EXPLORING THE POTENTIAL TO MINIMIZE FOREST ROAD COST IN ONTARIO WITH LIDAR AND ROADENG

by

Alexandr Kurulak

FACULTY OF NATURAL RESOURCES MANAGEMENT
LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

April 17th, 2019

EXPLORING THE POTENTIAL TO MINIMIZE FOREST ROAD COST IN ONTARIO WITH LIDAR AND ROADENG

by

Alexandr Kurulak

An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management
Lakehead University
April 2019

Dr. Reino Pulkki, R.P.F.

Kevin Shorthouse, M.Sc.F, R.P.F.

LIBRARY RIGHTS STATEMENT

A CAUTION TO THE READER

MAJOR ADVISOR COMMENTS

ABSTRACT

Kurulak, A. 2019. Exploring the potential to minimize forest road cost in Ontario with LiDAR and RoadENG. Lakehead University, Thunder Bay, ON. 105 pp.

Keywords: RoadENG, LiDAR, Ontario forestry, forest roads, road planning, forest engineering.

The objective of this study was to determine if light detection and ranging (LiDAR) and RoadENG could produce a more cost-effective road design than a field-based road design. A Triangulated irregular network (TIN) was created from raw LiDAR files (LAS). Roads were created within the TIN and had attributes for soil layer, road class, road templates, culverts, soil swell and shrinkage factors for excavation, and hauling. Three iterations were done, each with different excavation costs applied to compare road cost by iteration. Each iteration was run through Softree Opitmal to determine the lowest optimized road cost for each road section. Compared to Eacom's field-based road designs, the blind design had a decrease in total cost by 1.5% and the second attempt had an increase in cost by 23.4%. Future research in this area type of study should include the added cost and time spent doing field-based layout compared to office-based reconnaissance with ground truthing. There should be no existing roads within the generated TIN model when comparing road alignment cost. As well, a more detailed soil layers, and more detailed cost for excavation and hauling cost. Making these changes would increase the accuracy and usefulness of the RoadENG Forest Engineer program and achieve a more ideal analysis tool for road building in Ontario forestry.

CONTENTS

TABLES

FIGURES

ACKNOWLEDGEMENTS

I want to thank my thesis advisor Dr. Reino Pulkki, RPF for giving me the idea to compare road design with LiDAR and RoadENG to field-based designs. Dr. Pulkki gave his expert advice as well as his time and provided me with the resources necessary to complete this thesis. I would also like to thank my second reader, Kevin Shorthouse, RPF for reaching out to KBM Forestry Consultants and setting up the resources needed to complete this thesis such as the LiDAR files, soil layers, and culverts. Thank you to Dr. Triin Hart, RPF for helping set up the initial meeting with KBM Forestry Consultants and Shawn Mizon at KBM for providing the LiDAR data flown for Eacom Timber Corp. Thank you to Eacom Timber Corp, specifically, Paul Tremblay, RPF for setting up the data sharing agreement with Eacom and helping out with various sources of information, Denis Roy, PENG for providing Eacom's current road specifications and road building costs, and finally, Martin Lewynsky, PENG, RPF for providing road templates used for cut and fill slope angles. Without these people, this thesis would not have been completed.

INTRODUCTION

STUDY OUTLINE

The study is to explore whether RoadENG designs with LiDAR can minimize roads to have a decrease in overall road cost ($ CDN) and improve safety for road class by design speeds (km/hr) in the Spanish Forest Management Unit in Ontario. The roads designed with RoadENG, a computer software for locating roads, will be created "blind" without looking at the field-based, final road design of the present study area. A second attempt will be completed afterward looking at the two finished designs to see if there is a better possible route. This study looks to prove that there should be a greater emphasis on geometrical road design for forestry in Ontario.

Roads will be designed using light detection and ranging (LiDAR) with RoadENG to determine road locations and alignments (Akay et al. 2008). Variables to be measured include: total m^3 of cut and fills, cost of road cut, fill, and haul materials ($ CDN), mass haul from vertical alignment by freehaul, overhaul, and endhaul (m^3), material stripped (m^3), and total breakdown (m) by road classifications where mainline, branch, and block will be compared to actual roads present in the field. Additional site variables include, max road gradient (%), road subgrade and surface width (m), minimum horizontal curves (m), minimum vertical curves (k-value), the slope of terrain (%), soil substrate for cut and fill slope angles (%), and number of water crossings.

LITERATURE REVIEW

FOREST ROADS

Forest road building is the most expensive part of a forest operation (Samani et al. 2010). Road building and hauling can account for a third to over half the cost of a harvest operation (Pulkki 2018). In general, road networks should be planned at a regional scale and not at a harvest block scale. A regional scale allows for the optimal road network layout as the connectivity to many future harvest areas can be planned in advance to reduce the amount of road needed. Roads should also be planned at least one year before harvesting occurs to ensure all work phases are carried out during the most economical time of the year Also, early planning allows for roads to be built at the ideal time of year resulting in minimal negative site impacts from road building (Pulkki 2003). Roads need to be located on stable soils. As well, road planning must account for the variation in terrain; steeper terrain requires thorough planning to optimize the road, as steeper terrain increases building costs and environmental impacts. Road planning must also account for the overall construction and maintenance costs based on operational life expectancy. Planning road networks in advance, building during in the ideal conditions, and locating roads in the best soil and terrain will save costs, minimize the negative impacts of road building on the environment, and increase proficiency.

Roads can be designed in the field or on a computer using road building software when there is sufficient data available. Designing forestry roads in the office with LiDAR and RoadENG is a common practice for forestry companies in western Canada. Recently, LiDAR has been gaining popularity across Canada and is becoming a key component to aid in the daily planning of forest management (Akay et al. 2008). By using LiDAR in the pre-planning phase, roads can be more accurately located then compared to locating using aerial photos. Using RoadENG in the office allows for several accurate road options to be tested before going out to the field to ground truth the road. Ground truthing is verifying that the ground profile in the field accurately represents what was produced by the RoadENG model. In Ontario, RoadENG is not currently used to design forest roads. Planning of road locations is currently done using field layout techniques and three-dimensional (3D) modeling programs if they are available. Ontario also does not have LIDAR available on a wide scale and relies on very coarse digital elevation models (DEM) (Akay et al. 2008). Presently, Ontario is investing $100 million in LiDAR over the next 10 years to update the Provincial Forest Resources Inventory (FRI) (Mitacs 2019). The application of LiDAR makes it possible to easily locate road landings, identify stream crossing locations, detect unstable and infeasible road locations, and provide insight for ideal bench locations on difficult or steep slopes (Krogstad and Schiess 2004). Using the new LiDAR data in combination with computer road location software like RoadENG shows promise for more detailed road designs in the future of forest road building in Ontario.

FOREST ROAD CLASSES

Forest roads can be broken down into three different road classes: primary, secondary and tertiary or spur roads. Winter roads are classified separately of these three road classes (Pulkki 2003). Each road class has a specified road width, maximum road gradient, minimum curve radius, and a designated vehicle traveling speed (FOA 2012). Each type of road class is used to achieve a specified criterion; however, exceptions can be made where short sections of road can exceed maximum road gradient for requirements to mitigate environmental concerns (FOA 2012).

Primary forest roads are main forest roads highly traveled and account for roughly 10% of the total forest network (FAO 1977). The road width is usually 8 or 9 m and has two travel lanes to accommodate road speeds of up to 80 km/h in flat terrain and up to 50 km/h in mountainous terrain (FOA 2012). Typically, the maximum adverse road grade is 8%. Exceptions can occur in mountainous or steep terrain for short distances of 20 to 50 m; the road grade can be increased to 12%.

Secondary or branch roads stem off of primary roads. This road class accounts for roughly 20% of the total road network (FAO 1977). The road can be either a single lane or two lanes. Road speeds are 50 km/h in flat terrain and 40km/h in mountainous terrain. Branch road widths can range between 7.3 m in flat terrain to 6.7 m when in steeper terrain (FOA 2012). Road grades for secondary roads are higher than primary roads because of their slower traveling speed. The maximum adverse grades range from 10 to 12% on flatter terrain and can increase to 14% in steeper terrain for short distances. (FOA 2012).

Tertiary or block roads stem from branch roads and are built to access locations within the harvest block. These roads account for roughly 70% of the total road network (FAO 1977). Block roads are built at the lowest standard when compared to primary and secondary roads (FOA 2012). They are single lane roads, with a width of 4.3 m (FOA 2012). Driving speeds are 40 km/h on flat terrain and 30 km/h in steep terrain. Adverse road grades are higher than secondary roads and are typically 12 to 14% (FOA 2012). In steep terrain, road grades can be 18% and increase to 23% for short distances.

ROAD CHARACTERISTICS

When roads are being built, the following characteristics should be taken into account: designated road speed (km/h), minimum sight distance (m), minimum radius of curvature (m), maximum adverse loaded gradient (%), maximum length of loaded grade (m), road width (m), and pavement thickness (cm) (Pullki 2003). These variables are important because each road class has different road safety requirements. Safety is paramount and the number one priority to maintain and uphold in forest operations (FOA 2012).

Road characteristics and standards are important to build suitable roads for safety and design specifications. Each road classification has a predetermined travel speed because it increases the safety of all vehicles travelling on the road. Minimum sight distance is the distance at which two oncoming vehicles can see each other when traveling in opposite directions on the same road (FOA 2012). The higher the designated road speed is, the greater the line of sight must be to prevent a collision. For example, a road with a lower travel speed (e.g. 50 km/hr) requires less distance for line of sight than a road with a higher travel speed (e.g. 80 km/hr). The minimum radius of curvature refers to how long a curve in the road must be for a given road class. Higher traveling speeds require longer curves because fast-traveling vehicles cannot turn as sharp. Therefore, the slower the vehicle is traveling, the shorter the curvature can be designed. The maximum adverse loaded gradient is when a loaded logging truck is traveling away from the harvest block in an uphill direction. A loaded truck cannot travel up as steep of a grade as an empty truck. As a result, grade constraints must be made to guarantee that loaded trucks can travel the road. The maximum length of the adverse loaded gradient prevents long distances of steep grades. Placing limitations on the length of the maximum adverse gradient provides assurance that loaded trucks will be able to travel the road safely. In general, the distance a loaded truck can travel with maximum grade is 20 to 50 m (FOA 2012). Road width is specified for each road class; the higher the travel speed and the longer the line of sight, the wider the road is needed to be (Pulkki 2003). The surface of the road must be able to sustain the traffic densities of the road class over the expected lifespan. The expected life of a road differs greatly by road class (Pulkki 2003). The higher the life expectancy of the road, the greater the pavement thickness will be required to prolong the life and maintenance of the road (Pullki 2003). Road planning and building can be improved by tailoring the designated road speed, minimum sight distance, minimum radius of curvature, maximum adverse loaded gradient, maximum length of loaded grade, road width, and surface thickness to the road classification requirements.

ROAD DENSITIES

Several variables should be considered when planning the amount and density of forest roads (Figure 1). In general, the amount of road built should not exceed 16.7 m/ha; however, this number will vary based on the logging system being used (Pulkki 2003). From the variables in Figure 1, the following factors are most important to determine optimal spacing for roads (Figure 2): variable off-road transport cost (Ct), fixed off-road transport cost (Cv), road construction and maintenance (Cf), and equipment used to forward logs (Cr) (eg. grapple skidder, forwarder or hoe chuck) (Pulkki 2003). Road density considerations are important because building too much road can be costly and can affect planning for future roads.

- terrain conditions;
- stand density or volume to be removed per hectare;
- primary (off-road) transport cost;
- secondary (truck) transport cost and demands;
- road construction cost;
- road maintenance cost;
- forest area covered by roads and thus taken out of production (the opportunity cost of the land not growing wood);
- level of forest management practiced (extensive versus intensive);
- demands of other potential road users; and
- environmental protection factors.

Figure 1. Variables to consider when determining the amount of road to be built (Pulkki 2003).

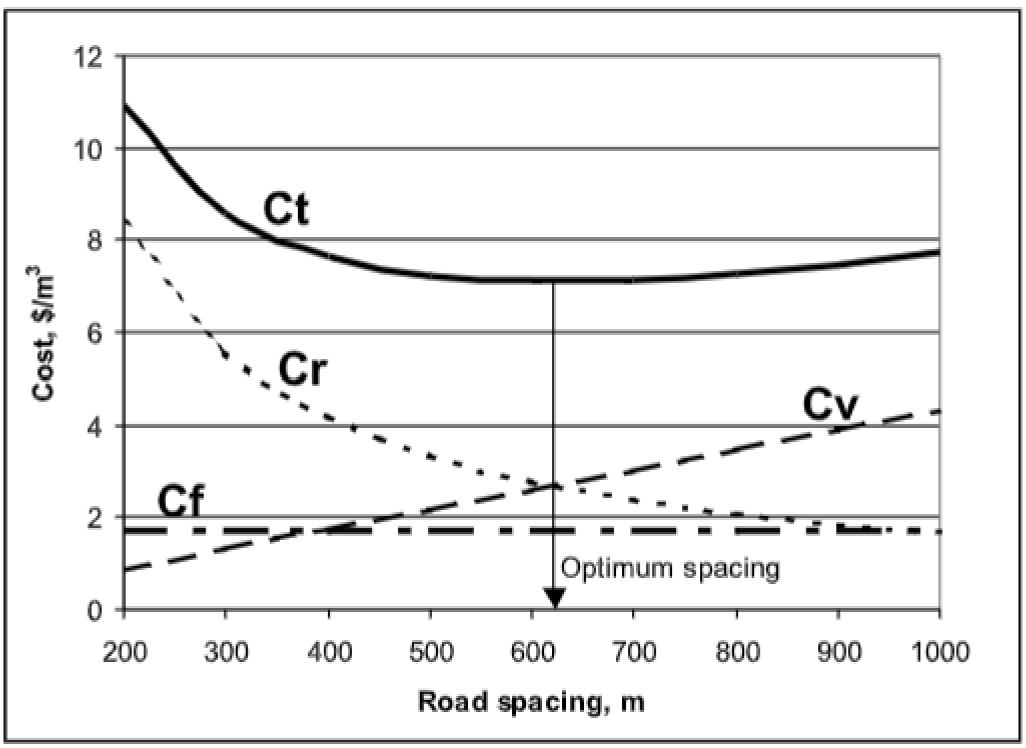


Figure 2. Optimal road spacing for a grapple skidder diagram (Pullki 2003).

CULVERTS

The purpose of culverts is to allow transport of water flow from one side of the roadway to the other, thereby reducing erosion of the roadside ditch line (MFLNRO 2002). Small or medium sized streams are the ideal for culvert usage. The stream must have a low level of stream bedload and not be at high risk of debris entering the stream (FOA 2012). Stream bedload is a movement of material carried by the stream (FOA 2012). Culverts can be made from corrugated polyethylene or steel and must be placed at every stream crossing and low-lying area of the road network. The culverts are positioned at the same grade as the natural stream grade to prevent damage to the natural stream channel (FOA 2012). Culverts should also be placed at a given interval along the road network, which is based on the road gradient and the erosion hazard of the immediate material. Sands, silts, and clays have the highest erosion hazard (MFLNRO 2002). The greater the erosion hazard and the road gradient, the shorter the distance between culverts. This distance prohibits excess water buildup. For fish-bearing streams, the stream channel must not be altered by the installation of culverts. Therefore, beveled or box culverts may be used in the stream to prevent negative impacts on fish. Figure 3 shows a flow chart to determine what type of culvert installation is needed on a given stream (FOA 2012).

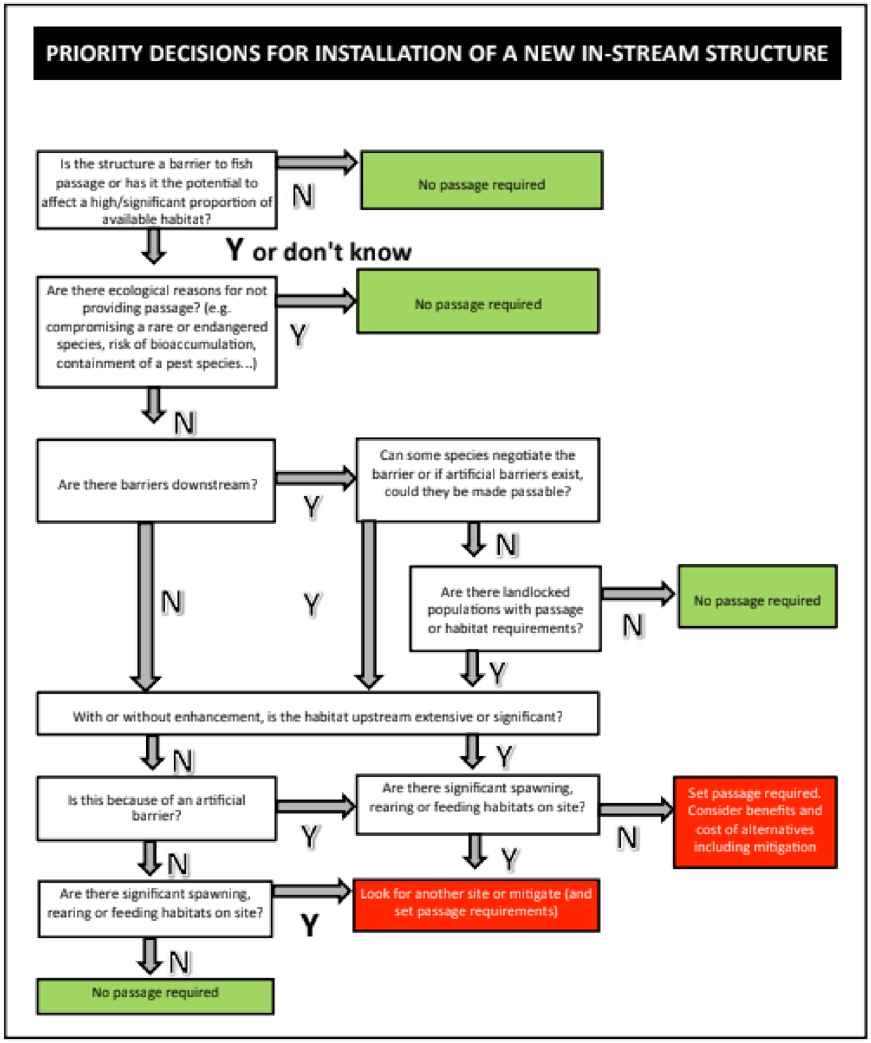


Figure 3. Understanding culverts needed for a given stream (FOA 2012).

In British Columbia, a Registered Professional Forester (RPF) is only able to prescribe culverts up to 2000 mm in diameter for a flow rate up to 6 m^3/sec (APEGBC/ABCFP 2014). These standards are similar to other provinces in Canada, especially Ontario. Foresters are still able to design battery culverts if each culvert is less than 2000 mm. Battery culverts are multiple culverts placed alongside each other in the streambed (FOA 2012). Battery culverts are cost-effective when compared to installing one single larger diameter culvert (FOA 2012).

Culverts are chosen based on the high-water mark, low water mark, and average water depth of the stream (MFLNRO 2002). The methods most commonly used are the high-water width method (Figure 4), Manning's formula, or the rational method. The high-water width method is used to determine the 10-year flood and the 100-year flood intervals (MFLNRO 2002). Manning's formula is used in open channel situations where the rational method is not practical to determine a flow measurement with great accuracy (Figure 5) (FOA 2012). The rational method is applied from watersheds that are 100 to 2,500 ha in size to determine flow rates (m^3/sec). Stream characteristics play an important role in determining culvert type and placement to accomodate high stream flows and reduce environmental hazards around streams

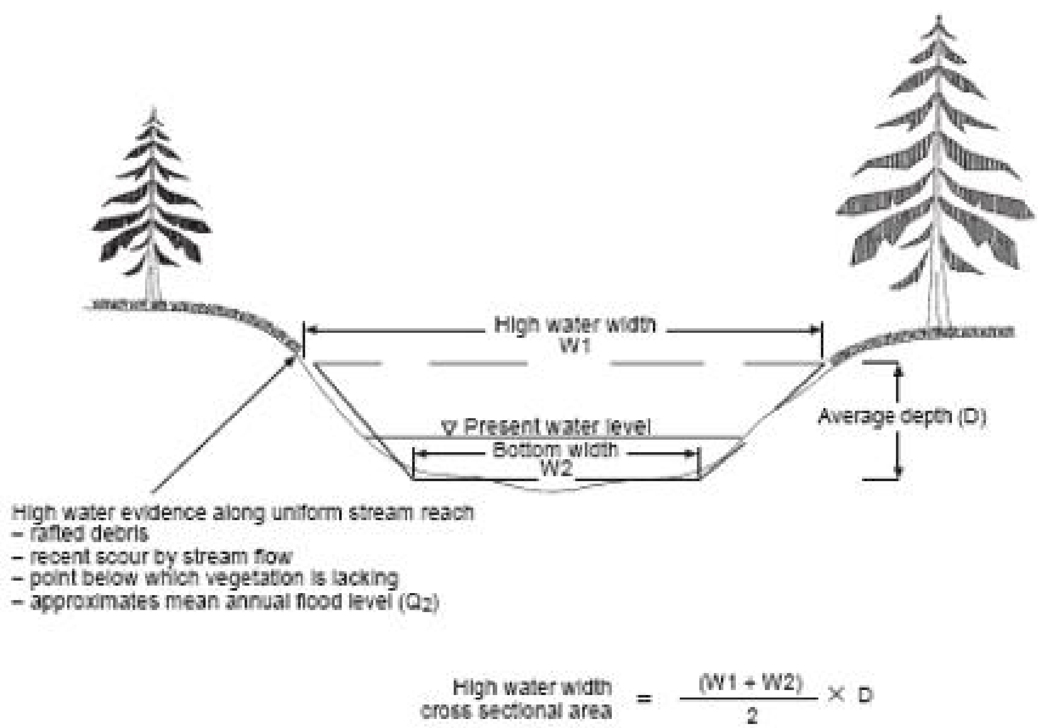


Figure 4. High water width cross-sectional area for culvert diameters (MFLNRO 2002).

Manning's Equation:

$$Q = VA = \left(\frac{1.49}{n}\right) AR^{\frac{2}{3}} \sqrt{S} \quad [U.S.]$$

$$Q = VA = \left(\frac{1.00}{n}\right) AR^{\frac{2}{3}} \sqrt{S} \quad [SI]$$

Where:

Q = Flow Rate, (ft^3/s)
v = Velocity, (ft/s)
A = Flow Area, (ft^2)
n = Manning's Roughness Coefficient
R = Hydraulic Radius, (ft)
S = Channel Slope, (ft/ft)

Figure 5. Manning's equation and variables (Oregon State University 2006).

ENVIRONMENTAL IMPACTS OF ROAD BUILDING

Forest roads should be constructed in consideration of hydrology, geological erosion, slope, and soil type (Samani et al. 2010). Forest roads disrupt the hydrological cycle and alter the natural water channel in the form of surface flow, intercepted surface flow, subsurface flow, soil, and infiltration (FESA 2005). Surface flow will become accelerated and increasingly concentrated along the sides and the surface of the road (FESA 2005). Subsurface flow will be converted to flow above ground after road building has occurred. Infiltration is also an issue because the soil will be compacted along the road surface making infiltration levels low. The soil is loosened during initial road building, which can increase the amount of soil erosion. Soil erosion is a major concern because sediment is transported in the water, which can negatively affect water quality and reduce water storage capacity of lakes (FESA 2005). These factors can greatly increase the life of the road when constructed properly, but if they are not considered, an added cost will be applied to the road in the future for maintenance.

Roads should be constructed with the proper amounts of culverts, bridges, and ditches along the road system to lower surface runoff of water. Having culverts at stream intercepts allows for water to travel in its natural pathway and limits water control issues. Culverts should be adequately sized in relation to waterways to accommodate the amount of running water. Culverts should also be placed in certain areas along the road network where streams are not present to help reduce water buildup during rain events. Bridges can be used to help preserve stream channels that are too large to accommodate culverts because they prevent damage to the channel by being built on the top of the banks. Keeping the stream channel clear and intact also allows an ideal passage for fish. Unlike bridges, culverts accelerate water speeds due to a narrowing of the stream at the culvert which can prevent fish from passing through. Ditches allow roads to shed water and to not increase water concentrations. Having a capped road surface will help direct water into the ditch passageways, thereby transporting water through to the culverts where it passes under the road network (FESA 2005). These techniques will mitigate the environmental effects of road building and ensure natural water flow.

ROAD BUILDING

Road building begins by clearing the right-of-way along the ribboned centerline. The next steps include grubbing, ditching and capping the road. The road right-of-way is the cross-section of the road that is cleared of trees to begin road building (Uusitalo 2010). The right-of-way can range in width from 8m to 30m and should be kept as narrow as possible to minimize impacts on other resources (MFLNRO 2002). The removal of additional trees along the width of the road can help allow more light in (daylighting), to help speed up the drying of soil (FOA 2012). Once the trees are removed, grubbing occurs. Grubbing is the removal of earth masses, organics, stumps, and boulders to expose the subgrade of the road, which is followed by building the ditches to the proper depth and width (Uusitalo 2010). During the subgrade phase, culverts are installed along the road way, and any unstable areas are reinforced with rock, geotextiles, or brush mats (Uusitalo 2010). The cut and fill slopes are positioned to the proper angle based on soil substrate (FOA 2012). Finally, the road is capped to allow for adequate drainage off the road surface.

There are two methods of building roads: the bulldozer method with a single pass process and the excavator method with either single or two pass process. Bulldozers are better suited for shorter distances and flatter terrain where earth needs to be moved along the road for cut and fill (Uusitalo 2010). Bulldozers are the most efficient machine for leveling roads (FOA 2012). The excavator method is suited for steeper terrain and moist sites. The excavator is typically a more general-purpose machine (FOA 2012). These two methods can be used together as a single method (Uusitalo 2010).

The single pass process is typically used on flat to moderate terrain (FOA 2012). In steep terrain, a two-pass process may be more suitable. In a two-pass system, an excavator creates a pilot track above the final road location and is kept below the top of the cut bank (FOA 2012). On the second pass, the excavator works its way down the pilot road clearing and building up the final road surface. The cut and fill slopes are then correctly angled once the road is created on the second pass. The fill slopes are compacted in layers to help increase strength and allow the fill slope to become stable (FOA 2012). Finally, the road is capped for the running surface. Figure 6 shows a typical road cross-section when properly built (FESA 2005).

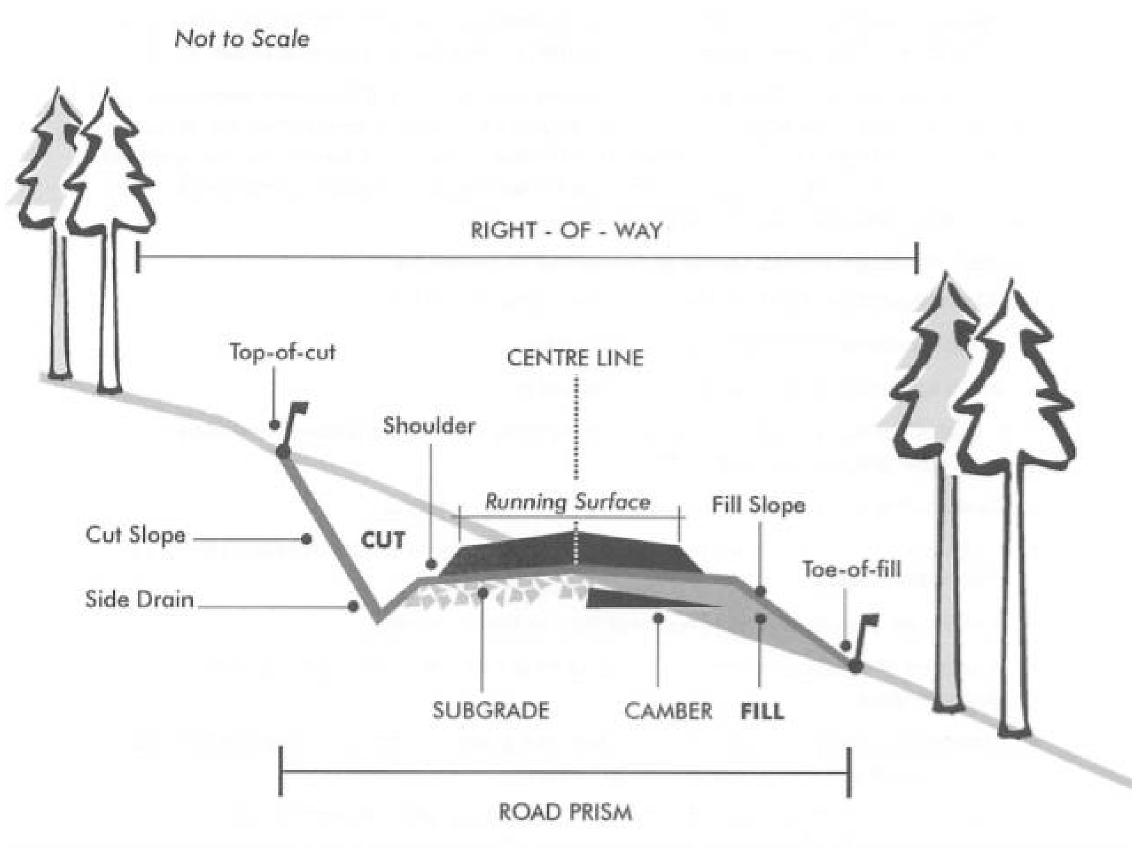


Figure 6. Final road prism when built. (FESA 2005).

CUT AND FILL CONSTRUCTION TYPES

There are three types of cut and fill construction types: cut and side cast, cut and bench fill, and full-bench construction (endhaul) (FOA 2012). Each method is used to achieve road building criteria for different terrain and soil types. All three methods use different variations of cut and fill slopes to produce the desired road.

Fill slopes are used to stabilize the lower section of the road and must consider the gravitational and water pressure forces, shear resistance of soil and material, and the angle of repose (MFLNRO 2002). Gravitational and water pressure are the forces that cause soil instability, whereas shear strength is the force that opposes instability in soil (MFLNRO 2002). The angle of repose is how steep an angle of a given soil material can be before slope failure occurs (MNFLRO 2002). Fill slopes should always be built to an angle lesser then the angle slope failure. Poorly drained fill slopes will have a higher chance of slope failure than well-drained fill slopes. Compacting the fill slope is a method used to help provide more structure and stability to the fill slope because the density and shear resistance of the soil is increased (MFLNRO 2002). Depending on the soil type, a horizontal (H) and vertical (V) ratio are given for each soil type when building the fill slope. Fine-grained soils, such as silts and clays need a higher horizontal ratio at 2H:1V whereas most other soil types are roughly a 1H: 1V ratio.

Cut slopes occur on the top bank of the road where the material is cut out of the hill. Cut slopes will remain slightly more stable at a steeper angle than the fill slope (MFLNRO 2002). This is because the undisturbed soil on the cut slope is in a denser state than the material on the fill slope and has more cohesive strength, which increases the shearing resistance (MFLNRO 2002). If cut slopes are cut at too low (flat) of an angle, the road can become very costly because larger volumes must be excavated. Therefore, steeper angles for cut slope are favoured because there is a greater chance of material slumping when the angle is too flat (MFLNRO 2002). Another reason to design steeper cut slopes is to minimize visible site disturbance and reduce the total length of the cut slope (MFLNRO 2002). When deciding between a steep cut bank or a shallow cut bank, the advantages and the disadvantages should be considered for each section of road being built (Figure 7) (FOA 2012).

Advantages of steep cut bank	Disadvantages of steep cut bank
1. Less right-of-way	1. Difficult to re-vegetate
2. Less excavated material	2. Prone to ravel and ditch plugging
3. Less side cast	3. Risk of increased slumping
4. Shorter slope exposed to erosion	4. Increased risk of rotational failure

Figure 7. Advantages and disadvantages of steep cut banks (FOA 2012).

The first type of cut and fill construction is the cut and side cast method which is primarily used for forest roads on flat or gentle terrain. The upper slope of the existing ground is cut and placed below the road centerline to form the remaining road (Figure 8) (FOA 2012). The cut and side cast method is unacceptable in steeper terrain because there is a higher risk for material to erode and enter streams (FOA 2012). The second type of cut and fill construction is cut and bench which is used on steep or unstable slopes and uses the two-pass system (FOA 2012). The pilot road is the first pass which helps create a bench to contain and stabilize the fill slope (Figure 9) (FOA 2012). The third type of cut and fill construction is full-bench which refers to a complete cut taken out of the existing ground to produce the road (Figure 10). This method is used on slopes greater than 70% where it is not possible to compact side material on the fill slope (FOA 2012). Full-bench combine with endhaul is very expensive when compared to other road building methods (FOA 2012). All material cut needs to be moved elsewhere along the road where fill is required; otherwise, the material is wasted off-site. Using the proper road building technique reduces environmental hazards, provides stable subgrades, and increases the life span of the road.

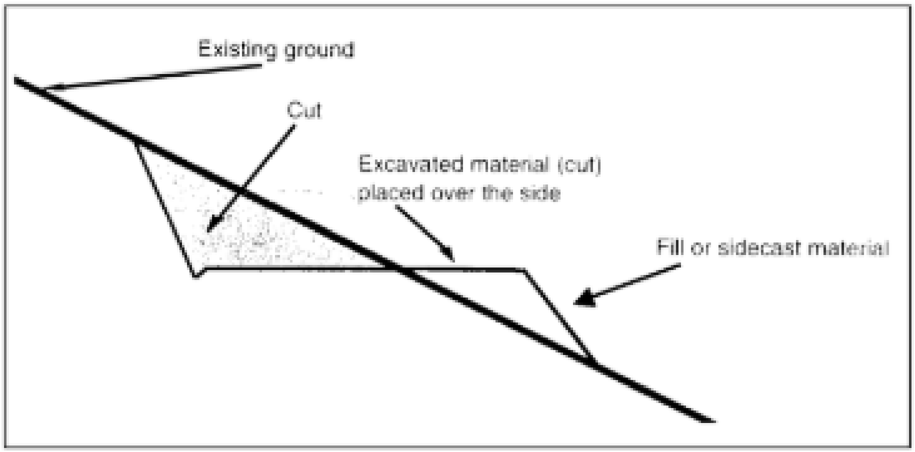


Figure 8. Cut and side cast road cross-sectional diagram (FOA 2012).

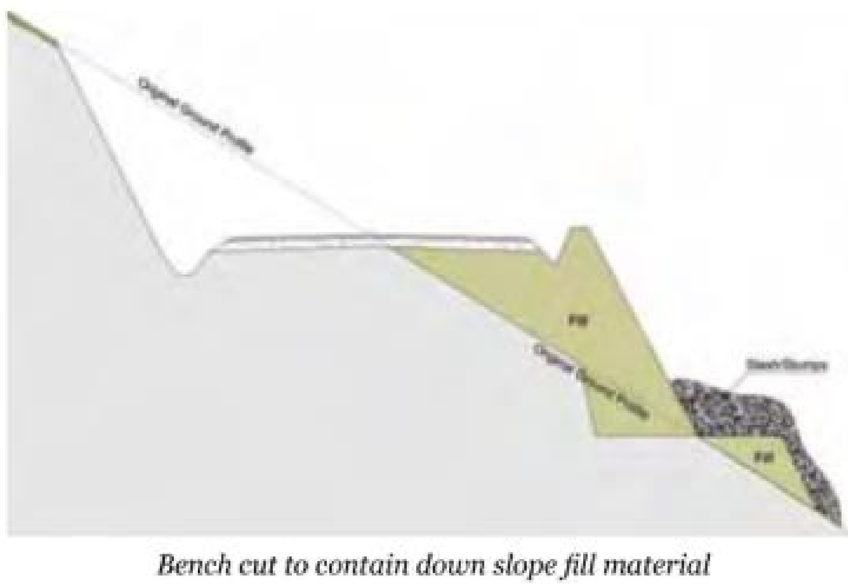


Figure 9. Cut and bench road cross-sectional diagram (FOA 2012).

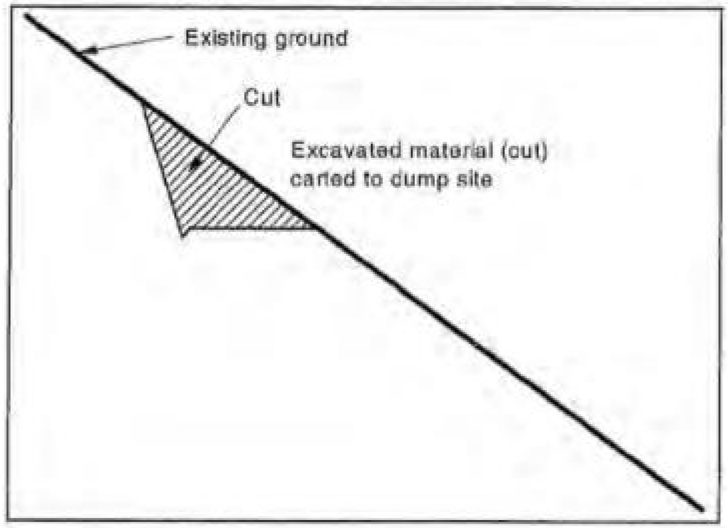


Figure 10. Full bench (endhaul) cross-sectional road diagram (FOA 2012).

SOIL SWELL AND SHRINKAGE FACTORS.

As soil is being cut, filled or hauled along the roadway, material will either swell or shrink based on the type of material. When material is in the ground as a bank or in situ, the volume factor is constant (FLNRO 2002). As the material is cut and excavated or even blasted, the material will swell. Therefore, the material being trucked along the road has more volume compared to the initial state (bank). The last state of material is compacted and, in this state, typically more material is needed to reach the same height when compared to the initial bank state. The factors affecting soil swell and shrinkage are soil or rock type, original in place density, moisture content of loose material at the time of placement and compaction; and the compactive work placed on the fill material (FLNRO 2002). Figure 11 illustrates how soil materials swell and how shrinkage is affected by time and the amount of volume (FLNRO 2002). Typically, solid rock, rippable rock, and dense soils will swell while fine-grained soils, such as clays and silts will shrink (FLNRO 2002). Sands and gravels have been found to have very slight swell and shrinkage volumes or none at all in some instances (FLNRO 2002).

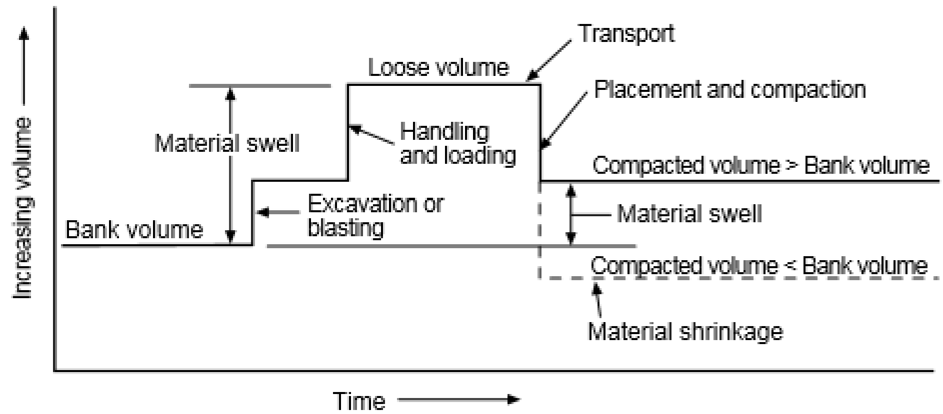


Figure 11. Affect of material with time and amount of volume being handled in road building (FLNRO 2002).

LiDAR

LiDAR is an active remote sensing technology used to collect elevation measurements of above-ground objects, such as trees, and ground surface of the topography (White et al. 2010). LiDAR is collected as either terrestrial LiDAR on the ground or as airborne laser scanning (Chasmer et al. 2006; Yen et al. 2011). Airborne LiDAR data is collected using a fixed-wing aircraft at low altitudes (Evans et al. 2009).

Aboard the aircraft contains a global positioning system device (GPS), an inertial measurement unit (IMU), and either a pulse or discrete return laser scanner used to collect the point data (White et al. 2010). The laser is used to measure the distance to the landscape below by sending pulses of infrared light which reflect off the objects below and return upwards back to the sensor (Evans et al. 2009). Acquisition parameters for LiDAR consist of the following: pulse repetition frequency, number of returns, pulse density, scan angle, flight overlap, data collection schedule, geodetic control, equipment, processing software, and accuracy (Evans et al. 2009). These parameters help determine the quality of the data captured.

LiDAR is superior traditional photogrammetric mapping practices because LiDAR can penetrate through the tree canopy and use shorter wavelengths than radio, which results in high-resolution terrain mapping that is highly accurate (Leclipteux 2015). LiDAR sends light pulses down and measures the time which the reflection returns to the sensor; the first return is usually the canopy layer for the forest (Anderson 1999). The second and final returns continue after the first return, which gives locations varying from mid tree canopy and to the ground surface (Anderson 1999). This process allows for a better representation for ground surface when compared to other forms of orthographic interpretation.

The results from LiDAR can provide 1 m resolution and greater, while delivering 20 cm accuracy for actual ground height (Akay et al. 2008). Penetrating through the tree canopy allows the ground profiles to be mapped more accuratly to produce a triangulated irregular network (TIN), which aids in road and block planning (Hodgson and Bresnaham 2004; Schiess and Krogstad 2003). The TIN generated has a significantly greater vertical and horizontal resolution than aerial photos because LiDAR has finer point scaling (Wulder et al. 2008). Therefore, LiDAR is very useful in forestry because it helps to accurately map terrain which is crucial for forest road planning.

RoadENG

RoadENG is a software program created by Softree as a forest engineering package with a total of four modules. Survey is the first of the four modules which is used to input field road notes. Once road notes are input, a shapefile can be created and georeferenced.

From the shapefile, the road can be geometrically designed in the third module called Location.

Terrain is the second module and is used for creating TIN from LiDAR or aerial photogrammetry (Softree 2017). Raw LiDAR data files (LAS) are the best way to develop models because the data can be manipulated to reduce the amount of points from the LiDAR data to increase the efficiency of the computer generated model (Softree 2017). Softree Terrain can create a full model with contours of an area, or a corridor if the road has been already established in Survey (Softree 2017). From the LiDAR data, RoadENG can estimate the earthwork for the area of interest which is the cut and fill of material being moved along the roadway (FOA 2012). Knowing the earthwork of the area also aids in minimizing the total amount of cut and fill depths needed to achieve the desirable road specifications (FOA 2012).

Location is the third module in creating a road design with RoadENG. Location helps determine the horizontal and vertical alignment of roads from generating cross-sections (Holgado-Barco et al. 2014). The vertical alignment aids in adjusting the slope and vertical curves of roads to ensure vehicles can travel safely (Holgado-Barco et al. 2014). Proper horizontal alignment ensures vehicles can navigate curves safely at the designated road speed. These two aspects are key elements within Location that help balance the cut and fill with the overall road based on haul requirements that can be manually adjusted (Cahskan 2013).

Softree Optimal is the fourth module of RoadENG and is an extension in the Location module . Optimal allows you to create road parameters, such as the cost of the cut and fill sections, and generates the most cost-effective alignment (Softree 2017). Soil layers can also be added into the parameters to help determine the cost for moving material. This tool is only as useful as the data that is inputed; therefore, designers should have a knowledge of the area Optimal is being applied to (Softree 2017).

CONVENTIONAL FIELD DESIGNS

Conventional field designs are first determined by obtaining data on a harvest block projection. The block projections give a general idea where the harvest block will be located. Roads are first broken down with control points to help with identifying road location (FOA 2012). Control points can vary from water crossing, gullies, steep slopes, flat areas on steep slopes (benches), bluffs or rock outcrops, and previous harvest blocks. Having control points helps to break down the road into sections and to optimize road gradients. Once control points are located, a field crew typically starting from a built road, can determine a grade line. A grade line is also known as a preliminary line and is referred to as a P-line (FOA 2012). The grade line continues forward from station to station. At each station, the road gradient is determined to make sure adverse and favourable grades are not exceeded (MFLNRO 2002). As road grades are determined from running the grade line, cut and fills may be applied to specific areas to help balance the road grades going forward. Areas such as water crossings use a cut and fill earthwork entering and exiting the area as streams are typically at a lower elevation than the surrounding ground profile.

After the road grade line is finished, a road centerline (L-line) is hung with ribbon. The goal of the road centerline is to smooth out the road and to reduce unnecessary curves throughout the grade line. The road centerline may also be placed off the grade line, either uphill or downhill of the grade line to help balance cut and fill with the road (FOA 2012). Road centerline placement is particularly critical on steep slopes where more cut and fill are needed and can help reduce unwanted clearing of road right-of-way.

Once the centerline is hung, a traverse crew is brought in to traverse the road. Methods of traversing can vary depending on the desired level of accuracy. Accuracy is of much higher concern in steeper terrain when compared to a road network that is primarily on flat ground. The traverse could be captured as a line feature with a GPS device which helps illustrate what level of detail is needed from the traverse (survey accuracy) (MFLNRO 2002). When accuracy is of less concern, a line feature can be traversed with point features for stream crossings for culverts and bridges. When traversing precision is of more concern, a hand traverse with detailed notes may take place. A hand traverse involves a crew of two people who either carry a 50 m tight chain or laser to measure slope distance (FOA 2012). Along the traverse, stations are created based on control points or line of sight. At each station the following is recorded: slope distance, horizontal distance, slope gradient (%), and side slopes roughly 15 m on the left and right side of the road. As well, overburden or terrain information is recorded. Once the hand traverse is complete, the field notes are brought back to the office where the notes are inputted into the computer to generate the line for the road feature. After the line feature is created, the road can be handed off to the road builders. However; if greater accuracy is needed, the road is designed using software such as RoadENG. The road can then be smoothed out with proper curves, cut and fill sections can be balanced to help reduce earthwork and road gradients can be kept within the required limits. Figure 12 shows the breakdown of how road planning is usually carried out.

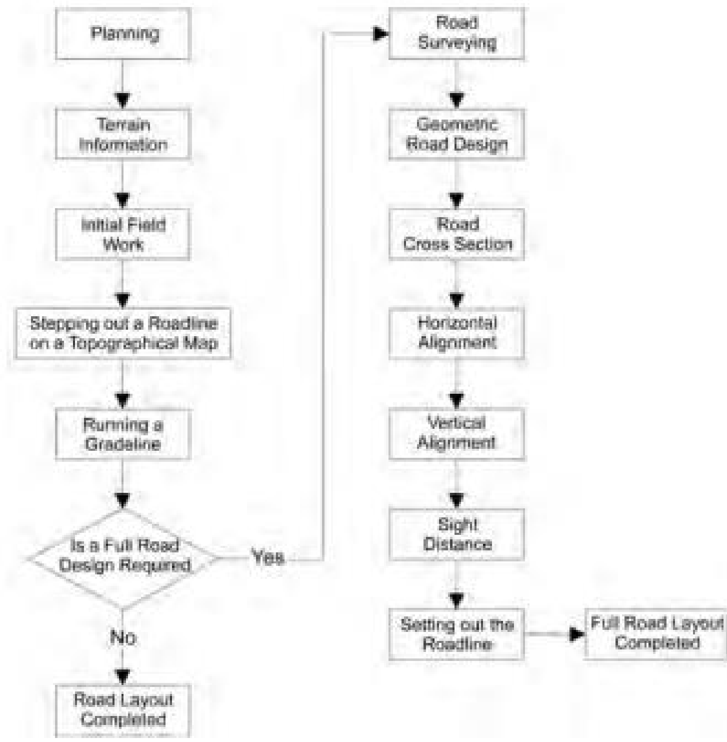


Figure 12. Procedure for designing forest roads (FOA 2012).

OFFICE-BASED TERRAIN MODELLING METHOD

Roads can be more extensively planned using LiDAR in the office, followed by ground truthing in the field. Using LiDAR allows the designer more certainty in road location beforehand. Office based terrain modeling method is considered the most cost-effective approach (FOA 2012). As well, full geometric designed roads are preferred for roads located in terrain where there is a moderate to high hazard for landslides (FOA 2012). The office design will begin with the designer inputting the LiDAR data into RoadEng. Next, control points will be created, and then the road centerline will be constructed in the TIN model. Multiple routes can be produced if the designer is uncertain that the first road location will work in the field. Once the office design is completed, the design can move on to ground truthing in the field to ensure the road design will work. This approach helps to speed up the completion of roads, to reduce the total cost in the planning of forest roads, and to increases productivity.

MATERIALS AND METHODS

STUDY AREA DESCRIPTION

The study area is 545 km^2 in size. The area is in the southwest corner of the Spanish Forest Management Unit (Figure 13). Coordinates for the study area are roughly 46 degrees Latitude and -82 degrees Longitude. The study area is positioned roughly 31 km north of Elliot Lake, Ontario.

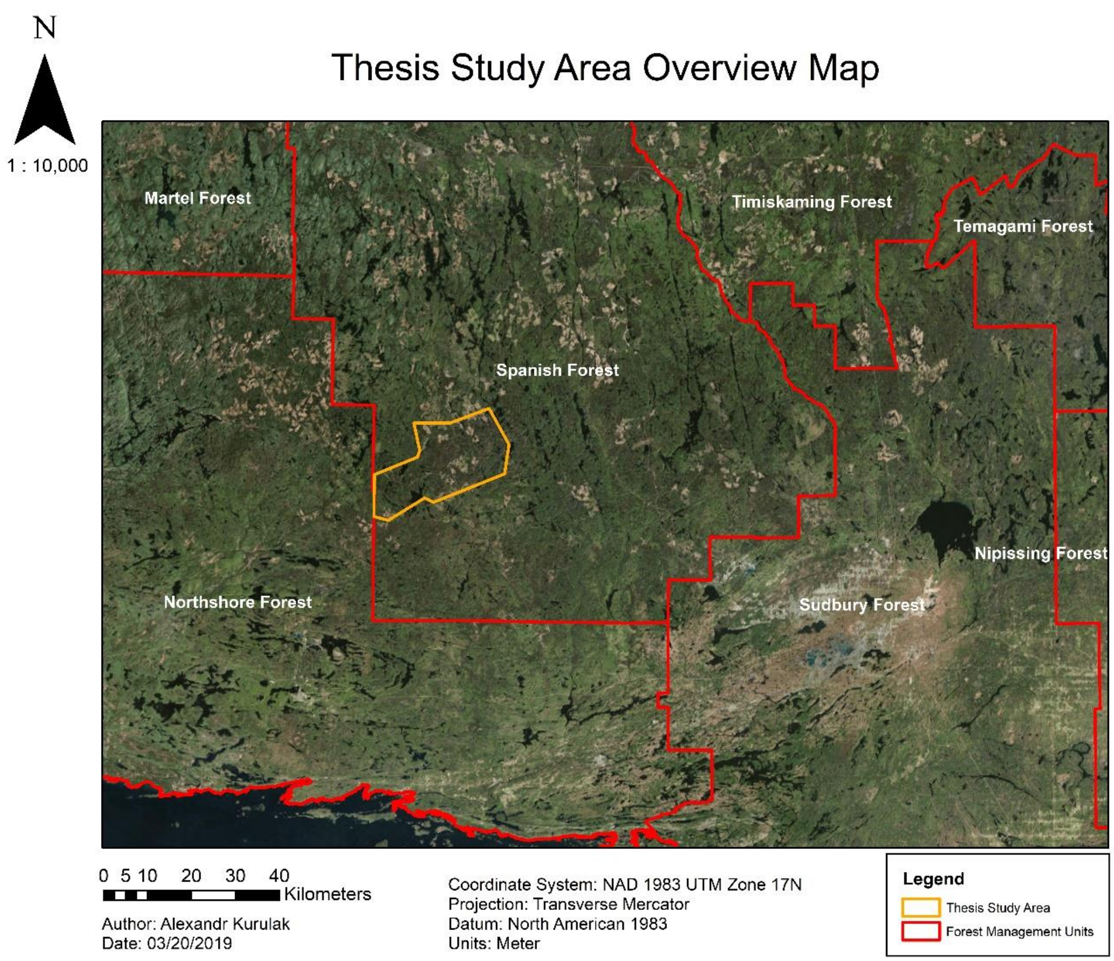


Figure 13: Overview map of the study area

TRIANGULATED IRREGULAR NETWORK (TIN) MODEL

The LiDAR data provided was inputinto Softree Terrain as raw data (LAS) tiles. The LiDAR data used was provided by Eacom Timber Corp and KBM Forestry Consultants. All LAS tiles of interest were overlapped with the study area. The border of each LAS tile was deleted to reduce the number of points within the TIN. Next, the TIN was generated with 1-metre minor contours and 50-metres major contours. After the TIN was created no points were reduced in the model. A total of 90,708,927 points were produced within the model.

TIN’s were then created for each road section once the road sections were selected. Smaller TIN’s allowed RoadENG Location to run faster and more efficiently. As well, all components of RoadENG could be accessed properly without causing the program to crash. For example, road templates are inaccessible with larger TIN models and cause the program to crash.

ROAD SECTIONS

Road sections were picked from mainline, branch and block roads within the study area. Road sections varied in length from one to two km in length. Five road sections were chosen from the study area. Road sections of interest were picked where multiple crossings or steep terrain occurred throughout the road section. These two parameters were determined using the TIN model and shapefiles in ArcGIS from culverts and streams. The breakdown of road classes for the study area was as followed: two sections of mainline, two sections of branch road and one section of block road.

The road sections selected were taken from ArcGIS as shapefiles then entered Softree Terrain. A point of commencement (POC) and point of termination (POT) were generated from the existing road. Next, the POC and POT were converted into Softree survey files, preliminary lines (P-lines) to be entered to Softree Location for design.

SOIL LAYER

The soil layer was determined from ecosite data embedded in the Ontario Forest Resource Inventory (FRI) for the study area. The shapefiles of the road sections were overlaid with the FRI ecosite data in ArcGIS. As ecosites changed along the road section, the new ecosite was assigned to the road segment. Ecosites in the surrounding area were also noted in case the designed road entered these ecosites.

For all road sections, three ecosites were observed to intersect with the road alignments. The ecosites for the road sections are NE02, NE03, and NE04. Looking at the species composition in the FRI data, the most suitable Ecosites with NE02, NE03 and NE04 were selected (Table 1). The parent material was determined to be sandy gravel (Figure 14) or rock knobs (Figure 15). OGSEarth data was used to determine the parent material (MNDM 2019). Litter, fermentation, and humus layer (LFH) were derived from *A Field Guide to Forest Ecosystems of Northeastern Ontario* (NEST) (Taylor et al. 2000).

Table 1. Ecosite with soil depths and parent material.

		Depth (cm)		
Ecosite	LFH (cm)	A and B horizons	Total Above PM (cm)	Parent Material
NE02	10	20	**30**	Solid rock or Sand
NE03	24	46	**70**	Solid rock or Sand
NE04	11	18	**29**	Solid rock or Sand

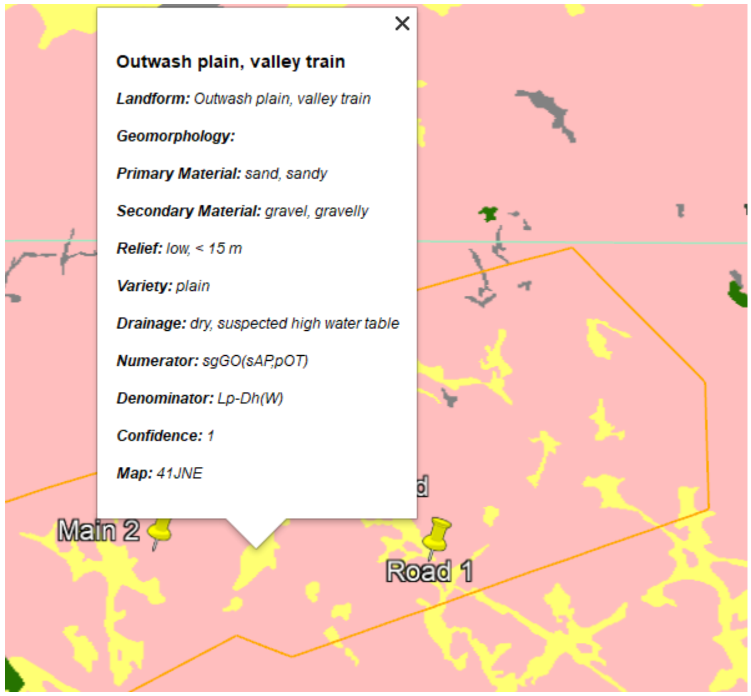


Figure 14. Study area parent material, yellow being sandy gravel from OGSEarth (MNDM 2019).

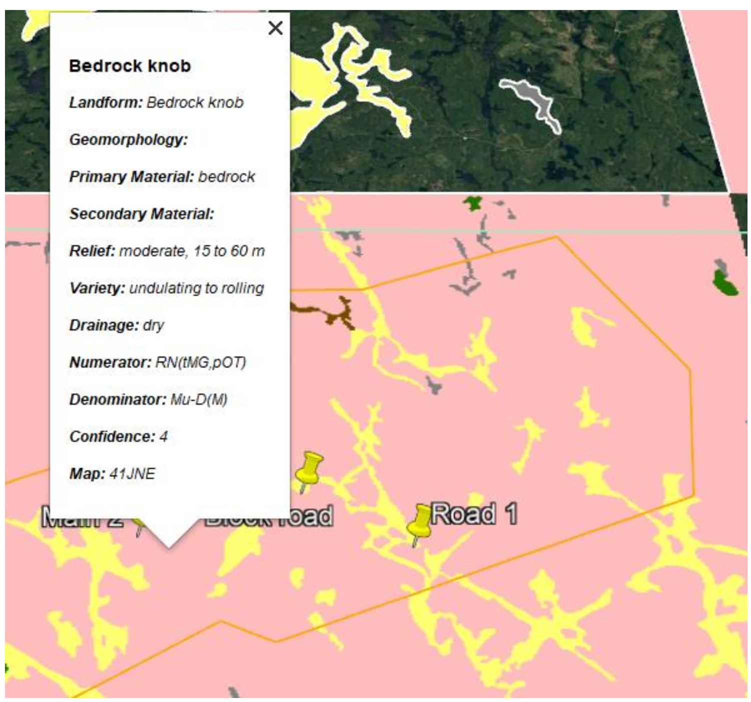


Figure 15. Study area parent material, pink being bedrock knobs from OGSEarth (MNDN 2019).

HAULING PARAMETERS

For simplicity, haul parameters within RoadENG were left as default (Figure 16). The parameters involved cost and distances for freehaul, overhaul, and endhaul. Also, no borrow or wasting pits were assigned to the design parameters. Hauling cost was derived from hauling of loose material. Cost of hauling as loose material allowed for a total cost of hauling to be determined from the soil excavated.

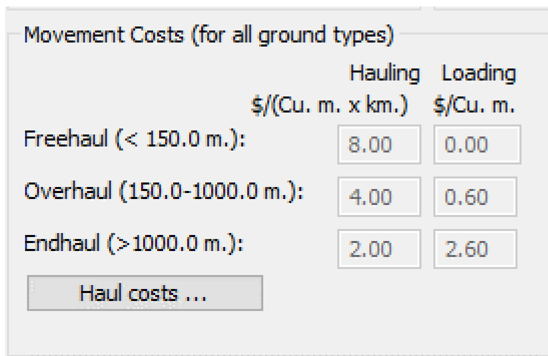


Figure 16. Movement cost for freehaul, overhaul and endhaul in RoadENG.

ROAD DESIGN

Roads alignments were determined by pegging roads blind of Eacom's actual road in RoadENG Location. Pegging is the equivalent to flagging road grade lines in the field (Softree 2017). A second road alignment was then chosen after seeing how the blind design differed from Eacom's design. The second attempt was to see if a better road design could still be created.

Grade constraints were taken from Eacom's road standards for mainline, branch and block roads. A grade could be exceeded in the horizontal alignment in certain sections of road to allow the road to reach the POT. If a higher grade did occur, a cut or fill was applied when using Softree Optimal to enable the road to maintain the grade constraints.

Once horizontal alignments were complete, road templates were set for each road by road class. The gravel layer in the template was configured to allow the road subgrade and surface width to meet the requirements. In RoadENG, the template width of the road is based on the top layer of the road. Travel speeds, k-values for sag and crest, and minimum road curvature radius were all assigned. All these parameters are based on Eacom's road building criteria (Table 2). The minimum vertical curve for sag and crest (k-values) was not given in Eacom's road specifications. Therefore, these values were derived from the BC Forest Engineering Manual (FLNRO 2002).

Table 2: Road design specifications

Road Type	Speed (Km/hr)	Subgrade Width (m)	Surface Width (m)	Maximum Slope Empty (%)	Maximum Slope Loaded (%)	Minimum Horizontal Curve Radius (m)	Minimum (K Value) Vertical Curve
Mainline	60	9.00	7.00	12%	10%	120.00	18.00
Branch	30	8.00	6.00	12%	10%	100.00	5.00
Block	16	6.80	5.00	14%	12%	80.00	2.00

Along the road alignment where soil type changed, the road was assigned the corresponding soil info for that section. Different soil information had different cost in excavation and embankment cost. Cut and slope angles for material where determined from roadside slope template provided by Martin Lewynsky, PENG, RPF (pers. com Feb 27, 2019) (Figure 17). These templates are used for road designs in Coastal British Columbia. The overburden layer in RoadENG used template four and solid rock used template five.

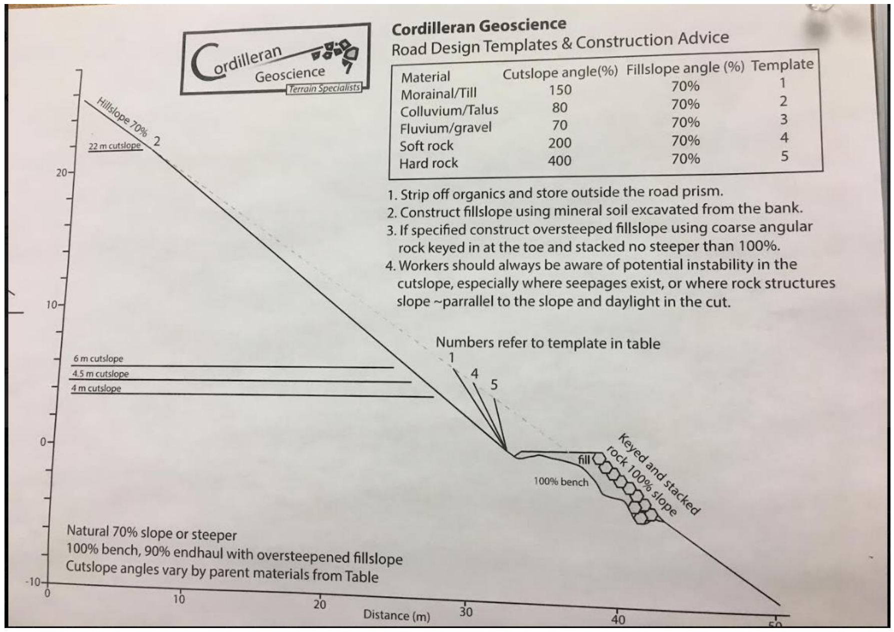


Figure 17. Road side slope templates based on the material.

Soil swell and shrinkage values for material were set based on the following values found in Table 3 and are for excavation only. Overburden encompassed both the LFH and sand. The layer was also interchangeable when the parent material was sandy gravel. This was strictly done for simplicity. A second soil swell and shrinkage factor was applied for hauling material as loose soil Table 4. Loose soil conversions were used to get a true cost for all hauling of material.

Table 3. Soil swell and shrinkage factors for excavation of bank material.

Material	Cut (bank)	Fill (compacted)
Overburden	1.00	1.05
Solid Rock	1.00	0.77

Table 4. Soil swell and shrinkage factors for hauled loose material.

Material	Cut (bank)	Fill (compacted)
Overburden	1.11	1.17
Solid Rock	1.50	1.15

A stripping parameter under the site prep tab was assigned to all road alignments. The stripping was applied to a depth of 30cm from slope base to slope base outside of the road prism and centerline to base within the road prism. The stripping depth was determined from the deepest LFH in NEST, 2000, being 24cm. This material was not used in the road building process and was wasted.

After the parameters for the road were set, the road was run with Softree optimal. One iteration was run with Softree's default settings for excavation and embankment cost for materials assigned (Table 5). A second iteration was run at half the cost to see the difference in how the road cost differ. These costs were also more representable with Eacom's excavation cost. A third iteration was run with excavation cost for overburden set back to Softree's default settings to see how the cost change with a closer overburden and solid rock excavation cost. The information collected once Softree optimal was run to determine total cost of the road ($), cost of cut and fill ($\$/m^3$), the length of the road (m), total material cut and fill (m^3), total material stripped (m^3), and the vertical alignment displaying mass haul for best balanced cut and fill along the road alignment.

Table 5. Road building cost for material for each iteration.

	Excavation Cost ($/m^3)					
Iteration	Overburden		Solid Rock		Embankment (Cost$/m^3)	
1	$	12.00	$	48.00	$	4.00
2	$	6.00	$	24.00	$	2.00
3	$	12.00	$	24.00	$	2.00

Next, the cost of culverts was applied to the roadways. Culverts were assigned based on Eacom's culvert layer in ArcGIS, since many of the crossings were in the same place. If a culvert size was allocated, the assigned width prescribe was used for the crossing. If a culvert did not have a size designated, the flow rate was determined with the Ontario flow assessment tool (OFAT) (MNRF 2019). Peak flood values assigned for Eacom roadways must abide by a Q25 flow rate because the OFAT tool does not have a Q25 rate the closest rate at Q20 was applied to the crossings if needed. Fortunately, all culvert sizes were in Eacom's culvert file. Where every culvert was placed, a culvert cost combined with the install fee was applied (Figure 18). The cost of culverts was provided by Kevin Shorthouse, RPF (pers. com March 5th, 2019) and are a conglomerate of various industry contacts in Ontario. Culverts under 450 mm were not included in this calculation because Eacom stated culverts under 450 mm are added in with the road building cost. Therefore, only culverts above 450 mm in size had a cost and installation fee applied.

Culvert Diameter (mm)	Maximum Discharge Rate (m^3/s)	Average Installation Cost
300	0.040	850.00
400	0.086	1,000.00
450	0.118	1,075.00
500	0.156	1,150.00
600	0.254	1,500.00
700	0.383	1,725.00
800	0.548	2,000.00
900	0.750	3,000.00
1,000	0.993	4,000.00
1,200	1.614	6,000.00
1,400	2.435	8,000.00
1,600	3.477	10,000.00
1,800	4.760	12,000.00
2,000	6.304	14,000.00
2,200	8.128	18,000.00
2,400	10.250	22,000.00
2,600	12.689	26,000.00
2,800	15.462	30,000.00
3,000	18.585	34,000.00

Figure 18. Culvert size needed to accommodate the maximum discharge rate (m^3/sec) and cost of culvert and install.

A flow analysis was developed to show all components created for the study. (Figure 19). All parts are broken down into sections and help show where resources were used to determine the result.

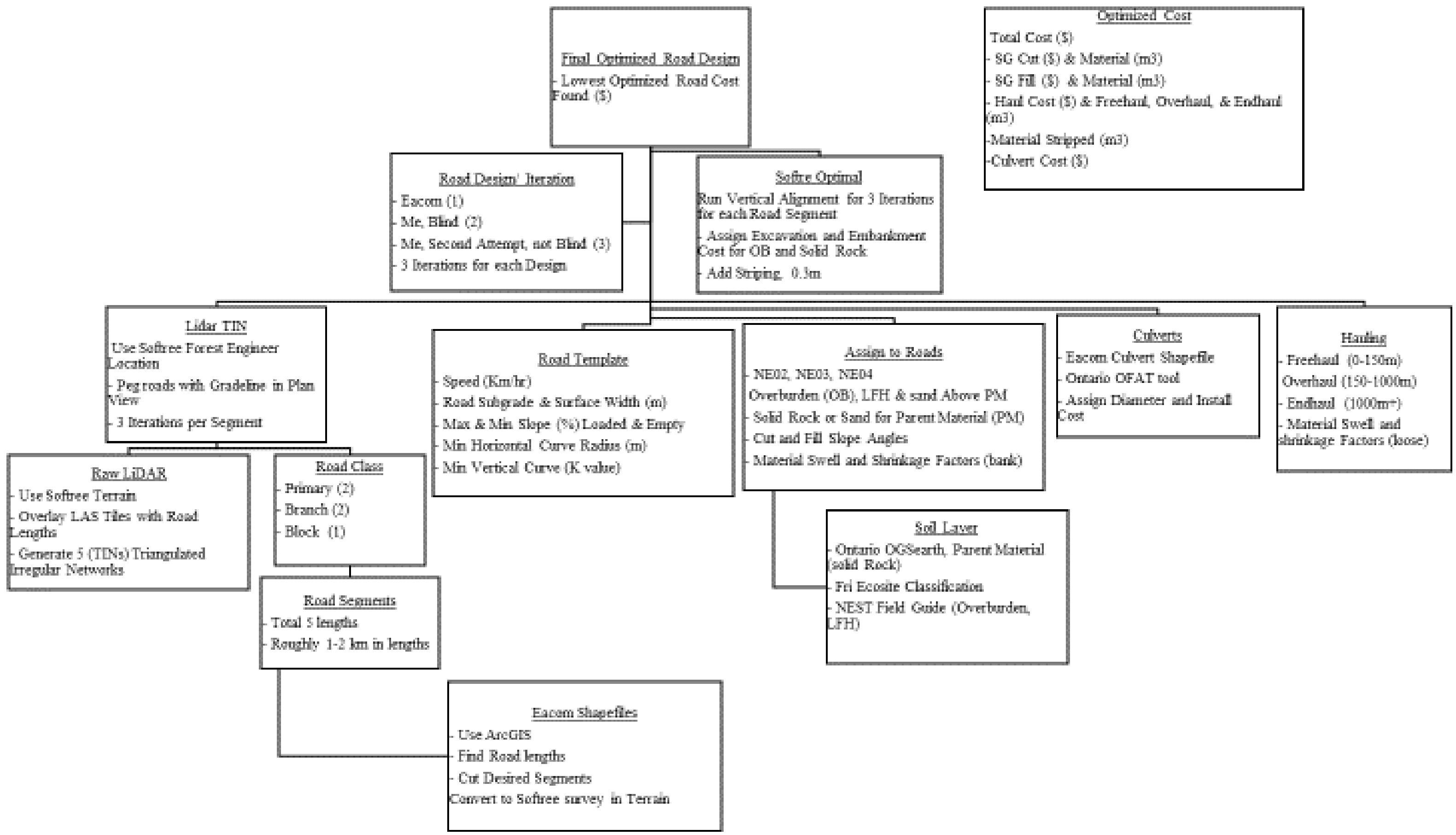


Figure 19. Flow analysis for methods.

RESULTS

RoadENG designs of road sections were compared to the field-based design produced from Eacom. These comparisons will determine if the study shows potential to minimize road cost through geometrical designs. The distance of each road design can be seen in Table 6. The table shows the distance of all five roads sections.

Table 6. Road Distance of designed roads by road section.

Section	Design	Distance (m)
Mainline 1	Eacom	2071.6
	Blind	2012.0
	Second Attempt	2045.0
Mainline 2	Eacom	2034.7
	Blind	2091.9
	Second Attempt	1979.7
Branch 1	Eacom	1118.3
	Blind	1163.6
	Second Attempt	1106.3
Branch 2	Eacom	1018.2
	Blind	1054.2
	Second Attempt	998.5
Block	Eacom	1721.9
	Blind	1736.8
	Second Attempt	1702.7

TOTAL COST

A total of 15 road sections were optimized using Softree Optimal within Softree Location with 3 iterations for various cut and fill cost applied. The road sections optimized were: Eacom, the blind design, and a second attempt. The second attempt was completed after the blind design by comparing the other two designs and trying to find a better route. The total road summary can be found in Appendix I. All road alignments for each section can be seen in Appendix II, and road mass haul diagrams can be seen in Appendix III. Table 7 shows the total cost of all road designs by iteration. Figures 20 through 24 show the total cost of each road section from each iteration.

Table 7. Total road cost by iteration and total.

Iteration	Eacom	Blind	Second Attempt
1	$ 1,314,670.00	$ 1,324,950.00	$ 1,711,260.00
2	$ 725,120.00	$ 689,540.00	$ 929,180.00
3	$ 767,140.00	$ 751,060.00	$ 1,023,510.00
Grand Total	**$ 2,806,930.00**	**$ 2,765,550.00**	**$ 3,663,950.00**

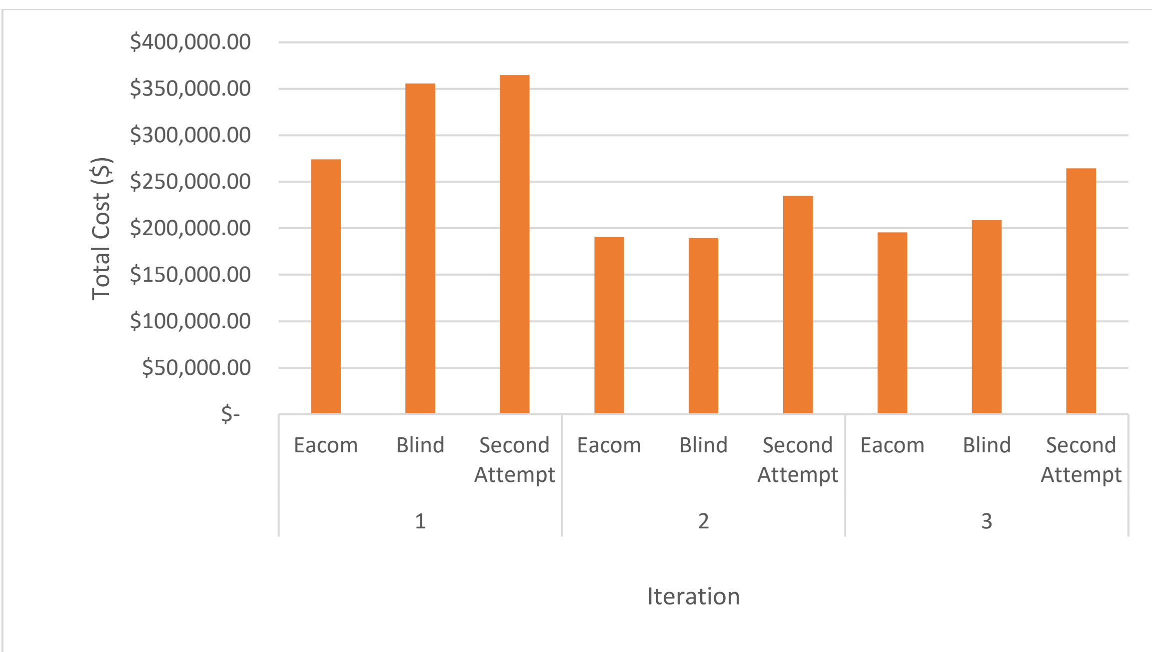


Figure 20. Total cost for mainline 1 road by design and iteration.

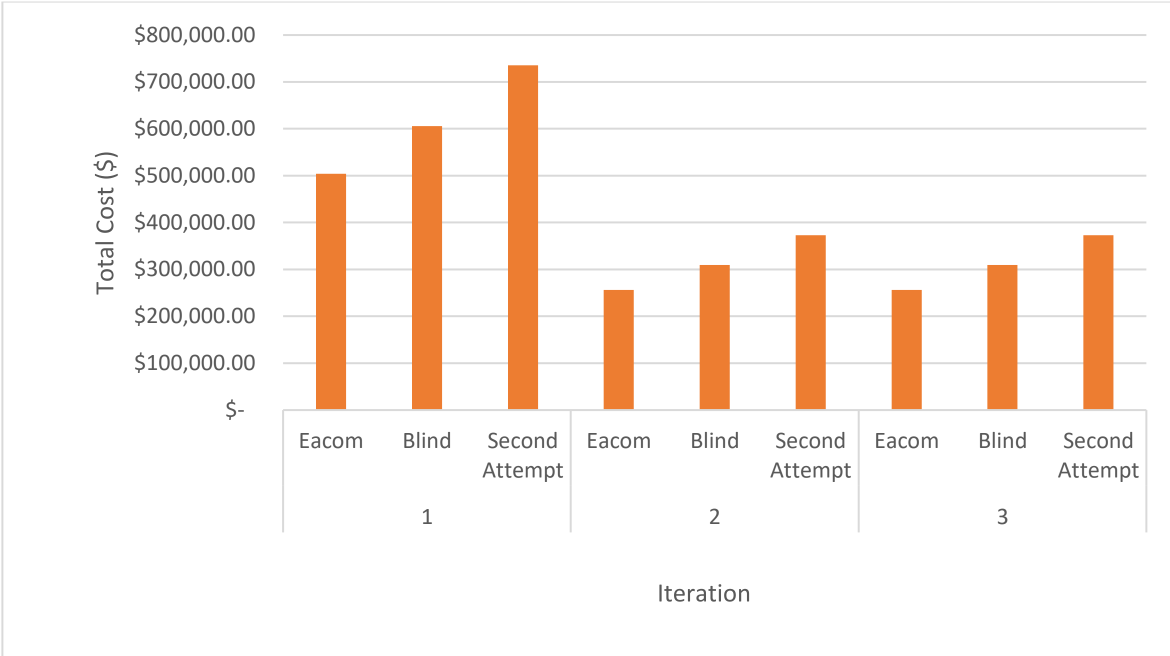


Figure 21. Total cost for mainline 1 road by design and iteration.

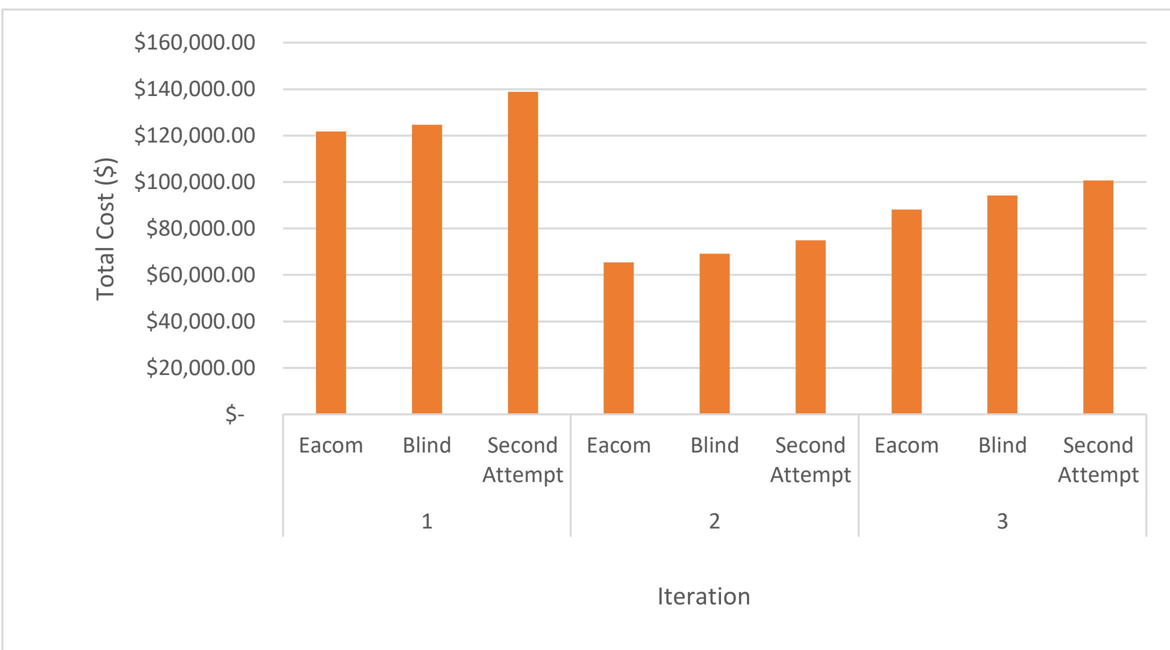


Figure 22. Total cost for branch 1 road by design and iteration.

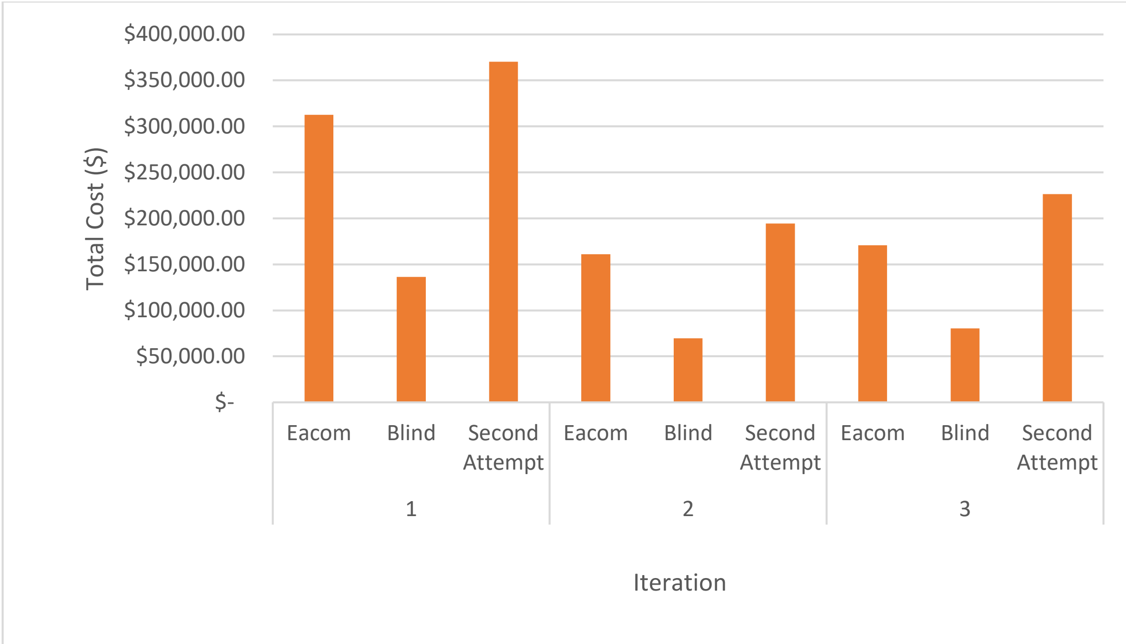


Figure 23. Total cost for branch 2 road by design and iteration.

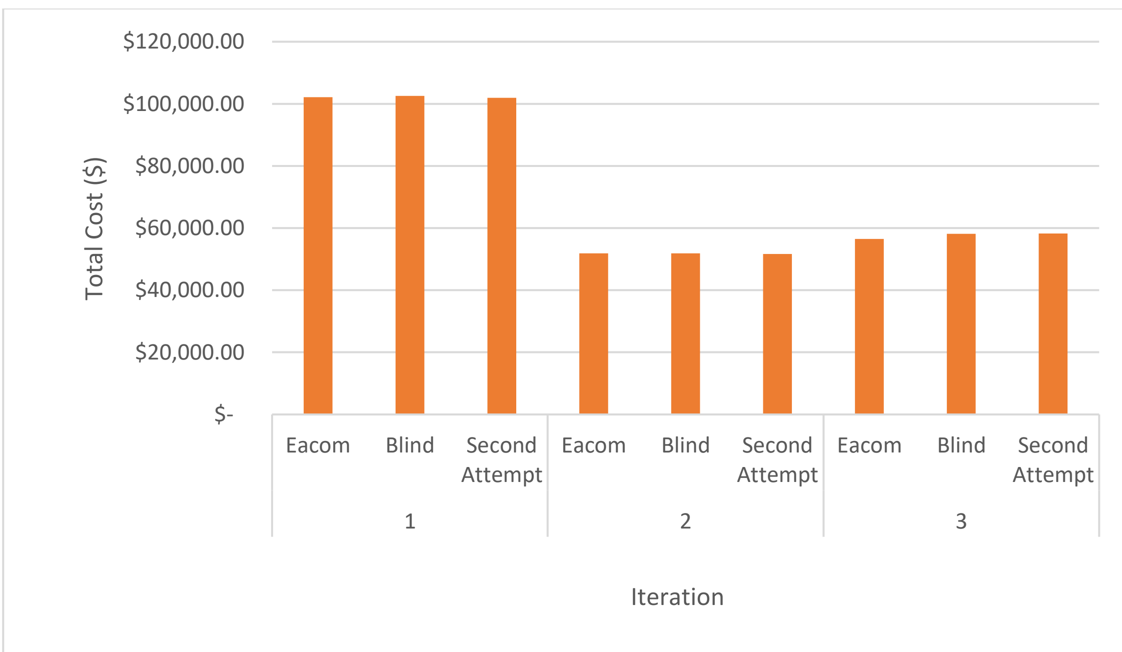


Figure 24. Total cost for block road by design and iteration.

EXCAVATION COST

The cost of excavation was broken up between soil types and cut and fill sections. Table 8 shows the breakdown of these costs for each road section and iteration. Total cost and cubic metres moved can be seen in Appendix IV. Assigned soils layers can be seen in Appendix V.

Table 8. Excavation cost for each iteration.

Iteration	Excavation Cost ($/m^3)				Embankment (Cost$/m^3)	
	Overburden		Solid Rock			
1	$	12.00	$	48.00	$	4.00
2	$	6.00	$	24.00	$	2.00
3	$	12.00	$	24.00	$	2.00

HAUL COST

Table 9 shows the haul cost of loose material along the road section. The table also displays the breakdown of endhaul, overhaul, and freehaul material in each road section and iteration. Figure 25 shows the breakdown in m^3 of material as freehaul, overhaul, and endhaul moved for each road section. Mass haul diagrams can be seen in Appendix IV.

Table 9. Haul cost and info. as loose volumes.

Road Section	Design	**Cost ($)**	Freehaul (m^3)	Overhaul (m^3)	Endhaul (m^3)	Stripped Material (m^3)
Mainline 1	Eacom	**$ 7,400.00**	5140.6	2688.6	180.5	9561.3
	Blind	**$11,340.00**	5506.3	2226.6	885.1	10713.9
	Second Attempt	**$ 5,390.00**	6311.3	2083.3	18.3	8572.7
Mainline 2	Eacom	**$ 8,140.00**	12134.9	2150.6	0.0	8719.9
	Blind	**$11,060.00**	13954.4	3141.1	0.0	9264.2
	Second Attempt	**$13,360.00**	18131.0	2678.5	0.0	8849.5
Branch 1	Eacom	**$ 1,090.00**	4947.8	165.6	0	4833.7
	Blind	**$ 5,560.00**	3266.1	1955.9	112.7	4856.8
	Second Attempt	**$ 6,220.00**	4445.6	2340.1	0	4316.1
Branch 2	Eacom	**$ 9,460.00**	4445.6	2340.1	0	4316.1
	Blind	**$ 2,760.00**	6790.8	3013.2	0	4907.5
	Second Attempt	**$18,300.00**	6761.8	6915.1	0	5103.3
Block	Eacom	**$ 1,470.00**	3319.4	459.7	0	6285.5
	Blind	**$ 1,130.00**	3319.4	459.7	0	6285.5
	Second Attempt	**$ 1,270.00**	3137.5	477.5	0	6273.2

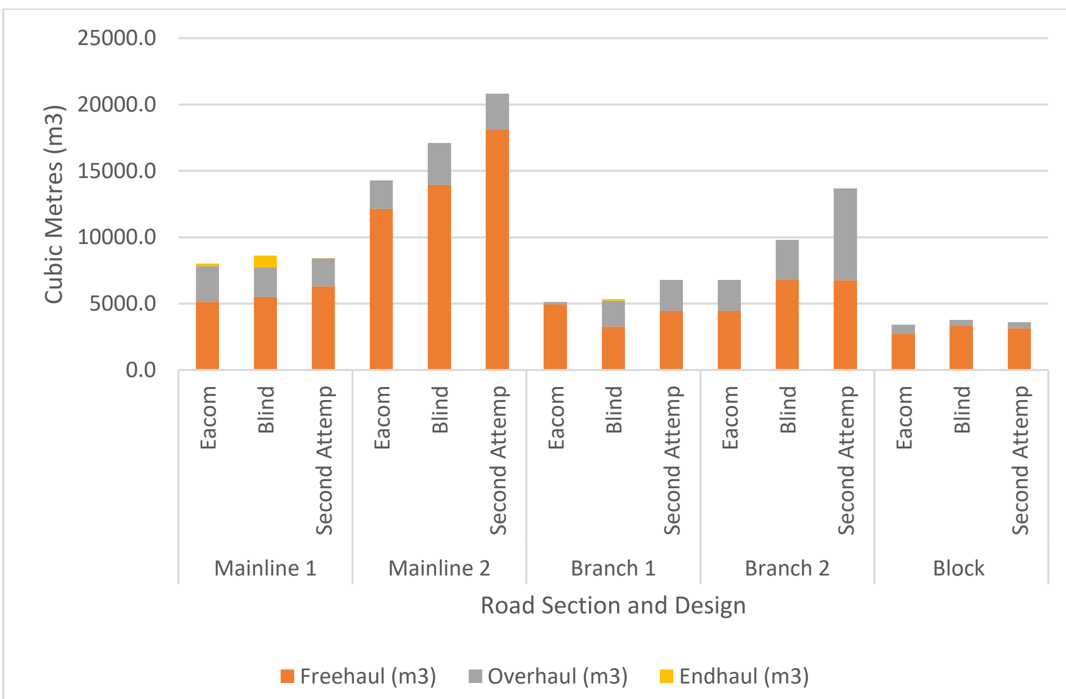


Figure 25. Freehaul, overhaul and endhaul material move along each road section.

CULVERT COST

Out of the 5 road sections, only 2 roads needed culverts over 450 mm. The road sections were mainline one and branch one. Table 10 shows the total cost for the culverts and install for each road section. Locations and size of the culverts for mainline 1 and branch 1 can be seen in Figures 26 through 31.

Table 10. Information for culverts over 450 mm on all road alignments

Section	Design	Discharge Rate (m^3/sec)	Culvert Size (mm)	Type of Culvert	Number of Culverts	Cost ($)	**Total Cost ($)**
Mainline 1	Eacom	4.3	1800	CMP	1	$ 12,000.00	
		13.3	2400	CMP	2	$ 44,000.00	
		13.3	2400	CMP	2	$ 44,000.00	**$ 100,000.00**
	Blind	4.3	1800	CMP	1	$ 12,000.00	**$ 12,000.00**
	Second Attempt	4.3	1800	CMP	1	$ 12,000.00	
		13.3	2400	CMP	2	$ 44,000.00	
		13.3	2400	CMP	2	$ 44,000.00	**$ 100,000.00**
Branch 1	Eacom	0.5	800	CMP	1	$ 2,000.00	
		1.6	1200	CMP	1	$ 6,000.00	**$ 8,000.00**
	Blind	0.5	800	CMP	1	$ 2,000.00	
		1.6	1200	CMP	1	$ 6,000.00	**$ 8,000.00**
	Second Attempt	0.5	800	CMP	1	$ 2,000.00	
		1.6	1200	CMP	1	$ 6,000.00	**$ 8,000.00**

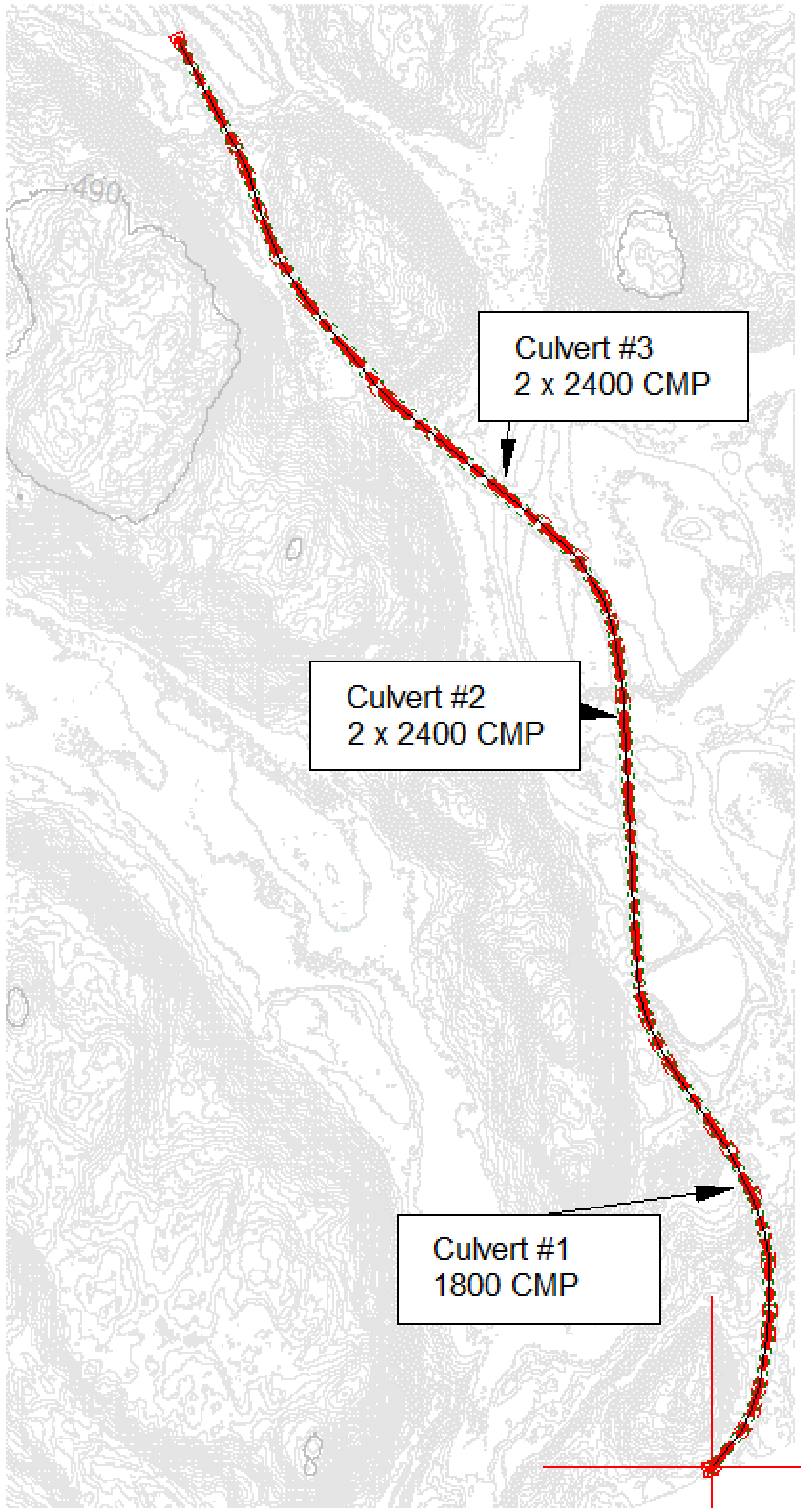


Figure 26. Eacom road design for mainline 1 with culvert locations and sizes.

Figure 27. Blind road design for mainline 1 with culvert locations and sizes.

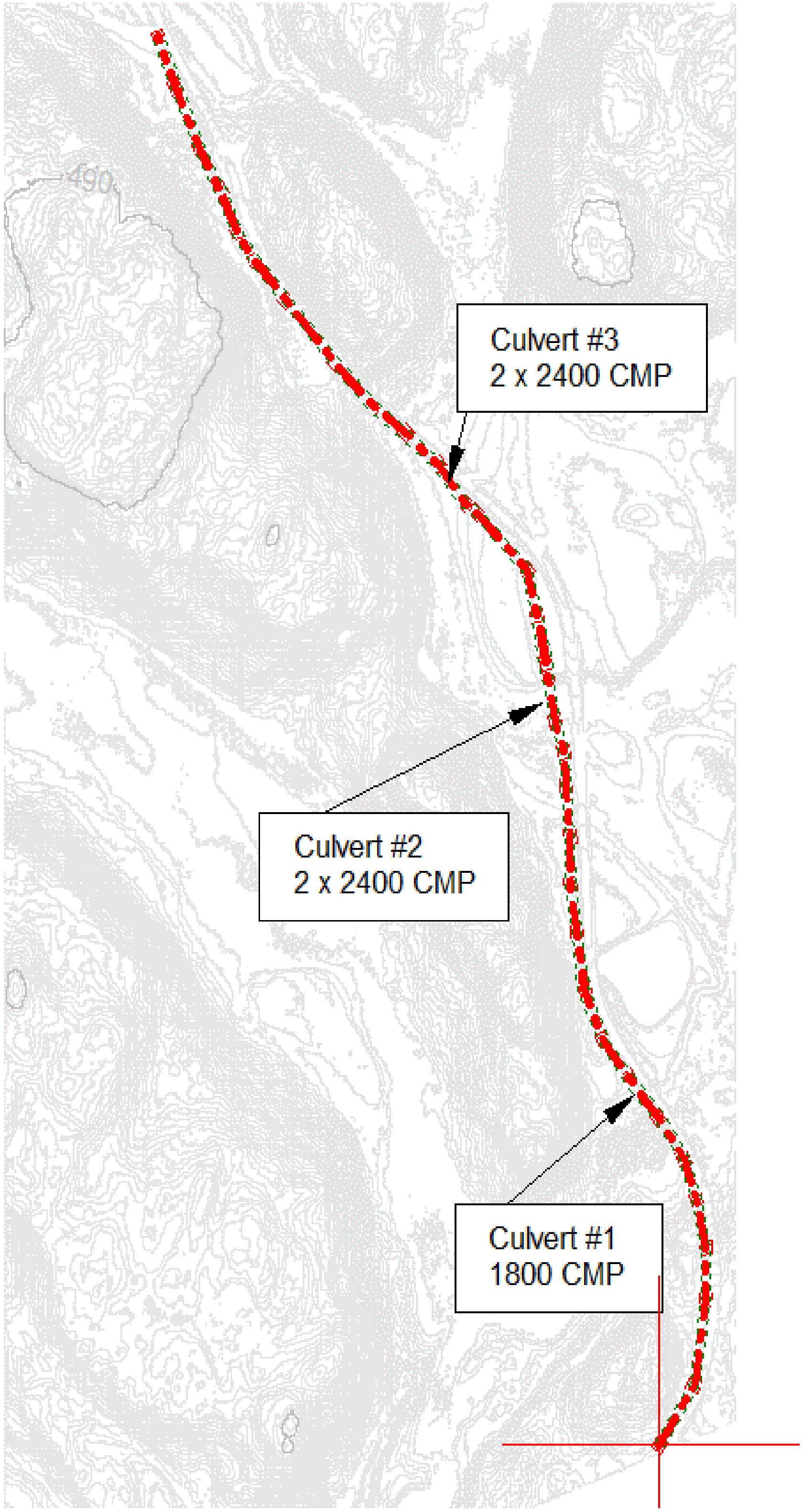


Figure 28. Second attempt road design with culvert locations and sizes.

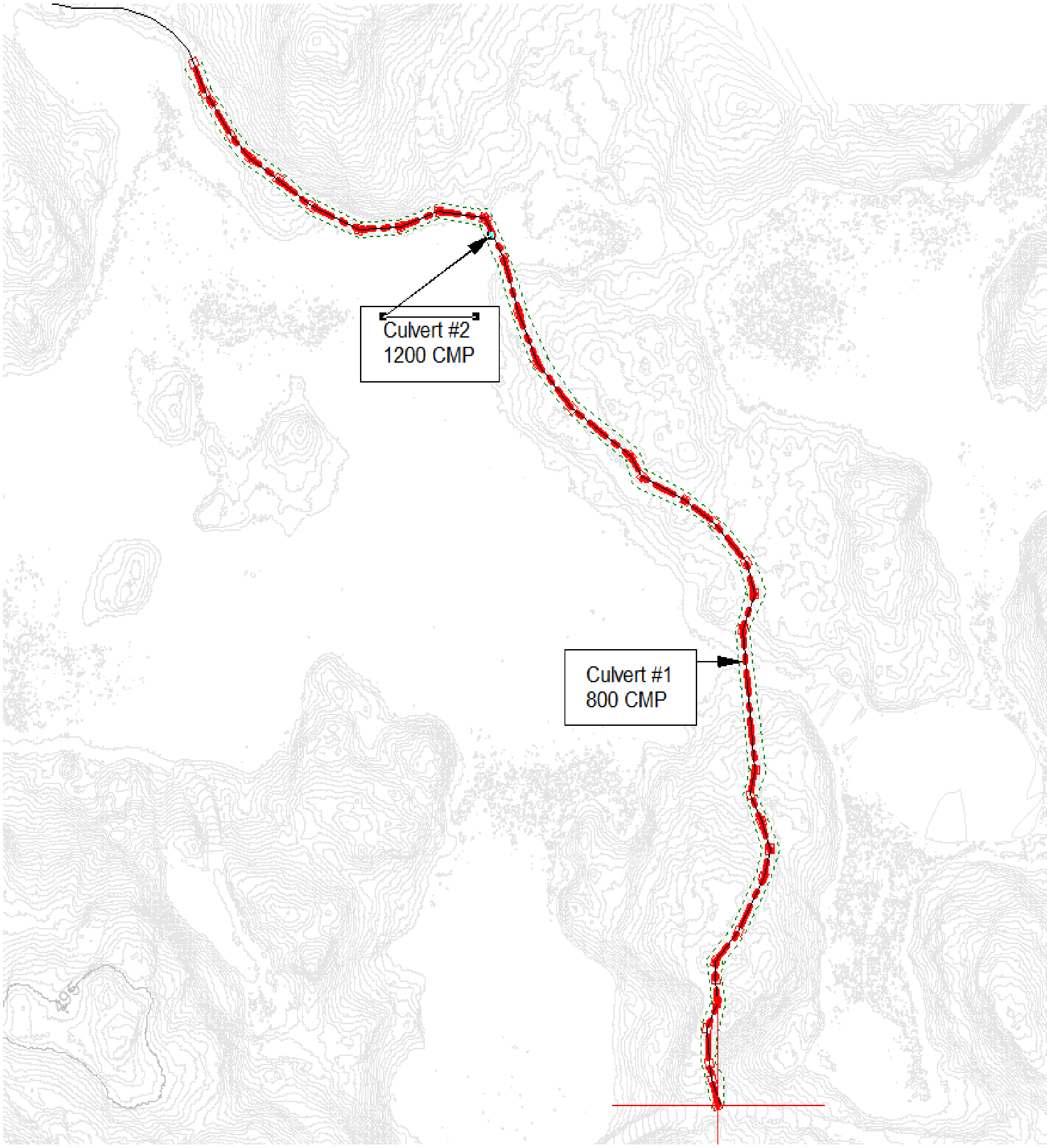


Figure 29. Eacom road design for branch 1 with culvert locations and sizes.

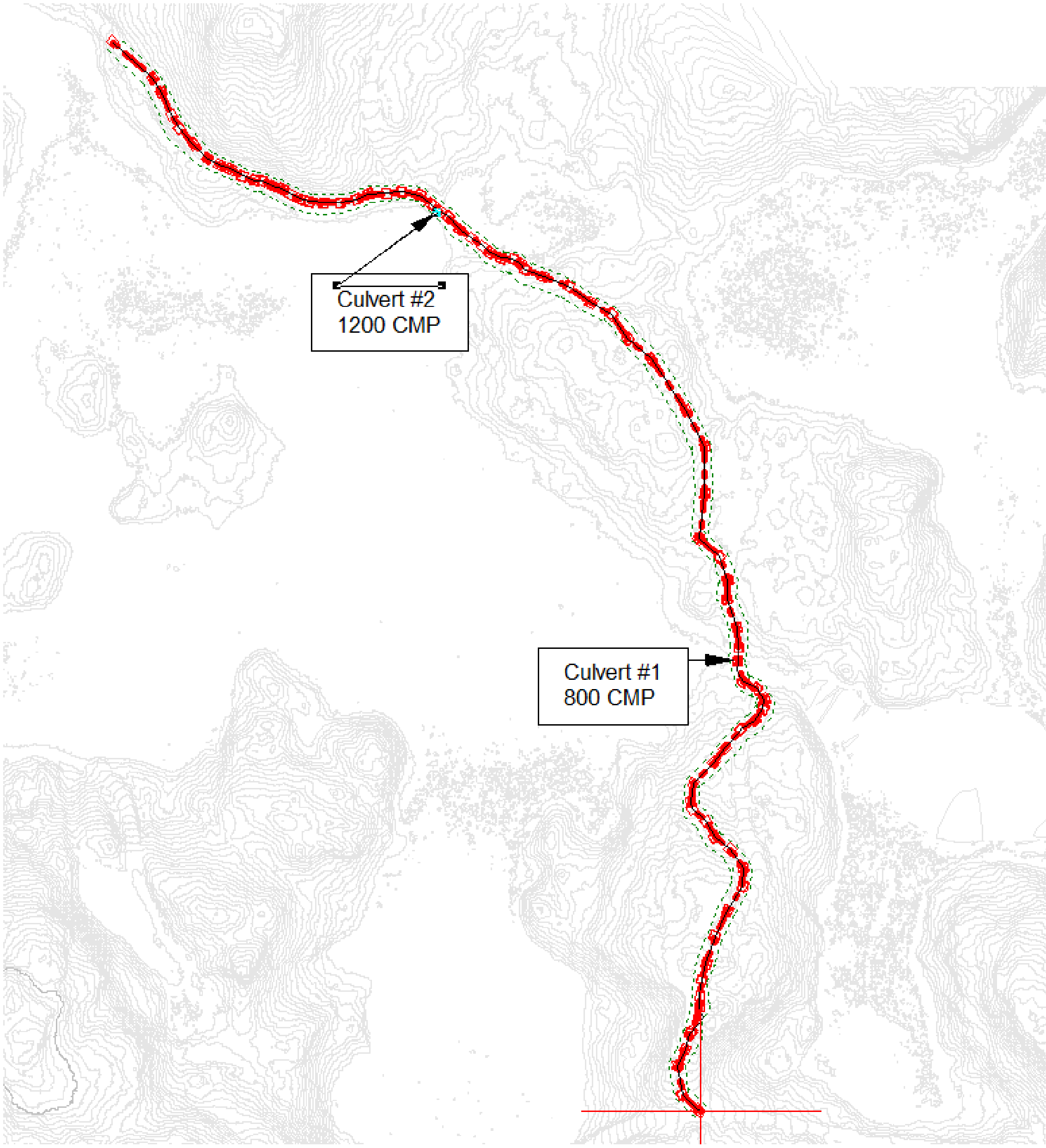


Figure 30. Blind road design with culvert locations and sizes.

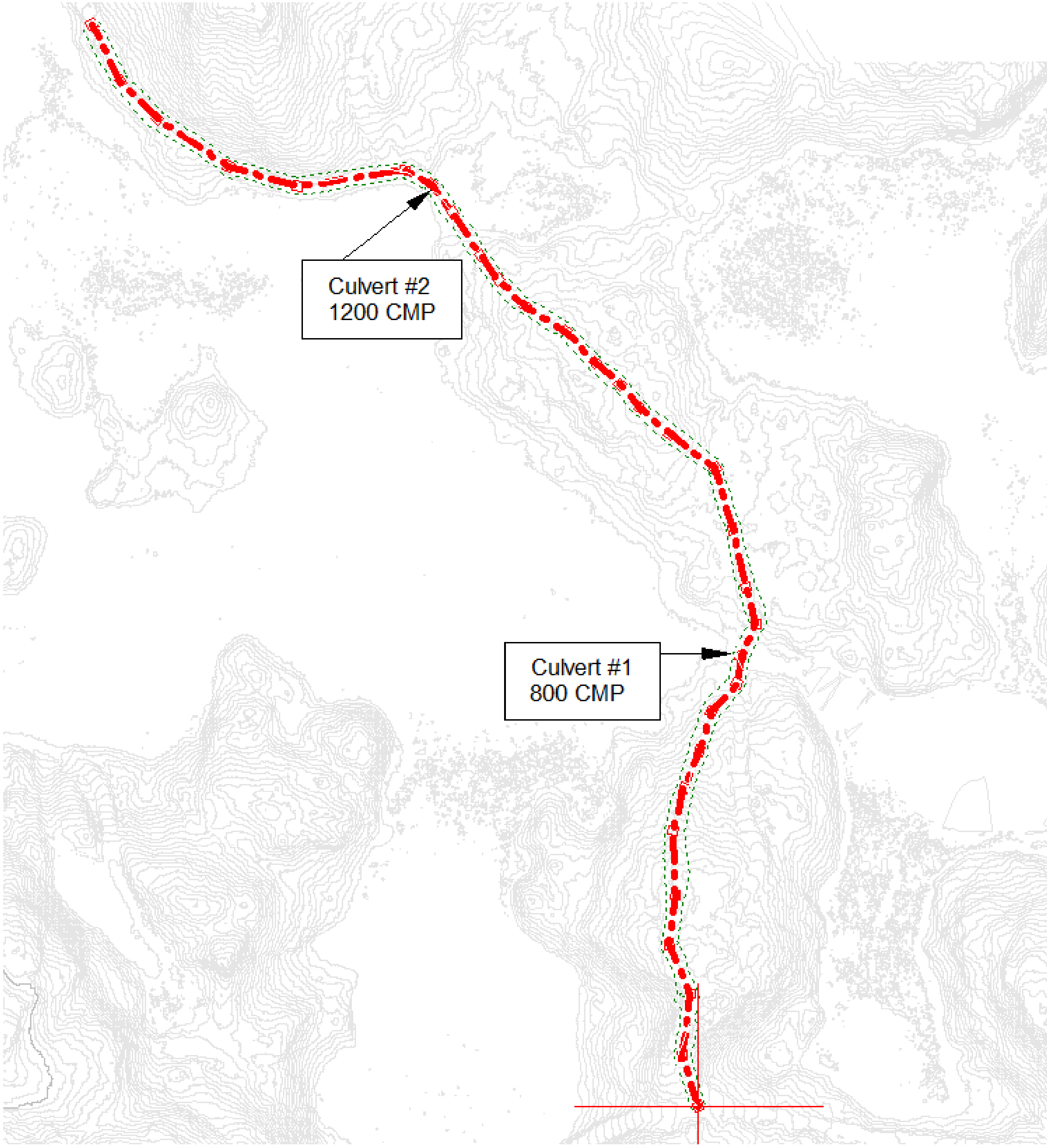


Figure 31. Second attempt road design with culvert locations and sizes.

DISCUSSION

The purpose of this study was to determine if office-based road alignments designed with LiDAR and RoadENG could minimize the amount of road built and produce a lower cost road compared to the field-based design. The office-based design (blind) was created without looking at the original field design. A second attempt was built after to see if there was a better alignment than the blind attempt. The second attempt was not done blind and was used to help determine if the field design had picked the best possible route or not. The benefit of this approach to forest road planning is it allows foresters insight into areas that should be avoided and helps to determine if a road alignment is feasible before going out into the field.

For mainline 1 during the first iteration, Eacom's road design was the most cost effective at $274,040. The blind design had a cost of $355,650 and the second attempt was $364,590. The most significant difference between Eacom's field design and the second attempt, RoadEng design is both had 5 culverts equalling $100,000 in additional cost. The blind attempt, which did not cross as many streams, resulted in only $12,000 worth of culverts and installations. This road section illustrates the trade-offs of culverts when compared to building through steeper terrain at a higher cost. The second iteration, with the excavation cost reduced by 50%, resulted in a closer cost between Eacom's design at $190,720 and the blind design totaling $189,490. The second attempt design remained the most expensive through all iterations. The comparison from iteration two illustrates that building through a cheaper road material but crossing more streams will increase cost from more culverts when compared to more expensive road building with less culverts installed. In the third iteration, with the excavation of overburden set back to $12.00/ m^3, Eacom's design proved to have the cheapest cost at $195,570. The blind design was second at $208,780 and the second attempt was the highest at $264,640. From all iterations, the two biggest cost factors were culverts and cost of material to cut and fill. These two factors emphasize the importance of accurate field information and terrain consideration should accompany road designs and road building (FOA 2012).

The road lengths of these designs were all within roughly 50 m of each other. The blind design did have the shortest road length at 2,012 m; however, the shortest designed road did not result in the most cost-effective road. The second attempt road followed Eacom's design very closely and was shorter by roughly 25 m in length but had a much higher cost associated with the design for each iteration. The higher cost of the second attempt illustrates a potential flaw in the study as Eacom's designed road is cheaper because the road was already present in the field when the LiDAR was flown. This occurrence could have resulted in less material needed for the road prism to meet RoadENG's design specifications.

The blind design in mainline 1 had the most expensive haul cost of all designs at $11,340. The result for the highest haul is from the road design moving 885.1 m^3 of endhaul. Endhaul is the most expensive type of road building (FOA 2012). The second attempt design had the cheapest hauling cost at $5,390 and only had 18.3 m^3 of endhaul. While Eacom's design had 180.5 m^3 of endhaul and a total haul cost of $7,400, these results show hauling is an important component to consider when road building because the most cost-effective road may not have the most cost-effective haul costs. This could result in an overall more expensive road resulting from an increased transportation cost.

The soils layer for mainline 1 is essential for road planners to easily understand the trade-offs of road material cost. The blind design was built through a rock knob section instead of crossing the same stream twice and staying in sandy gravel like the other two road designs. This comparison highlights the cost differential of building through more expensive ground compared to less expensive terrain and spending the savings on more stream crossings.

In mainline two, the cheapest overall road cost every time was Eacom's design. This section of the road had a bottleneck in the design where the road needed to cross at a certain point, specifically a lake to the right and left of the roadway and only a small section of solid ground to cross over. This reduced potential road alignments and needed extensive cut and fill coming down and exiting this control point. As a result, Eacom's design had the most cost-effective road. The route designed by Eacom also stayed lower in elevation resulting in less accumulation of cut and fill material along the road alignment and kept the overall cost for excavation and hauling down.

One interesting take away is iteration two and three had the same cost for all designs in this road section. The reason for this occurrence was the overburden layer being constant throughout the whole design at 29 cm. NE04 was the only ecosite observed for this road section. The stripping parameter was set to strip material from the first 30 cm of the road alignment. This resulted in the material being excavated being rock and did not matter for the different cost applied to overburden between iterations two and three. Understanding what material is on-site is essential to optimize forest road planning and construction.

In branch one, Eacom's road cost was the most cost effective in each iteration. The closest a second design came was the blind design was in the first iteration. This was the first time the RoadENG default parameters created the closest results. The total cost of Eacom's road was $121,800, and the blind design cost was $124,700. The breakdown where these two designs in this iteration change are cut material was cheaper for the blind design at $90,970 while Eacom's cut cost was $93,530. However, fill and haul cost was higher in the blind design which resulted in a higher overall cost in the end. Hauling was greater at $5,560 for the blind design because there was 112.7 m^3 of endhaul, Eacom had no endhaul and haul cost of $1,090. The difference in cost between Eacom's design and the blind design increased throughout each iteration afterward. The second attempt had the highest overall cost for each iteration but had a cheaper hauling cost than the blind design by $2,500.

Branch 2 road had a wide variation in the total overall cost. The most cost-effective road deign was the blind design. In each iteration, the blind design was greater than 50% less in total cost. For example, in iteration 1, the total cost of the blind design was $136,660 and Eacom's design was $270,490. There was little variation in road lengths between deigns, the blind design was 1054.2 m in length, and Eacom's was 1018.2 m in length. Where these two designed differed was the total material cut and filled. Eacom's design used roughly double the material needed for the blind design and resulted in a haul cost of $9,460 for Eacom and $2,760 for the blind design. From observations of Eacom's design, it was noticed the alignment nearing the end had a very large cut section going up a constant hill. This long cut section accumulated high costs and took to the top of the hill near the road POT to get out off the cut and onto flat terrain, whereas the blind design had smaller cut sections and was broken up by larger benches between cut sections.

The block road had near equal total cost and sections for cut, fill, and hauling for all three road designs. The block road design findings illustrate that when roads do not need rigorous design parameters, such as a mainline, it is possible for other road alignments to produce the same cost efficiency. These results illustrate that a greater emphasis should be placed on the design of mainline roads.

A drawback of this study is that the data produced is only as good as the parameters for soil, cost of excavation and hauling. The soil layer was granular for the simplicity of the study. If more detailed soil layers were derived, a more accurate overall cost could have been determined. For the cost of excavation, the cost set in iteration one used the default settings in RoadENG. The second iteration was half the cost of the first iteration; this iteration was more representable to the realized cost of road building by Eacom in their operations. As a result of these cost parameters, certain roads may be closer to actual road costs and other road sections will be much higher than the actual cost to construct that section of road. As for haul cost parameters, the set distances for freehaul, overhaul, and endhaul are distances used and understood in road building, but they can still change depending on the area where roading building takes place.

The opportunity cost for the cost of strictly field based layout compared to LiDAR designs was not looked at in this study. For example, determining three road options in the field takes much longer to determine compared to office-based reconnaissance with LiDAR. The field-based layout would overall cost more money due to time necessary to check all road options. By checking the options in the office first, road designs can be determined cost effectively.

Another aspect not considered was the volume and price of timber throughout the road sections. Certain species produce a greater income and help support road building operations when compared to building through areas with less valuable timber.

The material stripped within the site preparation parameter did not have a cost applied to it. No associated cost with site preparation is an issue with the Location module. Material that was removed was assumed to be wasted material. During road building, this is not always the case. When material is not suitable to be put into the road prism it is wasted, but if there is a suitable material such as sand and gravel these materials are placed in the road and can help lower the overall cost.

Finally, all of Eacom's designs were overlaid on an existing road network when the LiDAR survey was conducted. Therefore, it should be taken into consideration that some of the designs may have had less material needed to meet the road design parameters. This was not the case for all roads, and the results help show certain road sections produced a lower cost road than Eacom's designs.

CONCLUSION

This study has shown that designing roads with LiDAR and RoadENG can minimize the amount of road to be built and lower the costs associated. As well, the cost of road factors such as excavation of cut and fill, and hauling can be broken down in the program to show the amount of material needed to build the road based on road class and correlating specifications. This technique helps planners determine which road alignment provides is most cost effective from the office.

To improve the study, more accurate costs for hauling and excavation could improve the accuracy of the overall cost of forest roads presently being built in Ontario. Having more detailed soil layers would also provide a more accurate cost of material being moved along the road section. Finally, comparing field designed roads that are not presently built compared to office-based design on a LiDAR TIN would give a more accurate comparison.

Recommendations for future research should focus on how office-based design will differ once they ground truth the road in the field. Determining how much field-based designs cost compared to office-based designs with layout afterwards would help show productivity of road layout between the two methods. As well, developing a more realistic soil layer to apply to designs in Softree Location will help show total material and types used for road construction cost.

In conclusion, this study shows the potential LiDAR and RoadENG can provide for geometric road designs and road planning for Ontario forestry.

LITERATURE CITED

Akay, A.E., H. Oguz, I. R. Karas and K. Aruga. 2008. Using LiDAR technology in forest activities. Environ Monit Assess. 151:117–125.

Anderson, H.A. 1999. The use of airborne laser scanner data (LiDAR) for forest measurement applications. Seattle: Precision Forestry Cooperative, College of Forest Resources, University of Washington, 32pp.

[APEGBC/ABCFP] Association of professional engineers British Columbia/Associations of British Columbia forest professionals professional practice guidelines. 2014. Guidelines for professional services in forest sector-crossings V.2. APEGBC and ABCFP. https://abcfp.ca/WEB/Files/policies/Guideline_Forest_Crossings_2014.pdf?WebsiteKey=4b6af123-da4f-4a97-a963 579ada9e5955&=404%3bhttps%3a%2f%2fabcfp.ca%3a443%2fWEB%2fabcfp%2fFiles%2fpolicies%2fGuideline_Forest_Crossings_2014.pdf. 30 March 2019.

Cahskan, E. 2013. Planning of forest road network and analysis in mountainous area. Life Science Journal. 10 (2): 2456–2465.

Chasmer, L., C. Hopkins and P. Treitz. 2006. Investigating laser penetration through a conifer canopy by integrating airbourne and terrestrial LiDAR. Can J. Remote. Sensing. 32(2): 116-125.

Evans, J.S., A.T. Hudak, R. Faux and A.M.S. Smith. 2009. Discrete return lidar in natural resources: recommendations for project planning, data processing and deliverables. Remote Sens. 1(4): 776-794.

[FAO] Food and Agriculture Organization of the United Nations. 1977. Planning forest roads and harvesting systems. Forestry Paper no. 2. Rome. 148pp.

[FOA] Forest Owners Association. 2012. New Zealand forest road engineering manual. New Zealand Forest Owners Association Incorporated. 150pp.

[FESA] Forest Engineering Southern Africa 2005. South African Forest Road Handbook. Institute for Commercial Forestry Research. 212pp.

Hodgson, M.E. and P. Bresnaham. 2004. Accuracy of airborne LiDAR-derived elevation: Empirical assessment and error budget. Photogrammetric Engineering & Remote Sensing. 70(3): 331-339.

Holgado-Barco, A., D. Gonzalez-Aguilera, P. Arias-Sanchez and J. Martinez-Sanchez. 2014. An automated approach to vertical road characterisation using mobile LiDAR systems: Longitudinal profiles and cross-sections. ISPRS Journal of Photogrammetry and Remote Sensing. 96: 28–37.

Krogstad, F. and P. Schiess. 2004. The allure and pitfalls of using lidar topography in harvest and road design. Paper presented at a Joint Conference of IUFRO 3.06 Forest Operations under Mountainous Conditions and the 12th International Mountain Logging Conference June 13-16, 2004, Vancouver, B.C. 10pp.

Leclipteux, H. 2015. Advantages of integrating high density LiDAR in coastal forest operations planning. Lakehead University, Thunder Bay, ON. 61 pp.

[MFLNRO] Ministry of Forests, British Columbia, 2002: Forest Code of Practice of British Columbia. Forest Road Engineering Guidebook. Victoria, BC. 208pp.

Mitacs 2019. Ontario forest resource inventory enhancement using ADS40 aerial imagery and LiDAR data. Mitacs. Https://www.mitacs.ca/en/projects/ontario-forest- resource-inventory-enhancement-using-ads40-aerial-imagery-and-lidar-data. 10 April 2019.

[MNDN] Ministry of Energy, Northern Development and Mines, Ontario.2019. OGSEarth. Queen's Printer for Ontario. https://www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearth. 15 March 2019

[MNRF 2019] Ministry of Natural Resources and Forestry, Ontario. 2019. Ontario flow assessment tool. Queen's Printer for Ontario. https://www.gisapplication.lrc.gov.on.ca/OFAT/Index.html?site=OFAT&viewer=OFAT&locale=en-US. 17 Febuary 2019.

Oregon State University. 2006. Manning's equation. Oregon State University. http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Manning_s_Equation.htm. 30 March 2019.

Pulkki, R.E. 2003. Minimizing negative environmental impacts of forest harvesting operations pp 581-628 in Towards Sustainable Management of the Boreal Forest. Edited by P.J. Burton, C. messier, D.W. Smith, and W.L. Adamwicz. NRC Research Press, Ottawa, ON.

Pulkki, R.E. 2018. Forest Harvesting II: lecture notes for forestry 4134 on analyzing wood procurement systems and supply chain management (scm). Lakehead University, Thunder Bay, ON. 104pp.

Samami, K.M., S.A. Hosseiny, M. Lotfalian and A. Najafi. 2010. Planning road network in mountain forest using GIS and analytic hierarchical process (AHP). Caspian J. Env. Sci. 8(2): 151-162.

Schiess, P. and F. Krogstad. 2003. LiDAR-based topographic maps improve agreement between office designed and field verified road locations. Proceedings of the 26th Annual Meeting of the Council on Forest Engineering, Bar Harbor, ME, September 7-10, 2003. 6pp.

Softree, 2017. Softree Support: knowledge base. http://support.softree.com/. 17 February 2019

Taylor, K.C., R.W. Arnup, B.G. Merchant, W.J. Parton and J. Nieppola. 2000. A field guide to forest ecosystems of northeastern Ontario. Sudbury, ON. 343pp.

Uusitalo, J, 2010. Introduction to Forest Operations and Technology. JVP Forest Systems Oy. Hämeenlinna, Finalnd. 287pp.

White, R.A., B.C. Dietterick, T. Mastin and Rollin Strohman. 2010. Forest roads mapped using LiDAR in steep forested terrain. Remote Sens. 2(4): 1120- 1141.

Wulder, M.A., C.W. Bater, N.C. Coops, T. Hiker and J.C. White. 2008. The role of LiDAR in sustainable forest management. The Forestry Chronicle. 84(6): 807-826.

Yen, K.S., B. Ranvani and T.A Lasky. 2011. LiDAR for Data Efficiency. Final Report prepared for Washington State Department of Transportation. Advanced Highway Maintenance and Construction Technology Research Center, Department of Mechanical and Aerospace Engineering, University of California. Oakland, CA. 101 pp.

APPENDICES

APPENDIX I

Road summary table

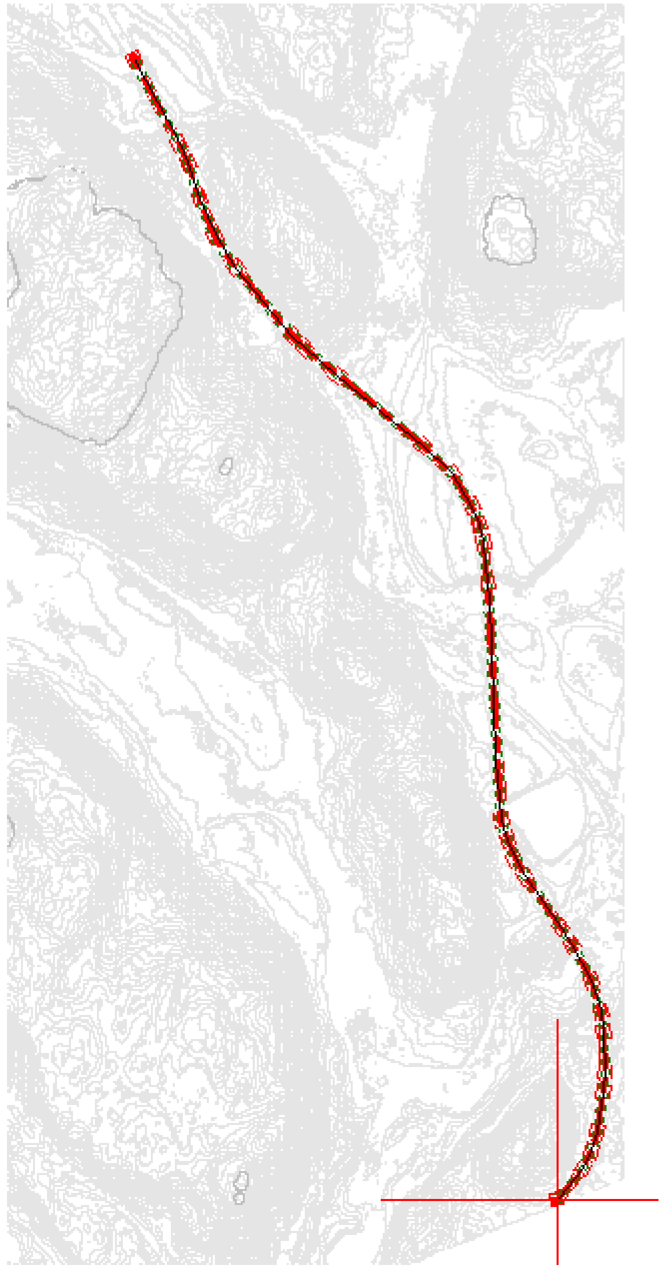
i

Roads Summary Sheet

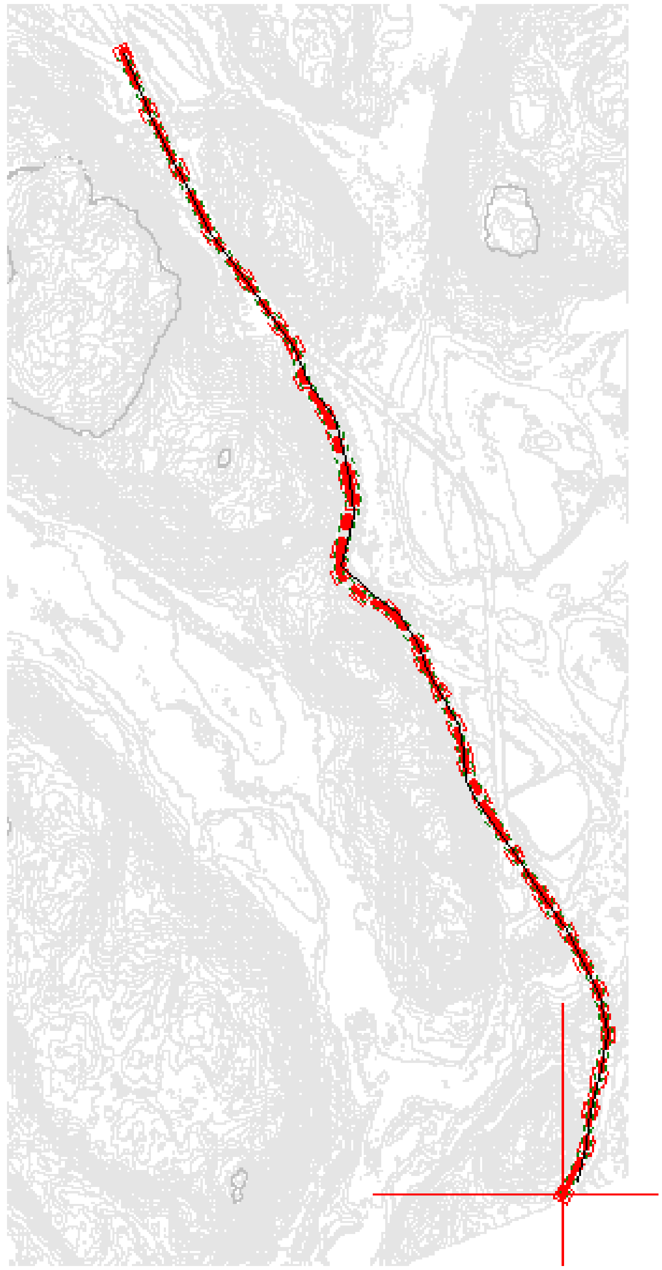
					Subgrade Cut				Subgrade Fill			Haul					Culverts	
Section	Iteration	Design	Distance (m)	**Total Cost ($)**	($)	m3	Overburden ($/m^3)	Solid Rock ($/m^3)	($)	m3	Embankment ($/m^3)	($)	Freehaul (m^3)	Overhaul (m^3)	Endhaul (m^3)	Stripped Material (m^3)	Total	Cost ($)
		Eacom	2071.6	**$ 274,040.00**	$ 140,260.00	6610.9			$ 26,380.00	6594.8		$ 7,400.00	5140.6	2688.6	180.5	9561.3	5	$ 100,000.00
	1	Blind	2012.0	**$ 355,650.00**	$ 297,950.00	8618.2			$ 34,360.00	8593.4		$ 11,340.00	5506.3	2226.6	885.1	10713.9	1	$ 12,000.00
		Second Attempt	2045.0	**$ 364,590.00**	$ 225,570.00	8396.7	$ 12.00	$ 48.00	$ 33,630.00	8413.5	$ 4.00	$ 5,390.00	6311.3	2083.3	18.3	8572.7	5	$ 100,000.00
		Eacom	2071.6	**$ 190,720.00**	$ 70,130.00	6610.9			$ 13,190.00	6594.8		$ 7,400.00	5140.6	2688.6	180.5	9561.3	5	$ 100,000.00
Mainline 1	2	Blind	2012.0	**$ 189,490.00**	$ 148,970.00	8618.2			$ 17,180.00	8593.4		$ 11,340.00	5506.3	2226.6	885.1	10713.9	1	$ 12,000.00
		Second Attempt	2045.0	**$ 234,990.00**	$ 112,790.00	8396.7	$ 6.00	$ 24.00	$ 16,810.00	8413.5	$ 2.00	$ 5,390.00	6311.3	2083.3	18.3	8572.7	5	$ 100,000.00
		Eacom	2071.6	**$ 195,570.00**	$ 74,980.00	6610.9			$ 13,190.00	6594.8		$ 7,400.00	5140.6	2688.6	180.5	9561.3	5	$ 100,000.00
	3	Blind	2012.0	**$ 208,780.00**	$ 168,260.00	8618.2			$ 17,180.00	8593.4		$ 11,340.00	5506.3	2226.6	885.1	10713.9	1	$ 12,000.00
		Second Attempt	2045.0	**$ 264,640.00**	$ 142,440.00	8396.7	$ 12.00	$ 24.00	$ 16,810.00	8413.5	$ 2.00	$ 5,390.00	6311.3	2083.3	18.3	8572.7	5	$ 100,000.00
		Eacom	2034.7	**$ 503,910.00**	$ 457,630.00	9523.5			$ 38,140.00	9534.3		$ 8,140.00	12134.9	2150.6	0.0	8719.9	0	$ -
	1	Blind	2091.9	**$ 605,710.00**	$ 547,060.00	13,831.90			$ 45,290.00	13,933.50		$ 11,060.00	13954.4	3141.1	0.0	9264.2	0	$ -
		Second Attempt	1979.7	**$ 735,580.00**	$ 668,790.00	11397.1	$ 12.00	$ 48.00	$ 55,730.00	11321.9	$ 4.00	$ 13,360.00	18131.0	2678.5	0.0	8849.5	0	$ -
		Eacom	2034.7	**$ 256,020.00**	$ 228,810.00	9523.5			$ 19,070.00	9534.3		$ 8,140.00	8104.2	1429.8	0.0	8719.9	0	$ -
Mainline 2	2	Blind	2091.9	**$ 309,530.00**	$ 273,530.00	13831.9			$ 22,640.00	13,933.50		$ 13,360.00	13954.4	3141.1	0.0	9264.2	0	$ -
		Second Attempt	1979.7	**$ 373,320.00**	$ 334,390.00	11,397.10	$ 6.00	$ 24.00	$ 27,870.00	11321.9	$ 2.00	$ 11,060.00	12182.3	1750.8	0.0	8849.5	0	$ -
		Eacom	2034.7	**$ 256,020.00**	$ 228,810.00	9523.5			$ 19,070.00	9534.3		$ 8,140.00	12134.9	2150.6	0.0	8719.9	0	$ -
	3	Blind	2091.9	**$ 309,530.00**	$ 273,530.00	13831.9			$ 22,640.00	13,933.50		$ 11,060.00	13954.4	3141.1	0.0	9264.2	0	$ -
		Second Attempt	1979.7	**$ 373,320.00**	$ 334,390.00	11,397.10	$ 12.00	$ 24.00	$ 27,870.00	11321.9	$ 2.00	$ 13,360.00	18131.0	2678.5	0.0	8849.5	0	$ -
		Eacom	1118.3	**$ 121,800.00**	$ 93,530.00	7797.5			$ 19,180.00	10042.6		$ 1,090.00	4947.8	165.6	0	4833.7	2	$ 8,000.00
	1	Blind	1163.6	**$ 124,700.00**	$ 90,970.00	5217.0			$ 20,170.00	5543.5		$ 5,560.00	3266.1	1955.9	112.7	4856.8	2	$ 8,000.00
		Second Attempt	1106.3	**$ 138,840.00**	$ 106,070.00	5007.1	$ 12.00	$ 48.00	$ 21,710.00	5,096.70	$ 4.00	$ 3,060.00	5758.9	721.5	0	4863.8	2	$ 8,000.00
		Eacom	1118.3	**$ 65,450.00**	$ 46,770.00	7797.5			$ 9,590.00	10042.6		$ 1,090.00	4749.9	45.7	0	4833.7	2	$ 8,000.00
Branch 1	2	Blind	1163.6	**$ 69,130.00**	$ 45,490.00	5217.0			$ 10,080.00	5543.5		$ 5,560.00	2937.1	1947.3	112.7	4856.8	2	$ 8,000.00
		Second Attempt	1106.3	**$ 74,960.00**	$ 53,040.00	5007.1	$ 6.00	$ 24.00	$ 10,860.00	5,096.70	$ 2.00	$ 3,060.00	4792.8	635.7	0	4863.8	2	$ 8,000.00
		Eacom	1118.3	**$ 88,220.00**	$ 69,540.00	7797.5			$ 9,590.00	10042.6		$ 1,090.00	4749.9	45.7	0	4833.7	2	$ 8,000.00
	3	Blind	1163.6	**$ 94,300.00**	$ 70,660.00	5217.0			$ 10,080.00	5543.5		$ 5,560.00	2937.1	1947.3	112.7	4856.8	2	$ 8,000.00
		Second Attempt	1106.3	**$ 100,710.00**	$ 78,790.00	5007.1	$ 12.00	$ 24.00	$ 10,860.00	5,096.70	$ 2.00	$ 3,060.00	4792.8	635.7	0	4863.8	2	$ 8,000.00
		Eacom	1018.2	**$ 312,750.00**	$ 275,490.00	6958.6			$ 19,180.00	10042.6		$ 9,460.00	4445.6	2340.1	0	4316.1	0	$ -
	1	Blind	1054.2	**$ 136,330.00**	$ 118,350.00	3740.4			$ 20,170.00	5543.5		$ 2,760.00	6790.8	3013.2	0	4907.5	0	$ -
		Second Attempt	998.5	**$ 370,260.00**	$ 310,000.00	10482.1	$ 12.00	$ 48.00	$ 21,710.00	5096.7	$ 4.00	$ 18,300.00	6761.8	6915.1	0	5103.3	0	$ -
		Eacom	1018.2	**$ 161,110.00**	$ 137,750.00	6958.6			$ 9,590.00	10042.6		$ 9,460.00	4445.6	2340.1	0	4316.1	0	$ -
Branch 2	2	Blind	1054.2	**$ 69,550.00**	$ 59,180.00	3740.4			$ 10,080.00	5543.5		$ 2,760.00	6790.8	3013.2	0	4907.5	0	$ -
		Second Attempt	998.5	**$ 194,280.00**	$ 155,000.00	10482.1	$ 6.00	$ 24.00	$ 10,860.00	5096.7	$ 2.00	$ 18,300.00	6761.8	6915.1	0	5103.3	0	$ -
		Eacom	1018.2	**$ 170,860.00**	$ 147,500.00	6958.6			$ 13,900.00	8889.1		$ 9,460.00	4445.6	2340.1	0	4316.1	0	$ -
	3	Blind	1054.2	**$ 80,250.00**	$ 69,880.00	3740.4			$ 7,610.00	4538.7		$ 2,760.00	6790.8	3013.2	0	4907.5	0	$ -
		Second Attempt	998.5	**$ 226,570.00**	$ 187,290.00	10482.1	$ 12.00	$ 24.00	$ 10,860.00	5096.7	$ 2.00	$ 18,300.00	6761.8	6915.1	0	5103.3	0	$ -
		Eacom	1721.9	**$ 102,170.00**	$ 90,990.00	2477.5			$ 9,710.00	2327.2		$ 1,470.00	2711.7	702.1	0	6068.8	0	$ -
	1	Blind	1736.8	**$ 102,560.00**	$ 90,710.00	2684.4			$ 10,720.00	2687.7		$ 1,130.00	3319.4	459.7	0	6285.5	0	$ -
		Second Attempt	1702.7	**$ 101,990.00**	$ 89,920.00	2633.0	$ 12.00	$ 48.00	$ 10,800.00	2700.8	$ 4.00	$ 1,270.00	3137.5	477.5	0	6273.2	0	$ -
		Eacom	1721.9	**$ 51,820.00**	$ 45,500.00	2477.5			$ 4,850.00	2327.2		$ 1,470.00	2711.7	702.1	0	6068.8	0	$ -
Block	2	Blind	1736.8	**$ 51,840.00**	$ 45,350.00	2684.4			$ 5,360.00	2687.7		$ 1,130.00	3319.4	459.7	0	6285.5	0	$ -
		Second Attempt	1702.7	**$ 51,630.00**	$ 44,960.00	2633.0	$ 6.00	$ 24.00	$ 5,400.00	2700.8	$ 2.00	$ 1,270.00	3137.5	477.5	0	6273.2	0	$ -
		Eacom	1721.9	**$ 56,470.00**	$ 50,150.00	2477.5			$ 4,850.00	2327.2		$ 1,470.00	2711.7	702.1	0	6068.8	0	$ -
	3	Blind	1736.8	**$ 58,200.00**	$ 51,710.00	2684.4			$ 5,360.00	2687.7		$ 1,130.00	3319.4	459.7	0	6285.5	0	$ -
		Second Attempt	1702.7	**$ 58,270.00**	$ 51,600.00	2633.0	$ 12.00	$ 24.00	$ 5,400.00	2700.8	$ 2.00	$ 1,270.00	3137.5	477.5	0	6273.2	0	$ -

APPENDIX II

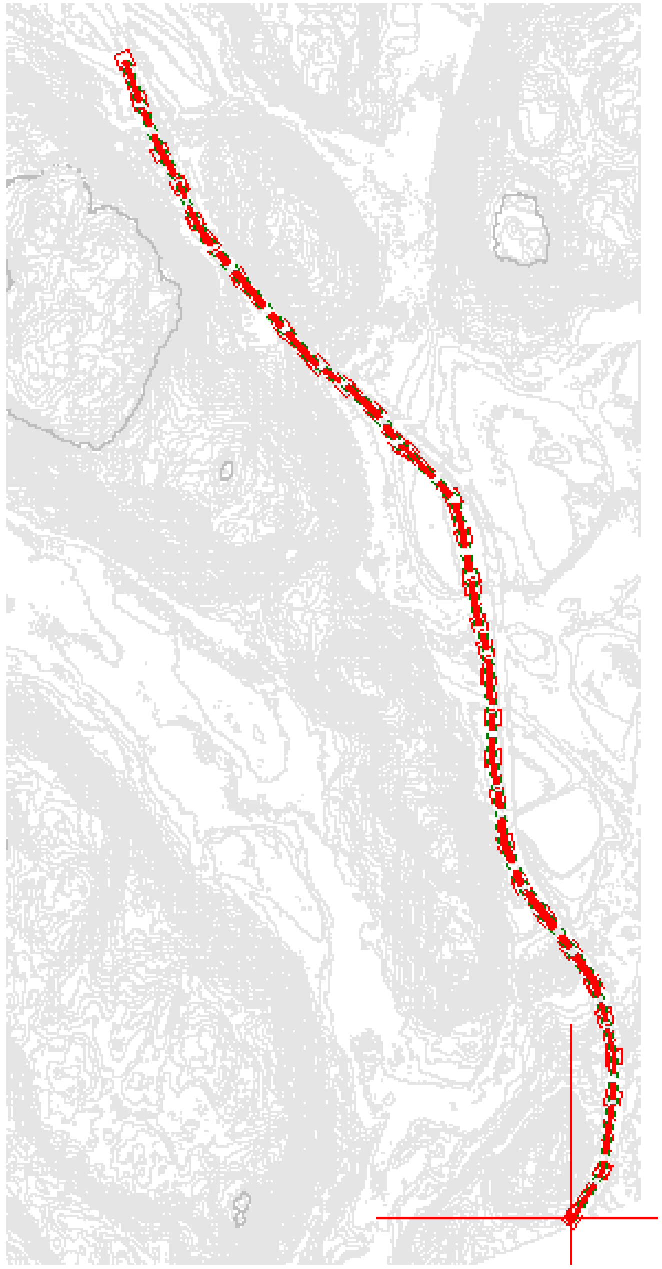
Road alignments for horizontal design and TIN



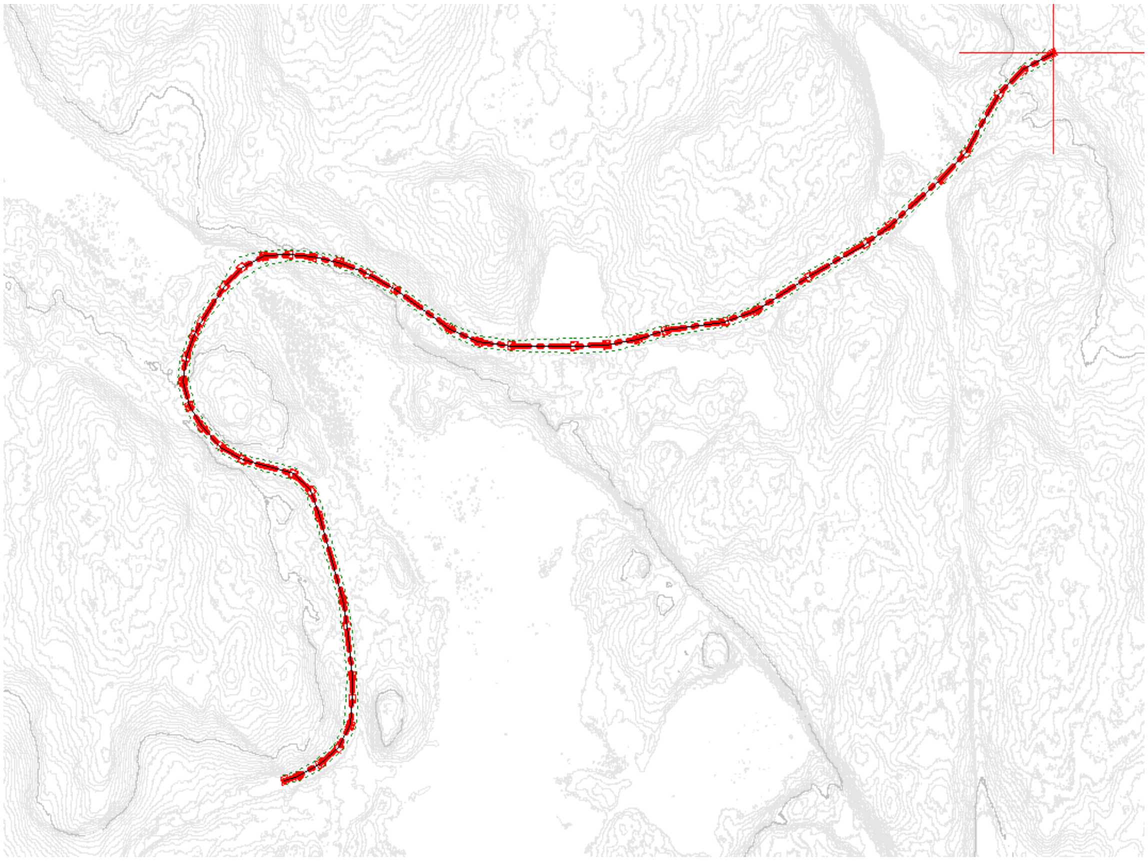
Mainline Road 1 Eacom



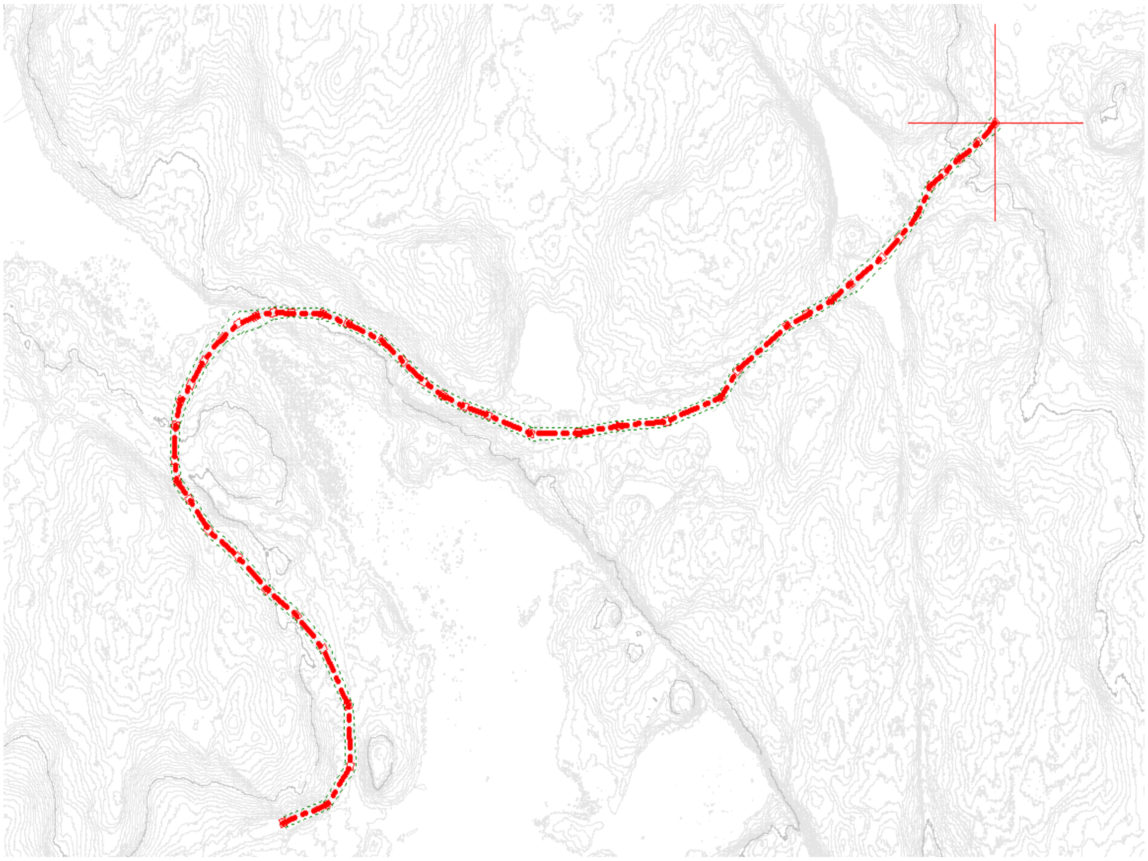
Mainline Road 1 Blind Attempt



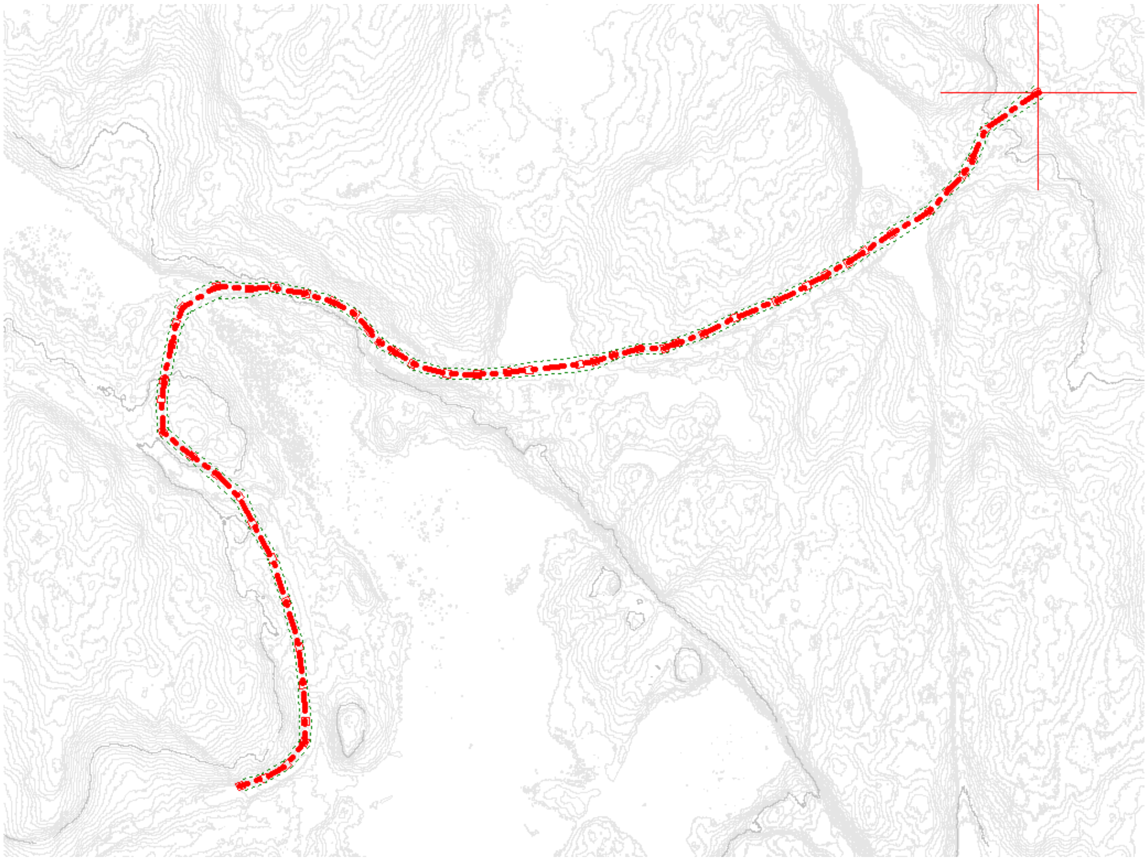
Mainline Road 1 Second Attempt



Mainline Road 2 Eacom

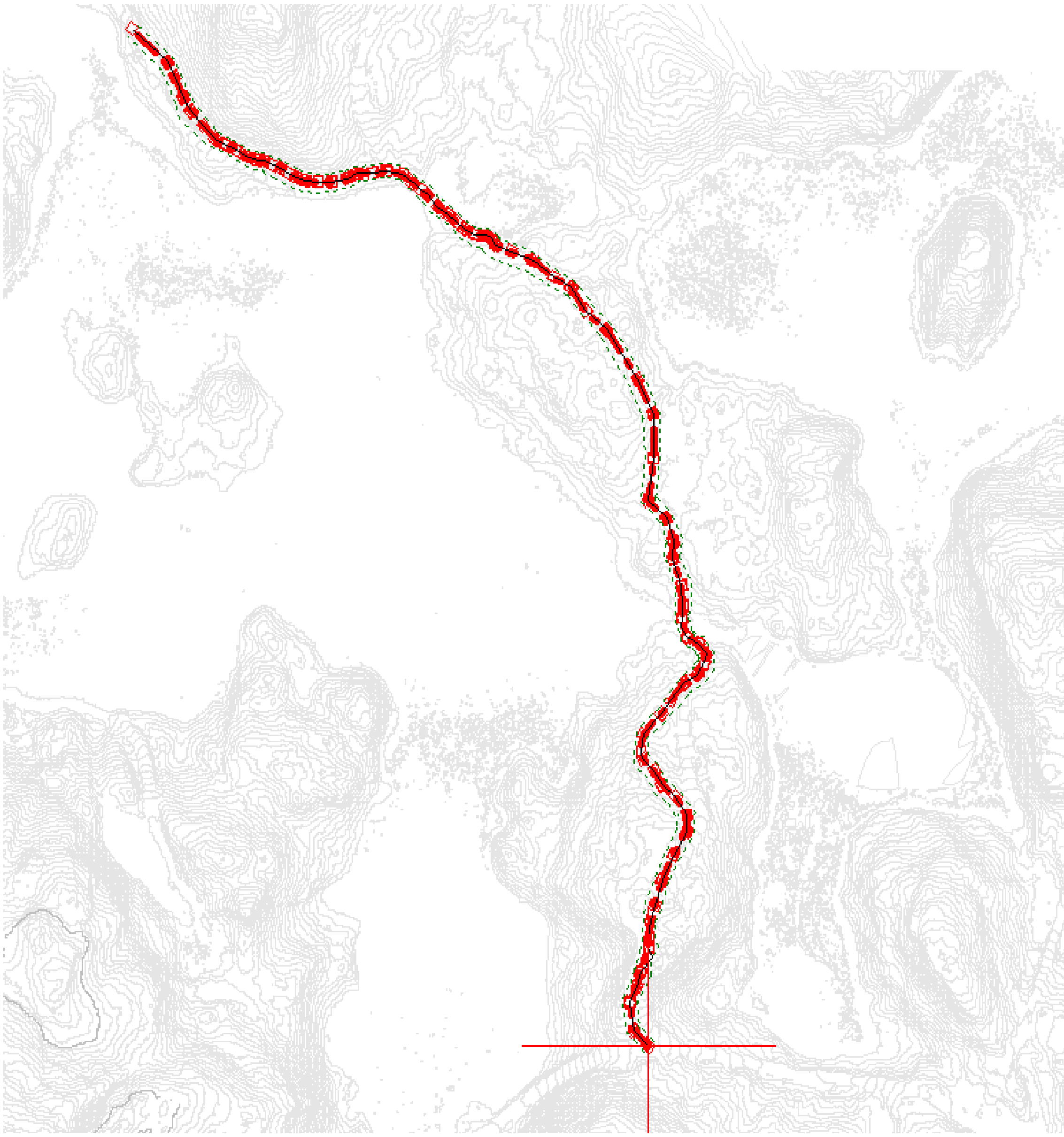


Mainline Road 2 Blind Attempt

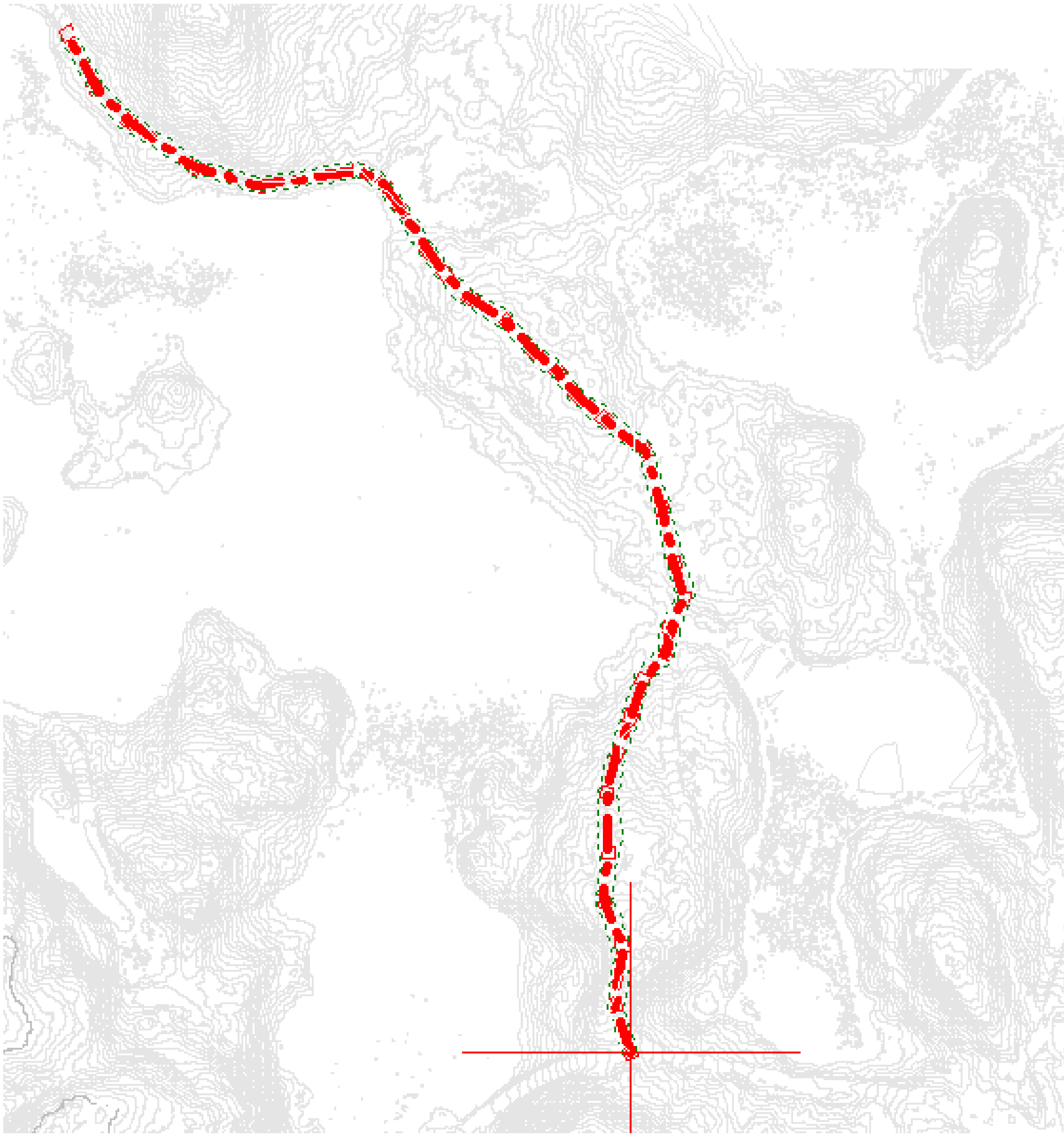


Mainline Road 2 Second Attempt

Branch Road 1 Eacom

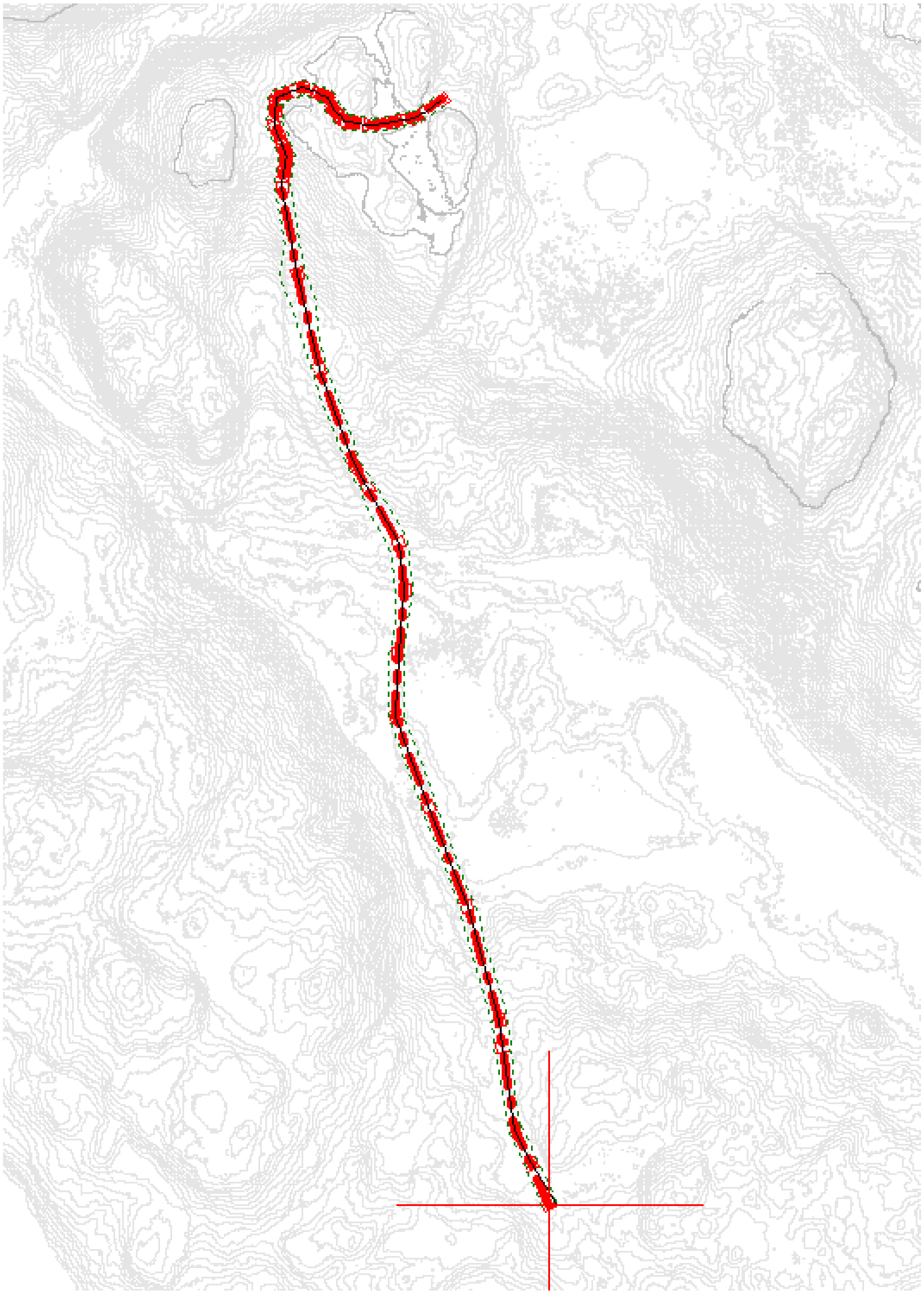


Branch Road 1 Blind Attempt

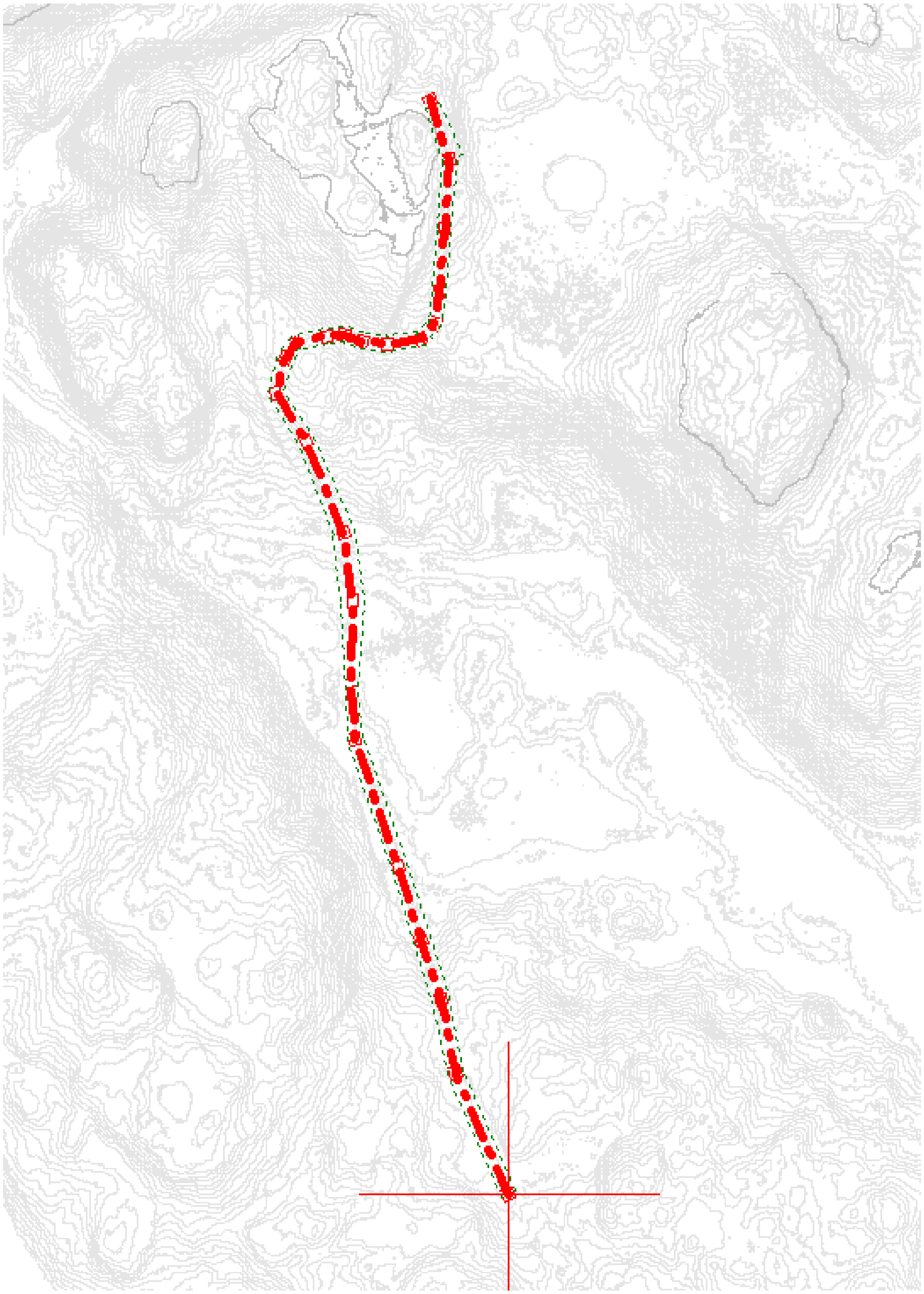


Branch Road 1 Second Attempt

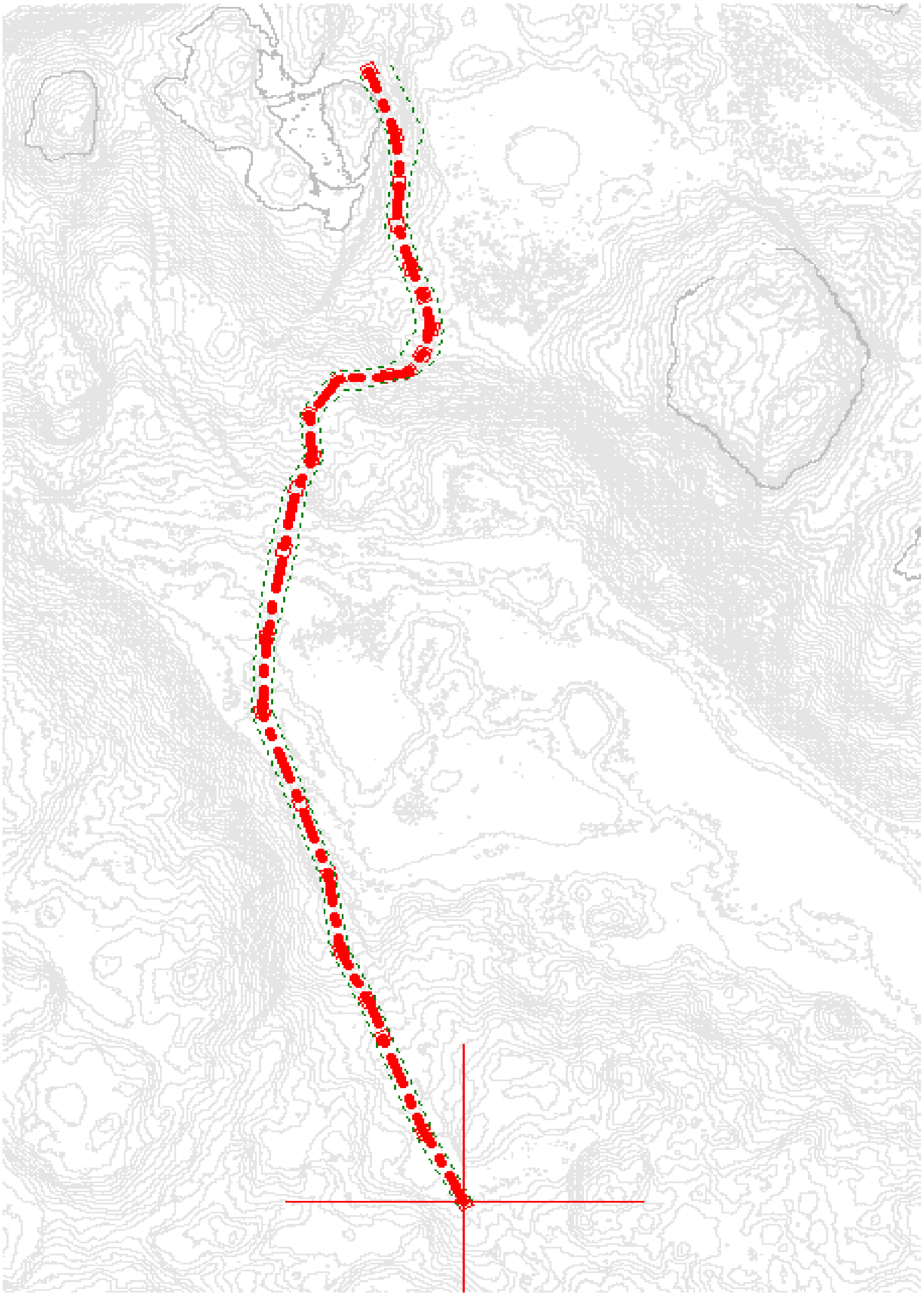
x



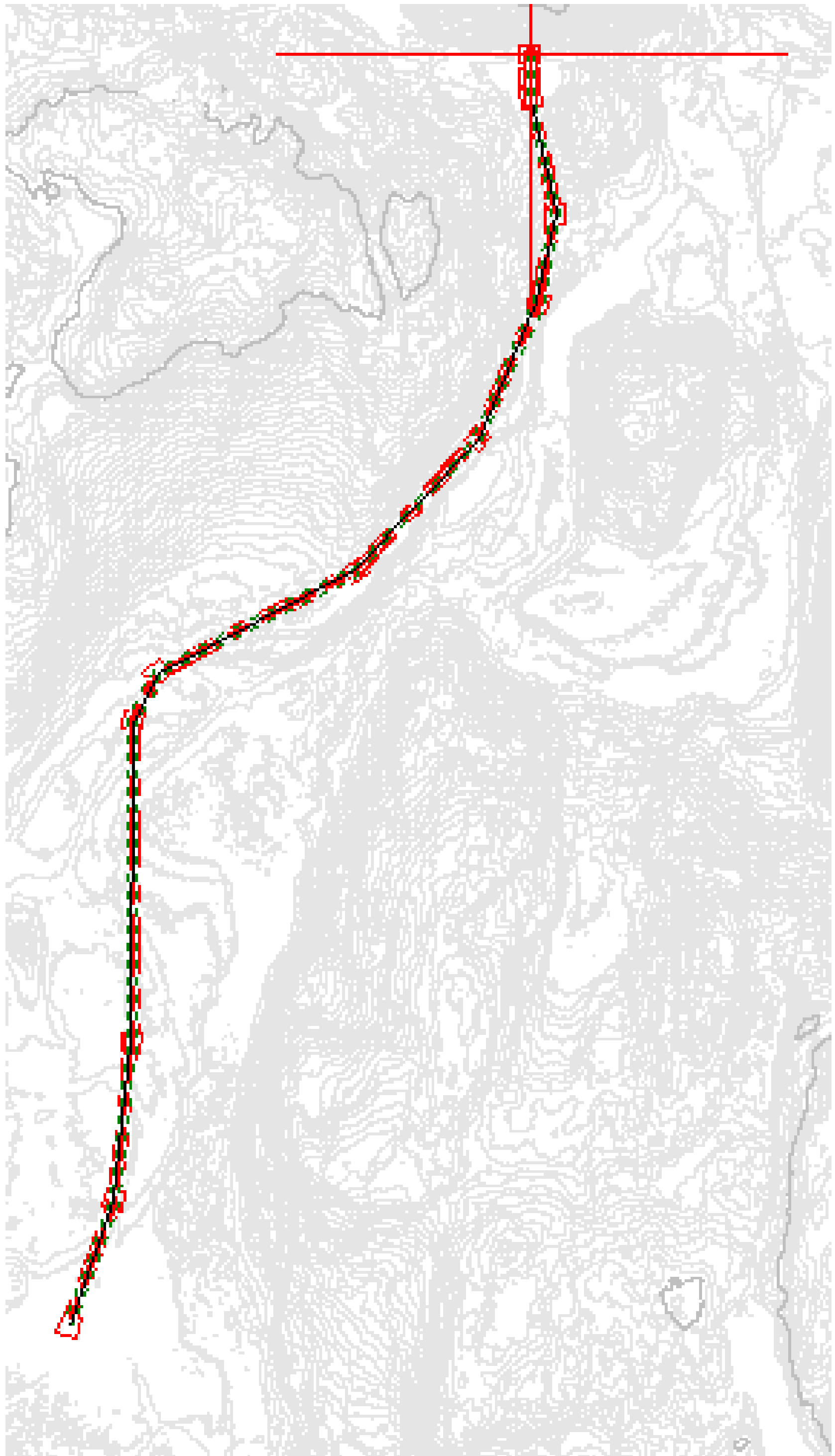
Branch Road 2 Eacom



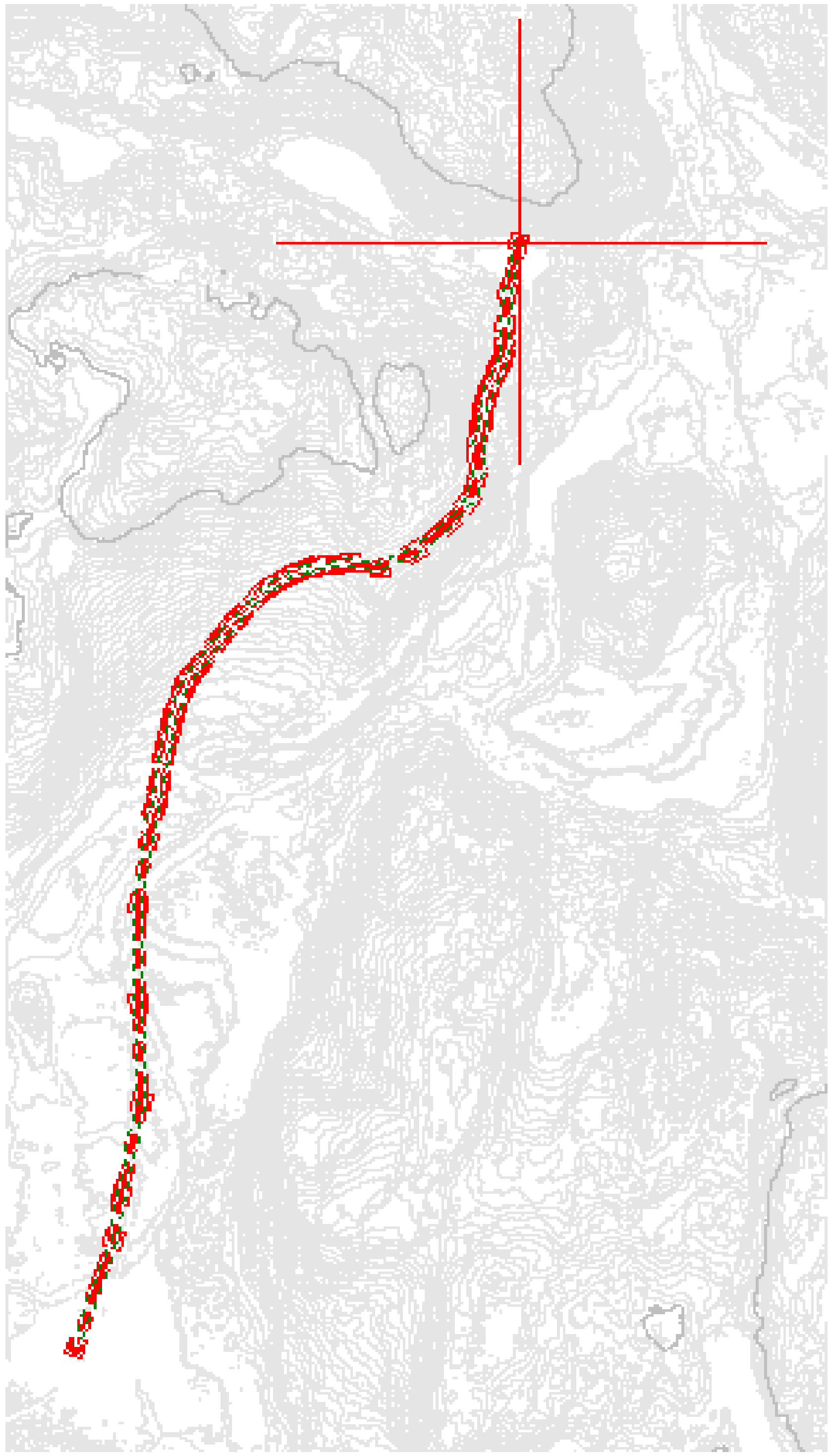
Branch Road 2 Blind Attempt



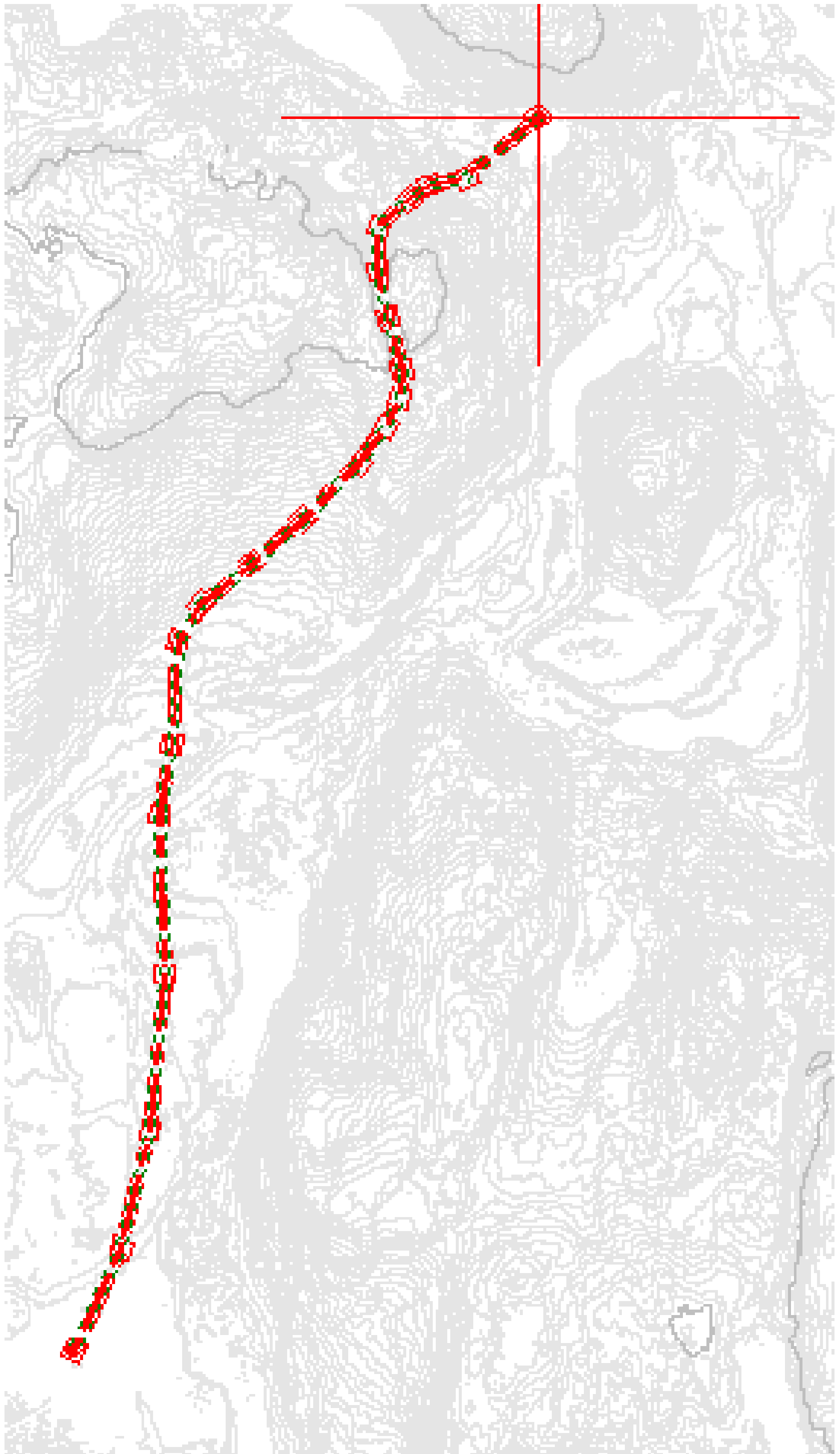
Branch Road 2 Second Attempt



Block Road Eacom



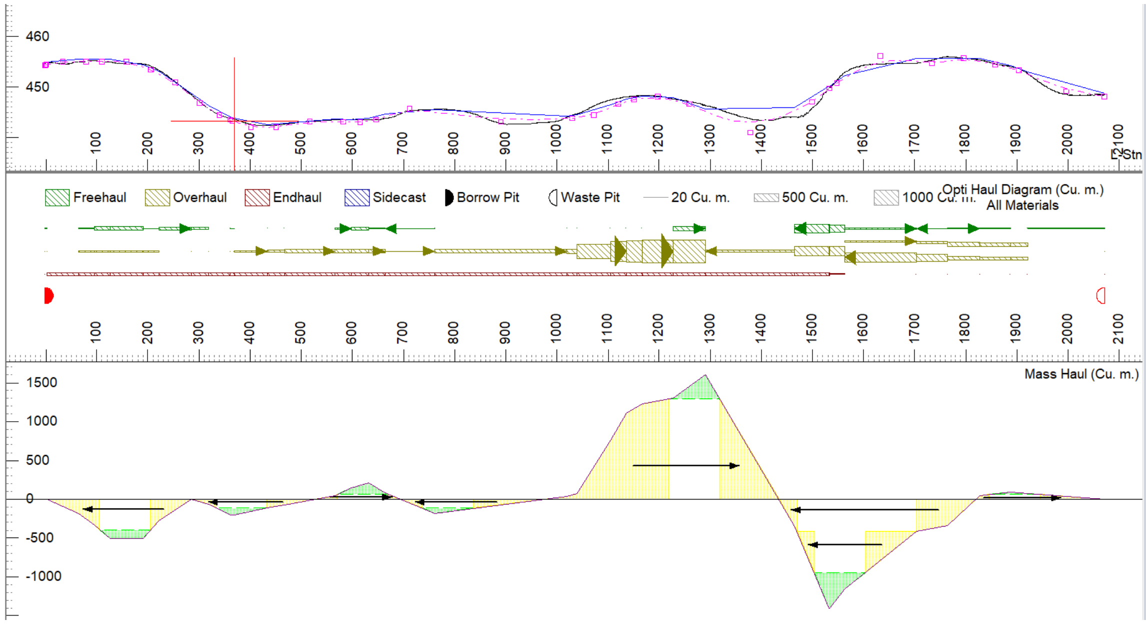
Block Road Blind Attempt



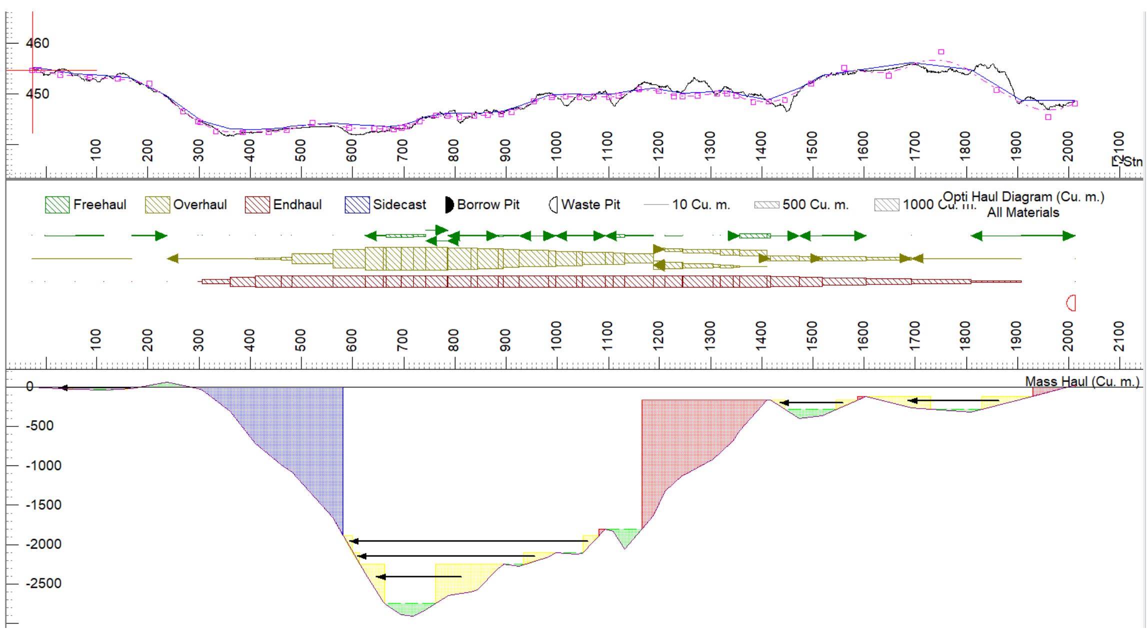
Block Road Second Atempt

APPENDIX III

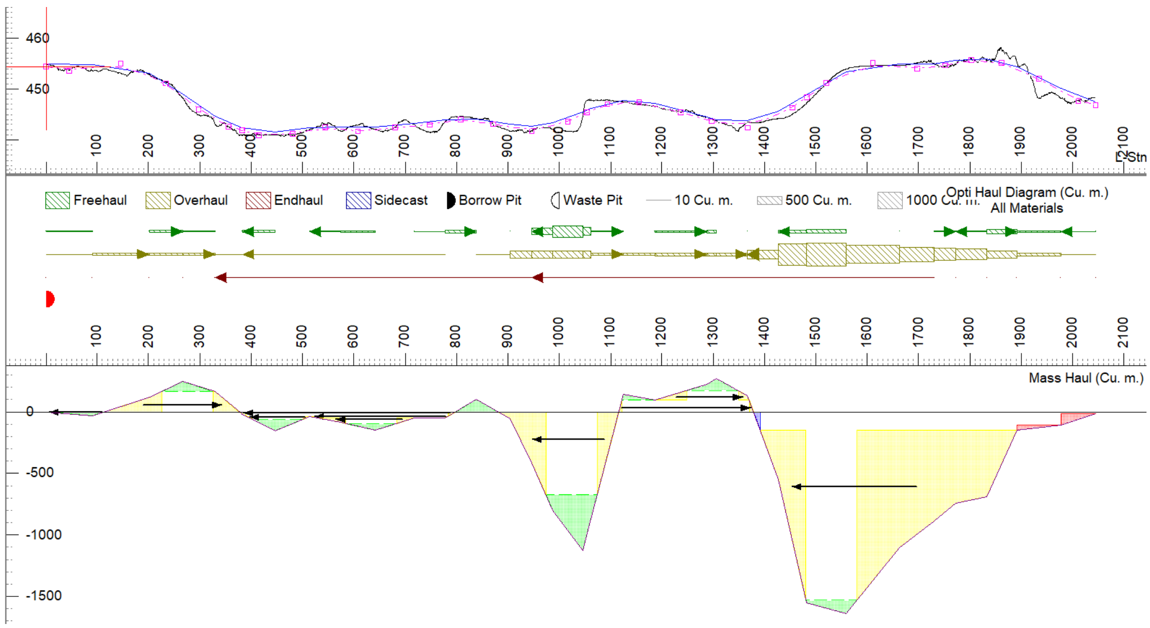
Road vertical alignments with mass haul



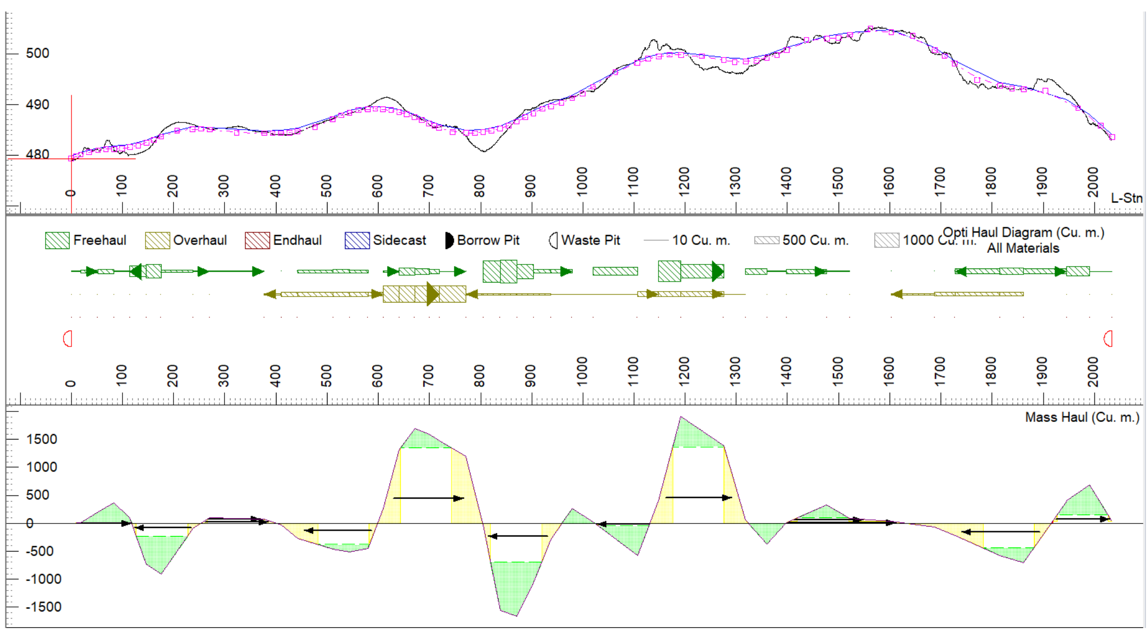
Mainline Road 1 Eacom



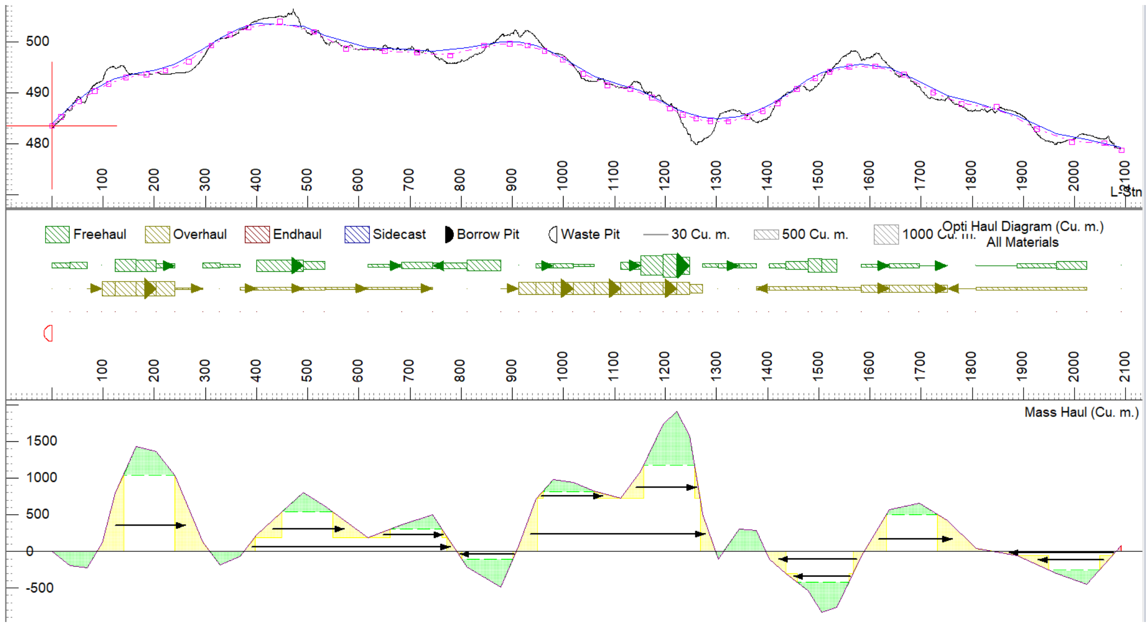
Mainline Road 1 Blind Attempt



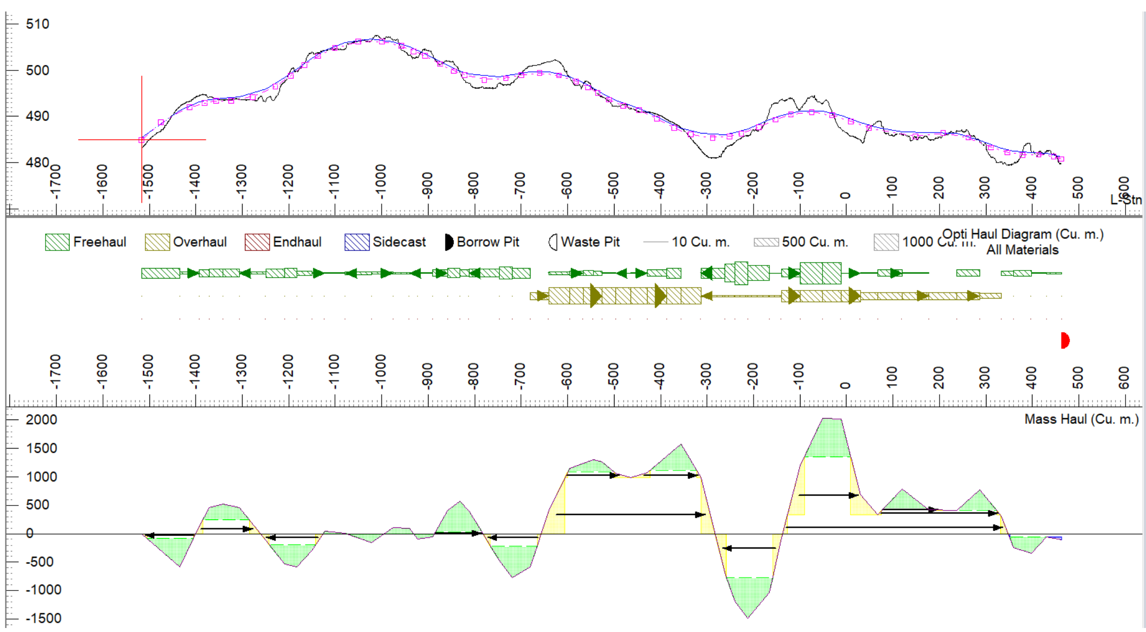
Mainline Road 1 Second Attempt



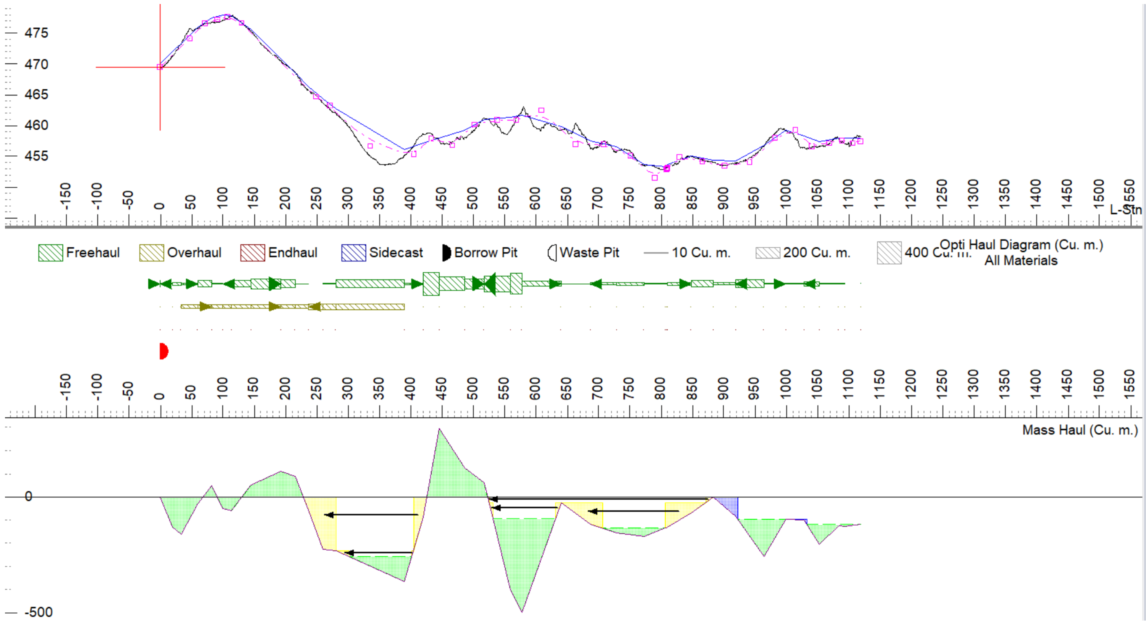
Mainline Road 2 Eacom



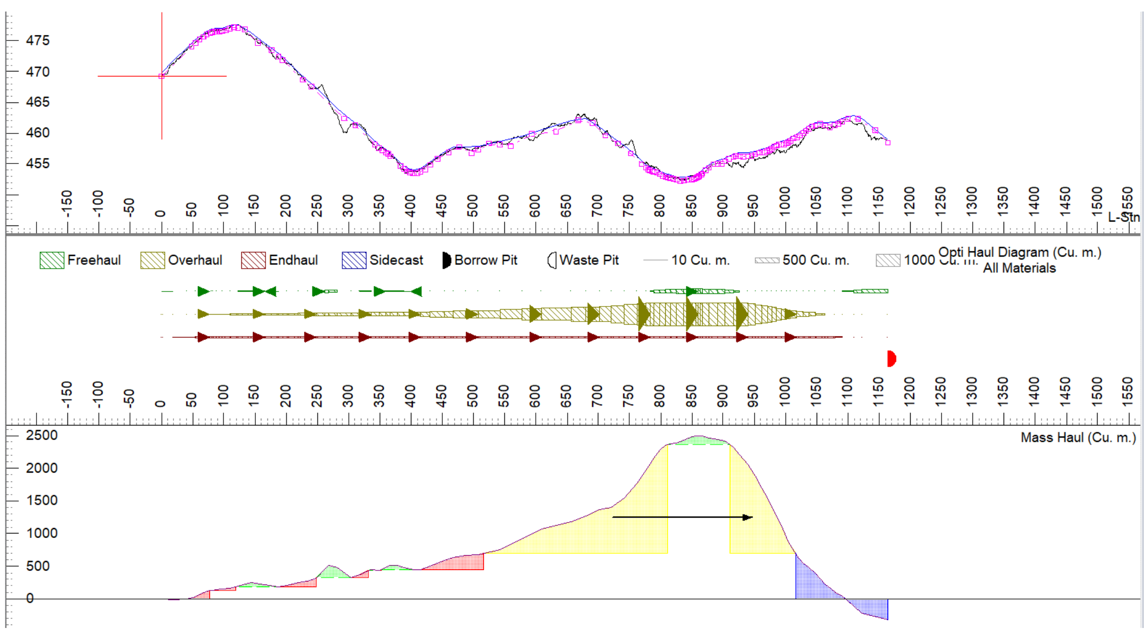
Mainline Road 2 Blind Attempt



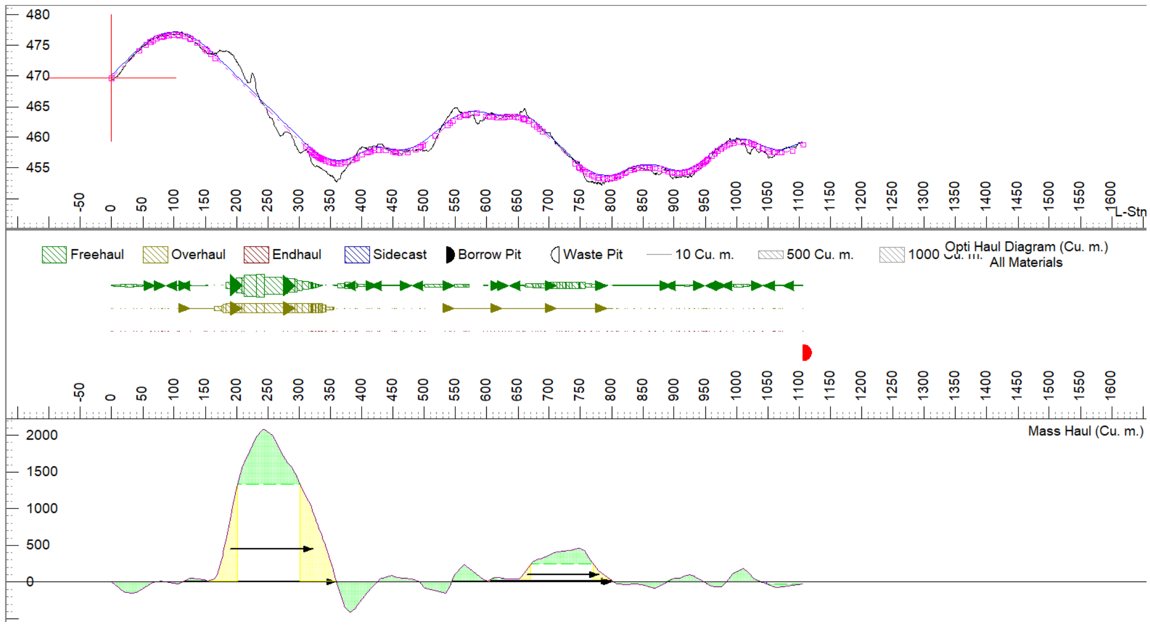
Mainline Road 2 Second Attempt



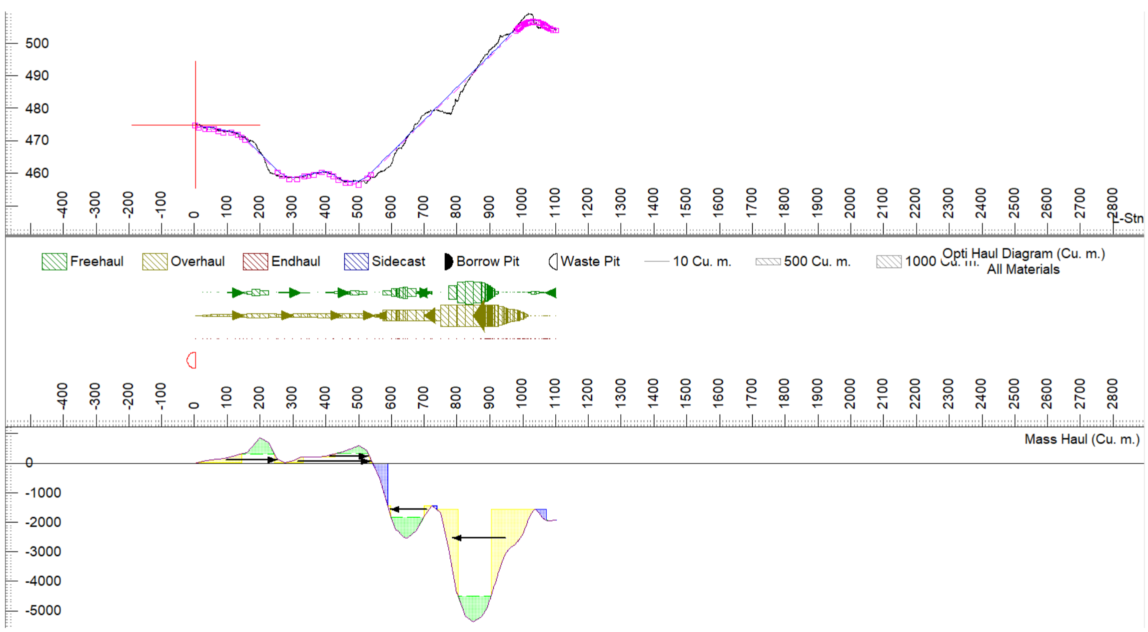
Branch Road 1 Eacom



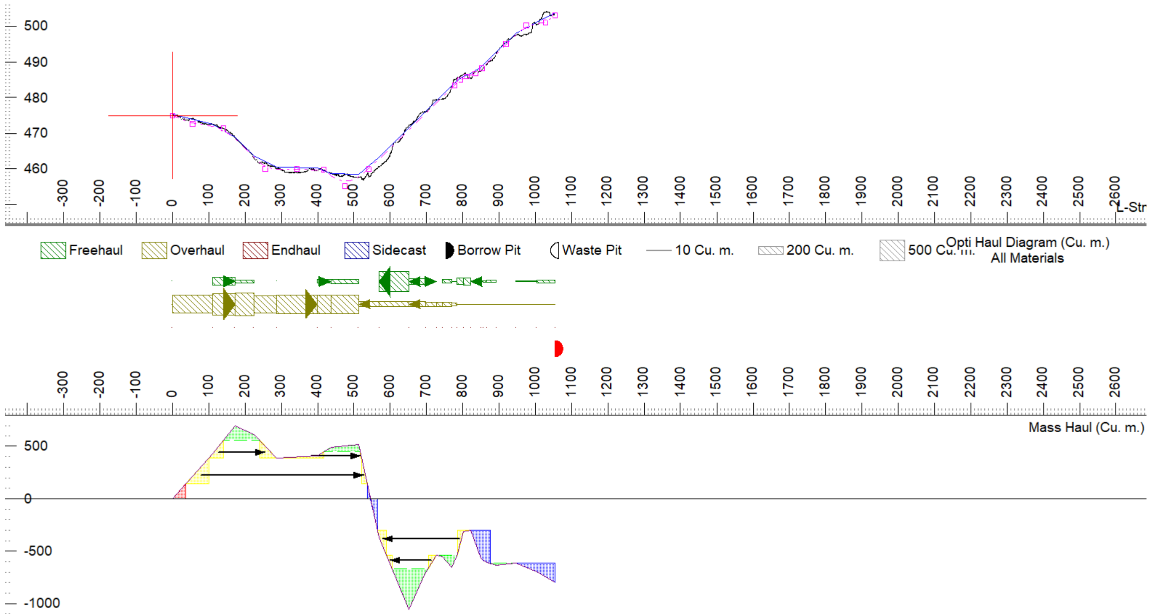
Branch Road 1 Blind Attempt



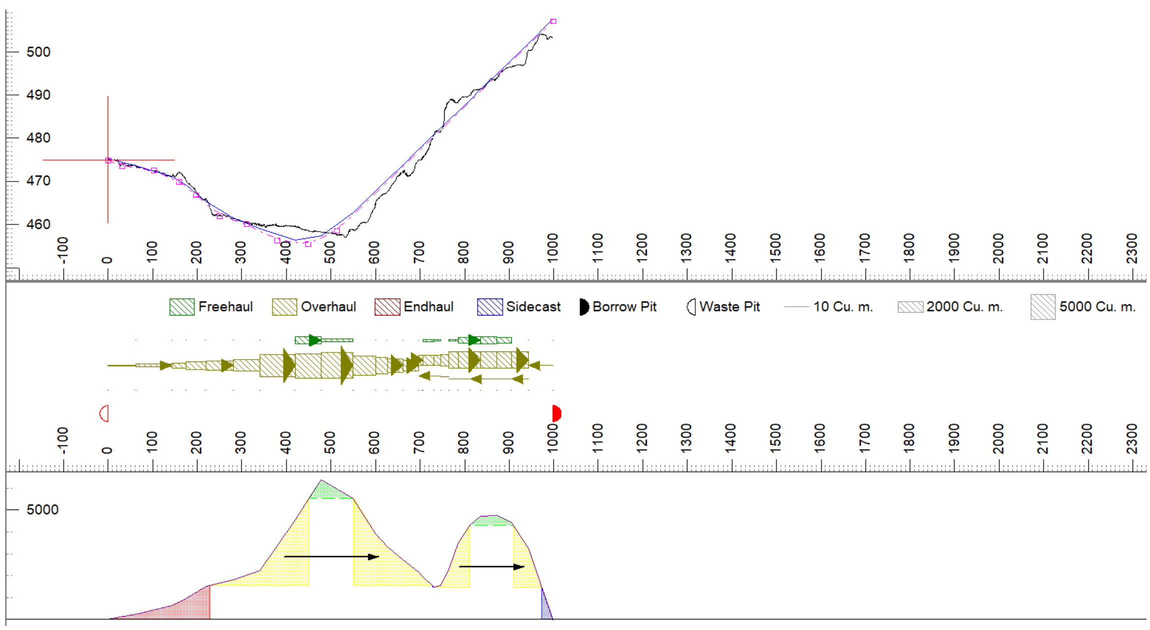
Branch Road 1 Second Attempt



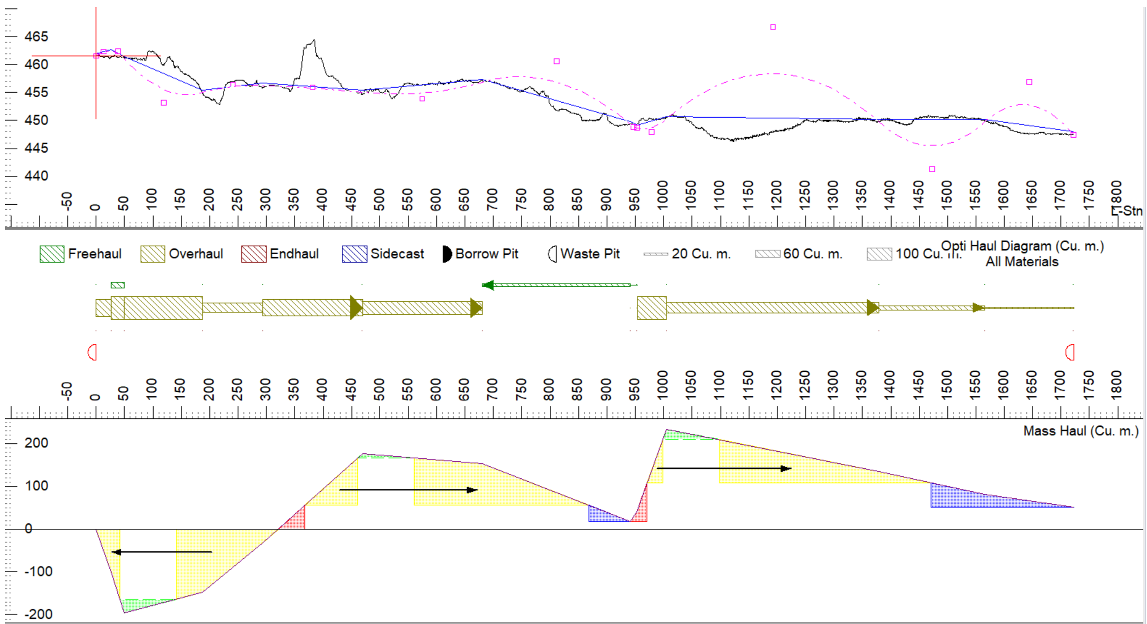
Branch Road 2 Eacom



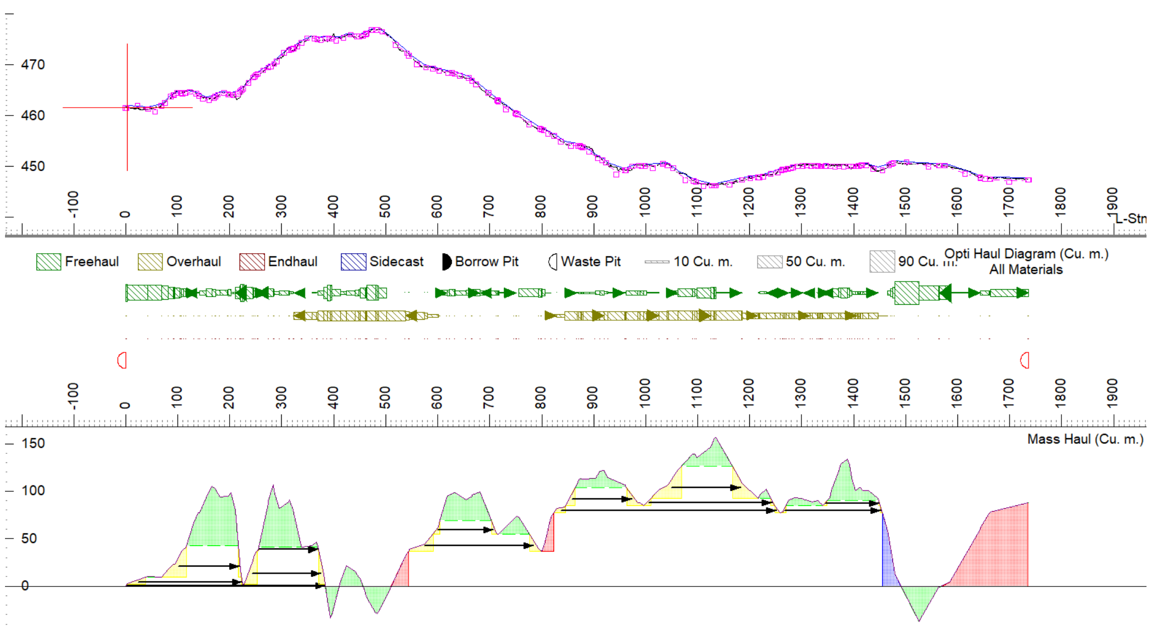
Branch Road 2 Blind Attempt



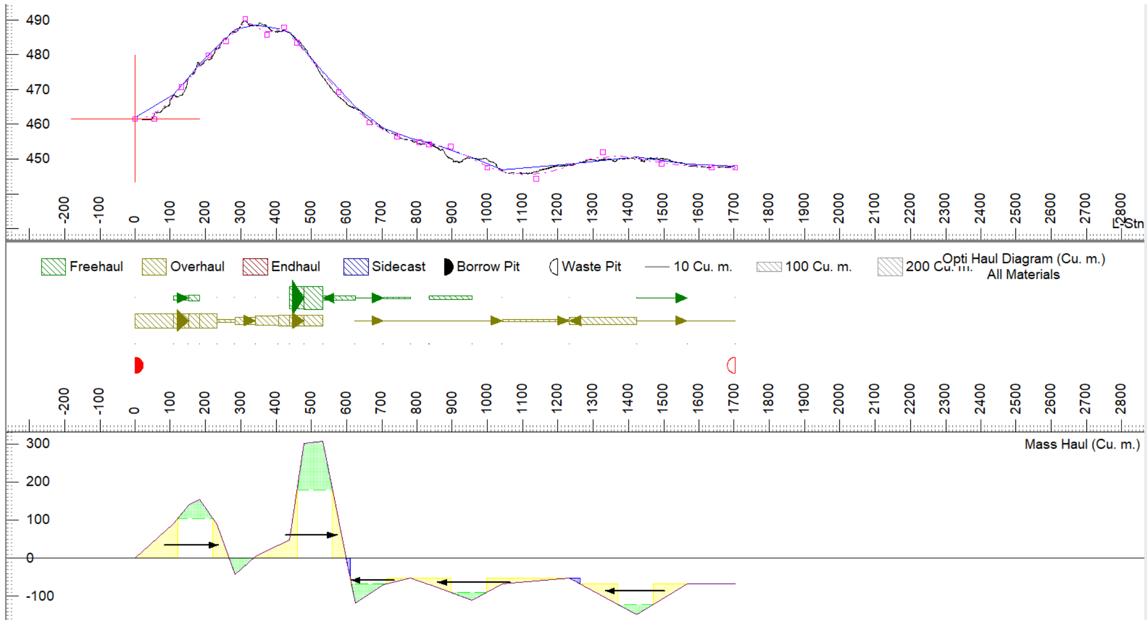
Branch Road 2 Second Attempt



Block Road Eacom



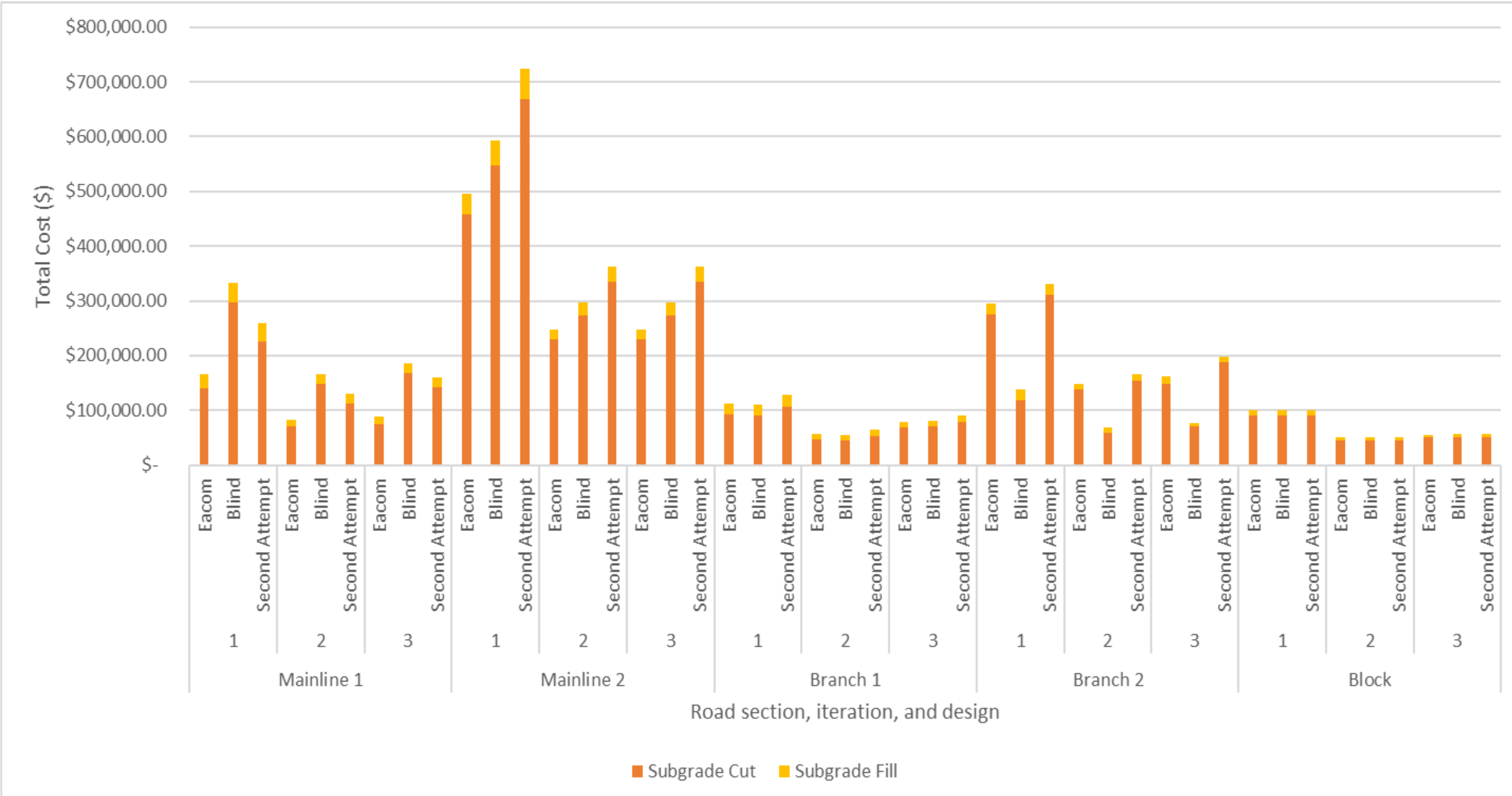
Block Road Blind Attempt

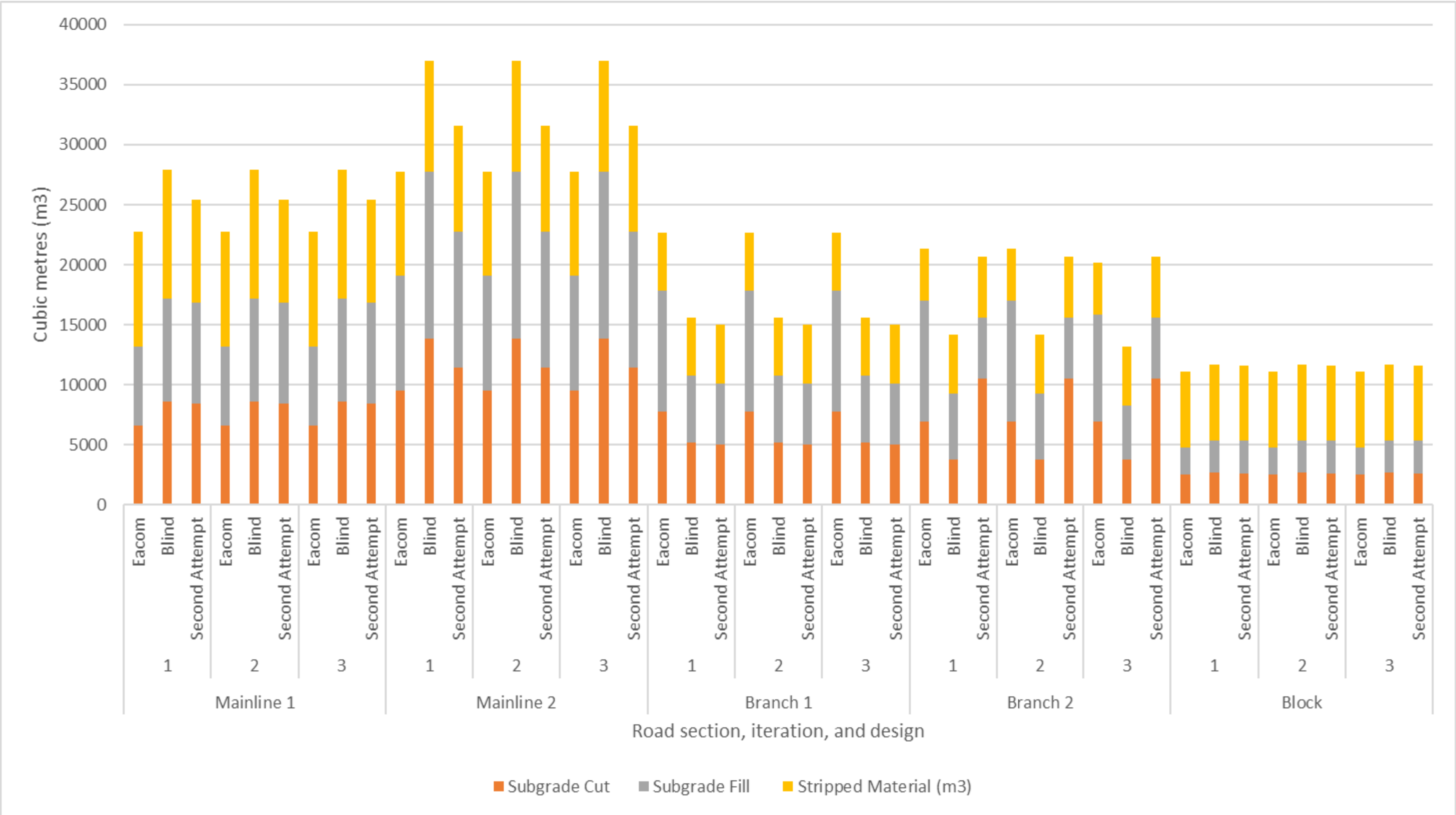


Block Road Second Attempt

APPENDIX IV

Road excavation cost ($) and material ($m^3$)


Total Cost ($)
$800,000.00
$700,000.00
$600,000.00
$500,000.00
$400,000.00
$300,000.00
$200,000.00
$100,000.00
$-
Eacom
Blind
Second Attempt
1
2
3
Mainline 1
Mainline 2
Branch 1
Branch 2
Block
Road section, iteration, and design
Subgrade Cut
Subgrade Fill



40000
35000
30000
25000
20000
15000
10000
5000
0
Cubic metres (m3)
Eacom
Blind
Second Attempt
1
2
3
Mainline 1
Mainline 2
Branch 1
Branch 2
Block
Road section, iteration, and design
Subgrade Cut
Subgrade Fill
Stripped Material (m3)

APPENDIX V

Assigned soil layers to roads

i

Eacom **Mainline 1**

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	361.0
OB	361.0	1533.0
OB/0.70/SR	1533.0	..

Blind

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	297.6
OB	297.6	695.6
OB/0.70/SR	695.6	..

Second Attempt

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	382.1
OB	382.1	1481.6
OB/0.70/SR	1481.6	..

Mainline 2 all

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	..

Eacom **Branch 1**

Ranges

Ground Layers	From Stn.	To Stn.
OB	..	810.0
OB/0.29/SR	810.0	..

Blind

Ranges

Ground Layers	From Stn.	To Stn.
OB	..	860.0
OB/0.29/SR	860.0	..

Second Attempt

Ranges

Ground Layers	From Stn.	To Stn.
OB	..	809.0
OB/0.29/SR	809.0	..

Eacoom **Branch 2**

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.70/SR	..	873.0
OB/0.29/SR	873.0	..

Blind

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.70/SR	..	855.8
OB/0.29/SR	855.8	..

Second Attempt

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.70/SR	..	706.3
OB/0.29/SR	706.3	..

Eacom **Block**

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	953.0
OB	953.0	..

Blind

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	875.0
OB	875.0	..

Second Attempt

Ranges

Ground Layers	From Stn.	To Stn.
OB/0.29/SR	..	834.4
OB	834.4	..