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A COMPUTER MODEL OF MUNICIPAL SNOW REMOVAL, (U)

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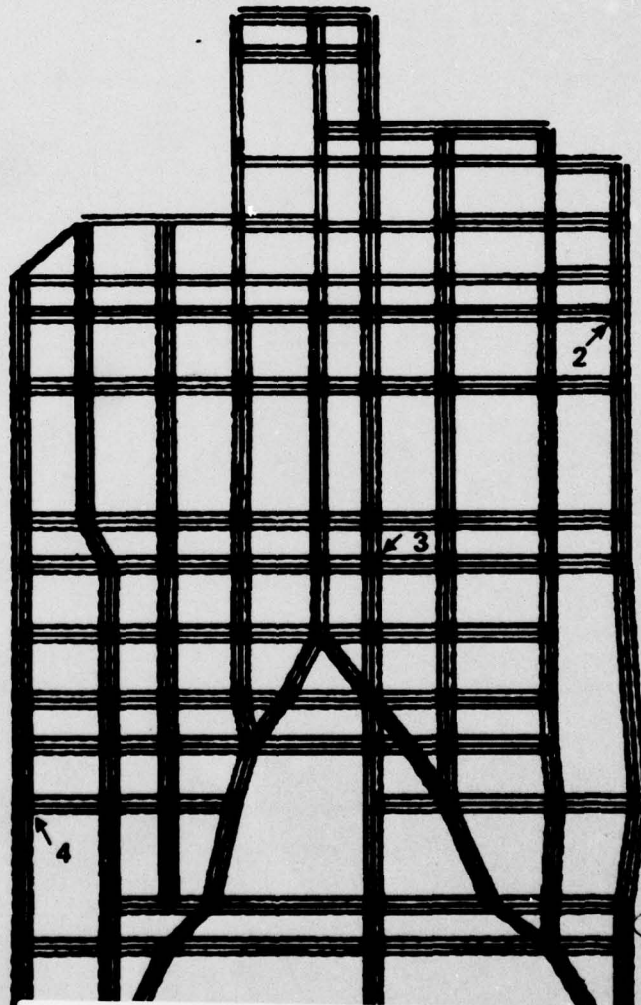
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A computer model of municipal snow removal

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*Cover: Graphic model of snowplow route for Holland,
Michigan, showing truck starting points.*

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Walter B. Tucker, III

November 1977

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PREFACE

This report was prepared by Walter B. Tucker III, Geologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this project was provided by National Science Foundation Grant No. APR 75-0621A02.

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A COMPUTER MODEL OF MUNICIPAL SNOW REMOVAL

Walter B. Tucker III

INTRODUCTION

The 1976-77 winter demonstrated to much of the United States that snow and ice control on streets and highways is indeed a serious problem, as overspending of road maintenance budgets occurred in many areas. All too often municipal budget planning, snow control included, takes place in the summer when winter road maintenance is conveniently out of mind. Annual expenditures for snow removal operations on state maintained roads alone are \$334 million (Minsk 1977), and total urban expenditures are probably at least this high. Without a substantial increase in the technology of snow removal, these costs are likely to continue to require a disproportionate amount of municipal budgets.

Optimum usage of a fleet of equipment held by a municipality could trim these costs considerably, as well as preparing it for more difficult winters. Optimum equipment usage is more than a phrase, and actual practice or experimentation is necessary. A snow removal emergency is no time for such testing, as critical situations call for only proven techniques (i.e. the way the streets were cleaned last year and the years before). These types of problems, however, lend themselves to computer simulation. A realistic snow removal simulation would allow many of the variables involved in the process to be assessed any time of the year in a rather convenient manner.

Simulations for snow removal have been attempted previously. Brown (1972) developed a simulator called AID, designed specifically for the small town. Unfortunately, the program was too large for computers to which most small towns have access. Experimentally it is a fine laboratory tool once an operator is trained to use it, as it contains practically every conceivable variable involved in the snow removal operation. Alprin (1975) also simulated snow control (actually only salting and sanding) for the city of Tulsa, Oklahoma. This simulation has been used successfully

for assessing truck routings and relocation of sand piles around the city (Cook and Alprin 1976). Snow plowing, including multiple passes to clear a street, overlapping routes, etc., was not considered in this model, however.

Our concern here was to develop a simulation package, usable by nearly any municipality, that will allow the important variables in a municipality's operations to be evaluated and new procedures to be tested before implementing them "on the road." This dictates having a straightforward simulation program with a minimum of inputs, yet able to handle the complex issues involved in snow removal. Our effort was aimed at only the snowplowing portion of road maintenance, but we see no obvious reason why the simulator cannot be applied to salting and sanding as well.

The snow removal simulation package was created in various program modules. First, a routing module using rather sophisticated computer graphics (certainly not available everywhere) to aid in the selection of optimum snowplow routes was created. (A simpler, yet useful, version of this module without computer graphics is also available.) The other part of the package is the simulation program with variable meteorological and equipment characteristics. The preselected routes plus the variable parameters are input, and the plowing time for each piece of equipment is output. Thus far, both modules operate on a computer system with minimum storage and in fairly rapid execution time.

SNOWPLOW ROUTING

Snow removal equipment routing is that phase of the operation which can potentially save the most money. Although certain methodology in the fields of graph theory and network analysis could aid in the routing problem (Beltrami and Bodin 1974, Marks and Stricker 1971), the techniques are somewhat difficult

to grasp and most city officials are out of touch with this type of technology. In many cases the routes followed are based on the driver's experience, these choices often being close to optimum. With the exception of a few cities that publish procedural manuals or plans, few attempts at routing improvement are made.

Straightforward routing problems are generally solvable using manual or heuristic methods (Glover 1967, Moss 1970) as mentioned above, but efficient computer solutions to such problems are not available (Marks and Stricker 1971). Adding multiple street passes, priority routes and other complexities associated with snow removal to the routing problem makes manual techniques useless. In this work, no attempt has been made to solve routing problems numerically, but we have developed techniques for interactive computer assistance to manual routing.

Each street in the network is coded and stored along with its characteristics (width, length, grade, normal speed) in a computer file. The time T_s required to clear that segment for the static case (no snow falling) is

$$T_s = N \frac{L}{V} + NC \quad (1)$$

where N = the number of passes required (segment width W_i /effective plow width W_p)

L = the segment length

V = the velocity of the plow along the segment

C = a delay factor for intersection wait time.

A program has been written which uses eq 1 and accesses the file of segment characteristics. As a segment number is input, cumulative plowing time is output. Time to plow any combination of segments in the static case can be rapidly determined.

The next logical step is to determine how long a particular vehicle should be plowing. For a given fleet of trucks having the same specifications, minimum plowing time T_{min} to clear the city is given by

$$T_{min} = \frac{1}{M} \sum_{i=1}^N \frac{W_i}{W_p} \frac{L_i}{V} + \frac{W_i}{W_p} C \quad (2)$$

where M is the total number of trucks, and L_i the street length.

For a fleet of trucks with mixed specifications, a close approximation of the minimum time is

$$T_{min} = \frac{1}{M^2} \sum_{k=1}^M \sum_{i=1}^N \frac{W_i}{W_k} \frac{L_i}{V} + \frac{W_i}{W_k} C \quad (3)$$

where W_k is the effective plow width for each of the trucks. This time is approximate because exactly which streets will be plowed by each truck is unknown at this point.

Knowing the optimum plowing time for a fleet and having the program which handles the bookkeeping (using eq 1), one uses an interactive computer terminal to key in the numbered streets over which the plowing vehicle progresses. An assumption basic to the entire simulation package is that individual vehicle routes are repeatable by that same vehicle. Therefore, when the cumulative plowing time from the interactive program nears the optimum plowing time, the vehicle should be approaching its starting point and establishing the repeatable route. As the route is ended, the keyed-in segment numbers are output to a storage device, saving them for the actual simulations to be made later. While routes that are optimum, in the strictest sense of the word, may be quite difficult to achieve, certainly routes of high efficiency may be constructed quite rapidly using these techniques.

The laboratory version of this routing module makes use of a cathode ray tube (CRT) interactive graphics terminal to display the network, and routes are keyed in with a lighted cursor on the screen. Contrary to statements made in Tucker (1976) concerning the wide availability of such devices, we have learned that most municipalities would have difficulty obtaining a graphics terminal. Most, however, could get access to some sort of more conventional terminal and a time sharing computer system. We also have discovered severe limitations as to the size of the network which may be displayed on available graphics terminals. However, the laboratory model will continue to use the CRT terminal when the network can be adequately displayed, as the keying in of routes in this way is much more rapid than the more conventional technique.

SIMULATING A SNOW REMOVAL OPERATION

Once the various repeatable routes are established, the complete simulation of any particular snow removal operation can be run by varying both meteorological and equipment specifications. Factors found later that affect program performance may be easily modified as the simulator is constructed in a modular form. Snow-storm parameters are storm length, rate of snowfall, snow density and storm starting time. Truck and route variables are truck weight, plow weight, plow width, normal plowing speed, route starting depth and route starting time. The file containing segment characteristics

and those containing truck routes are assumed to be accessible by the program.

Time to clear any network depends on the length of the storm, plow width and velocity that the plows can maintain. Initial velocity over any segment is taken to be the lesser of normal truck plowing speed or normal traffic speed along the segment reduced by a constant amount for hazardous conditions. Additionally the plowing force available to the truck is calculated to determine if it is adequate to remove the amount of snow in its path at the given velocity. If not, the velocity is reduced until the forces are balanced. Tanaka (1970) developed an equation for the force required for a truck to remove a given amount of snow:

$$F_R = R_r + R_s + R_p \quad (4)$$

where R_r = truck rolling resistance
 R_s = plow sliding resistance
 R_p = plow snow-removing resistance.

R_r , R_s and R_p can be further defined as

$$R_r = W_t(0.000123V + 0.05) \quad (5)$$

$$R_s = 0.41W_p \quad (6)$$

$$R_p = \rho s(0.00139V^2 + 0.005V + 0.331) \quad (7)$$

where W_t = truck weight
 W_p = plow weight
 V = truck velocity
 ρ = snow density
 s = cross-sectional area of snow being removed.

All numerical constants were empirically determined by Tanaka (1970). Force available to the truck is given by

$$F_T = \frac{P}{V} \quad (8)$$

where P is truck horsepower.

When both F_T and F_R are calculated, velocity is reduced until $F_T > F_R$. Time that plowing commences is dictated by two input variables, the minimum depth and the plowing start time. The time for the roads to accumulate the minimum snow depth is calculated and compared against the specified start time. The earlier of the two times is chosen for the plowing on this particular route to commence. This allows for the option of either holding out for a certain depth or a certain time, for example, early in the morning prior to rush hour.

Another consideration taken into account by the simulation is plowing windrow — the extra amount of snow cast into the next pass lane (to the right). We currently incorporate windrow by adding one-quarter of the depth of snow just plowed to that depth to be plowed on the next pass. This consideration is marked for modification as soon as empirical data give us better relationships for the effects of windrow on truck velocity.

Summarizing the operation of the simulation, plowing by a truck begins when the designated depth or time first occurs. Each truck progresses through its route, removing one blade width of snow from the segments. Velocity along each segment is calculated. From this, the time to make the pass is computed and added to the cumulative time of the truck. The width and depth of snow on the uncleared part of the street are stored in status registers. At designated constant intervals (currently 7.5 min), these street status registers are examined and new depths calculated if snow is still falling. The truck continues to make additional passes on its route until the storm has concluded and the streets contain less than a specified depth (1 in.*) of snow.

SNOW REMOVAL PARAMETER ANALYSIS

Many aspects of the snow removal operation can be examined with the simulation package. In this section we will attempt to show simple techniques for the evaluation of a few of these variables. For demonstration purposes a network similar to Holland, Michigan, was chosen. The CRT display of this network is shown in Figure 1. In the segment file, characteristics for the 406 segments of the Holland network are arbitrarily represented by typical values. While we are not yet able to validate the output results with actual data, the usefulness of the simulation can still be demonstrated here.

Establishing acceptable routes around the network was the first step in the analysis. For this network, four truck routes seemed to be acceptable. The primary design criterion was to attempt to limit plowing on any route to a primary street direction. That is, a truck either runs the majority of its route on vertically (for this illustration) or horizontally oriented streets. The routing programs described earlier were used to achieve nearly equal plowing times on individual routes with minimum route overlap. Figure 1 shows the segments covered by each vehicle. We refer to these later as the standard routings.

For comparison, other routes were designed using one continuous path for the entire city with very little overlap. By again using the interactive routing program, starting points were assigned to the trucks (i.e. a truck plows for the designated optimum time, then

* 1 in. = 25.4 mm.

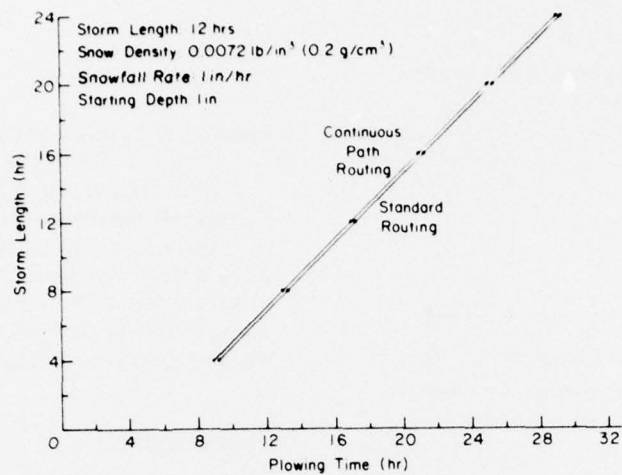


Figure 2. Total plowing time vs storm length for the continuous path and standard routing.

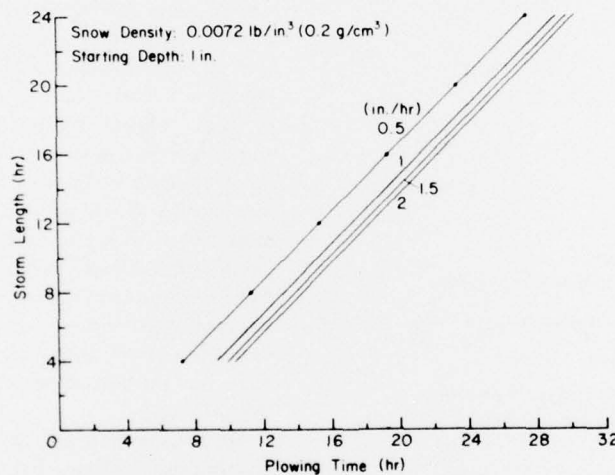


Figure 3. Total plowing time vs storm length for various snowfall rates.

another route starts). The cover shows where each of the four trucks begins plowing. In the simulation, the trucks plow on a route covering the entire city over segments plowed by earlier trucks until all segments are clear.

To compare the routing strategies, the simulation was run by varying only storm length for the different routings. Total plowing time was taken to be the plowing time of the last truck to finish (difference less than 0.5 hr) for each case. Total plowing time vs storm length for both routing strategies is shown in Figure 2. As shown, the plowing times differ very little. The continuous path method should be nearly optimum as very little overlapping occurs. As our standard routes are nearly equal to the continuous path times, they

seem to be quite acceptable. These standard routings will be used for the remainder of the simulations described here.

The sensitivity of plowing time vs storm length is an interesting aspect to examine in more detail. Again fixing equipment characteristics, starting depth and snow density, we varied the storm length from 4 to 24 hours for snowfall rates of 0.5, 1.0, 1.5 and 2 in./hr. The results are shown in Figure 3. For all rates the length vs plowing time relationship is linear. A regression line through the data for the 1-in./hr rate yields

$$T_p = L_s + 5.2 \quad (9)$$

where T_p is time plowing and L_s is storm length.

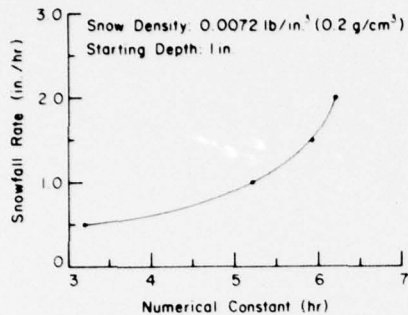


Figure 4. Numerical constants for linear regression equation vs snowfall rates.

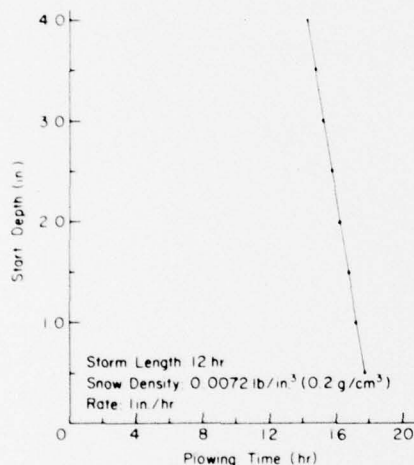


Figure 5. Starting depth vs total plowing time for fixed storm length (12 hr).

The numerical constant (5.2 hr) is the time for the truck to completely clear the route one time. For the other snowfall rates the slope of the regression line remains unchanged (1.0) and only the numerical constant (5.2 in eq 9) changes. Figure 4 shows these constants as they vary for the different rates. In this case, then, one need only have the curve of the constants varying with rate to estimate total plowing time. Assuming that this same behavior of storm length vs plowing time is observed when other parameters (starting depth, density) are varied, only a few expressions of the form of eq 9 need be kept by any municipality for a constant fleet of trucks.

For the same truck routes, we assessed the impact of starting depth on total plowing time. Figure 5 shows the results of holding storm length, density and equipment specifications constant, and varying starting depth from 0.5 to 4.0 in. Again a linear relationship is observed, this time of the form

$$T_p = 18.6 - 0.914D_s \quad (10)$$

where D_s is the route starting snow depth.

For this case also, varying the length of the storm changes only the constant (18.6 in eq 10) as the slope remains constant. The significance of this to a municipality is that for a forecast storm duration, the total plowing time saved by increasing the depth at which the plows start can be quickly calculated (merely by changing the constant 18.6) using eq 10.

CONCLUSIONS

With curves such as in Figures 3, 4, and 5, one can quickly determine the approximate plowing time for various storm conditions and the effects that delaying plowing will have. Of course, other negative impacts, such as increased traffic accidents and general complaints, will have to be considered as well. Taking the mean storm history for an area, and knowing the type and number of pieces of equipment used, we could quickly calculate what sort of snow removal budget a municipality should have available. Extreme years and especially extreme storms should be studied as well. Other variables likely to be assessed are the impact of new equipment and the rental of equipment from contractors. While we could continue listing uses that the simulation offers, most road agents and city managers know best the type of benefits that can be derived from this package.

We are now preparing validation tests for the model. As mentioned earlier, other factors in the snow removal process need to be evaluated. The present plan is to get one general model which will respond reasonably well in any municipality. Factors that have had more or less impact on certain municipalities may be easily added or deleted. We are still holding to the premise of having a model requiring a minimum of effort to obtain accurate, useful results.

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