OPTIMIZING SNOWPLOW ROUTES: FORMULATION AND IMPLEMENTATION

by

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Abstract

In this thesis, a new methodological framework was proposed and developed to address several important issues pertaining to snowplow route optimization. The framework defined an extensible snowplow trucks plow-with-precedence problem and captured the impact of the service order of snowplow routes. The tabu search algorithm was used to search for near-optimal routing priority arrangements that balanced the workload between trucks efficiently. The efficiency of the proposed framework was then tested in two case studies: 1) snowplow route optimization in a simulated connected vehicle (CV) environment and 2) a real-world application of snowplow route optimization in Perth County.

The first case study provides a proof of concept for snowplow route optimization in a simulated connected vehicle (CV) environment. In the CV environment, it was implicitly assumed that wireless communication technology can capture the traffic states on the road in real-time (e.g., the road users' on-route strategies and dynamic travelling decisions), and allows for deep insight into designing user centric winter maintenance strategies. The goal was to minimize both the total travel time of the traffic system and the operating time of the longest truck route. A simulation-based approach was used to simulate real-time communications between the road users and the truck operators in the CV environment. The results suggest that the dynamic routing strategy could save 97.4 hours in total system travel time when compared to the no snow condition. The amount of reduction in the total system delay for a given number of trucks used in plowing operations. The amount of reduction in the total system traffic delay was reduced by 39.3 hours when the number of snowplow trucks in the fleet increased from one to two. As the fleet size increased, the marginal benefit decreased until it became negligible.

Besides contributing to the theoretical expansion of winter maintenance operations, the second case study attempts to optimize snowplow routes by implementing realistic constraints on a real road network in Perth County, Ontario. The primary goal of this case study was to develop efficient plow routing strategies that could make the combined operations more efficient by sharing plow routes and by sharing, or eliminating, material storage yards while taking into account operational constraints. The results indicated that the average route length can be reduced by 3.2% without the changing service boundary or sharing depots. The results also found that by sharing depots, the county could retire 3 depots and 8 trucks without impacting their practical requirements.

Preface

Work presented in this thesis is either accepted, published or is under-review for publication in various journals and conferences in the areas of transportation engineering.

Peer-reviewed Journal & Conference Papers (Published)

1. **Xu, S.**, & Kwon, T. J. (2020). Optimizing Snowplow Routes using All-New Perspectives: Road Users and Winter Road Maintenance Operators. Canadian Journal of Civil Engineering. **Just-IN** https://doi.org/10.1139/cjce-2019-0768.
2. Li, Y., **Xu, S.**, Wu, L., AbouRizk, S., Kwon, T. J., & Lei, Z. (2019). A generic simulation model for selecting fleet size in snow plowing operations. Proceedings of the 2019 Winter Simulation Conference (WSC) (pp. 2966-2977). IEEE.

Technical Project Report (submitted)

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Nomenclature

G = A directed graph representing road network

V = Set of nodes at the road network, consisting of $\{0,i,j,\ldots\}$

A = Set of arcs at the road network, consisting of arc such as arc (i,j)

M = A sufficiently large number

$x_{i,j,k,t}$ = A binary variable for plowing decision of the truck k at step t, i.e. 1=if the arc (i,j) is plowed by truck k at step t; 0=otherwise

$y_{i,j,k,t}$ = A binary variable for deadhead decision of the truck k at step t, i.e. 1=if the arc (i,j) is deadheaded by truck k at step t; 0=otherwise

$\Psi i,j,k,t$ = A binary variable for decision of the truck k at step t, i.e. 1=if the arc (i,j) is plowed or deadheaded by truck k at step t; 0=otherwise

$T_{i,j}$ = The time needed for plow truck to transverse the arc (i,j)

$(0,0')$ = The hypothetical arc used represents the termination state of truck, and the terminal state was represented by the truck deadhead at the arc (0,0') (e.g., $y_{0,0',k,t}=1$).

d_k = The duration of truck k to complete the route

$\bar{d}$ = The average duration of k trucks to complete the route

d_{max} = The maximum duration of k trucks to complete the route

T_{max} = The upper limit of working hours for snowplowing truck.

α = Parameter used to balance the workload

λ = The weight for the longest tour time on the objective function (the default value is 50)

$k_{jam}(i,j,t)$ = The jam density for the arc (i,j) at step t

$v_{free}(i,j,t)$ = The free flow speed for the arc (i,j) at step t

$D(i,j,\tau)$ = The traffic demand from node i ending at node j at moment τ

$Q_{in/out}(i,j,\tau)$ = The accumulated vehicle counts driving in/out arc (i,j) at moment τ.

$Q(i,j,\tau)$ = The traffic counts in the arc (i,j) at moment τ

$k(i,j,\tau)$ = The traffic density in the arc (i,j) at moment τ

$t(i,j,\tau)$ = The time needed for road users to transverse from i to node j at moment τ

m = The next node for $D(i,j,t)$ at time instance t, this choice can be affected by user's routing preference.

τ = The simulation time for the system, consists of $\{0, \Delta\tau, \ldots, \tau_{max}\}$.

$\Delta\tau$ = Time step for the simulation

τ_{max} = The maximum time for the simulation process

$k_{jam}(i,j,\tau)$ = The jam density for the arc (i,j) at moment τ, which is affected by snowplow order

$V_{free}(i,j,\tau)$ = The free flow speed for arc (i,j) at moment τ, which is affected by snowplow order

$Left\_Turn$ = The number of left turns in the routes

U_Turn = The number of U-turns in the routes

$Right\_Turn$ = The number of right turns in the routes

$RDClass_{i,j}$ = The road class of the arc (i,j)

S = Set of serviceability of trucks, consisting of $\{S_1, S_2, \ldots\}$

δ = Set of depots, consisting of $\{\delta_1, \delta_2, \ldots\}$

SP = Shortest path

$l_{i,j}$ = The length of arc (i,j)

T_k = The maximum step for the truck K finishing serving the road network

Chapter 1. INTRODUCTION

1.1 Background

Developing efficient snow and ice control strategies is not only at the core of winter transportation management, but also an application exercise in the field of route optimization. As adverse winter weather events occur more frequently, many countries face significant challenges due to increased material (chemicals, abrasives, etc.), fuel, and maintenance costs. Snow accumulation on roads limit the handling and stopping ability of vehicles, posing serious safety issues by increasing the risk of collisions and causing traffic delays (Andrey, Mills & Vandermolen, 2001; Hranac et al. 2006; Usman, Fu & Miranda-Moreno, 2010). Existing studies suggest that heavy snowfall can reduce free-flow speeds on highways by up to 40% compared to normal weather conditions (Manual 2000). What's more, a survey conducted by Andrey, Mills and Vandermolen (2001) suggested traffic collisions can increase by up to 75% in adverse weather (rainfall and snowfall). In order to mitigate the congestion and traffic collision caused by adverse weather, it is important to execute the snow and ice control strategies carefully and effectively to restore the snow-covered road to bare pavement conditions (Blandford, Lammers & Green, 2018; Dowds et al., 2013; Miller et al., 2018;). Typical snow and ice control strategies focus on removing snow and ice from the roadway and spreading materials such as chemicals or abrasives over a given service area to increase the road friction via a hub-and-spoke system whereby multiple trucks work from a central hub. Two other winter road maintenance (WRM) strategies for controlling winter road surface conditions are anti-icing and de-icing. While de-icing operations are performed to melt snow or ice, anti-icing operations offer a sustainable way of keeping the roads clear of snow and ice by applying chemicals onto the road surface prior to snow events (Fu et at., 2012). Anti-icing chemicals prevent water from freezing and compacting into a hard layer that is not only difficult to remove, but could also turn into black ice with increased risk of vehicular collisions (Blackburn et al., 1994).

Of the various WRM operations being used to date, the snow plowing operation has been acknowledged as one of the most important snow and ice control strategies and is often at the forefront of any winter maintenance system. Properly utilized and efficiently executed snow plowing operations can dramatically alleviate the disruptive impact caused by snowstorms, and improve the overall traffic safety and mobility during winter months (Dong, Hallmark & Zhang, 2019). A study conducted by Usman, Fu and Miranda-Moreno (2010) showed that the average number of accidents was reduced by 31.2% after winter maintenance work, such as plowing, was carried out in contrast to when little maintenance work was done. Additionally, plowing operations can help reduce the build-up of a compacted snow layer on the road surface, which would in turn reduce the need for using environmentally harmful salting materials or chemicals.

Therefore, snow plowing, being the corner stone of WRM operations, needs to be carefully planned out in order to have an effective mobilization of available resources while minimizing the use of chemicals, materials, labour, and equipment. One of the most important requirements for realizing this goal would be to develop a timely and efficient plow routing strategy and provide decision makers with a tool they can use to evaluate and optimize their existing program in order to better adapt themselves to a fast-advancing technological and road traffic environment (i.e., connected or autonomous vehicles).

1.2 Problem Statement

When designing maintenance strategies, the maintenance trucks need to clear all snow-covered road segments while prioritizing their response effort and avoiding dangerous operations. To date, existing models often try to generate a snowplow route that minimizes the overall distance travelled while lacking a mechanism to avoid improper turning movements and road priority resulting in generated routes containing a plethora of dangerous and inefficient maneuvers from an operational standpoint (Liu et al., 2014; Kinable, van Hoeve and Smith, 2016). To fill in this gap, there is a need to develop an extensible framework to generate feasible and robust solutions, and evaluate their applicability under both simulated and real-world settings.

In real-world situations, WRM strategies for one large maintenance area is generally comprised of many independent maintenance organizations and contractors, typically one for each municipality within it. This level of disconnect between them could lead to increased maintenance costs, crew costs, and inefficient response times. Therefore, it is important to amalgamate operations in order to make the combined plowing strategy more efficient by no longer treating the municipalities independently, but instead as a whole group entity through collaboration (sharing routes, depots, and dropping boundaries).

Although recent developments in connected vehicle (CV) technology have shown promise for real-time vehicle to vehicle and vehicle to infrastructure communications, few attempts were made to consider the traveller’s on-route travelling experiences and dynamic decision-making during maintenance operations (Kim and Mahmassani, 2021; Sullivan et al., 2019;). In a CV environment, it can be reasonably assumed that truck operators are capable of collecting real-time traffic information such as traffic demand, vehicle location, routing decision, start time, and duration. However, it is still unknown how this high-resolution traffic information could help on-route drivers make better routing choices, affect their travelling experiences, or reduce the network system delay.

In the light of above-mentioned problems, there is an urgent need to develop a new methodological framework aimed at capturing universally applicable aspects of route planning. Such a development will lead to a decision-support tool that simulate plow routings under different planning scenarios thereby providing a more informed and evidence-based decision for future consideration and implementation.

1.3 Research Objectives

The primary objective of this thesis is to develop a timely and efficient snowplowing operation and resource allocation scheme that are suitable for both simulated and real-world implementations. In particular, the thesis has the following three specific objectives:

1. Present a new methodological framework for solving a snowplow routing with precedence problem;
2. Quantify the mobility benefits of optimizing snowplow routes using a discrete-event simulation model; and
3. Provide a decision-support tool for optimizing routes and allocating resources using a real-world case study.

1.4 Thesis Organization

The remaining parts are organized as follows: Chapter 2 summarizes the existing solutions and limitations for snowplow routing strategies, depot location allocation strategies, and fleet size problems.

Chapter 3 illustrates the methodology and solution algorithm targeted at solving the snowplow precedence problem. This chapter formally defines the mathematical formulation of the plowing with precedence problem, where the mathematical formulation of the proposed problem; namely, K-truck plow with precedence problem (K-PPP), and the modified tabu search algorithm are included.

Chapter 4 presents the thesis's first case study: optimizing snowplow routes in a simulated connected vehicle (CV) environment. This study streamlined snowplow routes by setting optimization goal as system traffic delay. Two different tests were conducted on the hypothetical road network. The first case study revealed the possible mobility benefit of the snowplow routing optimization, and the second one determined the optimal fleet size for the depot.

Chapter 5 details the second case study, which further extends the K-PPP by combining realistic constraints such as left-turn restrictions, road priority restrictions, service time window, etc. This chapter discusses the cases where depots were removed sequentially, and the extended algorithm was utilized to optimize the snow removal routes for each set of remaining depots until the minimum maintenance standard could no longer be satisfied. The trade-off analysis for depot closures was conducted to obtain a measure of performance of the snowplow routes after retiring depots.

Chapter 6 highlights the main contribution of this thesis and discusses possible future research extension.

Chapter 2. LITERATURE REVIEW

This chapter reviews existing literature on the optimization and decision rules for strategic planning and operation management of winter maintenance operations. Strategic planning includes depot location selection, while operations management includes fleet size and route optimization problems. This chapter also describes our motivation for the research by introducing the limitation of the current literature.

Section 2.1 reviews the existing literature related to the background and optimization rule for snow and ice control. Section 2.2 analyzes the methodology and solution technique for the snowplow routes optimization problem. Section 2.3 reports the development of the current literature on the depot location-allocation problem. Section 2.4 details the fleet size management problem.

2.1 Overview of Snow and Ice Control

Snow and ice control on road segments aims to improve road friction by plowing and spreading chemicals onto the pavement using various de-icing and anti-icing strategies (Haghani and Qiao 2001; Perrier, Langevin & Campbell, 2006a). Snowplowing is widely used as a de-icing strategy to loosen the strong bond between the ice and pavement (Bodin and Kursh., 1978; Perrier, Langevin & Campbell, 2007b). Feasible snowplow routes include the following components as list in the **Table 2-1**.

Table 2-1. Constraints for snowplow activities

Constraints	Snowplow	Spreading
Route prioritization	Yes	Yes
Mixed vehicle fleets	Yes	Yes
Road type	Yes	Yes
Tandem plowing	Yes	No
Turn constraints	Yes	No
Maximum working hours	Yes	Yes
Truck loading capacity	No	Yes

For the road priority consideration, due to the limited resources and required respond times, municipalities cannot ensure the highest level of service on all road segments. Agencies typically prioritize response efforts based on the average annual daily traffic volume, resulting in shorter response times on high traffic volume roads than on low traffic volume roads. To objectively measure the performance of snowplow routes, the municipalities set minimum maintenance standards (MMS) restricting the allowed service time limit allotted to different road classes. For example, the Alberta and Ontario governments have set 2 and 3 hours as the maximum response time for their highest class of highways, respectively, which means the snow-covered roads need to be serviced within those time frames. If the maintenance operation fails to clean the road within the maximum allowable time, the maintenance strategy would be considered untenable due to the untimely response time. As for turning constraints, snowplows usually push snow to the right side of the road and any left turn behaviour should be limited as it would cause snow windrows to be piled into an intersection. It is important to note that left turn restrictions can be relaxed if a truck passes over a road segment without servicing it. In general, turning restrictions are used as a penalty term in the objective function to reduce undesirable turning behaviours.

Spreading ice melting agents comes after snowplowing to maintain the bare pavement condition for as long as possible, and it shares a lot in common with snowplowing activities (Perrier, Langevin & Campbell, 2007a). Spreading trucks and snowplow trucks are often used as a team in snow removal operations, as spreading trucks could follow the same routes designed for snowplow trucks. Depressants such as salt and sand are used after the road segment has been plowed to improve friction as the exposed road surface could potentially ice over. Salt is expensive and is only applied to higher class rural roads to prevent the formation of ice, while sand is used to enhance the friction of roads in rural areas and upon lower classed roads. As trucks have a capacity limit, many trucks may need to make a detour to material depots to restock on materials during maintenance operation.

Besides real constraints that exist within winter maintenance operations, the network characteristics also complicates snow removal strategies. Researchers often optimize routing problems on undirected, directed, and mixed graphs to represent the geometry of the transportation network according to directionality requirements (Kinable, van Hoeve & Smith, 2020; Rao, Mitra & Zollweg, 2011; Salazar-Aguilar, Langevin & Laporte, 2012). Undirected maps are used to represent road networks that could be serviced bi-directionally, and directed maps impose directional constraints to the roads.

Typically, optimized snow and ice control route minimize the overall distance traversed while satisfying all the decision rules mentioned above. For any given road network, any combination of constraints such as road priority, turning restrictions, route length, loading capacity, truck type, and other constraints presents a challenge to find a feasible snowplow route (Minsk, 1998; Quirion-Blais, Trépanier & Langevin, 2015). The constraints can be divided into the following aspects:

Road priority:

- Routes are serviced before the MMS requirements (route time) for each road class;
- Cold spots such as bridges (if provided) are to be avoided;

Turning restrictions:

- The number of left-turn and U-turn is minimized; and
- Left-turn and U-turn are made at permitted intersections (if provided).

Route length and loading capacity:

- Sand/salt routes can only be assigned to sand/salt trucks, respectively;
- Salt/sand usage should not exceed the maximum given loading capacity of individual trucks; and
- The route length for each existing truck is limited by its maximum allowed distance provided by Agencies.

Truck type**:**

- Single-axle/tandem/tri-axle truck routes can only be serviced by single-axle/tandem/tri-axle trucks, respectively.
- Gravel/salt/sand routes can only be serviced by graders/truck spreading salt and sand, respectively;

Other constraints:

- Each road segment is serviced exactly once;
- The truck should start and end at the same depot;

- No material is used on gravel roads;
- Static weather conditions (i.e., snowstorm has ended); and
- Combo unit can deadhead (transverse without plowing) but will not service gravel roads, and graders are not applicable on other routes that require both plowing and salting;

Therefore, it is crucial to develop an efficient methodological framework targeted at solving snowplow routing problems by taking into account many legislative and operational constraints (e.g., MMS, turning restrictions, material usage, distance travelled, etc.) and solve it using some heuristic search algorithms in an attempt to determine the optimal solutions.

2.2 Snowplow Routes Optimization

Methodologically, optimizing snowplow routes is similar to the Chinese Postman Problem (CPP), which requires every link or arc to be serviced exactly once while also minimizing total travel distance (Guan, 1962; Malandraki & Daskin, 1993; Eiselt, Gendreau & Laporte, 1995; Perrier, Langevin & Amaya, 2008; Hajibabai, 2014; Liu et al., 2020;). For this reason, many researchers formulate this problem as the renowned CPP when optimizing snowplowing routes. The Chinese Postman Problem requires that the truck traverses every arc in the network at least once and then returns to the starting node. One of the earlier studies conducted by Malandraki and Daskin (1993) formulated the solution for the maximum CPP by allowing each arc to be visited multiple times to derive a snowplow route. Perrier, Langevin and Amaya (2008) formulated their snowplow route optimization into a hierarchy where all the trucks first service high priority roads, followed by low priority roads. A more recent study conducted by Dussault et al. (2013) dealt with the fact that snowplow trucks travel faster on plowed streets without the consideration of steep grades. Kinable, van Hoeve and Smith (2016) compared three different snowplow routing optimization methods in detail. Two exact solutions, named constraint programming and mixed-integer programming, were tested as a benchmark to compare the effectiveness of the heuristic algorithm. The results suggests that the proposed heuristic algorithm can generate a near-optimal solution in a short amount of time for a large road network. Sullivan et al. (2019) proposed an iterative heuristic algorithm to deal with the snow and ice control system concerning network clustering, vehicle allocation, and capacitated vehicle routing. Their findings show that vehicle-reallocation, in addition to increasing the truck fleet size, can result in a more effective snow and ice control strategy. While previous research contributes to the snowplow routes optimization within each municipality, it is still unknown about how snow removal activities could be improved through cooperation between nearby municipalities and future connected environments.

2.3 Depots Location Optimization

In winter maintenance operations, depots can be classified as a material depot, a vehicle depot, or both. The difference is that the vehicle depot will serve as the starting and ending point of the routes taken by trucks, and material depots serve as intermediate facilities for those trucks to replenish salt or sand during their service deployment. For economical and administrative reasons, many agencies combine vehicle depots and material depots to ensure that trucks could load depressants at their starting point. Since the location of material and vehicle depots affect the winter maintenance route design process, the depot selection process needs to incorporate the site, route, and vehicle maintenance costs. The compounding effect of depot location selection motivated various attempts to find an efficient and economical depot selection stratagem.

Existing research on depot location optimization generally involves two-stages — the first determines the depot location, and the second generates feasible routes. However, designing a customized route for some municipalities could be challenging as there are many local constraints such as cold spots and turning restrictions. Under these circumstances, a possible solution would be to keep the existing routes while allocating them to other depots. Reinert, Miller and Dickerson (1985) formulated this problem as a P-median problem. This study assigned pre-determined spreader routes to depots by minimizing the distance from the median point of arcs to the nearest material depot. Their test in the Columbia district revealed that the proposed framework reduces the overall deadhead by 27% compared to the existing depot configuration. Another possible solution is to generate feasible snowplow routes under different depot configuration. Korhonen et al. (1992) utilized a construction heuristic to determine the number of depots which is aimed at investigating the depots' effect economically. Depots are added sequentially until the marginal benefit reaches its predetermined benchmark. The objective function considered the traffic delay and depot location costs. Gupta (1998) developed a GIS-based decision support system to recommend depot locations under more realistic conditions. The proposed methodology would not provide an all-new scenario for locating depots but instead provides a depot location strategy by opening or closing depots using the existing depot configuration. Their case study for Hamilton County considered truck maintenance costs, fixed depot costs, and operating costs. Hayman and Howard (1972) took on the problem of fleet size optimization by considering the level of service needed for different road classes. The study conducted by Ungerer (1989) also considered the annual weather conditions as represented by a cumulative probability function that was simulated using the Monte Carlo method. The objective of that research was to determine the best fleet size to meet the level of service requirement. Liu et al. (2014) conducted a sensitivity analysis of depot location in Edmonton, which indicated that improper vehicle depot location placement could result in an 8% increase in total distance travelled by the truck. Also, the deadhead caused by improper depot placement would increase the unproductive travel time, thus lowering the level of service of winter maintenance operations.

Although previous research made notable contributions to the depot location allocation problem, it still has not been fully addressed. They do not provide any definitive steps on how to optimize the depot location in real world cases nor the relationship between the reduced number of depots to the resulting decreased level of service. Therefore, this thesis will develop and provide comprehensive procedural steps, along with a trade-off analysis, regarding depot optimization using a real-world case study.

2.4 Fleet Size Management

Another interesting topic for winter maintenance operations is to determine the fleet size for each depot. It is recognized that an improper crew assignment plan could lead to idle trucks, increased total travel time, and a reduced level of service. The current fleet sizing process designs routes for a set of workers. Each route should be well planned and feasible for dealing with operational constraints. Liu et al. (2014) gained insight into the effect of fleet size by analyzing the different number of routes performed by the trucks. The level of benefit for the various number of the trucks in the system was measured, and it revealed that adding trucks will not always result in an increase of benefit, and that the optimal fleet size could instead be achieved by enumerating a list of truck numbers. A recent study conducted by Li et al. (2019) incorporated new fleet size factors motivated by the fact that the fleet size could be affected by weather uncertainty and truck availability. They proposed a generic model for deciding the number of trucks for the depots by analyzing the historical weather data. The researchers used Monte Carlo methods to capture the general pattern of weather uncertainty and then used these results to analyze the truck fleet size for the depots under different weather patterns.

Previous studies have helped managers decide the long-term fleet size of the depots. In individual snowfall conditions, winter road maintenance authorities may also face the challenge of designing a short-term vehicle allocation strategy by reacting to extreme weather patterns. Sullivan et al.'s (2019) recent study proposed a framework to approach the short-term fleet-size problem under random weather conditions where idle trucks could be assigned to specific depots for different weather patterns. The result suggested that the truck reallocation process can better deal with varying weather and truck availability patterns.

Despite all the effort put into the fleet size problem, few researchers attempted to consider the fleet size problem in conjunction with current real-world and future connected vehicle environments. The goals for current fleet size optimization studies are to minimize operational times, operation distance, and/or increase the level of service. Many questions still exist in regards to how current fleet sizes could be utilized if the assigned plow routes were infeasible and how exploiting the road users’ travelling data could benefit the fleet size optimization process. Hence, this thesis will attempt to answer these questions via the two case studies as previously described.

Chapter 3. OPTIMAL SNOWPLOWING ROUTES WITH PRECEDENCE

Designing optimal routes for snowplow trucks is a core problem in the field of winter road maintenance. When deciding optimal routes, current studies usually treat the overall distance as a criterion. The reason for setting the overall distance as an optimization goal is that shorter overall distances usually indicate an efficient routing strategy resulting in reduced fuel costs, and improved level of service. However, the overall distance cannot describe the route precedence. As a result, it does not penalize solutions with unacceptable operating behavior or service order. If the goal is to highlight the service order or precedence problems in routes, setting the overall distance as the objective function would be inefficient and could possibly lead to solutions that are trapped in a local optimum. Thus, a new model is formulated by setting the winter maintenance goal that reflects the service order of road segments.

3.1 Mathematical Formulation

Snowplow routes optimization strategies consist of network partitioning and optimal route assignments. The network partitioning process partitions the entire network into a manageable size for computer manipulations and calculations. The road network is partitioned by considering the total maximum distance based on the availability of trucks at each depot. Once the routes are partitioned, the optimal route assignments or optimizations were conducted over many thousands of iterations to minimize the total deadhead distance for all trucks while satisfying the operational constraints and decision rules listed in the following section.

In this thesis, the snowplow route optimization problem is formulated as the k-truck plow with precedence problem (K-PPP) which can be described as follows. Consider a road network where k-number of trucks are stationed at one maintenance depot. The goal is to service all the snow-covered road segments exactly once while ensuring all the trucks (or k number of trucks) start and end at the depot, plow all road segments exactly once, balance the workload, and minimize the overall cost. The K-PPP differs from traditional routing problems in that the objective function is not only affected by the coverage of routes but also by their precedence. The formulated K-PPP is used to investigate the following two scenarios. The first scenario develops a CV-enabled snow and ice control strategy. In the CV environment, on-route road users' travelling decisions are affected by the snowplows' route precedence because the dynamic road conditions are accessible and will be provided to users in real time for dynamic routing choices. The second scenario is the investigation into the benefits from collaboration between municipalities to improve snowplow activities. Two different constraints: turning constraints and route priority constraints were considered through the optimization of route precedence. Therefore, the extensible model is formulated as follows:

$$\text{Min}\,(f(x)) \tag{3-1}$$

Subject to the following constraints:

$$\sum_t \sum_k x_{i,j,k,t} = 1 \qquad \forall (i,j) \neq (0,0') \tag{3-2}$$

$$\sum_j \psi_{0,j,k,0} = 1 \qquad \forall k \tag{3-3}$$

$$M(1 - y_{0,0',k,t}) \geq \sum_i \sum_j \sum_{t<t'} \psi_{i,j,k,t'} \qquad \forall (i,j) \neq (0,0'), k, t \tag{3-4}$$

$$\sum_i \psi_{i,j,k,t-1} = \sum_l \psi_{j,l,k,t} \qquad \forall (j,l) \neq (0,0'), k, t \tag{3-5}$$

$$\sum_i \sum_j \psi_{i,j,k,t} = 1 \qquad \forall (i,j) \neq (0,0'), k, t \tag{3-6}$$

$$\sum_{k}\sum_{t<t'-1} y_{i,j,k,t'} \le M\sum_{k}\sum_{t<t'} x_{i,j,k,t'} \qquad \forall (i,j)\ne(0,0'),t \tag{3-7}$$

$$d_k = \sum_{i}\sum_{j}\sum_{t} T_{i,j}\psi_{i,j,k,t} \qquad \forall k \tag{3-8}$$

$$d_k \le T_{\max} \qquad \forall (i,j)\ne(0,0'),k,t \tag{3-9}$$

$$\bar{d}(1+\alpha) \ge d_{\max} \tag{3-10}$$

$$\bar{d}(1-\alpha) \le d_k \qquad \forall k \tag{3-11}$$

The overall process seeks to minimize the objective function (3-1) as affected by route precedence. The proposed model can generate different optimized routes for any variation of the objective function, and can be adjusted based on any desired criteria. Constraint (3-2) ensures that every arc in the graph is serviced exactly once. Constraint (3-3) states that all the trucks should start at the depot, while constraint (3-4) ensures that the vehicle ends at the depot by traversing the hypothetical arc (0,0'). The deadhead on the hypothetical arc is used to represent the final arc of the route (e.g. $y_{0,0',k,t}=1$). Although this arc does not appear in the graph, it has been customarily used by many researchers to represent the stopping condition for snowplow trucks. Constraint (3-5) requires the snowplow trucks to leave the arc after servicing it, while constraint (3-6) states that only one arc is traversed at each step for all trucks. Constraint (3-7) requires that the arc should first be plowed by the snowplow truck before deadheading. Constraints (3-8) and (3-9) describe the work shift limitation for each truck. Constraints (3-10) and (3-11) are used to balance the workload, which requires that all route times should be within the range affected by parameter *α*.

3.2 Solution Algorithm

3.2.1 Network Partitioning

In practice, the road network may have multiple depots. This thesis first partitioned the whole road network into a set of independent sub-networks with only one depot. The multi-depot network is then converted into several one depot networks, and the k-truck plow with precedence framework proposed could be formulated to solve the issue raised here. What is more, the divided sub-network could help reduce the solution space into manageable sizes to reduce computation times. The following procedure involving a heuristic algorithm is used in the network partitioning.

1. Partition Strategy

Let G= (V, A) be a directed graph that represents the service map, where V= *{0,i,j,…}* represents the vertex set, and A= {(i, j): i, j∈V, i≠j} represents the arc set. Each arc has a different service requirement $\{S_1, S_2, \dots\}$. The depot is represented by $\delta = \{\delta_1, \delta_2, \dots\}$ and each depot equipped with a subset of serviceability among $\{S_1, S_2, \dots\}$ according to their equipped fleet characteristics. Let $SP_{i,\delta j}$ represents the shortest path from vertex i to depot δ_j, and $SP_{i,j}$ represents the shortest path from vertex i to vertex j.

a. Partition the road network based on current serviceability for each depot. For arc (i, j) with service requirement S_m, based on its service requirement, calculate the shortest path from the midpoint of the arc to depots with serviceability S_m.
b. Compare the distance to all depots with serviceability S_m. Assign the arc (i, j) to the nearest active depots.

c. Link depots to the nearest assigned road segment using the shortest path algorithm.

2. Insertion Strategy

Check the contiguity of the assigned road segments. For each unconnected road segment or unserved arcs, link the unconnected road segments to the connected arcs for depots using the shortest path.

3.2.2 Optimal Route Assignment

After dividing the multi-depot road network into many independent single-depot road networks, the tabu search algorithm was used to obtain the optimal snowplow routes for each single-depot road network. The tabu search algorithm, known for being one of the most adopted metaheuristic algorithms, was used to solve the proposed optimization problem (Glover, 1989). Metaheuristic methods are widely used since they are able to generate near-optimal solutions within a reasonable time period for problems that are analytically intractable or very difficult to solve in polynomial time due to large-scale instances. For this reason, significant research effort has been dedicated to the development of an efficient algorithm, one of which is the tabu search. Similar to other metaheuristics, tabu search starts with a set of initial solutions and progresses iteratively by searching for alternative solutions. During the search process, it uses a set of predefined local search schemes and unique memory structures, allowing solutions to escape from a local optimum (maxima/minima) without being stuck in those suboptimal traps. The pseudocode of the tabu search implemented in our study is summarized as follows:

Input: An initial solution of the k-truck route, the maximum iteration number, the length of the tabu list.

```
Output: The possible improved k-truck route.
Step 1. (Initialization)
    Set CurrentSolution= InitialSolution
    CurrentValue=InitialValue
    BestSolution= InitialSolution
    BestValue=a large number
    The maximum iteration number = A large number
Step 2. (Forward updating objective function value)
    For iteration number=1 to maximum iteration number:
      While (BestValue>=CurrentValue) Then:
       Randomly generate 24 different neighbourhoods based on CurrentSolution using
       the permutation procedure
       CurrentSolution= best found solution not in tabu
       CurrentValue= Objective Function (CurrentSolution)
            If (BestValue> CurrentValue) and (CurrentSolution not in tabu list) Then:
              BestSolution= CurrentSolution
              BestValue= CurrentValue
              add the CurrentSolution to the tabu list
      End
    End
          Randomly generate 24 different new neighbourhood based on
              CurrentSolution using the merging and separating edges procedure
          CurrentSolution= best found solution not in tabu
```

```
            CurrentValue= Objective Function (CurrentSolution)
            If (BestValue> CurrentValue) and (CurrentSolution not in tabu list) Then:
            BestSolution= CurrentSolution
            BestValue= CurrentValue
            add the CurrentSolution to the tabu list
        End
    End
```

Since the quality and computing time of the solutions depends primarily on the initial solutions and neighbourhood structures chosen, it is very important that those values be carefully designed and constructed beforehand. Similar to the Frederickson-Hecht-Kim (FHK) algorithm, this study constructed the initial solutions for k-trucks plowing scenarios by minimizing their total travel time (Hierholzer, 1873; Frederickson, Hecht & Kim, 1978). After finding the initial route, the next step is to generate an efficient neighbourhood. The procedure called *permutation* is used to generate 24 different neighbourhoods. Dussault et al. (2013) suggested that the *permutation* procedure may produce a significant number of neighbourhoods, and the large size of the neighbourhoods could in turn enlarge the search space and thus increase the computation time. To limit the neighbourhood size, one possible way is to adopt part of the neighbourhoods. The number 24 was used to limit the number of neighbourhood sizes. Once the shortest route is selected among the 24 neighbourhoods, the next step was to check if any of the solutions generated is better than the initial solution. If a better solution is found, the permutation procedure is then repeated to generate another set of 24 different neighbourhoods. Otherwise, the *merging and separating edges* procedure is used to search for a different combination of routes. This said procedure continues until an iteration limit of 700 (the maximum iteration number) is reached, and the best solution obtained becomes the optimal solution. The heuristic algorithm terminates at 700 iterations because the outputs of the objective function remain stable for the last 500 iterations. Also, the proposed tabu search algorithm will have compared a sufficiently large number of alternative solutions (16800 different routes) at 700 iterations thus confidently providing the global optimal solution. For more detailed descriptions and implementations about the *merging and separating edges* procedure and *permutation* procedure, readers are advised to refer to Dussault et al. (2013) and Ahr and Reinelt (2006).

3.3 Summary

This chapter presents a variant of the plow with precedence problem that addresses the route assignment for k trucks in servicing the road network. The proposed problem incorporates the precedence problem, which is usually ignored by current winter maintenance research. This thesis first provided the mathematical formulation for the problem and then introduce a metaheuristic algorithm to solve it. The solution algorithm continuously improves the solution quality by iterating and updating the tabu list to avoid becoming trapped in a local optimum.

The efficiency of the proposed formula and solution algorithm will be demonstrated in the following chapters via two case studies. To link road service order with an optimization goal, the objective function of the first scenario (i.e., connected-vehicle) was set to traffic system delay, while the objective function of the second scenario (i.e., real world) included improper turn and road priority penalty terms. Case studies 1 and 2 are described in Chapters 4 and 5, respectively.

Chapter 4. OPTIMIZING SNOWPLOW ROUTES UNDER A SIMULATED CONNECTED-VEHICLE (CV) ENVIRONMENT

This Chapter describes snow and ice control routing optimization in a CV environment. While previous research has made notable contributions in deriving feasible plowing routes by decreasing their workload and fleet size, their focus was strictly from the perspective of the snowplow trucks only (e.g., minimizing operating times and the number of deadheads). With the advancement of wireless communication technology including radio-frequency identification (RFID) (Roberts, 2016) and the fifth generation of cellular network technology (Kumar & Gupta., 2018), real-time communications between vehicles are now a real possibility for the future connected vehicle environment. In most cases, the level of service indicator used is the average annual daily traffic information, which is often a poor representation of realistic traffic demand. The emerging CV environment technology allows for real-time communication between vehicle to vehicle and vehicle to infrastructure (generally known as V2X). As such, traffic state information such as real-time traffic demand, location, routing decision, and speed are fully tractable and can be exploited by traffic system administrators. Some critical performance criteria such as system traffic delay can be incorporated in deciding optimal snowplow activities. Another major drawback was evidently found in previous studies showing the lack of practicality. For instance, the impact that road surface conditions (RSC) have on drivers has been ignored, resulting in ineffective routing choices. In real-world applications, the enhanced speed provided by snow removal activities can affect the road users' routing choices, but this phenomenon is largely ignored by all models to date. As such, current static algorithms for optimizing route choice may not reflect the dynamic road conditions that occur during snowplowing operations.

In the CV environment, on-route road users are assumed to be equipped with perfect knowledge of the real-time road conditions and would continuously update their shortest path route until the end of their trip. These CV-enabled snowplow strategies are believed to greatly enhance the ability of winter maintenance planners to provide a safe and convenient environment for vehicles efficiently, thus maximizing the benefits to the travelling public during and/or after inclement weather events.

The remainder of this chapter is organized as follows: Section 4.1 describes the proposed CV-enabled routing strategies. Section 4.2 describes the data preparation while Section 4.3 presents the modified problem definition and mathematical formulation. Section 4.4 describes the simulation process implemented in this study and Section 4.5 discusses the results. Lastly, Section 4.6 provides a summary of the findings.

4.1 CV-Enabled Snowplow Routing Strategies

The basic premise of the proposed method of using a simulated CV environment entails the use of real-time travel demands (i.e., assuming that we have perfect knowledge on the locations of individual vehicles within the network) for determining optimal snowplow routes and examining how it would affect the total travel time for both the road users and plow truck operators. To achieve this goal, a k-truck plowing with precedence model was formulated in Chapter 3. The overview of the proposed method is depicted in **Figure 4-1.**

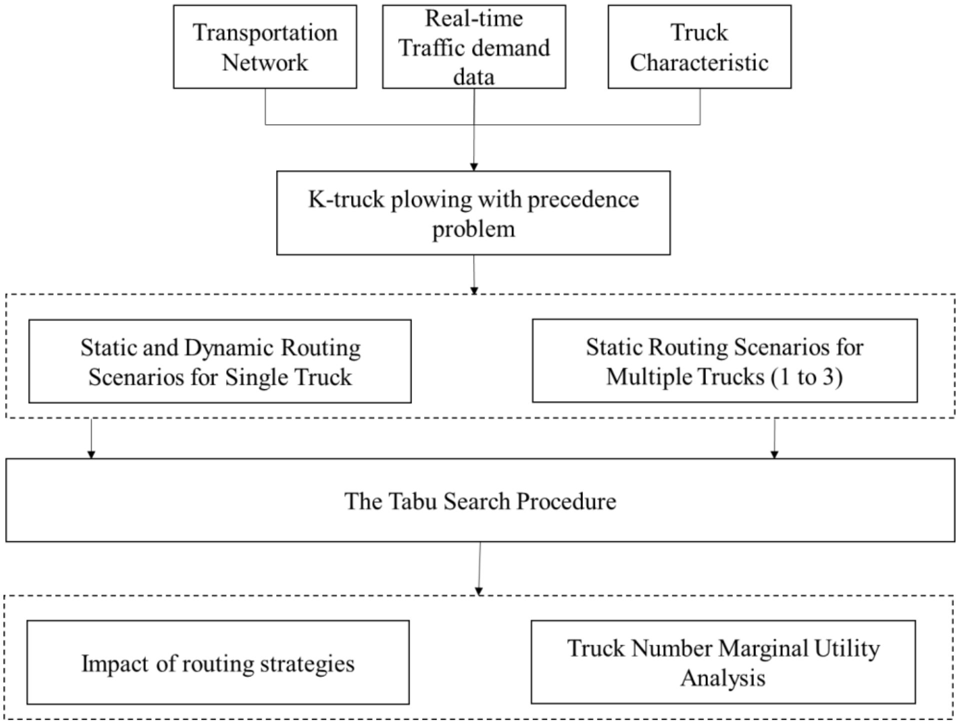


Figure 4-1 Workflow of the proposed method

With real-time traffic demands, truck data, and road network data, the relationships between snowplow routes, traffic routing choices, and travelling information is modelled using the proposed K-truck plowing with precedence model, which describes road users' movement during snowplowing. Consequently, two traffic routing strategies; namely, static and dynamic, are set to simulate different scenarios, for which a metaheuristic tabu search algorithm was used to obtain (near) optimal solutions. The static scenario indicates an environment where vehicles are unconnected and the road users choose the route based on experience, while the dynamic scenario represents the CV environment where the road conditions are dynamically available to all road users enabling them to make real-time adjustments to their routing choice. Both static and dynamic routing strategies are used based on reasonable assumptions about whether or not drivers have access to real-time traffic information, and to examine their implications via computer-aided simulations. To further evaluate the robustness of the method proposed herein, multiple truck scenarios were used to examine the impact a varying number of trucks have on travel / operational time. Note that the research assumes a static routing scenario only for the multiple trucks' scenario, as the primary intent is to validate its feasibility for future large-scale implementation. Finally, the results are analyzed, including the impact of different scenarios and the marginal utility of truck numbers (i.e., benefit assessments). The impact of the different scenarios demonstrates the benefit of having updated snowplow information sent as live feedback to drivers and the marginal utility of different truck deployment numbers to help managers decide upon the fleet size required to service the road network.

4.2 Data Preparation

In this section, a hypothetical network is used to confirm the validity of the proposed method and evaluate its feasibility for real-world applications. **Figure 4-2** shows an arbitrarily created network that consists of roads/links, truck depots, and intersections.

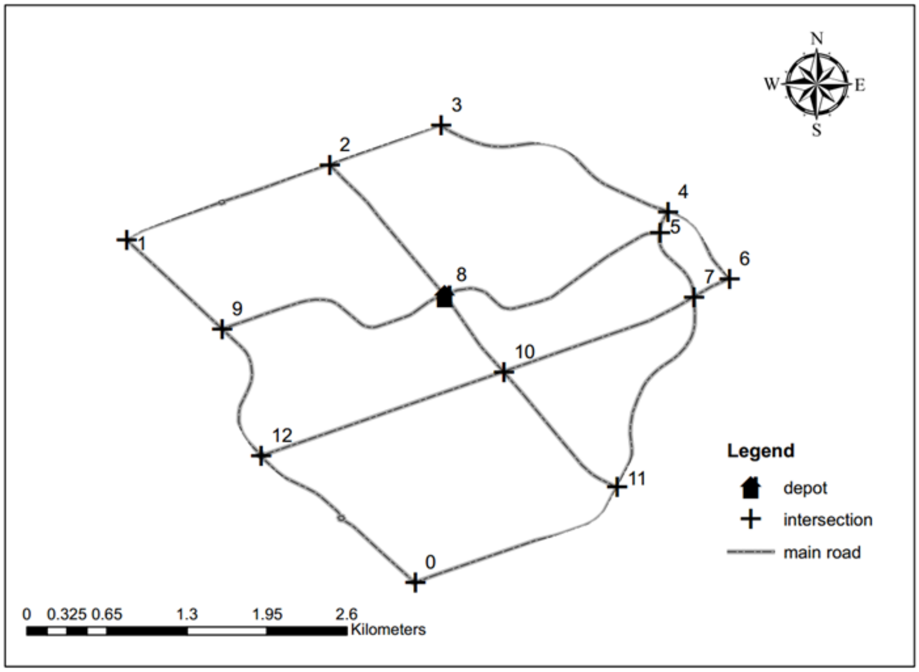


Figure 4-2. Road network characteristics

Table 4-1 summarizes the parameters used for simulation.

Table 4-1. Simulation parameters

Parameter Setting	Attribute Value
Number of vehicles	62400 vehicles
Network length	82 Kilometers
Vehicle generation duration	6000s
Vehicle loading time step	5s
Snowplow truck speed	25km/h
Free flow speed (snow-removed road)	60km/h
Free flow speed (snow-covered road)	48km/h
Jam density (snow-removed road)	120veh/km
Jam density (snow-covered road)	100veh/km
Road capacity (snow-removed road)	1800veh/h
Road capacity (snow-covered road)	1200veh/h

To investigate the effect of a snowplow on the users' travel time, the vehicle generation duration is set to be longer than the minimum plowing completion time of one plow truck (5890s). In other words, the simulation set the vehicle generation horizon to 6000s, after which no vehicle shall enter the network. The time interval for the discrete-event simulation is 5 seconds, which means all values change discretely every 5 seconds. To simulate the road users' speed on the road, the speed of road users was calculated using the Greenshields model as discussed above. To quantify the benefit of snowplowing activities, two different free-flow speeds were assumed to represent the movement of traffic on the network. Given that the free-flow speed for the majority of roads is 60 km/hr and the presence of snow will likely reduce that speed by up to 40% as indicated in the Highway Capacity Manual (Manual 2000), a 20% speed reduction, or 48km/hr, is used as our assumed free flow speed value for snow-covered conditions. Considering the decrease in jam density on snow-covered roads, 100 veh/km was used as the jam density. To reduce the complexity of the problem at hand, this study assumed that the state of the vehicles on a link will change from snow-covered conditions to snow removed conditions after the entire link has been plowed, and there is no longer any congestion or traffic delays caused by plowing activities. Furthermore, the traffic demand between each node in the study is assumed to be known. The traffic demand used in the simulation is 62,400 vehicles, which was randomly generated and evenly loaded into the road network at every time step. For the simulation, the real-time traffic demand was also assumed to have a uniform distribution and its value can be easily modified to fit the practical operation. The traffic demand for each time step is given in **Table 4-2**.

Table 4-2. Traffic demand at every time step

From/To	0	1	2	3	4	5	6	7	8	9	10	11	12
0	0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	1	1	0	0	0	0	0	0	0	0	0
2	0	1	0	2	0	0	0	0	1	0	0	0	0
3	0	1	2	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	1	1	0	0	0	0	0	1
5	0	0	0	0	1	0	0	0	3	1	0	0	1
6	0	0	0	0	1	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	1	2	1	0
8	0	0	1	0	0	3	0	0	0	2	1	0	0
9	0	0	0	0	0	1	0	1	2	0	0	0	0
10	0	0	0	0	0	0	0	2	1	0	0	3	2
11	0	0	0	0	0	0	0	1	0	0	3	0	0
12	1	0	0	0	1	1	0	0	0	0	2	0	0

4.3 Modification to Problem Definition and Formulation

Differing from the CPP, the result for the K-truck plowing with precedence problem (K-PPP) can vary when the service order of the arcs changes. In other words, CPP does not consider the difference between service order, which are critical for snowplow routing optimizations. The K-PPP can be formulated on the basis of a directed road network, where arcs are used to represent roads and nodes are used to represent intersections. This study assumed that weather conditions were deterministic for all scenarios (i.e., after snowstorms) and that all arcs in the network are covered with snow and require snow removal. This study also considered the routes to be a sequence of steps that represent the working order of different snowplow trucks. These steps should ensure that the trucks start and end at the same depot (represented by node 0) while servicing all the arcs in the road network. Furthermore, this study considered time-dependent traffic demand between different nodes during snowplowing activities since drivers are able to traverse faster and/or choose a different path to travel due to improved road surface conditions. Therefore, the objective function (**Equation 4-1**) is formulated to minimize the total travel time of road users and the snowplow completion time of maintenance operators. The parameter and decision variables for the proposed mathematical formulations are summarized in **Nomenclature**.

$$\text{Min} \sum_{\forall i} \sum_{\forall j} \int k(i,j,t) l_{ij} dt + \lambda d_{\max} \tag{4-1}$$

Subject to:

Constraints (3-2) to (3-11)

$$k_{jam}(i,j,t) \cdot v(i,j,t) = -v_{free}(i,j,t) \cdot (k(i,j,t) - k_{jam}) \quad \forall (i,j) \neq (0,0'), t \tag{4-2}$$

In this research, the constant value 50 was used as the weight factor λ, because the weight of the snowplow delay is assumed to be 50 times the weight of other road users' delay. Our proposed model can generate different optimized routes based on various weighting factors, and it can be adjusted based on our criteria. Because the longest snowplow operation duration is usually treated as a constraint to make the snowplow routes realistic, this research tries to optimize the snowplow routes in a way that balances the completion time of snowplow operation and the total travel time of road users. Compared to the average road users' travel time, the snowplow completion time need to be emphasized. The total users' travel time is calculated by using the simulation method from Section 3.3. Constraints (3-2) to (3-11) are used as was defined in Chapter 3. Constraint (4-2) describes the linear relationship between density and speed on the road, for which the Greenshields model (Greenshields et al. 1953) is used. Here the research assumes that when the vehicle enters an arc, its speed will be based on the density of the road segment and it will maintain that speed until it leaves the arc.

4.4 Simulation Process

This study obtains the total users' travel time using a discrete-event simulation (DES) method. The DES was widely used in the network modelling problem (Mahut, 2001; Florian, Mahut & Tremblay, 2008), and it can simplify the complexity of the continuous problem in a discrete manner. Since the total travel time of road users follows a continuous function, the discrete-event simulation period breaks up a continuous-time interval into small discrete time intervals $\{0, \Delta\tau, \ldots, \tau_{\max}\}$, and the system update process was used to update traffic count data *k(i,j,τ)* at every discrete time step. The vehicle travel time can be approximately estimated by $\Delta\tau \cdot \sum_i \sum_j \sum_\tau k(i,j,\tau) \cdot l_{ij}$. A computational program using python has been developed to calculate the total travel time of the hypothetical traffic system. **Figure 4-3** illustrates the simulation process's computational steps while the notations used are provided in the Nomenclature**.**

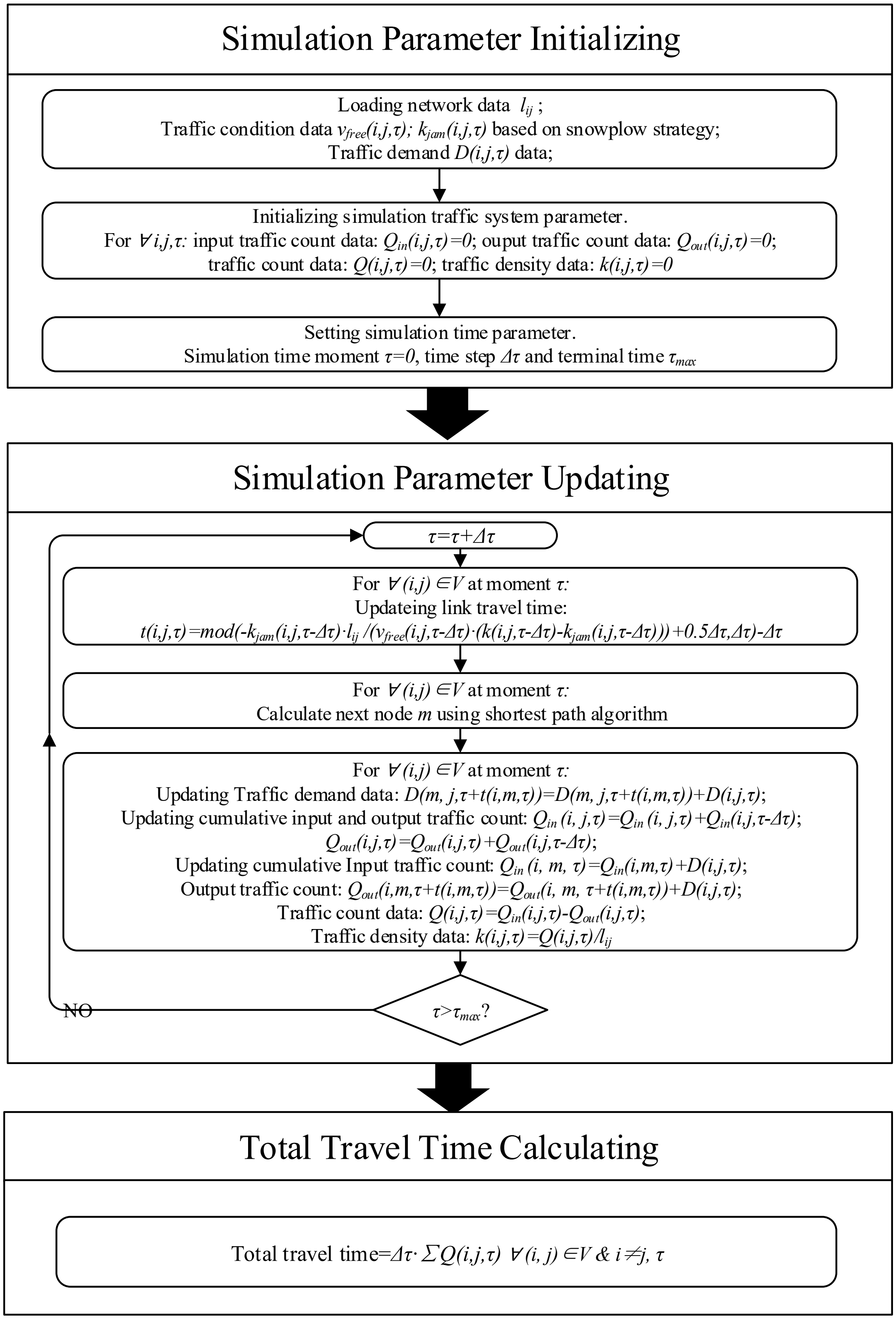


Figure 4-3. Flow chart for calculating the total travel time under snowplow service

In the simulation parameter initializing process, this study first imports the road network data and time-dependent traffic demand data for each time step τ according to the snowplow service order. Note that time-dependent traffic demand data is deterministic over time. Then the free-flow speed and traffic density for the arc at different time steps are initialized according to the snow-covered traffic conditions, snow-removed traffic conditions, and the snowplow service order.

Then, the study initialized the system feature data to zero at a different time step. These data values include the cumulative input traffic count $Q_{in}(i,j,\tau)$, the cumulative output traffic count $Q_{in}(i,j,\tau)$, the traffic count data $Q(i,j,\tau)$, and traffic density data $k(i,j,\tau)$. Our next step is to set the simulation parameter data, including the initialization of time step τ, time step $\Delta\tau$, and terminal time τ_{max}.

After initializing the system parameter, the algorithm updates the simulation parameter at every time step in the system update process. The first step is to acquire the link/arc travel time for different links/arcs at time τ. To simplify the problem, this study assumed that the vehicle will reach the speed from **Equation (4-2)** when it enters the arc and will maintain this speed until it leaves the arc. The link travel time for the arc can be expressed as:

$$t(i,j,\tau) = l_{ij} / v(i,j,\tau) = -k_{jam}(i,j,\tau) \cdot l_{ij} / (v_{free}(i,j,\tau) \cdot (k(i,j,\tau) - k_{jam}(i,j,\tau))) \qquad (4\text{-}3)$$

Note that the jam density and free-flow speed of the arc can be different according to the road surface condition at time step τ (e.g., snow-covered or snow-free). **Equation (4-3)** provides the relationship between the snowplow service with the system's total travel time given that the service order affects the link travel time at every time step, thus affecting the total user travelling time.

Considering our simulation time step is a discrete value, the link travel time $t(i,j,\tau)$ was rounded to simulation step τ, and the link travel time can be re-expressed as:

$$t(i,j,\tau) = \mathrm{mod}(-k_{jam}(i,j,\tau-\Delta\tau) \cdot l_{ij} / ((v_{free}(k(i,j,\tau-\Delta\tau) - k_{jam}(i,j,\tau-\Delta\tau))) + 0.5\Delta\tau, \Delta\tau) \quad (4\text{-}4)$$

After getting link travel time for all arcs in the network, for all the traffic demand data the study calculates the next node *m* for the traffic demand and the time $t(i,j,\tau)$ it needs to arrive at the next node based on the shortest path algorithm (Dijkstra 1959). Note that, the next node *m* can be different according to the user's routing strategy preference (i.e., static routing or dynamic routing). Static routing drivers are drivers who choose routes based on their past experience, while dynamic routing drivers choose routes based on the most up to date information on link travel time.

After getting the next node *m* and the time needed to arrive in the next node $t(i,m,\tau)$, the simulation updates the cumulative input and output traffic count at the current time step based on values in the previous step; for all the arc (i,j) in the road network, the current value is updated using the following **Equations (4-5,4-6)**:

$$Q_{in}(i,j,\tau)=Q_{in}(i,j,\tau)+Q_{in}(i,j,\tau-\Delta\tau) \tag{4-5}$$

$$Q_{out}(i,j,\tau)=Q_{out}(i,j,\tau)+Q_{out}(i,j,\tau-\Delta\tau) \tag{4-6}$$

The traffic demand $D(i,j,\tau)$ generated from the origin to the destination can be broken into two parts. The first part was the traffic demand $D(i,m,\tau)$ from the origin to the next node *m*, which takes time $t(i,m,\tau)$. The second part was the traffic demand $D(m,j,\tau+t(i,m,\tau))$ from the next node *m* to the destination *j* after time $t(i,m,\tau)$.

The accumulated input flow $Q_{in}(i,m,\tau)$ can be aggregated using the first part of the traffic demand, whose next node is m. For all arcs (i,j), this process can be expressed as:

$$Q_{in}(i,m,\tau)=Q_{in}(i,m,\tau)+D(i,j,\tau) \tag{4-7}$$

The second part contributes to the updating of the traffic demand. For all the arcs (i,j), the traffic demands $D(m,j,\tau+t(i,m,\tau))$ can be aggregated using the following equation:

$$D(m,j,\tau+t(i,m,\tau)) = D(m,j,\tau+t(i,m,\tau)) + D(i,j,\tau) \tag{4-8}$$

The vehicle takes time *t(i,m,τ)* to leave arc *im*, and this can be integrated into the accumulative output flow. For all the *(i,j)*, It can be expressed as:

$$Q_{out}(i,m,\tau+t(i,m,\tau)) = Q_{out}(i,m,\tau+t(i,m,\tau)) + D(i,j,\tau) \tag{4-9}$$

After getting the cumulative input traffic count for the link and the cumulative output traffic count for the link, for all the arcs *(i,j)*, the traffic flow data at different time steps can be expressed as:

$$Q(i,j,\tau) = Q_{in}(i,j,\tau) - Q_{out}(i,j,\tau) \tag{4-10}$$

The traffic count (*Q(i,j,τ)*) can be transformed into the density of the road, and this can be converted into the speed of the vehicle according to the fundamental diagram. The following equation describes the relationship between traffic density and traffic count:

$$k(i,j,\tau) = Q(i,j,\tau)/l_{ij} \tag{4-11}$$

Once the road density is determined, the time simulation was set to the next time step. This updated travel time information can then be used to determine the link travel time at the next time step. This system update process lasts until the stopping criteria is met.

After terminating the system update process, the total user travel time can be estimated by using the traffic count data at different simulation time steps. **Equation (4-12)** gives the total travel time of the road network under the snowplow routing strategy.

$$\text{Total travel time}=\Delta\tau\cdot\sum_{i}\sum_{j}\sum_{\tau}Q(i,j,\tau)=\Delta\tau\cdot\sum_{i}\sum_{j}\sum_{\tau}k(i,j,\tau)\cdot l_{ij}\quad\forall(\mathrm{i},\mathrm{j})\in V, i\neq j \tag{4-12}$$

Combined with the longest route of the snowplow truck, the objective function (**Equation (4-1)**) can be calculated to evaluate the objective function of the varying snowplow routing strategies.

4.5 Results and Discussions

4.5.1 Effects of Routing Strategies

This research tackles this challenge in an integrated manner under two distinct hypothetical scenarios – *static routing* and *dynamic routing*. In the static routing scenario, it is assumed that plowing activities do not influence drivers' route choices. This scenario would be a good representation of the drivers' general path selection as they tend to use the same route to reach their destination regardless of plowing operations. The dynamic routing scenario, on the other hand, assumes that drivers have access to real-time traffic information (readily available to many road users through smart devices), and they will thereby choose a different path accordingly. The second scenario is constructed similarly to the well-studied problem of system-optimal routing of traffic flows with constraints on user equilibrium (UE), and is specifically designed to evaluate and benchmark the system optimal (SO) performance. Additionally, provided that emerging connected vehicle technologies enable direct communications between all road users and infrastructures, a realization of the second scenario may not be too distant in the future.

Four different scenarios were tested to compare the effect snowplowing has on the hypothetical network using the proposed tabu search algorithm. The algorithm was coded in Python and run on the supercomputer "beluga" from the "University of Alberta", managed by Calcul Québec and Compute Canada. With 32 CPUs, each of which runs at 2.4 GHz with 1GB memory, it takes around 10 hours for the proposed tabu search algorithm to output one solution in one scenario. The four scenarios tested include no snow conditions (S_1), snow without snowplowing conditions (S_2), static traffic routing (S_3), and dynamic traffic routing (S_4). Because the state of traffic does not go through a transition for both S_1 and S_2 (no plowing is necessary), these scenarios are used as a benchmark with which to compare S_3 and S_4 with. S_3 refers to drivers choosing their route based on experiences, while S_4 has drivers dynamically find the shortest path every time they arrive at a node. Therefore, the traffic conditions transition from snow-covered to snow removal every time a snowplow truck finishes servicing an arc.

This study ran the proposed tabu search algorithm ten times and the best results for S_3 and S_4 obtained are represented in **Figure 4-4** which shows that the optimization implemented was able to reach convergence as the iterations continue. It also shows that the dynamic routing scenario (S_4) outperforms the static routing scenario (S_3) as anticipated. It is worthwhile noting that due to the randomness of the *permutation* and *merging and separating edges* procedures and the nature of the problem being tackled, the results could vary as all heuristic algorithms can only generate near-optimal solutions.

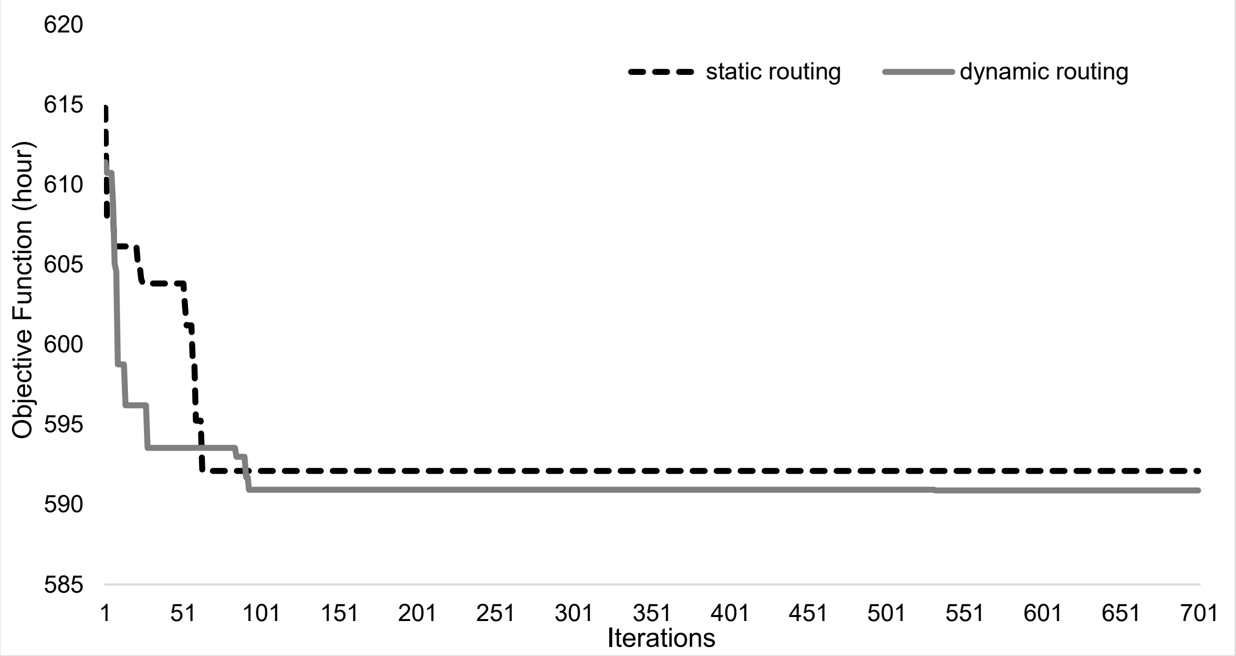


Figure 4-4. Tabu search performance for static and dynamic routing

Table 4-3 compares the average difference in objective function values of 10 optimization runs for the different scenarios. Here, one truck case where it services all the arcs was considered. For the sake of comparison between S_3 and S_4, the same routes were chosen.

Table 4-3. Difference in objective function for scenarios

Scenario (routing strategy)	Difference in Total Travel Times (hour)			
	S_1 vs. S_k	S_2 vs. S_k	S_3 vs. S_k	S_4 vs. S_k
S_1: No snow condition	0	N/A	N/A	N/A
S_2: Snow without snowplowing condition	+159.1	0	N/A	N/A
S_3: Static routing condition with snow	+97.4	-62.0	0	N/A
S_4: Dynamic routing condition with snow	+97.1	-61.7	-0.3	0

The positive sign of the values presented in **Table 4-3** indicates the total additional hours spent by road users on the network. The comparison between S_1 and S_2 reveals that the total travel times were increased by 159.1 hours during the assumed deterministic snow events. Furthermore, the comparison between S_2 and S_3 indicates that the total hours spent by road users were reduced by 61.7 hours due to static routing decisions made due to plowing activities. The comparison between S_3 and S_4 shows how drivers with real-time information on the roads being plowed can benefit by choosing different routes, thereby reducing their travel time. The difference between S_3 and S_4 is 0.3 hours, indicating that drivers equipped with real-time traffic conditions that are influenced by plowing activities, can save 0.3 hours compared to the static routing strategy. Although S_3 is considered a more reasonable option than S_4, S_4 can provide some useful information for winter road maintenance agencies to evaluate the effectiveness of the snowplowing activities and how it can contribute to improving traffic flows during inclement weather events.

Lastly, the best path found for S_3 static routing is {8→ 5→ 8→ 9→ 8→ 10→ 12→ 10→ 7→ 5→ 4→ 6→ 7→ 11→ 10→ 11→ 0→ 12→ 9→ 1→ 2→ 1→ 9→ 12→ 0→ 11→ 7→ 6→ 4→ 3→ 2→ 3→ 4→ 5→ 7→ 10→ 8→ 2→ 8}, and the best path found for S_4 dynamic routing is {8→ 5→ 8→ 9→ 8→ 10→ 11→ 0→ 12→ 10→ 7→ 6→ 4→ 5→ 4→ 3→ 2→ 1→ 9→ 1→ 2→ 8→ 2→ 3→ 4→ 6→ 7→ 11→ 10→ 12→ 9→ 12→ 0→ 11→ 7→ 5→ 7→ 10→ 8}.

4.5.2 Analysis of Fleet Size

Another important aspect of snowplowing operations is determining the impact that the varying number of plowing trucks has on reducing traffic delays. The same optimization approach implemented for the single truck case (Section 4.2) is used to determine how the total hours spent by road users would change if the fleet size was increased to 2 and 3 trucks. **Figure 4-5** depicts the time savings for the different numbers of trucks as a result of 10 optimization runs for each fleet size considered herein. When the number of snowplow trucks increases from one to two, the amount of reduction in traffic delays from the resulting snowplowing activities increases from 61.7 to 101.0 hours, indicating a total reduction of travel times by 39.3 hours.

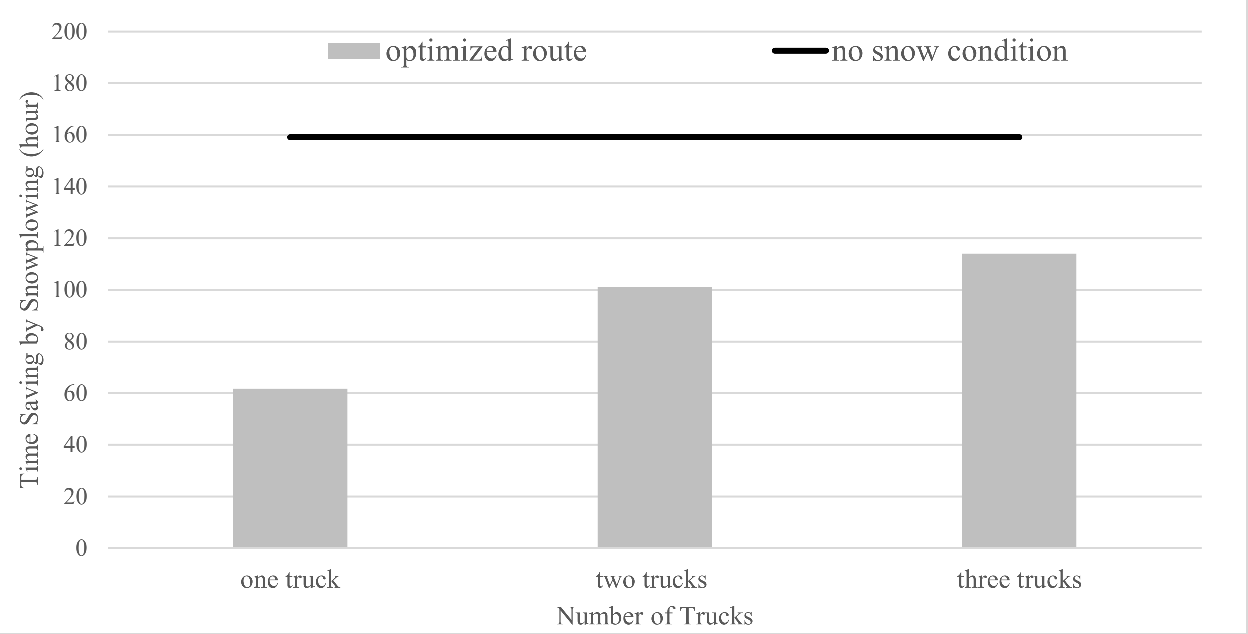


Figure 4-5. Reduced travel time delay of different numbers of trucks (1-3)

Similarly, as the number of trucks increases from one to three, the total travel time decreases by 52.3 hours. From this, it can be observed that there is a diminishing return on the marginal benefit as the fleet size increases. Although the proposed algorithm was tested under a hypothetical scenario with assumed values, the proposed model can be used to help transportation authorities make more informed decisions on determining the optimal fleet size required.

4.6 Summary

This study presented a novel K-PPP to address the current gaps in academic literature. The objective function was expressed in two parts: 1) ensuring a plowing operation times were as short as possible while 2) improving the traffic system that ultimately shortens the drivers' total journey time. Detailed traffic data that captures the dynamic travelling demand were used as input for the model. The fundamental diagram of Greenshields was developed to represent the varying free-flow speeds of snow-covered conditions and snow-removed (or plowed) conditions. Two different scenarios for driver behaviour were tested to evaluate the effect of routing strategies on the total users' travel time. The scenarios include travellers choosing routes without additional information (static routing strategy) and travellers choosing routes based on current information about road conditions (dynamic routing strategy). The simulation result indicated that people with update-to-date road information could save on overall travelling time.

Chapter 5. OPTIMIZING SNOWPLOW ROUTES FOR REAL-WORLD IMPLEMENTATIONS

To further demonstrate the utility of the snowplow optimization algorithm developed, this chapter examines the potential benefits of intra-municipal cooperation using winter maintenance data from maintenance operations in Perth County, Ontario, Canada. Due to its high latitude, Perth County is subject to extremely low temperatures and heavy snowfall during the winter months. There is a total of six municipalities known as North Perth, Perth East, West Perth, Perth County, Town of Saint Mary's, and Perth South. Each municipality has developed their own independent WRM strategy based on their delineated service area, available maintenance resources, and crew resources. While the optimizations achieved within each independent municipality help mitigate the detrimental effect caused by adverse weather, these individual strategies fail to see the full picture across the entirety of Perth County. This results in an unbalanced snow removal stratagem that restricts the maximum potential benefits of a globally optimized holistic WRM strategy. Therefore, this study considers the entirety of Perth County as a single study area and examines how the collaboration between municipalities can help reduce maintenance costs or improve service levels. Specifically, this study focuses on answering the following three questions. (1) Can the current snowplow strategy be considered effective? (2) What are the potential benefits of unifying the region and combining their resources? (3) How does the performance of having shared depots compare to an all-new, and optimized, depot location setup? The proposed framework can be used to answer these questions thereby further demonstrating its usefulness in practical applications.

The remainder of this chapter is organized as follows: Section 5.1 describes the proposed methods to each problem. Section 5.2 describes the data preparation stage for maintenance operation in

Perth County. Section 5.3 presents the mathematical formulation for the feasible routes; Section 5.4 lists the answers for different questions, and Section 5.5 summarizes the findings.

5.1 Real-World Snowplow Routing Strategies

This case study can be better understood when it is broken down into 4 tasks as shown in **Figure 5-1.**

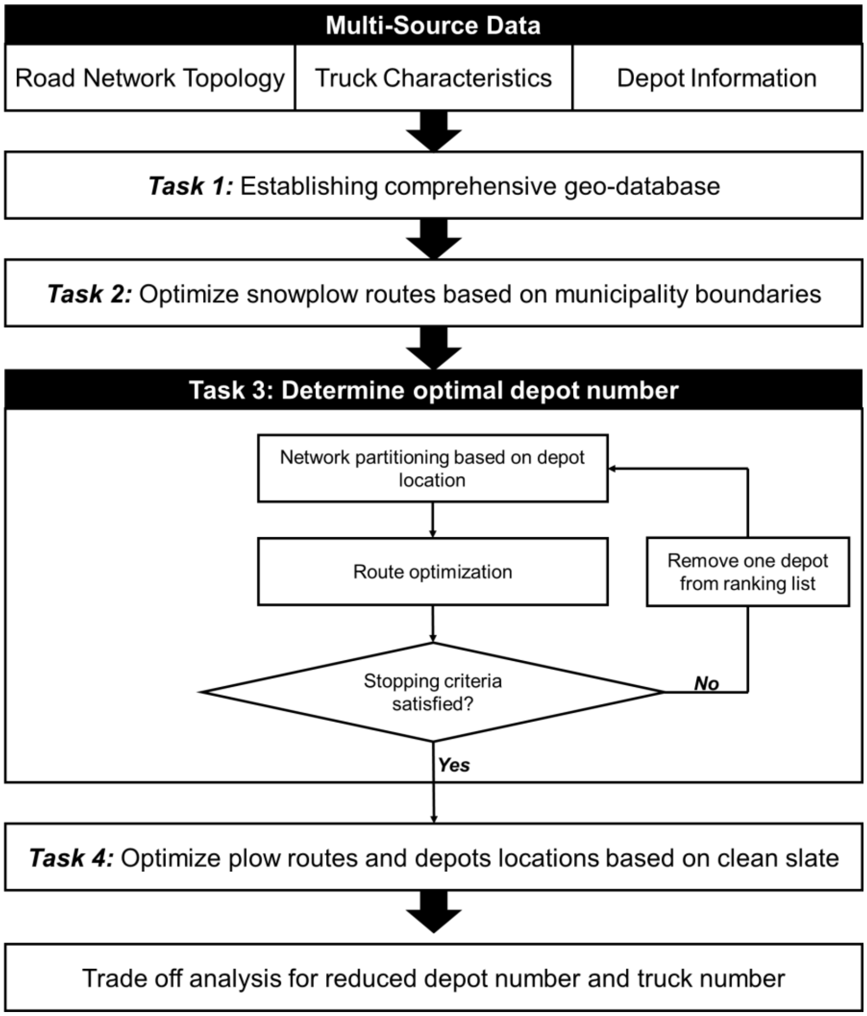


Figure 5-1. The framework for deciding optimal configuration of depots

The first task (***Task 1***) is data collection and management. The data came in a multitude of files in different formats and they required additional work in order to combine all the separate information from each municipality. Once combined, it was then used to construct a comprehensive GIS database by integrating road topology data, depot information, and truck characteristics as was shared by the six independent municipalities. The established GIS database includes detailed records of current snowplow operations thus allowing it to establish a performance baseline (i.e., benchmark) using existing routes and available resources. Based on the geo-database constructed, ***Task 2*** determines if the current snowplow routes can be considered efficient. This is done by optimizing routes by minimizing the total deadhead distance while simultaneously satisfying a set of specific operational constraints within the existing municipal boundaries as listed in **Table 5-1**. A comparison is then made between the current snowplow strategy and the results of ***Task 2*** thereby determining the level of efficiency of the current snowplow operations. This will also provide a benchmark with which to compare the optimized snowplow routes generated when municipal boundaries are no longer considered in ***Task 3***. ***Task 2*** could be regarded as the most optimal snowplow routes achievable based on the current boundary restrictions and depot setup. ***Task 3*** explores the potential benefits of intra-municipality cooperation if the restrictive municipal boundaries were removed, instituting shared routes and joint operations, while utilizing existing depots. The cooperation between municipalities (sharing of maintenance resources) allows for the retirement of unnecessary depots to reduce fixed costs. In the optimization by removal part, select existing maintenance depots were removed one-by-one consecutively in the priority order provided in **Appendix A**. For each configuration of remaining depots, plows routes were re-optimized to service the entire network. To reduce the complexity associated with route optimizations and to overcome the potential issues that can arise from combining operations, the following decision rules are shown in **Table 5-1** have been added.

Finally, ***Task 4*** evaluates the shared depot result by conducting the clean slate optimizations of plow routes and depot locations. By using the determined optimal number of depots found in ***Task 3***, ***Task 4*** will place those depots at optimal locations, as if they were all brand new. Then based on which trucks were re-allocated, new route optimizations were generated to create what is known as the all-new optimal routing scenarios. This provides a measure of how optimal the current setup is, compared to the theoretical optimal.

Table 5-1 Assumptions and constraints used in Tasks 2 & 3

	Task 2	***Task 3***
Assumption		
• When one depot is removed, its equipped resources is also removed	No	Yes
• Urban road can only be serviced by single-axle trucks	Yes	Yes
• Sand and salt routes can be serviced by all other trucks	Yes	Yes
• Application rate for sand is 141 kg/single lane km	Yes	Yes
• Application rate for salt is 75 kg/single lane km	Yes	Yes
• The process of depot removal ended when the constraints of service time (i.e., MMS requirements) OR 100% of spreader capacity could no longer be met.	No	Yes
Constraint		
• Road priority	Yes	Yes
• Turning restriction	Yes	Yes
• Gravel routes can only be serviced by graders	Yes	Yes
• Road segment being serviced exactly once	Yes	Yes

5.2 Data Preparation

The geodatabase for Perth County's winter maintenance operation contains six municipalities, 2972 intersections, 8750 roads, and 46 maintenance routes totalling over 4000 kms. The six different municipalities are named Perth County, Perth East, Perth South, North Perth, and West Perth. A total of 13 depots and 45 trucks are used to provide winter maintenance services for the entire road network.

5.2.1 Road Network Topology

GIS layers were extracted from data files provided by the Ontario Government (https://geohub.lio.gov.on.ca/datasets), including administrative boundaries and road networks. **Figure 5-2** shows the service boundaries for each municipality. The roadway in Perth County consists of highways, country roads, and urban roads. There are five road level classes in the system to distinguish their level of importance, with each road class having a specific service time window. The minimum service standard can be seen as a strict time limit imposed by the government limiting the maximum service time for snow removal activity on icy roads. The minimum maintenance standard varies based on the different road classes. **Table 5-2** lists the minimum service times for each road class.

Table 5-2. Minimum maintenance standard for road classes

Road Class	Service Time Window
2	6 hours
3	12 hours
4	16 hours
5	24 hours

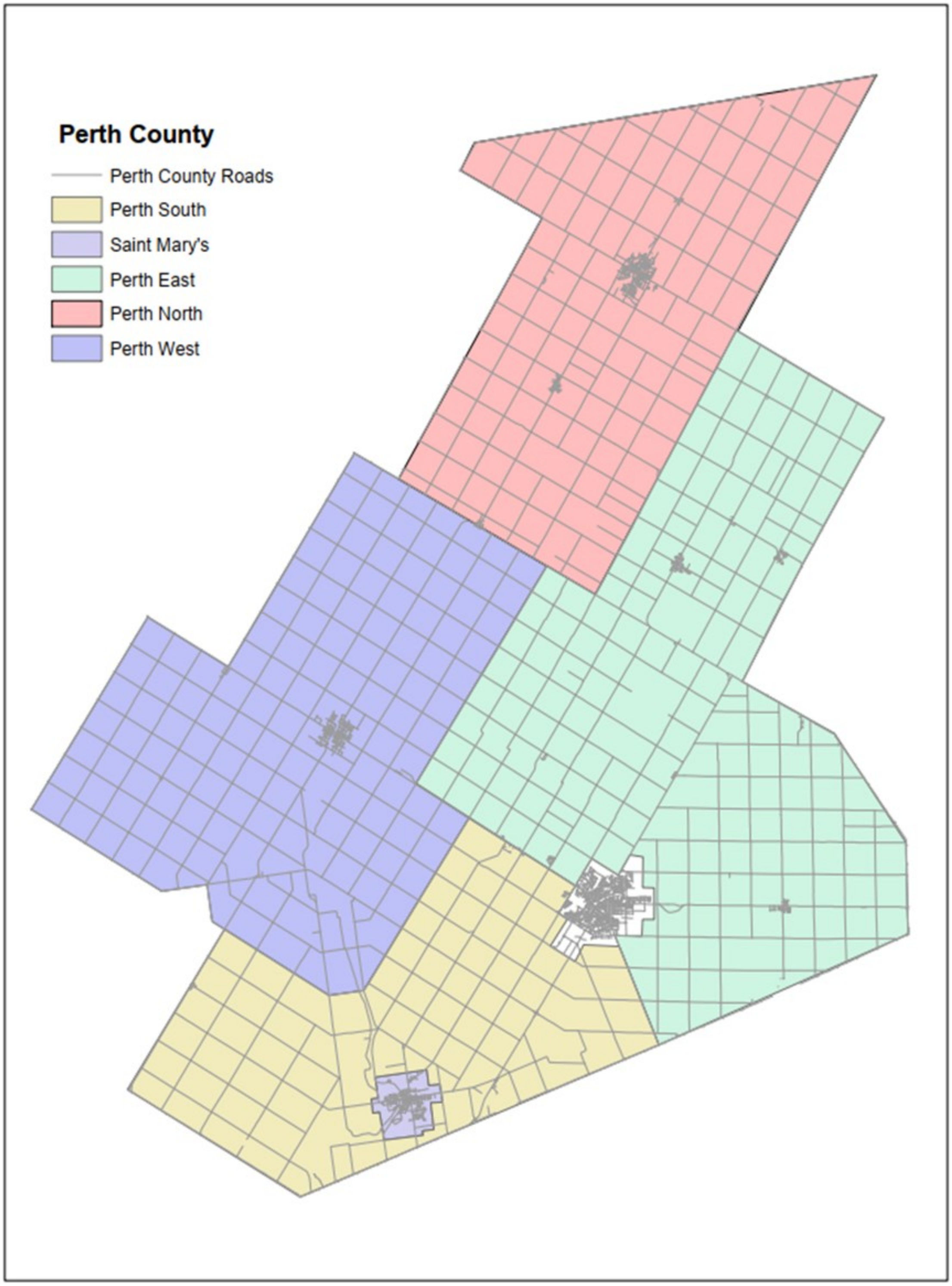


Figure 5-2. Service boundary for each municipality

5.2.2 Depots Information

In its current setup, there are a total of 13 depots that are responsible for supplying the trucks and materials for servicing the entire road network and they each vary in their truck handling capacity. Each of the current depots underwent a comprehensive utility assessment and were ranked according to their storage capacity, land use, environmental sensitivity, and accessibility of services and it summarized in **Appendix A**. A depot's workload is defined as the total length of roads that trucks need cover when assigned to that depot. For example, the Mitchell depot has a maximum workload of 919 km, which means that the fleet of trucks assigned to Mitchell will have 919 km of roads to service. **Figure 5-3** shows the current workload for each depot. It is clear that the workload varies considerably from depot to depot with Mitchell having a disproportionately larger workload over other depots. Alternatively, MTO Listowel appears to have a 0 workload but this depot actually serves as a material restock depot for trucks requiring refills during ongoing maintenance operations.

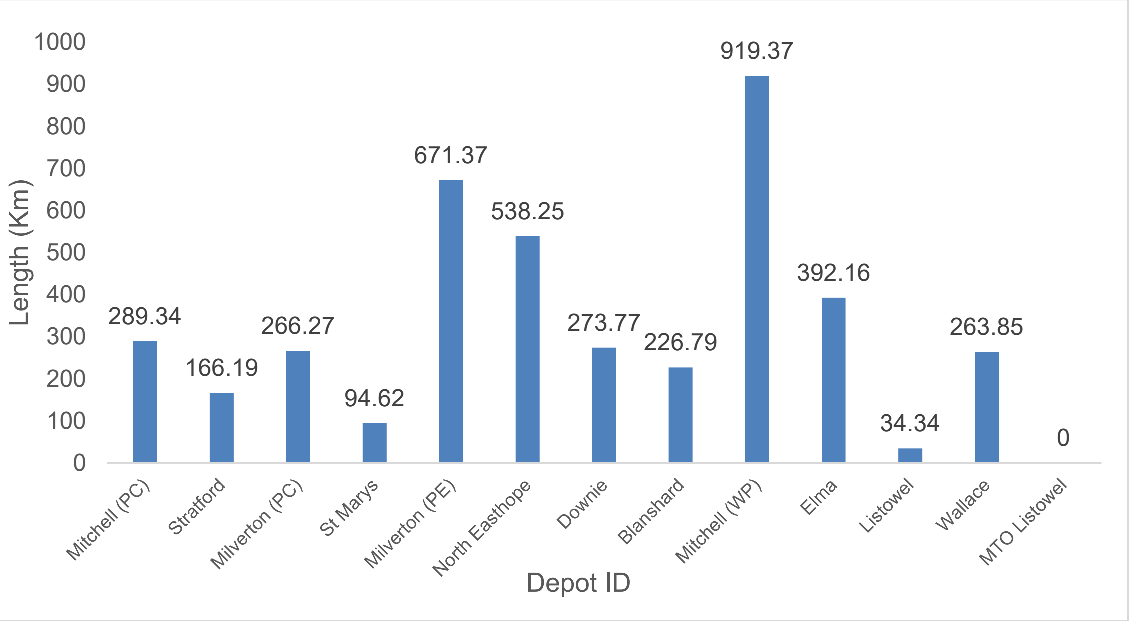


Figure 5-3. Route length by maintenance yard

5.2.3 Truck Characteristics

Perth County has a fleet of 45 trucks that are assigned specific routes based on their serviceability and the type of road surface they will encounter and come in two types, graders and combo units. Graders are primarily used to service gravel roads as no material spreading normally occurs on them. Combo units are trucks that come equipped with a combination of snowplowing attachments and material hauling/spreading capabilities. These units are used on paved roads to perform both snow removal and spreading activities, sometimes simultaneously. The trucks tasked with spreading salt or sand do so at the following application rates - 75 kg/single-lane km for road salt and 140 kg/single-lane km for friction sand. The combo-unit trucks are further sub-classified as either a single-axle truck, tandem truck, or tri-axle truck (see **Appendix B**) and are indicative of the truck's physical size and weight which limits where they can operate. Single-axle trucks are the smallest of the three sizes and are used to remove snow on urban roads that are narrower and have smaller radii in their road geometry. Tandem and tri-axle trucks are much larger units which limits their usability in an urban environment due to geometry and weight restrictions, thus they are primarily used to service county roads and larger highways. The route optimization process should also ensure that the appropriate trucks are assigned to their corresponding road type, and a violation of this would result in an impractical route assignment.

Three constraints were instituted during the performance level testing of the of the generated maintenance strategy. First, higher classed roads are to be completely serviced before lower classed roads. Second, U-turn and left turns should be eliminated, but if it is unavoidable, then they should be conducted at designated locations. Finally, the completion times for the routes should satisfy the prescribed minimum maintenance standards while ensuring that the material usage does not exceed the trucks' material capacity.

5.3 Modifications to the Problem Definition and Formulation

The original problem setup only took into account one depot with many trucks. However, this would run into several challenges as the goal of this section is to identify feasible routes that can be used in the real world.

The first challenge stems from the fact that instead of solving the routing problem for one depot, it now needs to account for multiple depots which complicates the arc routing problem. Specifically, the snowplow routes now need to be optimized for multiple depots while ignoring all municipal boundaries. This expands the search space and increases the complexity of the problem.

The second challenge faced is a result of the district officials imposing several practical requirements during the route optimization process for snow removal and material spreading activities. The requirements could be minor such as instituting turning restrictions and road prioritization or stricter such as service time limits for high-grade roads.

Even with the expanded depot count and additional practical constraints, the route optimization process could still be solved using the same solution algorithm proposed in **Chapter 3** by merely modifying the objective function to **Equation 5-1** below:

$$\text{Min} \sum_{\forall i}\sum_{\forall j}\sum_{\forall k}\sum_{\forall t} \psi_{i,j,k,t} \cdot l_{i,j} + U\_Turn + Left\_Turn + \frac{t}{T_k} \cdot x_{i,j,k,t} \cdot Rdclass_{i,j} \tag{5-1}$$

Here, the objective function is set to minimize the overall distance while reducing the number of undesired turning movements and giving route priority to select roads.

5.3.1 Turning Restriction

Turning movements can be dangerous as they often create movement conflict points that could result in a collision. For winter maintenance vehicles, the risks are compounded by the fact that they are quite heavy and large making for slow moving vehicles that require a lot of space to maneuver. Therefore, turning restrictions are put in place in order to mitigate the risks to the general public and the operators. To model turning movements in a computer-aided system, the turning angle is used to determine the various types turning behaviour (left turn, right turn, go straight, and U-turn) during operations. The turning angle can be understood as the angle from the truck's oncoming direction to the route's outgoing path. **Figure 5-4** illustrates the turning angle for the route sequence 207→224→295.

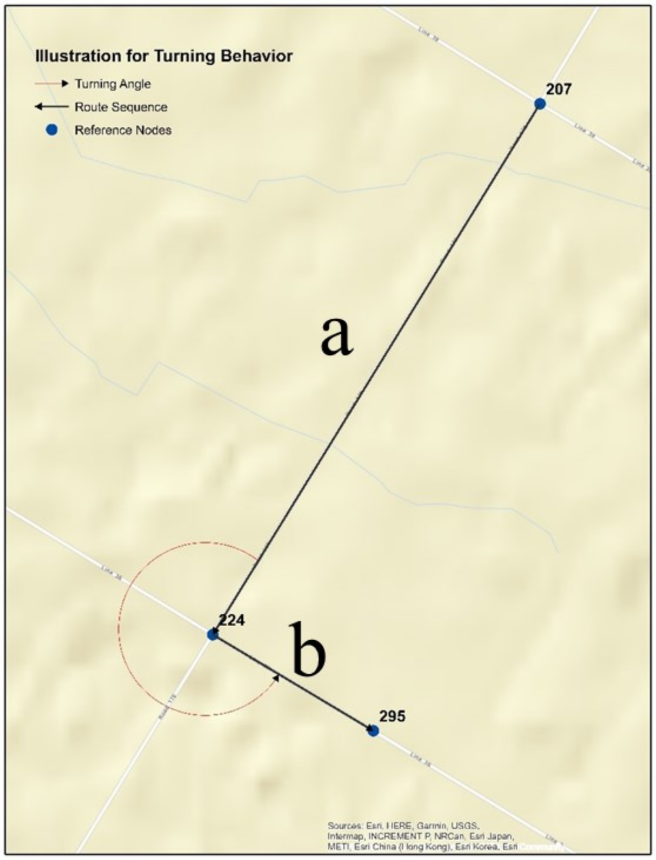


Figure 5-4. Illustration of turning angle calculation

Assume $\vec{a}$ represents the vector from node 207 to node 224, and $\vec{b}$ represents the vector from node 224 to node 295. Then θ is the resulting angle between vectors $\vec{a}$ and $\vec{b}$ and is defined as the turning angle for that path.

$$\vec{a} \cdot \vec{b} = \|a\|\|b\| \cos\theta \tag{5-2}$$

$$\theta = \cos^{-1}\left(\frac{\vec{a}\cdot\vec{b}}{\|a\|\|b\|}\right) \tag{5-3}$$

After determining the turning angle, the next step is to convert that turning angle into a rotation angle which is then used to detect if the movement is a possible turning behaviour.

$$v = \vec{a} \times \vec{b} \tag{5-4}$$

Let φ = rotation angle, then the following equation is:

$$\varphi = \begin{cases} \theta, if\ v > 0; \\ \theta + \pi, if\ v < 0; \end{cases} \tag{5-5}$$

Various thresholds were defined for different rotation angles to differentiate between left turn, right turn, and U-turn behaviours. The thresholds are as follows:

$$Turning\ Type = \begin{cases} left\ turn,\ if\ \pi/4 < \varphi \leq 3\pi/4; \\ right\ turn, if\ 5\pi/4 < \varphi \leq 7\pi/4; \\ U\ turn, if\ 3\pi/4 < \varphi \leq 5\pi/4; \\ Straight, if\ \varphi \leq \pi/4\ or\ \varphi > 7\pi/4\ ; \end{cases} \tag{5-6}$$

5.3.2 Road Prioritization Restriction

Road prioritization by agencies is meant to ensure that the greatest good is provided as fast as possible and this usually means prioritizing service on roads with a high traffic over roads with a low count. This does not guarantee that the best level of service for the whole road network is achieved, but is still a client-imposed constraint that must be met. **Equation (5-7)** sets the precedence constraint to ensure that higher classed roads are completely serviced first:

$$\text{Min} \sum_{\forall i}\sum_{\forall j}\sum_{\forall k}\sum_{\forall t} \frac{t}{T_k} \cdot x_{i,j,k,t} \cdot Rdclass_{i,j} \tag{5-7}$$

Equation (5-7) will rank the different routes generated from the heuristic algorithm according to their road priority performance. The optimization of the minimized road priority objective function is able to finish higher-class roads first before the lower classed roads.

5.4 Results and Discussions

To complete all the tasks as outline in section 5.1, the python coded algorithm made use of the supercomputer "beluga" managed by Calcul Québec and Compute Canada. With a 2.4 GHz CPU and 1GB of memory, it took around 5 hours for the proposed algorithm to run its course for each optimization case. The results of which are as follows:

5.4.1 Construction of Complete Geodatabase for Perth County

The established geodatabase contained four categories of data that required preparation from their various sources. These included the truck characteristic data, maintenance route data, and depot information from district officials, and the road network layer data from the Ontario Road Network (ORN). The base layer was set using the road network map from the ORN by including the number of lanes, road segment length, one-way/two-way information, and speed limit information. The crew information and maintenance data were provided in pdf excel file formats that needed to be converted into a geo-database format before it could be incorporated into the working geodatabase in ArcGIS. The depots were on their own database layer where detailed depot information, such as the number of available trucks and resource storage (see **Appendix B**) was embedded into the layer.

During the geo-coding process, a discrepancy between the pre-geocoded data and post-geocoded data was found. **Figure 5-5** suggests that the average difference between the pre-geocoded and post-geocoded data is 3.9%, which is considered as acceptable. One possible explanation for this discrepancy is that the pre-geocoded route miles provided were calculated based on manual tabular summation, which is likely to introduce a level of human error to the result.

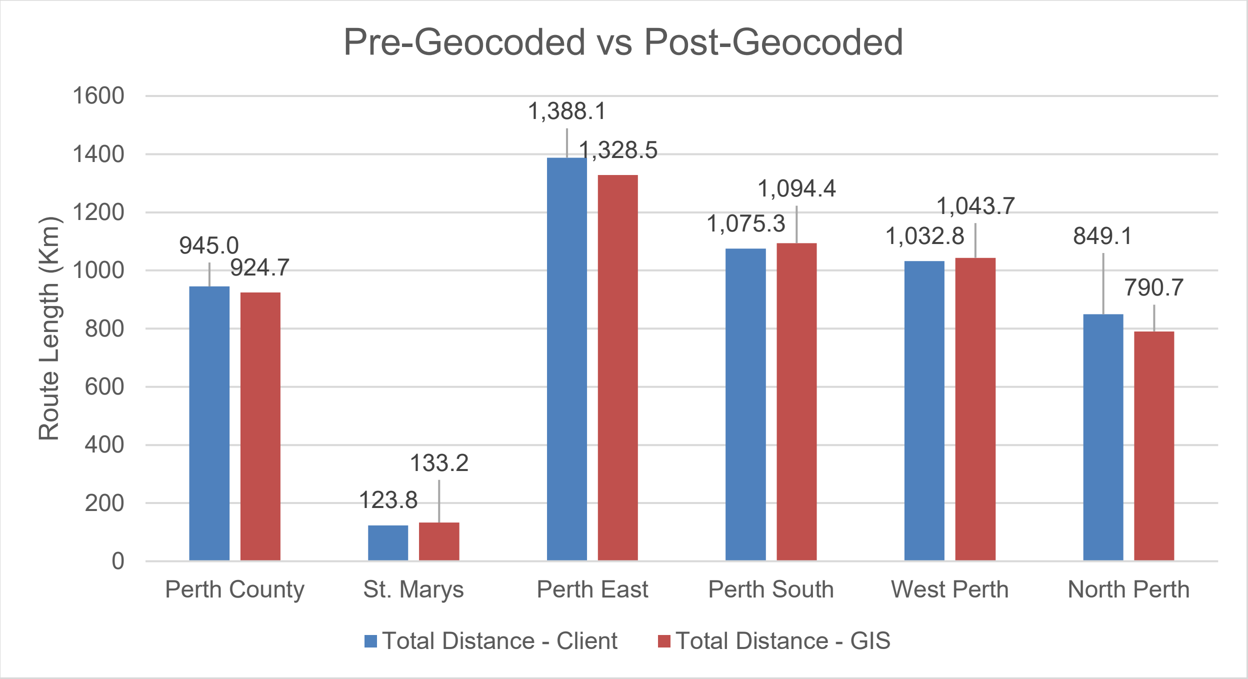


Figure 5-5. Total length difference between pre-geocode and post-geocoded

5.4.2 Optimization of Plow Routes with Existing Municipal Boundaries

After establishing the geo-database, the next step is to optimize the snowplow routes within existing municipal boundaries. The optimized results could evaluate the performance of current snowplow routes. The constraints in **Table 5-1** were implemented when generating snowplow routes (see **Appendix C** for the optimized snowplow routes). The optimization of existing routes within existing municipal boundaries saw a reduction of 3.2% in the total route length for spreader routes and 2.14% for grader routes.

Figure 5-6 illustrates the reduction rate for each municipality, which ranges from 0.9% to 5.83%. To ensure the feasibility, the study then checks the constraint of the minimum maintenance standard (MMS) and loading capacity for each generated route. The minimum maintenance standard restricts the maximum allowable completion time for each road class and any violation to the MMS in each road class will be treated as infeasible solution.

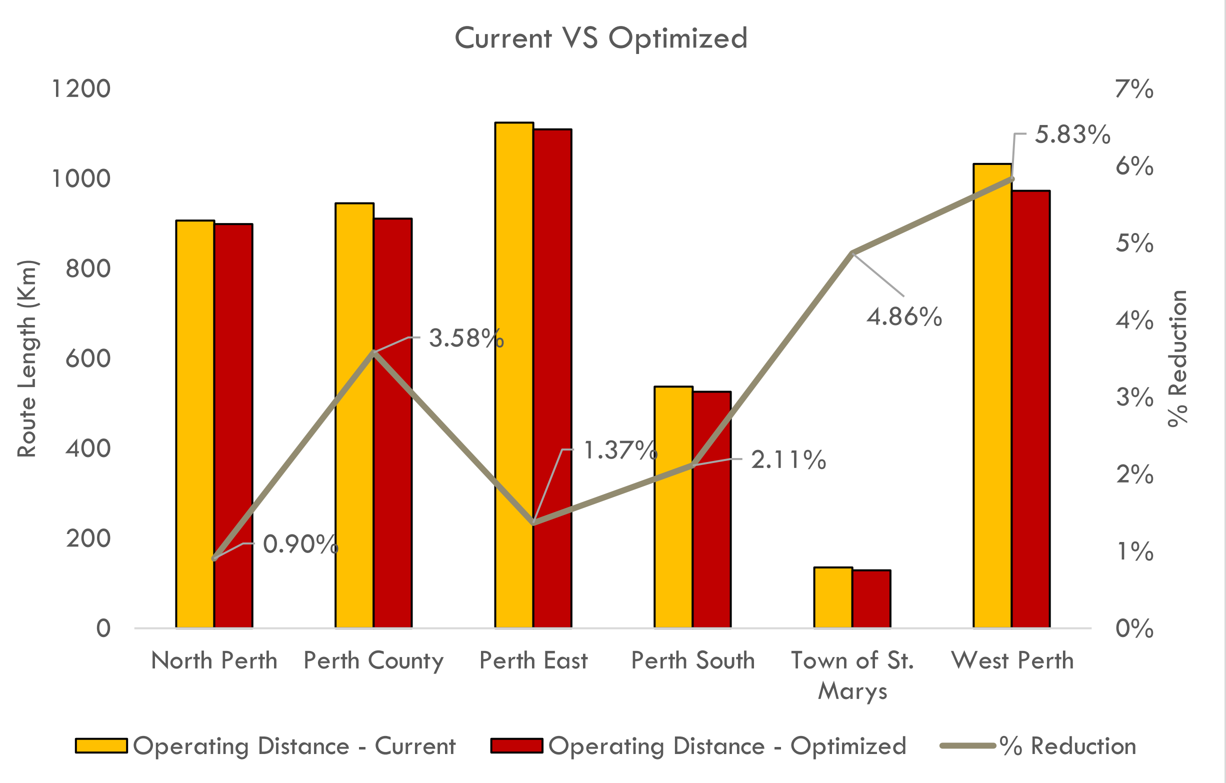


Figure 5-6. Spreader route optimization within existing municipal boundaries

Figure 5-7 describes the cumulative operating hours within each route versus the MMS. The result suggests that the truck will finish the service for each road class while also achieving or bettering the MMS requirement.

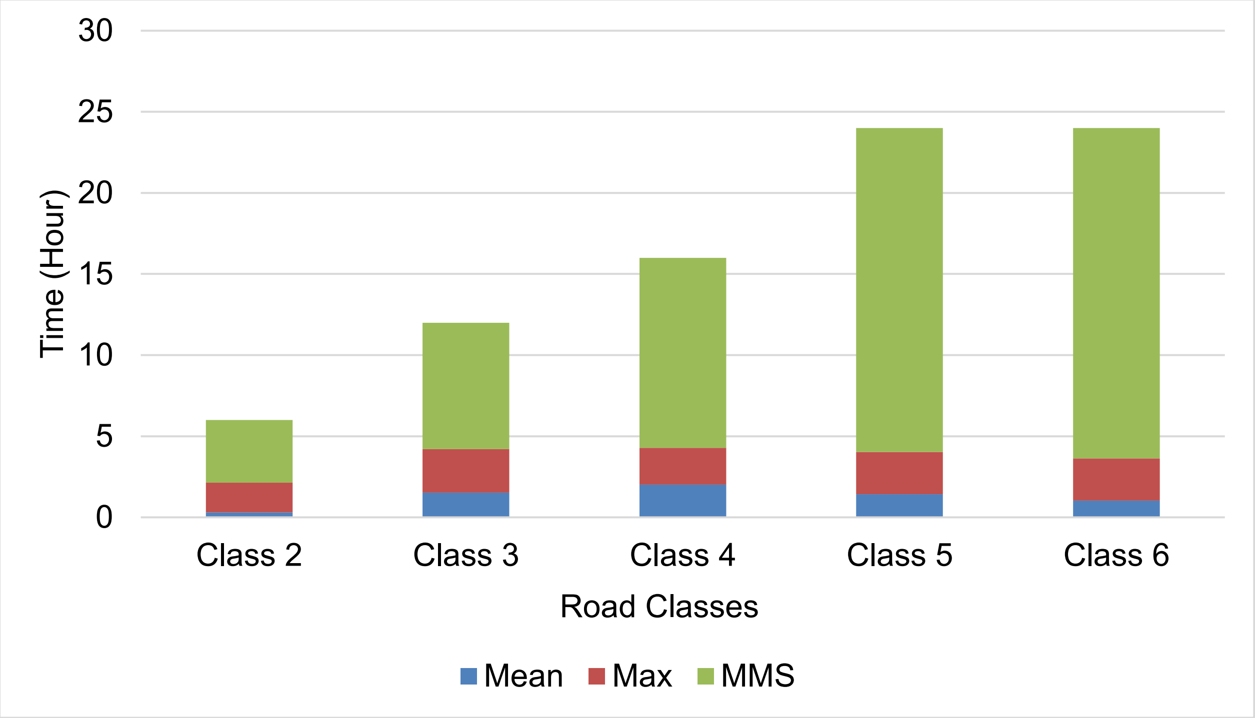


Figure 5-7. Accumulative operating hours by road classes

Figure 5-8 indicates that the estimated material usage for each plow truck is within the loading capacity when assuming the average salt/sand spreading rate. The results from ***Task 2*** provides a benchmark to compare to our optimized routes while also providing the client a measure of efficiency for their current routing scheme. If maintaining the current municipal boundary and depots, the total route lengths could be decreased by 3.2 percent by changing the routes for each truck.

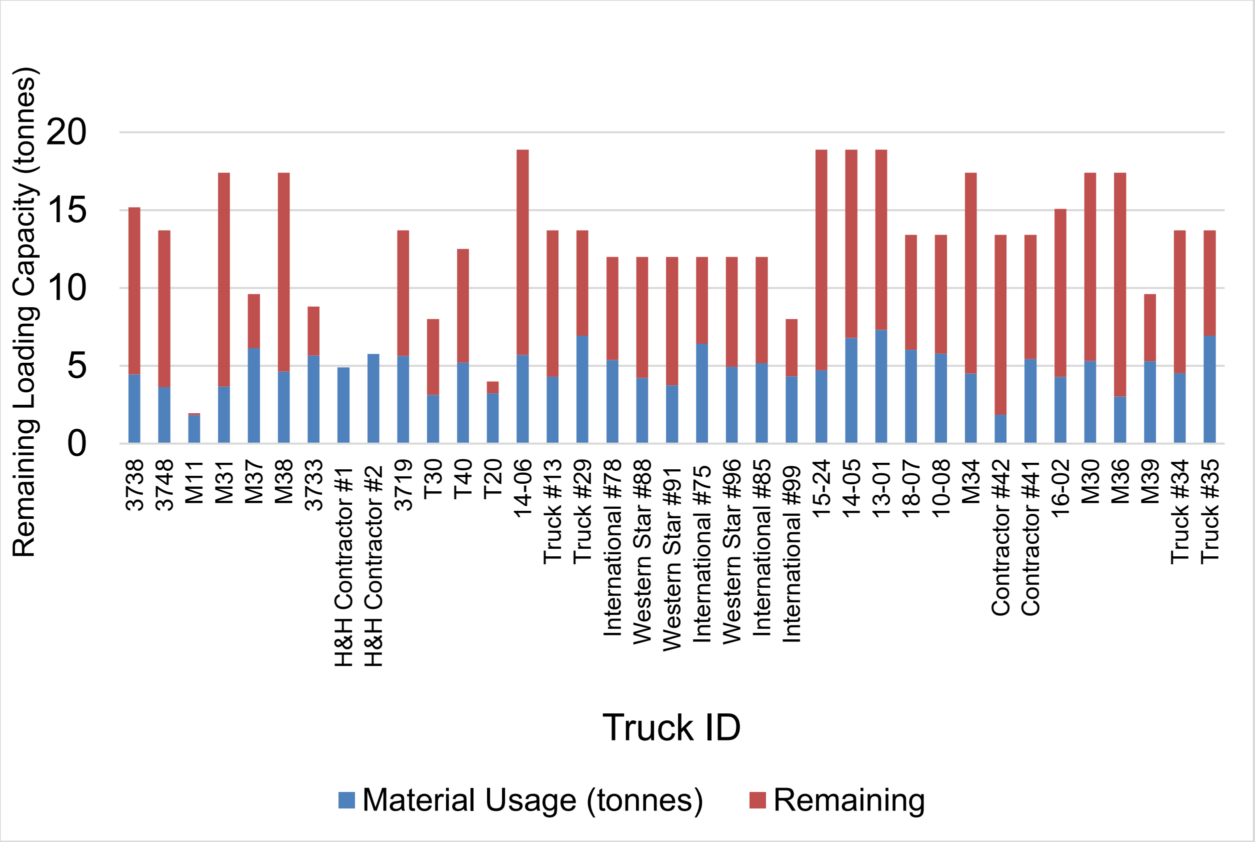


Figure 5-8. Estimated salt usage for different trucks

5.4.3 Optimization of Plow Routes by Intra-municipality Collaboration

In ***Task 3***, the maximum possible benefits achievable under the current fleet characteristics, existing maintenance yards while removing the municipal boundary and sharing maintenance resources was found. The collaboration between municipalities is defined as the sharing of the service area and maintenance resources. In doing so, the resources could be re-allocated or removed from a holistic viewpoint. The methods for collaboration are investigated using the following scheme: As the maintenance resources are shared amongst those within the county, many depots can possibly be retired to reduce the maintenance cost as long as the new maintenance strategies are feasible. Therefore, the maintenance yard removal scenario retired yards from service according to the yards' weighted function rank as shown in **Table 5-3**, and the snowplow routes that will be generated for each depot removal condition.

Table 5-3. Yard removal process

Yard Removed	Vehicles Removed (total)	Change in Total Route Distance
Blanshard	2	5%
Milverton (PC)	3 (5)	12%
Downie	3 (8)	18%

Every time a maintenance yard was removed from service, its assigned spreaders or plows were also removed, and its routes were assigned to the nearest remaining yards. The process was repeated until the optimized routes no longer met the constraints of the MMS service time or the spreaders' material capacity to complete the route. The optimized result suggests that removing the boundary could result in a 2% reduction in overall distance travelled. The MTO Listowel and Contractor's yards were eliminated prior to the beginning of the analysis, but the Contractor's service vehicles were retained. This result suggests that ten depots with a total of 37 vehicles is the least viable solution for depot removal. **Table 5-3** also shows that, on average, the route lengths will increase by 5%, 12%, and 18% if removing one, two, or three depots, respectively. Intuitively, the decrease in fleet size and depot numbers would result in longer average route lengths and an increase in the chance of violating the service standards. Refer to **Appendix D** and **E** for a record of the detailed route lengths and service times for the optimized snowplow routes.

Figure 5-9 lists the average remaining loading capacity for sand and salt for each depot removal scenario. For the three-depot removal scenario, the material usage for salt will exceed the truck loading capacity due to the limited capability of the salt spreading truck. The results suggest that the stopping criteria is met when four depots are retired, as the average sand usage would exceed the available truck capacity. Also, the maintenance time for each road class was checked for each depot removal scenario.

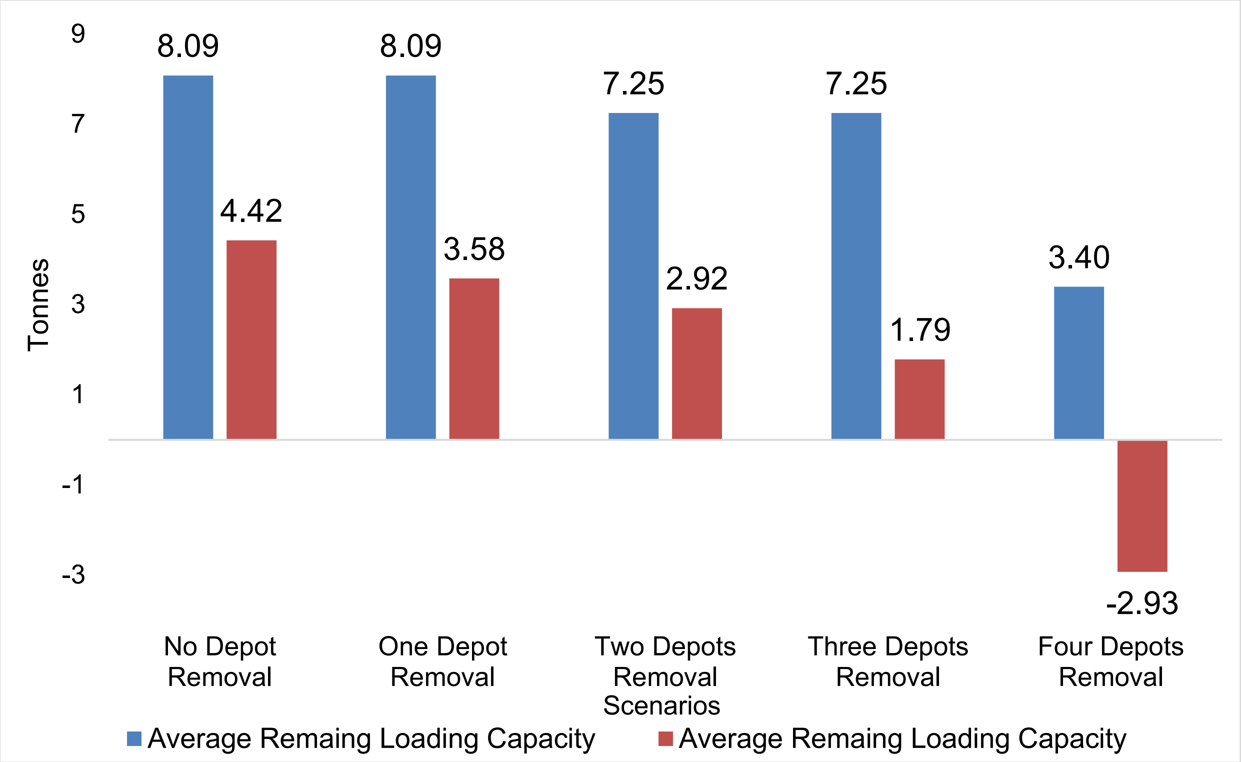


Figure 5-9. Remaining sand/salt loading capacity with yard removal

Figure 5-10 suggests that a general deteriorating level of service trend is noted when the available resources were decreased from 13 depot with 45 trucks to 10 depots with 37 trucks. Depot retirement reduces the availability of maintenance resources, which leads to the longer response times for each road class.

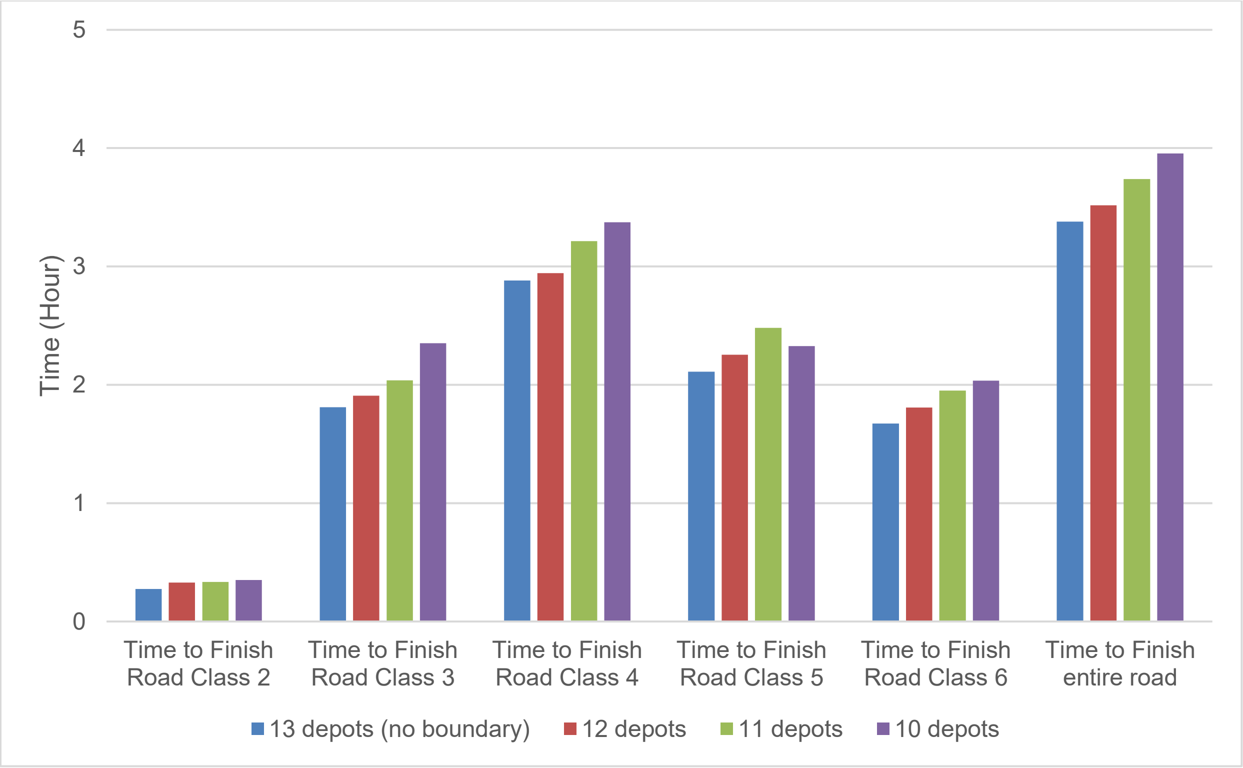


Figure 5-10. Average completion time per truck

5.4.4 Clean Slate Optimizations of Plow Routes and Depot Locations

Task 4 is an exercise in optimal depot location-allocation and a measure of how optimal the current layout is by comparing it to the theoretically ideal optimal depot location-allocations. This ideal optimum begins by removing all existing maintenance yards from the map and then generates an optimal configuration for a given number of yards (1 to 13) by applying the classic location modelling method, the *p-median method* (Mladenović & Daskin, 2007). This method's goal is to locate *p* number of facilities such that it minimizes the distance between the demand nodes and the nearest service facility. The algorithm iteratively searches for optimal locations that will maximize the route coverage of the road network. In this case, the facilities are the maintenance depots and the demand nodes are the mid-points of the arcs representing the road network.

The location optimization model was iteratively implemented to determine the recommended number of depots (density) and their spatial configuration. The constrained optimization algorithm started with 1 depot and then the number was incrementally increased to 13 depots. In order to make a comparison between depot densities, a total travel cost value (i.e., travel distance, potential service times, truck rental fees, operators' wage, etc.) for each configuration was calculated and normalized. The resulting plot is as shown in **Figure 5-11**.

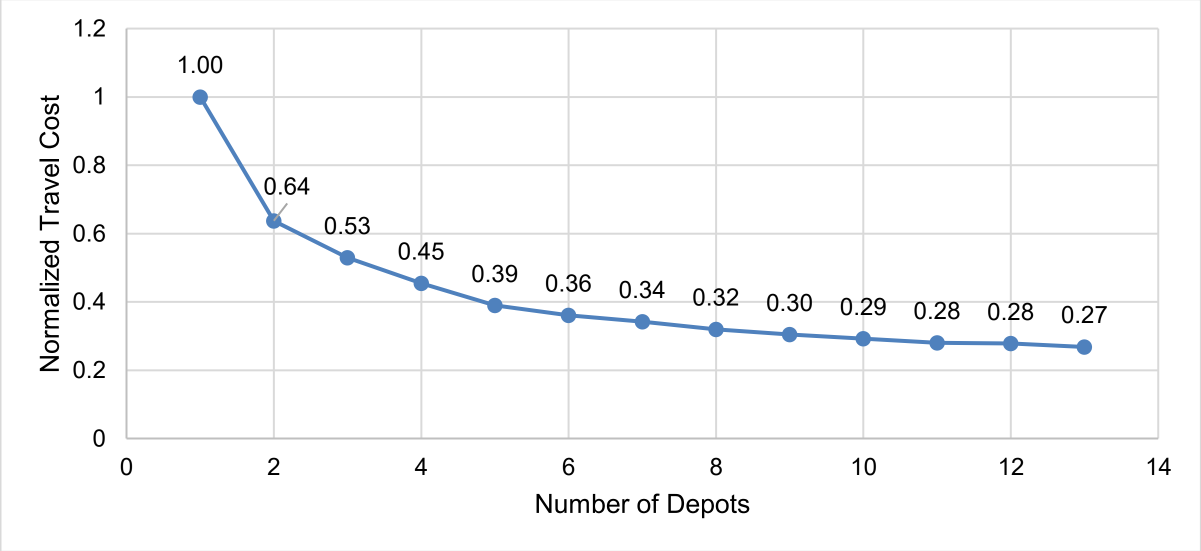
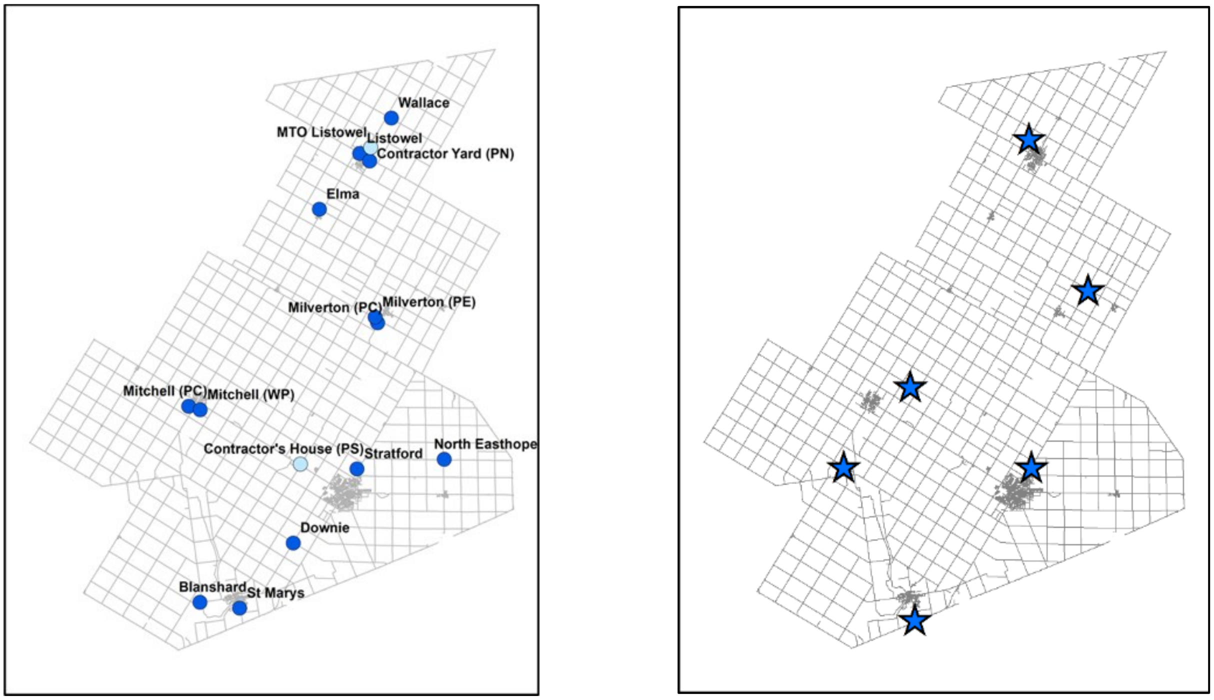


Figure 5-11. Depot density optimization curve

The plot clearly shows how the travel cost decreases as the number of depots increases, but also reveals that travel cost savings experiences diminishing returns. Given how the gain in marginal benefits tapers off so quickly, it stands to reason then that the optimum number of depots is between five and eight so long as all depots are positioned in their optimum location as opposed to their current locations. Therefore, from the results of ***Task 4***, the density of six optimally located depots was chosen to be used as a basis for route optimizations for individual trucks. **Figure 5-12** shows the existing depot locations, and 6 depots generated from the optimal location model. The truck resources for 6 depots were done by considering the spatial similarity to the current depot resource allocation for each depot. The number of trucks available for ***Task 4*** is 37 trucks, which is the minimum number of trucks needed to service the entire road network in ***Task 3*** while meeting service time and spreader capacity requirements as closely as possible. In doing so, the same constraints used in ***Tasks 2-3*** are applied to ***Task 4*** with an added assumption that a single spreader capacity be used for route optimizations.



(a) Existing 13 depots (b) Optimal 6 depot

Figure 5-12. Current depot locations and optimized locations

The same optimization step was used to output the optimized routes (refer to **Appendix F** for the detailed plow routes sequence). To demonstrate the performance of the optimization model developed for ***Task 4*** and its superiority over ***Task 3***, the level of service for ***Task 3*** (10 depots) and ***Task 4*** (all-new 6 depots) are respectively compared as shown in **Figure 5-13**. The result suggests that optimizing the location for 6 all-new depots will result in the same level of service as through the collaborative depot configuration, with selected depot retirements.

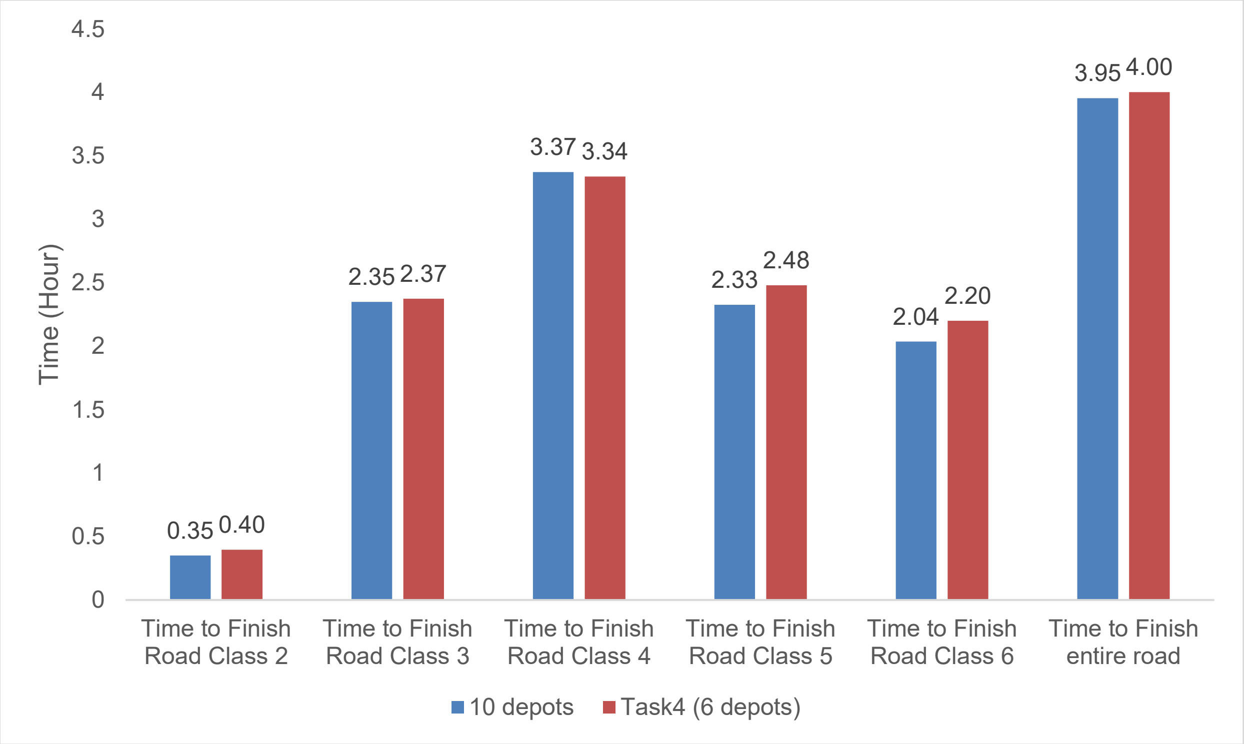


Figure 5-13. Comparison between Task 4 (all-new 6 depots) and Task 3 (10 depots)

5.4.5 Trade-off Analysis for Reduced Depot and Truck Numbers

When investigating the prospect of retiring a depot, there are costs and trade offs associated with it that must be considered. Every depot removed/retired will have a direct effect on the service levels, total distance travelled per truck, and material usage. As such, **Figure 5-14** is provided to summarize the service time ratio and the material volume to capacity ratio under different optimization scenarios. The material volume to capacity ratio shows an increasing trend when a depot is retired, suggesting that the average truckload will increase. The results of the service time ratio from ***Tasks 2*** and ***3*** showed a decreased trade-off suggesting that the optimized routes will lower the service times. One possible explanation could be the reduction in deadhead movements for the optimized routes thus decreasing the total distance travelled, and in turn increasing the level of service. However, when a depot is retired, so to are their assigned trucks. The resulting reduction in truck numbers leads to longer route lengths as each remaining truck will need to make up the difference. This naturally results in a reduced level of service as service times and expenditures increase. It is interesting to note that in ***Task 4,*** where the total number of trucks is maintained while the number of depots was reduced from 10 to 6, there was a reduction rate of approximately 7 percent in the service ratio while the material volume to capacity ratio remained the same.

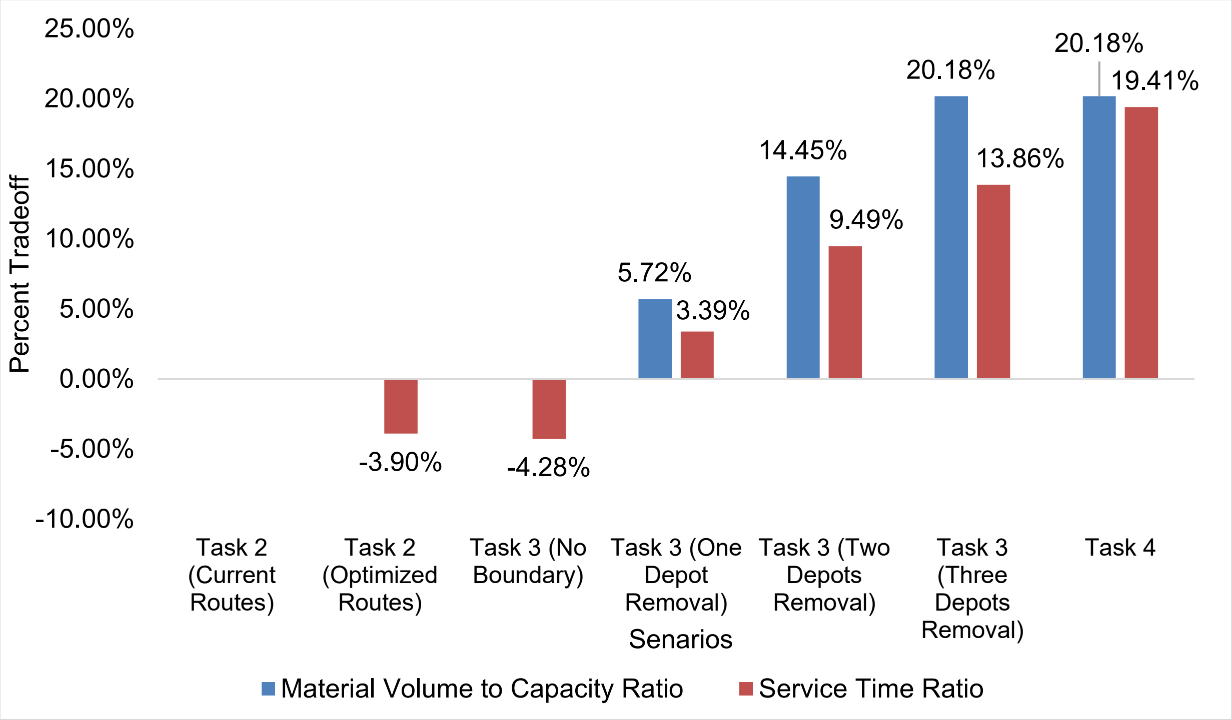


Figure 5-14. Trade off analysis using task 2 current routes as a basis

5.5 Summary

This chapter complements the proposed framework by dealing with a more realistic scenario where the routes are optimized with shared municipal boundaries and road maintenance sources. To understand the efficiency of its current routes, plow routes were optimized based on the current boundary configuration, available trucks, and depot distribution providing a baseline for the highest possible benefit achievable under the current, individualistic municipal setup. The extensive amount of time and efforts were put forth to generate a fully-connected and comprehensive geodatabase as it served as a basis for undertaking all remaining tasks. The result of ***Task 2*** (optimized vs current) suggests that the average route length can be reduced by 3.2% without the changing service boundary or sharing resources. Next, this study investigated the possible benefits from cooperation between municipalities (***Task 3***). Two types of cooperation were used to reduce maintenance costs; the amalgamation of boundaries and the sharing of maintenance depots. Amalgamating boundaries created more room for route optimization, and shared depots allows for the removal of redundant depots (***Task 4***). The result suggests that amalgamating boundaries could result in a 2% reduction in the total travelled distances when compared to optimizing within boundaries, and the sharing of depots could allow for the retirement of 3 depots and 8 trucks without violating their practical requirements. To evaluate the benefits of the new depot configuration, a *p-median* based approach was used to assign the depots. Thirty-seven trucks were assigned to six depots based on its spatial similarity to the existing resource configuration. The results show that 6 optimally located depots can achieve a level of service comparable to that of 10 non-optimally located depots through city partnerships. Finally, as the reduction in depot numbers and fleet sizes could negatively impacting the level of service of their WRM operations, a trade-off analysis for their depot removal plan was conducted to evaluate the relationship between the level of service and the number of depots removed in an objective manner. Trade-off analysis shows that service times would get longer as the number of depots and winter road maintenance trucks decreases, while the average material volume to capacity ratio stayed the same as the number of depots decreases. These results can be used to determine the optimal number of depots that can be decommissioned. For example, managers can be provided with the optimal number of depots based on the level of service they would like to retain.

Chapter 6. CONCLUSIONS

Restoring and maintaining traffic mobility and safety is a crucial task in winter transportation. Transportation authorities are responsible for the design, strategic planning, and operational management of winter maintenance operations that maintain a high level of service. One way to achieve their operational goals is to maximize their service vehicle operations via optimizing snow plow routes.

As a way to compare and contrast the benefits from snowplow route optimization, the proposed plow route optimization method constructed upon a novel K-PPP technique was applied over two case studies. The first case study looked at its benefit in a future hypothetical setting where technology has advanced enough such that a fully connected vehicle (CV) environment has been achieved and drivers can now take advantage of real-time road condition information. This case study shows the impact that route service order has on the overall efficiency of the road network from the driver's point of view in a fully CV world. The second case study applied the optimization framework to a real-world project where the optimization of routing strategies can be used to adjust service plans, fleet sizes, and even maintenance depot densities and locations. This case study showcases the framework's ability to be utilized to solve a real-world problem by providing the clients the necessary information for them to make operational decisions.

6.1 Research Findings

This section summarizes the findings from both case study scenarios.

Scenario I: Snowplow routes optimization in a simulated CV environment.

- This case study evaluated the efficiency of the tabu search algorithm by checking the performance of the objective function’s system traffic delay for each iteration. The results suggest that the optimization process remains stable after 700 iterations. Compared to the initial solution, the tabu search algorithm can help reduce the total system travel time by around 22 hours under the static routing condition and 21 hours for the dynamic routing condition. The result indicates that the proposed tabu search algorithm could improve the solution gradually over 700 of iterations.
- Two different routing strategies were taken into consideration for the snowplow route planning phase. The static routing strategy is a case where vehicles are unconnected and drivers will choose the route based on historical road information. The dynamic routing strategy is a case where road users choose their paths based on real-time road information. The comparison between them suggests that the CV environment could reduce system traffic delay by 0.3 hours and 97.4 hours compared to the unconnected environment and no snow condition, respectively. Based on this result, it was proven that the road users' travelling time could be reduced if they are provided with the latest road condition information so that they can make real-time route adjustments while on-route.
- The optimization of snowplow routes by minimizing system traffic delay has the added benefit of also being a decision support tool for fleet size management. When the number of snowplow trucks increases from one to two, the reduction in traffic delays from the resulting snowplowing activities increases from 61.7 to 101.0 hours, indicating a total decrease in travel times by 39.3 hours. Likewise, the total reduction for travel time will decrease to 23 hours when the truck number increases from two to three. By tracking the diminishing marginal benefit as the number of trucks increases, decision makers can make

a more informed decision on their desired fleet size, which in turn can be used to determine the optimal number of maintenance depots desired.

Scenario II: Real-world application of snowplow route optimization

- This research evaluated the current performance of Perth County's existing snowplowing strategy by optimizing snowplow routes that minimizes the overall distance travelled while keeping the current maintenance depot configuration. Prior to doing so, the entire existing road network of Perth County has been assimilated, processed, and constructed on a GIS platform for computer manipulations and representation. The optimization problem formulated earlier was modified to take account for both operational and legislative constraints. The results of the route optimization suggest that the reduction rate of the overall distance travelled for each municipality ranges from 0.9% to 5.83%. While maintaining the minimum maintenance standard (MMS) as set by the province. With relatively small gains, the current snowplow strategy for Perth County could be regarded as already efficient. The results also found that if Perth County decides to maintain the current service boundaries, then optimizing the routes within each zone will still result in total route length savings of 3.2% for spreaders and 2.14% for graders.
- To understand how many maintenance depots could be retired if the municipalities within Perth County started to share depots and maintenance resources, this study generated optimized snowplow routes for different depot configurations. The results indicate that the total route distance will change by 5% by removing one depot, 12% by removing two depots, and 18% by removing three depots. Intuitively, fewer depots will increase the chance of overloading trucks as they have to pick up the slack left by the retired depots and

their assigned trucks. From the material usage perspective, the loading capacity for current snowplow trucks is insufficient when a fourth depot is removed, suggesting that the maximum number of depots that can be retired for Perth county is three.

- To understand the performance of the non-optimally placed depots under their current setup, but with intra-municipal collaboration, a clean-state approach was taken to depot placement. In this case, the p-median method was employed to iteratively determine the optimal depot location-allocation for 1 to 13 depots. Then for each clean-slate depot configuration, the same route optimization framework was used to generate feasible and optimal snow plowing route solutions. Via this density analysis, it was found that having 5 to 8 optimally placed depots is the optimal clean-slate solution while also accounting for the total travel costs (i.e., travel distance, potential service times, truck fees, wages, etc.). For comparison purposes, 6 clean-slate optimal depots were chosen and had its optimal snow plowing route solution determined. After comparing the results, it was found that 6 clean-slate optimally placed depots will perform just as well as the snow plow route solution for the collaborative depot configuration after select depot retirements.

6.2 Research Contributions

The primary contribution of this thesis was the development of a new methodological framework aimed at solving the challenging k-truck plowing with precedence problem (K-PPP). Before this research, very few studies have ever investigated the precedence problem for snowplow route optimization, especially for multiple trucks. This study defines this problem and applies a metaheuristic algorithm for generating near-optimal solutions.

The second contribution made by this thesis is the planning of snowplow routes for the future CV environment. By considering the interaction between road users and truck operators, this study investigates how the routing strategy could be designed in the connected vehicle environment while taking into account the road users' real-time traffic demand and dynamic routing decisions. Previous research failed to investigate the effects of the road users' routing choices on achieving the desired winter maintenance service level. For example, the road user's real-time routing choices in models to date are independent of the planning of snow removal routes. Additionally, this study proposes a new depot optimization process by retiring redundant service depots through intra-municipality collaboration. Allocating and operating depots requires a substantial amount of finances, workforce, space, and time, the availability of which is limited. Therefore, this study proposed a framework to evaluate operational conditions where potential depots are removed/retired one at a time. The results of the framework provide a comprehensive and convincing decision support tool for the retirement of excess depots.

From a practical standpoint, this study helped to investigate the potential benefits of intra-municipality cooperation through shared routes, depots, and merged municipal boundaries. Starting with the creation of a comprehensive geographical database for the entirety of Perth County, this system allowed for the interaction between municipalities to solve their common problems in a holistic manner. Secondly, should the municipalities decide not to merge their resources, this study also generated optimized snow plowing routes while maintaining the existing maintenance strategy, resource allocation, and municipal boundaries. The resulting, non-holistic snow plow routes still reduced the total travel length by about 3.2% and can be used as a guideline for future implementation. The Perth County case study further showed that they could remove up to three depots and still be able to maintain their operational and legislated commitments to a minimum level of service. Generally, the level of service has a downward trend as available resources are retired or removed as in the case of going from 13 depots with 45 trucks, to 10 depots with 37 trucks. This analysis helped the region identify depot decommissioning issues along with any potential maintenance cost savings.

6.3 Future Research

This thesis proposed a new framework that could be modified to support WRM strategies and decision-making processes in fleet and resource management in both the real-world and in an idealized CV world. By introducing the precedence problem in snowplow routes optimization, this study deals with realistic constraints and road users during winter maintenance operations. Nevertheless, this research can also be improved by incorporating more advanced solution techniques, case studies, and sensitivity analysis.

Improvements to the extensible framework can take the following directions. Current studies assume that all arcs serviced were under snow-covered conditions. However, for a large-scale network, weather events tend to vary over space and time. Therefore, road conditions should be modelled in a stochastic way in order to capture the temporal and spatial heterogeneity of the road conditions over the entire network. It would also be interesting to compare the efficiencies differences between different solution algorithms for solving the proposed K-truck plow with precedence problem. Possible future algorithms could include the genetic algorithm, local search scheme, and dynamic programming.

Since proposed method for snowplowing in a simulated connected environment was tested using a hypothetical road network with assumed traffic demands, future research could utilize real-world datasets to test the validity of the method presented and ascertain the conclusiveness of the results found herein. Likewise, future research could create a sensitivity analysis to investigate how the resulting optimal routes could change when external factors such as free-flow speeds, traffic demands distributions, weighting parameters etc. are incorporated into the framework (i.e., different connected vehicle penetration rates).

A future research direction for real-world snowplowing could be the cost-benefit analysis for the depot retiring process, thus helping managers decide how many depots could be closed from a cost-benefit perspective. Current studies focus on investigating the maximum number of depots that could be removed while satisfying the operational rule. A possible extension is to incorporate crew cost information, depot maintenance expenditure information, and material usage cost to estimate the financial cost for each depot configuration. It would help clients decide how many depots could be removed from a practical application standpoint.

At the same time, by testing the WRM strategy for a differing number of trucks stationed at a depot, the resource allocation for the clean state analysis can be further investigated. Additionally, a sensitivity analysis for the weight of penalty term can be conducted to analyze how optimal routes will change when stricter constraints are imposed. This can be especially helpful in generating customized operational management guidelines that meet a client's requirements.

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Appendix A: Ranking List for Depots in Perth County

Yard Name	Municipality	Address	Murray's Ranking of Existing Operations
Mitchell (PC)	Perth County	4 Napier Street, Mitchell, ON	2
Stratford	Perth County	4312 Perth County Road 119, Gads Hill, ON	4 (tied)
Milverton (PC)	Perth County	6372 Perth Road 131, Milverton, ON	11
St Marys	St Marys	408 James St S, Lakeside, ON	3
Milverton (PE)	Perth East	4700 Line 61, Perth East, ON	1
North Easthope	Perth East	2188 40 Line, New Hamburg, ON	5
Downie	Perth South	3193 County Rd 122, Saint Pauls Station, ON	9
Blanshard	Perth South	1766 Perth Rd 139, Granton, ON	12
Mitchell (WP)	West Perth	50 Arthur Street, Mitchell, ON	8
Elma	North Perth	171 Monument Rd, Palmerston, ON	6
Listowel	North Perth	580 Main Street West, Listowel, ON	7
Wallace	North Perth	5882 88 Line Gowanstown, ON	4 (tied)
MTO Listowel	North Perth	245 McDonald St E, Listowel, ON	10

Appendix B: Active Depots and Truck Resources

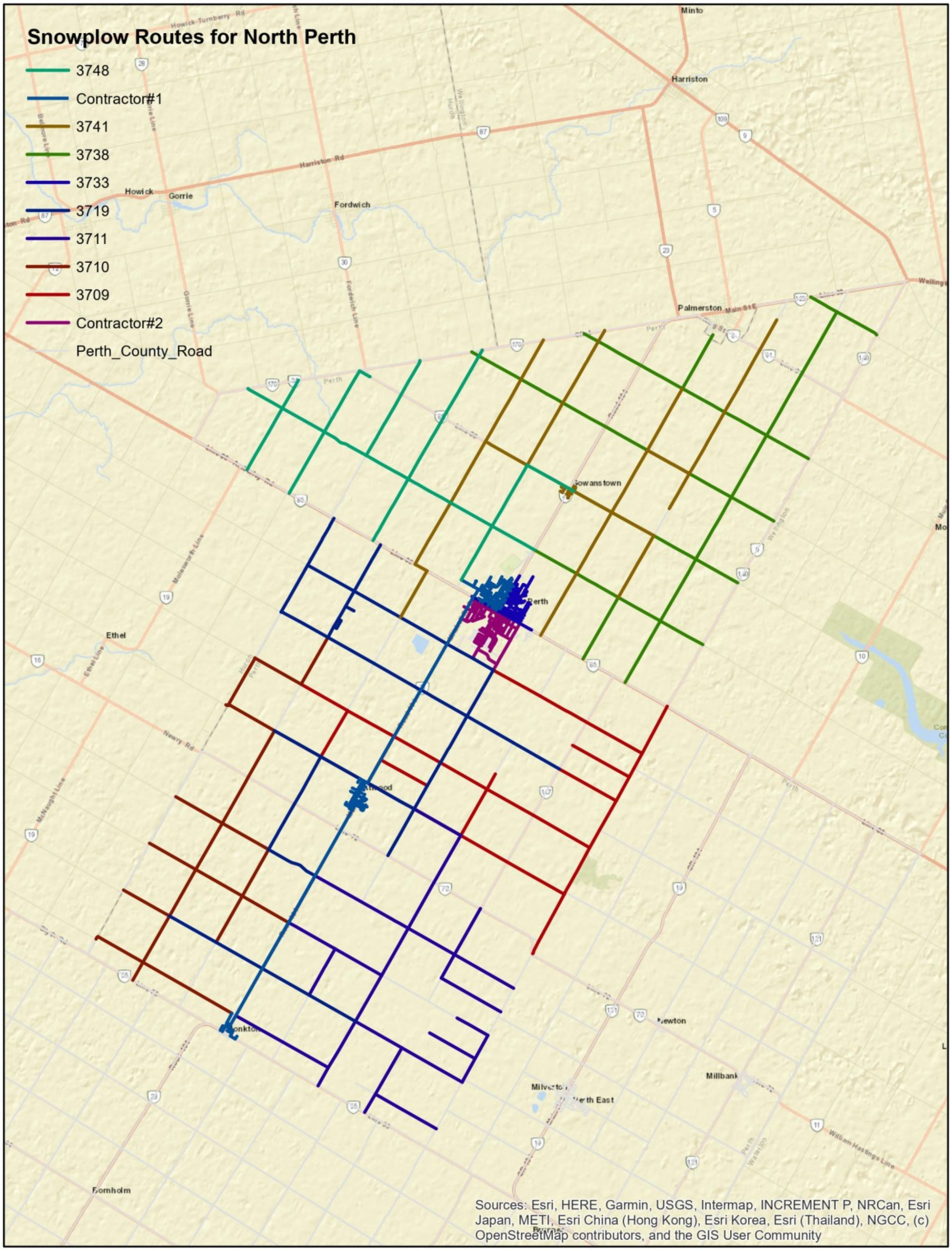
Agency	Depot	Route ID	Truck ID	Truck Type	Number of Axles	Spreader Capacity (tonnes)
North Perth	Contractor Yard (PN)	Beat A	H&H Contractor #1	Single Axle	1	4.895
North Perth	Listowel	Beat B	3733	Single Axle	1	8.811
North Perth	Contractor Yard (PN)	Beat C	H&H Contractor #2	Single Axle	1	4.895

North Perth	Elma	Beat D	3709	Grader	N/A	N/A
North Perth	Elma	Beat E	3710	Grader	N/A	N/A
North Perth	Elma	Beat F	3711	Grader	N/A	N/A
North Perth	Elma	Beat G	3719	Tandem	2	13.706
North Perth	Wallace	Beat H	3738	Tandem	2	15.175
North Perth	Wallace	Beat I	3748	Tandem	2	13.706
North Perth	Wallace	Beat J	3741	Grader	N/A	N/A
North Perth	Contractor Yard (PN)	Beat K	H&H Contractor #1	Single Axle	1	4.895
Perth County	Milverton (PC)	Route 1	16 02	Tandem	2	15.07
Perth County	Milverton (PC)	Route 2	Contractor #41	Tandem	2	13.42
Perth County	Milverton (PC)	Route 3	Contractor #42	Tandem	2	13.42
Perth County	Stratford	Route 4	10 08	Tri Axle	3	13.41
Perth County	Stratford	Route 5	18 07	Tri Axle	3	13.41
Perth County	St Marys	Route 6	14 06	Tri Axle	3	18.89
Perth County	Mitchell (PC)	Route 7	15 24	Tri Axle	3	18.89
Perth County	Mitchell (PC)	Route 8	14 05	Tri Axle	3	18.89
Perth County	Mitchell (PC)	Route 9	13 01	Tri Axle	3	18.89
Perth East	Milverton (PE)	22	M22	Grader	N/A	N/A
Perth East	Milverton (PE)	27	M27	Grader	N/A	N/A

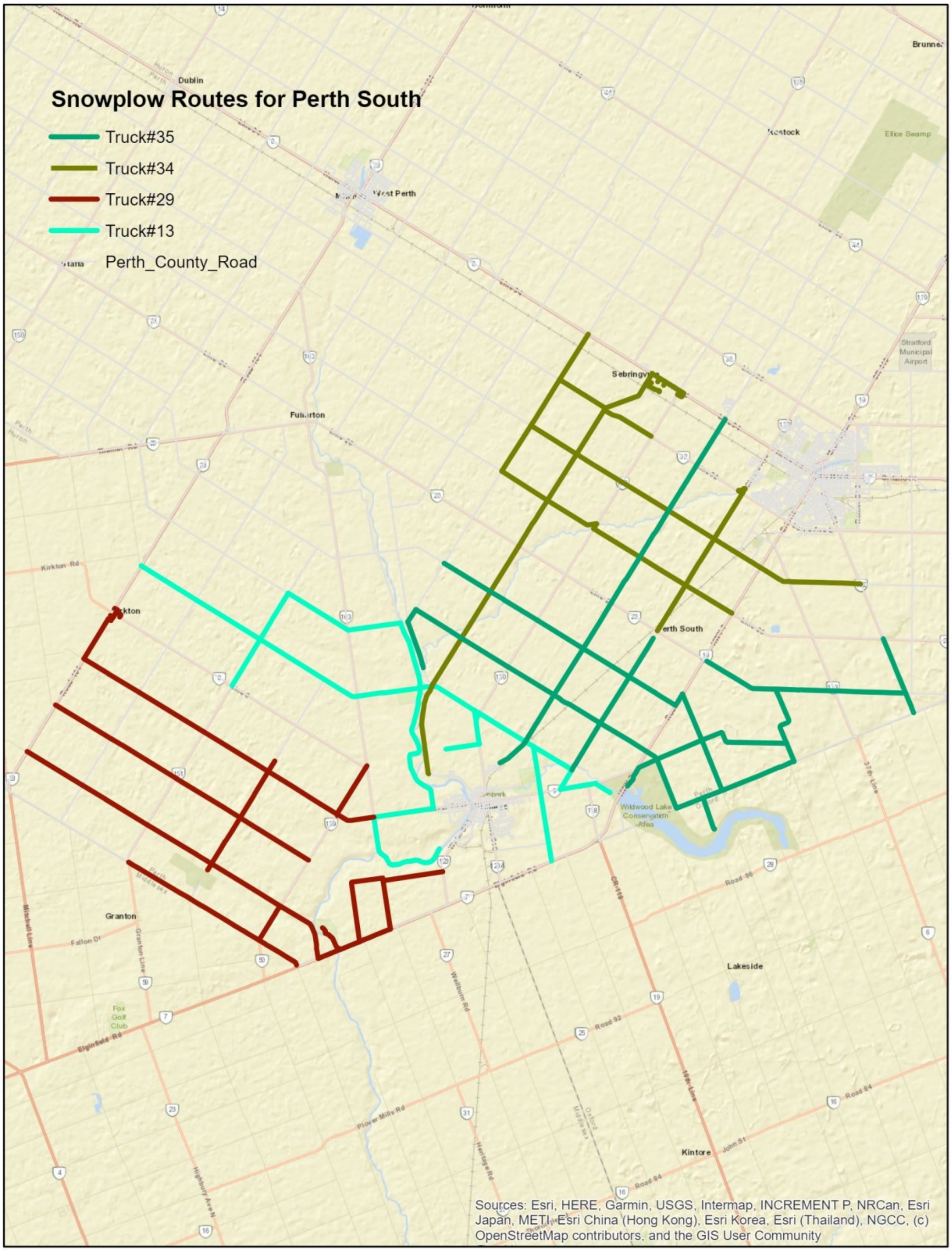
Perth East	Milverton (PE)	30	M30	Tri Axle	3	17.4
Perth East	North Easthope	31	M31	Tri Axle	3	17.4
Perth East	Milverton (PE)	34	M34	Tri Axle	3	17.4
Perth East	Milverton (PE)	36	M36	Tri Axle	3	17.4
Perth East	North Easthope	37	M37	Tandem	2	9.6
Perth East	North Easthope	38	M38	Tri Axle	3	17.4
Perth East	Milverton (PE)	39	M39	Tandem	2	9.6
Perth South	Downie	PR1	Truck #34	Tandem	2	13.706 (16.643 tonnes with 10" sideboards)
Perth South	Downie	PR2	Truck #35	Tandem	2	13.706 (16.643 tonnes with 10" sideboards)
Perth South	Blanshard	PR3	Truck #13	Tandem	2	13.706 (16.643 tonnes with 10" sideboards)
Perth South	Blanshard	PR4	Truck #29	Tandem	2	13.706 (16.643 tonnes with 10" sideboards)

St Marys	St Marys	J-30	J39	Parking Lot Type Vehicle	N/A	N/A
St Marys	St Marys	T-20	T20	Single Axle	1	4
St Marys	St Marys	T-30	T30	Single Axle	1	8
St Marys	St Marys	T-40	T40	Tandem	2	12.5
West Perth	Mitchell (WP)	Fullerton North	Western Star #96	Tandem	2	12
West Perth	Mitchell (WP)	Fullerton South	International #85	Tandem	2	12
West Perth	Mitchell (WP)	Hibbert North	International #78	Tandem	2	12
West Perth	Mitchell (WP)	Hibbert South	Western Star #88	Tandem	2	12
West Perth	Mitchell (WP)	Logan Grader	J.D. 772G #74	Grader	N/A	N/A
West Perth	Mitchell (WP)	Logan North	Western Star #91	Tandem	2	12
West Perth	Mitchell (WP)	Logan South	International #75	Tandem	2	12
West Perth	Mitchell (WP)	Mitchell Ward	International #99	Single Axle	1	8

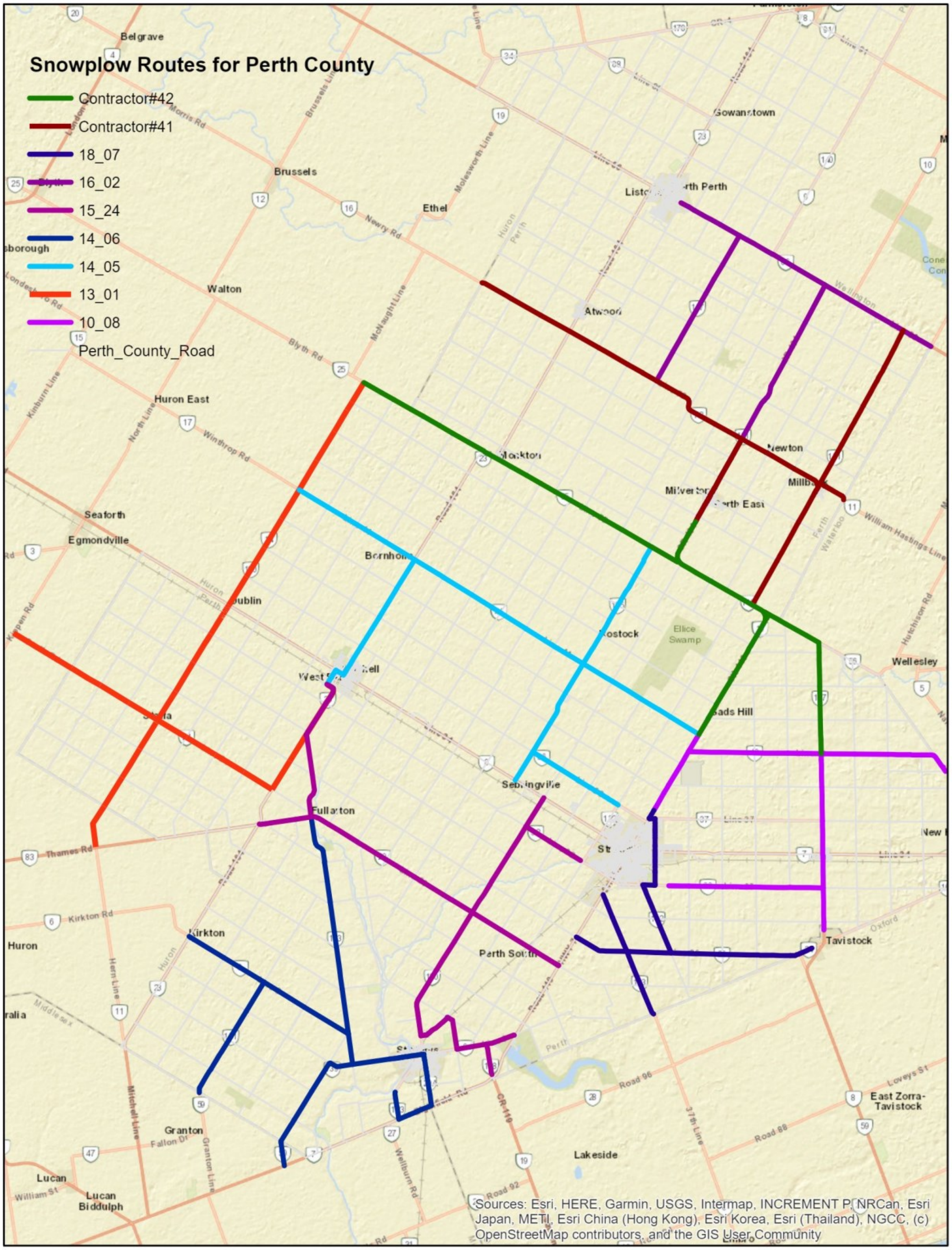
Appendix C: Optimized Plow Routes for Task 2



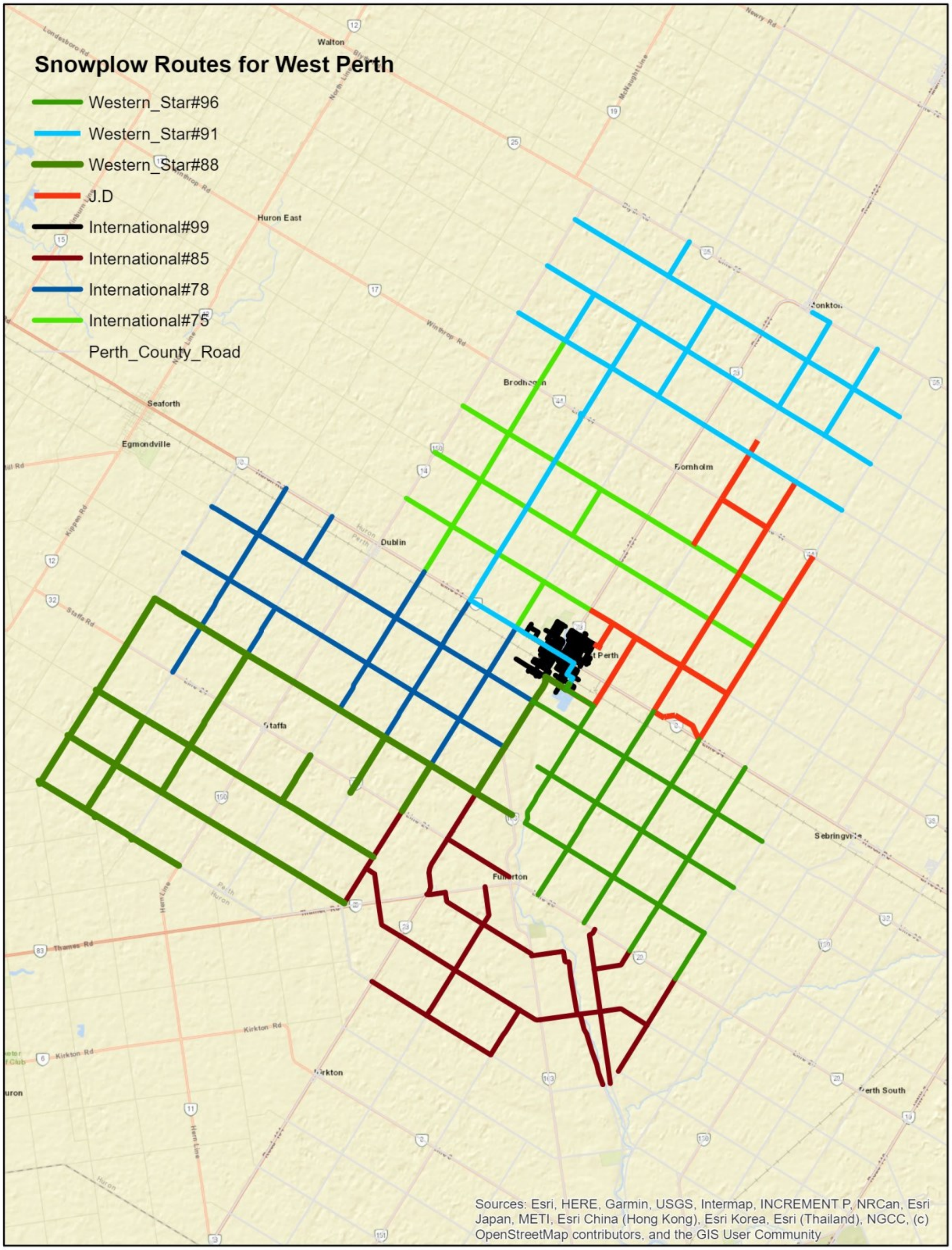
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community



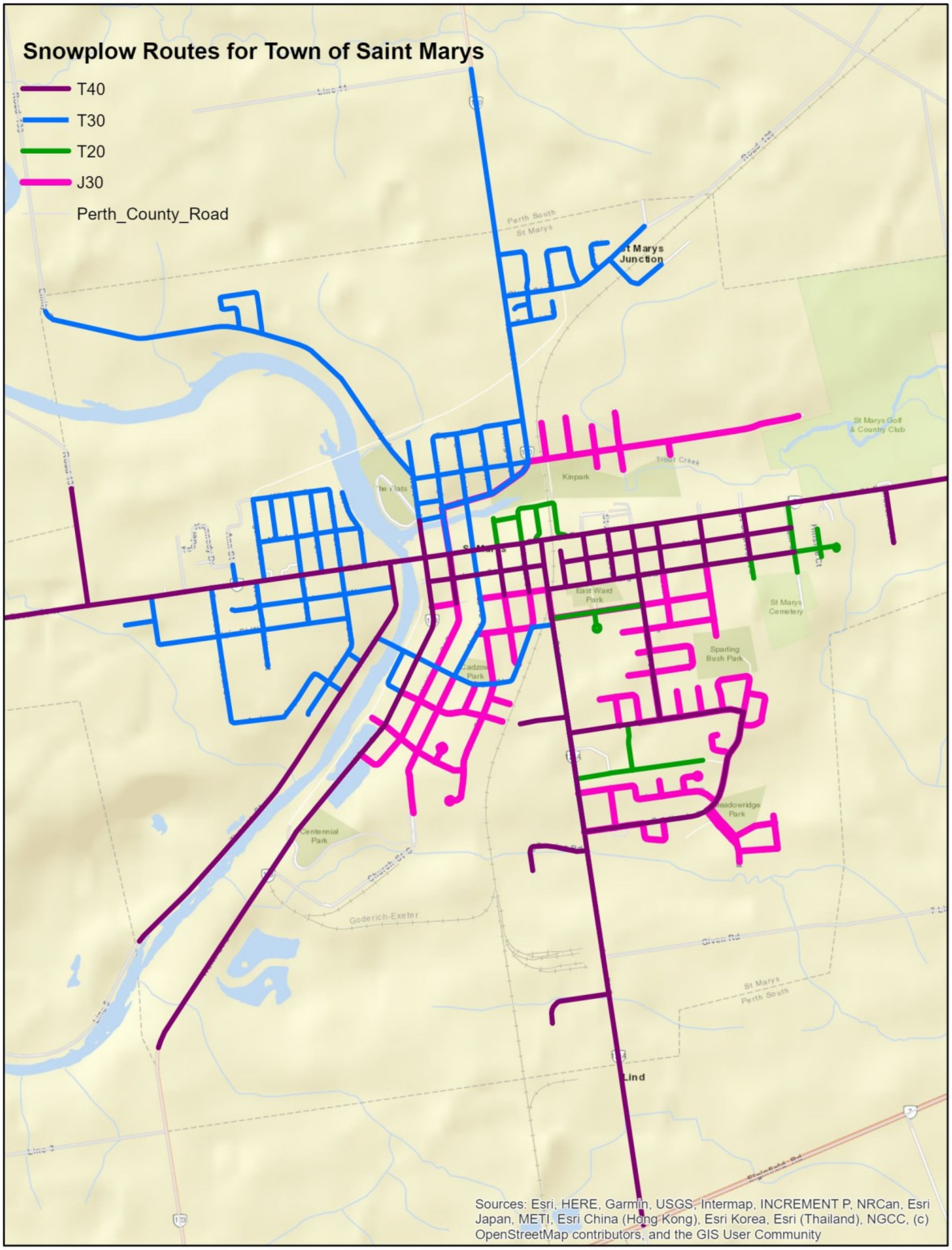
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community



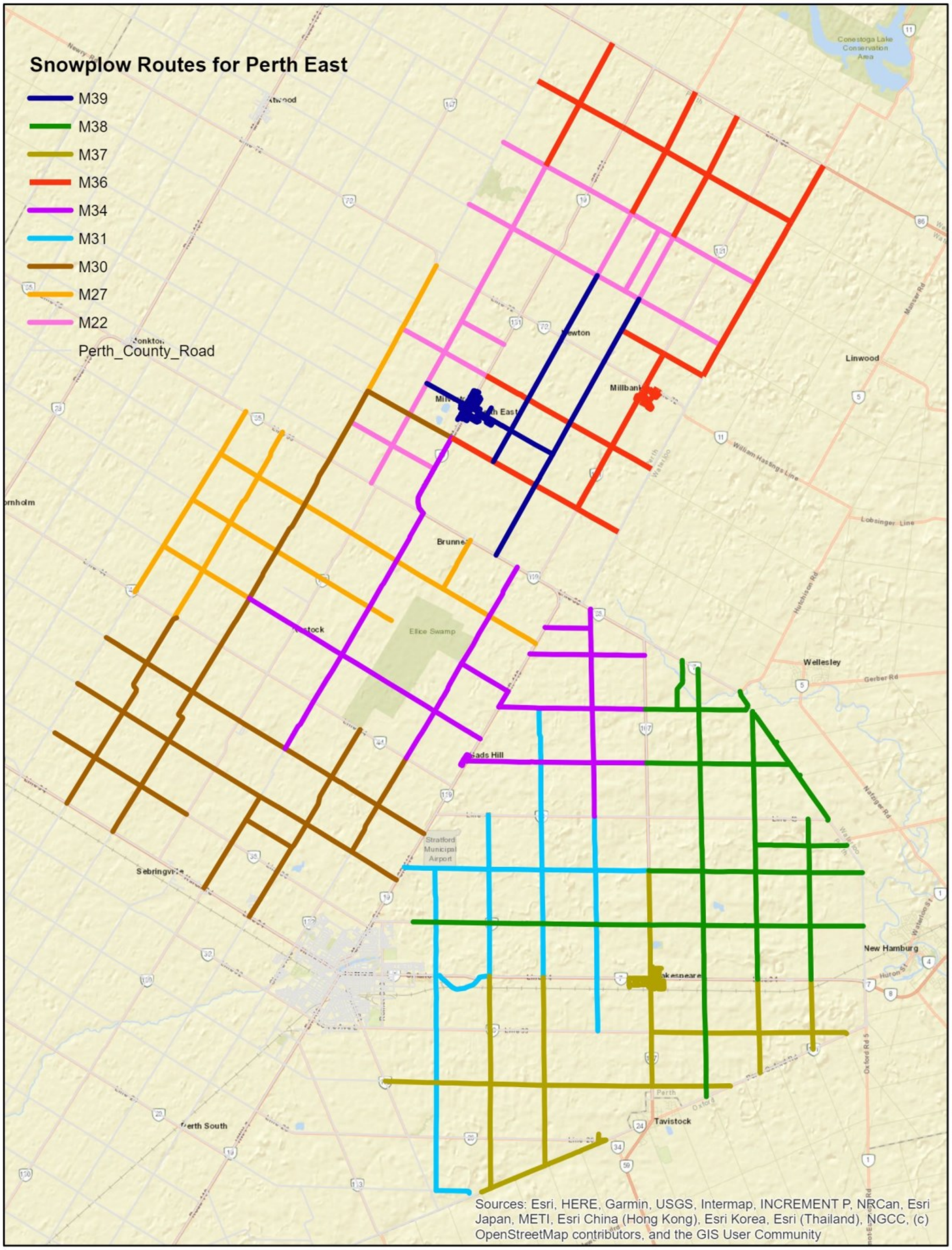
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community



Snowplow Routes for West Perth
Western_Star#96
Western_Star#91
Western_Star#88
J.D
International#99
International#85
International#78
International#75
Perth_County_Road
Walton
Huron East
Brodhagen
Seaforth
Egmondville
Dublin
Bornholm
Monkton
Staffa
Fullarton
Sebringville
Kirkton
Perth South
Thames Rd
Kirkton Rd
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

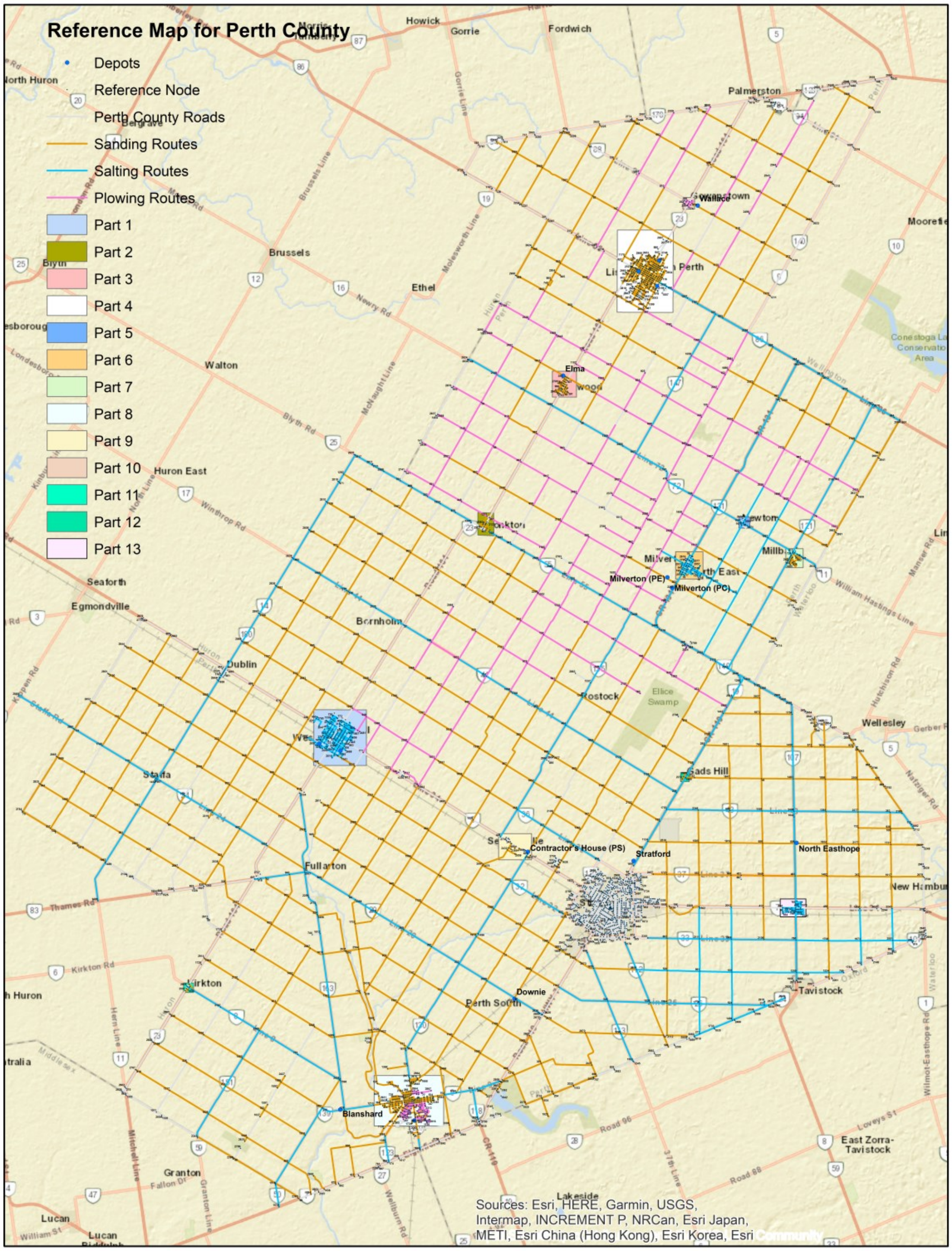


Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

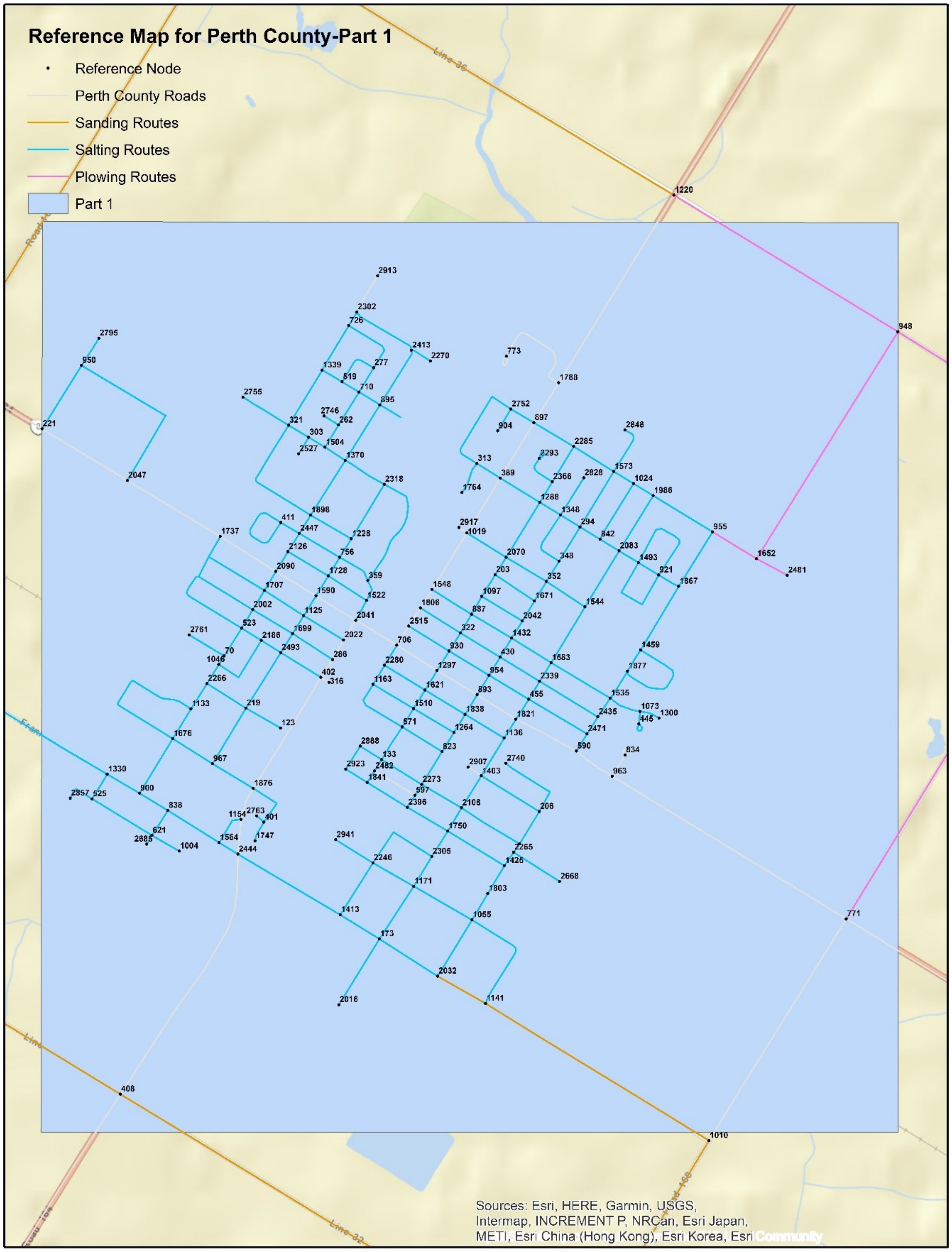


Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Appendix D: Reference Maps for Task 3 and Task 4

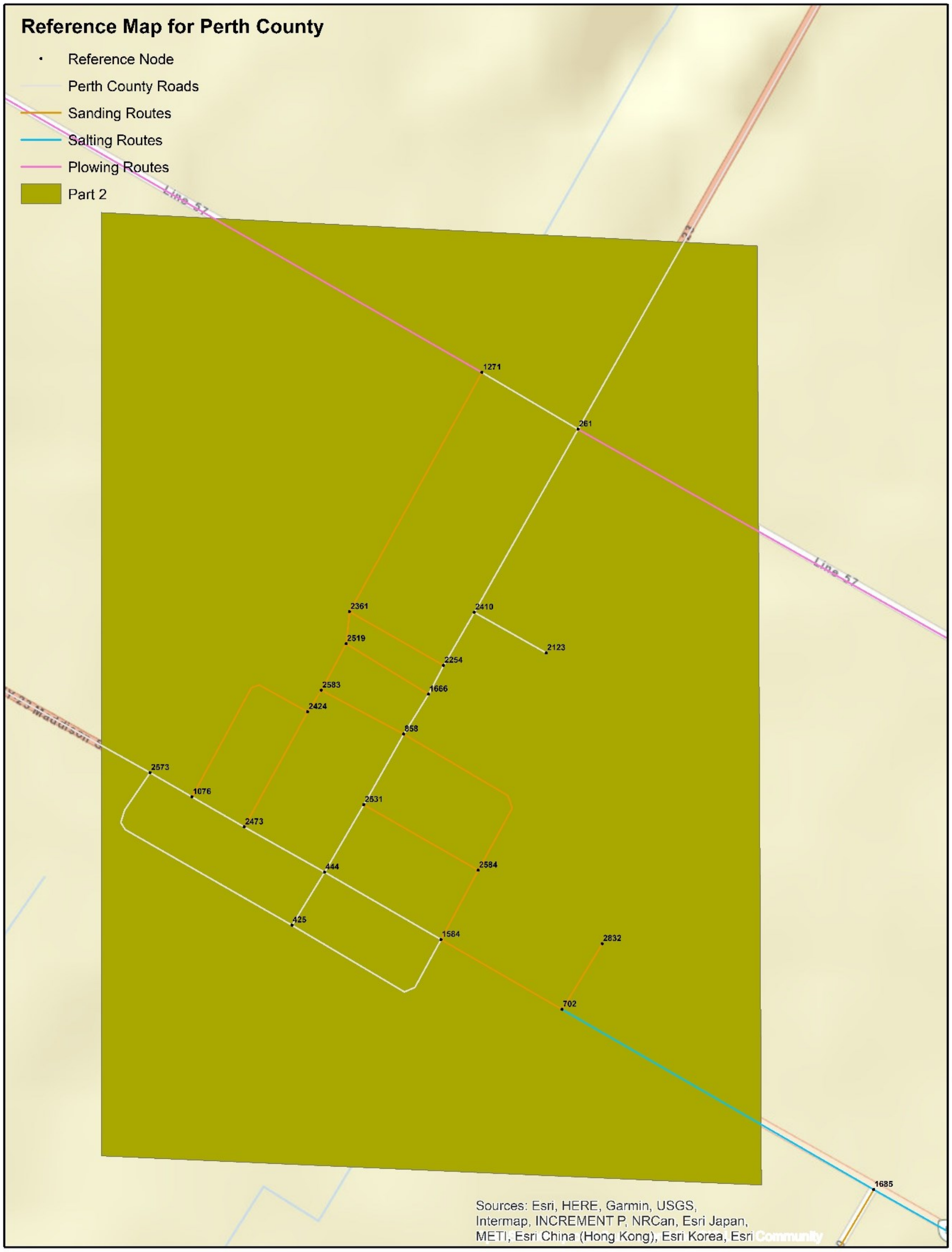


Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri



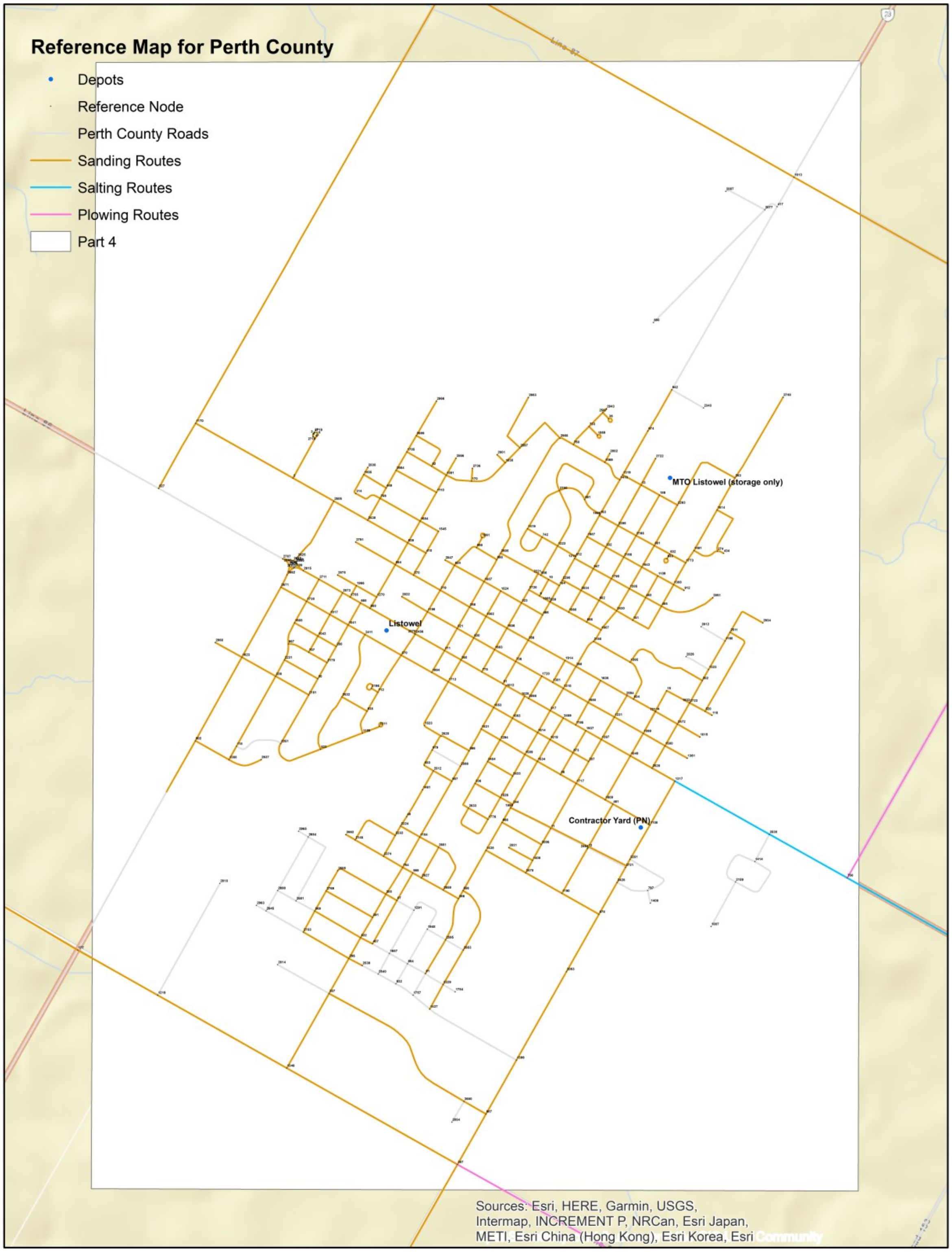
Reference Map for Perth County-Part 1

Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community

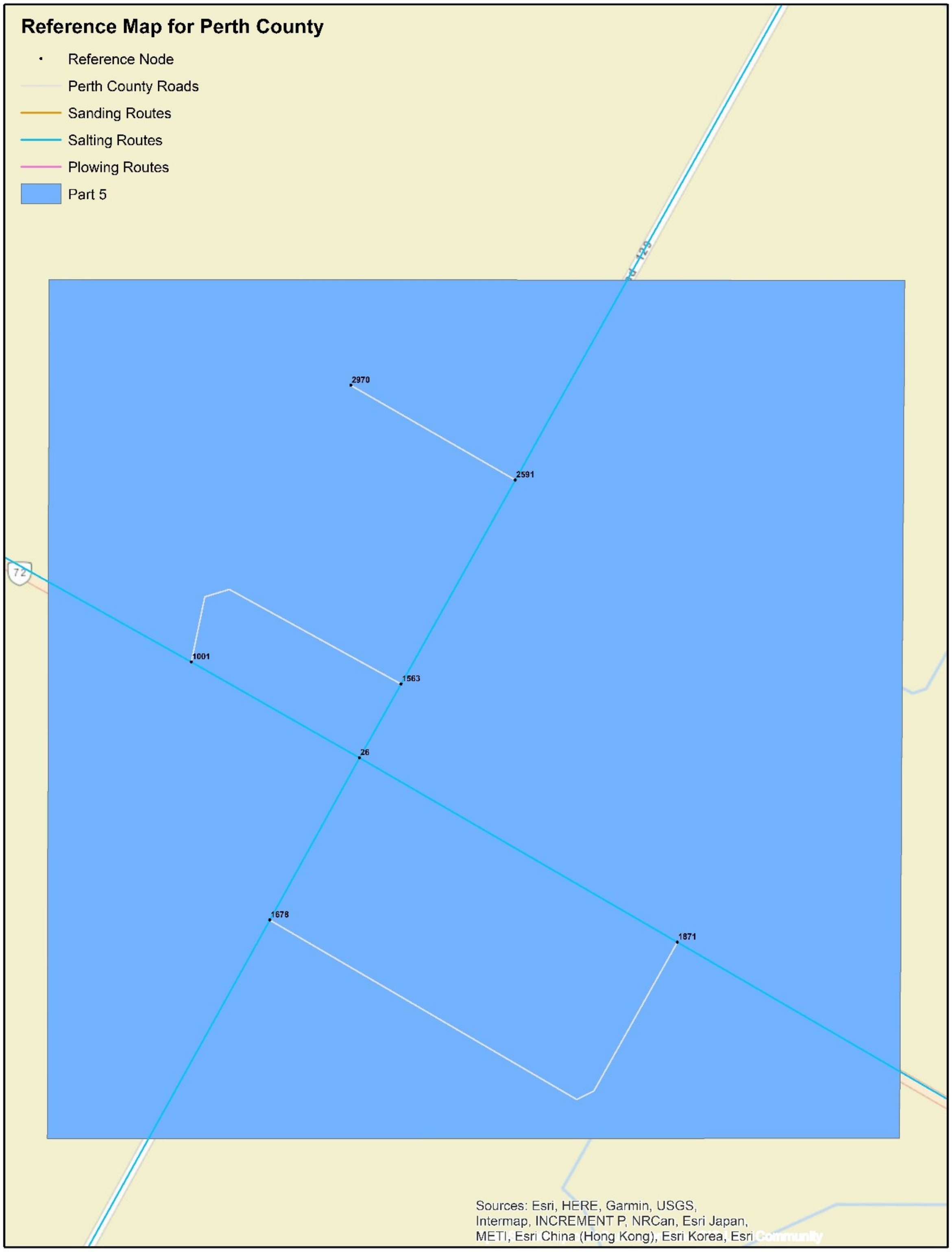


Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community

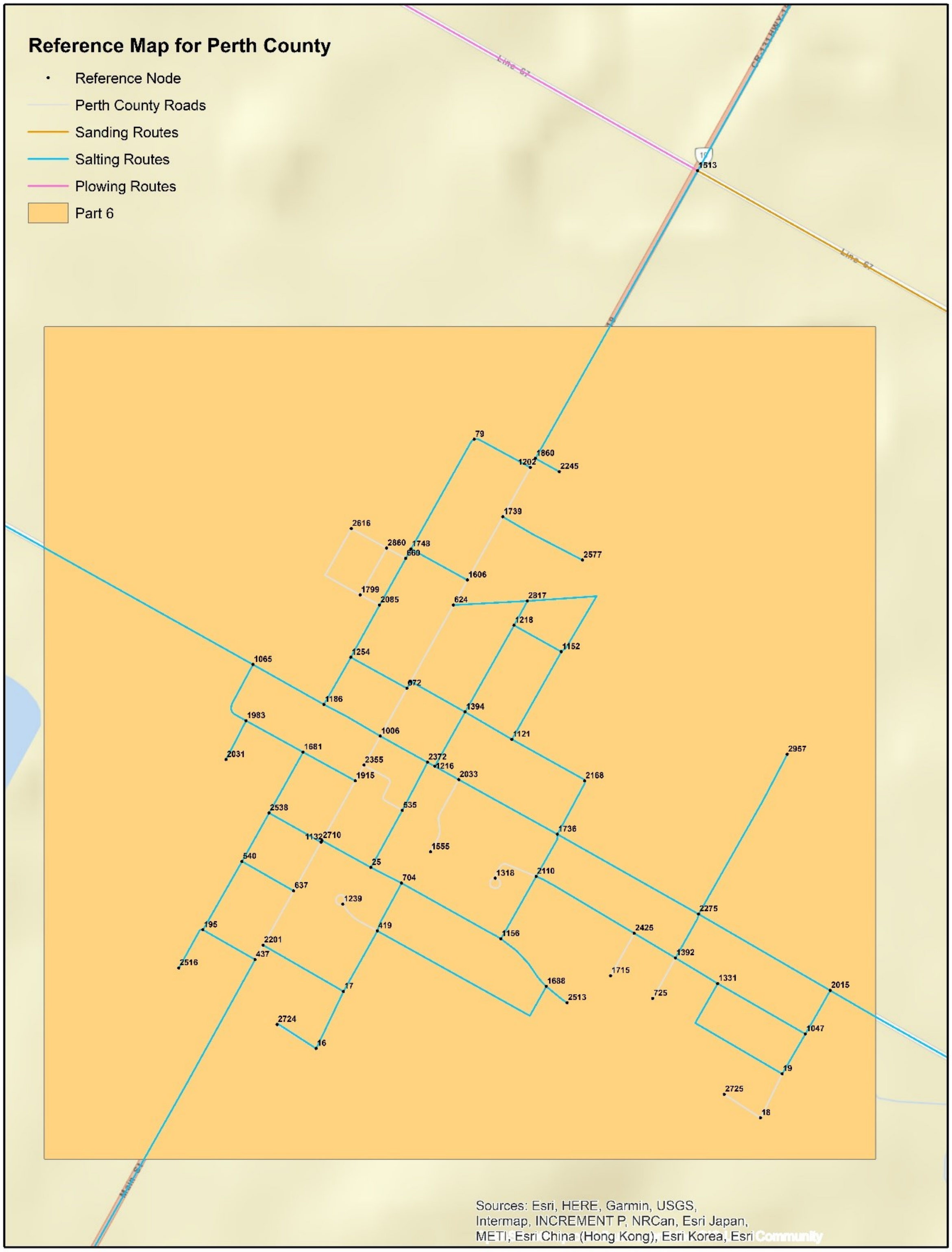

Reference Map for Perth County
Reference Node
Perth County Roads
Sanding Routes
Salting Routes
Plowing Routes
Part 3
2469
2446
243
2464
1088
2233
2371
507
2578
2729
1311
1070
60
2785
705
23
803
2940
2415
882
406
2554
1909
1778
996
943
1546
122
2782
708
2699
1222
2962
2376
2779
2189
2871
1946
643
2644
391
2647
2669
42
1662
2703
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community



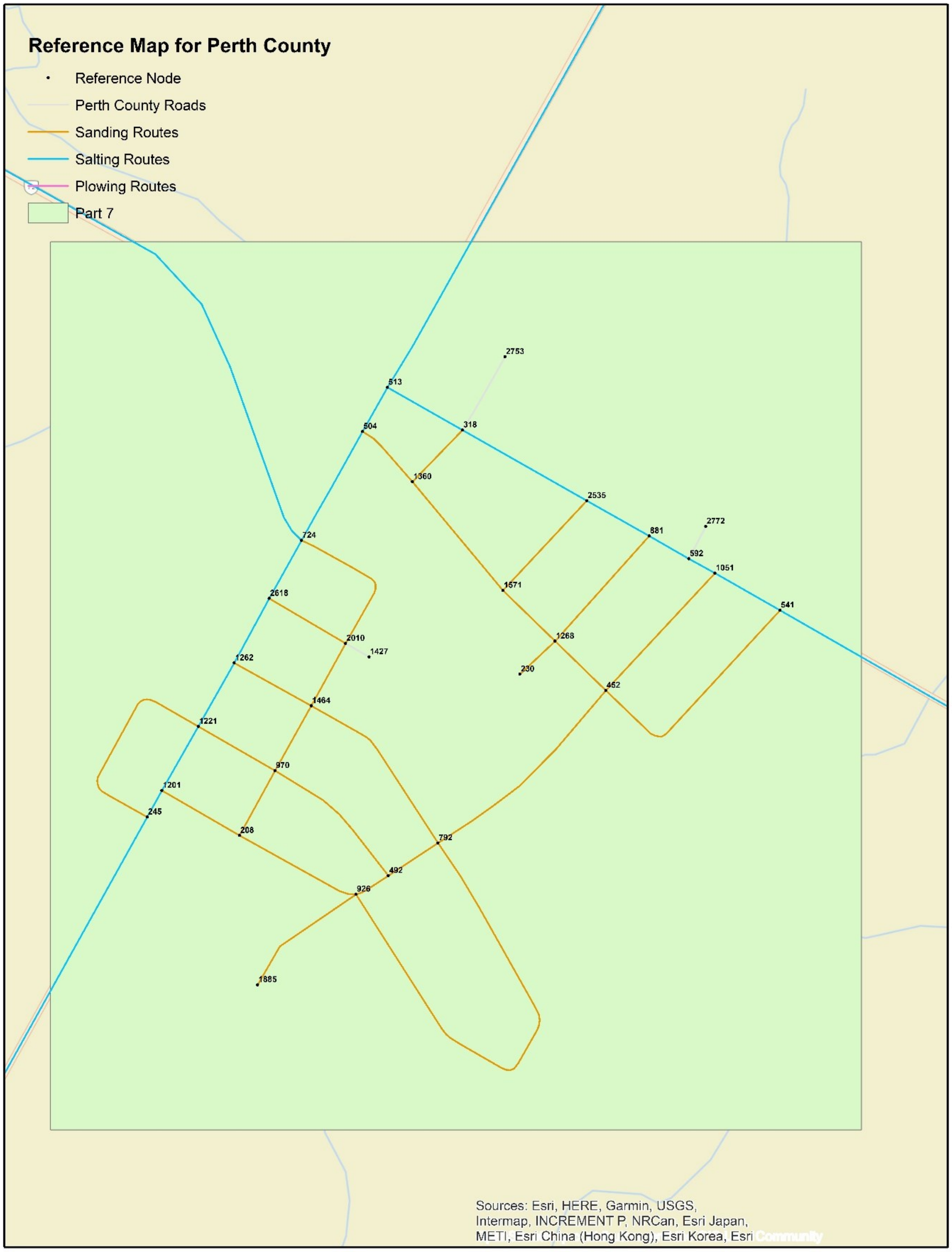
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community

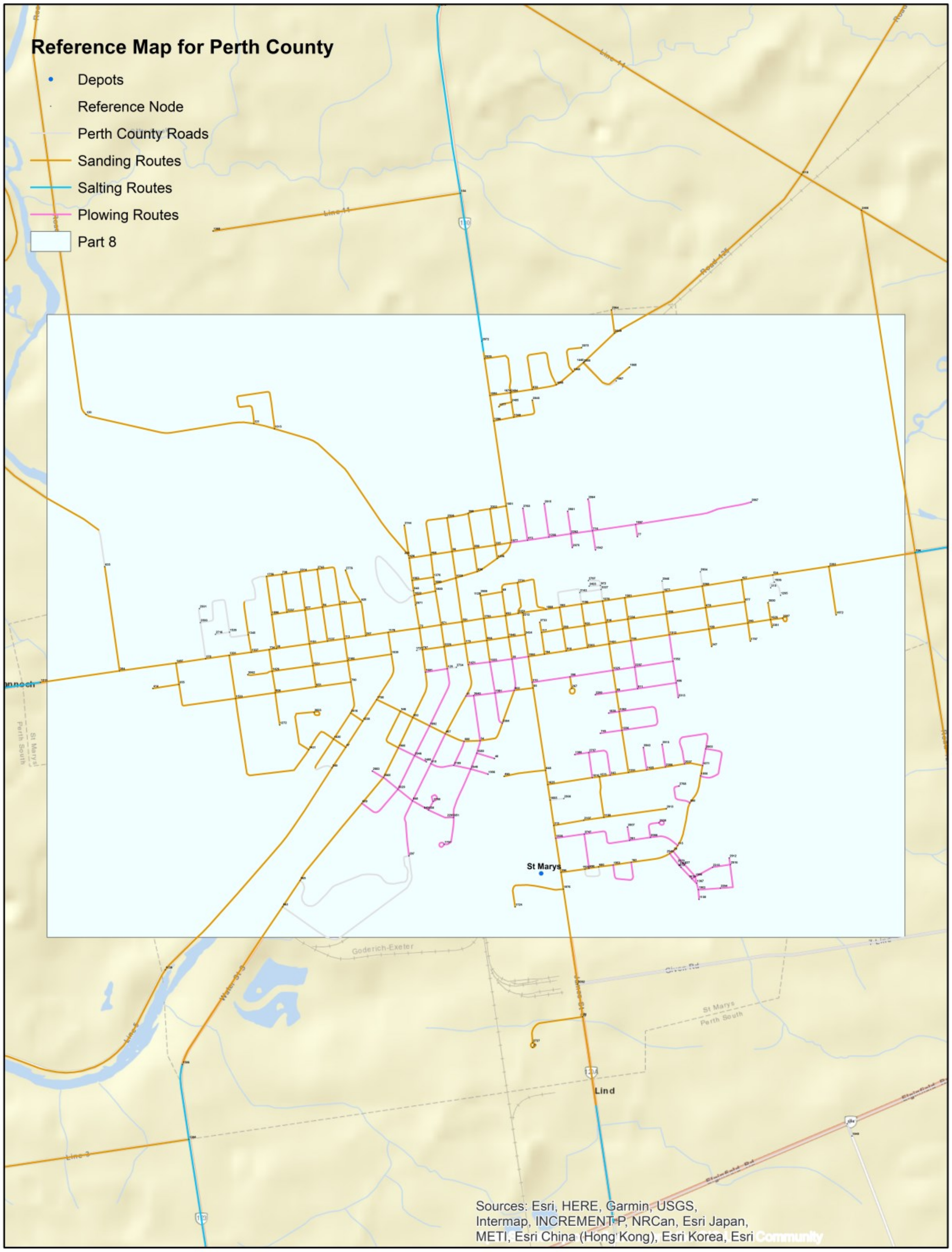


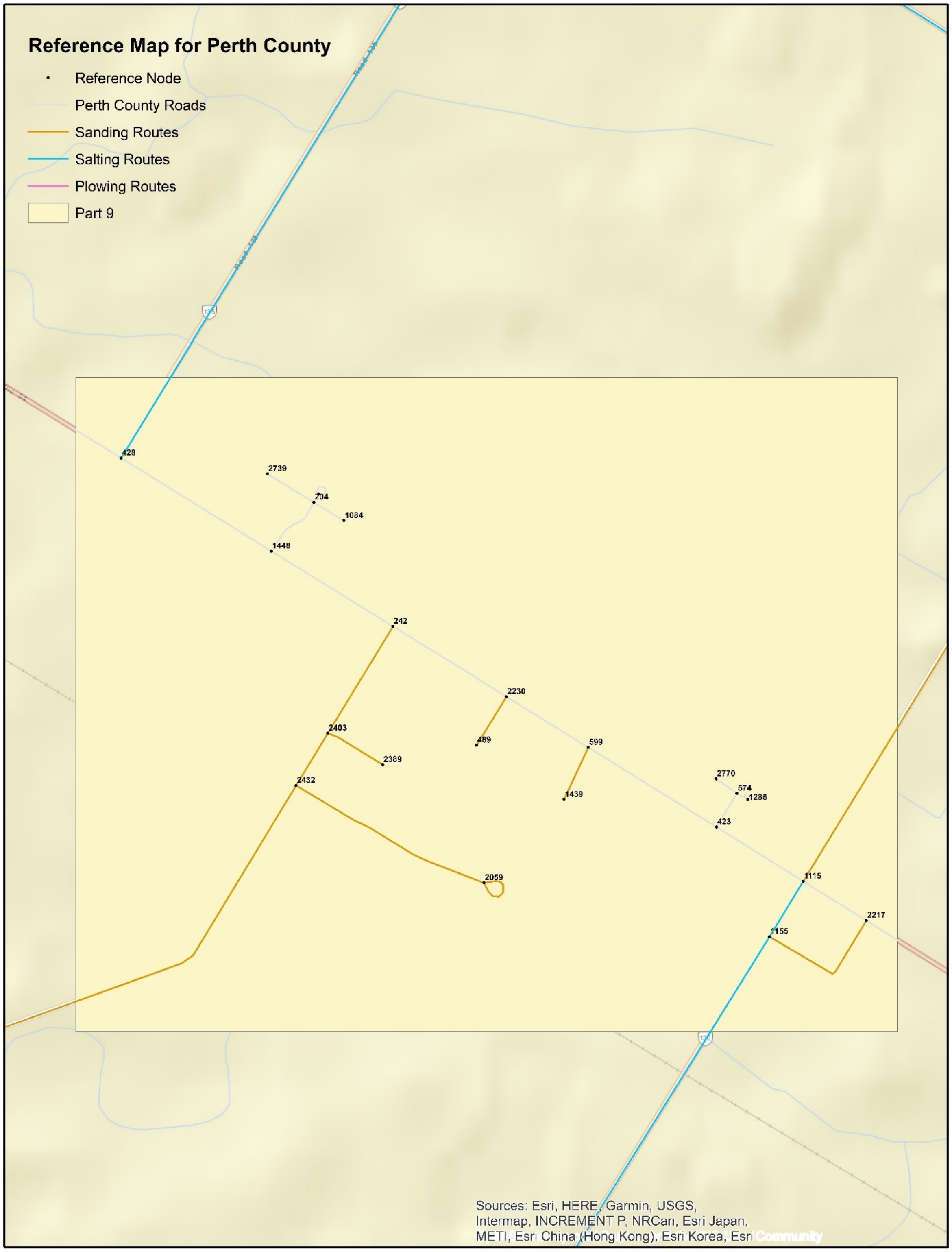
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community



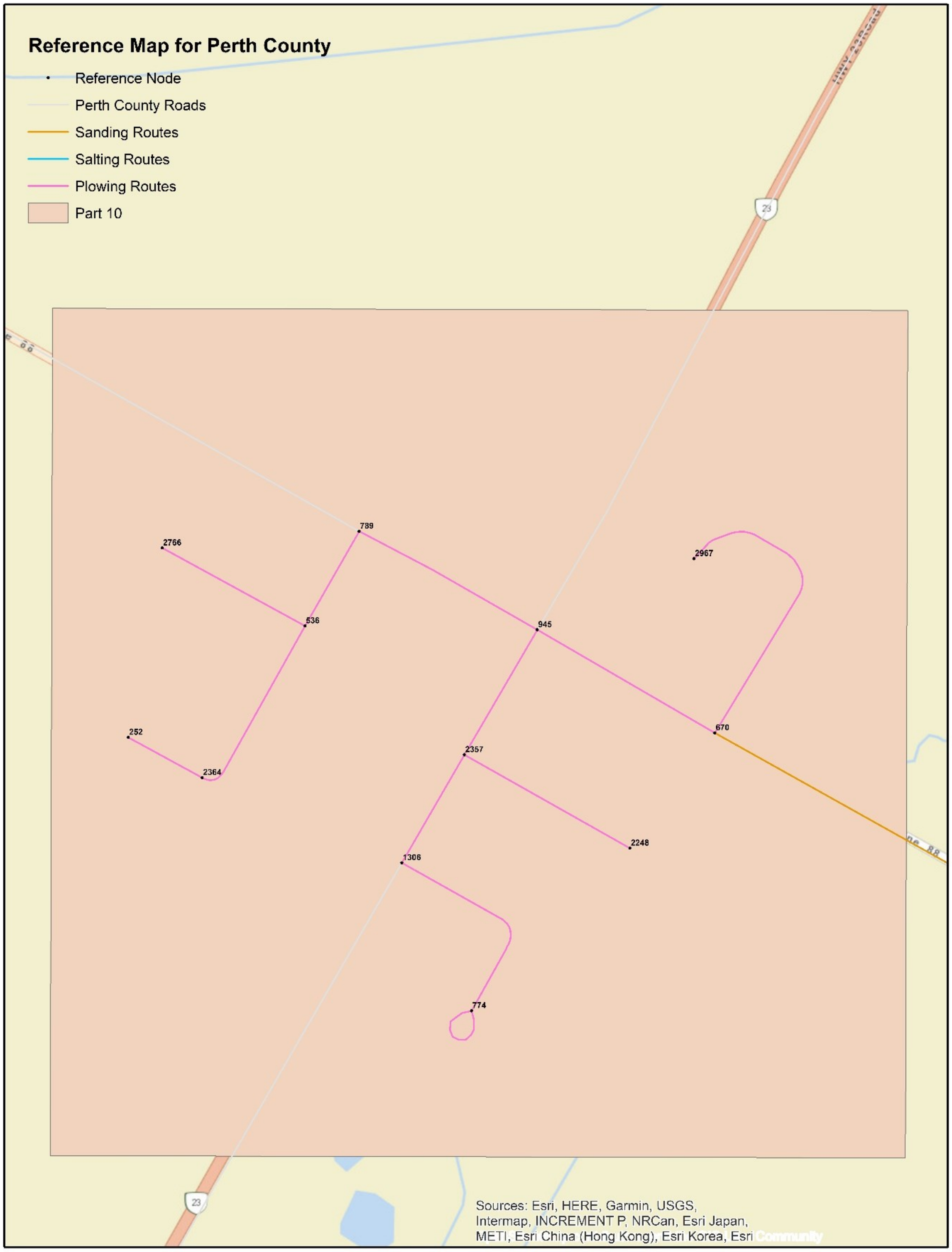
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community


Reference Map for Perth County
Reference Node
Perth County Roads
Sanding Routes
Salting Routes
Plowing Routes
Part 7
2753
513
318
504
1360
2535
2772
881
592
1051
724
2618
1571
541
2010
1427
1268
1262
230
462
1464
1221
970
1201
245
208
792
492
926
1885
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri

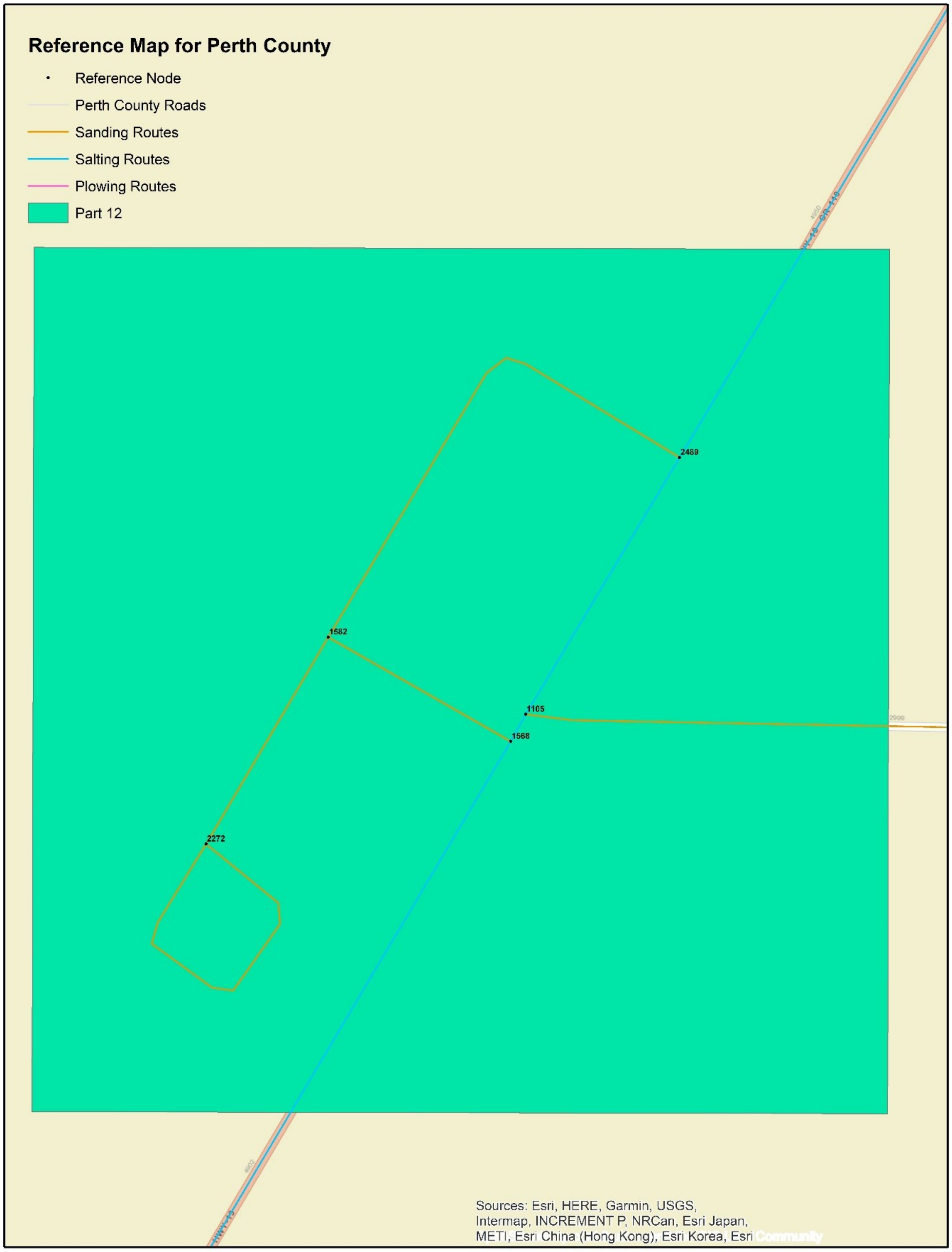

Reference Map for Perth County
Depots
Reference Node
Perth County Roads
Sanding Routes
Salting Routes
Plowing Routes
Part 8
Line 11
Road 139
St Marys
Perth South
Goderich-Exeter
Water St S
Line 3
Lind
Line 9
St Marys
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community

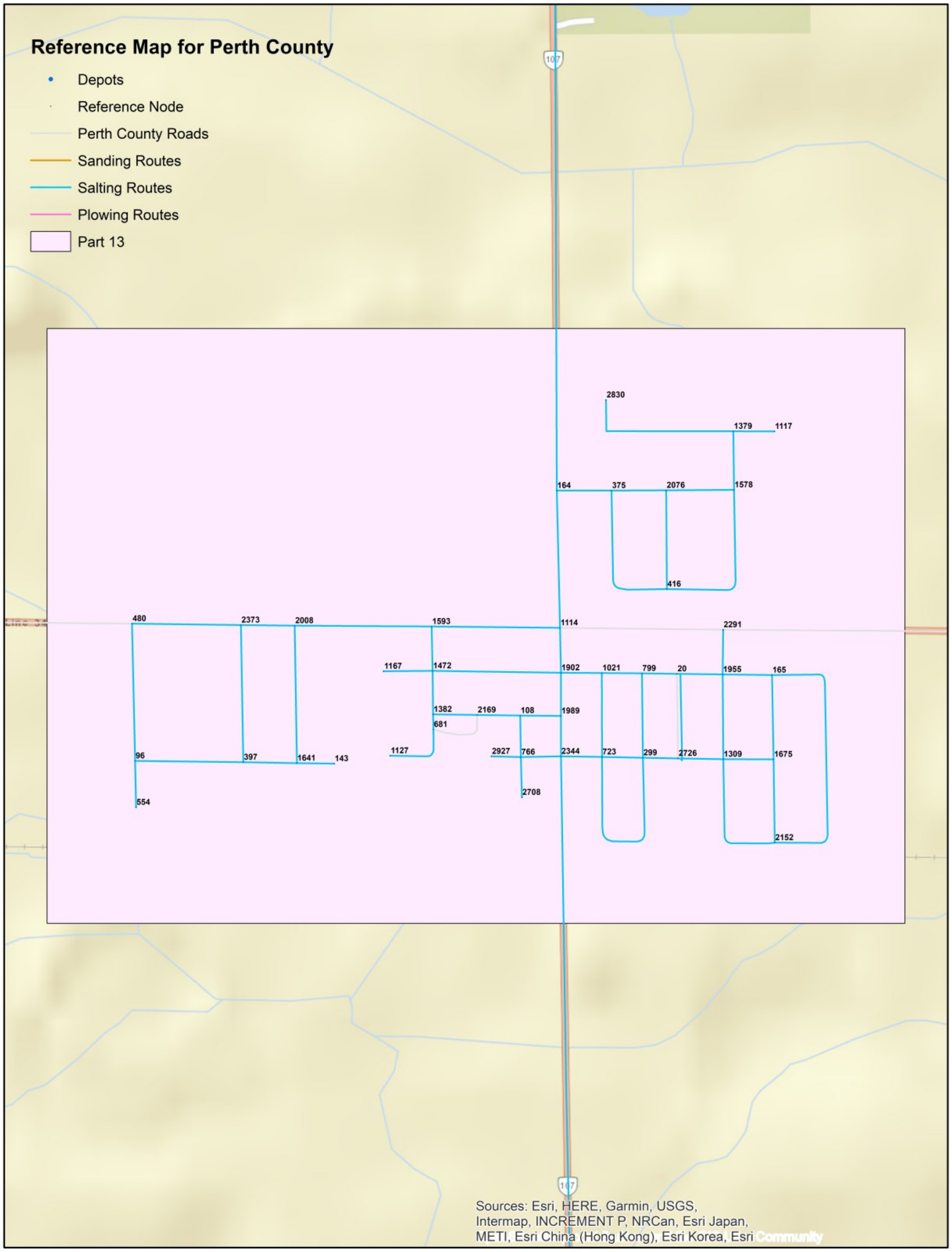

Reference Map for Perth County
Reference Node
Perth County Roads
Sanding Routes
Salting Routes
Plowing Routes
Part 10
23
789
2766
536
945
2967
670
252
2364
2357
2248
1306
774
23
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri

Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community



Reference Map for Perth County

Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community


Reference Map for Perth County
Depots
Reference Node
Perth County Roads
Sanding Routes
Salting Routes
Plowing Routes
Part 13
107
2830
1379
1117
164
375
2076
1578
416
480
2373
2008
1593
1114
2291
1167
1472
1902
1021
799
20
1955
165
1382
2169
108
1989
681
96
397
1641
143
1127
2927
766
2344
723
299
2726
1309
1675
554
2708
2152
107
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri Community

Appendix E: Detailed Plow Routes Sequence for Task 3

E1: Task 3 (No Boundary)

Truck ID	Route Sequence
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Western Star #91 (tandem)	['1055', '1803', '1425', '1750', '2108', '1403', '1136', '1821', '893', '1297', '706', '2041', '1590', '2090', '1737', '2047', '221', '248', '614', '514', '695', '2317', '1791', '130', '400', '494', '1068', '2063', '325', '1721', '325', '2063', '1068', '494', '603', '1605', '980', '1605', '1447', '488', '302', '181', '2001', '662', '2330', '659', '2195', '659', '2330', '662', '2001', '181', '302', '488', '1447', '1601', '1282', '1601', '1447', '1605', '603', '494', '400', '1093', '603', '1130', '764', '279', '334', '279', '362', '1052', '362', '563', '362', '1532', '980', '1532', '362', '279', '764', '1532', '1685', '702', '1584', '702', '1685', '1532', '764', '1130', '603', '1093', '1655', '1126', '1655', '1093', '400', '572', '1655', '572', '640', '572', '400', '130', '1791', '2317', '695', '514', '614', '248', '221', '2047', '1737', '2090', '1590', '2041', '706', '1297', '893', '1821', '1136', '1403', '2108', '1750', '1425', '1803', '1055']
Western Star #88 (tandem)	['1055', '2032', '173', '1413', '2444', '408', '819', '2334', '1577', '172', '832', '2058', '2138', '1416', '770', '1416', '110', '728', '214', '1889', '131', '329', '770', '329', '131', '1889', '2865', '1889', '564', '2835', '564', '1495', '537', '626', '564', '1889', '214', '1495', '214', '728', '1327', '1495', '564', '626', '2784', '626', '75', '626', '537', '2562', '722', '2562', '2401', '1970', '2401', '1997', '2401', '2562', '537', '1495', '1327', '201', '205', '2097', '1085', '2097', '205', '201', '1327', '728', '1371', '62', '2218', '521', '2218', '62', '758', '62', '1371', '728', '110', '1416', '2138', '2058', '832', '2080', '2219', '2080', '832', '172', '442', '172', '1577', '2579', '1577', '2334', '819', '408', '2444', '1413', '173', '2032', '1055']
Western Star #96 (tandem)	['1055', '2032', '1141', '1010', '1507', '408', '1507', '2019', '2089', '1129', '2580', '2340', '995', '2019', '1507', '2331', '2089', '2340', '509', '2340', '2089', '2331', '2210', '1129', '1594', '940', '2580', '1129', '2210', '664', '1594', '1129', '2089', '2019', '2911', '2019', '995', '2340', '2580', '64', '2580', '940', '1276', '940', '1120', '365', '1120', '940', '1594', '37', '1594', '664', '1048', '664', '2492', '664', '2210', '779', '2210', '2331', '1333', '2331', '1507', '1010', '1141', '2032', '1055']
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3733 (single axle dump/plow)	['670', '945', '789', '810', '596', '747', '92', '158', '892', '693', '1558', '498', '1558', '693', '892', '2494', '892', '1358', '892', '158', '92', '1307', '65', '1225', '65', '1307', '2069', '2388', '2209', '2388', '2069', '1984', '737', '1984', '2288', '1984', '136', '1984', '2069', '1227', '2069', '1307', '92', '317', '92', '747', '596', '1170', '527', '1170', '596', '1613', '596', '810', '789', '945', '670']
H&H Contractor #1 (single axle combo sander/plow)	['670', '429', '518', '869', '911', '1175', '491', '1613', '491', '1175', '1161', '1175', '911', '653', '911', '1375', '911', '869', '272', '869', '857', '2495', '857', '68', '1230', '68', '827', '1566', '1636', '1566', '1035', '1566', '827', '68', '1749', '2332', '2926', '2332', '2044', '867', '431', '867', '2044', '2332', '1749', '68', '857', '1081', '2048', '498', '2048', '1081', '857', '869', '518', '429', '670']
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3709 (grader with scarifier and plow)	['2456', '270', '2411', '1041', '1017', '1041', '2411', '2532', '938', '1159', '833', '2532', '2411', '270', '1994', '1713', '1523', '2520', '1523', '1713', '1053', '1531', '1294', '1589', '2433', '1526', '1776', '2633', '1776', '1526', '336', '2404', '336', '2633', '336', '1526', '244', '1995', '666', '1438', '556', '2653', '2329', '1437', '2329', '2653', '556', '386', '2659', '2651', '2627', '2659', '386', '2595', '91', '2595', '386', '556', '1438', '666', '1995', '11', '12', '2721', '12', '11', '1717', '1609', '461', '2454', '1190', '2478', '1408', '2831', '1408', '2478', '1438', '2478', '1190', '878', '2053', '1399', '987', '2680', '307', '296', '532', '291', '300', '87', '407', '87', '999', '87',

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E2: Task 3 (One Depots Removal)

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Western Star #96 (tandem)	['1055', '2032', '1141', '1010', '1507', '408', '1507', '2019', '2089', '1129', '2580', '2340', '995', '2019', '1507', '2331', '2089', '2340', '509', '2340', '2089', '2331', '2210', '1129', '1594', '940', '2580', '1129', '2210', '664', '1594', '1129', '2089', '2019', '2911', '2019', '995', '2340', '2580', '64', '2580', '940', '1276', '1703', '2368', '1703', '2564', '338', '2564', '1703', '1276', '940', '1120', '365', '978', '2564', '2631', '2564', '978', '2439', '978', '365', '1120', '940', '1594', '37', '1594', '664', '1048', '664', '2492', '664', '2210', '779', '2210', '2331', '1333', '2331', '1507', '1010', '1141', '2032', '1055']
International #78 (tandem)	['1055', '2032', '173', '1413', '2444', '408', '570', '248', '570', '57', '614', '57', '1576', '1805', '1782', '1899', '1782', '915', '969', '915', '1210', '915', '856', '2190', '856', '770', '329', '131', '1889', '564', '1495', '537', '626', '564', '1889', '214', '1495', '564', '626', '537', '2562', '2401', '1997', '2401', '2562', '537', '1495', '1327', '201', '205', '2097', '1085', '2097', '205', '201', '1327', '1495', '214', '728', '1327', '728', '1371', '62', '2218', '62', '758', '62', '1371', '728', '110', '1416', '110', '728', '214', '1889', '131', '329', '770', '856', '2211', '856', '915', '1782', '1805', '1576', '57', '949', '832', '2080', '2219', '2080', '832', '949', '57', '570', '306', '949', '333', '2621',

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International #99 (single axle 5-tonne)	['1055', '1803', '1425', '2265', '2668', '2265', '1882', '2265', '1425', '1803', '1055', '1171', '2246', '1413', '2444', '1564', '1154', '1564', '838', '900', '1676', '967', '1876', '967', '219', '2493', '402', '2493', '1699', '1125', '2022', '2041', '2022', '1125', '1707', '1737', '2047', '950', '2795', '950', '221', '950', '2047', '1737', '1707', '1125', '1590', '1728', '2126', '1728', '1522', '2041', '1522', '1728', '756', '359', '1522', '359', '2318', '359', '756', '1228', '2318', '1370', '1504', '262', '710', '895', '1370', '1898', '321', '303', '2527', '303', '1504', '1370', '2318', '1228', '1898', '1370', '895', '2413', '2270', '2413', '895', '710', '519', '277', '710', '262', '2746', '262', '1504', '303', '321', '1339', '519', '710', '277', '726', '277', '519', '1339', '726', '2302', '2413', '2302', '726', '1339', '321', '2755', '321', '1898', '1228', '756', '2447', '1898', '2447', '411', '411', '2447', '756', '1728', '1590', '1125', '1699', '2493', '2186', '2493', '219', '2266', '1046', '2186', '1046', '70', '523', '2186', '523', '2002', '1699', '286', '402', '1876', '401', '2763', '401', '1747', '401', '1876', '402', '286', '2022', '286', '1699', '2002', '1707', '2090', '2126', '2447', '2126', '2090', '1707', '2002', '523', '70', '2761', '70', '1046', '2266', '219', '123', '219', '967', '1676', '1133', '2266', '1133', '1676', '900', '1330', '2827', '1330', '900', '838', '621', '2685', '621', '1004', '621', '525', '1330', '525', '2857', '525', '621', '838', '1564', '2444', '1413', '2246', '1171', '1055', '1141', '2032', '173', '1171', '2305', '1750', '2396', '597', '2273', '2108', '1882', '206', '2740', '206', '1403', '206', '1882', '2108', '2273', '823', '2273', '133', '2888', '133', '2482', '133', '571', '1510', '1621', '1297', '930', '2515', '1806', '2515', '930', '954', '930', '322', '430', '2339', '2435', '2471', '2435', '2339', '430', '1432', '2042', '1671', '2042', '1432', '430', '954', '893', '954', '455', '2471', '590', '2471', '455', '954', '430', '322', '887', '1548', '1019', '2070', '352', '2070', '1019', '1548', '887', '1432', '1583', '2339', '455', '1821', '1136', '1821', '455', '2339', '1583', '1544', '2083', '1986', '2083', '1544', '1583', '1535', '2435', '1535', '1877', '1535', '1073', '445', '445', '1073', '1300', '1073', '1535', '1583', '1432', '887', '1097', '2042', '1097', '203', '1671', '352', '1544', '352', '348', '1348', '2828', '1348', '1288', '2366', '2285', '2366', '2293', '2293', '2366', '1288', '389', '897', '2285', '1573', '1024', '1986', '1024', '1573', '294', '1348', '294', '842', '2083', '1493', '921', '1867', '1459', '1877', '1459', '1867', '955', '1986', '955', '1867', '921', '1493', '2083', '842', '1024', '842', '294', '348', '352', '1671', '203', '2070', '1288', '1348', '348', '294', '1573', '2848', '1573', '2285', '897', '2752', '904', '2752', '897', '389', '313', '2752', '313', '1764', '313', '389', '1019', '389', '1288', '2070', '203', '1097', '887', '322', '1806', '1548', '1806', '322', '930', '1297', '1621', '1510', '1264', '1838', '1264', '1510', '1163', '2280', '1163', '1510', '571', '1163', '571', '823', '1264', '823', '571', '133', '2273', '597', '2396', '1841', '2482', '1841', '2923', '1841', '2396', '1750', '2305', '2246', '2941', '2246', '2305', '1171', '173', '1413', '173', '2016', '173', '2032', '1141', '1055']
3733 (single axle dump/plow)	['670', '945', '789', '810', '596', '747', '92', '158', '892', '693', '1558', '498', '1558', '693', '892', '2494', '892', '1358', '892', '158', '92', '1307', '65', '1225', '65', '1307', '2069', '2388', '2209', '2388', '2069', '1984', '737', '1984', '2288', '1984', '136', '1984', '2069', '1227', '2069', '1307', '92', '317', '92', '747', '596', '1170', '527', '1170', '596', '1613', '596', '810', '789', '945', '670']
H&H Contractor #1 (single axle combo sander/plow)	['670', '429', '518', '869', '911', '1175', '491', '1613', '491', '1175', '1161', '1175', '911', '653', '911', '1375', '911', '869', '272', '869', '857', '2495', '857', '68', '1230', '68', '827', '1566', '1636', '1566', '1035', '1566', '827', '68', '1749', '2332', '2926', '2332', '2044', '867', '431', '867', '2044', '2332', '1749', '68', '857', '1081', '2048', '498', '2048', '1081', '857', '869', '518', '429', '670']

H&H Contractor #2 (single axle combo sander/plow)	['2469', '1815', '2452', '1815', '257', '818', '585', '818', '257', '1815', '2469', '2446', '2464', '1088', '1551', '58', '1551', '1005', '1411', '1918', '778', '2043', '778', '1918', '387', '1346', '1219', '177', '1648', '905', '628', '905', '496', '2367', '496', '2824', '496', '888', '1802', '550', '654', '550', '1802', '740', '865', '2504', '665', '2504', '865', '740', '1802', '888', '496', '905', '2504', '905', '1648', '177', '1219', '1346', '387', '1918', '654', '1918', '1411', '1005', '1551', '1088', '2464', '2446', '2469']
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E3: Task 3 (Two Depots Removal)

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3733 (single axle dump/plow)	['670', '945', '789', '810', '596', '747', '92', '158', '892', '693', '1558', '498', '1558', '693', '892', '2494', '892', '1358', '892', '158', '92', '1307', '65', '1225', '65', '1307', '2069', '2388', '2209', '2388', '2069', '1984', '737', '1984', '2288', '1984', '136', '1984', '2069', '1227', '2069', '1307', '92', '317', '92', '747', '596', '1170', '527', '1170', '596', '1613', '596', '810', '789', '945', '670']
H&H Contractor #1 (single axle combo sander/plow)	['670', '429', '518', '869', '911', '1175', '491', '1613', '491', '1175', '1161', '1175', '911', '653', '911', '1375', '911', '869', '272', '869', '857', '2495', '857', '68', '1230', '68', '827', '1566', '1636', '1566', '1035', '1566', '827', '68', '1749', '2332', '2926', '2332', '2044', '867', '431', '867', '2044', '2332', '1749', '68', '857', '1081', '2048', '498', '2048', '1081', '857', '869', '518', '429', '670']
H&H Contractor #2 (single axle combo sander/plow)	['2469', '1815', '2452', '1815', '257', '818', '585', '818', '257', '1815', '2469', '2446', '2464', '1088', '1551', '58', '1551', '1005', '1411', '1918', '778', '2043', '778', '1918', '387', '1346', '1219', '177', '1648', '905', '628', '905', '496', '2367', '496', '2824', '496', '888', '1802', '550', '654', '550', '1802', '740', '865', '2504', '665', '2504', '865', '740', '1802', '888', '496', '905', '2504', '905', '1648', '177', '1219', '1346', '387', '1918', '654', '1918', '1411', '1005', '1551', '1088', '2464', '2446', '2469']
3709 (grader with scarifier and plow)	['2456', '270', '2411', '1041', '1017', '1041', '2411', '2532', '938', '1159', '833', '2532', '2411', '270', '1994', '1713', '1523', '2520', '1523', '1713', '1053', '1531', '1294', '1589', '2433', '1526', '1776', '2633', '1776', '1526', '336', '2404', '336', '2633', '336', '1526', '244', '1995', '666', '1438', '556', '2653', '2329', '1437', '2329', '2653', '556', '386', '2659', '2651', '2627', '2659', '386', '2595', '91', '2595', '386', '556', '1438', '666', '1995', '11', '12', '2721', '12', '11', '1717', '1609', '461', '2454', '1190', '2478', '1408', '2831', '1408', '2478', '1438', '2478', '1190', '878', '2053', '1399', '987', '2680', '307', '296', '532', '291', '300', '87', '407', '87', '999', '87', '300', '754', '1184', '2651', '2659', '2627', '2651', '1184', '907', '2566', '566', '1531', '1053', '1083', '1614', '1819', '1534', '1589', '1294', '1531', '566', '2520', '979', '883', '2512', '1461', '2512', '907', '2512', '883', '979', '2520', '566', '2566', '907', '1184', '2224', '48', '1461', '48', '2224', '2232', '2374', '2232', '2224', '1184', '754', '2374', '2145', '2952', '2145', '2232', '2145', '2374', '754', '999', '2627', '999', '754', '300', '2585', '2769', '2585', '300', '291', '2769', '569', '2769', '291', '532', '569', '2153', '569', '532', '407', '532', '296', '2539', '296', '2153', '296', '307', '1346', '307', '2680', '987', '387', '987', '1399', '2053', '878', '2428', '2251', '2428', '878', '1190', '2454', '461', '1108', '2251', '1108', '1317', '1108', '461', '1609', '1849', '1609', '1717', '207', '1717', '86', '1717', '11', '2006', '666', '2006', '1408', '2006', '11', '1995', '244', '1534', '1819', '873', '86', '1534', '86', '873', '207', '1397', '207', '873', '1937', '873', '1819', '2459', '1819', '1614', '1083', '1294', '2404', '2433', '1589', '1614', '517', '1614', '1589', '1534', '244', '1526', '2433', '2404', '1294', '1083', '1028', '1083', '1053', '1012', '1053', '1713', '360', '1713', '1994', '311', '1994', '270', '712', '2196', '2196', '712', '938', '2532', '833', '2051', '2181', '30', '2170', '288', '1041', '658', '1041', '288', '1043', '1608', '1730', '2711', '1730', '2671', '1730', '1608', '1043', '1017', '2073', '1017', '1730', '1017', '1043', '707', '997', '707', '1043', '288', '2170', '707', '2170', '30', '2231', '30', '2181', '236', '2231', '997', '1608', '997', '2231', '236', '1623', '2960', '1623', '236', '118', '1388', '502', '1388', '2937',

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E4: Task 3 (Three Depots Removal)

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3733 (single axle dump/plow)	['670', '945', '789', '810', '596', '747', '92', '158', '892', '693', '1558', '498', '1558', '693', '892', '2494', '892', '1358', '892', '158', '92', '1307', '65', '1225', '65', '1307', '2069', '2388', '2209', '2388', '2069', '1984', '737', '1984', '2288', '1984', '136',

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H&H Contractor #1 (single axle combo sander/plow)	['670', '429', '518', '869', '911', '1175', '491', '1613', '491', '1175', '1161', '1175', '911', '653', '911', '1375', '911', '869', '272', '869', '857', '2495', '857', '68', '1230', '68', '827', '1566', '1636', '1566', '1035', '1566', '827', '68', '1749', '2332', '2926', '2332', '2044', '867', '431', '867', '2044', '2332', '1749', '68', '857', '1081', '2048', '498', '2048', '1081', '857', '869', '518', '429', '670']
H&H Contractor #2 (single axle combo sander/plow)	['2469', '1815', '2452', '1815', '257', '818', '585', '818', '257', '1815', '2469', '2446', '2464', '1088', '1551', '58', '1551', '1005', '1411', '1918', '778', '2043', '778', '1918', '387', '1346', '1219', '177', '1648', '905', '628', '905', '496', '2367', '496', '2824', '496', '888', '1802', '550', '654', '550', '1802', '740', '865', '2504', '665', '2504', '865', '740', '1802', '888', '496', '905', '2504', '905', '1648', '177', '1219', '1346', '387', '1918', '654', '1918', '1411', '1005', '1551', '1088', '2464', '2446', '2469']
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Appendix F: Detailed Plow Routes Sequence for Task 4

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