Exhibit A (Research Proposal)

Snow Plow Route Analysis and Design for Lake County

Prepared for:

Lake County Division of Transportation

By:

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June 24, 2011
(revised June 28, 2011)

1. Introduction

Snow control is a key component of winter maintenance for many urban and regional public works agencies, especially in case of heavy snowfall. Winter road maintenance planning involves various decisions related to treating roadways, loading/unloading anti-icing materials on to the trucks, routing of snowplow vehicles for spreading chemicals and plowing roads, etc. Snow plowing in urban areas is particularly difficult and expensive due to the greater population densities and the lack of space for allowing snow to accumulate. Ensuring safe mobility for passengers and travelers, even in the worst of winter weather, is a difficult task which requires timely, expedient, and cost effective road maintenance, significantly affected by routing of snowplows. Such a routing problem becomes more complex when additional operational constraints are required.

Lake County Division of Transportation (LCDOT) currently runs a fleet of 25 snow plow trucks to cover about 800 lane-miles of arterial highways using 25 snow routes in Lake County, Illinois. A number of new technologies have recently been implemented to improve the efficiency of snow removal. For example, the plow trucks now pre-wet dry salt with a blend of beet juice mixed with salt brine and calcium chloride prior to discharge to reduce the amount of salt that needs to be used. Also, GPS units have been installed in all these snow plow trucks to better route the vehicles removing snow. An average snow route includes about 33 lane-miles and requires 5.7 tons of salt, and a snow plow truck normally travels about 50 miles to cover them (with about 20 miles of deadhead), incurring an efficiency (i.e., salting/plowing distance divided by total travel distance) of about 60%.

Despite all the technological improvements, the design and management of snow routes is still a challenge. For example, there are often multiple objectives and complex design requirements related to the snow route design problem. We not only want to minimize and balance cycle times (i.e., the time it takes to travel a route from the central yard and come back), but also want to maximize and balance individual route efficiencies. We will need to design snow routes that will work well for at least two storm scenarios: (a) short storm scenario, in which each truck travels to the snow route, makes one cycle and returns to shop; and (b) long storm scenario, in which each truck travels to the snow route, makes multiple cycles and gets materials at satellite salt locations. In addition, different routes have different traffic volumes and often slower travel times due to traffic congestion. Routes with heavy traffic (which varies with time of day) should be relatively shorter. Hence, we need to factor congestion into calculation of route cycle time. Finally, there are a number of complicating implementation issues that must be considered, such as (a) salting distance for a route must match truck capacity, (b) the trucks have only limited turn around locations at end of roads in the network, and (c) facilitation of tandem operations between adjacent routes on shared multi-lane sections.

The LCDOT currently uses a manual method to create new snow plow routes each year. The procedure is based on a tabular summation of route segments for dead head miles and salting miles for a round from the central shop and back. The impact of traffic congestion on route cycle time is not currently being considered. Due to the lack of systematic optimization, the workload across different snow routes differs significantly. For example, the lane-miles from route to route vary from 27.0 miles to 37.4 miles (39% relative difference) in the 2010-2011 snow season, while the truck cycle time varied from 1.5 hours to 3.1 hours (106% relative difference) in the 2000-2001 season. Previous trial of commercial software application (CASPER about 15 years ago) did not produce useable results either, in which initial snow routes seemed good but the final ones were completely segmented to pick up whatever was missed.

Snow control operations involve spatial activities, e.g. travel on roadways to/from depots, and hence geographic information systems (GIS) can provide the foundation for creating, maintaining and analyzing relevant data. A key component of the data is the road network; however, the basic spatial data needs to be enhanced with a variety of road and traffic attribute data to be useful for the analyses. This includes information on the length, width, and priority class for each highway in the network, detailed information on interchanges, intersections, bridges and other special features, as well as traffic information such as volumes, speeds, delays at intersections, etc. In addition to the road data, information is needed on the available equipment, including the type of vehicle, operating characteristics and depot location; as well as the materials, including amount available and locations. Therefore, GIS-based decision support systems are potentially useful to optimize snow routes for chemical spreading and snow plowing operations. Using optimization techniques for optimal snowplow route planning and taking advantage of GIS applications to visualize the optimized routes will help maintenance engineers to effectively determine efficient snow removal plans in urban and regional highway operations organizations.

With the rapid advancement of computing techniques and software platforms (e.g., GIS), the Lake County Division of Transportation would like to have developed and implemented a state-of-the-art snow routing software application for its annual snow route analysis and design. The software should help county engineers and experts evaluate snow plow options (such as salt usage, vehicle capacities, fleet size, plowing time during the day) and provide snow route recommendations such that experts can still fine tune the results, by applying judgment.

2. Goals & Objectives

The goal of this project is to provide a computer software tool which uses a combination of user-set and fixed input parameters to optimize a set of snowplow routes based on selected level of service (LOS) measures. User-set input parameters may include the county highways to be salted and their individual lane-miles, the number of trucks and their individual salt carrying capacity, salt satellite locations, salt application rate, choice of treatment scenario (one treatment scenario as well as continuing treatment scenario), and time of the day. Fixed input parameters may include the maximum plowing/salting speed (e.g., 30 mph), the maximum travel speed without salting (e.g., the posted speed limit), plowing/salting speed and travel speeds lowered by traffic delays, and home base locations.

Level of Service measures can be divided into two categories: Primary and Secondary. The primary LOS measures can include average cycle time per route (hours/route), variance in cycle time, maximum cycle time, or minimum cycle time. Secondary LOS output of interest, in terms of "system totals," may include the total plowed mileage, the total deadhead mileage, or the total travel mileage. For "each route," the LOS output can include the total plowed mileage, the total deadhead mileage, the total travel mileage, the route cycle time, the route efficiency (plowed mileage divided by total travel mileage), the salt consumption, truck storage capacity utilization, or delay measure. The LOS output can also be used by decision makers to conduct "what if" analyses on resource allocation and budgeting.

The specific objectives of this project include:

1. Complete the literature review of applications of snow route design;
2. Conceptualize and formulate the snow routing problem with properly defined decision variables, input parameters, operational constraints, and system-wide performance measures of interest;
3. Develop suitable solution techniques to analytically obtain an optimal set of snow plow routes for the Lake County highway system;
4. Develop a GIS-based software module, with both optimization and visualization capabilities, to support snow route design in various user-specified scenarios, and integrate the software module with Lake County's existing GIS platform;
5. Prepare a final report to document the literature review, methodologies (model formulation and solution algorithm) and software details (e.g., user's guide).

3. Literature review

There have been some software applications with embedded heuristic approaches to find the optimum snow route solutions in urban areas. This section summarizes the related literature regarding the existing commercial software and research efforts on snow route analysis and design. Depending on the size of the problem and the significant operational constraints, each approach/system has advantages and limitations.

3.1. Commercial Software

RouteSmart.[1] This software includes a snow removal and street sweeping application software built within the ESRI ArcGIS platform. The route planning tool is provided for cities and municipalities of all sizes. Building upon integrated street data, the system allows the user to set up the number of passes, and snowplows for each street. Then, the user needs to determine the service priority for critical roadways (so as to ensure that those streets will be cleared). The user can define how quickly salt should be spread (flow/intake rate), the distance of each service location from the street, and determine how much trash (in case of sweeping) is being collected. The system computes the street sweeping routes (and street service layers), constrained days and times, and service to each side of a street. The system accounts for intermediate trips and considers a total fleet operating budget as well. It provides graphical route plans as well as tabular/chart reports for "what if" scenarios. According to the available literature and demos, however, it seems that the system does not utilize information on traffic control and traffic growth, which is an important goal of the LCDOT Snow Route Analysis and Design project. In addition, the goals and criteria considered in this software will not be suitable for the objectives and constraints needed for the Lake County Snow Route Analysis and Design Project.

Caliber.[2] Caliper Corporation developed an "Automated Snow Plow Routing Application" for Hennepin County Department of Public Works, Minnesota in 1999. Building upon Caliper's TransCAD transportation planning software, this application tries to increase the level of service and decrease operating costs by reducing snow plow deadheads. It also attempts to create routes that balance cycle times. Reports generated by the application include route descriptions that list highways to be serviced in a single route, the number of trucks assigned to this route, the starting truck station, the service time and the deadhead time. The routing procedures, along with a user interface and a geographic database which feature state and county highways, provide the basis for planning and managing snow removal operations. Unfortunately, it seems that the system does not consider traffic control information, traffic congestion effect, or specific constraints/options that address specific user needs.

C2Logix.[3] The "FleetRoute" is a vehicle routing software introduced by C2Logix for snow/disposal removal, meter readers, etc. It uses available local city GIS datasets and considers different priority levels of different roads, turning maneuvers at an intersection, side of street serviced, multi-lanes, and one-way roadways. The system was implemented by a disposal/removal company, Emerald Coast Utilities Authority (ECUA), in Pensacola, Florida in 2008. ECUA, with its fleet trucks, provides solid waste and yard trash collection to residential properties and commercial businesses within the unincorporated areas of Escambia County, Florida. The fast-tracked implementation of the FleetRoute optimization software was reported to result in balanced routes, reduced overtime, increased trash/recycling collection efficiency, and easier integration of new clients to existing routes. Unfortunately, it seems that the system again does not include traffic control information and traffic congestion information, the level of service for snow plowing operations, and sophisticated operational requirements, which are important components of the LC DOT Snow Route Analysis and Design project.

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[1] More information and a demo can be found at http://www.routesmart.com/publicworks.aspx.
[2] More information is available at http://www.caliper.com/Press/pr990104.htm.
[3] More information is available at http://www.c2logix.com/software/fleetroute, http://www.c2logix.com/industries/vehicle-routing-software-planning-routes-snow-plowing-truck-routing, and http://www.prweb.com/releases/C2RouteApp/Launch/prweb5163804.htm.

3.2. Other States' Efforts

Haghani and Qiao (1981) developed a decision support system for the Maryland State Highway Administration Office of Maintenance to design snow emergency routes for Calvert County, MD. This research focused on the design of the salting trucks routes. A mathematical optimization model was developed in the form of a capacitated rural postman problem, and a number of different heuristic algorithms were employed to solve the problem. Overall, this model formulation is rather simplistic for our purpose, as the LCDOT Snow Route Analysis and Design project includes higher complexities and more operational constraints.

Wang et al. (1995) developed a decision support system for Indiana DOT to improve snow and ice control service route design. This Computer Aided System for Planning Efficient Routes (CASPER) includes a multi-objective heuristic optimization method to find routes with optimal serviceability and efficient resource usage. It integrates a spatial network database (GIS/CAD) model and an interactive user interface. It has been implemented during winter 1992-1993 in three INDOT districts. Given a pre-designated partition of the service network, which are to be served by multiple vehicles from a single depot, and given detailed information on the serviceability of that sub-network (i.e., travel speeds as a function of service type, maneuverability at intersections, direction restrictions, etc.), CASPER determines the minimum number of routes needed to cover the sub-network to a pre-determined level of service, as well as the specific configuration of those routes. However, due to the complexity of the route design process, it is essential that the CASPER design tool be used by individuals having a detailed understanding of the problem. The system imposes considerable demand on user training and support by requiring the user to gain familiarity with the details of the CASPER computation environment. Therefore, it will be better to develop a system with less complexity of user inputs. Also, it seems that traffic control and traffic congestion information, as well as specific user constraints/options are not allowed by this system.

Tomaselli (1999) used GIS to analyze snowplow routing and facility location in four counties of Minnesota. Variations in speed, the number of lanes, the number of plows per route, cycle times, and plowing priorities are examples of the factors that were required as input information. The objectives were to effectively allocate snowplows to existing garages, and optimally utilize, close, or build garages. The goals and criteria considered in this project will not be suitable for the objectives and constraints of Lake County Snow Route Analysis and Design.

Later, Wilson et al (2003) developed a simulation model of snowplow operations for Minnesota DOT (MnDOT). The objective of this model was to help managers determine snow route length, assignment of snowplows to routes, placement of reloading points, and the collection of labor and material cost in "what-if" scenarios. Creating this model depended on input from experienced operators, internal management reports, and archived Road and Weather Information Systems (RWIS) data. This simulation model was successful in identifying key variables, determining the operational rules and logic, developing a user interface, and designing model flexibility for future development through Excel spreadsheets. However, model validation with field data remained an unresolved problem.

The Midwest Transportation Consortium (MTC, 2002) used GIS and AI techniques to develop an intelligent snow removal asset management system (SRAMS) for Iowa DOT. The system was evaluated through a case study in Black Hawk County, Iowa. The system required roadway data to support the allocation of routes, drivers, and other resources. Therefore, a GIS database for all roads in the case study area (Black Hawk County, Iowa) was obtained from the Iowa DOT in the form of a GIS shapefile and several related database files (with traffic volumes, roadway inventory information, etc). The main factors to be considered in improving the allocation of snow removal assets were annual average daily traffic (AADT), route prioritization, the number of lanes, operation time for each vehicle, pavement type (concrete or bituminous), availability of vehicles and drivers, treatment of roads with salt/sand, and the minimum snowfall thresholds to mobilize equipment. Snowplows, operators, and materials are resources for the snow removal process; therefore, once the routes are created, snowplows are assigned to each route. The system could be used to generate visualized snowplowing routes that optimize the allocation of plowing assets and track materials (e.g., salt and sand). A test of the system indicates an improvement in snowplowing time (by 1.9 percent for moderate snowfall and 9.7 percent for snowstorm conditions) over the current manual system. However, this system has the following limitations: (a) as the system is rule-based, an artificial intelligence tool is used to create the knowledge-base (Visual Studio 2.2) which require constant manual handling by the operators; (b) the ratio of costs to benefits of the asset management plan of the expert system can be further improved via the adoption of optimization techniques; and (c) the use of artificial intelligence techniques (e.g. neural networks or fuzzy systems) might require prediction of future conditions (e.g., meteorological changes and road conditions) based on current real-time data and stored historical data.

Later, MTC (2005) implemented a web-based Winter Maintenance Decision Support System (WMDSS) that enhances the capacity of stakeholders (city/county planners, resource managers, transportation personnel, citizens, and policy makers) to evaluate various procedures for optimally managing snow removal assets. This was accomplished by integrating geospatial analytical techniques (GIS and remote sensing), existing snow removal asset management systems, and web-based spatial decision support systems. The information on snow removal procedures is gathered and integrated into the system in the form of encoded business rules. The developed system is not only capable of managing the resources but also provides comments to help complex decision making, e.g. routing, optimal resource allocation, etc. This system was developed in collaboration with Black Hawk County, IA, the city of Columbia, MO, and the Iowa Department of Transportation. Various routes are color-coded according to priority to present the route information. Remote sensing technique is used to address the issues associated with the transportation infrastructure data collection methods (e.g. extensive field work, traffic disruptions, inefficient use of time, etc.). Considering the remote sensing approach as a means of data collection, it seems that the system does not include information on traffic control and traffic growth. Furthermore, this system does not taken into account the level of service or other user-specific operational constraints.

3.3. Modeling and Research Efforts

NCHRP Project 6-17 (Hanna et al., 2009) identified various measures to evaluate the performance of snow and ice removal activities. Some of these frequently used performance measures in this context include friction, time to bare pavement, etc. However, comparisons within and among jurisdictions require a common, reliable, repeatable performance measure along with a methodology to collect and report relevant data. The criteria that could be used to evaluate the performance measures include (a) the ability to directly measure safety, mobility, or public satisfaction; (b) the sensitivity to storm characteristics; and (c) the potential to improve snow and ice control operations. In addition, budget and staffing constraints make it difficult for state and local agencies to adopt new technologies to measure performance (e.g. use of friction meters). According to a survey, the most preferred performance measures are generally those related to accounting and statistics, including length of plowed roadway, consumed personnel and overtime hours, used material and equipment, and cost of operations. Use of automated vehicle location (AVL), global positioning system (GPS), friction meters, road weather information systems (RWIS), etc. would potentially facilitate data collection and improve performance measurements.

In 2004, Sochor and Yu (2004) developed heuristic algorithms to route snowplows after snowfalls. The objective was to develop and implement an algorithm to find a combination of routes which minimize the total system cost. The algorithm calculates a lower bound to the problem using a Lagrangian relaxation approach. A standard sub-gradient approach is used to find near-optimal dual variables to be sent to a column-generation program which returns the routes for the snowplows. A greedy heuristic is developed to choose a feasible solution, which gives an upper bound to the problem. This method for routing snowplows produced satisfactory results for relatively small problems (as compared with those presented in Golbaharan, 2001). However, an interesting experiment result showed that the allocation of vehicles in which certain depots were frequently over- or under- utilized. This suggests that the quantity and/or distribution of available vehicles may not be optimized. In addition, this system just considers a simple optimization formulation based on a standard set covering model, which includes only the cost of the used routes and penalty cost for using extra vehicles from the depots. In additional, other important factors such as dynamic traffic operations, delays at intersections are not considered. Therefore, this model formulation does not include all the requirements and constraints needed for the LC DOT Snow Route Analysis and Design project.

Perrier et al. (2006, 2007a) surveyed mathematical models and algorithms for winter road maintenance, including spreading of chemicals and abrasives, snow plowing, loading snow into trucks, and hauling snow to disposal sites. Most problems are formulated into vehicle routing problems in order to determine a set of routes, each covered by a vehicle that starts/ends at its own depot, in a way that all road segments will be served under a set of operational constraints. The variable costs include the costs of fuel, crew, vehicle maintenance, material, vehicle/material depots; and, costs of spreaders, plowing, equipment, and vehicle/material depots constitute the fixed costs. The objectives include minimizing deadheading and the fixed costs of vehicles and depots, minimizing fleet size, minimizing alternations between deadheading and servicing, and minimizing operational constraint violations. Three types of meta-heuristic approaches (i.e., simulated annealing, tabu search, and elite route pool) have been applied to such vehicle routing problems.

Perrier et al. (2007a, 2007b) also surveyed the snowplow depot location problem and the fleet sizing/replacement problems, which determine the location of snowplow depots and the number of dispatched plows to clear the roadways under a level of service requirement for each road class. In vehicle fleet replacement, there is a tradeoff between minimizing maintenance costs for keeping older vehicles and minimizing expenses for newer vehicles. The Bureau of Management Consulting, Transport Canada (1975) has proposed a basic replacement model to determine the cost of replacement for snow/ice control vehicles, while the objective function seeks to minimize the hourly cost for the use of the vehicle during cumulative hours.

Perrier et al. (2008) introduced an optimization model formulation and two heuristic solution approaches to find the optimum routing of snowplow vehicles in urban areas. The case study includes a district and a single depot for a number of snowplows. The objective is to find a set of routes, each performed by a single vehicle (starts and ends at the district's depot), in a way that all road segments are served in a minimum service time under several operational constraints. The model is based on a multi-commodity network flow structure to ensure the connectivity of the route covered by each truck. The model developed in this paper needs further modification so as to be useful for practical purposes. Each road segment should be associated with three traversal times, which might depend on the vehicle type, the time required to plow the road segment, the time of deadheading the road segment if it has not yet been plowed, and the time of deadheading the road segment if it has already been plowed. In addition, the model currently did not consider the possibility of serving multi-lane road segments anywhere in the sequence in order to reduce the service completion time.

4. Methodology and Data Needs

4.1. Software System Architecture

The snow route analysis and design system will be developed in the form of an application module and embedded in LCDOT's GIS platform, as illustrated in Figure 1. This extension consists of a user interface and an optimization model. The user interface in GIS environment includes two sets of input parameters, i.e., user-set and fixed input parameters. As discussed earlier, the user-set input parameters may include the county highways to be salted, the number of trucks, salt satellite locations, time of day, etc., while fixed input parameters may include the maximum plowing/salting speed, maximum travel speed without salting, maximum plowing/salting speed and travel speeds lowered by traffic delays, etc.

These parameters are the input data to the route optimization model which will be developed outside of the GIS system and then embedded/customized in ESRI ArcGIS. After running the optimization module, the resulting snowplow routes will be highlighted on GIS network map, and the level of service and system performance measures (both primary and secondary measures) will be reported. As mentioned earlier, this service level output can also be used by decision makers to conduct "what if" analyses on resource allocation and budgeting.

4.2. Preliminary Model Formulation and Solution Algorithms

Let S be the set of road segments to be plowed. Because a segment may need to be passed multiple times in the scheduling horizon (i.e., a cycle), we define a task as a single pass on a segment. So every segment $s \in S$ has a set of tasks, denoted as $I_{\text{Seg},s}$. Let $I = \bigcup_{s \in S} I_{\text{Seg},s}$ be the set of tasks on all segments. Let $t_{\text{task},i}$ be the duration of task $i \in I$, i.e., the time needed to perform the task. Let l_i be the length of task $i \in I$, which is proportional to the quantity of salt needed for the task. Let K be the set of snow plow vehicles, and L_k be the maximum road length that vehicle $k \in K$ can salt. L_k is determined by the salt capacity of vehicle $k \in K$.

Every road segment has two endpoints. The snow plow vehicle starts to perform a task from one endpoint, and completes the task at the other one. The two endpoints cannot be represented by the same spatial node, and thus we need to decide from which endpoint the vehicle starts a task (i.e., the direction for the vehicle to perform a task). In the model, the two possible directions of a task are represented by two directed arcs in opposite directions between the two endpoints. Let E be the set of all directed arcs, and E_i be the set of arcs representing the direction of task $i \in I$ (a task only has two possible directions so $|E_i| = 2$). Let $t_{\text{travel},e_1 e_2}$ be the travel time from the head of arc $e_1 \in E$ (i.e., the finish point of the corresponding task) to the tail of arc $e_2 \in E$ (i.e., the start point of the corresponding task).

Let D be the set of depots. Both the start location and the end location of the route of a vehicle must be at a depot. In one-cycle scenario, there is only one depot, which is the home base. In multiple-cycle scenario, both home base and satellite facilities are depots. We assume that the start depot and the end depot of a vehicle can be different, and a vehicle can reverse its route in the next cycle to return to its original depot. Every depot is represented by an extra arc which is added to E. Both endpoints of such arc are at the location of the corresponding depot. In this way, the travel time from a depot to any other arcs can be defined.

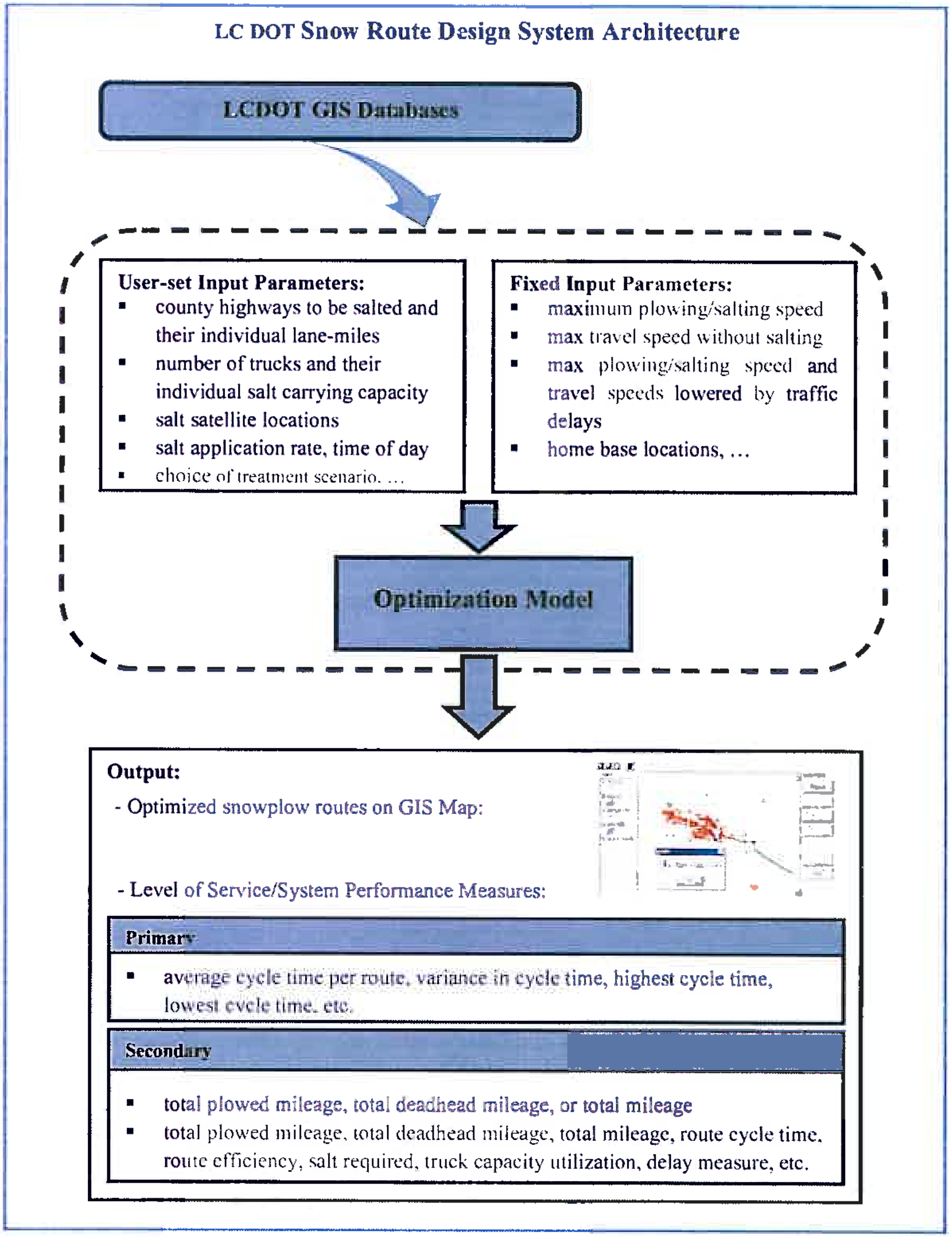

Figure 1. Snow Plow Route Design System Architecture.

Let $\mathbf{x} = \{x_{e_1e_2k} : e_1, e_2 \in E, k \in K\}$ be the set of binary decision variables for the movements of vehicles; i.e., $x_{e_1e_2k} = 1$ if vehicle $k \in K$ travels directly from the head of arc $e_1 \in E$ to the tail of arc $e_2 \in E$; and 0 otherwise. Let $\mathbf{u} = \{u_i : i \in I\}$ be the set of real-valued start times of tasks; i.e., u_i represents the start time of task $i \in I$. Without losing generality, let the scheduling horizon start at time 0. Let U be the horizon length as well as the end time of the scheduling horizon. Let $y_{ik} = \sum_{e_1 \in E_i} \sum_{e_2 \in E} x_{e_1e_2k}$. Then $y_{ik} = 1$ if task $i \in I$ is assigned to vehicle $k \in K$, or 0 otherwise.

Let z be the longest individual cycle time. A smaller z indicates a better level of service (LOS). By minimizing z, the model automatically tends to balance the workload among vehicles. Besides z, we probably also would like to minimize the total travel time of all vehicles in order to reduce the fuel consumption. Let c_{LOS} and c_{fuel} be respectively the weight of z and the weight of total travel time in the objective function.

The snow plow routing problem (SPRP) model can be formulated as follows:

$$\text{(SPRP)} \quad \min c_{\text{LOS}} z + c_{\text{fuel}} \sum_{k \in K} \sum_{e_1 \in E_i} \sum_{e_2 \in E} t_{\text{travel},e_1e_2} x_{e_1e_2k}, \tag{1}$$

s.t.

$$\sum_{e_1 \in D} \sum_{e_2 \in E} x_{e_1e_2k} = 1, \qquad \forall k \in K, \tag{2}$$

$$\sum_{e_2 \in E} x_{e_1e_2k} - \sum_{e_2 \in E} x_{e_2e_1k} = 0, \qquad \forall e_1 \in E \setminus D, k \in K, \tag{3}$$

$$y_{ik} = \sum_{e_1 \in E_i} \sum_{e_2 \in E} x_{e_1e_2k}, \qquad \forall i \in I, k \in K, \tag{4}$$

$$\sum_{k \in K} y_{ik} = 1, \qquad \forall i \in I, \tag{5}$$

$$u_i + t_{\text{task},i} + t_{\text{travel},e_1e_2} + U(x_{e_1e_2k} - 1) \le u_j, \qquad \forall e_1 \in E_i, e_2 \in E_j, i, j \in I, k \in K, \tag{6}$$

$$\sum_{i \in I} l_i y_{ik} \le L_k, \qquad \forall k \in K, \tag{7}$$

$$z \ge \sum_{i \in I} t_{\text{task},i} y_{ik} + \sum_{i \in I} \sum_{e_1 \in E_i} \sum_{e_2 \in E} t_{\text{travel},e_1e_2} x_{e_1e_2k}, \qquad \forall k \in K, \tag{8}$$

$$x_{e_1e_2k} \in \{0,1\}, \qquad \forall e_1, e_2 \in E, k \in K. \tag{9}$$

Objective (1) minimizes the total costs. Constraints (2) and (3) enforce flow conservation. Constraints (4) define variables $\{y_{ik}\}$. Constraints (5) require every task should be performed exactly once. Constraints (6) establish the relationships between task start times and vehicle routes, as well as eliminate subtours. Constraints (7) require the total road length salted by a vehicle should not exceed its salt capacity. Constraints (8) define the longest individual cycle time z. Constraints (9) define binary variables $\{x_{e_1e_2k}\}$.

SPRP is a vehicle routing problem (VRP), which is usually solved using constructive heuristics and local search algorithms. Constructive heuristics build a solution from scratch, while local search algorithms improve an existing solution. Constructive heuristics proposed for VRP includes "I1" by

Solomon (1987), where every route is initialized with a "seed" activity and the remaining unscheduled activities are added to the route until its total duration reaches the scheduling horizon. A parallel version of I1 by Potvin and Rousseau (1993) initializes all routes at once and then adds the remaining unscheduled activities one by one. Another I1-based algorithm by Ioannou et al. (2001) inserts activities in a way that the impact on all customers is minimized. A comprehensive review can be found in Braysy and Gendreau (2005). For large-scale routing and scheduling problems with many side constraints, constructive heuristics may be more customized and complex.

Local search algorithms proposed for VRP includes two categories of most commonly-used neighborhood structures: node interchange and edge interchange. Node interchange includes "insertion" or "relocation" (Savelsbergh, 1992), "exchange" or "swap" (Savelsbergh, 1992), CROSS-exchange (Taillard et al., 1997), and ejection chain (Glover, 1992). Edge interchange includes n-opt* (Potvin and Rousseau, 1995), n-opt (Russell, 1977), and Or-opt (Or, 1976). Besides these two neighborhood structures, many other structures are also developed, such as GENI-exchange (Gendreau et al., 1992) and cyclic transfers (Thompson and Psaraftis, 1993). A comprehensive review can be found in Braysy and Gendreau (2005) and Funke et al. (2005).

The implementation of a heuristic usually requires customized algorithm design based on the characteristics of the specific problem, and its computational performance highly depends on the problem structure and even the input data. Therefore, although the algorithms developed by previous studies can serve as useful references, it is very important to adapt and further improve them for the SPRP.

5. Work Plan and Deliverables

This project will be carried out in four phases. It will start on August 16, 2011 and end on August 15, 2012. The detailed schedule for the project is included in Table 1.

Phase 1 – Literature Review and Data Preparation
A thorough literature review on snowplow route analysis and design will be completed in this phase. It will include information on practical and theoretical developments, including model formulations (e.g., decision variables and input parameters), solution techniques, and finally advantages and disadvantages of existing applications. In this phase the needed datasets (e.g., GIS roadway network, traffic information) will be reviewed with and obtained from LCDOT. This phase starts on August 16, 2011 and ends on October 15, 2011.

Phase 2 – Develop the Mathematical Model Formulation
In this phase, mathematical models and solution algorithms will be developed for the snowplow routing problem. The formulation will consider all the operational constraints specified by LCDOT. The algorithm will be implemented into a standalone executable file with proper input and output interfaces. The models and algorithms will be validated using field data obtained from LCDOT. This phase starts on October 16, 2011 and ends on February 15, 2011.

Phase 3 – Develop and Implement the GIS Software Module for LCDOT
In this phase, a GIS module will be developed in the ESRI ArcGIS environment. This module will include the developed optimization program and a user interface for snowplow route analysis and design. The module will allow two different storm scenarios (i.e., short-storm and long-storm analyses) and a set of user-specified input variables. The optimized routes will be calculated through the computational module, and the results will be visually displayed on a GIS map. The model and

computer system shall be tested with full-scale field data during Summer 2012. The comments from LCDOT will be utilized to further refine the product before the final submission by August 15, 2012. This phase starts on February 16, 2012 and ends on July 15, 2012.

Phase 4 – Final Technical Report

The final report on the project (including a user's guide) will be prepared in this phase, from July 16, 2012 to August 15, 2012.

The detailed timeline for this project is summarized in Table 1.

Table 1. Detailed schedule of the project

Task Description	**Timetable**
Phase 1	**August 16, 2011 - October 15, 2011**
Review the appropriate literature on methods of analysis	August 2011
Review data needs and obtain data from LCDOT and complete data cleansing and preparation	September - October 2011
Phase 2	**October 16, 2011 - February 15, 2012**
Develop the analytical model formulation	October 16 - November 15, 2011
Model validation using the obtained data from LCDOT	November 16, 2011 - February 15, 2012
Phase 3	**February 16 - July 15, 2012**
Develop an embedded GIS software application for LCDOT to perform the route analysis and design	February 16 - June 15 2012
Field test the software application in LCDOT	June 16 - July 15, 2012
Phase 4	**July 16 - August 15, 2012**
Final technical report preparation	July 16 - August 15, 2012

The proposed research will develop a computer software tool that optimizes a set of snowplow routes for Lake County. The results will help Lake County automate the analysis and design of snow routes. The deliverables for this project are as follows:

1. New mathematical models and solution algorithms for snow route design;
2. New GIS-based software module, with both optimization and visualization capabilities, to support snow route design in various user-specified scenarios;
3. Technical report and user's guide that document the literature review, methodologies and software details.

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Exhibit B (Budget)

A budget of $68,304 is proposed. Two graduate students will be working with the PI to cover the outlined tasks. The detailed budget breakdown is listed below.

Sponsor: Lake County Illinois
Principal Investigator: Yanfeng Ouyang
Title: Snow Plow Route Analysis and Design for Lake County
Project Period: August 16, 2011 - August 15, 2012

Budget

A. Senior Personnel				
	Prof. Ouyang	1.0 mos.	$	10,250
B. Other Personnel				
	Post Doctoral Research Associate	0.0 mos.		-
	Research Assistant - Post BS	0.0 mos.		-
2	Research Assistant - Post MS	11.0 mos.		42,963
	Research Assistant - Post Prelim	0.0 mos.		-
	Hourly	0.0 hours		-
	Total Salary and Wages			53,214
C. Fringe				
	Academic 35.59%, RA 6.36%, Hourly 7.79%			6,381
	Total Personnel			59,594
D. Equipment				
E. Travel				
	Domestic			-
	Foreign			-
G. Other Direct Costs				
	Materials and Supplies			1,000
	Travel			1,500
	Publications			
	CS Service			-
	Services			-
	Tuition – N/A			-
	Total Other Direct Costs			2,500
Total Direct Costs				62,094
I. Indirect Costs				
	Facilities and Admin. 10% of TDC			6,209
	Total Project Cost		$	68,304