# Measurement of Highway Maintenance Patrol Efficiency: Model and Factors

ALEX KAZAKOV, WADE D. COOK, AND Y. ROLL

**A model for evaluating the relative efficiency of a set of highway maintenance patrols is discussed. The particular model structure used, the data envelopment analysis (DEA) method, is currently being implemented in Ontario. The paper concentrates primarily on the factors (inputs and outputs) that are appropriate for use in evaluating maintenance patrols. Sample results from the pilot study are discussed.**

This paper investigates the problem of evaluating the efficiency of highway maintenance patrols and discusses a tool for performing such an evaluation.

Efficiency evaluation has considerable benefit for highway departments and maintenance units. From the perspective of top management, this tool provides a means of distinguishing good managers from less effective ones. Moreover, it can provide an understanding of the impact of such factors as climatic condition, pavement health, and degree of privatization on maintenance effectiveness. In this manner, an efficiency monitoring tool can aid in budget planning and in the design of maintenance policies and practices. From the point of view of the decision-making unit (the maintenance patrol), particularly the maintenance engineer, routine efficiency evaluation facilitates a closer monitoring of how the patrol is conducting its business. The engineer receives an annual status report showing the patrol's standing relative to other patrols. Furthermore, the model provides an efficient subset (peer group) of patrols for comparison. Thus the engineer has a barometer for evaluating the patrol's current status and for choosing a direction for future changes.

Because of the need to consider qualitative factors such as climatic condition, road condition, and extent of privatization, "production" standards are difficult, if not impossible, to establish. This being the case, the usual industrial engineering approaches to productivity do not apply. The model that has been adopted for examining patrol maintenance in Ontario is referred to as the data envelopment analysis (DEA) approach. The DEA model was developed by Charnes et al. (*1*) specifically for evaluating the relative efficiency of a set of decision-making units. In particular, the technique has been applied to hospitals, schools, courts, airforce maintenance units, and so on. The ideal setting for this model occurs when there are similar decision-making units (such as maintenance patrols) with multiple inputs and outputs, where qualitative (noneconomic) factors need to be considered.

Because the model has been discussed at length in the literature, only brief mention of its structure is made here. The primary thrust of this paper is a discussion of the factors (inputs and outputs) that are appropriate for the maintenance area. In addition, the difficulties surrounding the quantification of some factors and the associated problem of collapsing subfactors into overall composite factors for use in the DEA model are addressed. Some preliminary results from the Ontario study are given.

## PATROL OPERATION

Most of the routine maintenance activities on Ontario's highways fall under the responsibility of the 244 patrols scattered through the province. Each patrol is responsible for a fixed number of highway lane-kilometers and oversees the activities associated with that portion of the network. More than 100 different categories of operations/activities exist. They are divided into five areas: surface, shoulder, right of way, median, and winter operations.

The current system for monitoring patrol activities within the Ontario Ministry of Transportation is known as the maintenance management system (MMS). The MMS is a computerized recordkeeping system that keeps track of total work accomplished by type of operation, patrol, and highway class. This system is similar to those used in other Canadian provinces and in the United States.

## METHODS FOR MEASURING EFFICIENCY

The productivity, or efficiency level, of any decision-making unit (DMU) (such as a factory, government department, or maintenance patrol) is a measure of the extent to which that DMU makes the best possible use of a given set of inputs (resources) to produce some set of outputs. In this context, "best possible use" loosely means getting the most out of available resources within a given set of circumstances.

In an industrial setting, efficiency or productivity is usually approached from an engineering perspective on the basis of on production standards. In this case, the productivity of a DMU is the ratio of standard or required inputs (needed to create the current level of output) to the actual inputs used.

An alternative to these absolute measures of efficiency is a measure that evaluates a DMU relative to some comparison group. Such an approach is not only realistic but may be the only one applicable in many not-for-profit environments. This is the principle on which the DEA approach is based. DEA is capable of handling a variety of factors, such as number of

A. Kazakov, Research and Development Branch, Ontario Ministry of Transportation, Downsview, Ontario, Canada. W. D. Cook, York University, Toronto, Canada. Y. Roll, Technion–Israel Institute of Technology, Haifa, Israel.

accidents, maintenance dollars, cars per day, average age of pavement, and so on, and allows for measurement of these factors on different scales. This approach seems particularly suited to the maintenance area because factors such as traffic intensity, safety parameters, and average age of pavements are an important part of the picture. Formally, the DEA method is defined as follows:

Given a set of $J$ DMUs, the model determines for each $DMU_0$ the best set of input weights $\{\nu_{i0}\}_{i=1}^{I}$ and output weights $\{\mu_{r0}\}_{r=1}^{R}$

such that the ratio of total weighted outputs to total weighted inputs is maximized. This is done subject to two constraints: that the corresponding ratio for each $DMU_j$ (including the one in question) does not exceed 1, and that the weights $\mu_{r0}$ and $\nu_{i0}$ fall within reasonable bounds. The ratio $e_0$ is the relative efficiency rating for $DMU_0$. Let the following notation be adopted:

$Y_{rj}$ = value of output factor $r$ for $DMU_j$,
$X_{ij}$ = value of input factor $i$ for $DMU_j$,
$\mu_{r0}$, $\nu_{i0}$, = "weights" for the corresponding factor,
$Q1_r$, $Q2_r$, $P1_i$, $P2_i$ = bounds imposed on weights, and
$T$ = transformation factor.

In mathematical terms, the DEA model involves solving the $J$ fractional programming problems:

Max

$$\left\{ e_0 = \frac{\Sigma_r \mu_{r0} Y_{r0}}{\Sigma_i \nu_{i0} x_{i0}} \right\}$$

Subject to:

$$\frac{\Sigma_r \mu_{r0} Y_{rj}}{\Sigma_i \nu_{i0} X_{ij}} \leq 1 \qquad \text{for all DMUs} \qquad j = 1, 2, \ldots, J$$

$$Q2_r \leq \mu_{r0} \leq Q1_r \qquad \forall\, r = 1, 2, \ldots, R$$

$$P2_i \leq \nu_{i0} \leq P1_i \qquad \forall\, i = 1, 2, \ldots, I$$

It can be shown that this ratio model reduces to a linear programming problem. Details can be found in the work of Charnes et al. (*1*) and Cook et al. (*2*).

In choosing weights for any patrol, the DEA model tries to present the patrol's position in the most favorable light. In this setting, then, if a patrol can be shown to be efficient (a ratio of 1) by some reasonable set of weights, it should be efficient in reality. A patrol will only be declared inefficient if it is dominated by other patrols or combinations of patrols. Thus, DEA should be viewed as a technique for identifying inefficiency.

## SELECTION OF FACTORS

The process of selecting factors in a DEA model should concentrate on finding effects of maintenance activities together with a set of explanatory, or causal, factors that allow these effects to be created. Outputs should measure the effectiveness of the patrols' actions. Potential candidates would be number of vehicles served, accidents (or reduction thereof), level of pavement quality, and so on. Inputs are of two types:

1. Controllable factors, such as the size of the budget and the percentage of work done under private contract; and
2. Factors not under the control of the patrol or district, such as environmental measures (for example, inches of snowfall) and average age of pavements.

These latter factors describe the circumstances under which a patrol is forced to operate and may have a strong effect on the outputs. In the Ontario study, maintenance staff have aided in the selection of factors.

After choosing the factors to be used in describing cause and effect for patrol activities, the issue of quantification must be addressed. While the DEA structure does not require that factors be reducible to a common unit, they must be quantified on some scale. For example, if safety is a principal consideration with regard to maintenance effort, some reasonable method of capturing safety (such as skid resistance, number of accidents, or number of fatal accidents) must be found. Severity of the environment is likely to be an important determinant of the extent to which patrol efforts are effective. Yet there is no obvious single measure of environmental impact. Again, quantification is a pressing issue in the selection of factors.

For the analysis of relative efficiency of maintenance patrols in Ontario, the following set of factors was chosen:

### Outputs

#### *Size of System*

This factor is intended to capture the size of the task facing patrol crews. It considers the amount of road surface to be tended, the shoulder and right-of-way area, and winter maintenance requirements. Specifically, the assignment size factor (ASF) is the sum over all road sections serviced by the patrol of

Length · Two Lane Equivalents (TLE) · Coefficient for Road Type
+ Length · TLE · Coefficient for Winter Operations
+ Length · Shoulder Width · Coefficient for Shoulder Type
+ Length · Coefficient for Other Operations (right of way, median, etc.)

Components of the assignment size were weighted as follows:

- For surfaces, per 1000 km TLE:

| *Type* | *Coefficient* |
|---|---|
| 1 | 1.97 |
| 2, 3 | 1.72 |
| 4 | .92 |
| 5 | .59 |
| 6, 7 | .31 |

- For winter operations, a coefficient of 3.14 per 1000 km TLE;
- For shoulders, per 100 $m^2$ of shoulder:

| *Type* | *Coefficient* |
|---|---|
| 2 | .18 |
| 4 | .12 |
| 6 | .14 |

TABLE 1 ACCIDENT FACTORS

| District & Patrol | Total Number of Accidents | Road State | | | | | Pavement Markings | | | | | | | Surface Condition | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Good | Under Repair | Under Construction | Other | Adjustment* | Good | Faded | Obscured | Not Visible | No Markings | Not Applicable | Adjustment* | Dry | Wet | Loose Snow | Slush | Packed Snow | Ice | Mud | Loose sand gravel | Adjustment* | Adjusted Number of Accidents |
| Kingston (8) | | 1 | 2 | 1.5 | 1 | | 1 | 1.2 | 1.5 | 1.5 | 2 | 1 | | 1 | .8 | .7 | .7 | 2 | .5 | .8 | 1 | | |
| # 1 | 79 | 78 | - | - | 1 | 0 | 63 | 4 | 3 | 8 | 1 | - | + 7.3 | 46 | 12 | 7 | 5 | 2 | 7 | - | - | -10.1 | 76.2 |
| # 2 | 15 | 14 | - | - | 1 | 0 | 14 | 1 | - | - | - | - | + .2 | 7 | 5 | 1 | - | - | 2 | - | - | - 2.3 | 12.9 |
| # 3 | 134 | 134 | - | - | - | 0 | 113 | 2 | 2 | 15 | 2 | - | +10.9 | 63 | 38 | 7 | 4 | 3 | 19 | - | - | -21.3 | 123.6 |
| # 4 | 83 | 83 | - | - | - | 0 | 63 | 5 | 3 | 11 | 1 | - | + 9 | 44 | 20 | 7 | 4 | 1 | 7 | - | - | -11.1 | 80.9 |
| # 5 | 52 | 52 | - | - | - | 0 | 43 | 2 | 3 | 3 | 1 | - | + 4.4 | 31 | 10 | 4 | 2 | 0 | 5 | - | - | - 6.3 | 50.1 |

- For rights of way, medians, and so on, a coefficient of 2.30 per 1000 km of road.

The types are those used in the highway inventory data, and the coefficients were determined from the corresponding expenditures in fiscal year 1986–87. Coefficients represent the relative proportions of the total maintenance expenditure on the various components. For example, surface type 4 work cost approximately three times as much as work on surface types 6 and 7 (.92 versus .31).

### *Average Traffic Serviced*

This factor recognizes that greater maintenance efforts may be required on roads with higher traffic. This is true for two reasons. First, larger crew sizes are needed for multilane roads than for lower volume roads. Second, a higher standard of serviceability is often needed on the higher traffic roads. The average traffic serviced (ATS) factor is the sum over all road sections of

$$\text{Length} \cdot \text{AADT} \cdot 10^{-4}$$

### *Accidents*

Maintenance crews are primarily occupied with the removal of problem areas that could result in accidents (such as wash-outs or potholes) or with work that results from accidents (such as repairs to damaged guardrails). One difficulty encountered with this factor is that accidents fall into different categories. In the model, therefore, accidents in a patrol are separated according to three groupings (see Table 1). The first group, Road State, includes four headings:

1. Good,
2. Under repair,
3. Under construction, and
4. Other.

For example, if there were 100 accidents in a patrol, it may turn out that 50 were on good roads, 20 on roads under repair, 20 on roads under construction, and 10 on other types of roads.

The second group, Pavement Markings, contains six headings:

1. Good,
2. Faded,
3. Obscured,
4. Not visible,
5. No markings, and
6. Not applicable.

The third group, Surface Condition, is divided into eight headings:

1. Dry,
2. Wet,
3. Loose snow,
4. Slush,
5. Packed snow,
6. Ice,
7. Mud, and
8. Loose sand gravel.

To obtain an accident statistic for a patrol, a set of importance weights were assigned to each heading under each of the three groups. The overall accident statistics ($A$) is then given as

$$A = \text{no. of accidents} + \sum_{i=1}^{3} (\text{adjustments})$$

where

$$\text{adjustment} = \sum_{j=1}^{k} (\text{no. of events}) \times (\text{Factor-1})$$

Here, $i = 1,2,3$ are the three groupings and $j = 1,2,\ldots,k$ are the headings under any given grouping.

Table 1 shows all factors and weights and illustrates a typical calculation.

### *Change in Pavement Condition*

Because both maintenance and rehabilitation expenditures are inputs (discussed below), one of their major observable effects is the resulting change in the condition of the pavement. Specifically, the model uses the change in a patrol's average pavement condition rating from its level in the previous year to its current level.

## Inputs

### *Maintenance Expenditures*

This factor is divided into two different inputs: expenses incurred in-house and those arising from work done by private contractors. This distinction is made because the proportion of privatized work may greatly influence a patrol's productivity standing. It is also pointed out that, if efficiency is being examined in terms of winter maintenance, for example, only that portion of the expenditure figures relating to winter work is used.

### *Rehabilitation Expenditures*

Because rehabilitation and maintenance expenditures go hand in hand, the total expenditure on rehabilitation (capital) is an important input. One problem with this factor has to do with when the rehabilitation was conducted. If, for example, maintenance expenditures for the year 1986 are used, the need for these expenditures is, to an extent, a function of the capital work done not only in 1986 but in several years preceding 1986. This being the case, capital expenditures for 5 yr (1982–1986) were taken in total and used as the rehabilitation budget input. Technically, a weighted total should be used (for example, capital expenditures in 1982 may have less influence than those of 1985). In this study, however, the simple sum was applied.

### *Climatic Input*

There is unanimous agreement that climatic conditions influence the need for maintenance. Not only do frost heaves necessitate surface work but snowfall clearly influences winter maintenance activities (such as snow removal and salting).

### *Subfactors*

Although no clear relationship has been established between pavement damage and such factors as frost depth, depth of water table, and number of freeze/thaw cycles, it is believed that these and other factors *do* influence the extent of damage. For the Ontario study, four subfactors were combined to arrive at an overall climatic impact parameter:

1. Number of major freeze/thaw cycles,
2. Number of minor freeze/thaw cycles,
3. Number of days where rainfall exceeded 10 mm, and
4. Total snowfall.

Standard definitions have been adopted within the Ministry of Transportation concerning freeze/thaw cycles. A major cycle occurs when there is significant thawing followed by full freezing. This phenomenon leads to water being trapped in the base and subbase of the pavement, causing volume shifts and pavement blow-ups. A threshold number of degree days for each thaw and freeze portion was chosen. A minor cycle is a similar phenomenon but with fewer degree days, meaning that the freeze/thaw is nearer the surface. This leads to chipping and separation of the asphalt.

Rainfall has two effects. First, precipitation during a freeze/thaw cycle can contribute to the severity of that cycle. Second, rain washes away unpaved shoulders, necessitating maintenance work.

Finally, snowfall is believed to have only a winter maintenance impact. The important statistic is the number of plowings. On the basis of Ontario experience, the total snowfall was divided by 2.5 cm to determine the number of times snow removal equipment would need to pass over the road.

The raw data used to compute the above parameters were obtained from Environment Canada. The information came from several hundred weather stations located throughout the province.

### *Scaling the Input Factors*

To combine the four subfactors into one overall climatic factor, it is necessary to take some form of weighted total factor value. One potential problem of combining the input factors is the scale difference in the numbers. Cycles, for example, may number 1, 2, or 3 per year. Snowfall, however, may be 200 or 300 cm per year. In a linear programming framework (used in DEA), vast scale differences can cause roundoff problems and lead to erroneous results. It is desirable, therefore, for the scales of numbers to be relatively similar.

One important feature of the DEA model structure is its scale variance characteristic. For example, if snowfall is 100.5, 173.2, and 98.4 cm, the same efficiency measures would arise if the numbers 1005, 1732, and 984 were used. Therefore, regardless of the size of the raw data numbers, they can be adjusted (by a factor of 10, for example) up or down without destroying the meaning of the final results.

This being the case, all input factors can be expressed in roughly the same scale terms. No information is lost, and computational difficulties with the optimization procedure are avoided.

To transform the four inputs to similar scales, four weights (transformation parameters) were chosen:

$$\alpha = 50 \qquad \beta = 300 \qquad \gamma = 20{,}000 \qquad \delta = 1{,}000$$

In choosing these values, an attempt was made to reflect the perceived degree of importance of each parameter. Maintenance staff, for example, feel that major cycles have an important impact on spring road conditions while minor cycles have significantly less importance.

Beyond these two considerations (scale difference and perceived importance), the choice of transformation parameters was arbitrary for this phase of the study. The next section of this paper describes a more structured procedure for deriving parameters.

Rather than taking a weighted sum of the four climatic subfactors, a reciprocal model was used in this study. Specifically, the station factor $F$ is computed as follows:

$$F = \frac{\alpha}{M_1} + \frac{\beta}{M_2} + \frac{\gamma}{S} + \frac{\delta}{R}$$

where

$M_1$ and $M_2$ = number of major and minor cycles, respectively,
$S$ = number of snow plowings,
$R$ = number of heavy rain days, and
$\alpha, \beta, \gamma, \delta$ = weights.

The rationale for using reciprocals of the four data parameters is that, since $F$ is to be an input, it should become smaller as the climate becomes more severe.

A typical calculation for a station is $M_1 = 1$, $M_2 = 2$, $S = 54.6$, and $R = 16$. Therefore,

$$F = \frac{50}{1} + \frac{300}{2} + \frac{20{,}000}{54.6} + \frac{1{,}000}{16} = 629$$

To get a patrol factor, those stations within and near the patrol boundaries were combined. In some instances, only one station could reasonably be used to represent a patrol. In those cases, the climatic factor for that station became the patrol factor. When more than one station was used for a patrol, a weighted average of the values for those stations was applied, and the station weights were taken as proportional to their distances from the center of the patrol.

## WEIGHTING SUBFACTORS: A STRUCTURED APPROACH

One difficulty encountered in determining factor values, particularly accident and climatic factors, is that of arriving at appropriate weights for subfactor combinations. In the case of accidents, for example, a weight must be supplied to each of the stated surface conditions. Because there is no reliable data comparing the chances for an accident on ice and one on packed snow, weights must be primarily subjective.

One framework that can be used to obtain weights for a series of choices, options, or criteria is based on pairwise comparisons. In trying to determine the likelihood of an accident on each of the surface conditions, the only option may be to solicit expert opinions (for example, maintenance staff or police). The most convenient form in which to capture these opinions is by comparing pairs of options using a ratio scale. Specifically, the expert would be requested to supply a value $a_{ij}$ where $a_{ij}$ is the extent to which option $i$ dominates option $j$. If, for example, $i \equiv$ packed snow and $j \equiv$ slush, then if $a_{ij} = 3.5$, an accident is 3.5 times as likely to occur on packed snow as on slush. Of course, if $a_{ij} = 3.5$, then

$$a_{ij} = \frac{1}{a_{ij}} = \frac{1}{3.5}$$

Thus, it can be argued that it is easier to supply such ratio-scale values as $a_{ij}$ than to actually provide a numerical weight $W_i$ (probability of an accident occurring on surface type $i$, for example).

A possible matrix $A$ for all surface conditions might be

| A | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | .5 | .4 | .3 | .8 | 2 |
| 2 | 8 | 1 | 3 | 2 | 4 | 6 | 7 |
| 3 | 2 | .33 | 1 | 2 | .8 | 2 | 4 |
| 4 | 2.5 | .5 | .5 | 1 | .8 | 3 | 3 |
| 5 | 3.3 | .25 | 1.25 | 1.25 | 1 | 2 | 3 |
| 6 | 1.25 | .17 | .5 | .33 | .5 | 1 | 2 |
| 7 | .5 | .14 | .25 | .33 | .33 | .5 | 1 |

One property that a rational set of comparisons should possess is transitivity. Specifically, if option 2 is four times as likely as option 5 ($a_{25} = 4$) and option 5 is two times as likely as option 6 ($a_{56} = 2$), then it should be true that option 2 is eight times as likely as option 6 (that is, $a_{25} \times a_{56}$ should equal $a_{26}$). However, $a_{26} = 6$. Thus, the results are intransitive. This phenomenon is very common, since inconsistencies in reasoning are bound to happen in any situation.

To arrive at a set of consistent results that will lead to weights, various approaches can be taken. One of the simplest, as suggested by Barzilai et al. (*3*) and Crawford and Williams (*4*), is to use the geometric mean of row $i$ to get weight $W_i$.
That is,

$$W_i = \left(\prod_{j=1}^{7} a_{ij}\right)^{1/7}$$

So, for the example,

$$W_1 = (1 \times 2 \times .5 \times .4 \times .3 \times .8 \times 2)^{1/7}$$
$$= .56$$

Similarly,

$W_2 = 3.61$
$W_3 = 1.36$
$W_4 = 1.24$
$W_5 = 1.34$
$W_6 = 0.62$
$W_7 = 0.37$

Note that these are relative weights. If they must add to 1 (for example, if they are to represent probabilities), then they would need to be normalized.

The above process gives a logical framework for deriving importance weights when subjective information must be considered.

The next section provides the results of a pilot study conducted in Ontario.

## PILOT STUDY OF EFFICIENCY

The general structure of the DEA model was presented earlier. To illustrate how the model works, an example is provided of one patrol from district 2 in Ontario (the province is divided into 18 geographical districts). In the pilot study, the following output and input values were used for the patrol:

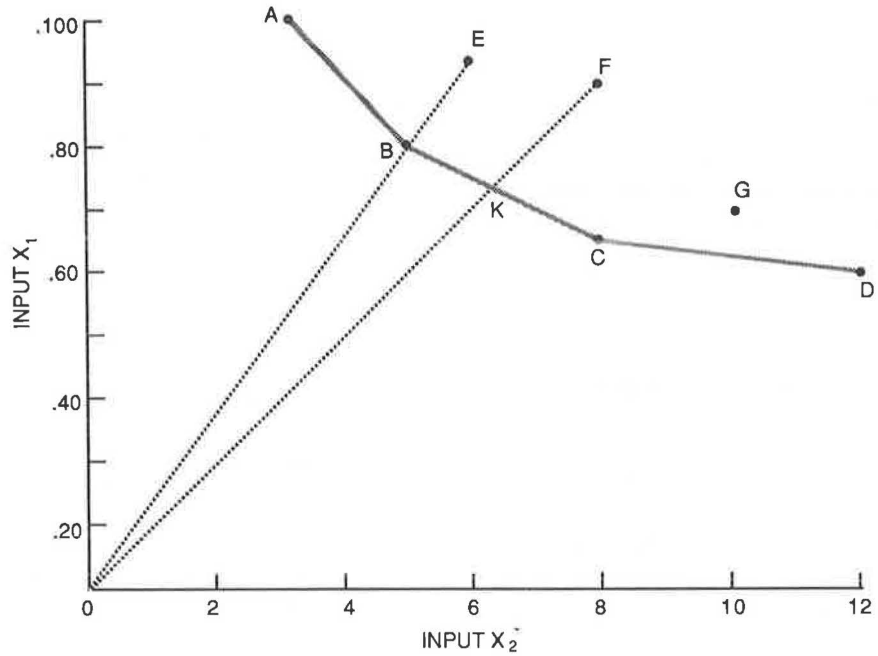


**FIGURE 1 Efficient frontier.**

*Outputs:*

1. Size of system = 404,
2. Traffic served = 267,
3. Condition rating factor = 184, and
4. Accident factor = 331.

*Inputs:*

1. Maintenance budget = 585,
2. Capital budget = 264, and
3. Climatic factor = 715.

The DEA model tries to determine the set of seven factor weights or multipliers ($M_1$, $M_2$, $M_3$, $M_4$ on outputs and $N_1$, $N_2$, $N_3$ on inputs) that makes this patrol's efficiency ratio as large as possible, while ensuring that the corresponding ratio for all other patrols does not exceed 1.0. This restriction limits the possible values that the multipliers $M_i$ and $N_j$ can assume. The patrol's efficiency ratio is as follows:

$$\frac{404M_1 + 267M_2 + 184M_3 + 331M_4}{585N_1 + 264N_2 + 715N_3}$$

The DEA model finds the set of multipliers that maximizes this ratio. For this particular patrol, the values of the seven multipliers are $M_1 = 206$, $M_2 = 308$, $M_3 = 1{,}747$, $M_4 = 720$, $N_1 = 209$, $N_2 = 103$, and $N_3 = 1{,}190$. The efficiency ratio is then

$$e = \frac{404 \times 206 + 267 \times 308 + 184 \times 1{,}747 + 331 \times 720}{585 \times 209 + 264 \times 103 + 715 \times 1{,}190}$$

$$= .725$$

Therefore, the best that can be said of this patrol is that its efficiency does not exceed 72.5 percent, compared with other patrols. That is, in the process of searching for multipliers $M_i$ and $N_j$, no better set than the ones shown above can be found. In fact, some patrols must have a ratio of 1.0 relative to this set since this was the constraint imposed in deriving the multipliers.

Geometrically, this process can be illustrated as follows. Suppose there is only a single output (number of lane-kilometers serviced) and two inputs (maintenance budget and climatic conditions). Further, assume the patrols all service exactly 100 lane-km of road. On a two-dimensional graph, the pair of inputs for each patrol might be plotted as shown in Figure 1. Those points (patrols) closest to the origin are the most efficient since they involve the least amounts of inputs for the same level of output. Patrol $E$ is, for example, less efficient than patrol $B$ since $B$ is using less of each input than $E$ (to service the same size network). Patrols $A$, $B$, $C$, and $D$ are considered efficient since there are no others closer to the origin that "dominate" them. However, patrol $E$ is dominated by $B$ while patrol $F$ is dominated, in a sense, by patrols $B$ and $C$. At least, a hypothetical patrol $K$ could be defined whose inputs were linear combinations of those of $B$ and $C$, then $F$ would be dominated by $K$.

In summary, the DEA model would compute a ratio of 1.0 for patrols $A$, $B$, $C$, and $D$. The ratio of $F$ would equal $OK/OF$. Thus, the "efficient frontier" made up of the line segments joining $A$, $B$, $C$, and $D$ defines the highest level of efficiency obtainable. Anything on this frontier would have a ratio of 1.0 and would be considered efficient. Any patrol behind the frontier ($E$, $F$, and $G$) would have a ratio less than 1.0 and would be considered inefficient.

In the process of finding the best set of multipliers for patrol $F$ (suppose $F$ is patrol 1 in the above numerical example), the ratios for $B$ and $C$ would have been driven to 1.0, which would have limited the possible choice of multipliers for $F$. Thus, $B$ and $C$ are said to constitute the "peer group" for patrol $F$ because they are the efficient patrols that are most like patrol $F$ in terms of resource consumption (input values).

As an example of the likely results from a DEA of patrol

TABLE 2 RESULTS OF DEA

| Patrol | Efficiency Rating | Peer Group |
|---|---|---|
| 1 | 1.00 | 1 |
| 2 | .99 | 1,4 |
| 3 | .80 | 4,8 |
| 4 | 1.00 | 4 |
| 5 | .86 | 1,4 |
| 6 | .93 | 8 |
| 7 | .89 | 4,8 |
| 8 | 1.00 | 8 |
| 9 | .91 | 1,4 |
| 10 | .72 | 1,4 |
| 11 | .87 | 1,4,12 |
| 12 | 1.00 | 12 |
| 13 | 1.00 | 13 |
| 14 | .62 | 1,4,12 |

efficiency, Table 2 displays the ratings and peer groups for the 14 patrols in the pilot district chosen for the Ontario study. This indicates that patrols 1, 4, 8, 12, and 13 are efficient (have a ratio of 1.0). The others are considered inefficient; some to greater degrees than others. For example, compared to the others, patrol 14 cannot be rated any higher than 62 percent. One interpretation of this number is that patrol 14 should be able to do better—either by servicing a larger network with the same resources or by consuming fewer resources.

## CONCLUSIONS

In this paper, a model for examining maintenance patrol efficiency was presented, and relevant factors upon which to base this model were discussed. The model provides a way to calibrate the impact of various factors and gain a better understanding of the circumstances within which patrols operate.

This approach offers a framework for further investigation of a patrol's operations if the patrol appears inefficient. In addition, it can provide possible explanations for that inefficiency.

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