups. On the basis of the analysis, the following conclusions were made:

1. A high correlation was observed between pavement maintenance costs in a year and the average of maintenance costs in the previous two or three years.
2. It was found that the level of expenditure in patching activity in a fiscal year was negatively correlated with the expenditure in sealing activity during the same fiscal year.
3. Pavement maintenance cost in the northern zone of Indiana could be as much as 40% more than that in the southern zone. However, this ratio was found to be a function of traffic level.
4. A possible savings of about 5,500 to 28,000 gallons of fuel per year can be achieved through an increased level of sealing activity.
5. The information developed in the study can also be used to assess the effect of different resurfacing timings on the level of pavement routine maintenance costs.

The objective of the final phase was to answer the following questions:

1. On what types of maintenance activities should energy conserva-

tion programs focus first?

2. What types of maintenance equipment must be included in energy conservation programs?
3. What type of equipment should be assigned to which activity in order to minimize fuel consumption?
4. What is the optimal mix of equipment fleet in a subdistrict?
5. What are the possible actions that can be taken to effect energy conservation and cost savings in routine maintenance?

A trend analysis of fuel use was conducted on the basis of the maintenance data from fiscal years 1981 through 1984 using the equipment usage and fuel consumption rates developed in the first phase of the study. An optimization model was then developed for optimal assignment of the equipment fleet to maintenance activities. The use of the model was illustrated through an example application. A set of guidelines was then outlined that can be used to develop strategies for energy conservation and cost savings in routine maintenance. The major findings of the final phase of the study are mentioned below:

1. Out of 63 activities excluding the snow and ice removal, thirteen activities use about 70% of the total fuel consumed in routine maintenance. Similarly, 13 equipment types out of 79 use up to about 95% of the fuel. These activity and equipment types are the ones that should be considered first in a conservation program.

2. Some equipment types are interchangeable to do the same task. Equipment types used for hauling materials are the ones which are most frequently interchanged. These equipment types are also among the major fuel consuming and they should contribute most to energy conservation.
3. Maintenance of Class 2 highways (OSH) in Indiana requires a large portion of fuel compared to Class 1 highways (IS). However, consumption rate per mile per year is much higher on IS than that on OSH.
4. Routine maintenance activities excluding snow and ice removal on the state highway system require about 3.3 million gallons of fuel and this amount has remained stable during the last few years.
5. A mathematical optimization technique can be applied to the maintenance equipment scheduling process. Such an optimization technique can help develop guidelines on equipment usage for minimizing total fuel consumption.

Suggestions for Implementation

The following suggestions are offered for implementing the findings of the study.

1. Energy conservation efforts should be first directed to major fuel consuming equipment and activity types. Major equipment types include pickup truck, pickup crew cab, dump truck, and do-all truck. Major activities are those included in the road and shoulder, road-side, and drainage maintenance groups.

2. The road and shoulder group incurs the largest amount of material cost. In this group, shallow patching (Activity 201), seal coating (Activity 205), and crack sealing (Activity 207) are the three major material consuming activities. Since these three activities require a substantial amount of bituminous materials, careful management of these activities would not only reduce direct energy consumption, but would also result in an overall conservation of petroleum products.
3. Adherence to planned accomplishments should be monitored, especially for activities in the limited category. Limited activities include preventive maintenance and the completion of such activities would reduce the amount of corrective maintenance, contributing to energy and cost savings.
4. The procedure for assessing maintenance needs should be improved and strengthened to enable more accurate estimates of maintenance work. Without a fairly accurate estimation of annual accomplishments and compliance with the planned accomplishments, it is difficult to prepare plans for energy savings. It should be mentioned here that a study is currently underway at Purdue University to develop improved procedures to assess maintenance needs.
5. Efficient use of equipment units and selection of proper equipment types should be emphasized. Efficient equipment use in routine maintenance may involve the reduction of idling time. In addition, use of equipment units which are commensurable with the task requirement should reduce excess travel distance by reducing

unnecessarily repeated runs.

6. Dieselization of major fuel consuming equipment units should be considered, because diesel-powered engines have been found to be economical in terms of fuel use.
7. Equipment usage guidelines based on the results of the optimization model should be incorporated into the daily scheduling routine. A procedure similar to the current activity scheduling process can be used. Such guidelines would help minimize fuel use, if closely followed. Also, if incorporated, the program would be able to indicate when and what additional units would be necessary at a subdistrict.

Benefits of Implementing Suggested Energy Conservation Measures

The expected benefits of the implementation of the suggested energy conservation measures can be substantial. Cost savings accrued from the suggested conservation efforts would pay back the costs for conducting and implementing the study in a short period. The total study cost was \$79,000 for three years and some additional cost can be expected for implementation. However, the implementation does not call for any radical change in the existing maintenance management process. Thus, the additional cost for implementation will not be substantial. Furthermore, the actual additional cost for implementation will depend on the specific measures undertaken. Assuming the implementation would require the equivalent of one half man-year, the range of implementation cost can be expected to be \$15-20,000 per year. However, the expected benefits of the proposed measures would far exceed the additional cost.

Fuel savings that can be derived from optimizing the use of five major equipment types (pickup truck, pickup crew cab, utility truck, dump truck and do-all truck) was estimated to be about 6,570 gallons in one year for the example subdistrict used in the study. Although there are variations among subdistricts, a simple multiplication of the number of subdistricts (37 subdistricts in Indiana) would result in a savings of about 243,000 gallons of fuel every year. In addition to this reduction, fuel savings can be achieved by various actions within maintenance management. For example, a 10% increase of sealing activities could save about 11,000 gallons of fuel every year.

Fuel savings from other maintenance management efforts are difficult to estimate at present because of various factors that are involved. However, if it is assumed that a saving of merely 1% of the total amount of fuel consumed for routine maintenance can be achieved by maintenance management, approximately 35,000 gallons of fuel can be saved. When these fuel savings are added up, upto approximately 289,000 gallons of fuel can be saved each year. This can amount to \$217,000 to \$578,000 of cost savings every year if the fuel price ranged from \$0.75 to \$2.00 per gallon, respectively. At the minimum, if one assumes only 1% of fuel use in specific routine maintenance activities considered in the study can be saved, cost saving would reach \$26,250 to \$70,000 every year with the fuel price ranging from \$0.75 to \$2.00 per gallon, respectively. It is obvious, therefore, the cost of the study and possible subsequent implementation would be paid back in a few years once energy conservation programs were put into practice.

Recommendations for Further Study

Based on the findings of this study the following areas are recommended for further study:

1. Only a few types of maintenance activities and equipment account for a significant part of total maintenance cost and energy consumption. For the most costly maintenance activities, Shallow Patching (201), Deep Patching (202), and Sealing Cracks (207), a value engineering analysis is recommended to investigate components of these activities and to identify what could be done to make these repairs cost-effective and long lasting. In such analysis, use of major equipment types should be also monitored and evaluated.
2. The trade-off relation between crack sealing and shallow patching was obtained through statistical analysis on available expenditure data. A field experiment is recommended to be designed such that these relationships can be evaluated under controlled field conditions.
3. The optimization techniques developed in this study require manual operations to prepare input data files. Additional work is necessary to develop appropriate computer programs to prepare the input data which can be fed into available linear programming packages. Such programs are desired to be of interactive type requiring simple queries from the user.
4. A micro-computer based computer package needs to be developed to transfer the research findings into practice. This package would include a check list of actions that can be pursued in energy and cost saving measures. Each action can then be evaluated in terms of

the extent of energy and cost savings as well as the expected cost of implementation.

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