Optimization of Equipment Use in Routine Highway Maintenance

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An optimization procedure was developed for assigning equipment to routine highway maintenance activities so as to minimize total fuel consumption. The procedure is based on a linear programming technique and determines the optimal assignment of equipment in number of equipment days for which a particular equipment type is to be assigned to a specific maintenance activity. The program is capable of handling a large number of activity-equipment combinations and performs optimization of fuel use provided that some of the equipment types considered are interchangeable. An application of the procedure to an equipment assignment problem is presented using the actual equipment use data from a typical subdistrict in Indiana. The technique was found to be efficient and provided feasible results for establishment of equipment assignment guidelines for fuel conservation.

Highway maintenance consists of a variety of activities that require 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 actual maintenance cost *(1)*. A previous study concerning fuel use in routine highway maintenance found that the same task was performed by interchanging different types of equipment that had substantially different fuel consumption rates *(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 types of equipment to various maintenance activities so as to minimize total fuel consumption.

Mathematical modeling techniques have been successfully applied to the problems related to pavement management *(2–4)*. However, the application of mathematical optimization techniques to routine highway maintenance has long been considered infeasible because of the wide variation in the characteristics of routine maintenance activities and because of many uncertain elements such as the weather and the 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 1970s *(5)*. Later a highway maintenance simulation model was developed for the Louisiana Department of Highways *(6)*. Other than these two simulation models, however, there have been no serious efforts in this area. One reason is that simulation models often require a great many assumptions, such as a probability distribution of activity occurrences, which may inversely affect the validity of the models.

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Because the specific objective of the current 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. A sample 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 this study is based on the interchangeability of equipment types for particular tasks within each activity. Equipment that would use less fuel should be assigned as much as possible to minimize total fuel consumption. The fuel survey data collected in a previous study *(1)* and field observations conducted in this study showed that different equipment types are used to perform the same tasks. For example, pickup crew cabs and dump trucks are used interchangeably in rest area maintenance. Similarly, for hauling purposes, pickup trucks, pickup crew cabs, dump trucks, and do-all trucks have also been used interchangeably. However, the fuel use rates of this equipment vary considerably. Furthermore, the same equipment type has different fuel use rates when used in different activities. It is possible, therefore, to optimize the equipment assignment so as to minimize total fuel consumption in the performance of various activities.

A trend analysis conducted on fuel use during the study indicated that pickup trucks, pickup crew cabs, dump trucks, and do-all trucks used about 70 percent of the total fuel consumed for all routine maintenance activities excluding snow and ice removal. Therefore, consideration of only these equipment types can save a substantial amount of fuel.

The optimization model approaches the problem of fuel savings on an aggregate 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 level of accomplishment, equipment availability, labor availability, and weather conditions. Specific scheduling can best be dealt with by experienced schedulers. Scheduling equipment units while making efforts to conform to targeted values is typical of the activity-scheduling procedure currently used by subdistricts of the Indiana Department of Highways for preparing the biweekly activity plan *(7)*.

Model Development

The optimization model developed in this study has two types of constraints: *(a)* planned level of accomplishment of activities included in the model and *(b)* equipment availability. Both constraints are expressed in equipment days. Figure 1 is a flowchart showing the process of model development. A data base containing equipment use, fuel use, productivity, and equipment breakdown data is frequently used during model development.

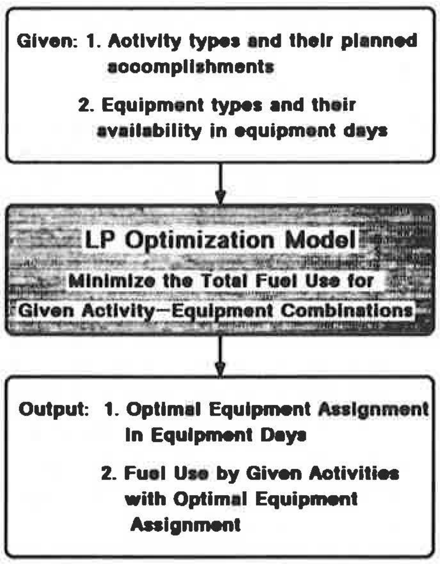

FIGURE 1 Maintenance equipment assignment technique.

First, the planned level of accomplishment of all maintenance activities is set and activities that 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 is 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 lost because of mechanical breakdowns and the number of equipment days necessary to perform other activities that are not considered in the model must be subtracted. The remaining equipment days for each selected equipment type, then, forms the equipment availability constraint.

After the equipment-activity combinations have been identified, interchangeable equipment types are grouped within each activity. Groups consist of only equipment types that are interchangeable for a specific task. If only a particular equipment type can be used to perform a task, constraints are appropriately formulated to indicate this requirement. The equipment-use factor of each equipment type within an interchangeable-equipment group is provided as input and the resulting sum of equipment-use rates is considered as a combined-equipment-use factor. The equipment-use factor is defined as the average number of equipment units of a particular type used to complete a scheduled amount of activity within one working day. The combined-equipment-use factor reflects the actual need for equipment for an activity. For example, if a pickup truck and a pickup crew cab are used interchangeably in shallow patching, and if the pickup truck's use factor is 0.5 and that of the pickup crew cab is 0.7, the combined-use 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-use factors are used to compute conversion factors called K-values, which translate the level of accomplishment for an activity into the number of equipment days necessary to complete the activity by a particular type of equipment within an analysis period. The resulting equipment days, then, forms the equipment requirement constraint.

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

Model Formulation

The formulation of the maintenance equipment assignment technique using linear programming is discussed below. The objective function is to minimize the total number of gallons of fuel consumed in performing all scheduled maintenance activities considered.

Minimize

$$\sum_i \sum_j R_{i,j} \times U_{i,j(l)} \times K_{i,j(l)} \times Y_{i,j}$$

Subject to the following constraints:

1. Demand constraints: The demand for all scheduled activities must be met.

$$\sum_j Y_{i,j} \geq D_{i(l)} \qquad \text{for all } i$$

2. Capacity constraints: The total number of equipment days assigned to any equipment type must not exceed the number of equipment days available.

$$\sum_i Y_{i,j} \leq C_j \qquad \text{for all } j$$

3. Nonnegativity constraints: All variables must be greater than or equal to zero.

$$Y_{i,j} \geq 0 \qquad \text{for all } i, j$$

where

$Y_{i,j}$ = number of equipment days of equipment type j assigned to activity i,
$R_{i,j}$ = fuel consumed by one unit of equipment type j in accomplishing one production unit of activity i,
$U_{i,j(l)}$ = combined-use factor of equipment type j in interchangeable-equipment group l when used in activity i,
N_i = scheduled level of accomplishment of activity i,
$D_{i(l)}$ = number of equipment days required to perform the scheduled level of accomplishment (N_i) of activity i by equipment type j that belongs to an interchangeable-equipment group l,
C_j = number of available equipment days of equipment type j, and
$K_{i,j(l)}$ = units of accomplishment of activity i by equipment type j of equipment group l.

$D_{i,(l)}$ is computed as follows:

$$D_{i,(l)} = \frac{N_i}{K_{i,j(l)}}$$

It should be noted that the interchangeable equipment types must have the same K-value.

Estimation of K-Values

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

For example, a K-value of 1.1 for dump trucks when used in crack sealing indicates that 1.1 lane-mi of sealing can be accomplished on the average by one dump truck per crew day. The use of K-values allows the consolidation of different units of measurement into one common unit for the decision variables employed—equipment days. K-values are used to translate the information on scheduled production units for different activities into the 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 the original production units of each activity so that fuel consumption can be computed by using available fuel-use rates, given in gallons per production unit. K-values are computed by the following formula:

$$K_{ij(l)} = \frac{P_i}{\sum_{j \in l} F_{ij}}$$

where

$K_{ij(l)}$ = K-value for equipment type j in an interchangeable-equipment group l for activity i,
P_i = production per crew day for activity i,
F_{ij} = use factor of equipment type j when used in activity i,
$\sum_{j \in l} F_{ij}$ = combined-use factor for equipment type j in an interchangeable-equipment group l when used in activity i.

The combined-use factor indicates how many equipment units would be required to accomplish a certain level per crew day if only one type of equipment is used.

Model Output

The decision variables are given in units of equipment days. For example, $Y_{207,1}$ is the number of equipment days allowed for equipment type 1, a pickup truck, to be used for activity 207, crack sealing. The model tries to minimize the total amount of fuel consumed by the activity-equipment combinations considered. Therefore, the optimization model may indicate that some activities should receive more or fewer equipment days for certain equipment types than what is normally used for those activities. As long as the equipment types can be interchanged, such recommendations should be followed because the overall fuel use will eventually be minimized by letting other activities use less fuel-consuming types of equipment. If the results appear to be grossly misrepresented or not realistic, equipment grouping needs to be reconsidered and constraints need to be adjusted to reflect any corresponding changes.

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

APPLICATION OF THE MODEL

A sample problem applied to the subdistrict level was used to compare the fuel use expected by the current equipment assignment practice observed in the field survey with the optimal equipment assignment determined by the model. The problem was developed by using the routine maintenance accomplishment data *(8)*, equipment use data *(1)*, and equipment availability data compiled during the study.

Description of Sample Subdistrict

The Fowler subdistrict chosen for the analysis is a typical subdistrict in Indiana, where most of the highways are non-Interstate routes. This sample subdistrict was one of the six subdistricts in which a field survey on equipment and fuel use was conducted earlier *(1)*.

Description of Maintenance Demand

Table 1 gives the 1984 maintenance level of accomplishment of the subdistrict for the 12 major fuel-consuming activities. It provides an overall view of the maintenance needs for this subdistrict, including the work done on both Interstate and other state highways. In this subdistrict, activities on the Interstate require less fuel. On the other hand, most of the activities on other state highways consume a considerable amount of fuel. Therefore, for modeling purposes the sample problem considered only the 12 activities on other state highways.

Equipment Availability

Table 2 shows how equipment availability constraints were derived. In this sample problem, five types of hauling equipment were considered. First, four major equipment types were selected: pickup truck, pickup crew cab, dump truck, and do-all truck. 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 1984, the sample subdistrict had 11 pickup trucks, 6 pickup crew cabs, 1 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 was used. The value for annual available equipment days was adjusted for possible mechanical breakdowns. The statewide average breakdown rates were used here because the existing equipment management system does not provide equipment breakdown rates for each equipment type by subdistrict.

From the adjusted equipment days were subtracted the equipment days used for activities not included in the optimization model. It was also necessary to subtract equipment days used for 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 one pickup is used for each of the supervisory positions on each working day. The remaining equipment days then becomes the constraint to the optimization model.

Computation of K*-Values*

The computation of K-values is a key element of the maintenance equipment assignment technique. In a previous report *(1)* equipment-use factors were computed for all equipment-activity combinations. The use factor indicates how often a particular type of equipment is used. For example, a use factor of 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 that more than one unit is used on some of the crew days.

A comparison of computed use factors, field survey data (crew-day cards), and the field operations handbook *(7)* shows which equipment types can be interchanged. For example, for Activity 207, crack sealing, the equipment-use factors for

TABLE 1 ACTUAL LEVEL OF ACCOMPLISHMENT FOR 12 MAJOR ACTIVITIES AND ESTIMATED FUEL CONSUMPTION, FY 1984, FOWLER SUBDISTRICT

				INT		OSH		ALL	
Activity Code	Activity Name	Unit of Measurement	Fuel Use * (gal/unit)	Actual Accomp. ** (units)	Estimated Fuel Use (gallons)	Actual Accomp.** (units)	Estimated Fuel Use (gallons)	Actual Accomp. ** (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
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 8.

TABLE 2 ESTIMATED AVAILABLE EQUIPMENT DAYS OF FIVE EQUIPMENT TYPES FOR 12 ACTIVITIES INCLUDED IN MODEL, FY 198[illegible], FOWLER SUBDISTRICT

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%	18%	12%
Remaining equipment days available	2,420	1,440	245	4,100	1,540
* Equipment days used for activities other than 12 activities included in the model					
Interstate (INT)	76	637	37	1,021	10
Other State Highways (OSH)	404	224	69	2,014	57
INT + OSH	480	861	106	3,035	67
Supervision (c)	1,000	-	-	-	-
Total excluded	1,480	861	106	3,035	67
* Equipment days available for 12 activities included in the model	940	579	139	1,165	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 to supervise field maintenance activities

dump trucks (No. 9) and do-all trucks (No. 10) are 1.77 and 0.57, respectively, as shown in Table 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 in this work. Because these two types are used for the same purpose, they form an interchangeable group for this particular activity (207), and the use factor of this group is the summation of the use factors of dump trucks and do-all trucks. For the sample analysis, the combined-use factor then becomes 2.34. This value is reasonable, because the

TABLE 3 INDIVIDUAL EQUIPMENT-USE FACTORS AND COMBINED-USE 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	-
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 #2 - Pickup crew cab #8 - Utility truck #9 - Dump truck #10 - Do-all truck

* Source: Reference 1.

handbook for foremen *(7)* estimates that two dump trucks are necessary for each crack-sealing operation.

This basic idea of a trade-off between equipment types was used to estimate other combined-use factors. Table 3 gives the 12 activities and equipment-use factors for the five types of major hauling equipment. Basically, pickup trucks could be interchanged with pickup crew cabs, and dump trucks with do-all trucks. Where equipment types are not interchangeable, constraints were constructed accordingly. For sign maintenance, pickup trucks, pickup crew cabs, and utility trucks can be interchanged.

After the combined-use factors for the equipment types needed for different activities were determined, *K*-values were computed. The annual average level of accomplishment per crew day for the 12 activities in the Fowler subdistrict during FY 1984 are given in Table 4. The *K*-value is obtained by dividing the average level of accomplishment per day by the combined-use factor as shown in Table 4. The *K*-value is therefore measured in the accomplished production units per equipment unit per crew day. Figure 2 shows which equipment types were considered interchangeable for 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. In the unconstrained case, optimal equipment assignment was derived without considering the equipment availability at the subdistrict level, whereas in the constrained

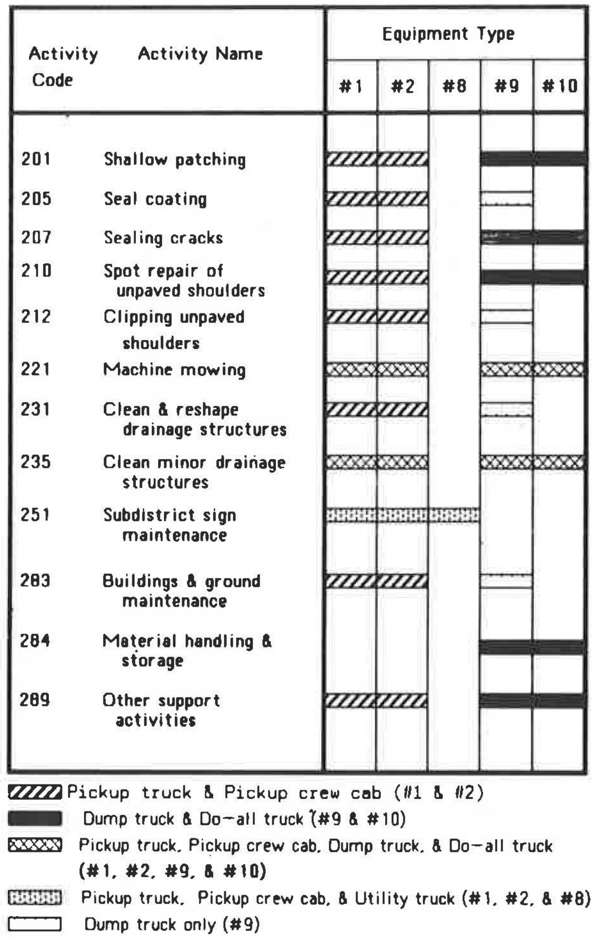

FIGURE 2 Interchangeable equipment types for example subdistrict.

TABLE 4 ESTIMATED CAPACITY OF EQUIPMENT TYPES: *K*-VALUES

Act. Code	Accomp. per Day*	Unit of Measure	Combined Usage Factors (no. of equipment/crewday) 1 Pickup truck	2 Pickup crew cab	8 Utility truck	9 Dump truck	10 Do-all truck	K-Values (production/equipment/crewday) 1 Pickup truck	2 Pickup crew cab	8 Utility truck	9 Dump truck	10 Do-all truck
201	3.79	tons of aggregate	1.20	1.20	-	1.03	1.03	3.16	3.16	-	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	1.51	1.51	-	1.07	1.07
210	26.20	tons of aggregate	1.11	1.11	-	1.83	1.83	23.60	23.60	-	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	1.01	1.01	-	1.01	1.01	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	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	-	-
283	32.00	man-hours	0.74	0.74	-	1.05	-	43.24	43.24	-	30.48	-
284	16.19	man-hours	-	-	-	1.37	1.37	-	-	-	11.81	11.81
289	12.23	man-hours	0.33	0.33	-	0.84	0.84	37.06	37.06	-	14.56	14.56

* Estimated from crewday cards and IDOH's accomplishment records (MM-113): Reference 8.

case, the actual equipment availability was considered. The fuel consumption calculated under both cases was compared with actual fuel consumption, as estimated. Table 5 gives fuel consumption rates of equipment types for different activities included as input to the optimization model. The values of estimated fuel consumed by various equipment types under current assignment practice were computed by using these rates. Table 6 shows the fuel consumption for the activities included in the model for the sample subdistrict in FY 1984.

Summary of Results

The Linear, Interactive and Discrete Optimization (LINDO) computer program developed at the University of Chicago *(9)* was used to solve the problem. Results of the optimization efforts are summarized in Tables 7 through 9 and discussed below.

Constrained Problem

Table 7 shows a comparison of optimal equipment assignment resulting from the model and the estimated equipment use derived from the field survey data *(1)*. For the constrained case the disposable equipment days given in Table 2 formed the equipment availability constraints. It can be seen that there is a difference between the estimated field equipment use and optimal equipment use. For example, in the case of crack sealing, 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 in the estimated field assignment.

The estimated fuel consumption by the equipment-activity combinations included in the model under the field assignment practice was 44,442 gal (Table 6), whereas the fuel consumption for the optimal equipment assignment was 40,612 gal (Table 8), resulting in an 8.6 percent reduction from the estimated field equipment use. This reduction is substantial because the fuel consumed by the activities considered in the model accounts for only about 60 percent 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 of reduction remained the same. A simple multiplication of the reduction of this example by the number of subdistricts (37 subdistricts in Indiana) can mean a savings of approximately 141,710 gal of fuel every year. This could amount to about $106,283 in cost savings every year when fuel cost is $0.75/gal. Table 8 also shows (in parentheses) which activities would use less or more fuel in the optimal case than was estimated for the field assignment.

Table 9 shows the available equipment days and the consumed equipment days for each type of equipment for both the estimated field 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 decreased in the current fleet. For example, the most critical equipment type for this subdistrict is

TABLE 5 FUEL CONSUMPTION RATES OF FIVE EQUIPMENT TYPES FOR DIFFERENT ACTIVITIES INCLUDED IN OPTIMIZATION MODEL

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	-	-
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

Note: gallons per production unit/miles per gallon.
Source: Reference 1.

TABLE 6 FUEL CONSUMED BY FIVE MAJOR TYPES OF HAULING EQUIPMENT FOR 12 MAJOR ACTIVITIES, FOWLER SUBDISTRICT

Activity Types	Fuel Use by Equipment Type per Activity in Percentage *						Total Fuel Used by All Equipment Types **	Fuel Used by the Five Equipment Types
	#1	#2	#8	#9	#10	Total	OSH	OSH
	%	%	%	%	%	%	(gallons)	(gallons)
201	4.17	33.70	-	49.54	5.07	92.5	7,150	6,614
205	1.29	2.84	-	84.88	-	89.0	8,090	7,200
207	6.58	14.91	-	46.78	16.04	84.3	4,330	3,650
210	7.33	9.04	-	21.63	47.01	85.0	1,410	1,199
212	6.95	4.67	-	64.96	-	76.6	3,960	3,033
221	3.20	28.80	-	8.30	0.59	40.9	2,940	1,202
231	2.32	7.82	-	58.18	-	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
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	44,442

* Estimated using data found in Reference 1.
** From Table 1.

the pickup crew cab. The other four types considered in the model are in sufficient supply for this subdistrict to carry out regular maintenance activities. The equipment days available for do-all trucks greatly exceeds the actual demand. The reason for this abundance is, however, that most do-all trucks are kept for snow and ice removal in winter, and the model did not include this emergency activity.

Unconstrained Problem

In order to see how much fuel could be saved if all necessary equipment were available, an unconstrained case was analyzed. Table 7 shows the equipment assignment obtained by the unconstrained version of the optimization model. The unconstrained equipment assignment is somewhat different from both the field assignment and constrained assignment. The fuel

TABLE 7 EQUIPMENT DAYS FOR ESTIMATED FIELD ACTUAL EQUIPMENT ASSIGNMENT VERSUS OPTIMAL EQUIPMENT ASSIGNMENT

	Estimated Field Assignment *					Optimal - Constrained					Optimal - Unconstrained				
	Equipment Types					Equipment Types					Equipment Types				
Activity	#1	#2	#8	#9	#10	#1	#2	#8	#9	#10	#1	#2	#8	#9	#10
201	22	237	-	196	26	0	258	-	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	0	23	-	0	0	0	23	-	0	0
251	28	5	121	-	-	0	154	0	-	-	0	154	0	-	-
283	48	48	-	137	-	0	96	-	137	-	0	96	-	137	-
284	12	3	-	164	19	-	-	-	182	0	-	-	-	182	0
289	58	43	-	214	43	53	48	-	257	0	0	101	-	257	0
Total	306	579	121	1,165	165	424	579	0	1,050	267	336	667	0	1,050	266

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

* Estimated using data found in Reference 1 and 8.

TABLE 8 FUEL CONSUMED BY EACH ACTIVITY UNDER THREE EQUIPMENT ASSIGNMENT SCENARIOS

Activity Number	Estimated Field Assignment	Optimal Assignment for Constrained Case	Optimal Assignment for Unconstrained Case
	gallons	gallons	gallons
201	6,614	5,738 (-876)	5,738 (-876)
205	7,200	7,078 (-122)	7,078 (-122)
207	3,650	3,568 (-82)	3,568 (-82)
210	1,199	1,063 (-136)	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	432 (-500)	432 (-500)
251	2,350	1,602 (-748)	1,602 (-748)
283	2,549	2,376 (-173)	2,376 (-173)
284	4,040	3,981 (-59)	3,981 (-59)
289	5,448	5,112 (-336)	5,073 (-375)
Total	44,442	40,612 (-3,830)	40,550 (-3,892)

TABLE 9 EQUIPMENT DAYS USED BY EACH EQUIPMENT TYPE UNDER THREE EQUIPMENT ASSIGNMENT SCENARIOS

Equip. No.	Equipment Type	Available Equipment Days	Equipment Days Used: Estimated Field Assignment	Optimal Assignment: Constrained	Optimal Assignment: Unconstrained
1	Pickup truck	940	306	424	336
2	Pickup crew cab	579	579	579	667
3	Utility truck	139	121	0	0
9	Dump truck	1,165	1,165	1,050	1,050
10	Do-all truck	1,473	165	267	267

consumption for the unconstrained optimal assignment was 40,550 gal, as shown in Table 8. There could be as much as an 8.8 percent reduction from the estimated current fuel consumption. However, because 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 0.2 percent for this subdistrict.

Sensitivity Analysis

A sensitivity analysis is recommended when any equipment type is found to be critical for equipment assignment. The critical equipment type can be identified by examining the results of the constrained and unconstrained versions of the optimization program. The objective of the sensitivity analysis is to determine explicitly the impact of each type of equipment on overall fuel consumption. In the sample problem, only the pickup crew cab was found to be critical. Adding an extra pickup crew cab to the current fleet of the subdistrict would help conserve fuel; however, the marginal fuel savings is only 0.2 percent. In other subdistricts the marginal fuel savings may be substantial if one or two equipment types were critical. In such situations, it may be beneficial to borrow the necessary units from other subdistricts as needed.

Importance of the Input Data

The validity of the results of the optimization technique developed in this study is largely dependent on the accuracy of the input data. Three types of information are critical: equipment-use factors, fuel consumption rates, and interchangeability of equipment types.

Currently, use factors obtained from the field survey *(1)* are the averages for six subdistricts selected for the survey. Therefore, they may not necessarily reflect exactly the equipment-use pattern of a particular subdistrict. Also, there is a problem of the time lapse between the period (FY 1982) when the field data were taken for computing equipment-use factors and the study period (FY 1984).

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 in which equipment units are used can also substantially affect the fuel requirement for one unit of production. Fuel consumption rates now available are also the 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 observing crew-day cards and by field observation. In the example, it was assumed that the interchangeability observed in the period during which the field survey was done would remain the same for the study period. However, equipment interchangeability may alter over the years. Such alterations need to be taken into account before the optimization program is run.

These problems of use factors, fuel consumption rates, and interchangeability of equipment types, however, can be resolved by regularly updating the equipment-use and fuel consumption data. Any changes in equipment interchangeability can be evaluated by examining updated equipment-use factors. The only data not currently recorded on crew-day cards are those for fuel consumption. 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.

CONCLUSIONS

The example discussed in this paper demonstrated the usefulness and efficiency of the maintenance equipment assignment technique developed in this study. The technique allocates equipment to various maintenance activities within the given constraints of resources and maintenance requirements.

Because this technique treats the equipment assignment problem macroscopically, it will not be 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 regardless of the existence of interchangeability of equipment types. Fuel reduction will not, of course, be attained unless interchangeable equipment types or units exist, because it is basically the result of trading off one type of equipment for another so as to minimize fuel consumption. The potential use of such an optimization technique in highway maintenance equipment management is considered to be feasible.

ACKNOWLEDGMENT

This paper is a product of a research study conducted as part of a Highway Planning and Research Program project funded by FHWA and the Indiana Department of Highways (IDOH). The assistance of R. Clay Whitmire and John Burkhardt of the Maintenance Division of IDOH is gratefully acknowledged.

REFERENCES

1. E. A. Sharaf, K. C. Sinha, and E. J. Yoder. *Energy Conservation and Cost Saving Related to Highway Routine Maintenance: Data Collection and Analysis of Fuel Consumption.* Report FHWA/IN/JHRP-82/83. FHWA, U.S. Department of Transportation, Dec. 1982.
2. B. Colucci-Rios and K. C. Sinha. Optimal Pavement Management Approach Using Roughness Measurements. Presented at 64th Annual Meeting of the Transportation Research Board, Washington, D.C., 1985.
3. K. Golabi, D. Kulkarnia, and G. B. Way. A Statewide Pavement Management System. *Interfaces*, Dec. 1982, pp. 5–21.
4. J. P. Mahoney, N. U. Ahmed, and R. L. Lytton. Optimization of Pavement Rehabilitation and Maintenance by Use of Integer Programming. In *Transportation Research Record 674*, TRB, National Research Council, Washington, D.C., 1978, pp. 15–22.
5. R. J. Stone. Simulation Modeling of Highway Maintenance Operations Applied to Roadside Mowing. In *Highway Research Record 451*, HRB, National Research Council, Washington, D.C., 1973, pp. 23–25.
6. J. M. Pruett. Highway Maintenance Simulation Model. Final Report. Department of Industrial Engineering, Louisiana State University, Baton Rouge, April 1981.
7. *Operations Handbook for Foremen*. Indiana Department of Highways, Indianapolis, 1983–1984.
8. *Accomplishment and Performance Analysis*. Report MM-113. Indiana Department of Highways, Indianapolis, 1981–1982, 1982–1983, 1983–1984.
9. L. Schrage. *User's Manual for LINDO*. Scientific Press, Palo Alto, Calif., 1981.

Publication of this paper sponsored by Committee on Maintenance Equipment.