UNIVERSITÀ DEGLI STUDI DI PADOVA
Department of Land, Environment Agriculture and Forestry

Second Cycle Degree (MSc)
in Forest Science

Eco-Efficient Design of Forest Roads in Steep Terrain: A Case Study in the Italian Alps

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July 8, 2024

ACADEMIC YEAR 2023-2024

Abstract

The construction of forest roads as key access points to forest resources and to allow timber harvesting activities is a process that has been in constant operation and is continuously looking for more efficient solutions. The principles concerning the construction standards of forest roads are regularly reviewed to ensure that advances in the most current off-road and on-road transportation technology and the best environmental practices are incorporated. While efforts are being aimed towards the optimization of the forest road network layout, there is a serious lack of research concerning the energy, cost and emissions created in the use of a forest road, the relationship between initial and future costs and the overall cost of a forest road during its lifetime. Using high spatial resolution LiDAR data this thesis investigates the in-depth cost concerning the construction and use of a forest road through the creation of forest road alignments in steep terrain. Key variables will be identified and analyzed with respect to their impact on the viability of a forest road, and the advantages of constructing forest roads to allow the most efficient extraction of forest resources.

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1.0 Introduction

While mountainous regions are more often remote and are less capable of supporting traditional agricultural practices, the abundance of other natural resources such as timber has placed demands upon these regions. Forest roads are often considered the backbone for any timber harvesting undertakings and are key infrastructure to allow access to these mountainous forest regions (Bont, 2012; Heinimann, 2017).

A problem commonly seen in forest roads are outdated design principles, because as the principles change due to scientific advancements and the evolution of both off-road and on-road transportation technology (Heinimann, 2017; Akay et al., 2021). Economic efficiency is a key aspect of forest roads and is determined by the costs of constructing those roads, as well as the transportation expenses. The overall goal in planning is to find the combination of transportation and infrastructure components that minimizes overall cost (Bont et al., 2015). In central Europe, the planning of road networks has often been done through rule of thumb or heuristic solutions, and only few attempts though mathematical optima (Bont et al., 2015). Cost estimation is likely the most decisive factor in the process of computer-aided preliminary planning for forest road networks (Stückelberger et al., 2006) which is an important factor to consider, however lower initial cost is not always the cheapest when considering the life span of a forest road.

Forest road managers should consider not only the total road cost, but also environmental impacts caused by the road construction (Caliskan, 2013). Forest roads have the potential to have a large impact on the forest environment in which they are built. It is widely accepted that forest roads may alter the hydrologic response of the watersheds (Kastridis, 2020). This means that it is sometimes difficult to find the right balance between cost of the forest road and the forest road being built to the proper standards, while also having adequate features to minimize impact on its environment. The use of natural relief and avoidance of sensitive areas are among solutions to minimize costs, environmental damage and are considered best practices along with limiting road widths to only what is necessary (Aguiar et al., 2021).

While there have been individual studies on aspects of forest road networks and their construction, the analysis on initial and future costs of a forest road is a less common practice and is an aspect of the forestry industry that should be explored. The future costs of these forest roads, such as the fuel consumption and emissions of the vehicles traversing these often isolated and steep roads can provide important inputs in determining future costs of a road as well as determining its viability characteristics. Aside from initial construction costs and future costs of maintaining a roadway, aiming to build a road in a manner to accommodate these vehicles could result in large savings over time and should be investigated.

Improving road standards might result in some additional costs in the road construction stage, but total net profit of forest products increases since transportation costs along with maintenance and repair costs considerably decrease in the long term (Akay et al., 2021). Road widths, lengths and grades should all be considered in the planning stage for a forest road, as these attributes may contribute to slight increases in initial cost, however a more favourable grade in the long term may contribute to better fuel efficiency and thus make that initial cost acceptable.

It is common practice for road engineers to use published machine productivity equations to estimate costs or other related information (Loeffler et al., 2009). Using published fuel consumption data from manufacturers, or data produced by individual testing, it is possible for road engineers or interested parties make estimations to gain greater insight into the future costs of these roads. Forest roads are the most costly structures in forestry and inadequately constructed forest roads can have severe environmental impacts (Caliskan, 2013). In recent years concerns regarding environmental impacts and notably greenhouse gas emissions, and the significance of their repercussions, have become much more important as a design element.

1.1 Objectives

The main goal of this project is to examine the possible alternatives for the current forest road alignments within the selective portion of Taibon Agordino region, considering initial construction costs as well as future costs. Of the two existing roads, the primary road is very steep and has many switchbacks, however it provides access to an important section of forest resources, however it is inaccessible to most vehicles. Determining the viability of connecting the secondary road to the primary road above the steep sections allowing for more efficient wood extraction from this section of the forest is the aim. This will be done by achieving the following objectives.

- Create models of the current forest roads in the region and use those models to create several different connections between them based on specific road standards as well as other significant design principles.

- Compare attributes such as length, slope, haul volumes and construction costs, in the different solutions resulting from the modelling exercise for connecting the two existing forest roads to determine the most suitable option.

- After comparing possible connections, create new alternative routes. Analyze each road alignment as well as routes created using the chosen connections. Calculate and compare fuel consumption and CO_2 emission estimations, as well as costs and haul volumes.

2.0 Materials and Methods

The methodologies employed during this project have been vital in the creation of the forest road alignments as well as analyze initial and future costs associated with forest roads and their relationship to one another. This will be conducted by using a combination of GIS and road design software to create these alignments.

Using available LiDAR data from the selected site, as well as shapefiles provided of current features, such as the existing road network, road alignments will be created. These road alignments will all be assessed on their initial cost of construction and haul volumes. Future costs will also be assessed, which includes an analysis of the future costs associated with its construction such as fuel consumption and carbon dioxide emissions. Lastly, ground truth data using Global Navigation Satellite System (GNSS) will be collected during a field visit, which will be used to validate design features by comparing designs to field data.

2.1 Case Study Area

The area of study for this project is in the Taibon Agordino municipality, located within the Belluno province, in North-Eastern Italy. The Extents of the Taibon Agordino municipality are shown in Figure 2.1.

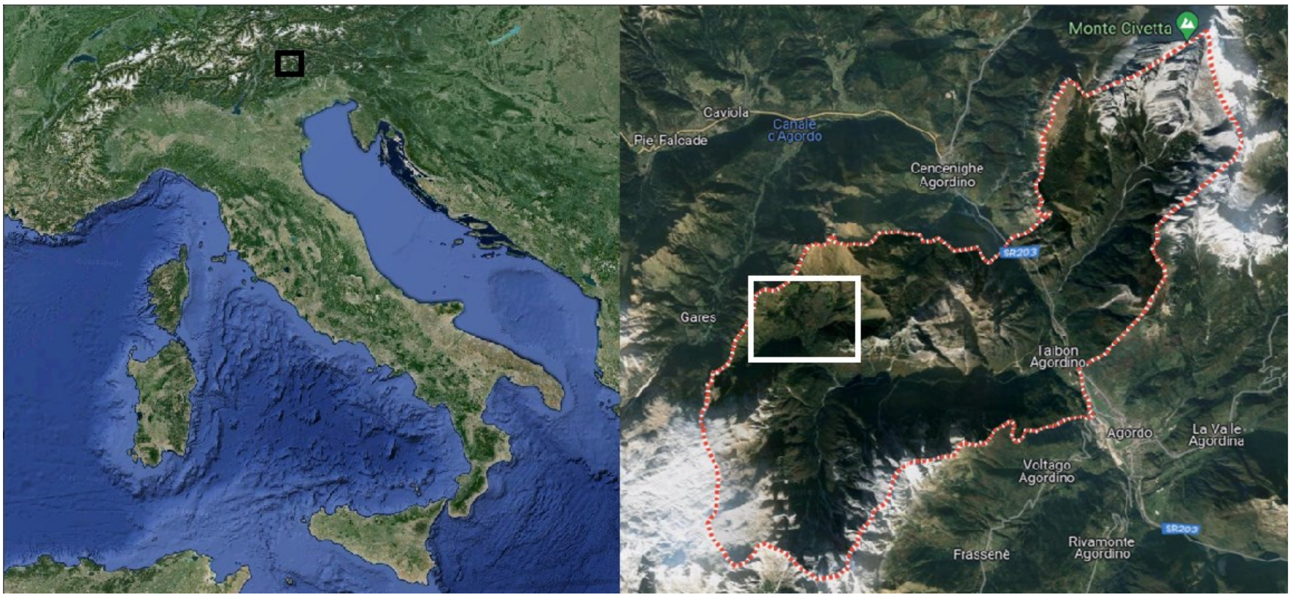

Figure 2.1: Location of Taibon Agordino Municipality within Italy, and Case Study Location within Taibon Agordino Municipality

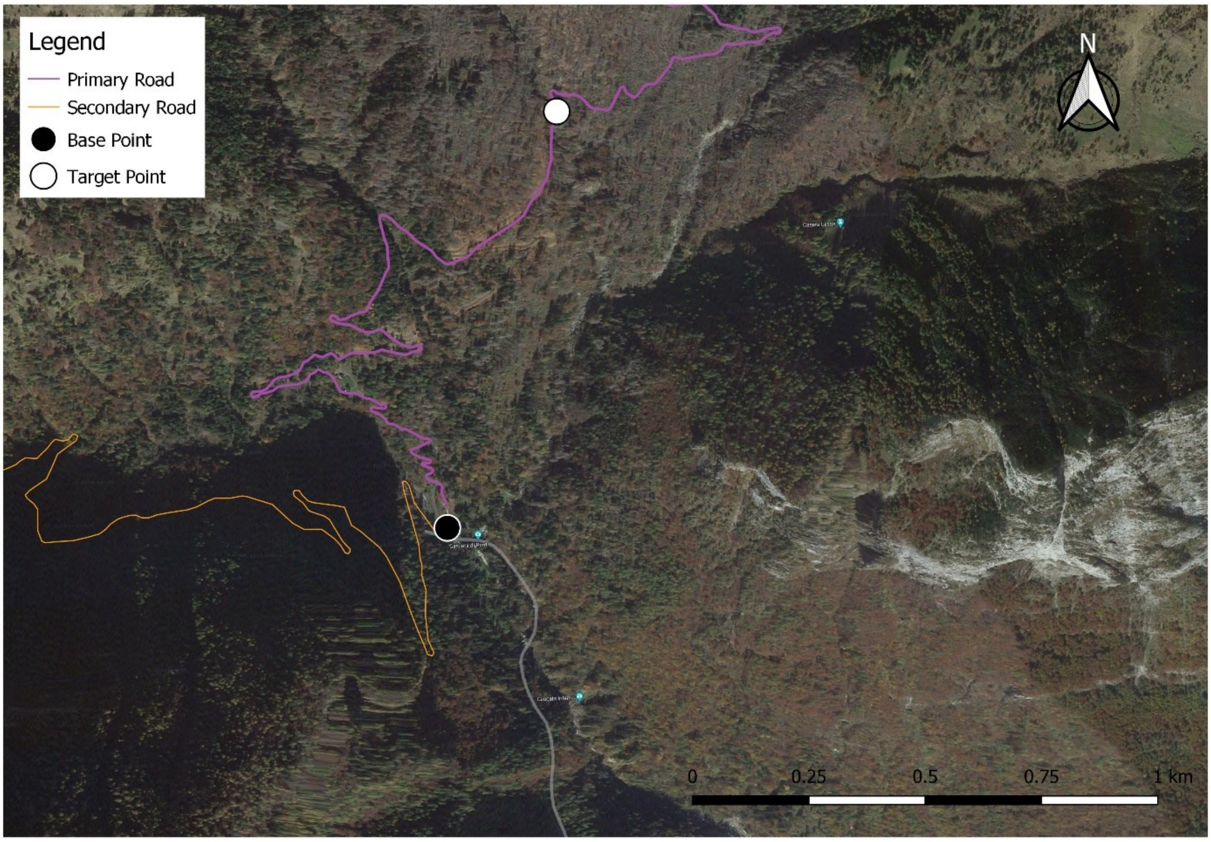

Figure 2.2: Case Study Location in Taibon Agordino Municipality

Shown in Figure 2.2, the case study location contains two main roads, the primary road (purple) and the secondary road (orange). The lower section of the primary road is dangerously steep with sections exceeding 30% and contains many switchbacks making it very difficult for vehicles other than tractors and other small off-road vehicles to use this road, and impossible for larger more efficient timber haul trucks. The primary road was built to a standard of 3m, 1.25m per lane with a 0.25m shoulder, whereas the secondary road has a width of 4m total. Due to the wider width and more gradual slope, this makes the secondary road much more accessible. While the start points of both roads, indicated by the point at the base (black point) is the same, the roads are built to access different sections of the forest. The target point (white point) is used as a reference along the primary road, which is currently inaccessible by larger forest haul trucks. The creation of a connection between the secondary and primary road, bypassing the steeper lower section of the primary road and reaching the target point to provide access to the forest resources beyond is the goal.

2.2 Software

To complete the aims of this project, several different software programs were used. Each one was chosen based on its unique ability to facilitate the completion of different steps required to further the project. The main programs used throughout this project were QGIS version 3.28.12, the RoadEng 10 (Both RoadEng 10 Terrain & RoadEng 10 Location), Microsoft Excel and Avenza Maps version 5.3.3.

2.2.1 QGIS

QGIS was chosen as it is a free and open-source software that allows a user to visualize and manipulate geospatial data. Having been provided a Digital Terrain Model (DTM) at 1-metre spatial resolution by the UniPD TESAF department, QGIS was used to create a hillshade model to acquire a sharper picture of the study areas topography. The provided DTM was also used to create contours in QGIS at a 10m spacing. The created contours were used in the planning process for testing possible connections between the existing roads. The hillshade generated from the DTM was helpful to create polylines that would approximate the currently existing roads within the study area.

2.2.2 RoadEng 10

RoadEng 10 is a road and infrastructure design suite, that is particularly well suited for the design of rural and forest roads. The RoadEng suite is a combination of RoadEng Survey, RoadEng Terrain and RoadEng Location, however for this project, only RoadEng Terrain and Location were used.

RoadEng Terrain was used as a stepping stone to prepare the data and layers created in QGIS for RoadEng Location. RoadEng Terrain allows for the manipulation of various 2D and 3D features and layers. Bringing in the DTM and polylines from QGIS, a Triangulated Irregular Network (TIN) was created, and polylines modelled on this surface.

RoadEng Location is the program within the RoadEng suite that facilitates the creation and design of road alignments and was used heavily throughout the project. Using the polylines as a reference, road alignments were created and modified in RoadEng Location. RoadEng Location allows for the manipulation of the horizontal and vertical alignments for each road depending on required road specifications, as well as cost and haul volumes.

2.2.3 Microsoft Excel

Microsoft Excel is a spreadsheet program useful for data analysis and is capable of working with large quantities of data and applying queries of varying complexity to this data. Microsoft Excel was used primarily for the analysis of the road alignments, specifically regarding fuel consumption and CO2 emissions.

2.2.4 Avenza Maps

Avenza Maps by Avenza Systems Inc. is a mobile application used during the field visit. Avenza Maps is an application that allows the user to upload their own maps and uses the mobile devices GPS to track its position. Avenza Maps can also record photos and coordinates, which was done during the field visit. Avenza Maps was used while taking measurements of the road width and slope during the field visit. Each time these measurements were taken a point was stored in Avenza which included the coordinates as well as a photo of the specific section of road being measured.

2.3 Surveying equipment

While much of the processing work throughout this project was done through the software's mentioned previously, a field trip was performed to acquire ground truth data for validation. Listed below are the various instruments used throughout this project.

2.3.1 GNSS

During the field visit, a base station was setup which was the Emlid Reach RS2+, and a rover, which was the Emlid Reach M2 was used to collect data on the road widths of the primary road. The maximum positional accuracies of both base and rover are listed below in Table 2.1.

Table 2.1: Emlid Reach RS2+ & Emlid Reach M2 Positional Accuracies (Emlid, 2019; Emlid, 2022)

Hardware	Emlid Reach RS2+	Emlid Reach M2
Static Horizontal (mm)	4mm	4mm
Static Vertical (mm)	8mm	8mm

2.3.2 Vertex Laser Geo Hypsometer

The Vertex Laser Geo Hypsometer is a handheld tool that provides height, distance, and angle values. This is done by combining a laser, ultrasound and tilt sensor. The Vertex Laser Geo Hypsometer was used to gather slope data for the primary road, and to gather slope data and road widths of the secondary road. The accuracies of the Vertex Laser Geo Hypsometer are listed below in Table 2.2.

Table 2.2: Vertex Laser Geo Hypsometer Accuracies (Vertex Laser Geo/ Laser Geo User Guide, n.d.).

Aspect	Accuracy
Vertical Angle	0.1°
Horizontal Angle (Compass)	1.5° RMSE
Laser	0.1ft/4cm
GPS (Automatic Position)	2.5m CEP (circular error probable)

2.3.3 Laptop

For this project, a computer was required to meet the software needs as well as to be able to process any relevant data. An ASUS TUF A15 506QM was used to meet all computing needs for this project with 32GB 3200MHz DDR4 RAM, and an AMD Ryzen 7 5800H processor.

2.4 Methods

The methods used during this project can be divided into two distinct phases. The first section is the modelling of the existing roads within the study area, as well as the creation of possible connections between the two. The second section was to estimate fuel consumption and CO2 emissions for the current and potential road alignments as well as compare whether any benefits existed in the connection of the road alignments.

2.4.1 Road Alignments

The first step was the use the LiDAR derived DTM model at 1m resolution that was provided to create a hillshade layer (Figure 2.3). This was done in QGIS by using the hillshade tool provided by its library. The hillshade model would provide greater definition of the topography by computing shaded relief values by considering illumination and shadows. This step was helpful as it allowed a greater ability to visualize aspects of the study areas topography. The hillshade was then enhanced by creating a contour layer as well. A contour layer was generated with 10m spacing (Figure 2.4), 10m was chosen as the interval so it would provide enough information but not become cluttered.

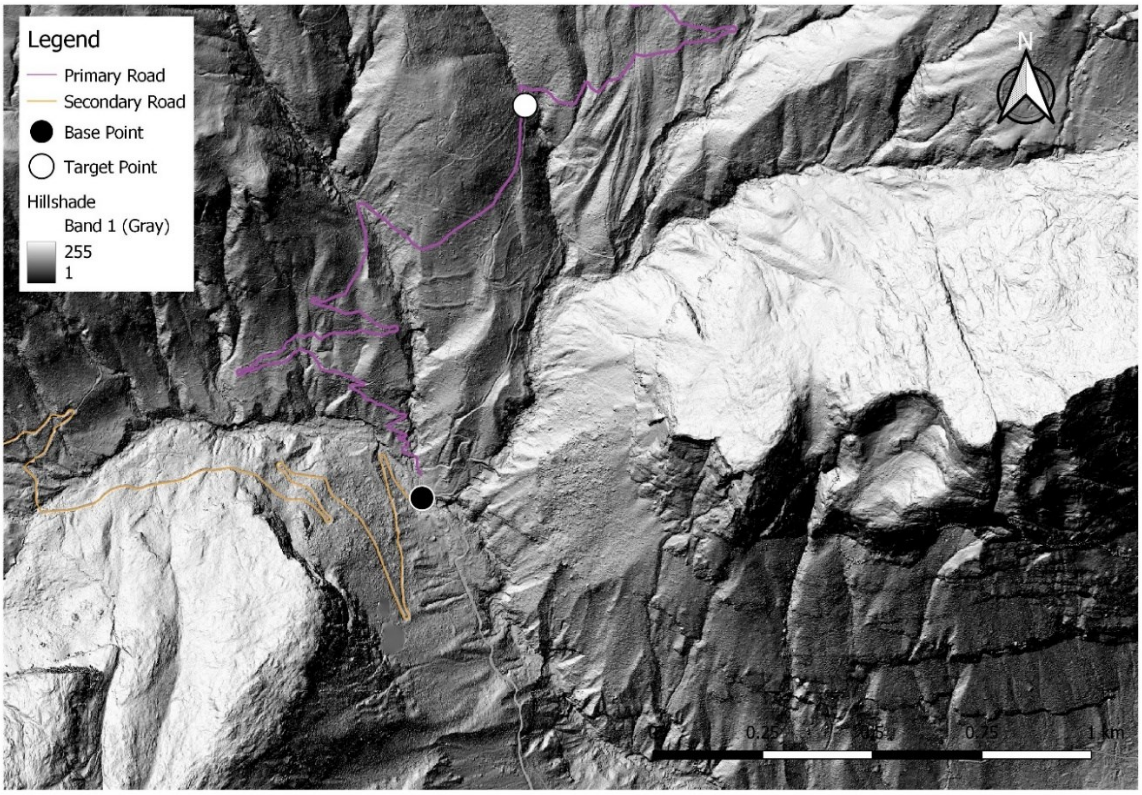

Figure 2.3: Hillshade Layer of Case Study Location Generated in QGIS

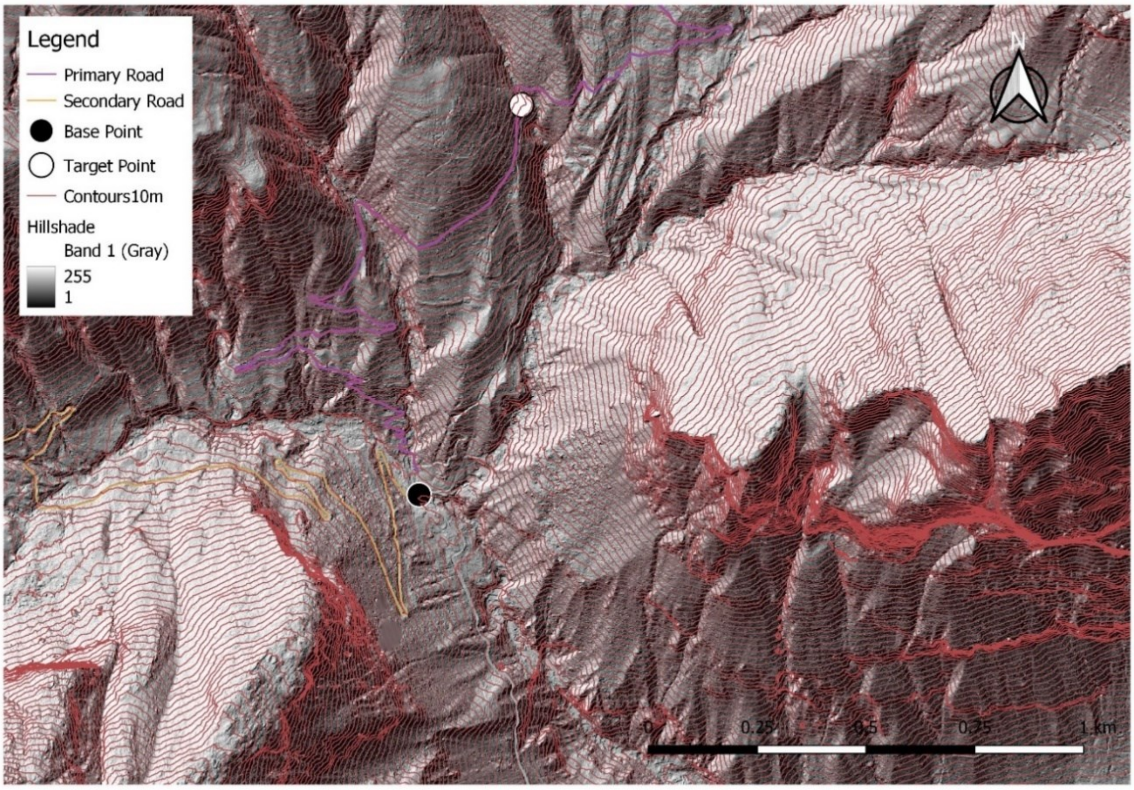

Figure 2.4: Hillshade Layer and 10-metre contours of Case Study Location Generated in QGIS

Using the hillshade and contour layers, polylines were created with the purpose of acting as baselines for the creation of the road alignments in RoadEng 10. Using the defined features of the hillshade, polylines were created approximating the two existing roads in the study area. Due to the steep grades and tight switchbacks of the primary road, several polylines were also created as connections between the secondary road and the primary road, that would bypass the problem areas of the primary road. Based on previous research and best practices, various aspects were taken into consideration when choosing the location for the connections such as grade, shortest route, and going with contours vs. against. These polylines are shown below in Figure 2.5.

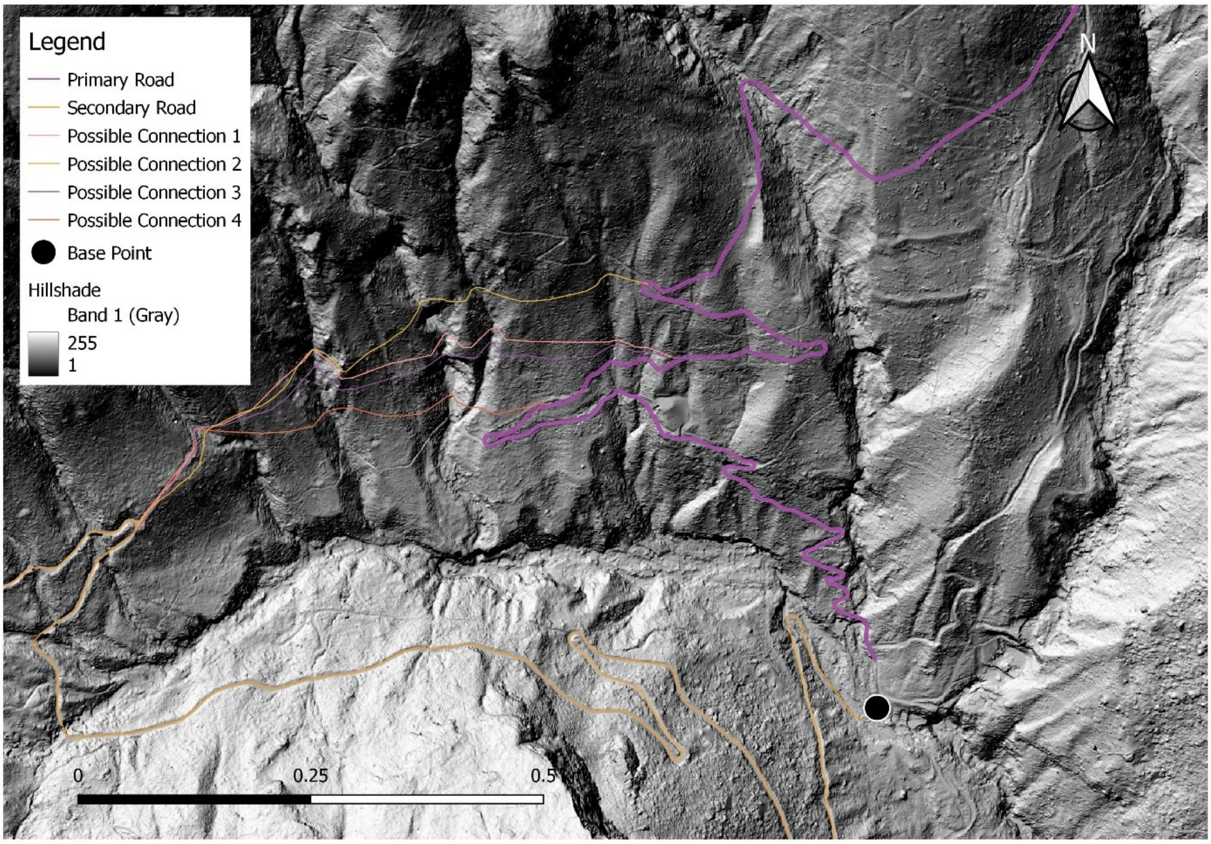

Figure 2.5: Polylines of Possible Connections Between Secondary and Primary Roads

The next step was to bring the polylines and DTM into RoadEng Terrain. While the process within the Terrain module of RoadEng isn't extensive, it is an important step in preparing the features for RoadEng Location. Within RoadEng Terrain a TIN model is created by using the DTM and the polylines are also then modelled on this surface. The file is then saved and can be opened in RoadEng Location.

RoadEng Location was employed for a large portion of this project. RoadEng Location was the software used to create the road alignments using the polylines as references and then model those road alignments in 3D. This was done by first bringing in the 3D surface created in RoadEng Terrain, as well as the polylines to use as reference. The Primary and Secondary roads, that currently exist within the area of the case study were first to be designed. This was done by creating a horizontal alignment for each one and following the polylines that had been imported. The road alignments are a serious of horizontal tangents and curves which show the proposed roadway location with respect to the existing terrain. This is done by the creation of individual intersection points that can form individual segments of the road and can be moved around and together create the road alignment. For the primary road a road width of 3m was chosen, the primary road was built with 1.25m per lane as well as 0.25m per shoulder. The terrain model was also used as a visual aid, to keep the road alignment as accurate as possible. For the secondary road a road width of 4m was chosen, as there was no information detailing the roads dimensions, this was solely based on using the terrain model and cross section window to help ascertain road width and positional accuracy. For both the primary and secondary roads, a field visit would later be conducted to acquire ground truth data in the form of slope measurements as well as road width measurements to verify decisions made in the modelling process.

Each potential connection was unique however they all used the secondary road as a starting point and somewhere along the primary road as an end point. Due to this, modelling the connections were done after the primary and secondary roads were modelled, as they needed to be anchored at their start and end points. Using the horizontal alignments that had been created for each road and connection, it was possible to render a 3D model for each. This was done by relating the linework and structure set forth for each alignment to the existing terrain and topographic features surrounding area. The 3D model generates the road surface as well as calculates cut and fill volumes along the road alignment. The goal of the connection between the two was to create a viable alternative to the steep and tight first section of the primary road that would provide access to haul trucks. Keeping this in mind it was important to keep the grade of the road as low as possible as well as maintaining as large a radius as possible for any required turns. The biggest difference between the connections and the existing roads, however, is that there was no ability to change the existing roads. The connections would be modelled based on standards set forth by the Ministry of Agricultural, Food and Forestry Policies, which are detailed below.

Table 2.3: Ministry of Agricultural, Food and Forestry Policies Forest Road Standards (MINISTERO DELLE POLITICHE AGRICOLE E FORESTALI, 2021)

Category	Road Layer	Roadway Width (m)	Shoulder Width (m)	Maximum Longitudinal Slope (%)	Optimal Longitudinal Slope (%)	Switchback Turn Radius (m)
Second Level Forestry Road	Stabilized or Improved	2.5-3.5	0.5	16-22	3-8	Greater or equal to 8

After each horizontal alignment was completed for the possible connections, their vertical alignment was designed using the longitudinal profile window in the RoadEng Location module. Within this window it is possible to manipulate the grade of the alignment. It is also possible to visualize haul volumes within this window, which can be changed by changing the slope of the road alignment. This reflects required cut and fill volumes along the alignment and can increase or decrease the total estimated cost of the alignment based on the nature of these volumes. Figure 2.6 below shows an example of the haul volumes, which indicate where there is a need or an excess of material. The breakdown of colours is as follows.

- Green: Free Haul, this is material that can easily be moved within 100m.
- Yellow: Over Haul, this is material that requires greater energy to be moved within 500m.
- Blue: Borrow, this is an area in need of material that needs to be hauled in.
- Red: Waste, this is material that is excess and must be hauled away.

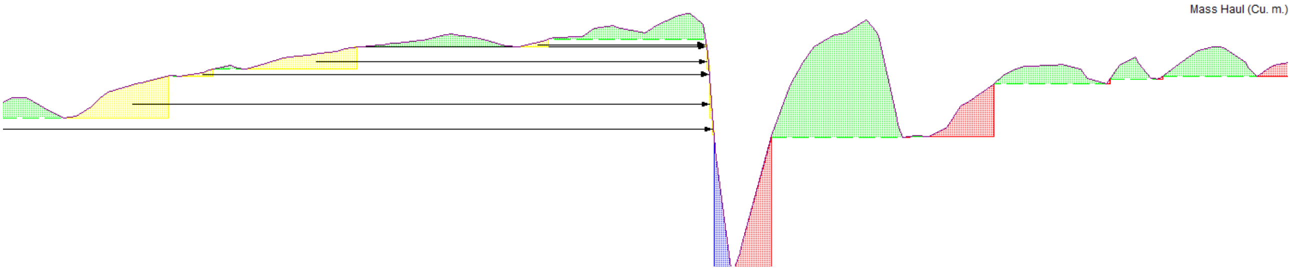

Figure 2.6: RoadEng Location Haul Volumes

Figure 2.7 below shows an example of the longitudinal profile view. The top half is the vertical alignment, the pink line showing the road alignment, and the black line the topography. The bottom half is an example of haul volumes that have successfully been balanced.

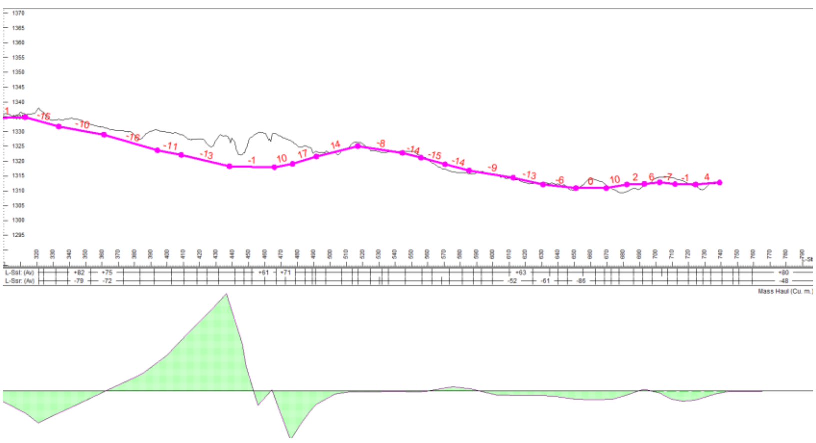

Figure 2.7: RoadEng Location Longitudinal Profile

A total of four different possible connections had originally been chosen to be modelled. After modelling them only two of the four connections made practical sense and were considered viable options. Figure 2.7 shows a connection that has been balanced so that the only material present is free haul. While a road can be built with over haul, needing borrow material, or having waste material, it is not ideal as it then requires larger equipment to move material further or having trucks hauling material to or from the road location. Connections were considered not viable due to the roads falling outside the previously mentioned road standards by requiring steep sections of roadway, or by requiring large amounts of material to balance road haul volumes and thus making the road very expensive. After deciding on the two best options, their data was then imported to Microsoft excel to perform further analysis as described in section 2.4.2.

2.4.2 Fuel Consumption and CO2 Emissions

Data for each road alignment was exported from RoadEng Location and brought into Excel for further processing. Data that was used included station distances, elevations and grades. From this data, for each road alignment distances between alignments were determined in metres. An example of this would be if you had two points, B and C, and was done by taking station C's location (11m) along the alignment and subtracting stations B's (5m) which would give us the distance between the two stations from B to C (6m). After distances were determined in metres, they were converted to kilometres by dividing each value by 1000. For each segment of each road, there was now a linear distance as well as a slope value, which could then be used for the fuel consumption calculations and route comparisons.

Several different vehicles were chosen to help assess the efficiency of the modelled road alignments. Firstly, a standard half tonne pickup truck the Ram 1500 which was the only gas vehicle with a fuel consumption rate of 16.7 L/100km (*2012 Ram 1500 MPG*, n.d.). Popular forest haul trucks found throughout the alps such as the Volvo FH16 750 and Scania R 520 were also used with fuel consumptions of 39 L/100km (TruckScout24 GmbH, 2013) and 33.1 L/100km (Scania CV AB, 2019) respectively. Table 2.4 below shows the fuel efficiency of these vehicles in L/100km and L/km. Table 2.4 also lists fuel efficiency achieved by haul trucks with 20 and 40 tonne payloads of 36.1 L/100km and 69.3 L/100km respectively using an international model (Ghaffariyan et al., n.d.)

Table 2.4: Fuel Consumption Rates for Trucks

Vehicle	L/100km	L/Km
2012 Ram 1500	16.7	0.167
Scania R 520	33.1	0.331
Volvo FH16 750 8x4	39	0.39
International Model 20 (t)	36.1	0.361
International Model 40 (t)	69.3	0.693

While the lengths of each road segment would not change whether a vehicle was travelling up or down hill, the grade would either be positive or negative. So, when calculating the fuel consumption for any given vehicle, the grades were reversed when calculating fuel consumption down hill. Estimations of how much addition fuel is consumed when driving upslope compared to on flat ground exist, however these assertions are not all found to be reliable or proven. Due to this an assumption was made that when travelling uphill, a vehicle would be consuming a greater amount of fuel between 1-2% per 1% slope. Due to this, any segment with a positive slope had a multiplier of 1.5% added to the fuel consumption rate for that segment, as demonstrated in Table 2.5.

Table 2.5: Fuel Consumption Uphill Vs. Downhill

Segment Distance (km)	Slope (%)	2012 Ram 1500 Fuel Consumption (L/km)	Fuel Consumption Multiplier	New Fuel Consumption (L/km)	Fuel Consumption for Segment (L)
0.0030	8	0.167	((1.5*8)/100) +1= 1.12	0.167*1.12=0.187.	0.0030*0.187= 0.00056
0.0030	-8	0.167	0	0.167	0.0030*0.167= 0.00050

For each vehicle, each road alignment was broken down into their individual segments and the fuel consumption was then calculated at the individual segment level, and then summed. This was done for each road alignment going uphill, as well as downhill. Fuel consumption was calculated both for each road alignment but also for each route. Route 1 used the secondary road, connection 1 and then finished with the primary road. Route 2 used the secondary road, connection 2 and then finished with the primary road (Figure 2.8). Analysis could then be performed using the total fuel consumption between Route 1, Route 2, and the primary road.

However, it is not possible for haul trucks to navigate the steep grade and tight switchbacks of the primary road. Due to this a comparison was made between Route 1 and Route 2 using haul trucks and the primary road using tractor and trailer.

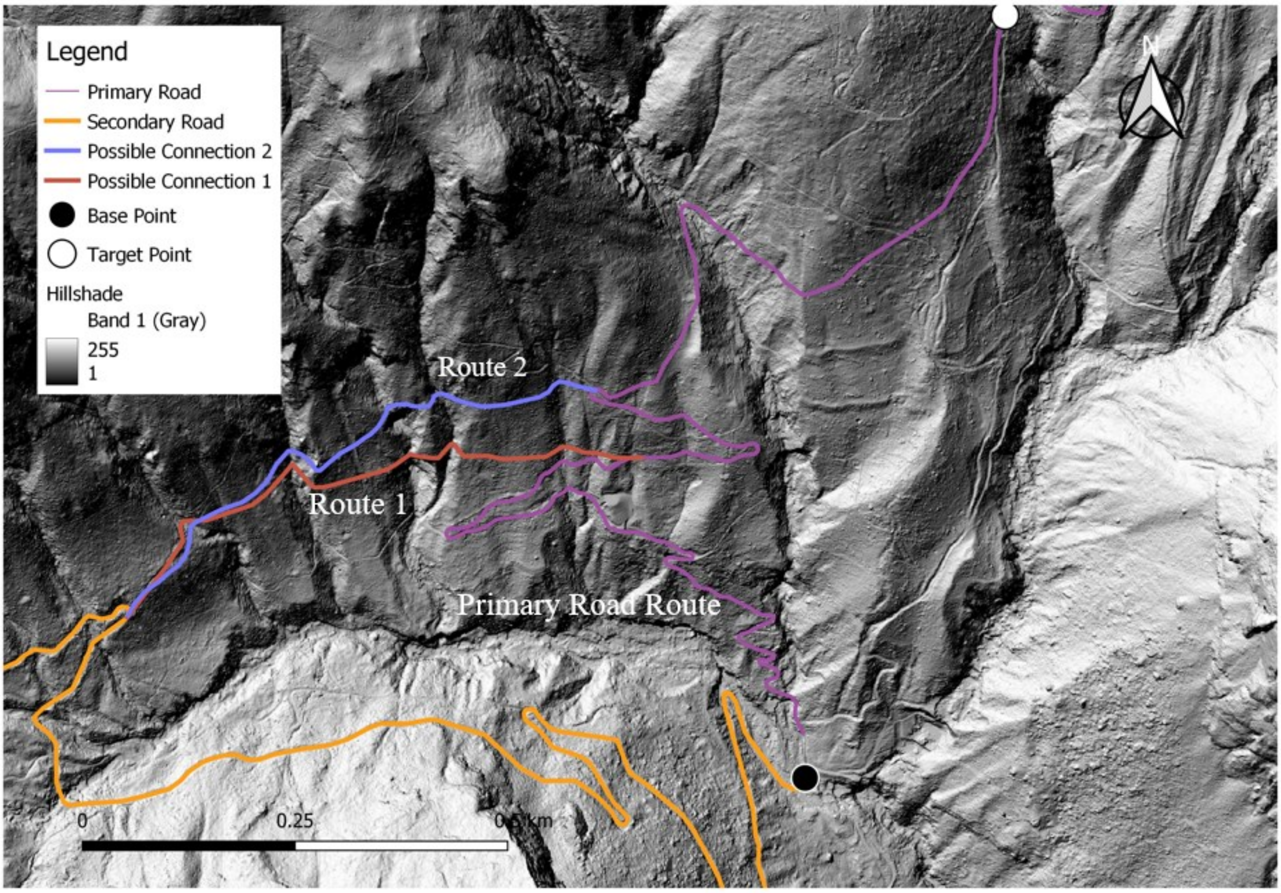

Figure 2.8: Three Tested Routes within the Case Study Area

Table 2.6 shows the fuel efficiency for a few tractors commonly used in Italy, these are the Valtra N series tractor and the New Holland T5110. The fuel efficiency for tractors however is recorded in L/H where H is hours and are 14.5 L/H for the Valtra N Series (Valtra Team, 2010) and 22 L/H for the New Holland T5110 (Brent, n.d.).

Table 2.6: Fuel Consumption Rates for Tractors

Tractor	L/H
Valtra N Series Tractor	14.5
New Holland T5110 Tractor	22

The final comparison between the routes was done by analyzing the fuel consumption of the Volve FH16 750 8x4 and its 22.87-tonne load capacity on route 1 and route 2, and the Valtra and New Holland Tractors using a 14-tonne load capacity Kesla trailer on the primary road. Due to the fuel consumption for the tractors being measure in L/H, an assumption was made that each tractor could perform one trip up and down the hill, every 2 hours, and then was also tested at one hour per trip.

After the fuel consumption totals were calculated for each route, it was possible to determine the CO2 emissions for each scenario. Diesel engines produce 2.7 kg of CO2 per litre of diesel consumed (Resources Canada, n.d.). The total fuel consumed for each scenario was then multiplied by 2.7, providing the total emissions of CO2 for each scenario in kg.

2.4.4 Field Data Acquisition

On June 13th, 2024, a field visit was conducted to the study area within Taibon Agordino. During this field visit, various data was collected. Road slopes were measured using the Vertex Laser Geo Hypsometer for both the primary and secondary roads. This was especially important for the primary road as the beginning section contained segments of steep slopes exceeding 30% which creates a very dangerous environment for most vehicles especially any hauling forest material. This was important to verify in the field as these slopes exceeded the normal threshold for maximum grades for forest roads which is 22%. These measurements were done by having one person hold the Vertex Laser Geo Hypsometer at the bottom of the segment of road aiming uphill, while a second person stood at the top. The second person was used as a target to keep the measurements level with the ground while the shot was being taken.

The Vertex Laser Geo Hypsometer was also used to collect road widths for the secondary road. This was done by standing on one edge of the road, and taking a measurement aimed at the other road edge. The Vertex Laser Geo Hypsometer would then provide measurements such as the slope distance as well as the horizontal distance. For the primary road, road widths were also recorded however it was possible to setup a GNSS base station using the Emlid Reach RS2+ antenna and take measurements using an Emlid Reach M2 module as rover. For this survey, a section of roughly 550 metres was chosen for its proximity to the base station and lack of tree canopy. Points were shot and recorded on both sides of the road every 15-20 metres throughout this section.

3.0 Results

Results for this project have been divided into three sections. Firstly, the results of the road alignments created in RoadEng Location. Each of these alignments were also modelled in 3D using RoadEng Location. Secondly, the haul volumes and costs of the connections. Finally, the comparisons done concerning fuel consumption and CO_2 Emissions.

3.1 Field Data

Slope measurements were taken facing uphill from the points shown in Figure 3.1.

Figure 3.1: Primary Road Slope Measurement Locations

Table 3.1: Primary Road Slope Comparison Between Observed Values in the Field and Model

Point Number	Observed Slope (%)	Average Modelled Slope (%)
1	21.5	25.0
2	22	22.8
3	19.7	19.8
4	23.4	19.3
5	17.9	21.5
6	18.8	21.5
7	25.5	19.8
8	20.5	19.2
9	33.1	27.0
10	26.5	22.0

During the field visit, a roughly 550-metre section of the primary road was surveyed (Figure 3.2) to obtain an average road width as verification that what was in the field matched the information that had been provided. This was done by setting up the Emlid Reach RS2+ as a base station and using the Emlid Reach M2 as a rover. A total of 64 points were recorded, resulting in 32 pairs as shown in Figure 3.3.

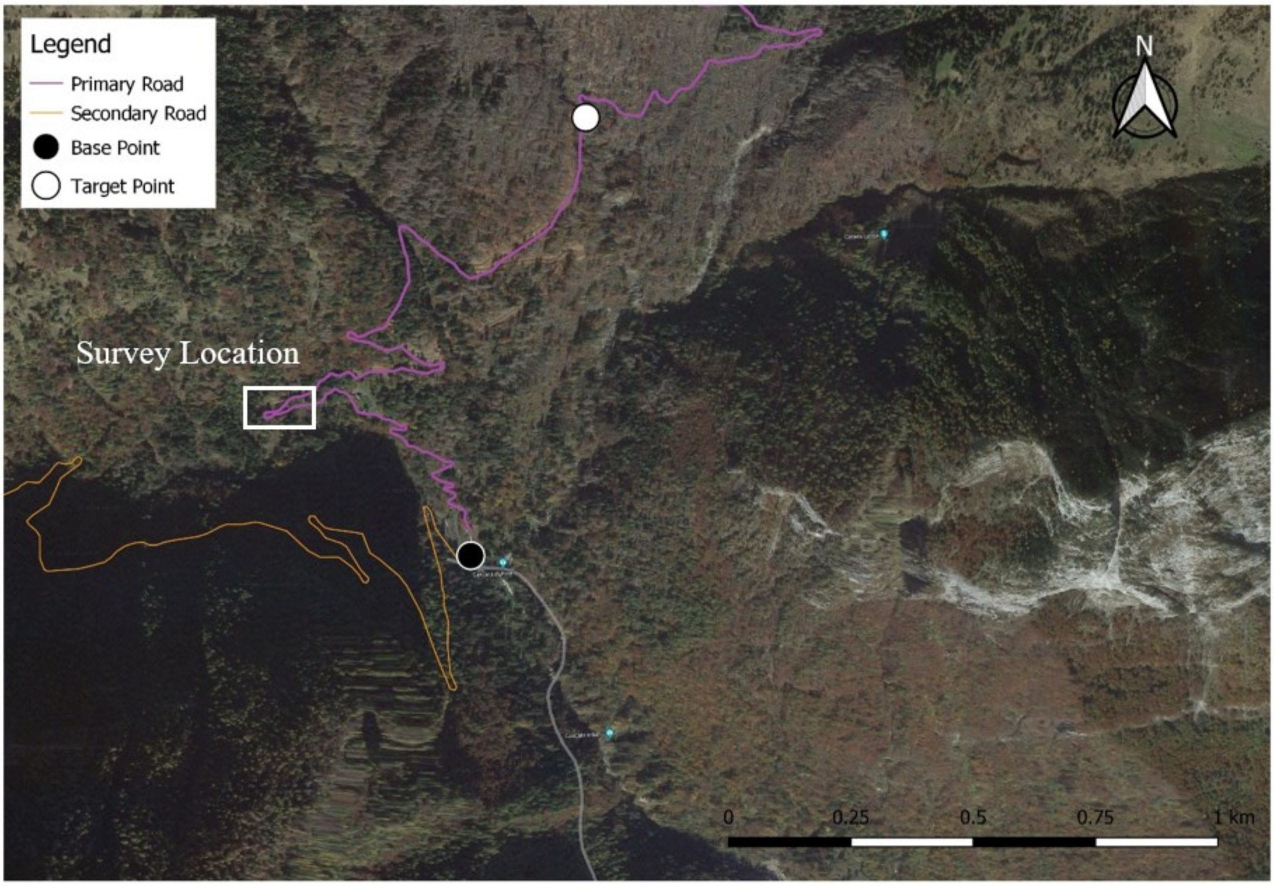

Figure 3.2: Road Width Survey Location for the Primary Road

Figure 3.3: Primary Road Survey Points

The average road width including the three pairs of points at the switchback where the roadway widens is 3.55 metres. The average road width without the wider switchback pairs included is 3.24 metres.

During the field visit, measurements were taken at the base of the secondary road as it was the most difficult to determine for a consistent width using solely the model. In the field however, it was evident that the secondary road was more consistent in its road width than the primary road, slope observations were also taken on the secondary road while in the field which are shown in Figure 3.4.

Figure 3.4: Secondary Road Slope Measurements (Red) and Width Measurements (Blue)

Table 3.2: Secondary Road Width Observations and Average

Point Number	Road Width (m)
1	3.2
2	3.9
4	4.0
5	4.0
7	3.3
Average	3.68

Table 3.3: Secondary Road Slope Comparison Between Observed Values in the Field and Model

Point Number	Observed Slope (%)	Average Modelled Slope (%)
3	13.2	9.8
6	10.4	9.2

3.2 Road Alignments

Results of the horizontal alignments and 3D models of all roadways are shown in Figures 3.5-3.12.

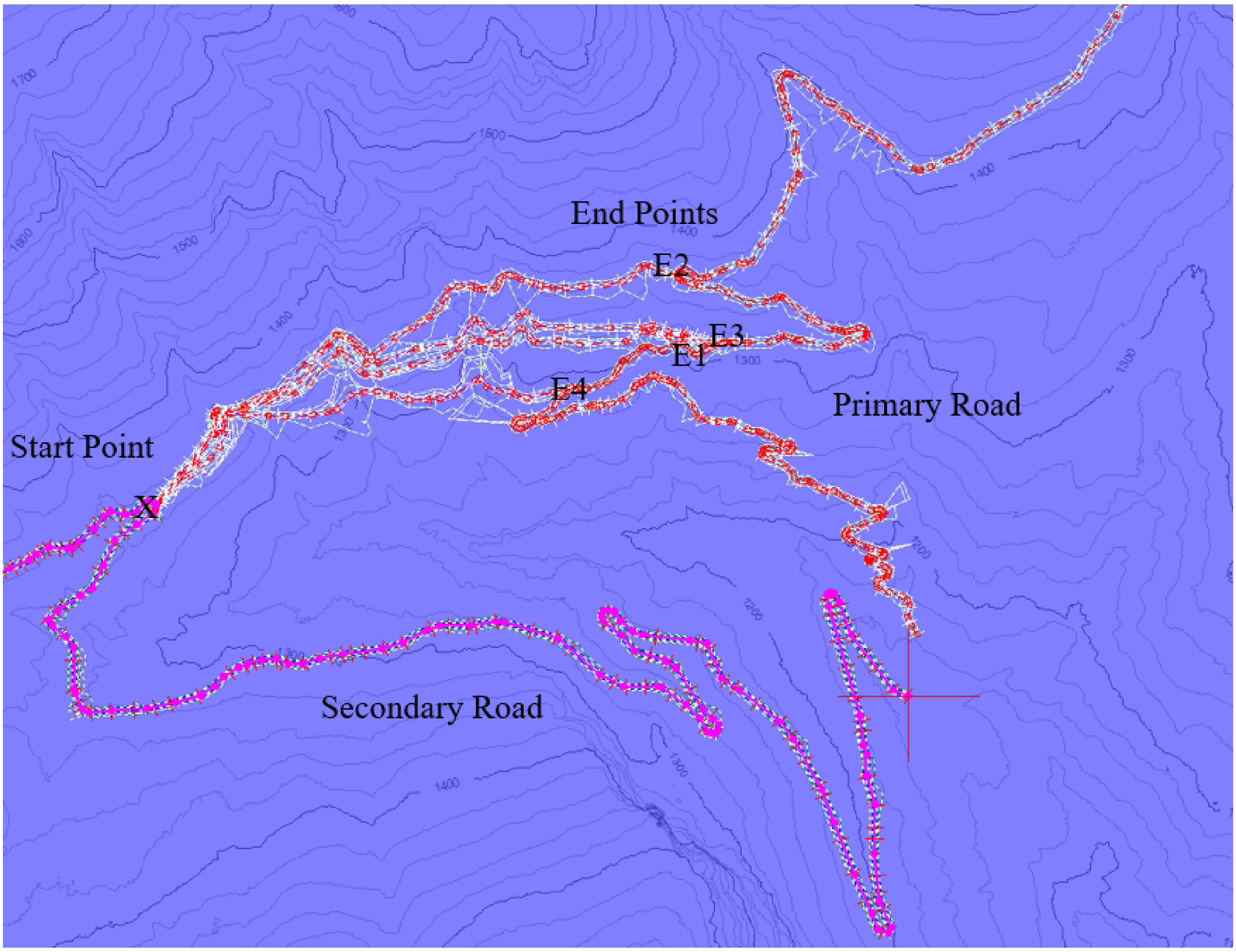

Figure 3.5: Horizontal Alignments of the primary road, secondary road and four connections

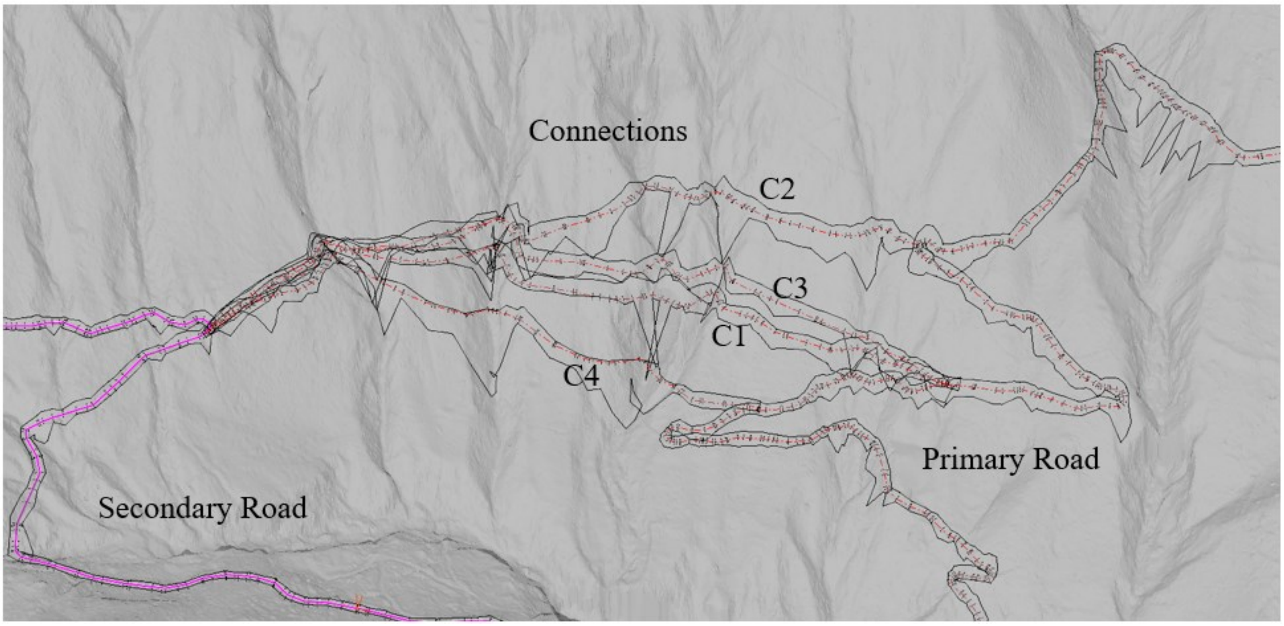

Figure 3.6: Horizontal Alignments of the Primary Road, Secondary Road and Four Connections in 3D

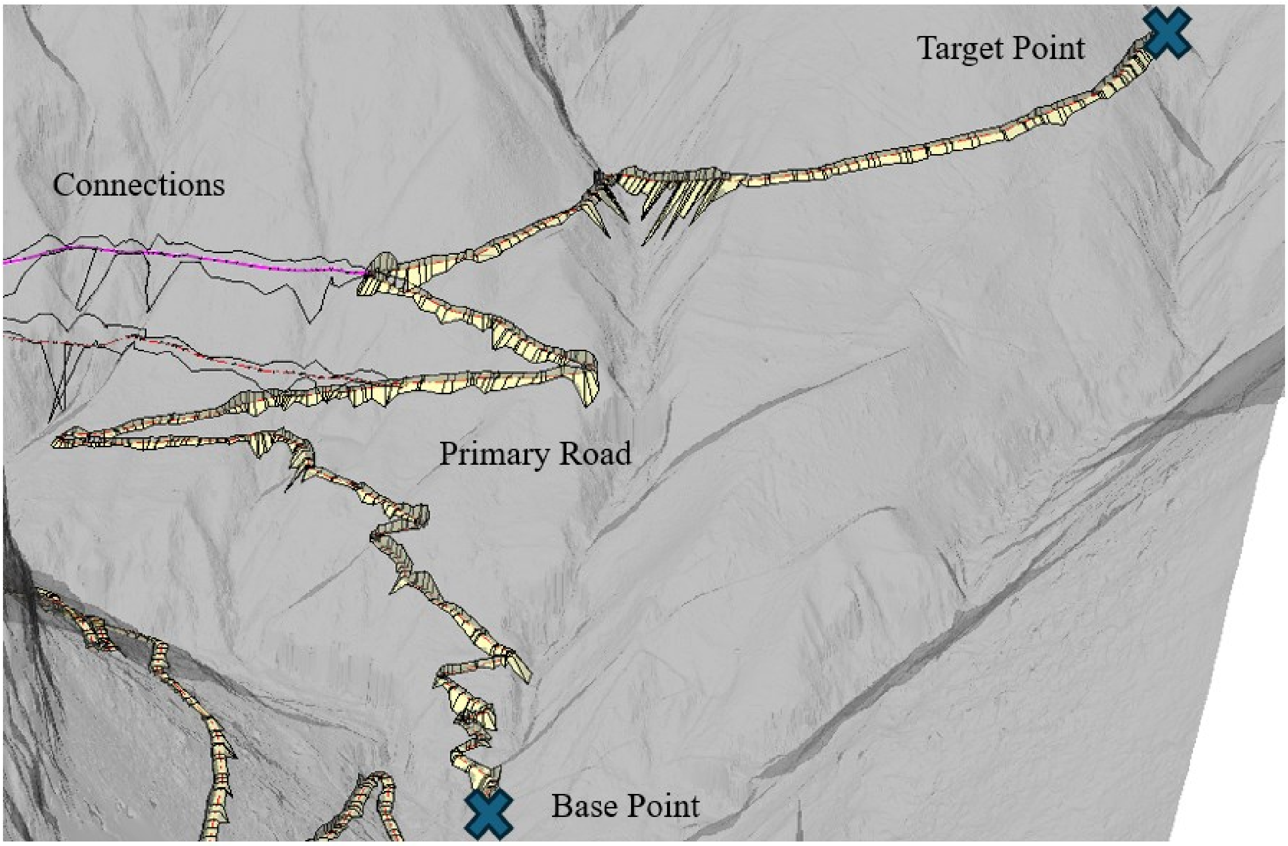

Figure 3.7: 3D Model of the Primary Road

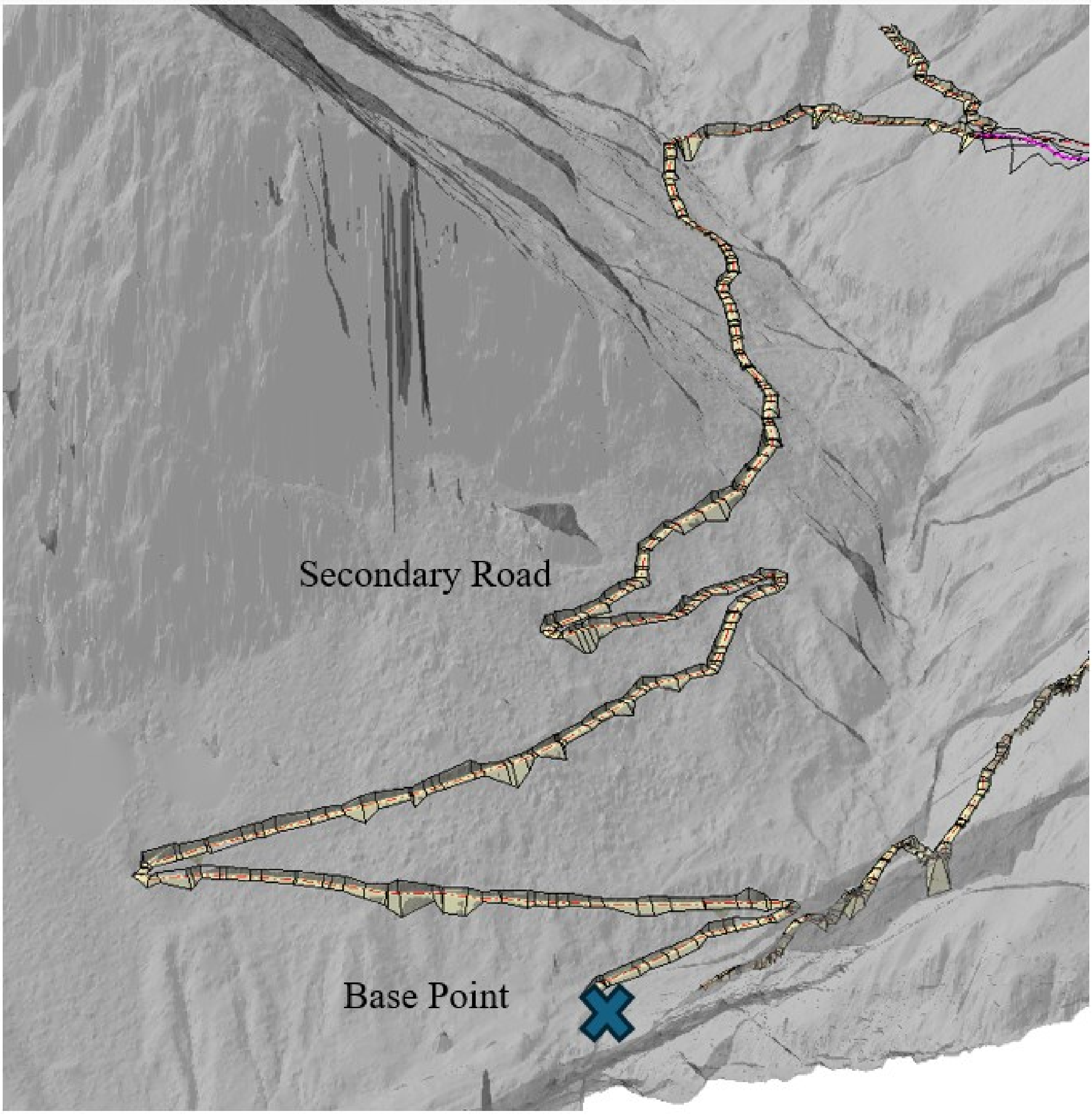

Figure 3.8: 3D Model of the Secondary Road

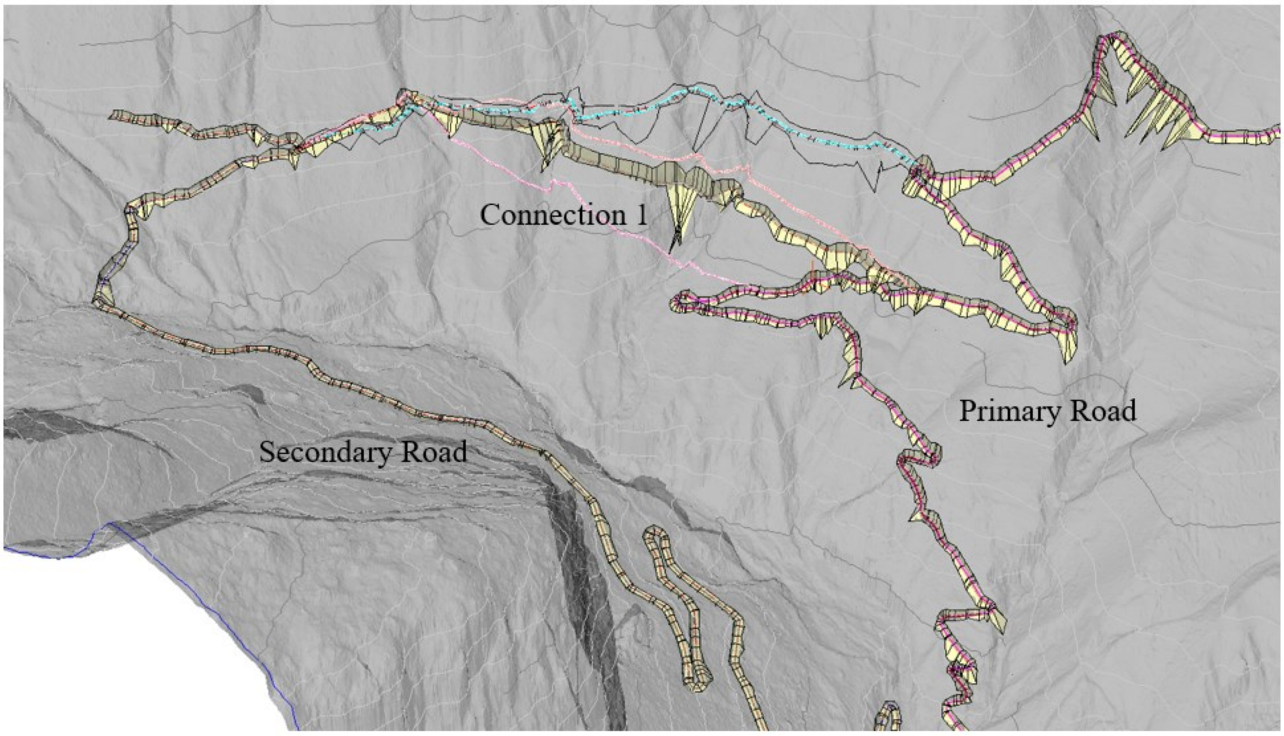

Figure 3.9: 3D Model of Primary Road, Secondary Road and Connection 1

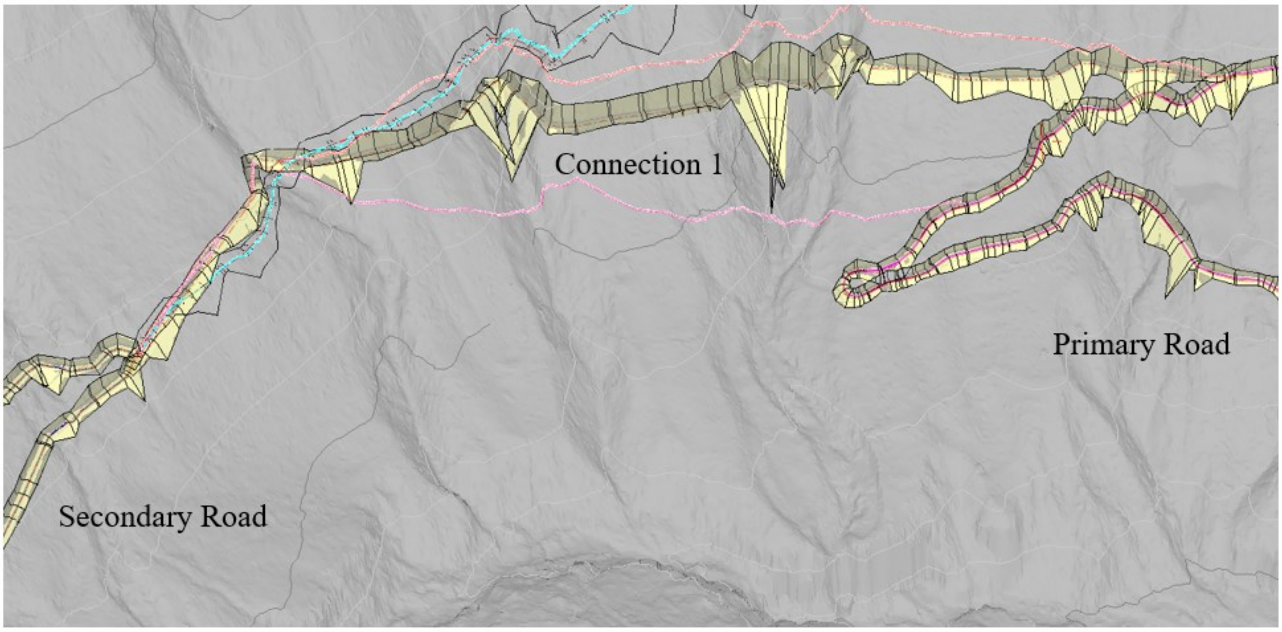

Figure 3.10: 3D Model of Connection 1

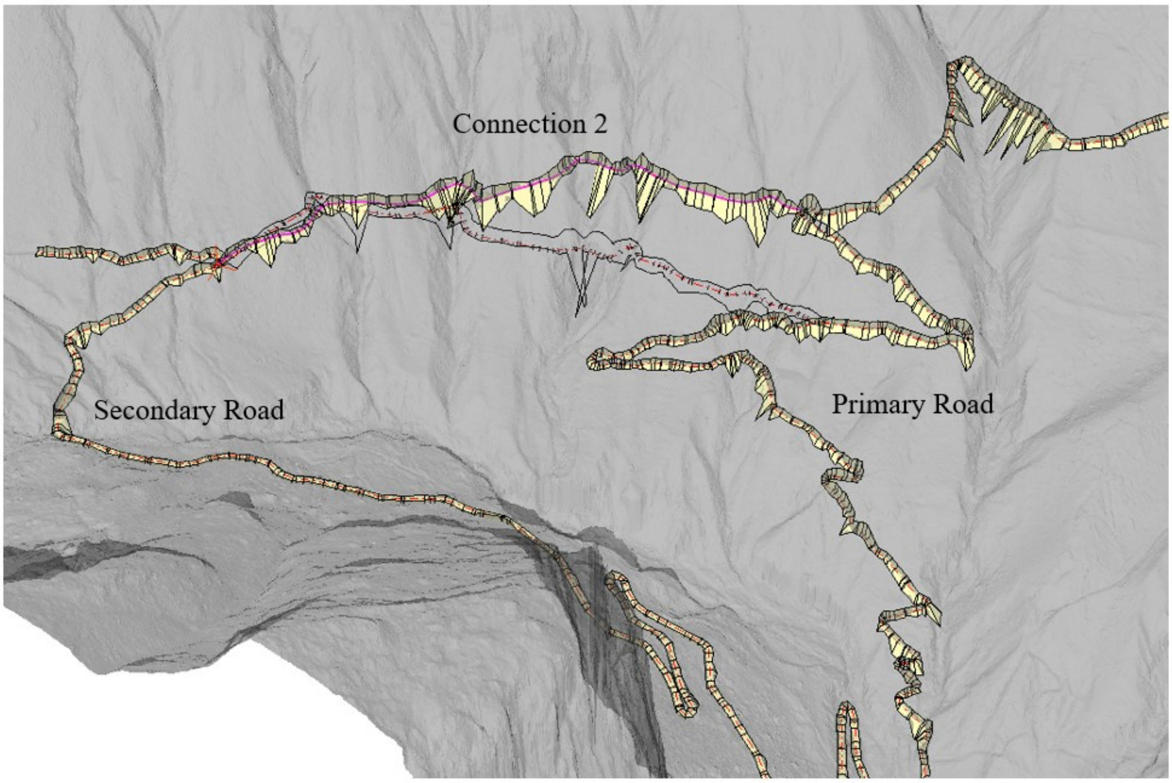

Figure 3.11: 3D Model of Primary Road, Secondary Road and Connection 2

Figure 3.12: 3D Model of Connection 1

3.3 Haul Volumes and Cost

After creating road alignments for four possible connections between the secondary and primary roads, it was determined that only two of the four were viable options. Connections were determined not to be viable due to not being able to sufficiently balance the connections, which then contained excess haul volumes, significantly increasing their cost as well as grades exceeding the maximum allowed of 22%.

It was possible to successfully balance connection 1 (Figures 3.13-3.14), while keeping all the road segments at an acceptable grade. Table 3.4 shows a break down of the Haul volumes for connection 1, as well as a cost breakdown for the road alignment calculated in USD.

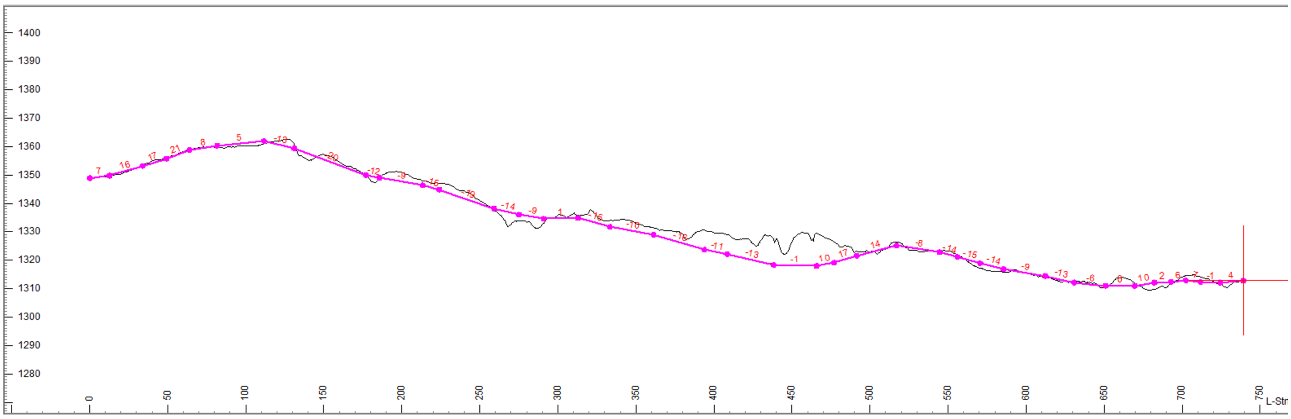

Figure 3.13: Connection 1 Longitudinal Profile

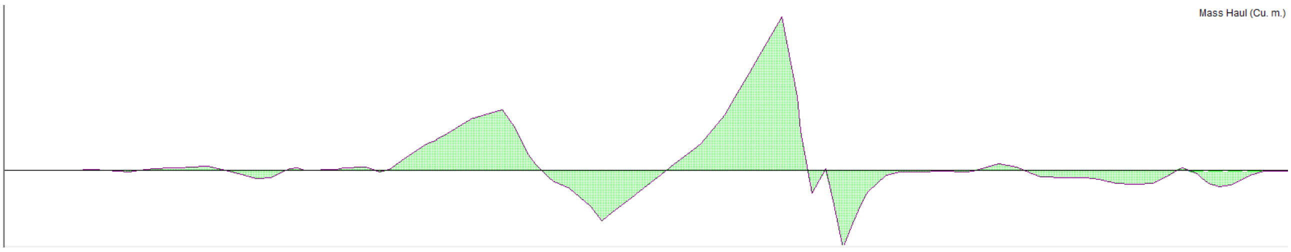

Figure 3.14: Connection 1 Haul Volume Profile

Table 3.4: Connection 1 Cost Breakdown (USD) & Haul Volumes

Road Alignment	Connection 1
Freehaul Volume (cu. m.)	13788.4
Overhaul Volume (cu. m.)	0
Endhaul Volume (cu. m.)	0
Haul Cost (1000's $)	2.46
Fill Cost (1000's $)	55.15
Cut Cost (1000's $)	165.46
Total Cost (1000's $)	223.07

Connection 2 was also able to have its haul volumes balanced successfully, removing the presence of any overhaul (Figures 3.15-3.16), waste or borrow. Table 3.5 shows a break down of the Haul volumes for connection 2, as well as a cost breakdown for the road alignment calculated in USD.

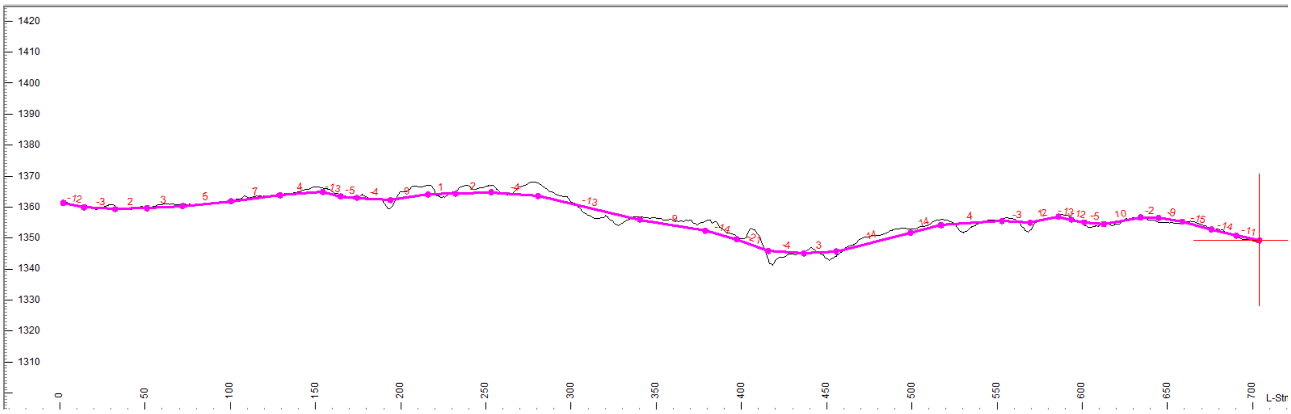

Figure 3.15: Connection 2 Longitudinal Profile

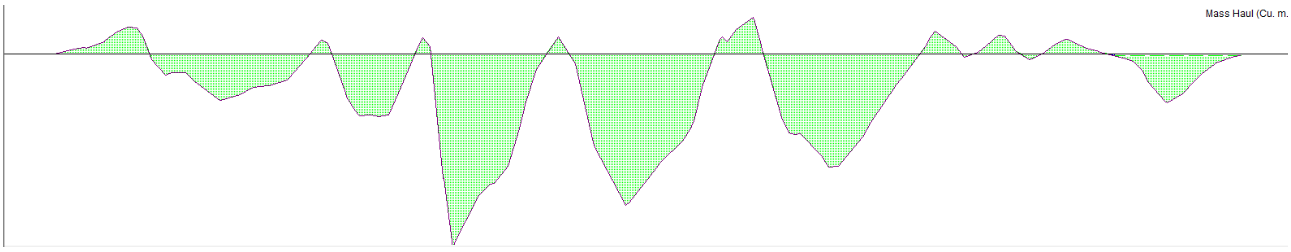

Figure 3.16: Connection 2 Haul Volume Profile

Table 3.5: Connection 2 Cost Breakdown (USD) & Haul Volumes

Road Alignment	Connection 1
Freehaul Volume (cu. m.)	8524.0
Overhaul Volume (cu. m.)	0
Endhaul Volume (cu. m.)	0
Haul Cost (1000's $)	1.46
Fill Cost (1000's $)	34.10
Cut Cost (1000's $)	102.29
Total Cost (1000's $)	137.85

3.4 Fuel Consumption and CO2 Emissions

Fuel consumption rates were calculated for each road alignment. The following tables (Tables 3.6-3.9) contain the fuel consumption for each vehicle, both uphill and downhill. Fuel consumption rates for trucks were also calculated for the primary road (Table 3.6), as well as every other alignment, however this road is not suitable for these vehicles and so this was simply for comparison.

Table 3.6: Primary Road Fuel Consumption

Vehicle	Fuel Consumption Uphill (L)	Fuel Consumption Downhill (L)
2012 Ram 1500	0.469	0.392
Scania R 520	0.929	0.777
Volvo FH16 750 8x4	1.095	0.916
International Model 20 (t)	1.014	0.847
International Model 40 (t)	1.946	1.627

Table 3.7: Secondary Road Fuel Consumption

Vehicle	Fuel Consumption Uphill (L)	Fuel Consumption Downhill (L)
2012 Ram 1500	0.462	0.408
Scania R 520	0.916	0.810
Volvo FH16 750 8x4	1.080	0.954
International Model 20 (t)	0.999	0.883
International Model 40 (t)	1.918	1.695

Table 3.8: Connection 1 Fuel Consumption

Vehicle	Fuel Consumption Uphill (L)	Fuel Consumption Downhill (L)
2012 Ram 1500	0.129	0.138
Scania R 520	0.256	0.274
Volvo FH16 750 8x4	0.302	0.323
International Model 20 (t)	0.279	0.299
International Model 40 (t)	0.536	0.574

Table 3.9: Connection 2 Fuel Consumption

Vehicle	Fuel Consumption Uphill (L)	Fuel Consumption Downhill (L)
2012 Ram 1500	0.126	0.123
Scania R 520	0.249	0.244
Volvo FH16 750 8x4	0.294	0.287
International Model 20 (t)	0.272	0.266
International Model 40 (t)	0.522	0.510

After the road alignments were created, three separate routes were created to be tested. Route 1, using the first connection, route 2 using the second connection and the primary road by itself. These three routes were then compared in a scenario calculating the total fuel consumption and CO2 emissions produced moving 1000 tonnes of material. Due to steep grades and tight switchbacks on the primary road it is impossible for haul trucks to navigate the road, requiring a tractor and trailer. Calculations regarding the primary road were done using two separate tractor models, the New Holland T5110 and the Valtra N Series. Both alternative routes could be navigated by haul trucks and so the Volvo FH16 750 8x4 timber truck was chosen for the comparison.

Table 3.10: Primary Road Fuel Consumption 1000 Tonne Test With New Holland Tractor with 2 Hour Trips

Vehicle	New Holland T5110 Tractor
Load Capacity (Tonnes)	14
Total Target Material (Tonnes)	1000
Number of Trips	71.43
Rounded Number of Trips	72
Hours Per Trip	2
Fuel Consumption (L/H)	22
Total Diesel Fuel Consumption (L)	3168
Total CO2 Emissions (Kg)	8553.6

Table 3.11: Primary Road Fuel Consumption 1000 Tonne Test with New Holland Tractor with 1 Hour Trips

Vehicle	New Holland T5110 Tractor
Load Capacity (Tonnes)	14
Total Target Material (Tonnes)	1000
Number of Trips	71.43
Rounded Number of Trips	72
Hours Per Trip	1
Fuel Consumption (L/H)	22
Total Diesel Fuel Consumption (L)	1584
Total CO2 Emissions (Kg)	4276.8

Table 3.12: Primary Road Fuel Consumption 1000 Tonne Test with Valtra Tractor with 2 Hour Trips

Vehicle	Valtra N Series Tractor
Load Capacity (Tonnes)	14
Total Target Material (Tonnes)	1000
Number of Trips	71.43
Rounded Number of Trips	72
Hours Per Trip	2
Fuel Consumption (L/H)	14.5
Total Diesel Fuel Consumption (L)	2088
Total CO2 Emissions (Kg)	5637.6

Table 3.13: Primary Road Fuel Consumption 1000 Tonne Test with Valtra Tractor with 1 Hour Trips

Vehicle	Valtra N Series Tractor
Load Capacity (Tonnes)	14
Total Target Material (Tonnes)	1000
Number of Trips	71.43
Rounded Number of Trips	72
Hours Per Trip	1
Fuel Consumption (L/H)	14.5

Total Diesel Fuel Consumption (L)	1044
Total CO2 Emissions (Kg)	2818.8

Table 3.14: Route 1 Fuel Consumption 1000 Tonne Test with Volvo FH16 750 8x4

Vehicle	Volvo FH16 750 8x4
Load Capacity (Tonnes)	22.87
Total Target Material (Tonnes)	1000
Number of Trips	43.73
Rounded Number of Trips	44
Fuel Consumption Uphill (L)	1.887
Fuel Consumption Downhill (L)	1.70
Total Diesel Fuel Consumption (L)	157.93
Total CO2 Emissions (Kg)	426.41

Table 3.15: Route 2 Fuel Consumption 1000 Tonne Test with Volvo FH16 750 8x4

Vehicle	Volvo FH16 750 8x4
Load Capacity (Tonnes)	22.87
Total Target Material (Tonnes)	1000
Number of Trips	43.73
Rounded Number of Trips	44
Fuel Consumption Uphill (L)	1.71
Fuel Consumption Downhill (L)	1.52
Total Diesel Fuel Consumption (L)	142.20
Total CO2 Emissions (Kg)	383.94

4.0 Discussion

This section will consist of a breakdown of the results obtained during this study and a discussion of their significance. This section will also highlight any limitations encountered during this study or the data used in the study.

4.1 Alignments

A total of four road alignments were successfully completed and modelled, this included the Primary Road, the Secondary Road, as well as two viable options as a connection between the two existing roads.

The primary road had a total length of 2,338.5m with an average slope of 13.36%. While this average slope does not seem overly steep, or treacherous, if only the first section of the primary road is considered before the connection point of either of the suggested roads it is not as navigable. The first section of the primary road has a total length of 540.5m and an average slope of 21.13%, a minimum slope of -10% and is the location of the maximum slope along the whole roadway which is 31%. Considering the absolute maximum allowable longitudinal slope for these forest roads is 22%, an average of 21.13% for over 500m is unacceptable. The primary road was also modelled with a road width of 3m. The average width of the roughly 550m section surveyed was 3.55m, however this included the width of a wider section of the road at the switchback increasing the average. With this small section excluded, the average road width was 3.24m, 24 centimetres larger than the model.

The Secondary Road had a total length of 2,446m with an average slope of 8.61%. The maximum slope of the secondary road is 15% and the minimum slope is 2%. The secondary road has a much more agreeable slope, providing a more gradual increase in elevation accommodating a larger variety of vehicles. The secondary road was modelled with a road width of 4m, the average width of the field survey was 3.68, however some sections of this roadway were becoming overgrown with encroaching vegetation. The field average was 32 centimetres narrower than the model.

Of the four originally investigated connections between the primary and secondary roads, two were selected as being viable and to undergo further analysis. Of the two, connection 1 was the longest with a total length of 739.2m, an average slope of -4.35%, a maximum slope of 21% and a minimum slope of -20%. The average slope for this connection is negative as the connection starts at a higher elevation along the secondary road compared to where it connects to the primary road, a difference in elevation of 36.1m.

Connection 2 is the second option chosen as the possible connection between the primary and secondary roads. It has a total length of 703.9m, an average slope of -2.34%, a maximum slope of 14% and a minimum slope of -21%.

Comparing the two connections between themselves, Connection 2 has a shorter overall distance, as well as a smaller average slope and smaller maximum slope. However, connection 2 has a slightly steeper minimum slope.

With the addition of the connections, it was possible to now create new routes to the top of the primary road. These routes consisted of Route 1, Route 2 and the Primary Road itself.

Route 1 used the secondary road, connection 1, and the primary road to create a new path to the top of the primary road. Route 1 had a total length of 4274m, an average slope of 7.69%, a maximum slope of 21% and a minimum slope of -20%. Route 1 also requires a total of 13788.4 cubic metres (m^3) of Freehaul and costs a total of $223,070 USD.

Route 2 used the secondary road, connection 2, and the primary road to create a new path to the top of the primary road. Route 2 had a total length of or 3869m, an average slope of 6.80%, a maximum slope of 19% and a minimum slope of -21%. Route 2 also requires a total of 8524.0 cubic metres (m^3) of Freehaul and costs a total of $137,850 USD.

Comparing the two routes with each other, route 2 has a shorter length, a lower average slope and a lower maximum slope. It does however have a slightly steeper minimum slope. Comparing the routes with the primary road itself, route 2 still has the lowest average slope, as well as the lowest maximum slope. The primary road is the shortest route overall and has the lowest minimum slope at -10%.

4.2 Fuel Consumption and CO2 Emissions

To perform an analysis on all three of the routes, fuel consumption rates and CO2 emissions were calculated for several different vehicles. The main comparison was to calculate total fuel consumption and CO2 emissions for a scenario in which 1000 tonnes of material was to be hauled from the top of the primary road to the base, using the three different routes. Due to the steepness of the primary road, and tight switchbacks a haul truck such as the Volvo FH16 750 could not navigate this route and so for a realistic comparison a tractor trailer combination was used for this route. This was done to determine whether there was any benefit in constructing these connections, to allow larger more efficient haul trucks access to the forest resources located at the upper reaches of the primary road.

Table 4.1: Route 1 Results 1000 Tonne Comparison

Route	1
Vehicle	Volvo FH16 750 8x4 Timber Truck
Total Material Hauled (Tonnes)	1000
Total Fuel Consumption Diesel (L)	157.93
Total CO2 Emissions (Kg)	426.41

Table 4.2: Route 2 Results 1000 Tonne Comparison

Route	2
Vehicle	Volvo FH16 750 8x4 Timber Truck
Total Material Hauled (Tonnes)	1000
Total Fuel Consumption Diesel (L)	142.20
Total CO2 Emissions (Kg)	383.94

Table 4.3: Primary Road Results 1000 Tonne Comparison

Route	Primary Road
Vehicle	Valtra N Series
Total Material Hauled (Tonnes)	1000
Hours per Trip (h)	1
Total Fuel Consumption Diesel (L)	1044
Total CO2 Emissions (Kg)	2818.8

During the analysis of the primary road, multiple tractors were assessed, and with different assumptions on the length each trip would take, a trip meaning to drive from the base of the route to the top and back. The results using the Valtra N Series tractor with one-hour trips provided the most favourable results for the primary road and will be used to compare with the other routes.

Comparing all three routes, route 2 achieves the most favourable fuel consumption and CO2 rates, at 142.200 liters of diesel consumed, and 383.940 kilograms of CO2 emitted. This is a difference in 15.728 liters of fuel consumed and 42.466 kilograms of CO2 emitted compared to route 2. Compared to the primary road using a tractor trailer combination, 901.8 liters of fuel is saved, and 2434.86 kilograms less CO2 is emitted.

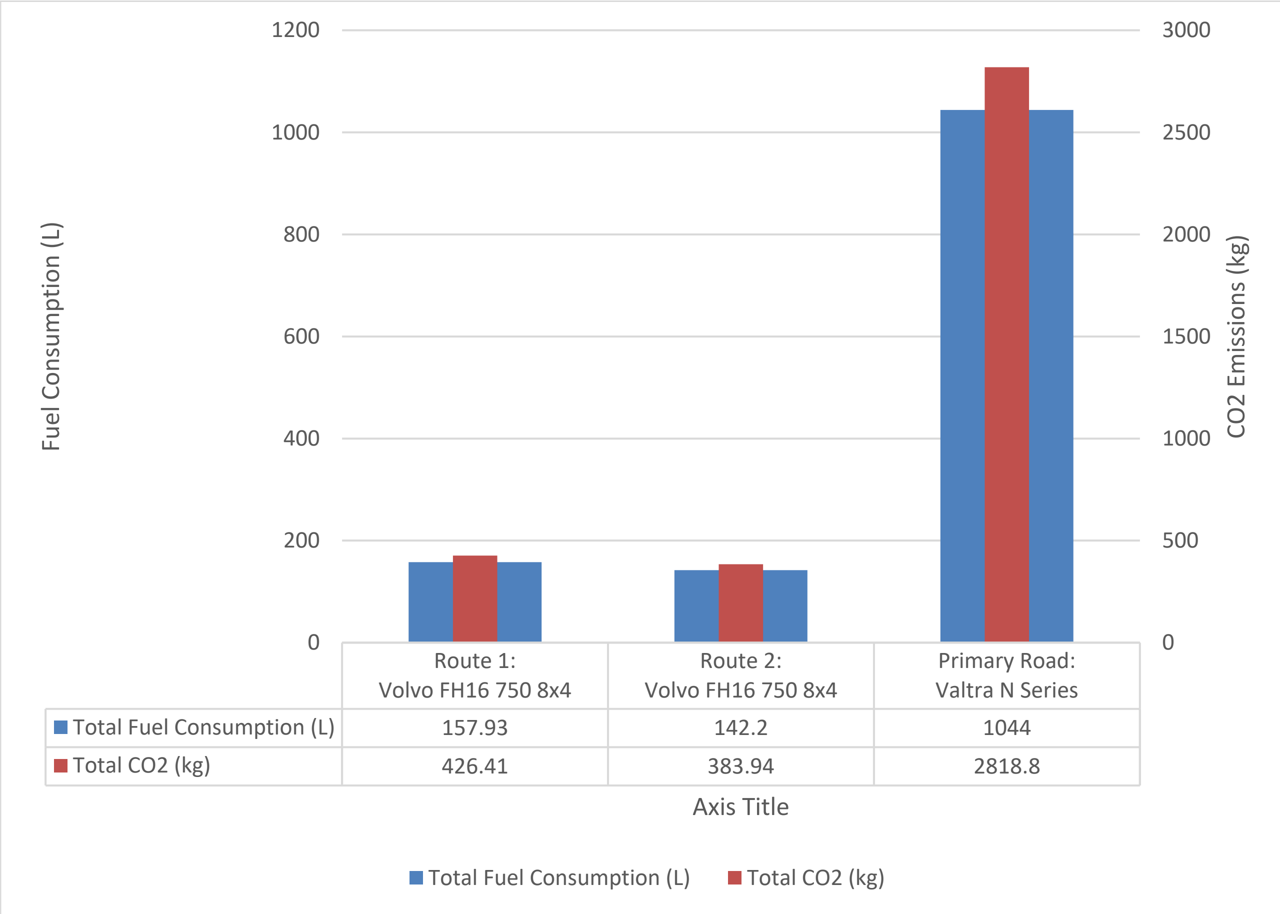

Figure 4.1: Comparison of the Three Possible Routes Fuel Consumption (Blue, Primary Y-Axis, Left) and CO2 Emissions (Red, Secondary Y-Axis, Right)

4.3 Limitations

For a project of this nature, it is important to understand that certain limitations will always be present. The following list details certain inherent limitations as well as assumptions made during this project.

- Fuel consumption rates for many farming and construction related machinery is measured in liters of fuel consumed per work hour or L/H. Due to the tractors for the comparison providing fuel consumption data in this format, it was required to estimate the duration of trips for comparing fuel consumption with the haul trucks. Comparisons were made assuming individual trips would take 2 hours, as well as 1 hour. The accuracy of these assumptions could be affected by multiple factors, many uncontrollable. The duration it takes for a tractor to complete a trip, from base to the end of the route and back, could be influenced by weather conditions, road conditions, idle time, manpower, or whether logs were prepped ahead of time to be loaded.

- Fuel consumption for the haul trucks was also estimated based on values found for each model of vehicle, and it was assumed that these values would provide an enough information to make credible comparisons between road alignments. Fuel efficiency for each vehicle however would likely increase or decrease for a multitude of reasons, like slope of the road, truck load, or even a driver's familiarity with the route. An assumption was made that the fuel consumption would increase between 1-2% per 1% grade increase. A 1.5% multiplier was added for each 1% grade increase for each segment of the road alignments when calculating the total fuel consumption for each vehicle.
- An assumption of the secondary road's width being 4 metres was made, as there was no documentation on its original built width. This assumption was based on the LiDAR data used to create the TIN model. While the project wasn't specifically concerned with the width (cost and haul volumes) of the primary and secondary roadways, and were used as anchors for the possible connections, it is important to create the model as accurately as possible. A full GNSS survey of both roadways would have provided ground truth data for validation however that was outside the scope of this project, and while conducting a field visit, sections of both roads that provided the most uncertainty were targeted for data collection.

5.0 Conclusion

In conclusion, it was possible to successfully model the current road alignments using QGIS as well as the RoadEng 10 suite. Using these alignments, it was also possible to create viable options for connections between the primary and secondary roads within the study area. The main goal of these road alignments was to provide possible solutions for a safer and more affordable method of extraction for forest resources by use of larger and more efficient forest haul trucks. Using these road alignments also allowed for the estimation of the fuel consumption and CO2 emissions these roadways could produce, as well as compare those outputs to those produce by the current methods of extraction.

After comparing the multiple different routes produced, it became clear that Route 2 was by far the most suitable and efficient route tested. This route produced the lowest fuel consumption and CO2 emissions during the 1000 tonne test scenario at 142.2 L of diesel and 383.94 kilograms of CO2 respectively with the Volvo FH16 740 8x4 Timber Truck. These numbers have been influenced by a number of factors, including the shorter length of the route compared to the other possible route, as well as the much more forgiving grades along the route.

Route 2 did not only produce the best fuel consumption rate and CO2 emissions, but it also had the best constructions costs as well for its new connection portion. While it was possible to successfully balance both connection 1 and 2 in terms of their haul volumes, eliminating unnecessary costs on material, ultimately route 2 required less work in its construction. Connection 2 had a total Freehaul volume of 8524.0 Cubic metres. Due to the greater ease in constructing connection 2, the total cost was 137,850$ a difference in cost of 85,220$ compared to connection 1.

Ultimately, should a new connection be built such as connection 2 from this project, a forest haul truck like the Volvo FH16 750 is capable of hauling forest material much more efficiently than a tractor and trailer combination, which is all the current infrastructure can safely support. Even though there would be a significant upfront cost in the construction of this connection, it is something that can maintained and used for many years to come. With this connection a haul truck can move 1000 tonnes and only consume 142.2 liters of diesel fuel compared to the 1044 liters consumed by a tractor hauling the same material. This allows for further development of the industry within the area in a much more efficient capacity.

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7.0 Annexes

Figure 7.1: Primary Road Point 1 Location

Figure 7.2: Primary Road Point 2 Location

Figure 7.3: Primary Road Point 3 Location

Figure 7.4: Primary Road Point 4 Location

Figure 7.5: Primary Road Point 5 Location

Figure 7.6: Primary Road Point 6 Location

Figure 7.7: Primary Road Point 7 Location

Figure 7.8: Primary Road Point 8 Location

Figure 7.9: Primary Road Point 9 Location

Figure 7.10: Primary Road Point 10 Location

Figure 7.11: Secondary Road Point 1 Location

Figure 7.12: Secondary Road Point 2 Location

Figure 7.13: Secondary Road Point 3 Location

Figure 7.14: Secondary Road Point 4 Location

Figure 7.15: Secondary Road Point 5 Location

Figure 7.16: Secondary Road Point 6 Location

Figure 7.17: Secondary Road Point 7 Location