Computer Simulation of Urban Snow Removal

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A general computer model to simulate urban snow removal has been developed. One part of the package includes several programs which assist in the routing of snow removal vehicles using computer graphics. The primary element, however, is a program which, once specific vehicle routes are input, allows the simulation of any particular snow removal scenario. Parameters that can be varied include both truck and snowstorm characteristics. This simulation program is tested using truck routes and storm data from Newington, Connecticut. Results indicate that the simulation predicts plowing times quite reasonably. Using the simulation model, the sensitivity of plowing time to storm length, accumulation rate and plowing start depth is examined. The plowing time exhibits a nonlinear relationship with accumulation rate, varying inversely with it, while the dependence on starting depth and storm length is linear for both. A route designed by the authors is tested against the actual route used in Newington, demonstrating a near-optimum configuration for the current Newington route with regard to the present resolution capabilities of the simulation program.

The winters of 1977 and 1978 demonstrated to much of the U.S. that snow and ice control on streets and highways is indeed a serious problem. Many midwestern and northeastern metropolitan areas were brought to catastrophic standstills for periods of several days. Numerous urban communities tremendously overspent their winter road maintenance budgets. 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 dollars (1), and total urban expenditures are probably at least this high. Without a substantial improvement 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 owned 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 (2) developed a simulator called AID, designed specifically for the small town. Unfortunately, the program was too large for the 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 (3) also simulated snow control (actually only salting and sanding) for the city of Tulsa, Oklahoma. This simulation has been used successfully for assessing truck routing and relocation of sand piles around the city (4). 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 that 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 that has a minimum of inputs, yet is 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, with some minor changes, cannot be applied to salting and sanding as well.

The snow removal simulation package was created in various program modules. First, a routing module was created that uses sophisticated computer graphics (certainly not available every-

where) to aid in the selection of optimum snowplow routes. (A simpler, yet still 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 plowing time for each piece of equipment is calculated. 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 (5, 6), 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 drivers' experience, and these choices often may be close to optimum. Frequently, however, particularly in the larger urban areas where yearly personnel changes can be high, the routes followed are far from 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 (7, 8) as mentioned above, but efficient computer solutions to such problems are not available (6). Adding multiple street passes, priority routes and other complexities associated with snow removal to the routing problem makes even manual techniques difficult to implement. 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 numerically labeled 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

$$T_s = N \cdot (L/V) + N \cdot C \qquad (1)$$

where: N = Number of passes required (segment width W_i/ effective plow width W_p)

L = Segment length

V = Velocity of the plow along the segment

C = Delay factor for intersection wait time (15 s)

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

The next logical step was 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

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

where: M = Total number of trucks

L_i = Street length

N = Number of streets

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

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

where: W_k = 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 equation 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, 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 optimum routes in the strictest sense of the word may be difficult to achieve, certainly routes of high efficiency may be constructed 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 using a lighted cursor on the screen. Contrary to statements made in Tucker (9) 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 the graphics terminal. However, the laboratory model will continue to use the CRT terminal when possible as the keying in of routes is much more rapid on it than on the conventional terminal.

Snow Removal Simulation Model

Once the various repeatable routes for a municipality are established, another computer program allows the simulation of any particular snow removal operation by permitting both meteorological and equipment parameters to be varied. Variable snowstorm 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. Truck routes are also input to the program and the file containing segment characteristics must be accessible.

Time to clear any network once the number of trucks and their routes are fixed depends on the length of storm, plow width and the 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 (10) developed the equation for the force required of a specified truck to remove the 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

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

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

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

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 (10). Force available to the truck is given by:

$$F_T = P/V \quad (8)$$

where: P = truck horsepower.

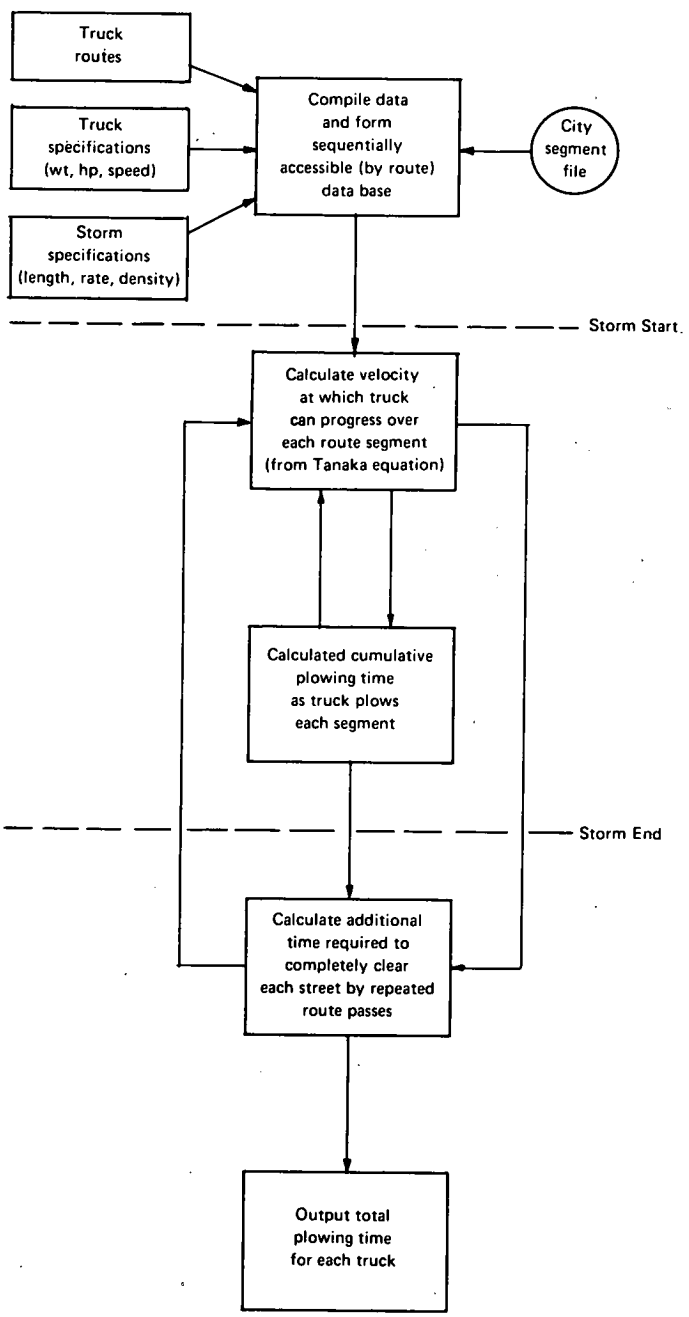
When both forces are calculated, velocity is reduced until $F_T \geq F_R$. As pointed out in Tucker (9), the condition for reduced velocity as dictated by this technique in an urban area is rarely encountered. It is included in the simulation model however, until more applicable relationships are developed.

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 depth is calculated and compared against the specified start time. The earlier of the two times is chosen for plowing on this particular route to commence. This allows the option of either holding out for a certain starting depth or a certain time, for example, very early in the morning prior to rush hour.

Another consideration taken into account by the simulation is plowing windrow - the extra amount of snow which is 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 also 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 program, plowing by a truck begins in time when the designated depth or time first occurs. Each truck progresses through its route, removing one blade width of snow from each segment along the route. Velocity along each segment is calculated, and from this, the time to make the pass is computed and added to the cumulative time of the truck. The width of the uncleared part of the street and depth of snow on it are stored in status registers. At designated constant intervals (presently 7.5 min), these street status registers are examined and new depths are 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. A block diagram of the simulation program is presented in Figure 1.

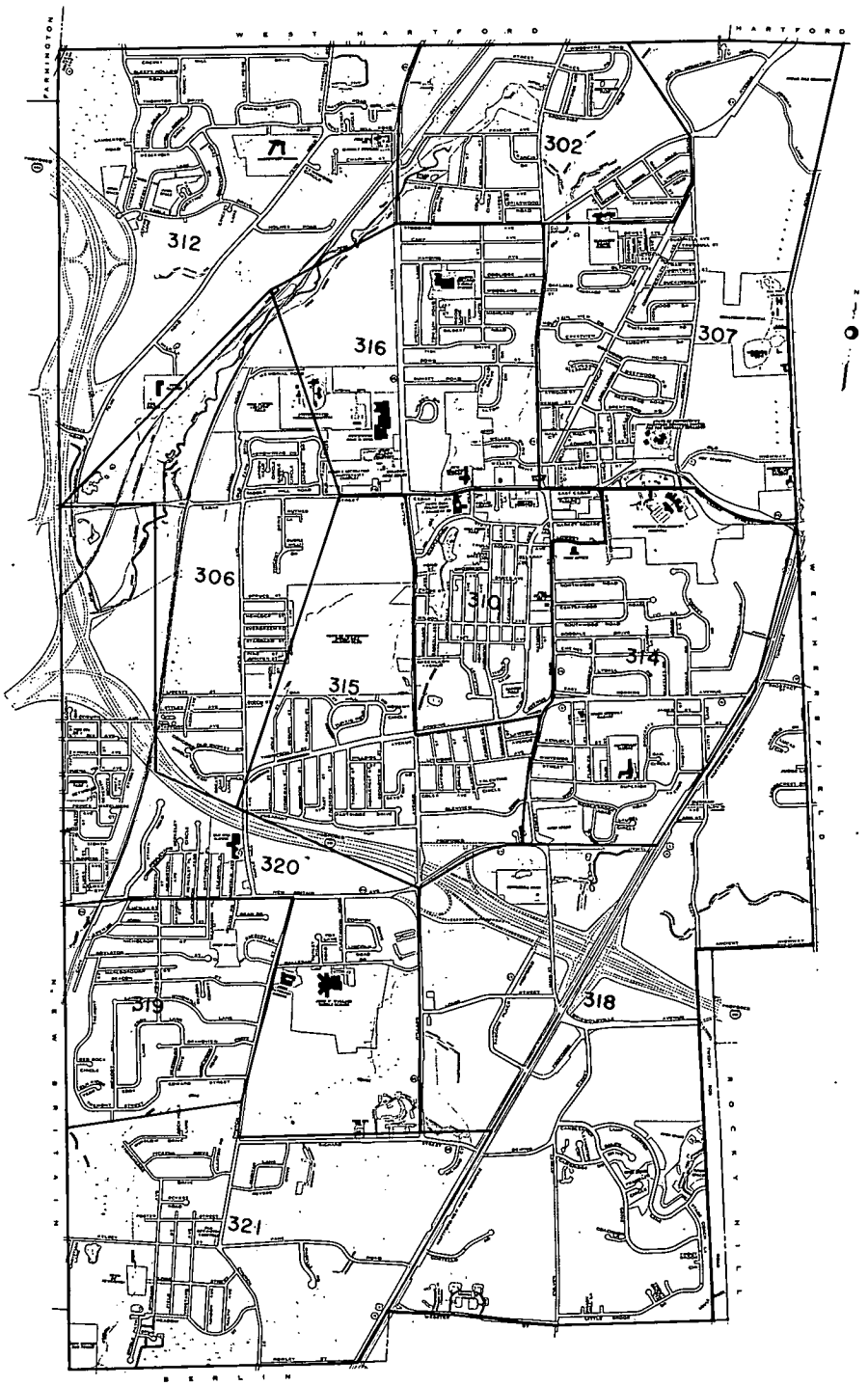
Figure 1. Block diagram of snow removal simulation model.



Validation of the Simulation Model

In previous reports (9, 11), the simulation program was demonstrated using arbitrary data, thought to be representative of actual cases. The results of these earlier tests appeared reasonable, but we had no means of actually assessing the validity of the output. For this study, however, a detailed validation effort has been undertaken using the town of Newington, Connecticut, as a test base. Newington, population 26,000, has a very efficient snow removal program proven by its performance during past severe snowstorms. In addition, highway administration personnel in Newington had an adequate collection of storm and operation data and spent a great deal of time preparing and coding data for the segment file. Newington also has a street layout, topography and problems (parking, etc.) typical of much larger cities. The only apparent disadvantage in working with Newington is that their snow removal operation seemed so efficient that the program, once validated, would be of little use in pointing out possible improvements.

Figure 2. Newington, Connecticut, with assigned truck sections.



The city is divided into 12 sections as shown in Figure 2, with each section assigned to a specific truck. Table 1 gives the equipment specifications for each truck, as represented by the section number that it is responsible for plowing.

Table 1. Truck specifications. (For all trucks the plow weight was taken as 3000 lb (1361 kg), the effective plow width as 8.5 ft (2.6 m) the normal plowing speed as 16 mi/hr(25.7 km/hr).

Section No.	Truck Weight (lb)	Truck Weight (kg)	Horse-power
302	37,000	16783	290
306	29,000	13154	200
307	37,000	16783	290
310	37,000	16783	190
312	29,000	13154	200
314	37,000	16783	210
315	37,000	16783	290
316	29,000	13154	200
318	37,000	16783	210
319	37,000	16783	210
320	37,000	16783	210
321	37,000	16783	210

Highway department personnel also provided the actual routes that the drivers generally follow. It was to our satisfaction to find that the majority of the drivers follow the same general route each storm, and that they repeat that route during an individual storm until all streets on the route are clear. While the findings thus far were consistent with methodology applied within the program, several situations were not. On several major city streets, tandem plowing operations are routinely used. Generally this is handled by the truck in whose section the priority street lies, with the next closest truck coming to assist. This cannot be exactly simulated in the program, but the situation is handled in a sense by having that same segment in both route files. The status of the segment then reflects the operations of both trucks. Where the program fails in this respect is that the times of plowing the segment by the two trucks could be quite different, far from simultaneous. Another problem in the simulation occurs when the storm has ended and all but a few segments are completely clear. The program has the truck continue on its assigned route until these segments are clear. In an actual operation the truck would proceed directly to the unclean segments by the shortest route. The impact of this discrepancy in the Newington case is suspected to be small as the routes are short. For the simulation test runs, no use was made of the routing programs as the routes were provided. Routes were simply taken from maps, coded by segment number and input to a computer file.

Five reasonably large snowstorms were chosen for simulation testing. For each storm, only one clearing time was provided, that supposedly being the average of all trucks. In general, trucks will move to another route and assist if their own route is completed early. Table 2 shows the results of our computer runs for each storm with the calculated plowing time to clear each section presented. Also we show an average calculated plowing time as well as the observed completion time. In all cases the plowing began when the snow reached a depth of 0.5 in(1.27 cm) and the snow density was a constant 12.49 lb/ft^3 (200 kg/m^3).

Table 2. Route plowing times (hr) for various storms.

Route No.	Length (mi)	Storm 1 Length=14.5 hr Rate=0.28 in./hr (0.71 cm/hr)	Storm 2 16.5 hr 0.55 in./hr (1.39 cm/hr)	Storm 3 15.0 hr 0.20 in./hr (0.50 cm/hr)	Storm 4 24.0 hr 0.25 in./hr (0.64 cm/hr)	Storm 5 16.0 hr 0.44 in./hr (1.12 cm/hr)
302	5.56	14.9	18.3	14.9	24.7	17.5
306	6.95	14.1	18.5	13.9	23.4	17.8
307	6.0	17.2	20.5	16.0	26.4	19.3
310	6.4	15.6	19.0	15.7	25.4	18.3
312	8.6	16.4	19.7	16.2	25.9	18.8
314	9.15	14.6	18.8	14.5	24.2	18.0
315	6.1	15.4	18.4	15.3	24.6	17.9
316	5.67	15.1	18.3	14.7	23.9	17.6
318	5.76	15.3	18.8	15.5	24.9	18.3
319	7.71	15.3	18.8	15.5	24.9	18.0
320	6.01	15.4	18.5	15.5	23.9	17.8
321	8.05	14.9	19.0	14.9	24.9	18.3
Average		15.3	18.8	15.2	24.7	18.1
Observed		15.5	17.5	16.0	25.0	17.0

Table 2 shows a wide variability in completion times among different routes for a single storm. Also, upon examination of different storms, a consistent imbalance for some of the routes becomes obvious. For example, route 312 always requires more than the average time for completion. This route could possibly be shortened, giving excess segments to an adjoining route, say 302, that may show less than average completion times. It is our understanding that imbalances such as this are resolved in Newington by distributing the routes according to driver ability.

Another interesting fact is that section plowing times seem to have very little correlation with the overall length of the section. While not obvious, this is to be expected because the plowing time as calculated is a function of the number

of intersections and the width of segments as well as the length of the route. In fact, the number of intersections varies from a minimum of 69 (section 318) to a maximum of 224 (section 307) for each route pass. This accounts for a 0.65-hour time difference alone, for each complete traverse of the route, at 15 seconds delay time per intersection. While segment widths are more nearly standard (13 to 14 ft), a few of the main streets are significantly wider, causing more passes of the route to be necessary for complete clearing.

Of major interest in Table 2, however, is the comparison of the calculated completion times with the observed completion times. For storms 1, 3 and 4, the calculated average plowing times are less than the observed, while for storms 2 and 5, the calculated times are significantly longer than the observed times. Examination of storm characteristics shows that storms 2 and 5 had accumulation rates significantly higher than the other storms. The inference here is that at higher accumulation rates near (in time) the storm end, with each traverse of the route the truck is plowing only the leftmost plow width of each segment. This is necessary because the segments at the beginning of the route have accumulated the minimum plowing depth by the time the truck finishes a complete pass and is ready to repeat the route. In the case of the lower accumulation rates, the truck may easily complete a traverse before the depth on the previously cleared leftmost passes of the segments at the beginning of the route is again up to minimum plowing depth. Since the accumulated depth is not up to the specified depth, the truck proceeds to plow the remaining width of each segment (progressing to the right curb). If the storm ends when these leftmost segments contain less than the minimum depth of snow, route completion time is significantly reduced. It is also significant to mention that the observed plowing times are exactly the storm length plus 1 hour for all cases. Here, we tend to believe that the observed data may be in error for the higher accumulation rates. Chapman (Newington assistant highway supervisor, personal communication) confirms that the data are somewhat speculative.

In general the validation results are encouraging. We feel that for a "first order" simulation model, the predictions are reasonable and that the simulation model can be used in its present form with confidence. These tests have also pointed out areas in the program where improvements are most justified; these will be discussed later.

Sensitivity Examination

For evaluation of what appear to be key parameters in the snow removal operation, it was decided to make demonstration runs on only one particular route. Section 321 was chosen as being fairly representative of the average performance of all routes for the five storms. Also, as discussed later in this section, section 321 has what appears to be a near-optimum routing.

Probably the most obvious parameter to examine is storm length. Figure 3 shows plowing time vs. storm length for four accumulation rates. All other parameters remained fixed for the simulation runs. Not surprisingly, the relationship for all rates is linear. For the 0.5-in./hr (1.27 cm/hr) accumulation rate

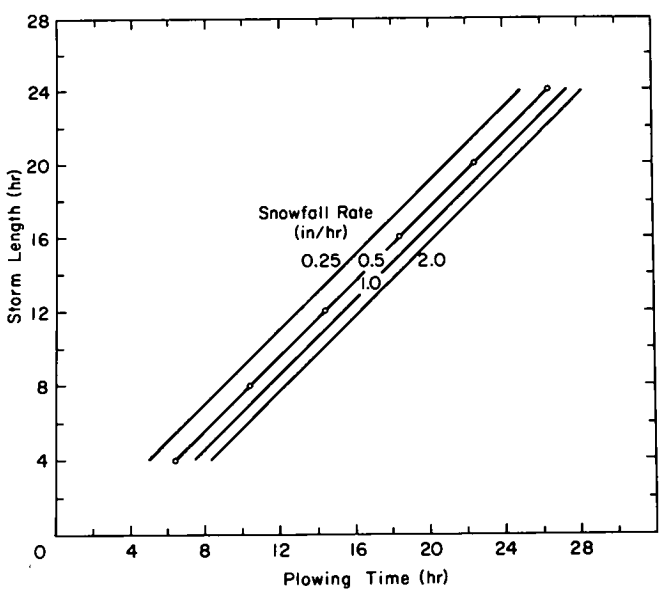
$$T_p = L_s + 2.46 \qquad (9)$$

where: T_p = Plowing time in hours

L_s = Storm length in hours

The numerical constant (2.46) is the time required to completely clear the route after cessation of the snowfall. As Figure 3 shows, only this constant varies with a change in accumulation rate. As mentioned earlier, this variation is a function of the route traverse time and the status of each segment when the storm ends. The implication of this linear relationship is that for a municipality, once these sorts of sensitivity evaluations are conducted, plowing times can be accurately predicted at weather forecast time (depending, of course, on the accuracy of the forecast). For fixed routes, only a few expressions of the form of equation 9 for different accumulation rates need be determined and kept on hand. Newington, for example, presently uses the "storm length plus one hour" rule of thumb to predict plowing times.

Figure 3. Plowing time versus storm length on route 321 for four accumulation rates. The snow density was 12.49 lb/ft^3. (200 kg/m^3) and the starting depth was 0.5 in (1.27 cm).

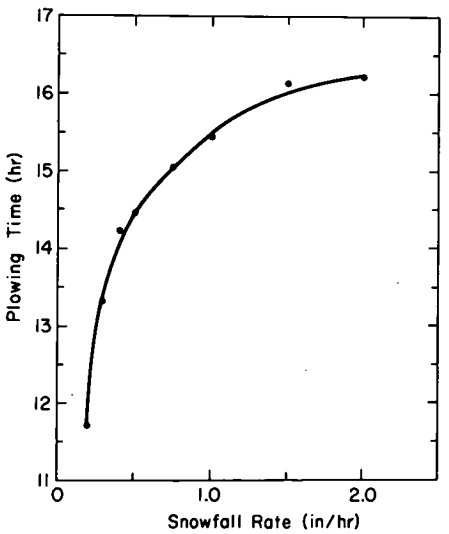


As the simulation shows a great sensitivity to accumulation rate combined with the fact that this seems to be the critical factor in the calculated plowing time discrepancies with Newington, a more detailed examination of this parameter is warranted. Figure 4 shows the sensitivity of plowing time to accumulation rate. Here the rate was varied while holding all other parameters constant for a 12-hour storm. In contrast to the convenient linear relationship that was established with storm length we find a nonlinear dependence which is best fit by a regression line of the form:

$$T_p = 16.57 - 0.983/r \quad (10)$$

where: r = Accumulation rate in inches per hour

Figure 4. Plowing time versus accumulation rate on route 321 for a 12-hour storm. Snow density was 12.49 lb/ft.^{3} (200 kg/m^3) and the starting depth was 0.5 in. (1.27 cm).

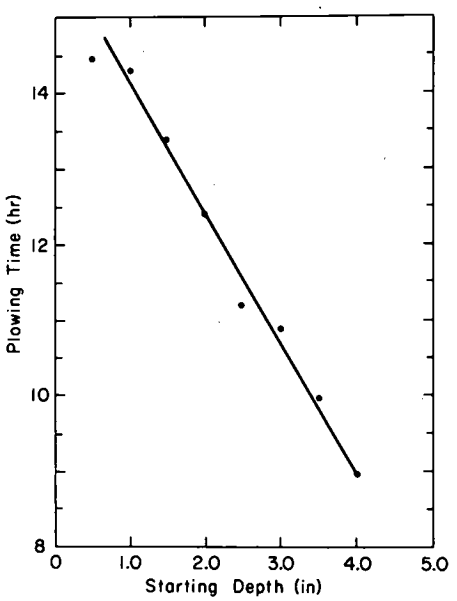


As a result of this inverse relationship, the constants in this case do not represent anything physically meaningful. The significant effect here is that changes in accumulation rate below 1.0 in./hr (2.54 cm/hr) drastically affect total plowing time while at rates greater than 1.0 in./hr (2.54 cm/hr) the curve becomes asymptotic, with very little increase in plowing time. The 1.0 in./hr (2.54 cm/hr) rate appears to be the point above which the entire route must be cleared at storm end. At this high accumulation rate the truck is merely repeating the first pass on each street until snowfall has ceased. Any increase in total plowing time after this point is caused by the fact that the truck must begin plowing earlier, the starting criterion being the 0.5-in. (1.27 cm) snow depth in all cases.

Although the sensitivity to accumulation rate is not reflected in the Newington data, we tend to believe that it is a real effect. Admittedly the variation in observed rates in our validation tests was small (0.20 to 0.55 in./hr), but we feel that if records were more carefully maintained, the effect would be noticeable. It is not advocated, however, that real plowing times would be as sensitive to the rates as the simulation program predicts. In fact, the sensitivity may be somewhat less than that shown by the simulation, due to the fact that a driver can use discretion, and the computer must make a decision based on predetermined criteria.

A municipality has no control over storm length or accumulation rate. But one parameter in a fixed-route, fixed-equipment system that can be varied which significantly impacts total plowing time is the starting depth. Figure 5 shows this impact as calculated by the simulation program. By delaying the starting depth from 1 in. (2.54 cm) to 4 in. (10.2 cm) on a 12-hour storm with a 0.5-in./hr (1.27 cm/hr) accumulation rate, approximately 5 hours of total plowing time is saved. Substantial economic benefits can be derived from this practice, and in fact the technique is well known and used in many Northern New England communities, particularly during storms that occur overnight. On the other hand, larger, more populated areas may have difficulty implementing the technique due to the obvious hazards that may result. It may be possible, however, to delay the plowing of certain low priority routes during nighttime snowfalls. Once again this sort of relationship derived from the simulation is linear, and once it is established for a given route, the time savings can be quickly calculated for any storm length. Only several curves or equations characterizing different accumulation rates need be created.

Figure 5. Plowing time versus starting depth on route 321 for a 12-hour storm. Snow density was 12.49 lb/ft.^{3} (200 kg/m^3) and the accumulation rate was 0.5 in./hr. (1.27 cm).

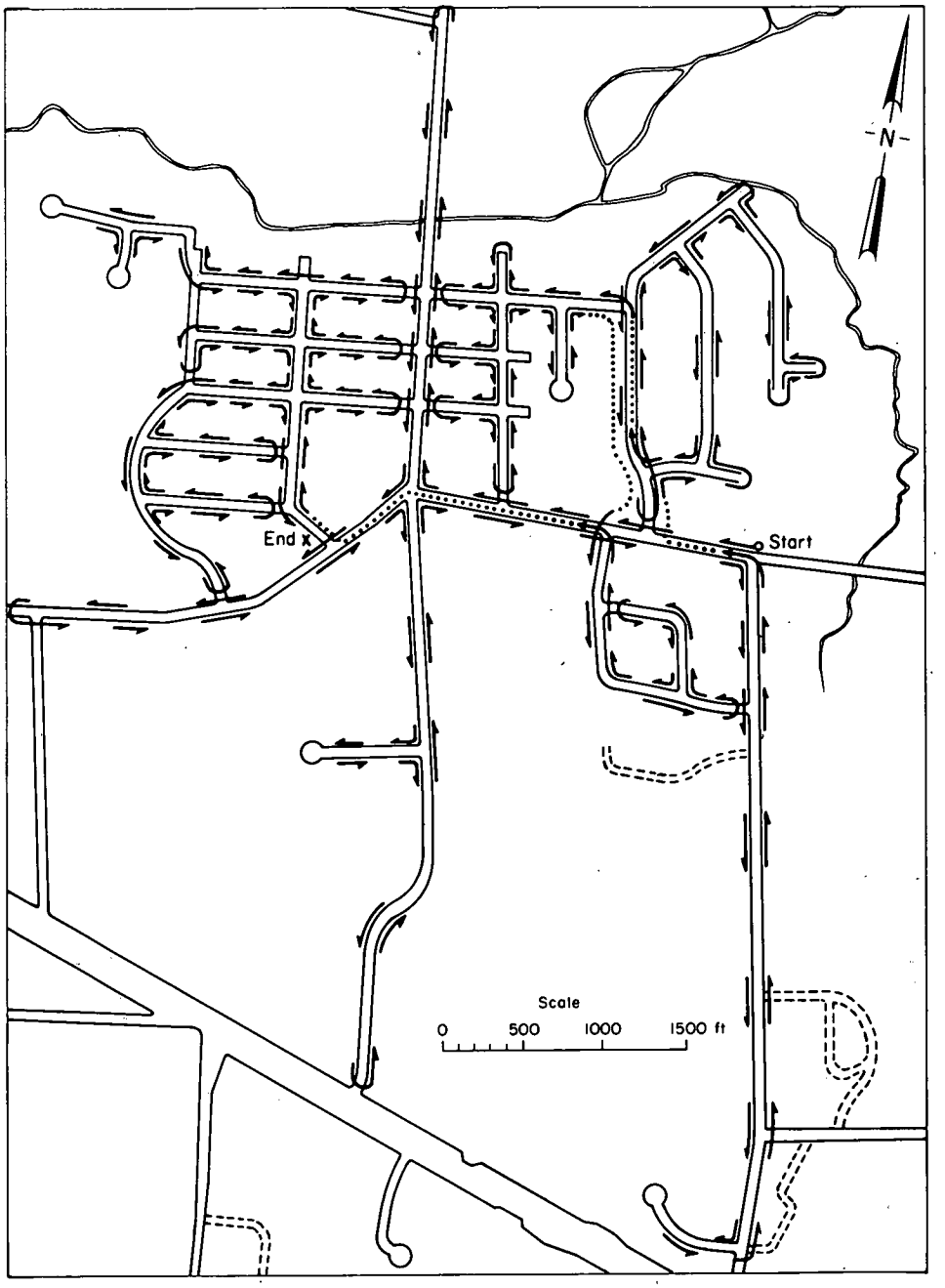


Although the simulation program cannot design optimum routes, it may be used to test different routing strategies. As a test case we attempted to design an optimum route for section 321. Figure 6a shows the route presently followed by the driver on route 321. Figure 6b is our version of what could be a near-optimum route. It is worth mentioning that our routing strategy consisted of the following guidelines:

1. As few intersection U-turns as possible.
2. As few left turns as possible.
3. As little "deadheading" as possible.
4. Completion of plowing at the starting point.

We were able to adhere to all of the above rules fairly rigidly except for left turns. It was found necessary to make left turns often in order to avoid U-turns at intersections. Although the program does not discern types of turns but uses a constant 15-second penalty at intersections, we believed, when the route was designed, that intersection U-turns (or intersection clearing "k-turns") would be costly in time as well as difficult to execute if other vehicles were using the

Figure 6a. Snowplow routing for Newington, section 321. Route currently used.



streets. Studying Figure 6a, apparently the belief in Newington is that these turns are necessary and efficient. As they are used successfully there, our ideas have also since changed, but for demonstration purposes we shall use the route layout previously designed. Table 3 shows the completion times for both routes for the five storms used in earlier tests.

The Newington route is more efficient in 3 of the 5 cases and our route is superior for the other cases; however, all differences are small. Because the completion times are nearly equal for both routing strategies it is difficult to pick an overall superior route based on program results. The differences in times obviously depend on subleties such as the status of the segments and position of the truck when the storm ends. The facts that the priority (also wider) streets are traversed early in the Newington routing and that some of these wider segments are crossed twice in the routing seems to give it some advantage for the storms with lower accumulation rates (1,3,4). On the other hand, our route appears to benefit from having a slightly shorter single traverse time (known from other program output information) for the higher accumulation rate storms (2,5). Considering other factors, one would expect the U-turns in the Newington route to be costly in time if the simulation accounted for them. In

Figure 6b. Snowplow routing for Newington, section 321. Route designed by the authors.

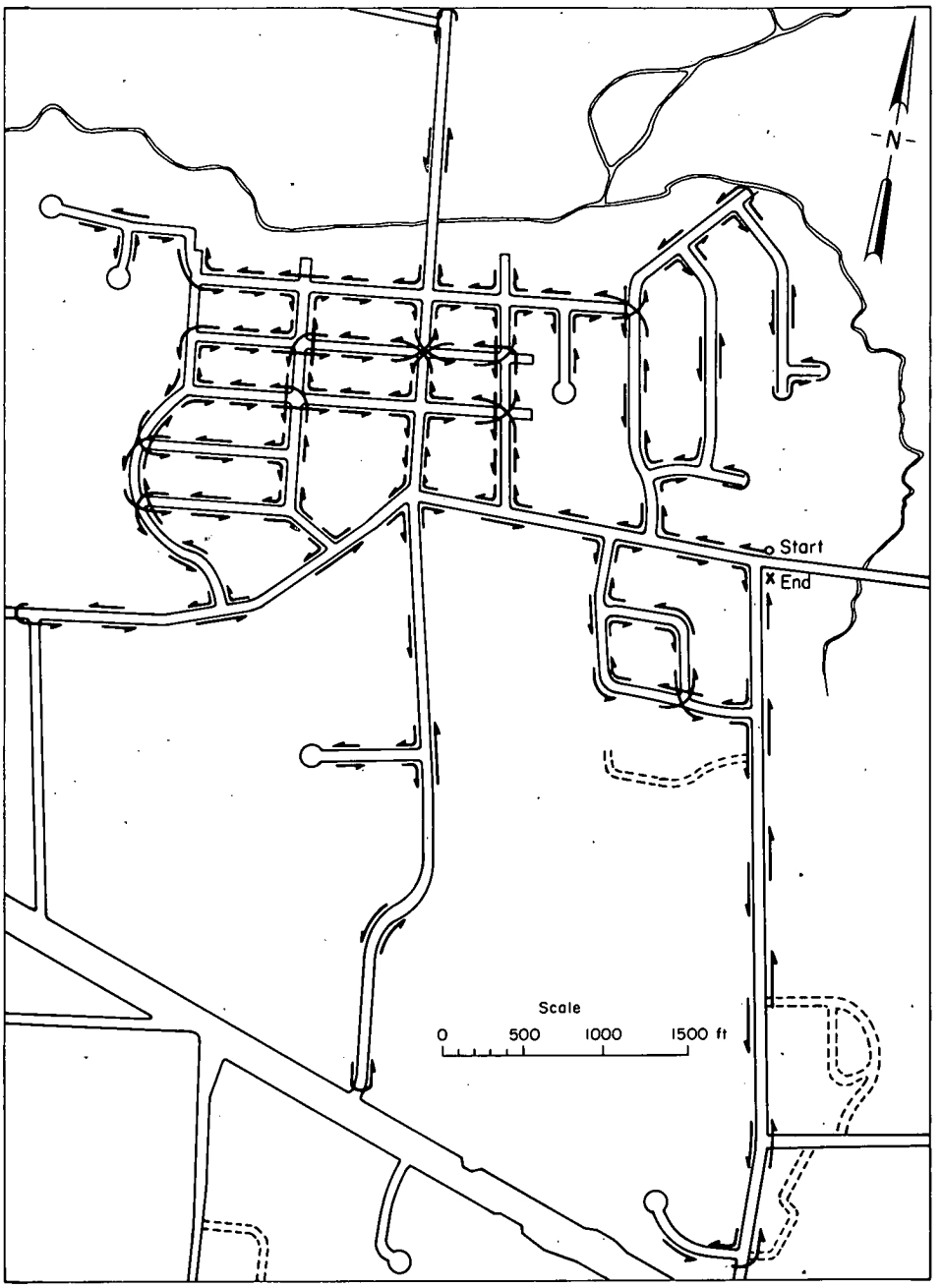


Table 3. Comparison of different routes for section 321 (time in hours).

	Storm 1 Length=14.5 hr Rate = 0.28 in./hr (0.71 cm/hr)	Storm 2 16.5 hr 0.55 in./hr (1.39 cm/hr)	Storm 3 15 hr 0.20 in./hr (0.50 cm/hr)	Storm 4 24 hr 0.25 in./hr (0.64 cm/hr)	Storm 5 16 hr 0.44 in./hr (1.12 cm/hr)
Newington Route	14.9	19.0	14.9	24.9	18.3
Authors' Route	15.6	18.8	15.4	25.0	18.0

contrast, however, the efficiency of removing snow from the intersections in our route is apparently lost, in particular with left turns. In reality this may require separate trips back to those intersections to completely clean them. This debate, however, is beyond the scope of this study, and beyond the resolution of the simulation without an additional programming effort. The point to be made here is that the simulation can now be utilized to test routings that are a function of length, number of intersections, and the amount of deadheading. Modification of the program will be necessary if the degree of efficiency of routes is to include the type of turns and cleanout procedures used at intersections.

Conclusions

The results of the validation tests on Newington are encouraging for a "first order" simulation scheme. Considering the fact that program constants or calculation procedures were not changed during the evaluation, we are especially satisfied that our original concepts seem to be adequate. It is also believed that our results would appear reasonable for storms with higher accumulation rates if additional data were available.

The simulation can be used in its present form to assess the sensitivity of a municipality to certain storm parameters. Plowing times will almost certainly have a linear response to storms of different lengths having the same accumulation rate. The effect that various snowfall rates will have seems to be a parameter that warrants further serious study. It seems intuitive that there should be a nonlinear response to accumulation rate as the program is showing. Once these parameters are examined with the simulation, a municipality can keep only equations or graphs on file for any potential equipment or route mix. Potential savings from such tactics as delaying the start of a plowing operation can be quickly calculated from the data on file.

The simulation program can be used to quickly assess the relative efficiency of various routing strategies as far as route length, number of intersections and amount of deadheading are concerned. Program modifications are necessary if the effect of the various intersection maneuvers is to be incorporated. The consequences of the operations should also be considered, however. That is, while left and right turns may be more efficient in time as far as normal route traverses are concerned, some sacrifice in time may be required for the truck to return at some point and completely clear the intersections. Another area of the program that should be improved is the slowing of the plow because of deeper snow. Although the speed of the truck appears to be more regulated by factors other than snow characteristics (i.e. curves, traffic, grade, etc.), it would be useful to have relationships which describe truck performance when the snowfall or windrow is extreme. Both of these potential modifications require further study of actual snow removal operations to obtain reasonable empirical relationships.

We feel that the general simulation model presented here would perform adequately in most communities. With the small improvements mentioned above, better plowing time predictions should be possible. If a community requires very accurate simulations, certain factors characteristic of that community may be added to the present program with little difficulty.

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