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Optimized Route to Clear Diverging Diamond Interchange Using Discrete Optimization Method

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Abstract: Interchanges and intersections are the most complex part of a roadway network and are very challenging for snow plowing operators. The objective of the study is to test if the empirical best plowing route to clear a Diverging Diamond Interchange (DDI) recommended by Clear Roads is also mathematically optimized. A discrete optimization method was employed to find the shortest route. In the study, the DDI is represented as a directed graph model. The task of clearing all lanes is treated as the well-known directed Chinese postman problem, which was then solved by an existing network optimization algorithm upon appropriate modification. The results showed that the best practice plowing route recommended by Clear Roads is one of the computed optimal routes with the Efficiency Index of 2/3. The approach proposed in the study can also be applied to other complex intersections and interchanges and help agencies achieve cost-effective snow control operations.

Keywords: Snow Plowing, Diverging Diamond Interchange (DDI), Chinese Postman Problem, Directed Graph, Euler tour, Efficiency Index (EI)

1. INTRODUCTION

Snow and ice control is a fundamental road maintenance winter operation activity of state and local transportation agencies. It can be performed as separate and distinct functions (snow plowing only or material spreading only) or simultaneously together. Both approaches require trucks of various sizes and equipment to travel along roadways to perform the plowing and/or spreading operations. The routes for the trucks operating in these different modes are influenced by a number of factors such as roadway classification, priority ranking, target Level of Service (LOS), roadway geometrics, topography, traffic volumes, traffic control systems, and restrictions, presence of bridges, overpasses, railway tracks and crossings, transit stops, etc. Optimized truck routes that integrate operational constraints will maximize snow plowing operation efficiency, improve travel safety and mobility, reduce truck fuel consumption, and save agencies money.

The road and street system in each jurisdiction (municipal, county, tribal, state, provincial, special district) consists of links and intersections (at-grade or separate-grade). Innovative intersection and interchange configurations are employed to reduce traffic congestion and improve safety. For instance, configurations such as Continuous Flow Intersections (CFI), roundabouts, "jug-handles" and Michigan Lefts, etc. are used on arterial routes or local streets. Likewise, limited-access highways have interchanges of different configurations, such as full and half diamond, diverging diamond, cloverleaf, single-point urban interchange, extended on-off ramps, stacks, and fly-overs, and "Texas turn-arounds." Although those configurations provide more efficient and safer traffic operations, they make the work of plow truck operators a lot more complicated. Additionally, freeways have median crossovers, safety pull-outs, and rest area parking lots that need to be plowed and turnpikes must deal with toll plazas and service islands as well. All these configurations add complexity to determining plow truck routes. Compounding

the problem is the composition of an agency's vehicle fleet. The type, size, and number of plows and blades on each truck are factors that influence plow truck routes.

Though there are standard guidelines for plowing and spreading, detailed practice manuals are lacking for clearing various complex interchanges and intersections. Most route planners and operations managers develop a recommended route of travel, but operators need latitude for adjusting to external, transient conditions and the capabilities of their equipment. Individual operators who are familiar with assigned routes develop their own techniques for handling diverse intersections, interchanges, roundabouts, cul-de-sacs, crossovers, and other challenging situations. The real-time traffic, pavement, and storm conditions may necessitate temporary deviation from prescribed routing.

Clear Roads, a consortium of most states in the Snow Belt and some major local agencies, recently sponsored a research study to identify best practices to clear ten different intersection and interchange configurations (Qi et al. 2018). Survey questionnaires were sent to Clear Roads member states and the general winter and ice community; the best practices of equipment and routing for clearing those ten layouts were identified based on the responses. However, those best practice routes obtained from the Clear Roads study are purely empirical and may differ from the theoretically optimized routes for clearing those ten configurations.

Using a typical Diverging Diamond Intersection (DDI) configuration as an example, this paper explored the discrete optimization algorithm approach to determine the optimized snow plowing routes. The optimized routes were compared with the best practice route obtained from the Clear Roads study. This approach can also be applied to other complex intersections and

interchanges and help agencies achieve cost- effective snow control operations, while improving traffic safety, saving travel time, and reducing plow truck fuel consumption.

This paper is organized as follows: in the next section, some existing models and algorithms for the snow plowing route problems are briefly reviewed; in Section 3, the proposed graph model and optimization methods are explained in detail, where the key steps of the main algorithm are outlined for solving the corresponding closed Chinese Postman Problem. The simulation results with optimized routes are presented and compared in Section 4. Finally, Section 5 concludes this study with possible future research directions.

2. LITERATURE REVIEW

Snow plowing route problems have not been widely addressed in the literature. This can be attributed to the complexity of the problems and the fact that they are often site-specific with numerous operational constraints. Of the published papers and articles discovered, very few focus solely on routes to clear interchanges and intersections. This section presents the literature review of recent relevant research.

Over the past 40 years, an impressive array of models and algorithms have been developed to integrate snow plowing operational constraints into the optimization procedure. Back in 1970, Moss used graph theory to determine economic routings of snowplows and trucks for highway winter maintenance. Euler graphs for deterministic purposes were applied in the study (Moss 1970). More recently, Golbaharan (2001) formulated a snow removal routing problem as a linear programming model, which was designed to find a set of low-cost routes for snowplow after the snowfall has stopped. A similar linear programming model was applied by Perrier et al. (2008) in their study for routing of vehicles in an urban area, which considered hierarchical objectives,

general precedence relation, different services, and deadhead speed possibilities, numerous passes for multiple lanes. For the real-time preparation of snow plowing and salt spreading operations, Damodaran & Krishnamurthi (2005) suggested a simulation model where the routes must be altered as weather conditions change. The model considered a hierarchical postman problem with a linear precedence relationship and used positive heuristic development.

Quirion-Blais et al. (2014) developed an adaptive large neighborhood search metaheuristic to design the snow plowing and salt spreading routes in a hybrid rural and urban network. Operational constraints considered include turn restrictions, network hierarchy, and equipment availability. Liu et al. (2014) proposed an MA-CARP algorithm to solve the Capacitated Arc Routing Problem (CARP) by minimizing the total distance traveled by a fleet of vehicles. It is a memetic algorithm embedded with a similarity-based parent selection scheme. According to the authors, roadway network size and complexity don't affect the algorithm performance, which can be used for networks with multiple lanes, one-way/two-way roads, and varying degrees of connectedness. Similarly, Kinable et al. (2020) treated a Snow Plow Routing Problem (SPRP) as the Capacitated Arc Routing Problem (CARP). The SPRP under consideration involves finding a set of vehicle routes to service a street network in a pre-defined service area while accounting for various vehicle constraints and traffic restrictions. A Constraint Programming formulation was proposed to solve the CARP, which was based on a graph transformation to transform CARP into an equivalent node routing problem. Other work on snow plow route optimization models and algorithms can be found in Perrier et al. (2008), Holmberg (2014), Fu et al. (2009), Perrier et al. (2006) and (2007), Soler et al. (2008), Jang et al. (2011), Campbell et al. (2001), Kinable et al. (2015), Schneider et al. (2016), etc.

Besides mathematical models and algorithms, many agencies use available geographic systems to solve snowplow route problems. Allen (2006) outlines the applications of geographic information systems (GIS) in public works, specifically in terms of route optimization and automatic vehicle location (AVL). The GIS optimizes plowing routes based on the real-time depiction of the fleet obtained from global positioning systems (GPS) and is designed to minimize plowing time. Ohio Department of Transportation (ODOT) introduced a snow plowing route optimization model developed in a GIS-based program (Holik et al. 2014) and validated GPS units placed in several snowplow trucks. Pennsylvania DOT developed a GIS-based tool to track winter maintenance data and generate maintenance route maps in collaboration with Geo-Decisions (Tosca 2015). Indiana DOT initially used the computerized route optimization tool Computer Aided Systems for Planning Efficient Routes (CASPER), but later shifted to manual route review practices supported by GIS visualization (Dowds et al. 2016).

Based on route optimization algorithms and models, many Commercial-Off-The-Shelf (COTS) software applications have been developed and used by agencies to configure snow plowing routes. For instance, GIRO developed GeoRoute software for route optimization of snow plowing, material spreading, and snow-blowing. It accommodates service time windows, service frequency, vehicle capacities, spreading rates, turn restrictions, and both-sides service restrictions. GeoRoute has been used in Ottawa, Laval, Charlesbourg, and Nepean, Canada for snowplowing; Suffolk County, UK for salt spreading (Perrier et al. 2007). Kentucky Transportation Cabinet (KYTC) used the COST package ArcGIS by ESRI for route optimization. The optimization accounts for individual truck material capacity in the winter, maintenance fleet, road prioritization, and lane-specific routing. When the old routes were checked with the new modeled routes it showed an average time saving of 8.4% (Blandford et al. 2018). The City of Centinal Colorado

contracted CH2M for public work services, which worked with C2logix to optimize the city's snowplow routes using C2Logix's software. Overall, it was estimated that total vehicle mileage and labor hours were reduced by approximately 50% on a yearly basis (Pisinger & Ropke 2007). Another example is FleetRoute™ developed by CIVIX L.L.C., which has many applications including snowplow routing. This software considers many operating constraints, can update the routes as required; and utilizes ArcGIS technology for its interface and mapping platform. It has been used in Canada, England, Northern Ireland, Portugal, Scotland, U.S.A, and Wales (CIVIX L.L.C. 2020)

The literature review results indicate that most literature focuses on plow route optimization in roadway networks. To the best knowledge of the authors, the Clear Roads study is the only one on snow plowing routes to clear various *intersection and interchange configurations* including DDIs. However, as mentioned above, the plowing route obtained from the Clear Roads study is purely empirical (based on the experience/recommendations of survey respondents). There is a need to use an optimization algorithm to check the best practice plowing routes. Due to the relatively small scale and complexity of DDIs, this study employed a discrete optimization algorithm to calculate the optimized routes for clearing DDIs and compare them with the Clear Roads best practice plowing route.

3. METHODOLOGY

The same geometric layout of a typical DDI used by the Clear Roads study (Qi et al. 2018) was examined (Figure 1). The arrows in the figure indicate the traffic flows, the freeway and crossover are both two-lane, and the ramps are 16 ft. wide. This way, all links of the DDI need two passes to clear the snow. Since it is easy to clear the freeway (two trucks in formation to clear eastbound

and then take a U-turn to clear the westbound), the DDI snow plowing routing problem is essentially how to clear its crossover and ramps.

To find an optimal route for clearing snow using optimization algorithms, a DDI network (crossover and ramps only) was modeled by a directed graph with a set of nodes/vertices (denoted by $V = \{1, 2, \dots, 16\}$) and a set of edges (denoted by E) as shown in Figure 2. The nodes (a--p) represent the switching points (direction changing points) for the truck and the edges stand for the lanes (links) in between. Since all links need two passes, two edges were modeled for each link. The length of the lane denotes the distance (in ft.) between two nodes, which were obtained from the DDI at the intersection of MN 15 and CO Rd. 120 in MN with simplification to make the graph symmetric. Given that the focus is to plow DDI crossover and ramps, the U-turn distance was set as zero for the first round of modelling. In the Clear Roads study, one truck was employed to clear the DDI crossover and ramps, therefore, only one truck was used in the model for comparison purposes. Also, from a practical point of view, the truck can only start from those points getting into the network (nodes b, l, o, and e in Figure 2).

The task of clearing a DDI is equivalent to travel through all lanes at least once from 4 possible starting nodes (nodes b, l, o, and e in Figure 2). In the literature of graph theory, this is known as directed Chinese Postman Problem (CPP) (Kwan 1962) & (Eiselt et al. 1995), or Route Inspection Problem, where the postman's job is to deliver all of the town's mail using the shortest route. This gives rise to a combinatorial optimization problem (Evans and Minieka 2017), which can be solved efficiently by some existing algorithms (Lin and Zhao 1988) & (Edmonds and Johnson 1973). In this study, the elegant algorithm implemented in (Thimbleby 2003) was employed, where the Java codes in (Thimbleby 2003) were modified accordingly.

Depending on whether the truck is required to return to the starting node, one may define a *closed* or an *open* CPP. In a closed CPP (ends at the starting node), the minimal total distance of an optimal route is independent of the starting point, while for an open CPP (ends at any node), the minimal total distance is highly sensitive to the starting point. Hence, one has to enumerate all possible starting points to find the best choice with a minimum total distance. For our considered DDI model, it is appropriate to consider only 4 possible starting nodes (b, ℓ , o, and e). The algorithm for solving an open CPP is based on a formulation of a closed CPP by introducing one virtual starting and one ending node (with zero distances), please refer to (Thimbleby 2003) for more technical details. Mathematically, a closed CPP solves an integer linear programming problem (known as a special minimum-cost flow problem), which is solvable in $O(|V|^2|E|)$ time complexity.

Following the notations used in (Thimbleby 2003) & (Lin and Zhao 1988), let $d(i,j)$ denotes the distance of arc $(i \rightarrow j)$ in the graph (V, E) and $f(i,j)$ represent the (to be optimized) number of times the arc $(i \rightarrow j)$ is traversed. The optimal Euler tour of a closed CPP is characterized by the minimizer of the following linear integer programming problem ($1 \leq i,j \leq 16$):

$$\text{minimize } \sum_{(i,j) \in E} f(i,j)d(i,j)$$

subject to the flow conservation constraint (with the integers $f(i,j) \geq 2$)

$$\sum_{j \in V} f(i,j) = \sum_{j \in V} f(j,i), \quad \text{for all } i \in V.$$

For better computational efficiency, it is not recommended to solve this integer programming problem directly, since it is in general NP-hard if simply solved by brute-force algorithms (e.g.,

branch and bound method). Instead, the more efficient network simplex algorithm (Lin and Zhao 1988) & (Orlin 1997) that has only a desirable polynomial complexity should be used.

This paragraph briefly explains the necessary key steps of the algorithm implemented in (Thimbleby 2003), the technical details are omitted for conciseness. In a strongly connected graph, a closed path is called an *Euler Tour*, if it contains all edges of the graph *exactly* once. It is well-known that a directed graph has an Euler Tour if and only if the In- and Out-degrees are the same for all vertices of the graph, where the number of incoming edges at a vertex is called the In-Degree of that vertex, the number of outgoing ones its Out-Degree. In our closed CPP, such an Euler Tour may not exist, unless additional edges could be added to the graph, such that all In- and Out-Degrees match. Hence, some additional edges need to be inserted optimally from those nodes with too few outgoing edges to those nodes with too few incoming edges, which can be achieved by making use of the shortest paths algorithms (e.g., Floyd-Warshall algorithm) and optimal weighted matching algorithms (e.g., Hungarian algorithm). After optimally inserting these additional paths to match all the In- and Out-degrees, an *Euler Tour* can be found using the Hierholzer's algorithm. The total cost of the optimal round trip is then given by the sum of all edge distance of this Euler Tour, where some edges may be visited repeatedly several times.

The overall computational complexity of the proposed algorithm consists of the following three components:

- (1) the Floyd-Warshall algorithm for finding shortest paths, which costs $O(|V|^3)$ operations;
- (2) the Hungarian method for constructing an optimal matching graph, which costs $O(|E|^3)$ operations;

(3) the Hierholzer method for finding one Euler tour, which needs $O(E)$ operations;

Therefore, the total time complexity is about $O(|E|^3)$, which runs efficiently for a medium-size network with up to several thousands of edges. It is possible to further speed up such algorithms via more heuristic techniques based on the network graph pattern, e.g. (Lum et al. 2019).

The optimized route found in the study is the shortest path that travels through all edges at least twice (except u-turn edges) to plow both lanes of the main highway and the crossover road as well as the 16 ft wide ramps. To travel through each edge at least twice, some edges will be unavoidably re-visited, which leads to wasted/useless travel distance (snow has already been cleared after two passes). **The basic cost** was defined as the total length (=16,800 ft.) of all directed edges in the model, which provides the lowest bound for the actual total travel distance. For measuring the quality of any feasible route, an **Efficiency Index (EI)** was defined in the study as *the ratio between the basic cost and the total travel distance (including wasted travel distance)*. Also, it should be noticed that the optimal route search did not take into consideration of prioritizing any particular lanes and simply found the shortest path to travel all lanes at least once from the 4 possible starting points. The detail optimized routes of the DDI network were computed by the Java codes given in (Thimbleby 2003), and then MATLAB was used to visualize optimized routes in several parts. It should be pointed out that MATLAB itself currently does not come with any built-in functions that can directly solve our open CPP problem yet.

4. RESULTS AND DISCUSSION

Based on the algorithm developed in (Thimbleby 2003), four different optimized routes with the same minimal total route distance and EI were found. Due to the symmetry (along the centerlines of the main highway and the crossover road) and the omitted U-turn distance in the DDI model,

the four optimized routes are essentially the same. One representative optimal route starts at **node b** and ends at **node c** after clearing all lanes with a minimum total distance, as shown in Figure 3. Here the full-length route was divided into 9 parts (per 6 edges except the last one) for better readability, where the red paths denote the route in each part. For simplicity, the route only showed one link between two nodes and each link was eventually travelled at least twice to meet the requirement of two passes. The other three optimized routes start and end at **node a** and **node d**, **node p** and **node m**, **node o** and **node n**, respectively. Note that when a non-symmetric DDI model is considered, the proposed algorithm will find only one optimal route, which will be one of the four routes found. All four optimal routes for the symmetric DDI have an **EI of 2/3**, which implies that one-third of the total travel distance was not spent on clearing the lanes. The EI was capped at 2/3 is mainly due to the restriction on the starting points, which is the optimized routes cannot start at an arbitrary node except the listed nodes (b, l, o, and e). If this restriction is removed, one unrealistic optimized route starting at **node d** can achieve a higher EI=0.7, which is about 4% better. The number of U-turns along the optimal routes is 15, including 7 U-turns on the main highway. The total numbers of merging and diverging points of the optimized route are 28 and 29, respectively.

In the Clear Roads report (Qi et al. 2018), a DDI plowing route was identified based on the best practices of agencies and a snow operator survey. For easy comparison, this Clear Roads DDI plowing route was depicted using the same directed graph as shown in Figure 4. Surprisingly, it turns out to have the same total distance and EI of 2/3 as the route in Figure 3. Such a result was unexpected at the beginning of the study. But note that the Clear Roads recommended route is as optimal as the optimized routes found by the algorithm only when the DDI model is symmetric with reasonable edge lengths. When an unsymmetric DDI model with extremely long or

unbalanced edge lengths is used, the Clear Roads recommended route is sub-optimal, while the algorithm proposed in the study will always find the optimal route with the shortest travel distance. The empirical plowing route recommended by Clear Roads is expected to work well as long as the DDI has reasonable edge lengths as the model in Figure 2, but it is in general not guaranteed to be optimal. The number of U-turns along the Clear Roads recommended routes is 15 (7 on the main highway), which is the same as the optimized routes found by the algorithm. The total numbers of merging and diverging points of the Clear Roads recommended route are 31 and 32, respectively, which are slightly higher than the numbers of the optimized routes found by the algorithm. Overall, the optimized routes found by the algorithm and the Clear Roads recommended route are comparable in terms of the number of conflict points. Note that crossing points of the DDI model were not counted, because those points are controlled by traffic signals.

Comparing the route sequence of the computed optimal route (Figure 3) and the Clear Roads empirical route (Figure 4), it can be seen that both start at the entry point of the eastbound off-ramp, the computed optimal route crosses the crossover road, clears the loop on the other side, then clear the crossover, and handles the loop on the starting point side at last. While the Clear Roads empirical route clears the loop on the starting point side first, then crosses the crossover road to clear the loop on the other side, handles the crossover at last. *From a practical point of view, it makes more sense for plow operators starting at the entering point of an off-ramp to clear the loop on that side first.* Also, the entrance and exit ramps for the freeway should have a higher priority than the local crossover road. Therefore, even having the same total route distance and EI, *the Clear Roads empirical route is the most suggested among the optimal routes.*

In practice, the total time cost can be reduced significantly by using two or more trucks simultaneously, but how to balance their coordinated optimal routes is nontrivial (Limon and

Azizoglu 2018). One simple solution with two trucks is to schedule the identical route for both trucks, since all edges (except U-turns) have two lanes to be cleared. Such cases can be similarly solved based on the corresponding graph model with one lane.

The model in Figure 2 has symmetric distances with respect to the main highway and the crossover road. In Figure 5, a more practical non-symmetric DDI model was considered, where the distances better reflect the realistic data from the DDI at the intersection of MN 15 and CO Rd. 120 in MN. Interestingly, the new optimal routes are exactly the same routes as obtained in the symmetric model in Figure. 2, but the basic cost is now 17,880 ft. and the EI is 0.6617321 ($< 2/3$). This implies the computed optimal routes are quite robust with respect to a small variation in some ramp and loop distances. Such desirable robustness would be very useful in practice since it is possible to reuse the same optimal route for clearing those DDIs with similar ramp and loop distances, which can facilitate the operation of the same truck driver. Of course, it is expected that the optimal routes would be different when the ramp and loop distances vary significantly. With the distance information of a DDI in hand, an optimal route can be computed in real-time.

For simplicity, U-turn distances have been set at 0 in the model given in Figure. 2. It is interesting to learn how the U-turn distances (assuming the U-turn distance on the freeway is 3 times of the crossover road distance) will affect the optimal route EI. Also, the ramp length is a major difference among different DDI designs. The joint influence of the ramp length and the U-turn lengths on the EI is plotted in Figure. 6. As expected, EI is a decreasing function of both ramp length and U-turn length, due to duplicated travel distances. This indicates an obvious fact that longer U-turn and ramp lengths will lead to lower EI. Moreover, it is observed that EI decreases dramatically as the U-turn length increases, which suggests design shorter U-turns in the DDI

design for higher EI. Of course, shorter U-turns and ramp lengths may also affect traffic and road safety.

Back to the symmetric model in Figure 2, it is also interesting to know how the EI depends on the left and right ramp lengths, which is another major difference among different DDI designs. In Figure 7, the EI was plotted as the function of both left and right ramp lengths between 500 and 2500 ft. It shows that EI decreases as the ramp lengths become longer, and the symmetric case with equal left and right ramp lengths leads to a local minimum of EI (along the diagonal direction).

The optimized routes for clearing different intersections can be easily integrated into a roadway network snow plowing operation. In the traditional snow removal routing optimization with a large network of highway and city roads, linear integer programming (LIP) models have been widely constructed with various constraints, e.g. (Campbell et al. 2014). In such LIP models, the objective function is usually defined as the total cost or distance of the routes and intersections are often treated as cost-free nodes. To integrate the optimized snow plowing route of different intersections (the nodes) into the traditional snowplow path optimization of a large network, an extra **one-time** cost/distance of clearing each intersection can be added to the objective function. Herein, *the algorithm proposed in the study can be used to compute the minimal cost or distance based on the local intersection configuration. When the plowing truck first enters the intersection (the node), it will first clear the intersection following the local optimized route and then continues plowing along the roadway network.* If additional plow trucks are available, prioritization of intersections could be added to the roadway network snow plowing route optimization as an additional constraint.

5. CONCLUSIONS AND FUTURE WORK

In this paper, the DDI was modeled as a directed graph with weights, whose optimal routes for clearing the roads were formulated as the well-known Chinese postman problem. The existing algorithm (based on Java codes in (Thimbleby 2003)) is modified for solving the proposed graph model, where one of the optimal routes was visually compared with the suggested route by Clear Roads. With discrete optimization techniques, it was found that the optimal routes (not unique) give the same efficiency index (EI) as the suggested route based on experience. In this perspective, the current research verified the optimality of the Clear Roads suggested route, but our approach can be used in a much complex setting (e.g., clearing a network of roads).

The research can be extended in at least two directions. The currently used algorithm does not prioritize any edges (such as ramps) that need to be cleared first. To impose additional priority constraints, it needs to solve the Chinese postman problem with priorities (Nilofer and Rizwanullah 2019) or the hierarchical Chinese postman problem (Ghiani and Improta 2000) & (Cabral et al. 2004). Using multiple trucks is a more challenging case and is known as the balanced k-Chinese postman problem, whose optimal routes need very different algorithms, which will be especially useful in clearing a larger network of roads in a crowded city.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Jun Liu, Ph.D. (Author), Yan Qi, Ph.D., P.E. (Author); Optimization Analysis: Jun Liu, Ph.D. (Author); Interpretation of Results: Jun Liu, Ph.D. (Author), Yan Qi, Ph.D., P.E. (Author); literature Review: Na Cui, Ph.D. (Author), Dave Bergner (Author); Draft Manuscript and Preparation: Jun Liu, Ph.D.

(Author), Yan Qi, Ph.D., P.E. (Author), Na Cui, Ph.D. (Author), Dave Bergner (Author). All authors reviewed the results and approved the final version of the manuscript.

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REFERENCES

- Allen, J. 2006. Fighting winter storms: a GIS approach to snow management. *Public Works*, **137**(6): 126-137.
- Blandford, B., Lammers, E., and Green, E. 2018. Snow and ice removal route optimization in Kentucky. *Transportation research record* 2672 (45): 294-304.
- Cabral, E. A., Gendreau, M., Ghiani, G., and Laporte, G. 2004. Solving the hierarchical Chinese postman problem as a rural postman problem. *European Journal of Operational Research* 155 (1): 44–50. doi:10.1016/s0377-2217(02)00813-5.
- Campbell, J. F., Labelle, A., and Langevie, A. 2001. A hybrid travel distance approximation for a GIKS-based decision support system. *Journal of Business Logistics* 22 (2): 165–181.
- Campbell, J., Langevin, A., and Perrier, N. 2015. Advances in vehicle routing for snow plowing. *in* Arc routing: problems, methods, and applications. *Edited by* Á. Corberán and G Laporte. Society for Industrial and Applied Mathematics, Philadelphia, PA. pp.321-350. doi.org/10.1137/1.9781611973679
- CIVIX L.L.C. 2020. *FleetRoute™*. Available from <http://www.fleetroute.com/k5/e.php> [accessed 4 March 2020].
- Damodaran, P., and Krishnamurthi, M. 2005. A continuous simulation model for snow removal. *International Journal of Industrial Engineering: Theory, Applications and Practice*, **12**(2): 189–199.
- Dowds, J., Sullivan, J., Novak, D. C., and Scott, D. 2016. Identifying best practices for snowplow route optimization. Clear Roads Report 14-07, Minnesota Department of Transportation, St. Paul, MN.
- Edmonds, J., and Johnson, E. L. 1973. Matching, Euler tours and the Chinese postman. *Mathematical Programming*, **5**(1): 88–124.
- Eiselt, H. A., Gendreau, M., and Laporte, G. 1995. Arc Routing problems, part I: the Chinese postman problem. *Operations Research*, **43**(2): 231–242. doi.org/10.1287/opre.43.2.231.
- Evans, J., and Minieka, E. 2017. *Optimization Algorithms for Networks and Graphs*, Second Edition, CRC Press, Boca Raton, New York. doi.org/10.1201/9780203744871.
- Fu, L., Trudel, M., and Kim, V. 2009. Optimizing winter road maintenance operations under real-time information. *European Journal of Operational Research*, **196**(2009):332– 341.
- Ghiani, G., and Improta, G. 2000. An algorithm for the hierarchical Chinese postman problem. *Operations Research Letters*, **26**(1): 27–32. doi:10.1016/s0167-6377(99)00046-2.
- Golbaharan, N. 2001. An application of optimization to the snow removal problem: A column generation approach. M.Sc thesis, Department of Mathematics, Linköping University, Linköping, Sweden.

- Holik, W. A., Crow, M., Schneider, W. H., and Miller, C. M. 2014. Winter maintenance asset allocation based on gis snow plow route optimization model. TRB 93rd Annual Meeting Compendium of Paper 14-1011. Washington D.C., 12-14 January 2014.
- Holmberg, K. 2014. Urban snow removal: modeling and relaxations. LITH-MAT-R, Issue 2014:08, Linköping University, Linköping, Sweden.
- Jang, W., Noble, J., and Nemmers, C. 2011. Optimizing winter/snow removal operations in modot st. Louis district – includes outcome based evaluation of operations. Final Report, No. Cmr1200 - 007, Missouri Department of Transportation.
- Kinable, J, Van hoeve W. J., and Smith, S. F. 2019. Snow Plow Route Optimization: A constraint programming Approach. IISE Transactions, DOI: 10.1080/24725854.2020.1831713.
- Kinable, J., Smith, S. F., and van Hoeve, W. 2015. Optimizing snow plowing operations in urban road networks. Final Report, No. DTRT12GUTG11, Technologies for Safety and Efficient Transportation Center, The National US DOT University Transportation Center for Safety, Carnegie Mellon University, Pittsburgh, PA.
- Kwan, M. K. 1962. Graphic Programming Using Odd or Even Points. Chinese Math **1**: 273-277.
- Limon, Y., and Azizoglu, M. 2018. New heuristics for the balanced k-Chinese postmen problem. International Journal of Planning and Scheduling, **2**(4): 331-349. doi:10.1504/IJPS.2018.10016594.
- Lin, Y., and Zhao, Y. 1988. A new algorithm for the directed chinese postman problem. Computers & Operations Research, **15**(6): 577–584. doi.org/10.1016/0305-0548(88)90053-6.
- Liu, M., Singh, H.K., and Ray, T. 2014. Application specific instance generator and a memetic algorithm for capacitated arc routing problems. Transportation Research Part C: Emerging Technologies, **43**(3): 249-266.
- Lum, O., Golden, B., and Wasil, E. 2019. OAR Lib: An open source arc routing library. Mathematical Programming Computation, **11**(3): 587-629.
- Moss, C. R. 1970. A routing methodology for snow plows and cinder trucks. Final Report, No. Ttsc 7015, Pennsylvania Transportation and Traffic Safety Center, Pennsylvania State University, University Park, PA
- Nilofer, M., and Rizwanullah, M. 2020. An implementation of Chinese postman problem with priorities. Journal of Intelligent & Fuzzy Systems, **38**(3): 3301-3305. doi:10.3233/jifs-190035.
- Orlin, J. B. 1997. A polynomial time primal network simplex algorithm for minimum cost flows. Mathematical Programming, **78**(2):109–129. doi:10.1007/BF02614365.
- Perrier, N., Langevin, A., and Amaya, C. A. 2008. Vehicle routing for urban snow plowing operations. Transportation Science, **42**(1): 44-56.
- Perrier, N., Langevin, A., and Campbell, J. F. 2007. A survey of models and algorithms for winter road maintenance. Part IV: Vehicle routing and fleet sizing for plowing and snow disposal. Computers & Operations Research, **34**(1): 258–294.

- Perrier, N., Langevin, A., and Campbell, J. F. 2006. A survey of models and algorithms for winter road maintenance: Part I: System design for spreading and plowing. *Computers and Operations Research*, **33**(1): 209–238.
- Pisinger, D., and Ropke, S. 2007. A general heuristic for vehicle routing problems. *Computers & operations research*, **34**(8): 2403-2435.
- Qi, Y., Bergner, D., Cui, N., and Mane, T. 2018. Manual of best practices and techniques for clearing intersection layouts. Clear Roads Report 14-03, Minnesota Department of Transportation, St. Paul, MN.
- Quirion-Blais, O., Trepanier, M., and Langevin, A. 2014. Addressing the challenges of planning snow plowing and salt spreading routes in a hybrid rural and urban network. TRB 93rd Annual Meeting Compendium of Paper 14-2039. 12-16 January 2014, Washington D.C.
- Schneider, W., Miller, T. M., and Holik, W. A. 2016. Route optimization. Final Report, FHWA/OH-2016-20, Ohio Department of Transportation, Columbus, OH .
- Soler, D., Martinez, E., and Mico, J. 2008. A transformation for the mixed general routing problem with turn penalties. *Journal of the Operational Research Society*, **59**: 540–547. doi.org/10.1057/palgrave.jors.2602385
- Thimbleby, H. 2003. The directed Chinese postman problem. *Software: Practice and Experience*, **33**(11): 1081–1096. doi:10.1002/spe.540.
- Tosca, S. 2015. Pennsylvania Department of Transportation's Snow Routes and Planning Process with GIS. GIS in Transportation, the Federal Highway Administration [online]. Available from https://www.gis.fhwa.dot.gov/newsletters/Newsletter_Jan2015.pdf [cited 9 March 2020]

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Figure 4 The visualization of the Clear Roads recommended route for clearing the DDI model in Fig. 2.

Figure 5 A non-symmetric DDI graph model

Figure 6 EI vs. ramp length and u-turn length

Figure 7 El vs left and right ramp lengths