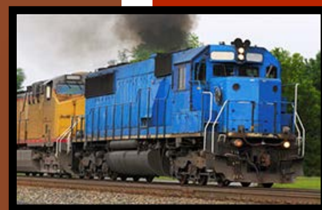
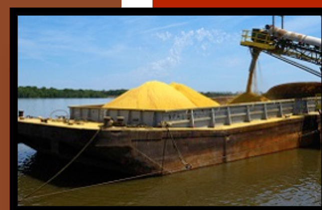
Freight Policy Transportation Insitute





Biomass Inventory Technology and Economics Assessment

Washington State University

FPTI

Biomass Inventory Technology and Economics Assessment

Final Report

FPTI Research Report Number 4

By

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FPTI Research Reports:
Background and Purpose

This is the fourth of a series of reports prepared by the Freight Policy Transportation Institute (FPTI). The reports prepared as part of this Institute provide information to help advance knowledge and analytics in the area of transportation policy. The specific analysis in this fourth report was partially funded by the Washington State Department of Ecology.

FPTI is funded by the United States Department of Transportation (USDOT). Dr. Ken Casavant of Washington State University is Director of the Institute. A Technical Advisory Committee (TAC) comprised of Federal, State and local representatives has been assembled in order to identify relevant and pressing issues for analysis, apply rigorous theoretical and analytical techniques and evaluate results and reports. The TAC includes Jerry Lenzi (WSDOT) as Chair, Ed Strocko (USDOT), Carol Swerdloff (USDOT), Bruce Blanton (USDA), Timothy Lynch (American Trucking Association), Rand Rogers (MARAD), John Gray (AAR) and Daniel Mathis (FHWA – Washington State). The following are key goals and objectives for the Freight Policy Transportation Institute:

- Improve understanding of the importance of efficient and effective freight transportation to both the regional and national economy

- Address the need for improved intermodal freight transportation, as well as policies and actions that can be implemented to lower operating costs, increase safety and lower environmental impacts of freight transportation nationwide

- Improve freight transportation performance to specific industries and sectors of the economy

For additional information about the Freight Policy Transportation Institute or this report, please contact Ken Casavant at the following address:

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1. Simmons, Sara and Ken Casavant. FPTI Research Report #1. "Historical Waterborne Commerce on the Columbia-Snake River System: Commodity Movements Up and Down River, 1991-2010." November 2010.

2. Simmons, Sara and Ken Casavant. FPTI Research Report #2. "Industry Preparations for the Columbia-Snake River Extended Lock Outage, July – December 2010." February 2011.

3. Khachatryan, Hayk, Jeff Poireman, and Ken Casavant. FPTI Research Report #3. "Determinants of Consumer Choice for Biofuels." March 2011.

ACKNOWLEDGEMENTS

The Washington State Department of Ecology provided funding for this project through the Beyond Waste Organics Waste to Resources (OWR) project. These funds were provided in the 2007-2009 Washington State budget from the Waste Reduction Recycling and Litter Control Account. OWR project goals and objectives were developed by the Beyond Waste Organics team, and were approved by the Solid Waste and Financial Assistance Program.

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INTRODUCTION AND BACKGROUND

This report is a component of the research project investigating Washington's bioresources, as part of an agreement between Washington State Department of Ecology, the Department of Biological Systems Engineering and the School of Economic Sciences at Washington State University. As a continuation of the first phase of the Biomass Inventory Technology and Economics Assessments report under the agreement, the Transportation Research Group (TRG) at WSU School of Economic Sciences analyzed economic feasibility of cellulosic ethanol processing using Washington's bioresources. The analyses include investigation of feedstock harvesting, transportation, processing and distribution costs.

Earlier part of the study (Phase 1) had identified field residue, animal waste, forestry residue, food packing/processing and municipal waste categories as potential biomass sources in the state of Washington at a county level. This study expands the previous work by spatially investigating types of available biomass, incorporates transportation costs, geographically varying road infrastructure and hauling distances from biomass sources to prospective biorefineries, as well as distribution costs from biorefineries to markets throughout the state of Washington.

Due to the spatially variable availability characteristic, the total biomass that was identified in the first phase of this project cannot be fully utilized at the same expense. To assess the delivered costs of the feedstocks to biorefineries, the farm-gate price of feedstocks, transportation costs, biomass availability and geographic distribution information were integrated. To evaluate the economically feasible scale of cellulosic ethanol processing, we have also considered the proximity of the processing plants to market locations in the state. For that purpose, we have developed a GIS-based model to support cellulosic ethanol plant least-cost location decisions by integrating delivery market destinations. After testing the model with the National Renewable Laboratory (NREL) data, we used the data compiled in the first phase of this project (Frear et al. 2005). The results emphasize that in addition to biomass-to-biofuel conversion costs, the economic viability of the cellulosic biofuels processing in the state is influenced by feedstock transportation and distribution costs, type of the biomass used as a feedstock, and biorefinery locations.

GOALS AND TASKS

The deliverables of this research include:

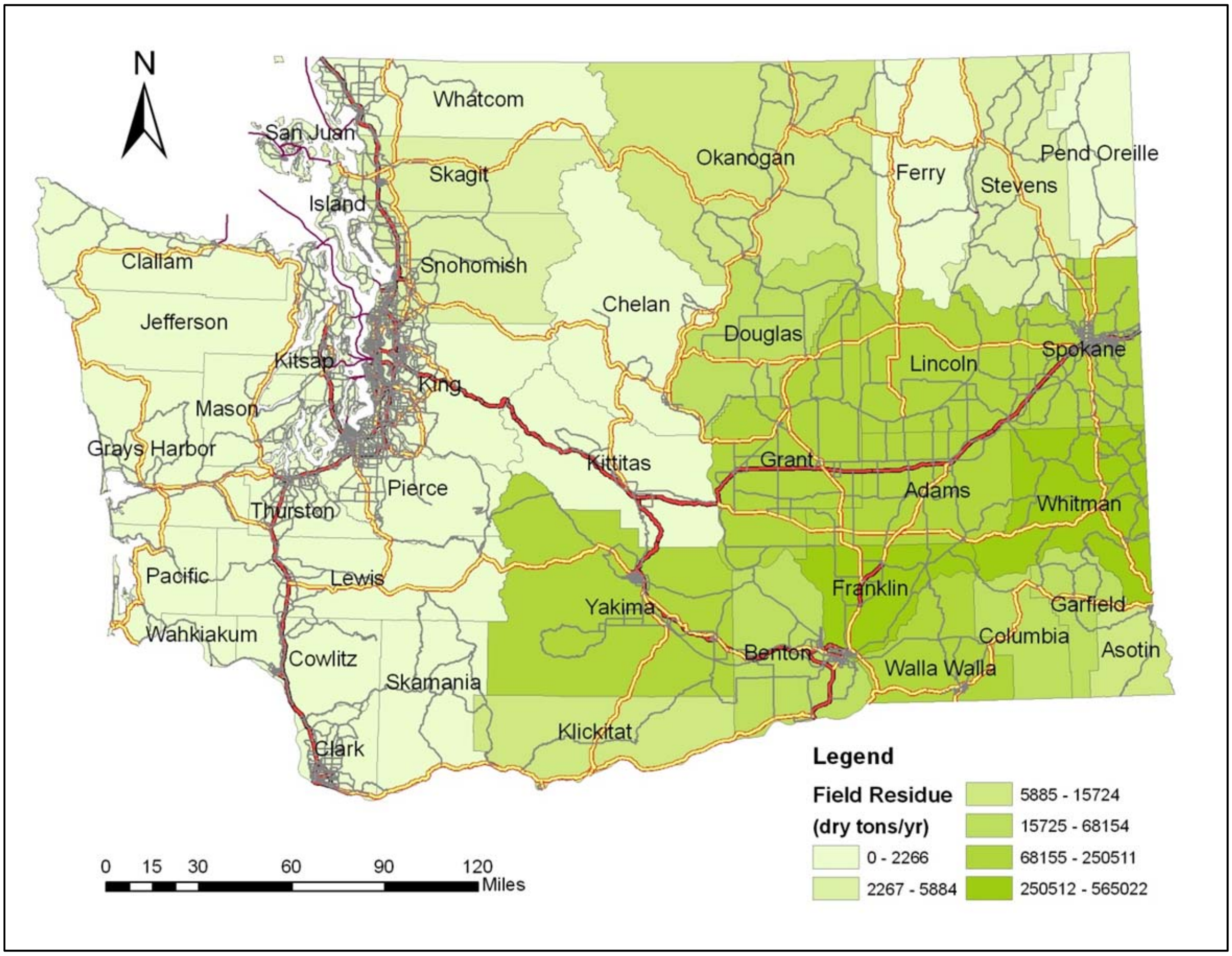
- Derivation of feedstock collection costs for feedstock categories identified in the first phase of the project.
- Development of feedstock supply curves to potential biorefineries in the state.
- Development of GIS spatial overlays to support feedstock transportation and biofuel distribution cost derivations.
- Development of a GIS-based model to support biorefinery optimal location choice decisions.
- Development of a final report to summarize the findings.

METHODOLOGY

<u>GIS Overlays Development</u>

As an initial step for geographically identifying feedstock transportation and distribution cost-minimizing potential refinery locations, the biomass was mapped in relation to the Washington State highway network using GIS. Figure 1 shows the distribution of the crop residue category in relation to the road network. Geographic distributions for the rest of the feedstock categories are provided in the Geographic Distribution of Feedstocks section of the APPENDIX. Considering different harvesting technologies, feedstock collection costs of agricultural crops residue and forest residue were derived. Recovery costs of other sources of biomass, such as animal waste and municipal solid waste (including food waste, paper waste, and wood waste) were adapted from the recent research literature.

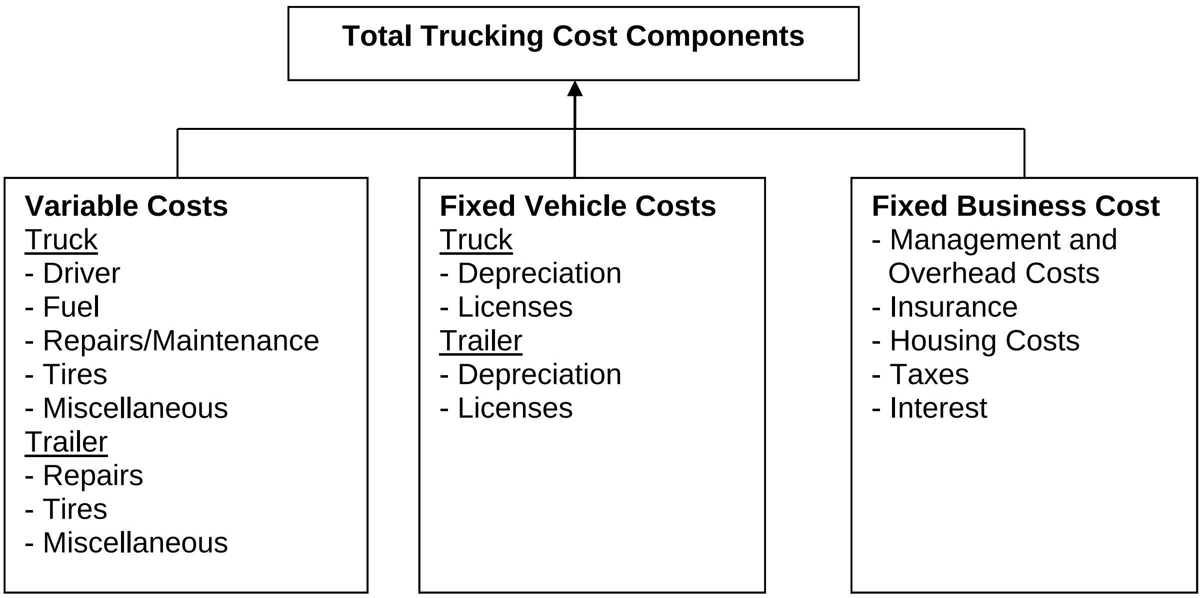
Figure 1: Geographic Distribution of Crop Residue in Relation to the Road Network



Feedstock Transportation Cost Derivation

The derivation of feedstock transportation costs requires information on factor prices that determine costs of a typical trucking firm (Casavant 1993). Per ton mile hauling costs of feedstocks were derived using an economic engineering approach that includes both fixed and variable costs of trucking operation for relevant truck configurations. Total trucking costs (Figure 2) include expenses, such as fixed vehicle costs (truck and trailer, depreciation and license fees, etc.), fixed business costs (management, insurance, interest, etc.) and variable costs (truck – driver wages, fuel, repairs, maintenance, tires, miscellaneous; trailer – repairs, maintenance, tires, miscellaneous).

Figure 2: Total Trucking Cost Components



Further, per ton mile transportation costs were incorporated with feedstock farm-gate costs and haul distances to derive the delivered feedstock costs. With appropriate truck configuration (tanker trailer truck) and hauling origin/destination modifications, trucking costs for ethanol distribution were derived. In the final stage of the investigation, feedstock transportation and processing costs, combined with the distribution costs will allow to derive the delivered cost of ethanol to alternative markets.

Feedstock Collection Costs

Crop Residue

Crop residue collection costs were derived using an economic engineering approach, combined with the survey data by Sokhansanj and Turhollow (2002) and Jenkins et al. (2000). The cost estimates for both large and small rectangular bales are summarized in Table 6. Based on our calculations (Table 6) and the estimates found in the recent literature, in this study the agricultural crop residue is considered to be available at $30 per dry ton farm-gate cost. Detailed discussion is provided in the Agricultural Crop Residue section.

Animal Manure

For purposes in this report, animal waste category includes five different manure categories – dairy, cattle, horse, swine, and poultry. Considering the time sensitivity of feedstock transportation to support consistent ethanol processing, we use dry manure cost estimates (i.e., $11.5 per dry manure) for purposes in this report. For additional information see Animal Waste Feedstock Cost section.

Forest Residue

More than 50% of the five main feedstock types (crop, animal waste, MSW, food packing/processing, and forestry) identified in Frear et al. (2005) is the forest residue category. To derive a cost estimate for analysis in this report, we use spreadsheet-based calculator Forest Residues Transportation Costing Model (FRTCM) developed by Rummer (2005). The resulting estimates were compared with estimates published in the recent literature on economic feasibility of forestry residue collection and transportation.

Graf and Koehler (2000) evaluated the potential for ethanol production in Oregon using cellulosic feedstocks. The study reported the cost of removing and delivering forest thinning to a facility within 50-mile radius to be in a range of $28-40 per dry ton. The estimates were partially based on information provided by private mill owners in Oregon ($28-35 per dry ton), and another source (The Quincy Library Group Study) that estimated the "farm-gate" cost of forest residue to be $40 per dry ton.

In this study, we modified the default values of the RFTCM calculator (Rummer 2005) to derive the cost of moving biomass from the forest to a site from where it can be hauled to a biorefinery. The flexibility of this model allows estimating biomass loading and hauling (to a site) costs for different combinations of equipment. The estimates found to be slightly above $40 per dry ton of biomass, if considering haul distance within 25 miles from the site (i.e., from the "farm-gate"). The second stage of the transportation expenses is included in the feedstock transportation to a biorefinery part.

Municipal Solid Waste

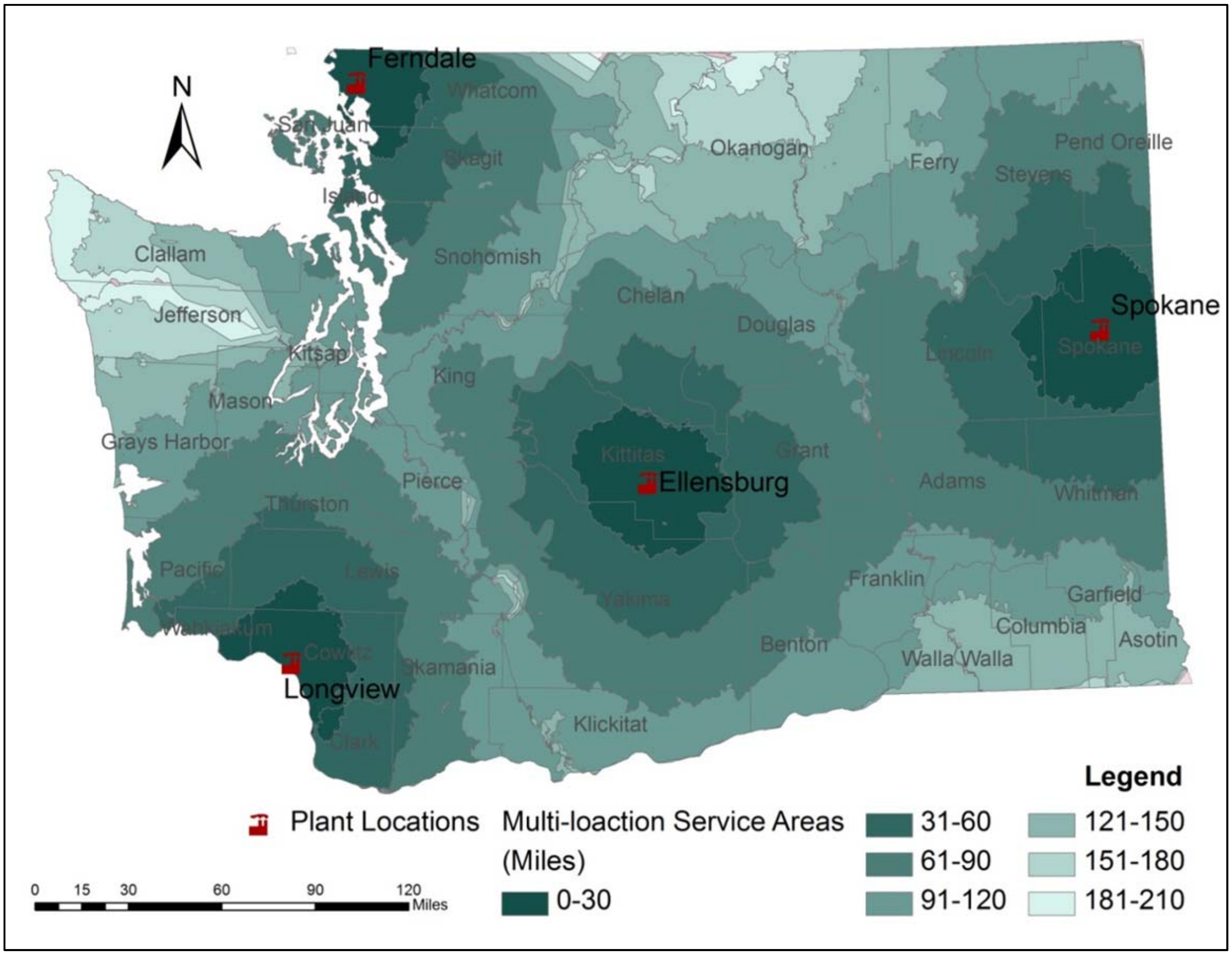
Three types of feedstocks were considered under the MSW category – paper waste, food waste, and wood residue. According to Frear et al. (2005), paper waste category represents about 14% of the total biomass identified in the state. However, food waste and wood residue categories account for only 1.46% and 4.93% of the total respectively. Because of their relatively low volumes, food waste and wood residue categories will be suitable as supplemental feedstocks. For purposes in this study, we assumed that about $25 tipping fee (Graf and Koehler 2000) will be spend on transporting food waste and wood residues to a site (the first stage of transportation expenses). Therefore, in this study the delivered feedstock cost for these two categories includes only the transportation expenses to the biorefinery.

According to Metro Waste Management Division (as reported in Graf and Koehler 2000) the prices for recycled and mixed paper waste ranges from $60-$125 per dry ton. However, the methodology used to calculate the paper waste availability in the state of Washington considered a combination of the percentage of paper in MSW and recyclables (Frear et al. 2005). Therefore, we assume that the "farm-gate" cost of paper to be lower than the estimates found in Graf and Koehler (2000). Several other sources (Baled Waste Paper Spot Market Prices 2009) reported spot market prices in a range of $22.5/$30 (for mixed paper), $69 (baled corrugated cardboard) to over $200 (for soft white paper) per ton depending on its quality. Based on spot market prices and the estimates found in the literature, in this report we consider $45 feedstock price per dry ton of paper waste.

<u>GIS Approach to Delivered Cost of Feedstocks</u>

Feedstock categories included in the investigation have spatially been analyzed with the use of GIS Network Analyst toolset to derive feedstock supply curves to potential biorefinery locations in the state (Figure 3). Using Census feature classification codes (CFCC),[1] speed limits have been assigned to all segments in the GIS roads shapefile (overlay file) to calculate haul distances and drive times to potential biorefinery locations. Different haul distances were used to estimate feedstock availability within each county.

Figure 3: GIS Service Areas for Feedstock Transportation Cost Derivation



Further, the feedstocks' physical availability, farm-gate price, transportation costs (from fields to a biorefinery), including loading/unloading, and geographic distribution (accounting for site-specific road infrastructure) information were combined to derive feedstock supply curves. From each biorefinery in the study area, per ton mile distribution costs have been calculated for ethanol distribution to alternative markets. To determine distribution costs, GIS methodology similar to the feedstock transportation costs was used by incorporating origin (processing plants/blending terminals) and destination (ethanol fueling station locations in the state) data.

<u>GIS Model for Biofuel Plant Least-Cost Location Decisions</u>

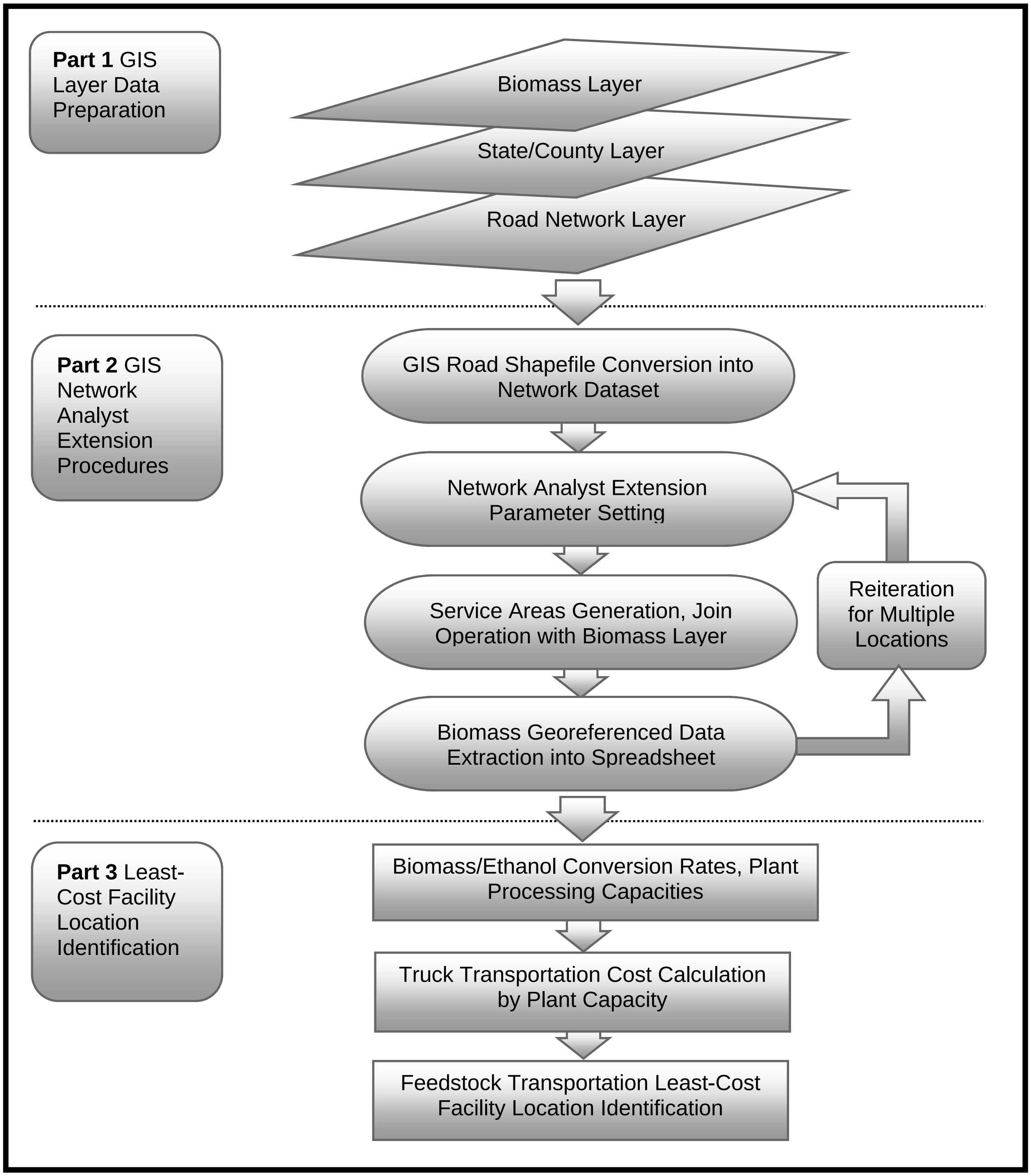
[1] CFCC provides an alphanumeric code for each line feature in the GIS road shapefile. Further, the codes are used to classify roads, railroads, water, and other linear features.

To support cellulosic ethanol plant least-cost location decisions, we developed a GIS-based model that integrates geographic distribution of biomass in the study area with associated transportation costs. The model was first tested using NREL (2007) data. Further, we used the model to analyze the state of Washington biomass data identified in the first phase of this project by Frear et al. (2005).

As an initial step of a multi-factor spatial optimization problem, including both feedstock transportation and ethanol distribution cost, we investigated the influence of feedstock transportation costs on optimal location decisions. To achieve that purpose, the feedstock resources, in this analysis forest biomass and agricultural crop residue, were spatially investigated relative to the road network and potential cellulosic ethanol plant locations in the state of Washington. The flexibility of the model allows spatial manipulation of the data for the least-cost location identifications considering both cumulative (e.g., agricultural crop and forest residue) and separate types of feedstock utilization scenarios. Study results showed that the ethanol plant transportation cost-minimizing location decisions are significantly influenced by the type of the feedstock utilized, and vary depending on the plants' processing capacities.

The GIS-based model consists of three main parts. In turn, each of the parts includes several procedures (Figure 4). The first part builds a dataset by layering GIS shapefiles that are necessary for the analysis in this section.

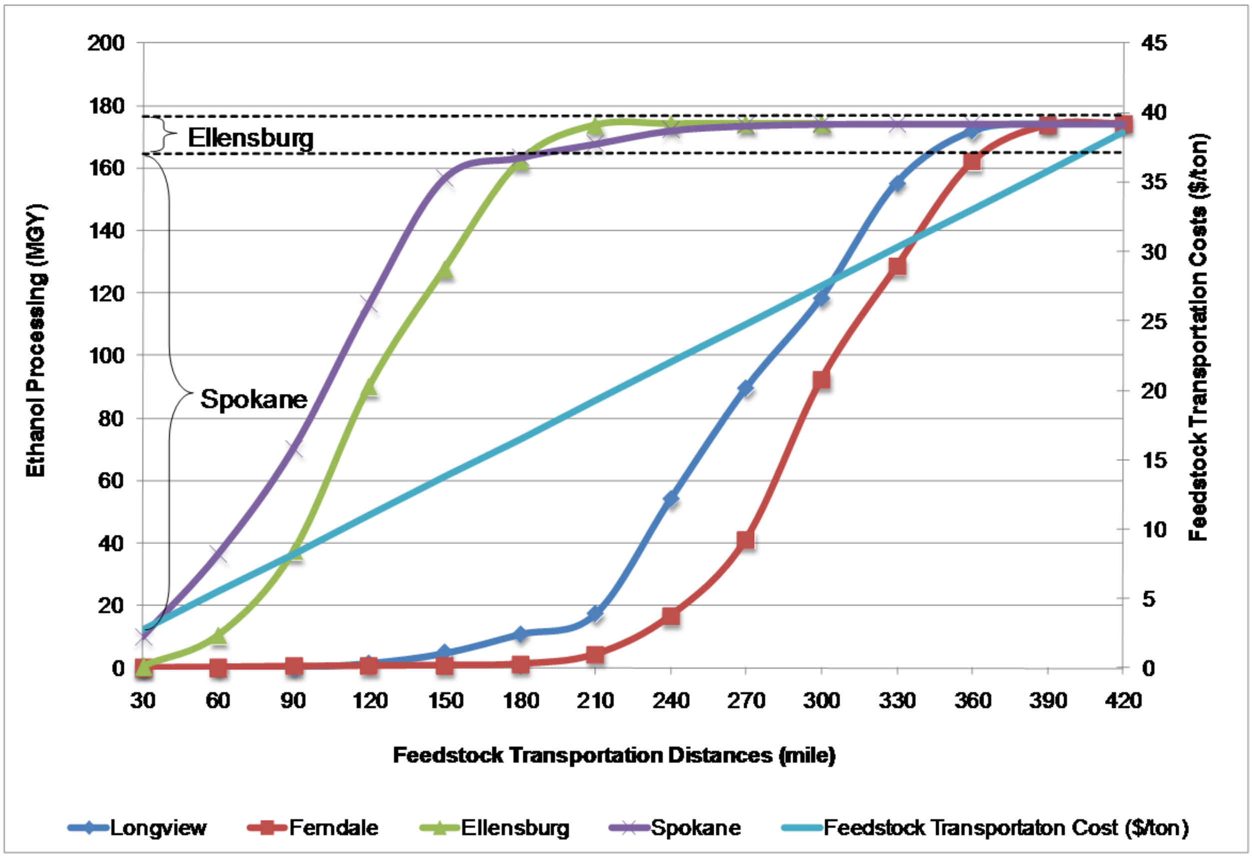
Figure 4: GIS-based feedstock transportation least-cost facility location decision model.



The second part involves GIS Network Analyst extension procedures for creating service area (a shapefile of driving zones) around processing plants included in the study area, as well as for joining and relating that new shapefile (service areas) with existing GIS layers. Reiteration of the procedures is undertaken for each of the processing plant locations. The final part of the model incorporates spreadsheet operations for further analysis with the GIS-generated spatial data. In particular, it links steps in which annual ethanol processing capacities (using biomass-to-ethanol conversion rates) and truck transportation per ton mile costs are derived for the least-cost facility location identification.

Analytical results indicate that transportation costs differ according to the processing plant capacity, since the larger plants require more feedstock to support their production level, hence longer haul distances. Figure 5 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities in million gallons per year (MGY) for the combined agricultural crop residue utilization scenario.

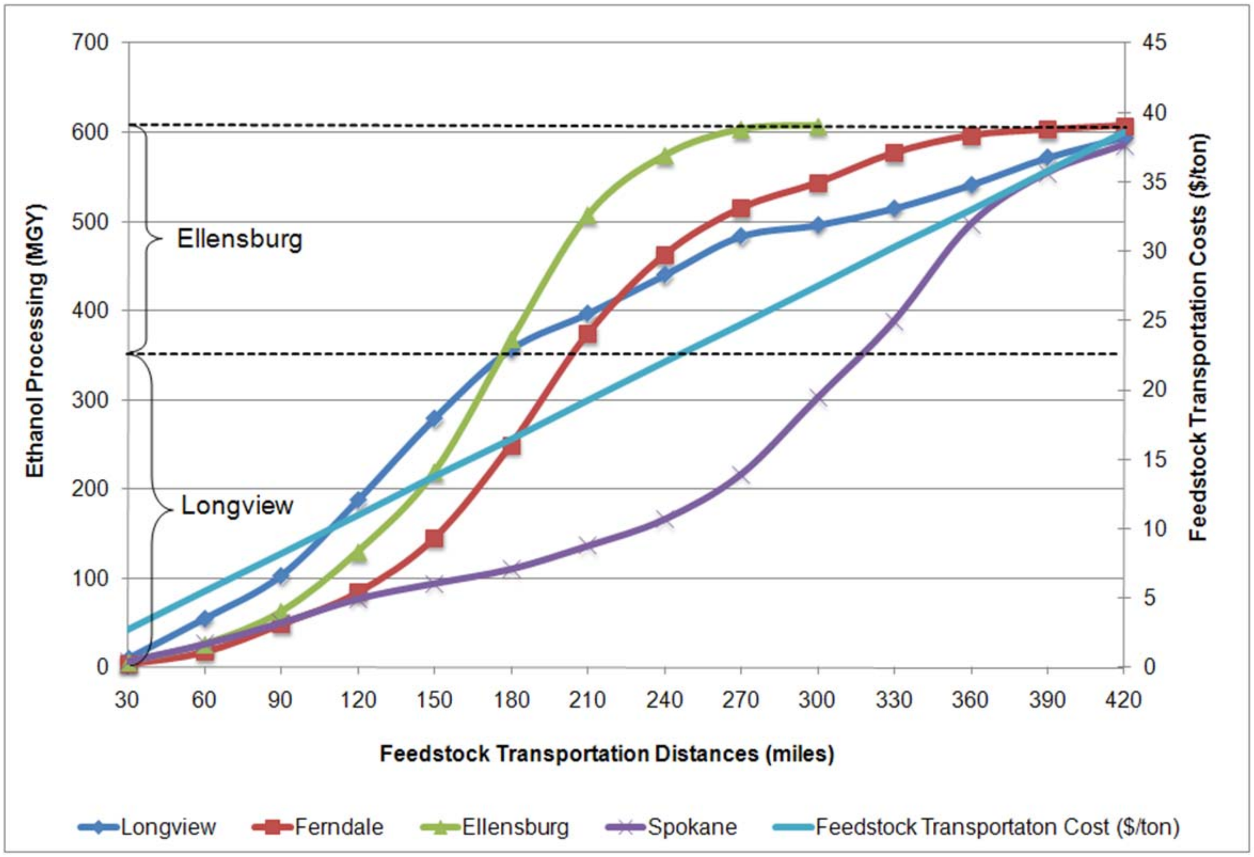
Figure 5: Feedstock Transportation Least-Cost Locations (Crop Residue)



The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to around 165 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within 130 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations will need to reach out almost twice as farther as it is required for the Spokane location.

Depending on the type of the feedstock considered for ethanol processing, feedstock transportation costs differ, since each type has different geographic distributions in the study area. The relationship between forest biomass transportation costs and annual ethanol processing for the same plant locations in the study depicted in Figure 6. The previous location (Spokane) does not necessarily sustain its cost competitiveness when considering forest residue.

Figure 6: Feedstock Transportation Least-Cost Locations (Forest Residue)

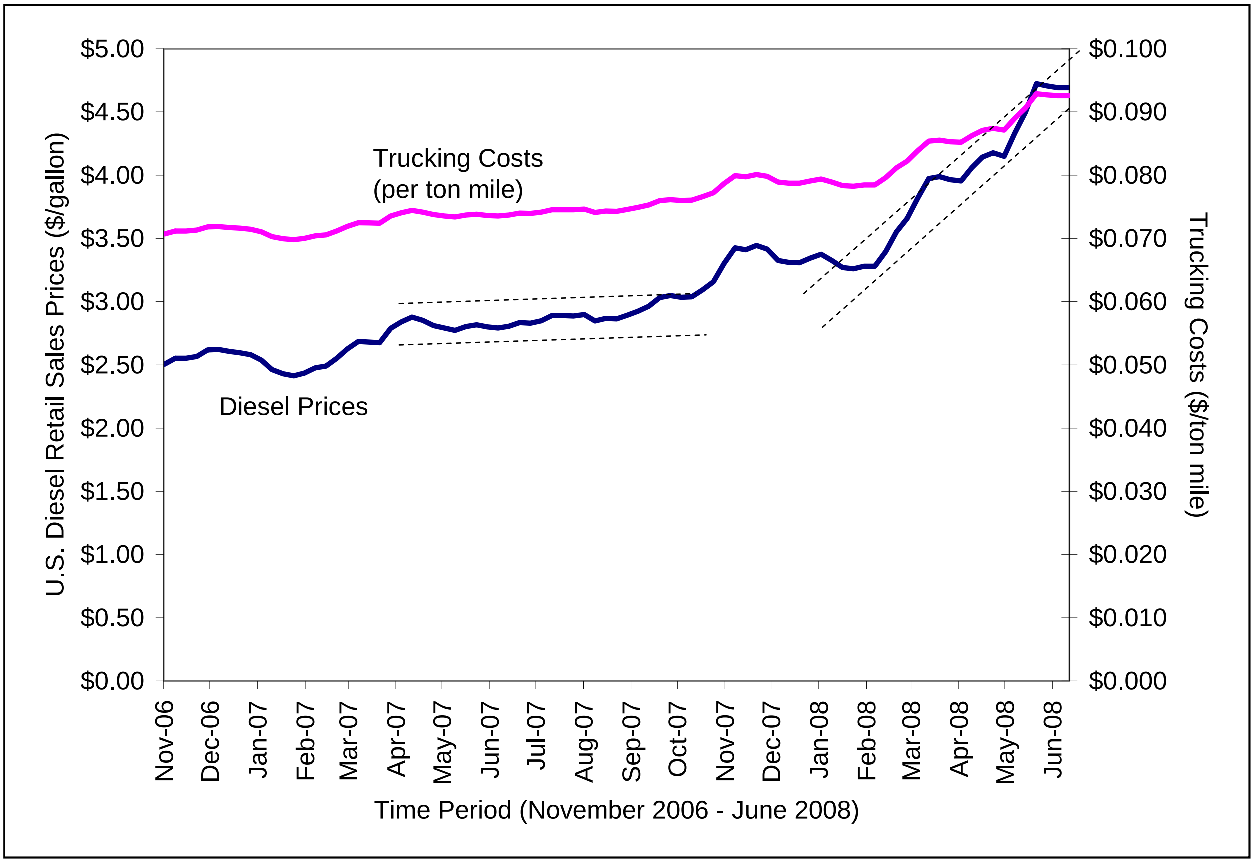


As shown in Figure 6, for the processing capacities up to 350 MGY, the Longview location retains the lowest transportation costs. This level of processing capacity can be supported by transporting feedstocks within 180 miles from the plant. The cost competitiveness results for the rest of the feedstock categories are discussed in the APPENDIX of this report.

<u>Feedstock Cost Sensitivity to Diesel Prices</u>

In addition to delivered feedstock cost sensitivity to farm-gate costs and haul distances, the feedstock costs at the refinery gate are sensitive to diesel prices. Fluctuations in diesel price may influence the feedstock delivered costs, since the fuel costs constitute about 46% of the per ton mile transportation costs. As illustrated in Figure 7, when diesel prices are in a range, as highlighted with dotted lines (Apr-07 through Oct-07), trucking costs stayed at almost the same level.

Figure 7: U.S. Diesel Retail Sales Prices and Trucking Cost Sensitivity

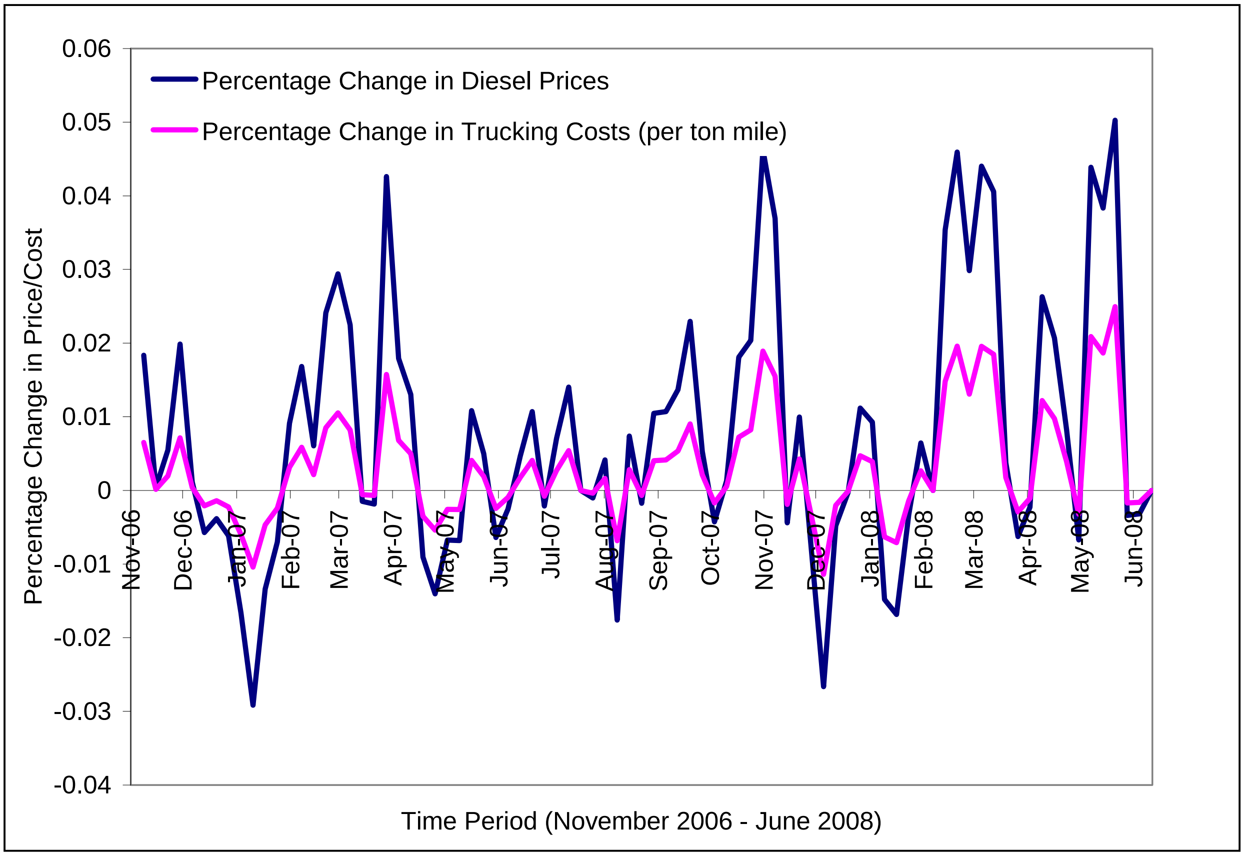


Data Source: Diesel prices were obtained from EIA (2008)b.

However, the chart pattern illustrates that the trucking costs significantly increase as diesel prices form a trend, as highlighted with dotted lines (Jan-08 through Jun-08). Not surprisingly, as illustrated in Figure 8, trucking costs are significantly sensitive to fuel prices, which according to our per ton mile cost calculations take up about 46% of the total transportation per ton mile costs.

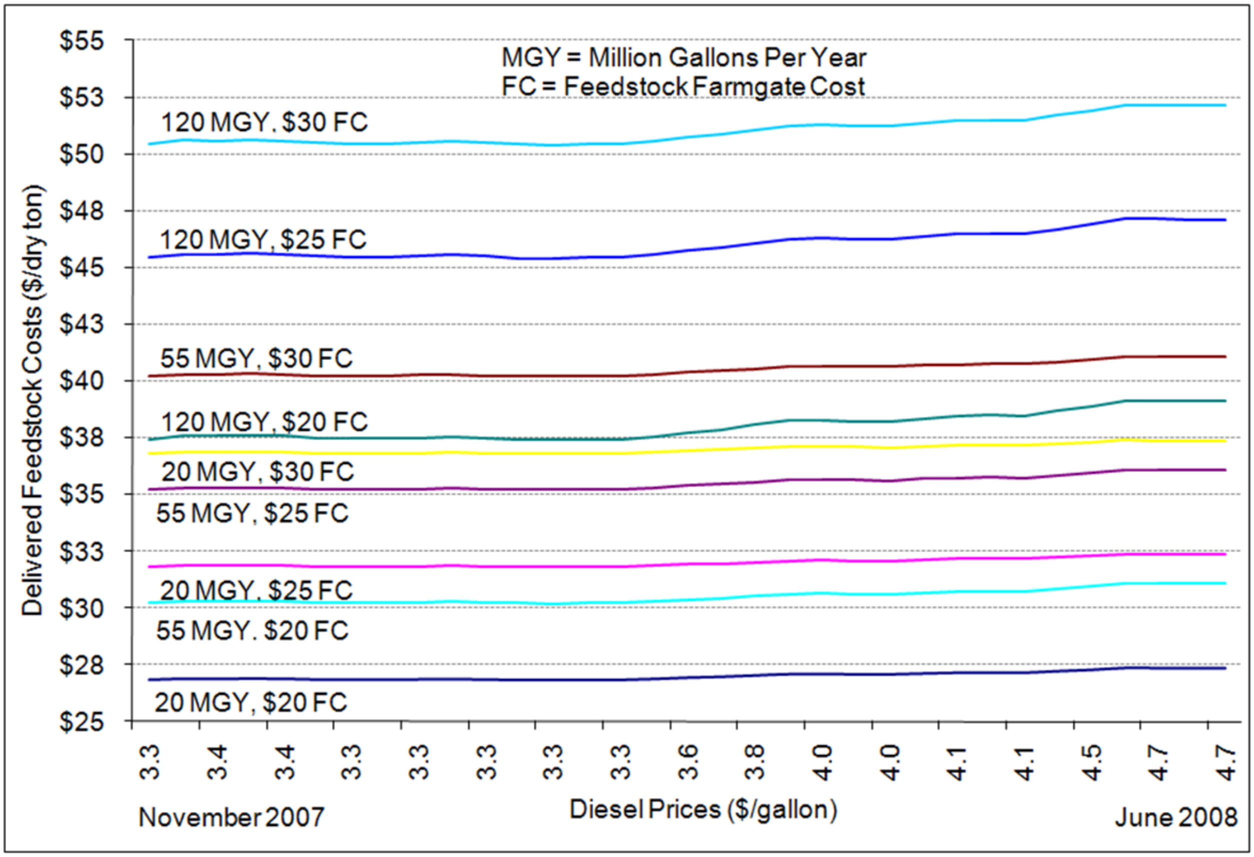
A sensitivity analysis with a range of diesel prices by incorporating different processing plant capacities was used to allow evaluating the delivered feedstock costs in relation to the different ethanol processing plant capacities. Diesel prices from November 2007 to June 2008 (EIA 2008b) were chosen to analyze the variation of feedstock delivered costs with different farm gate costs ($20, $25 and $30) and small, medium and large plant capacities (20 MGY, 55 MGY, and 120 MGY). As shown in Figure 9, small scale processing plants are comparatively less sensitive to diesel price increases in terms of the delivered feedstock costs, for all of the three farm gate cost scenarios.

Figure 8: Percentage Change in Diesel Prices and Trucking Costs



In comparison, the influence of the increasing diesel prices on the delivered feedstock costs for the medium and large processing plants is considerably higher. Particularly, as a result of increasing diesel prices since January 2008 (39% increase from January to June, 2008), the delivered costs of feedstocks for the 55 MGY plant increased by three percent considering $20 farm gate costs, and two percent considering $25 and $30 farm gate costs. Because larger plants involve more transportation activity, the delivered feedstock costs for the 120 MGY capacity plant increased by four percent considering $20 and $25 farm gate costs, and three percent for $30 farm gate cost.

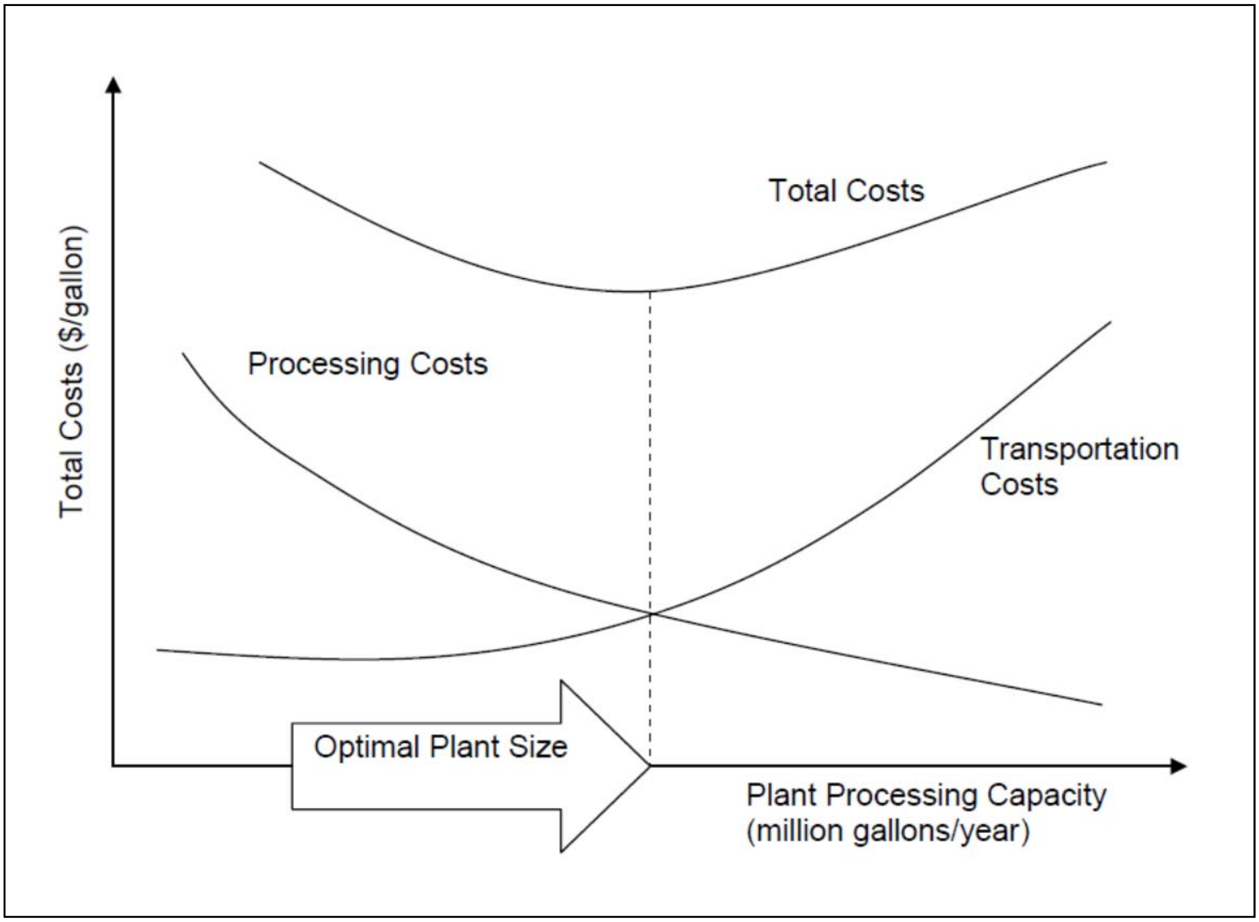
Figure 9: Delivered Feedstock Cost Sensitivity to Diesel Prices



Economies of Scale

The economies of scale refer to the cost advantage as the processing capacity of the plant increases. The higher volume of processing will allow spreading total operational costs over many gallons of final product, thus lowering the total processing costs. However, this cost advantage can be "enjoyed" up to the level where an increasing feedstock transportation costs, required for higher processing volume, can be offset. As shown in Figure 10, per gallon processing costs tend to decrease with increasing processing capacity, since capital and operation expenses are spread over more gallons of processing. Economies of scale are large enough to compensate the increasing feedstock transportation costs up to the processing capacity where the total cost is at its lowest point (shown with an arrow in Figure 10). The lowest point on the total costs curve determines the optimal capacity for the economically feasible ethanol processing. The transportation cost curve includes both feedstock transportation and ethanol distribution segments.

Figure 10: Total Delivered Costs and Processing Plant Optimal Size



Per ton mile transportation costs may differ depending on plant processing capacity, since larger plants require more feedstock to be processed. Cellulosic feedstocks, such as agricultural crop or forest residue are geographically dispersed. Consequently, more feedstock demanded by larger plants requires farther-distance hauling, which consequently increases transportation expenses. Consequently, the tradeoff for the economies in scale in biomass-to-ethanol processing is the increasing feedstock transportation costs.

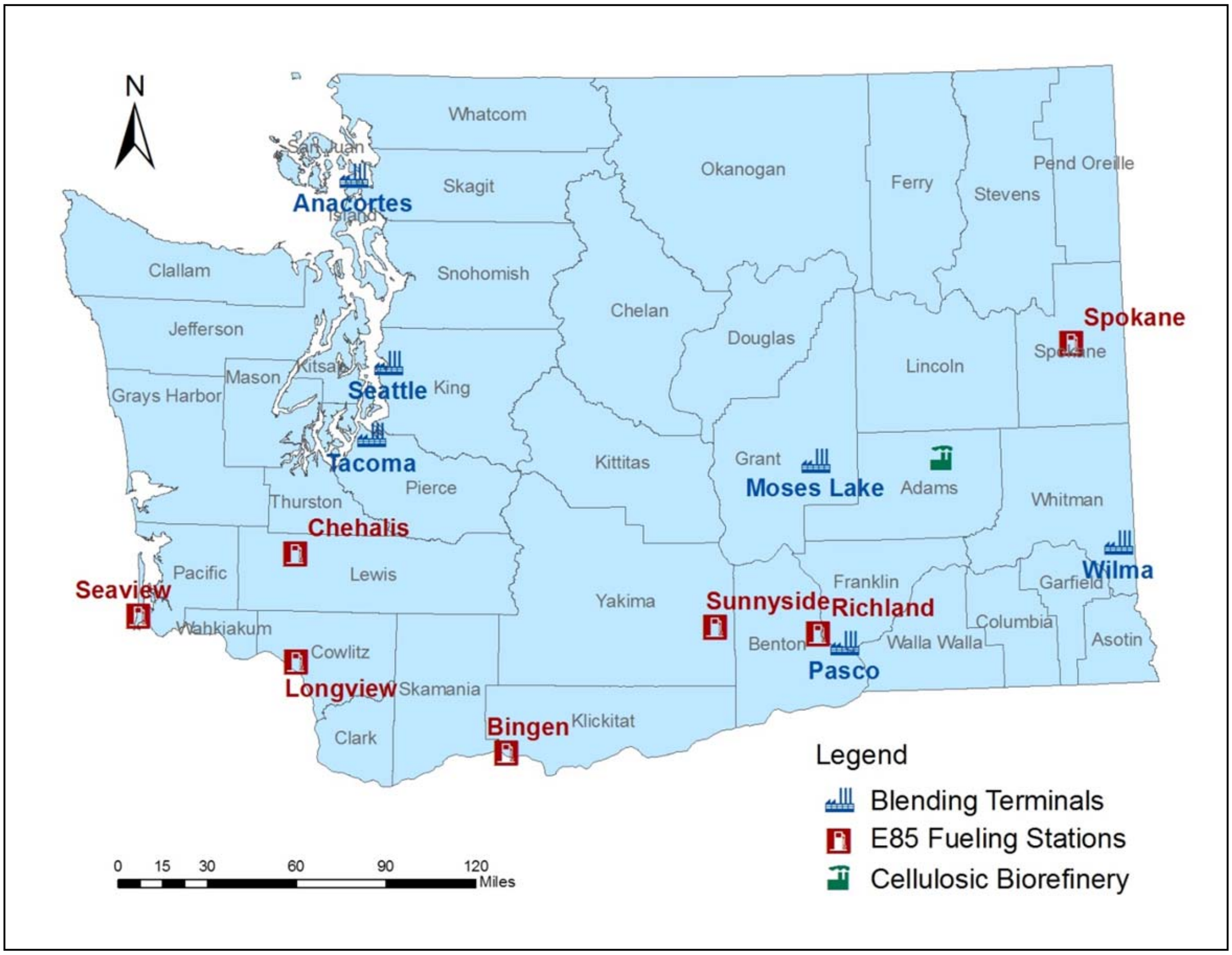
In addition to spatial characteristics, such as feedstock production geography and market locations, the optimal plant size decision may involve other factors, such as alternative transportation mode (rail, barge) accessibility. However, the fundamentals of the processing plant size decision making is based on two main components - increasing feedstock transportation costs and economies of scale in the (inside biorefinery) processing segment.

Distribution Costs Derivation

The ethanol distribution system consists of two segments. First, the processed ethanol is shipped to blending/distribution terminals (also known as racks). Racks also serve as storage facilities that the conventional gasoline is transported to, through pipelines, barge, truck or railroad modes. At the blending terminals the pure ethanol is blended into E10 or E85 (depending on the demand), which is then distributed by tank trailer trucks to the fueling stations offering E85 or E10 ethanol blend. According to Johnson and Melendez (2007), terminal shipment and storage costs add about $0.04 per gallon to the cost of gasoline. U.S. GAO (2007) estimated the overall cost of ethanol distribution, including shipments to blending terminals and distribution to gas stations, to $0.13 – 0.18 per gallon range depending on the proximity of markets from processing plants.

Figure **11** shows the distribution of existing blending terminals and E85 fueling stations in the state of Washington. The map includes only publicly accessible E85 fueling stations, leaving out three private or government-only facilities.

Figure 11: State of Washington Blending Terminals (Racks) and E85 Fueling Station Locations



Data Source: E85 fueling station location information - National Ethanol Vehicle Coalition webpage (NAVC 2008); Blending Terminal location information - OPIS Rack Cities (2008).

The economic engineering approach to calculating trucking costs used earlier in this report was modified to include tank trailers (different from flat bed or drop bed trailers considered for feedstock transportation). Because longer destinations increase transportation costs, the same logic as with the transportation of feedstocks can be applied to understand the relationship between distribution costs and haul distances. Since fueling stations have limited storage capacity, the larger the volume of the processing plant, the longer are the destinations that the ethanol needs to be distributed to reach out more fueling stations. In addition, GIS least cost or shortest route identification tools were used to find optimal routes from an ethanol processing plant to existing blending terminals, and further, to fueling stations in the state of Washington.

Considering ethanol shipments from one processing plant, the cost of the distribution to blending terminals (first segment) is relatively fixed, since the distances from processing plants to the terminals are constant. However, the distribution distances from the blending terminals to E85 fueling stations (second segment) are increasing as soon as stations in the vicinity from the rack receive their full capacity volumes of ethanol blend.

Total distribution costs can be derived by combining shipment costs to terminals and distribution costs to E85 stations. It should be noted, however, that depending on the business structure, ethanol plants may chose to ship (sell) their production to blending terminals, leaving the rest of the costs to other businesses, called jobbers or middleman (Johnson and Melendez 2007). Alternatively, terminals that are owned by independent companies may purchase the ethanol from refineries, blend, and distribute the fuel themselves. Regardless of the business structure, the delivered costs to final markets include costs associated with both segments – shipment costs to terminals, and distribution costs to ethanol blend fueling stations.

Processing Costs Derivation

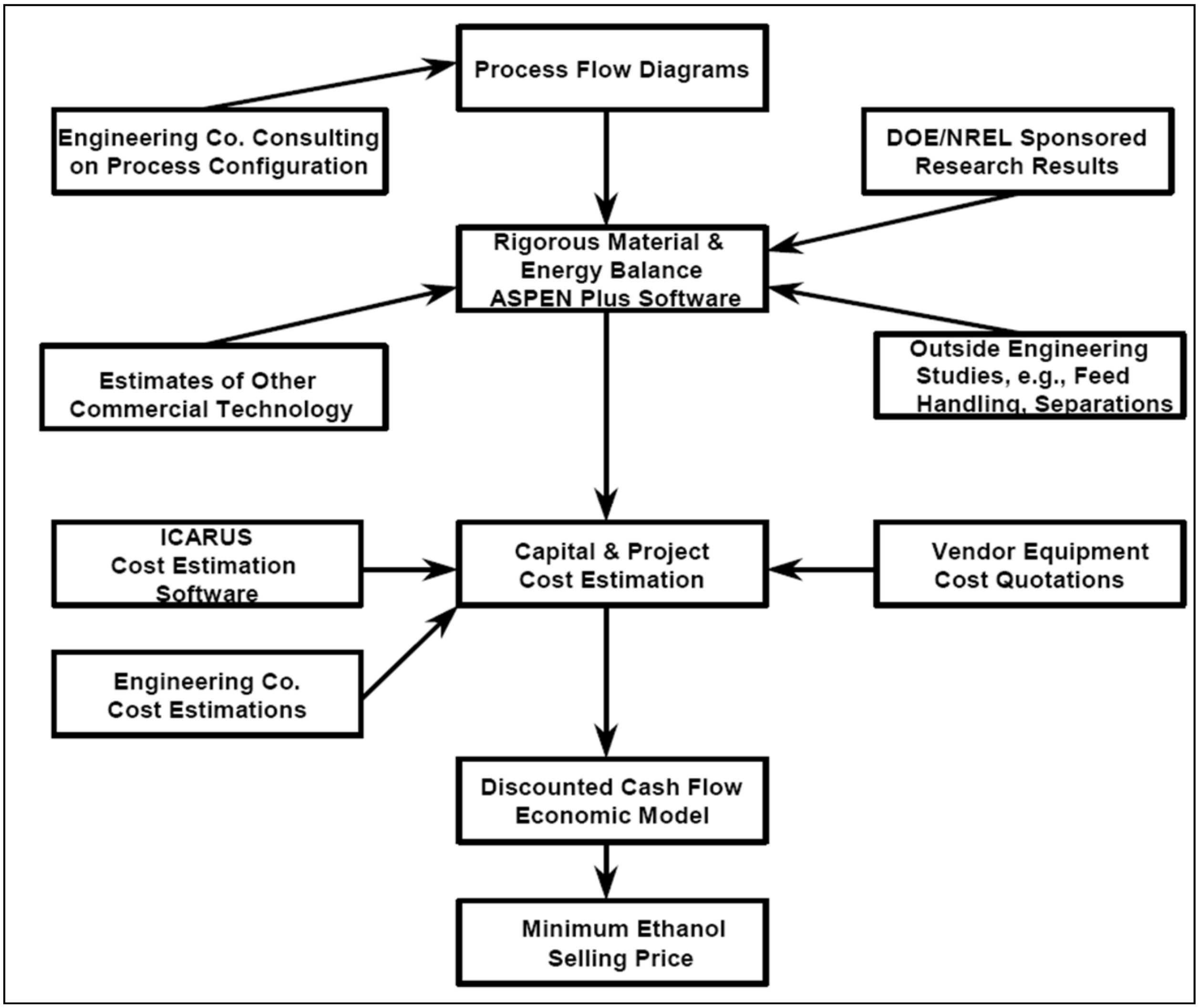
Overview of Processing Assessment Model

The ultimate goal of techno-economical assessments is a measure of profitability associated with some biorefinery technology options. Biorefinery plants are built to make a profit, thus in the early stage of project developments, estimation of the investment required and the cost of production are necessities. Even if insufficient technical information is available to design a plant completely, we must still make an economical evaluation to determine if it is economically and financially feasible. A biorefinery plant is economically feasible when its design is more profitable than any other competing designs and financial feasible when enough investments can be raised for project implementation. The traditional economic evaluation for a chemical engineering process may proceed in several steps:

i. Preparing a process flow diagram
ii. Calculating mass and energy flows
iii. Sizing major equipment
iv. Estimating the capital cost
v. Estimating the production cost
vi. Forecasting the product sales price
vii. Estimating the return on investment

In the occasion of evaluation some conceptual processes like biorefinery, there may be some difference. Figure 12 show NREL's approach to process design and economic analysis in the case of corn stove to ethanol via dilute acid pretreatment and SSCF. The final result of analysis is the minimum selling price. This type of working procedure was widely accepted by many other resemble projects. The only problem is limitation at the initial stage of R& D because too much resource is required for make such a thoroughly evaluation. While in some more simple analysis based on Excel spreadsheet, mass and energy flows calculations with system simulation were replaced by some simple equations. Their result obviously too rough to reveal overall difference between various technology options, e.g. when pretreatment method for LC-biomass changes, adjustment may be found in some other units of the whole project. Our aim of research works is to provide a set of flexible assessment tools with acceptable accuracy for decision making in the biorefinery process R&D or some related areas.

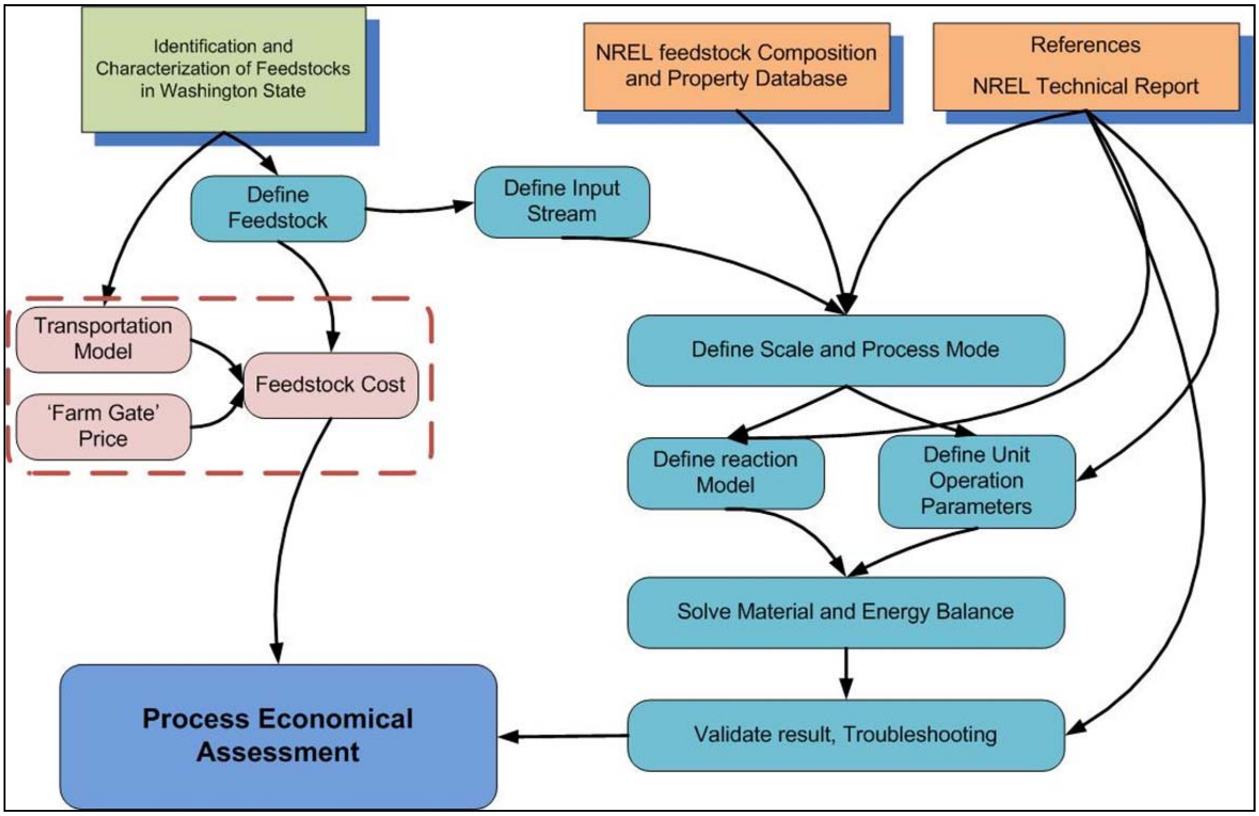
Figure 12: NREL’s Approach to Process Design and Economic Analysis



By now, most of the sustainable energy production projects are still in the stage of Research and Development. Thus for our project, we can only moving it forward by refer to other researcher's works. E.g. to understand a reaction system via gaining basic theoretical data, proving out basic process feasibilities, or achievements on a specific aspect of future plant like lignocelluloses material pretreatments. The principal function of our process assessment model is screening. Dozens of options on feedstocks and conversion processes exist while few of them are valid. Alterative process may be estimated for comparison purpose based on the matrix of conceptual designs assessment would be established. Two or more alterative processes can be quickly cost out to see if one is clearly superior or to eliminate clearly inferior options. As we made progresses on the process assessments, more should be known on the ultimate configuration of the future commercial plants that converse waste into energy and other useful by-product.

We will choose several feedstocks as input stream to process economic assessment within the framework showed in Figure 12. In order to get the final cost estimation results, two data stream were required. Feedstocks collective and transportation cost curve can be provided by Objective 4. Material and energy balance data came from output of bioenergy production process model. Mathematic models would be helpful to describe different conversion processes under different system definitions. These definitions mostly came from proved data sources such as book, reference, technical report, and some online database.

Figure 13: Working Process of Economic Assessment

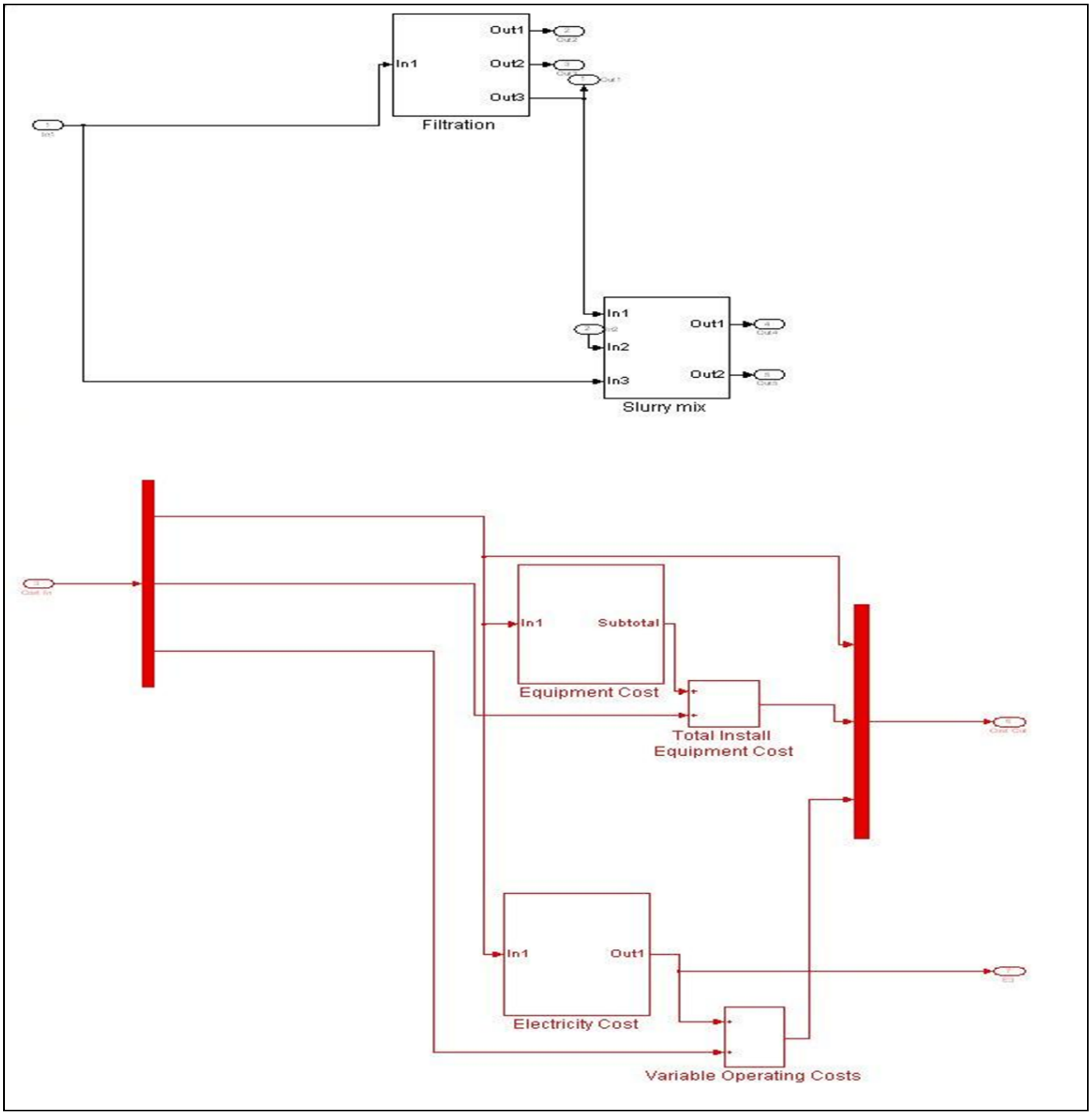


Three kinds of data need to be collected for process modeling.
Feedstock Data The feedstock database generate by phase I is configured by five categories (fiber/starch/sugar, ultimate analysis, elemental analysis, other parameters), and includes 33 parameters such as moisture, carbon, starch, cellulose, minerals, etc. The database would be used not only by the researchers to conduct the scientific studies, but also by farmers and producers to know more about the agricultural and municipal residues they are producing.
Process Flowchart The technological scheme connect feedstock to final product has been concerned. Methods such as anaerobic digestion, gasification, pyrolysis and fermentation, etc will be used in the production. Flowchart of these methods had been determined via reference and laboratory research. Aden et al. had developed a set of detail PFDs (Process Flow Diagrams) on lignocelluloses to ethanol via diluted acid pretreatment and SSCF processes. Philips et al. also presented a set of PFDs on production of thermochemical ethanol via Indirect gasification and mixed alcohol synthesis of lignocellulosic biomass in their final report. AD (Anaerobic Digestion) process flowcharts were developed by AD research group, BBEL of Biological System Engineering department in Washington State University.
Chemical/Biochemical Dynamics These data were used to descript every step in the whole process, and mostly gather from research report of relative process. Some other parts came from chemical engineering handbook.

For this project, we chose MATLAB & Simulink because they provide a powerful environment for the development of flowchart based simulation models. Different subsystems are developed by Simulink to characterize all kinds of unit used in biorefinery process. The structure of a sample module was shown in Figure 13.

The upper part of sample module represents the mass balance in the unit. The input of this part is the mass stream from the process before it, while the main output will connect to input port of the next unit. The red part of sample module represents the energy balance, equipment investment and raw material costs of the unit. The technological scheme connect feedstock to final product has been concerned. Methods such as anaerobic digestion, gasification and fermentation, etc will be used in the production.

Figure 14: The Structure of a Sample Module



Models for Various Conversion Technologies

The mathematical models of the bioethanol and thermo-ethanol production process consist of mass and energy balance equations. All equipments are modeled assuming the hypothesis of steady state.
14 and 7 modules are included respectively in the models to represent different units in the bioethanol/thermo-ethanol production system. Description of module structure can be found at methodology part of this report. Detail module information can be acquired from manual of SSCF process model. These modules provide three kinds of output:

- Mass stream in/out
- Energy Stream in/out
- Equipment cost

In the system configuration module, quantity and characters (composition, cost) of feedstock can be defined. The feed in quantity of feedstock will determine scale of the whole system. Base on mass/Energy balance results, a list of system input/output stream can be generated automatically. Plus cost information acquired from NREL's report or other sources, Variable Operation Cost can be estimated. Total salary was estimated based on the position categories and relate annual salary/ personnel number information. For some position, personnel number need to be adjusted acceding to the system scale and scale factors acquired from reference. With summarization of equipment costs generated by all the processing modules, the Total Install Equipment Cost (TIEC) can be calculated. In this calculation, factors of scale and CECPI are including in our concern. Total Project Investment (TPI) as well as Fix Operation Cost can be estimated with these data. TPI, Variable Operation Cost and Fix Operation Cost data will be insert into a excel spreadsheet. By virtue of Excel's economics function and parameters provided by references (So and Brown 1999; Aden, Ruth et al. 2002), ethanol production cost can be estimated.

The AD process is often modeled using ADM1 (Batstone et al. 2002) as a means to separate the enzymatic hydrolysis of solid wastes from the metabolic reactions utilizing soluble substrates. Zaher et al have developed GISCOD (a general integrated solid waste co-digestion model) based on ADM1 (Zaher et al. 2009). The main goal of this study was to develop and test a simulation tool of the anaerobic digestion (AD) process that is applicable to any combinations of waste streams using the simulation platform Matlab-Simulink. A general co-digestion assessment model is still needed to support operation decisions at full-scale plants and to assist co-digestion research. Thus we developed an AD process assessment model For analysis work on animal waste and food waste. GISCOD is the core of this model and provides steady state output estimation for the pre-configured AD process. Resulting data was stored in data files that could be utilized by the following for assessment modules. In most cases studied, only the digester and generator unit were discussed. Biogas purification and nutrients recovery processes are two additional and important options for AD technology. Specific modules were developed to evaluate the economic impact on the performance of the whole system. Output of all four assessment modules were summarized in a data presentation module.

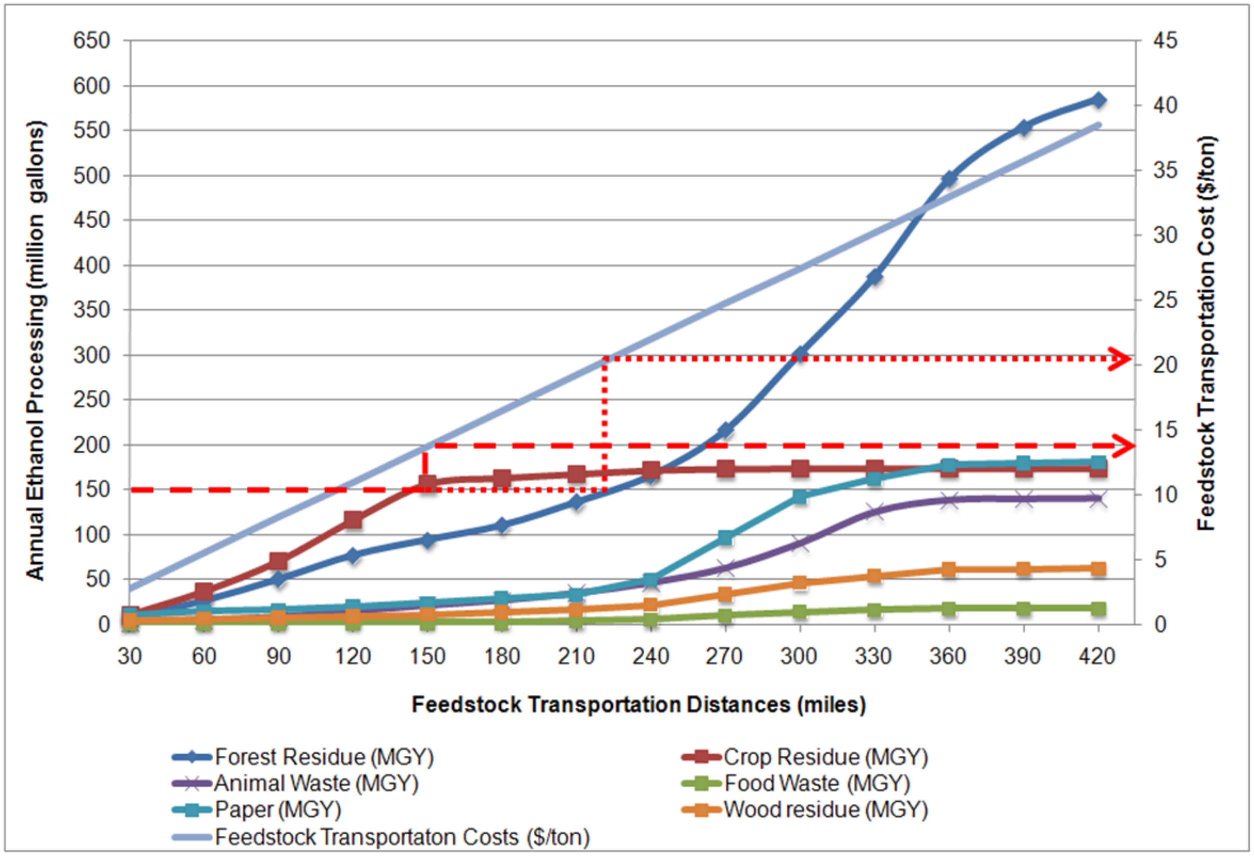
RESULTS

Feedstock Transportation Costs

Study results show that the economic feasibility of biofuels processing in the state is significantly influenced by feedstock transportation and distribution costs. Because of the geographically varying distribution of the feedstock resources and increasing transportation costs for longer destinations, all of the feedstock deposits cannot be utilized at the same expense. In turn, biomass-to-biofuel processing plant cost-minimizing location decisions are influenced by the type of the feedstock utilized, and vary depending on the processing plant capacities.

Figure 15 shows the relationship between increasing plant processing capacity (left vertical axis) and feedstock delivered costs per dry ton (right vertical axis) as haul distances increase. Depending on the feedstock category the feedstock costs change respectively. For instance, to support 150 MGY processing, agricultural crop residue can be collected from about 150 miles from the biorefinery location.

Figure 15: Feedstock Transportation Costs by Haul-Distances for Spokane Plant



As depicted (with red line) in the same figure, this residue can be transported at around $14 per ton. Alternatively, that level of processing can be supported by forest residue. However, with the forest residue feedstock haul distances increase from 150 to about 220 miles, consequently increasing transportation costs from $14 to about $20 per ton of feedstock. Results for several other biorefinery locations in the state are provided in the GIS Approach to Delivered Feedstock Costs (Frear et al. Data) section of the APPENDIX.

<u>Processing Costs</u>

Crop Residue in Washington State

Introduction

Crop residue (field residue) is one important resource of biofuel feedstocks. Because Washington State is one of the major wheat producing states in the country. Wheat straw covered nearly 80% of all crop residues (Phase I report). Washington State has around 1,614,234 dry tons of wheat straw. As one of woody materials, wheat straw is rich in cellulose and hemicelluloses, which is a potential raw material for commercial bioethanol production and gasification. Researchers in Washington State were interested in this kind of feedstock, and made some efforts on assessing the availability of wheat straw, the status of the conversion technologies, and the economics of ethanol production from wheat straw (Kerstetter and Lyons 2001).

Figure 16: Cost Curve for Bioethanol Production with Crop Residue as Feedstock

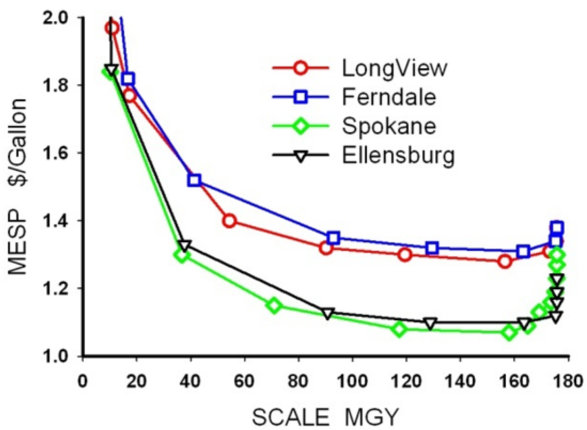
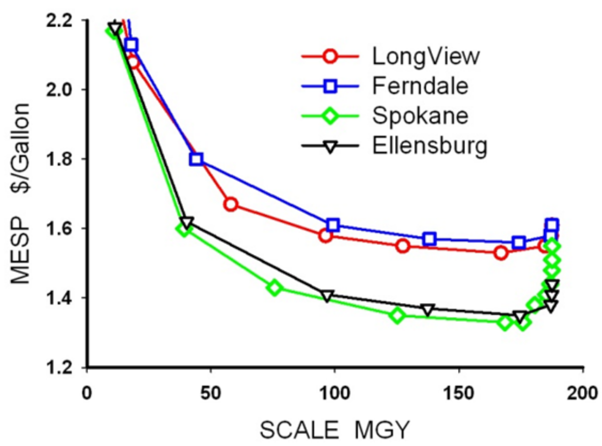


Figure 17: Cost Curve for Thermo-ethanol Production with Crop Residue as Feedstock



Analysis Results

Discussion

From the estimation of biomass conversion into bioethanol or thermo-ethanol with the feedstock availability information from GIS system, several conclusions can be made.

1. As far as the 420mile collection distance, the maximum capacity for the ethanol plant build with crop residue as feedstock can only reach the scale of around 180 MGY due to the limitation of material.
2. If only based on model output, gasification process shows some advantage over the SSCF process on production cost. But our models are base on two conception design, there are some technology barrier still need to be overcome for both technologies, like pretreatment unit of bioethanol production, and gasification process's carbon conversion rate. There is no commercialized example for comparison, so we can only conclude that the gasification technology may have more potential.
3. Almost in all the curves, the 20 MGY scale can be seen as a tipping point for production cost. Because ethanol MESP no longer decrease sharply with the increase of Plant scale, this value can be seen as a threshhold for ethanol plant sclae in washington state.
4. From 60MGY to 160MGY, the ethanol production cost curve enter a “flat bottom” zone, which means the cost can be neglected on considering the system scale. For example, large scale facilities may have lower ethanol production cost, but the return on investment per gallon also drop down. This may not be prefered by potential investors.
5. Spokane and Ellensburg are the best choice for future facility based on crop residue feedstock. This is mainly because of the availbility of feedstocks.
6. Upper limit of facility scale will determine by the market capacity. Accoding to the calculation in Objective 4, the ethanol dilivery cost rate will be $ 0.04 per mile per gallon. If the dilivery cost was taken into accout, there must be a optimized facility scale which balance the production cost and dilivery cost.

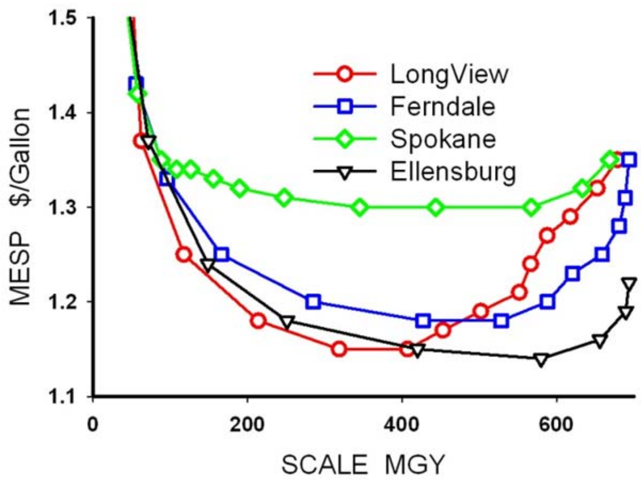
Forest Residue in Washington State

Introduction

The forest products industry generates large amounts of residual biomass as timber is harvested and manufactured into marketable goods such as lumber and paper. Forest derived biomass may originate directly from the forest (logging residues) or from timber processing mills (primary mill residues). According to Phase I report, 8,103,686 Tons of forest residues are distributed all over the Washington state. Forest residue is tested as feedstock of bioethanol and thermo-ethanol production.

Analysis Results

Figure 18: Cost Curve for Thermo-ethanol Production with Forest Residue as Feedstock



Discussion

The hugh quntity of forest residue feedstocks make it possible to manufacture up to nearly 800MGY of ethanol under the same transpotaion distance of crop residue,. It's 4-5 times of mximum output with crop residue as feedstock. From the biofuel output this feedstock can be seen as the most impottant in Washington State.
For forest residue, the gasification process also show some advantage. But still need more time to confirm.
Ellensburg is also the best site for biofuel production due to feedstock availbility, except Longview has a lower cost for bioethanol production befor the scale reach 400 MGY.

Municipal Waste in Washington State

Introduction

From decades of years ago, there are many individuals, institutes, communities, and companies tried to find creative ways to reduce and better manage municipal waste (more commonly known as trash or garbage) through a coordinated mix of practices that includes source reduction, recycling (including composting), and disposal. Among these practices, using biorefinery technology to converse them into sustainable energy is a choice that has been put great attention on.
Form the Phase I report, 45 potential sources in Washington geographically identified, categorized, and mapped at a county level, 34 of them are municipal waste. In this research phase, some of the very low quantity feedstocks studied in the earlier phase will be eliminated and the remaining feedstocks will be grouped according to their similarities. From all these materials, 4 types of feedstock with large quantity: Animal Waste, Food Waste, Paper, and Wood Residues, were chosen for investigation.
As cellulose materials, waste paper and wood residues are good feedstock for ethanol production. Animal Waste and food waste can be sent to AD process to generate biogas or electricity.
The composition of waste paper in terms of sugar content is not provided by phase I report. Mix waste paper data used in bioethanol model were acquired from one WSEO (Washington State Energy Office) report.

Waste Paper & Wood waste

Figure 19: Cost Curve for Bioethanol Production with Waste Paper as Feedstock

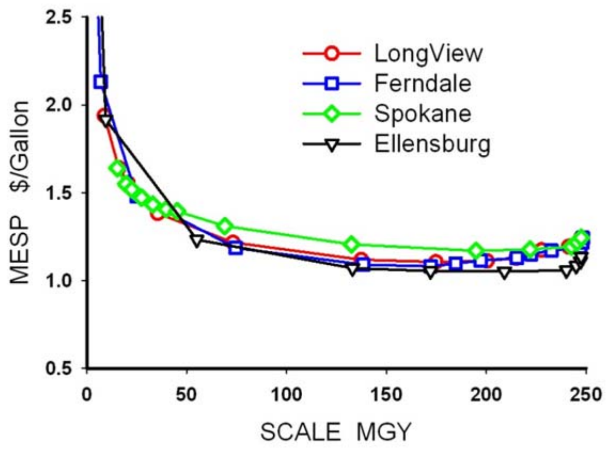
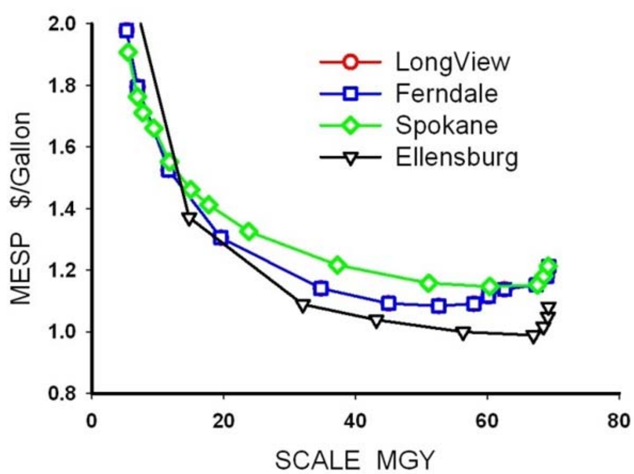


Figure 20: Cost Curve for Thermo-ethanol Production with Wood Residue as Feedstock



Paper has a nearly 20% percent of higher yield compared with other LC-biomass mateial because of its higher cellulose content. The composition we used here is for the residential mix waste paper (sample was taken from curbside program of the City of Olympia, WA) . If the feedstock is mainly comercial mix waste paper (paper from office) which contain more cellulose and less lignin, more ethanol will generated with requirements of interior power input.
Take waste paper as feedstock fot bioethanol prodction can significently reduce production cost. But feed it to the thermo-ethanol production shows slight difference.

Animal Waste & Food Waste

Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is widely used to treat wastewater sludges and organic waste because it provides volume and mass reduction of the input material. In Washington state, the first anaerobic digester for dairy had already install in the Vander Haak Dairy which was was one in Washington state. The dairy utilizes food waste and manure to feed the digester. Our system simulation and economic assessment were using data from this project as main parameters resource. Because the effluent of AD process that contain large quntities of nitrogen and phosphate need to be disposed on site. A scale limit of was set before analysis work. The simulation can only treat a maximum quantity of 500 ton/day (wet weight) feedstocks. Under this assumption, the possible tipping fee for excessive eluent liquid can be neglected.

Figure 21: With Fix Feedstock Price, Return of AD Process Increase with Manure Input

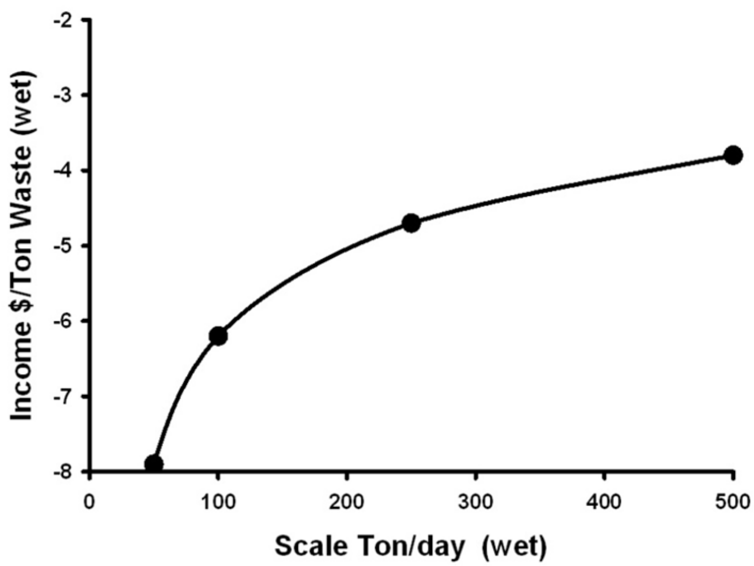
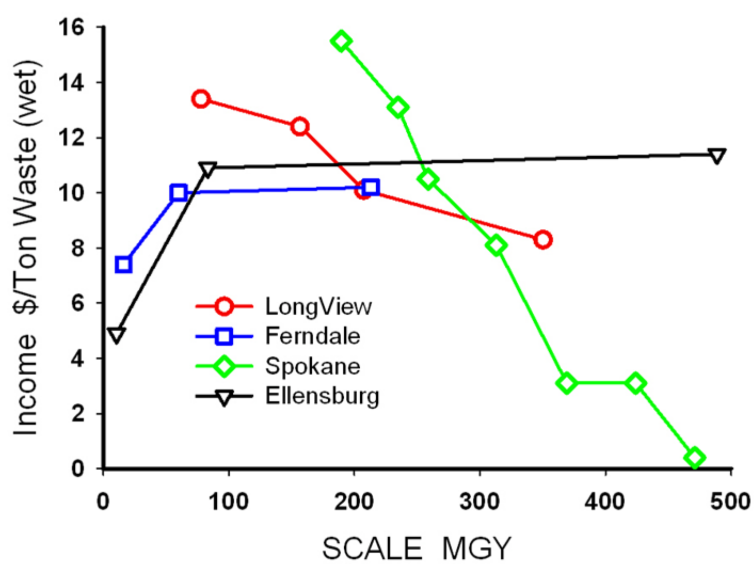


Figure 22: Site Comparison for Food Waste Facility on Financial Returns



If the animal waste was took as feedstock for AD system, there could be enough feedstock that exceed the limit of 500 ton/day within 30 miles distance for every site we tested. A anlysis on system financial feasibility was performed under different feedstock input rate and result was shown in Figure 21. With the stable feedstock transportation cost, the final system net income per
ton waste was increaseing due to the reduction in processing cost. In this case, if there are any tipping fee for animal waste, the income value may become positive as in Figure 22 with$ 25 per ton tipping fee for food waste. Food waste used as feedstock for AD system is much economical, and the system net income is higher when there are more feedstock and less transportation distance. From this point, small scale facilities in Longview and Spokane seems to be better choice.

Multi-feedstocks for Ethanol Production

Because most of our feedstocks are LC-materials that have similar content, they may be used to produce the ethanol in the same system. The advantages of multi-feedstocks for ethanol production are further reduction in feedstock cost and elevation on potential facility scale upper limit. If the universal system's performances on every possible feedstocks are the same, the ethanol production cost will reduced. We use all LC-materials (Corp residue, forest residue, wood residue, and waste paper) as feedstock to the system and estimate the production cost based on Ellensburg's data. The results are shown in Figure 23 and Figure 24.

Figure 23: Cost Curve for Thermo-ethanol Production with Multi-feedstock

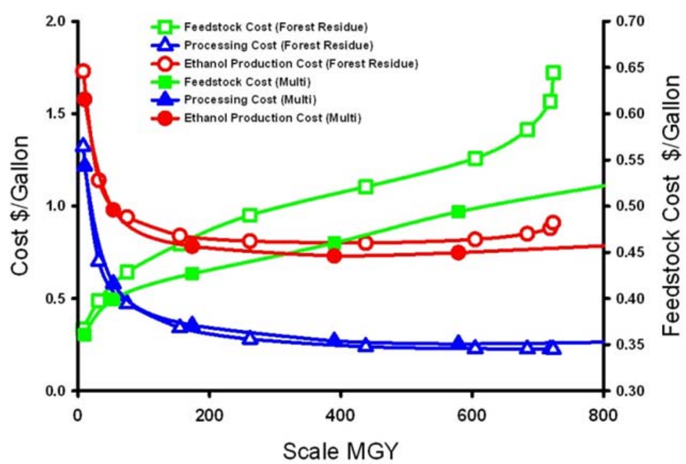
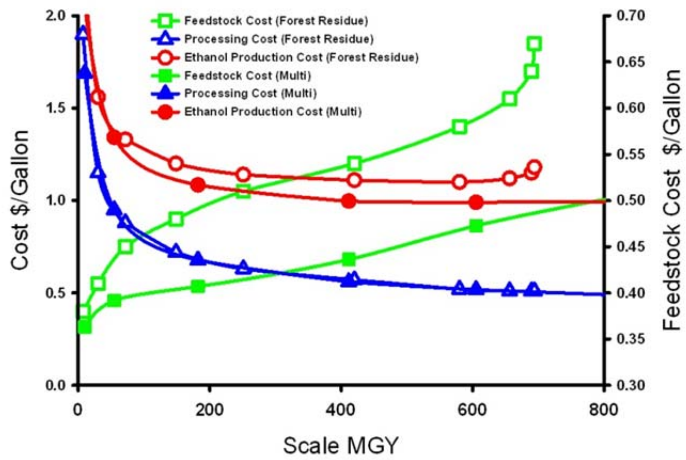


Figure 24: Cost Curve for Bioethanol Production with Multi-feedstock



Reduction on feedstock cost account for the main part of production cost decline. For bioethanol process this effects is more distinct. Under real condition, all system must be optimized for specific raw material, and there would be more unpredictable negative effect on conversion process with the increment of feedstock types. Impact of final ethanol yield reduction are analyzed for both processes, and the result shows 10% less ethanol yield would lead to loss of cost advantage for multi-feedstock strategy.

Figure 25: Impacts of Ethanol Yield Reduction on Production Cost of Thermo-ethanol Process

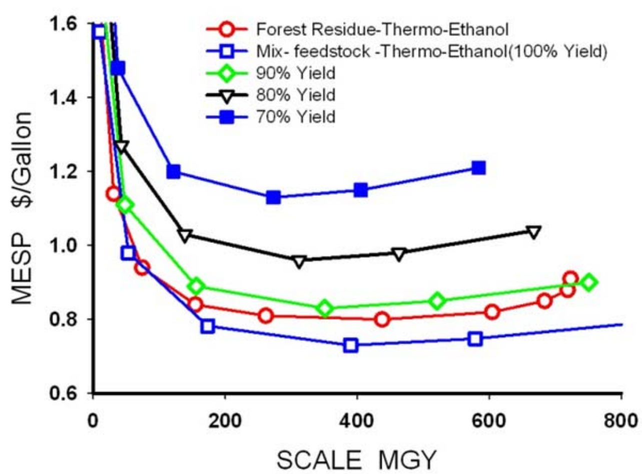
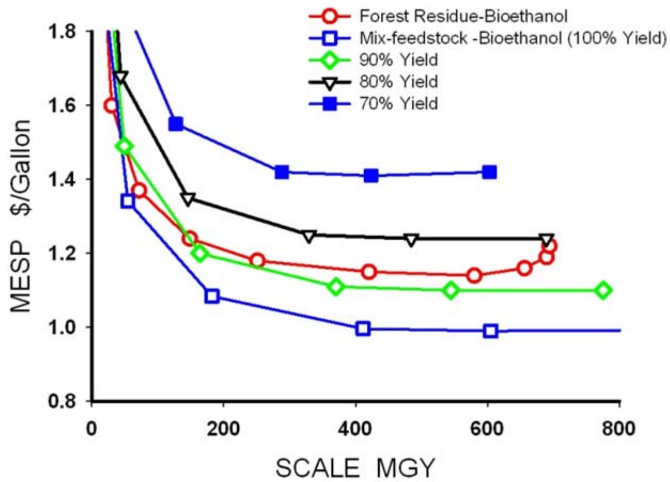


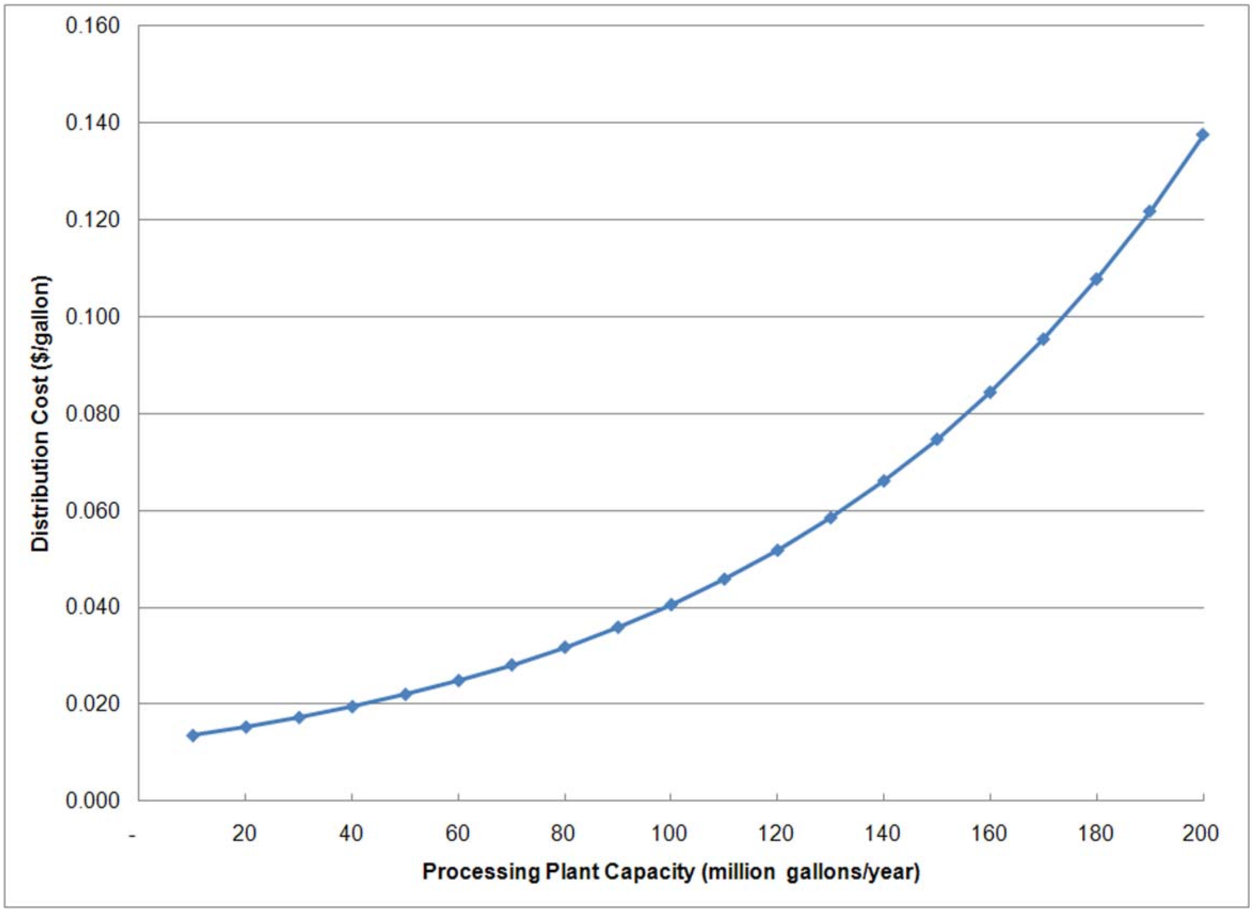
Figure 26: Impacts of Ethanol Yield Reduction on Production Cost of Bioethanol Process



Distribution Costs

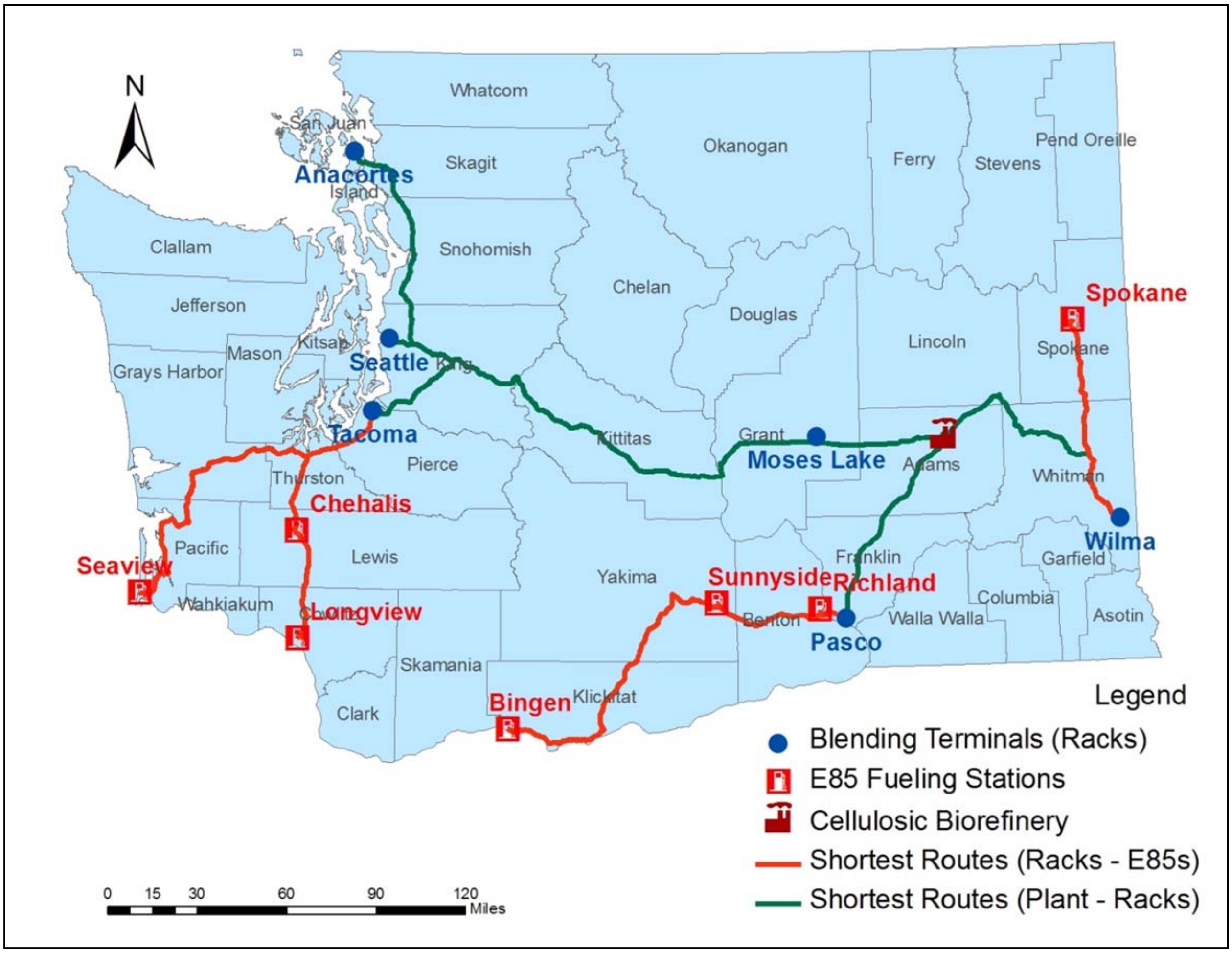
At each level of biofuel processing scale, distribution costs from processing plants to blending terminals can be added to costs accrued from terminals to bio-fueling stations to derive the total distribution costs. Applying per gallon mile truck transportation costs to increasing distances, distribution costs resulted an upward sloping curve ranging from $0.013 – 0.138 per gallon for 100 – 200 MGY processing plants respectively (Figure 27).

Figure 27: Distribution Costs per Gallon of Ethanol by Processing Plant Capacity



GIS least-cost or shortest route identification tools were used to find optimal routes from an ethanol processing plant to existing blending terminals, and further, to fueling stations in the state of Washington. For this first part of the spatial analysis, biorefinery, existing blending terminals, and E85 station location information was combined (Figure 28). For the second part, distribution routes from blending terminals to E85 fueling stations were identified with the use of GIS Network Analyst Origin-Destination Cost Matrix solver.

Figure 28: Shortest Routes from Processing Plant to Blending Terminals and E85 Fueling Stations



The resulting least-cost destinations (blending terminals) from the cellulosic biorefinery are as follows: Moses Lake ($0.03/gallon), Pasco ($0.05/gallon), Wilma ($0.07/gallon), Seattle ($0.15/gallon), Tacoma ($0.16/gallon), and Anacortes ($0.20/gallon) [Figure 29]. The consideration of only one processing plant and six blending terminal locations makes the computation of optimal routes relatively straightforward. However, with the growing ethanol industry that will eventually result in increasing number of processing plants and E85 fueling stations, the route optimization can be complicated. Therefore, this methodology is useful for the route optimization and distribution costs derivation with multiple ethanol processing plants serving hundreds of fueling stations in the state.

Figure 29: Ethanol Distribution Costs from Processing Plant to Washington's Blending Terminals

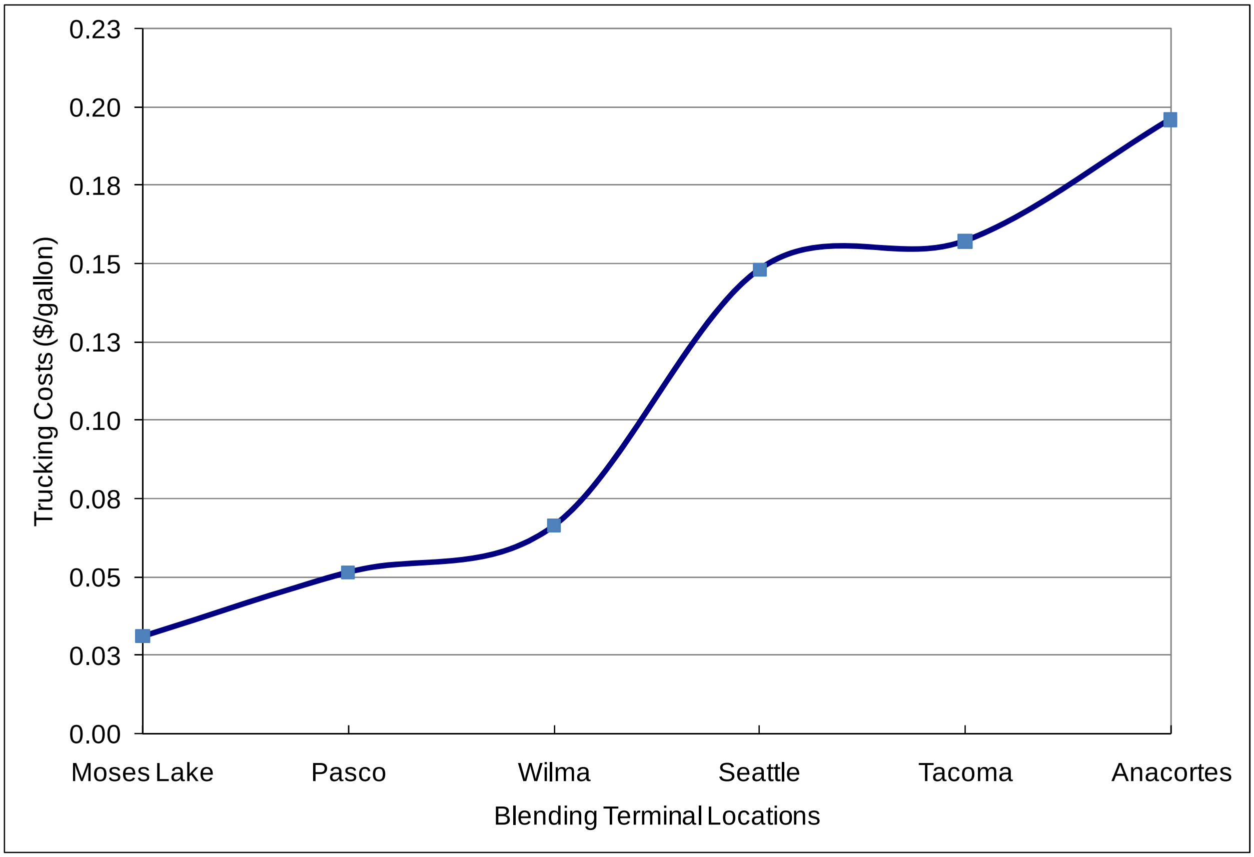
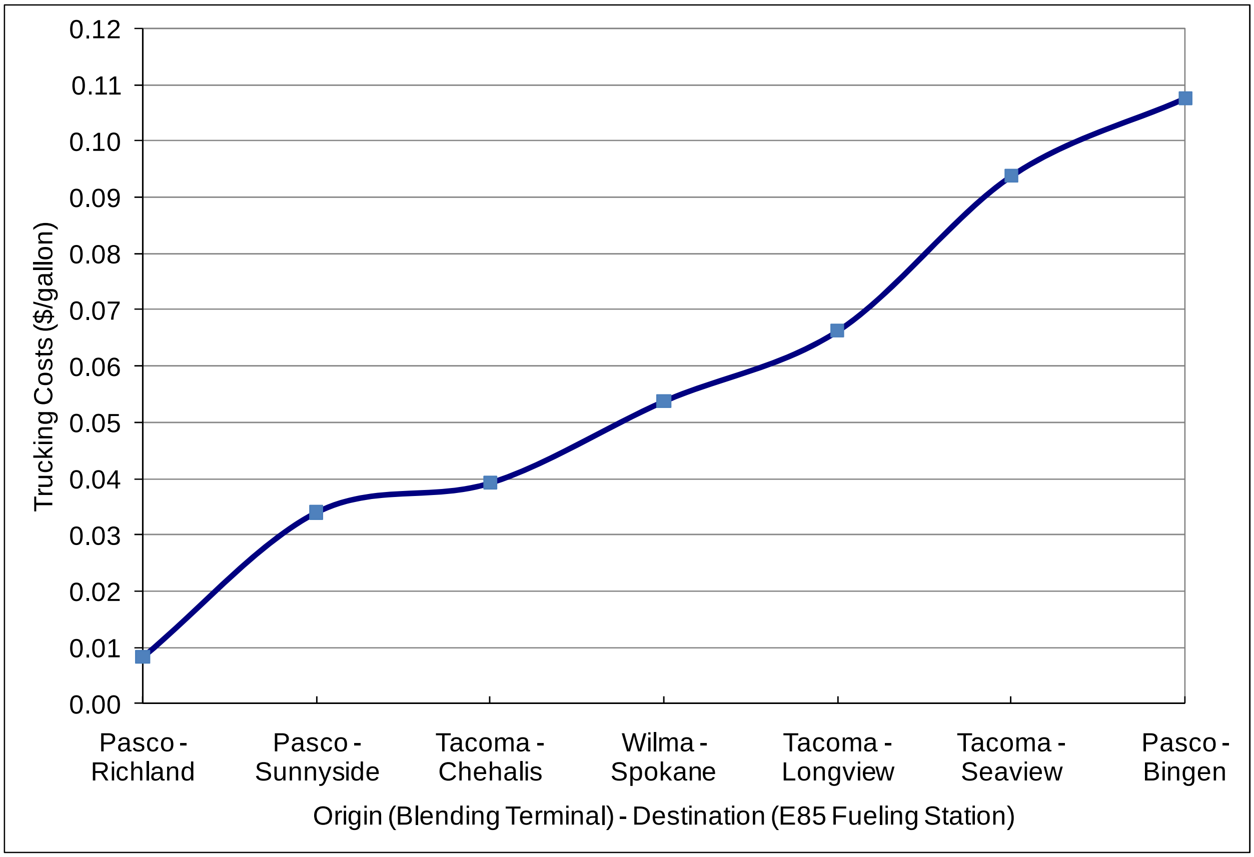


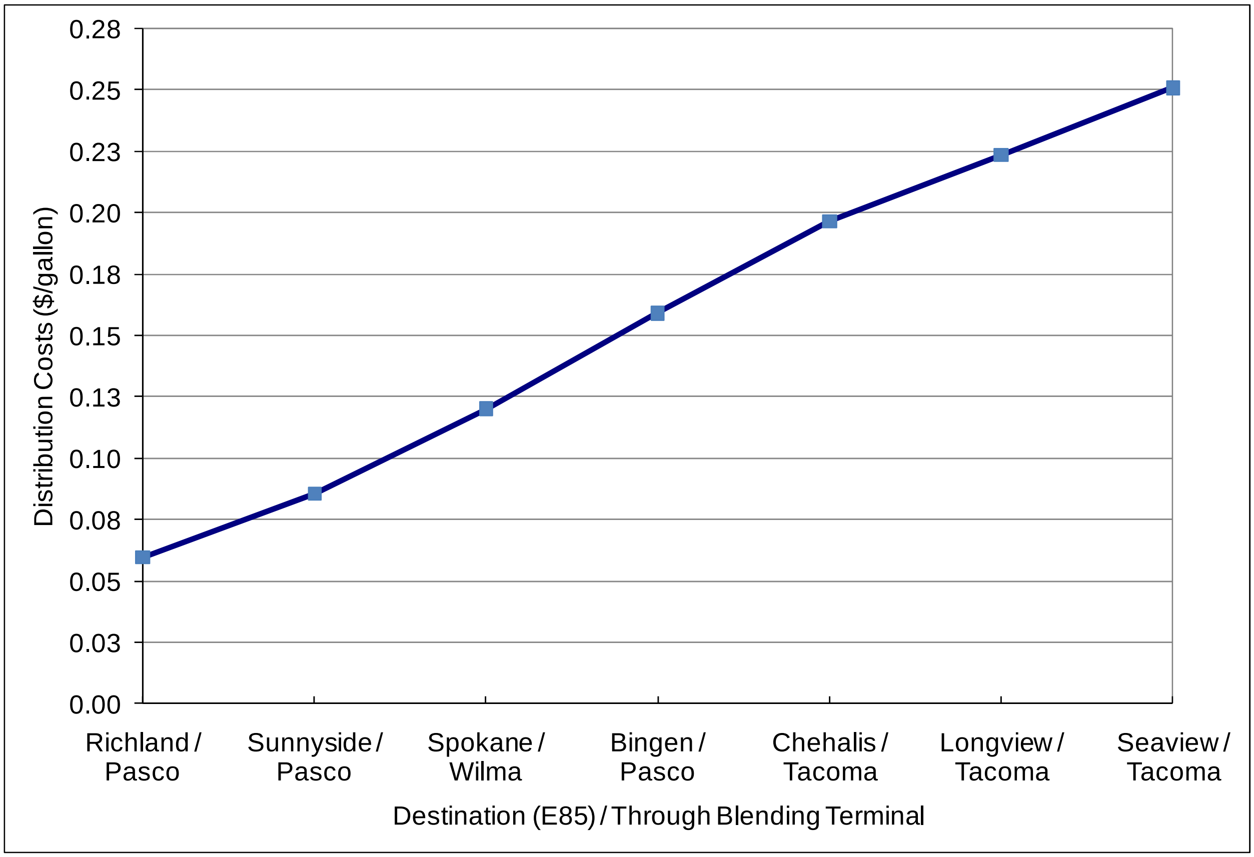
Figure 30 shows per gallon trucking costs associated with the final segment - the distribution of ethanol from blending terminals to existing E85 fueling stations. Note that only three blending terminals (in Tacoma, Pasco and Wilma) were plotted as origins against all seven E85 fueling stations. Terminals in Seattle, Anacortes and Moses Lake are relatively further away, and therefore, were dropped by the GIS Network Analyst Closest Facility toolset.

Figure 30: Ethanol Distribution Costs from Washington's Blending Terminals to E85 Fueling Stations



To finalize the distribution cost calculations for the entire distribution path, starting from the processing plant in the Eastern Washington to all E85 fueling stations through three closest blending terminals, costs for the both segments were combined (Figure 31). Resulted transportation costs for the ethanol distributed through the terminal in Pasco increase as $0.06, $0.09, and $0.16 per gallon for E85 stations in Richland, Sunnyside and Bingen respectively. Per gallon distribution costs through the Tacoma terminal start with $0.20 in Chehalis, and increase to $0.22 and $0.25 for the E85 destinations in Longview and Seaview respectively. Given current geographic distribution of E85 fueling stations, only one distribution route was identified for the fueling station in Spokane through the terminal in Wilma, resulting $0.12 per gallon transportation costs.

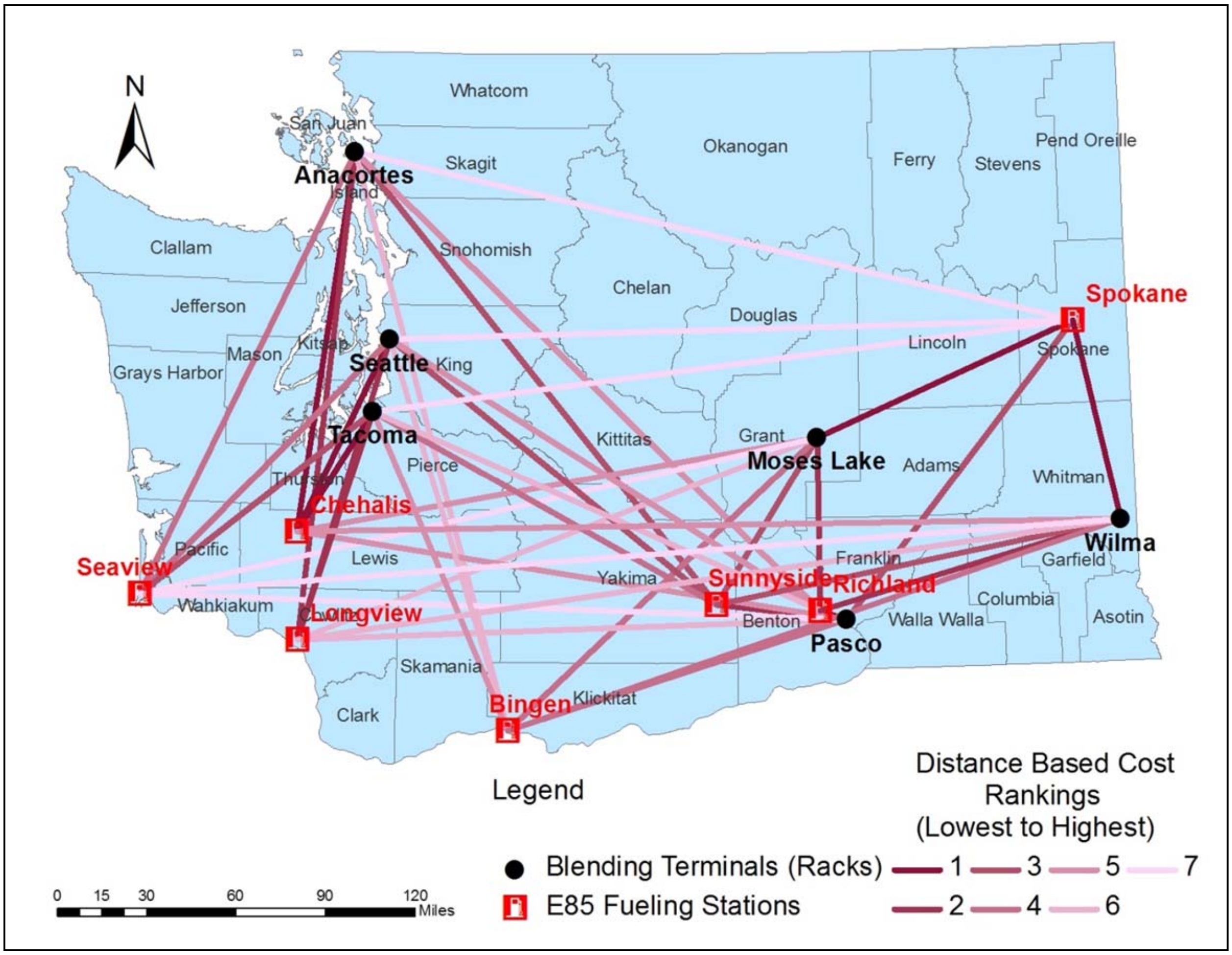
Figure 31: Distribution Costs from the Processing Plant through Three Blending Terminals to All E85 Fueling Stations in the State



As mentioned earlier, for the second part of the spatial investigation, an origin-destination cost matrix was created to rank the least cost distribution routes from blending terminals to the state's E85 gas stations. For this part of the analysis, the GIS Network Analysis toolset uses location information to rank distribution routes according to the lowest to highest transportation costs. Currently, with only six origins (blending terminals) and seven destinations (E85 stations (resulting 6×7 cost matrix), the current computation is relatively easy. However, with the development of the industry, the methodology may be useful to include hundreds of trips originating from existing blending terminals to future E85 stations in the state. Figure 32 shows a map with connection lines[2] illustrating the distance based cost ranking for the routes from the blending terminal to E85 fueling stations in the state. For each of the blending terminal location, route information was considered for calculating the closest E85 station location, and to rank according to the transportation costs.

Figure 32: Map for GIS Origin (Blending Terminal) Destination (E85 Fueling Station) Distance Based Cost Matrix

[2] Despite the lines in the map are shown as straight lines, the information they provide is based on origin-destination highway distances. To keep the map clear, the Washington's highway layer was not included.



Delivered Costs

This section of the report combines feedstock transportation, processing, and distribution costs to derive the delivered cost of biofuel to alternative markets. Results shown in the figures below include estimates using both bio-ethanol and thermo-ethanol conversion technologies. The feedstock transportation, processing, and distribution calculations were conducted for several potential biorefinery locations in the state. In this section results for only least-cost locations are shown. Cost estimates for the rest of the locations can be found in the Delivered Costs section of the APPENDIX. Figure 33 shows feedstock collection and transportation, plant processing, and distribution cost estimates (cumulatively representing delivered costs) using crop residue data.

As shown in Figure 33, processing cost curve is downward sloping, because of the economies of scale (the costs are spread over more gallons of production). However, cost for both feedstock transportation and distribution are positively correlated with the production scale.

Therefore, the delivered cost curve is downward sloping up to some processing capacity level (as discussed earlier, in the Economies of Scale section), after which the curve slops upward. The lowest point on the delivered cost curve ($1.31 per gallon) represents the least-cost of ethanol production using crop residue. For this particular location (Spokane), the optimal size of the processing plant is125 MGY. The lowest delivered cost estimate has important implications for the processing plant optimal size decisions. In particular, the corresponding plant capacity (MGY) on the horizontal axis shows the optimal size of the processing plant, given the feedstock type and the processing technology that was considered here.

Figure 33: Delivered Cost of Bio-ethanol Using Crop Residue

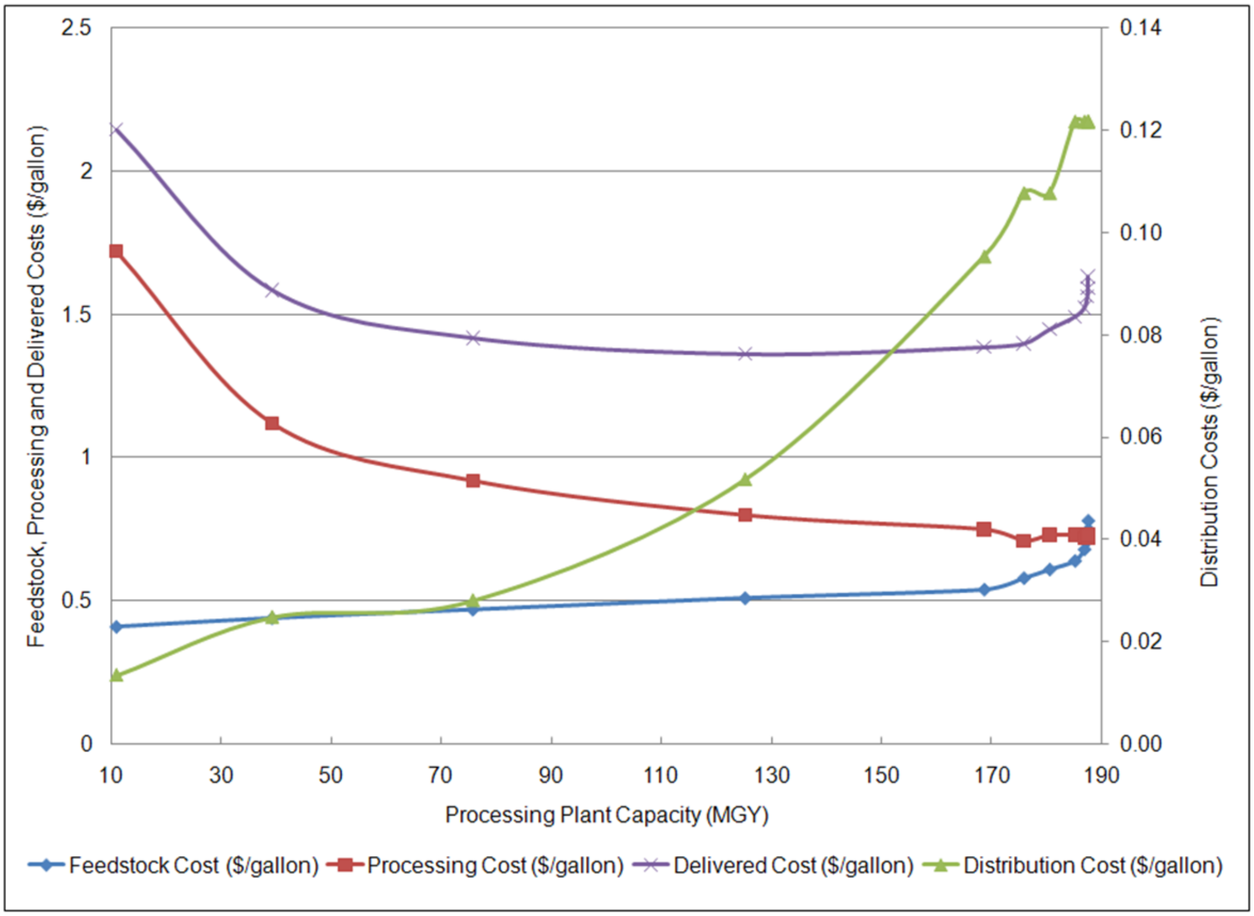


Figure 34 shows the delivered cost estimates using gasification technology for converting biomass into alcohol. The interpretation for downward sloping processing, and increasing transportation costs is similar to what was describe for the biological conversion technology above. The lowest point on the delivered cost curve ($1.09 per gallon) represents the least-cost of ethanol production using crop residue. The optimal size of the processing plant using gasification conversion technology is 117 MGY.

Figure 34: Delivered Cost of Thermo-ethanol Using Crop Residue

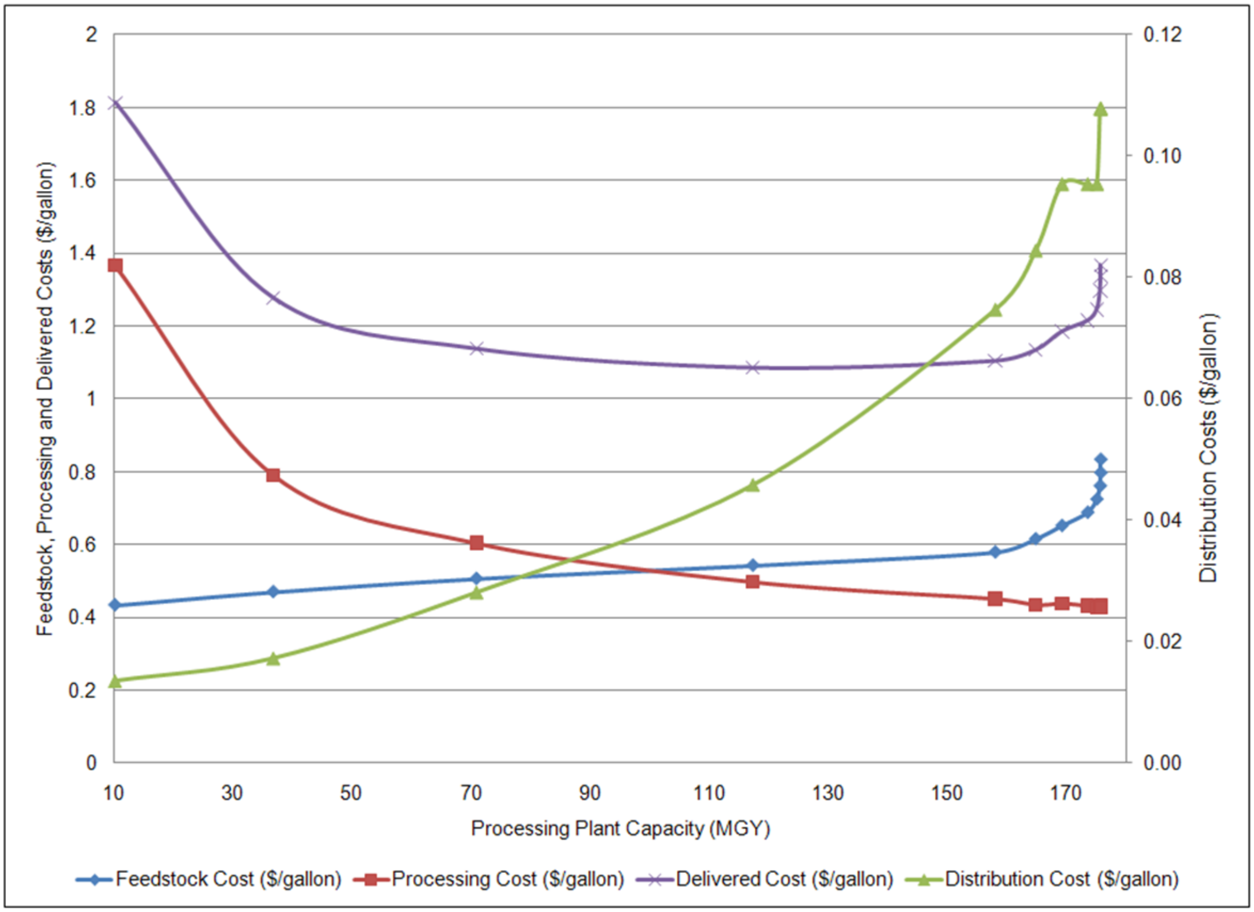


Figure 35 shows the delivered cost estimates using bio-ethanol technology for converting forest biomass into alcohol. The interpretation for downward sloping processing, and increasing transportation costs is similar to what was describe for the biological conversion technology above. The lowest point on the delivered cost curve ($1.26 per gallon) represents the least-cost of ethanol production using crop residue. The optimal size of the processing plant (Longview location) using gasification conversion technology is 117 MGY.

Figure 35: Delivered Cost of Bio-ethanol Using Forest Residue

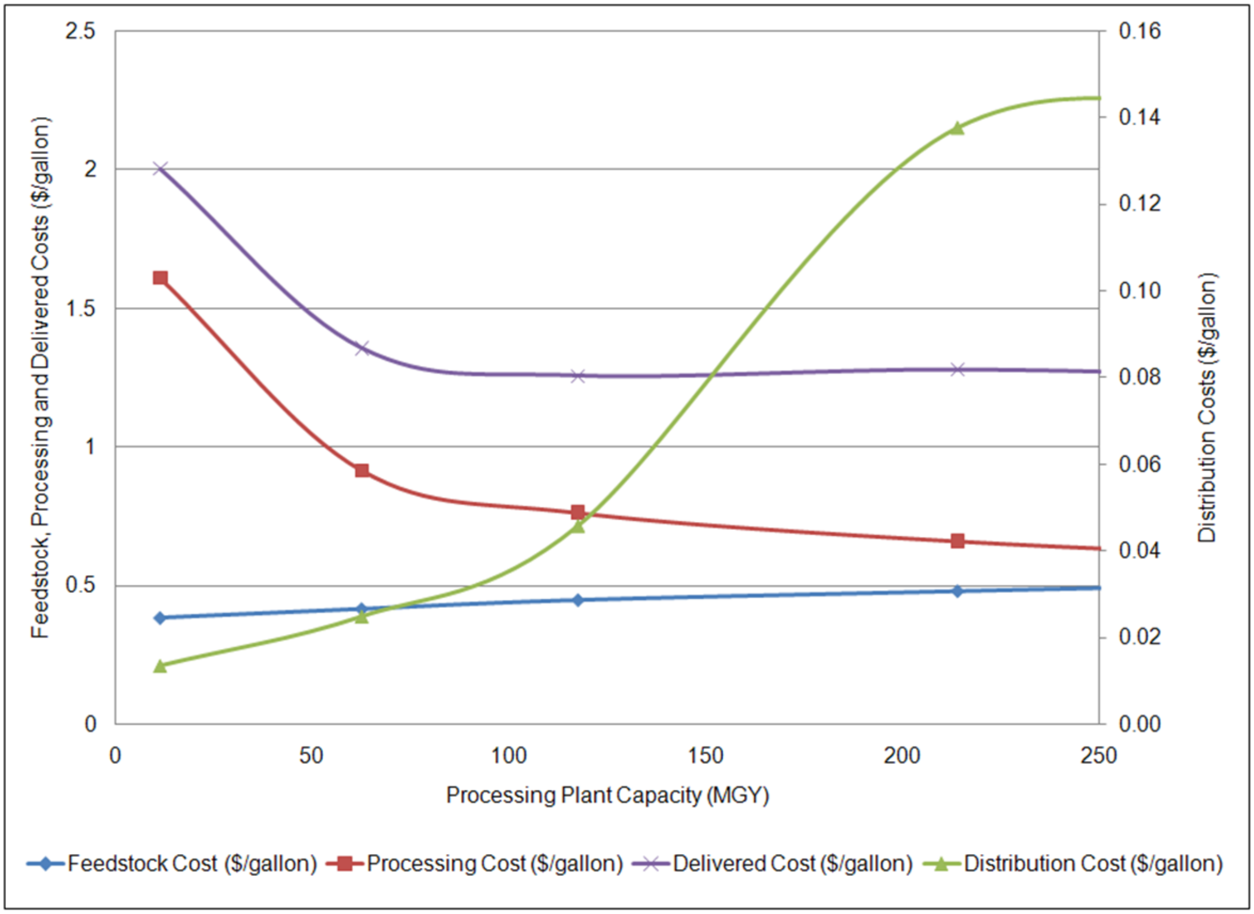
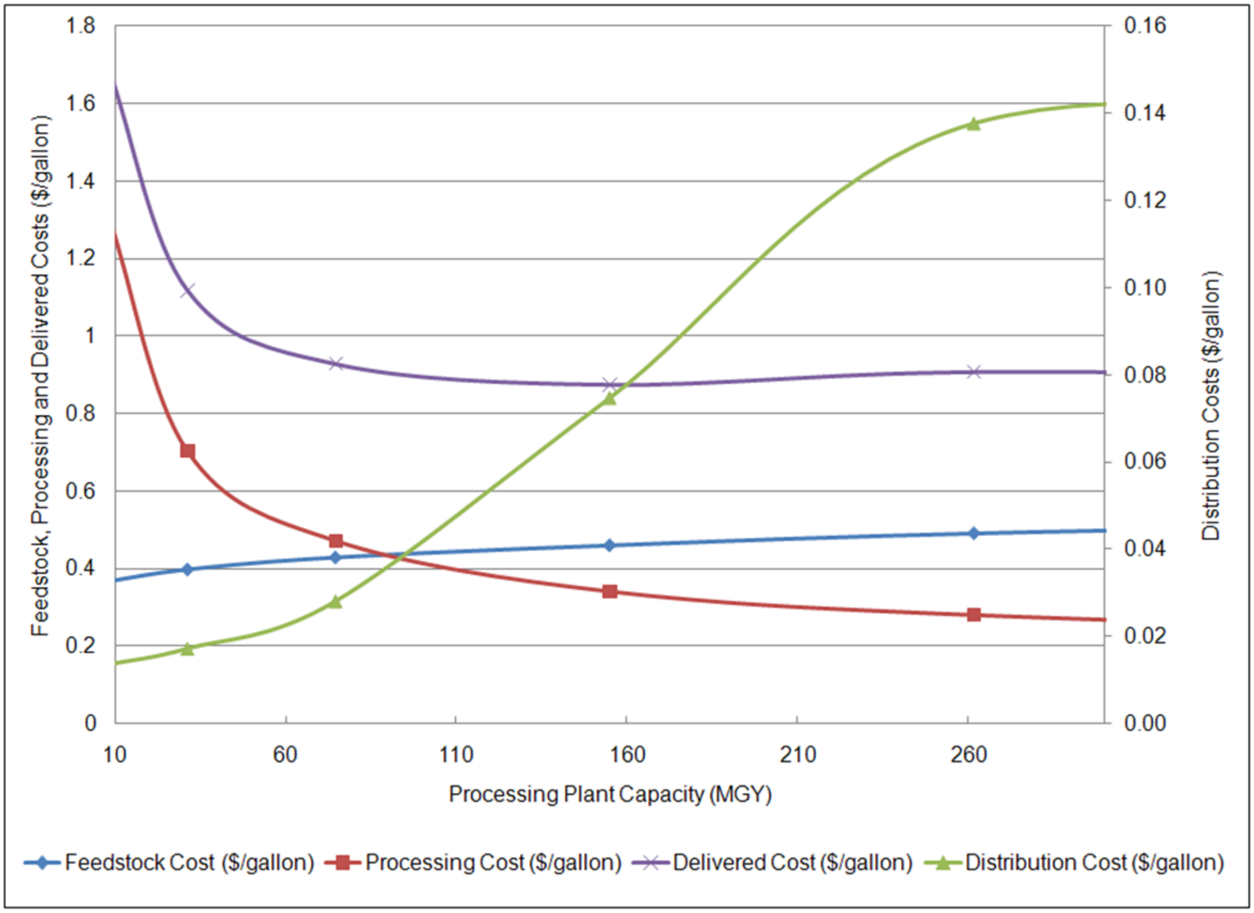


Figure 36 shows the delivered cost estimates using gasification technology for converting forest biomass into alcohol. The interpretation for downward sloping processing, and increasing transportation costs is similar to what was describe for the biological conversion technology above. The lowest point on the delivered cost curve ($0.87 per gallon) represents the least-cost of ethanol production using crop residue. The optimal size of the processing plant using gasification conversion technology at this location (Ellensburg) is 155 MGY.

Figure 36: Delivered Cost of Thermo-ethanol Using Forest Residue



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10
60
110
160
210
260
Feedstock, Processing and Delivered Costs ($/gallon)
Distribution Costs ($/gallon)
Processing Plant Capacity (MGY)
Feedstock Cost ($/gallon)
Processing Cost ($/gallon)
Delivered Cost ($/gallon)
Distribution Cost ($/gallon)

APPENDIX

Note: This appendix is an extended version of the transportation cost derivations summarized above.

Biomass Inventory Technology and Economics Assessments*
(Objective 4: Collection and Distribution Cost Curves)

By
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Transportation Research Group
School of Economic Sciences
Washington State University

***** The following is a supplemental material for the final report

Objective 4: Collection and Distribution Cost Curves *(WSU-Economic Sciences)*

Economists from the Transportation Research Group of WSU's School of Economic Sciences will build on the information available from the Phase I inventory by combining it with an extensive review of literature and analytical studies, as well as interviews, in the biomass arena to develop a business model of economic feasibility and financial returns. The first step is to determine the collection costs per ton-mile of the particular biomass, incorporating the form/condition of the biomass feedstocks since that is the first economic issue affecting collection costs. Then these supply cost curves will be combined with the internal plant processing costs from Objective 3 and the distribution costs (both fuel products and waste) per ton-mile to determine the delivered cost to alternative markets. The overall business model will consider alternative efficiencies in collection methods, incorporate the scale and size economies of the plant structure and the distribution costs to determine the least cost size, location and operation of the plant. The costs will be developed and presented in a spatial context by the use of GIS.

List of Acronyms

DOE	U.S. Department of Energy
EISA	Energy Independence and Security Act
EIA	Energy Information Administration
GIS	Geographic Information Systems
MGY	Million Gallons per Year
NREL	National Renewable Energy Laboratory
NADO	National Association of Development Organization
RFS	Renewable Fuel Standard
TRG	Transportation Research Group
TPEC	Total Purchased Equipment Cost
TPI	Total Project Investment
TIEC	Total Installed Equipment Cost
TPIC	Total Project Indirect Cost
WSU	Washington State University

Appendix Organization

Introduction and Background section introduces the objectives of this report, which is a part of the agreement between the Washington State Department of Ecology, the Department of Biological Systems Engineering and the School of Economic Sciences at Washington State University (WSU). It also provides an overview of the recent developments around cellulosic ethanol processing and challenges facing the biofuels industry in general. The section concludes with description of the Geographic Information Systems (GIS) methodology used for the feedstock collection and distribution cost derivations.

Geographic Distribution of Feedstocks introduces the spatial distribution of feedstocks in the study area by mapping available types of feedstocks in relation to the Washington State highway network using GIS.

An Overview of Transportation Modes section discuses alternative modes of transportation and compares carrying capacities for each mode.

Feedstock Production and Transportation section provides an extensive review of recent literature investigating cellulosic feedstocks harvesting and transportation methods. It also includes an economic engineering approach for deriving cellulosic feedstock transportation costs using truck transportation mode.

GIS Approach to Delivered Cost of Feedstocks (NREL Data) section demonstrates the application of GIS for deriving the delivered cost of feedstocks to a biorefinery in the state of Washington. This section uses data from National Renewable Energy Laboratory as a case study. Later in the report, we use this methodology to analyze Frear et al. (2005) data.

GIS Analysis for Biofuel Plant Least-Cost Location Decisions (NREL Data) section introduces a Geographic Information Systems based model (using NREL data) to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs. Similar to the previous section, we use the model in the next stage to analyze Frear et al. (2005) data.

GIS Approach to Delivered Feedstock Costs (Frear et al. Data) section introduces the results of the GIS method for deriving the delivered cost of feedstocks using biomass data identified in the first phase of this project (Frear et al. 2005).

GIS Analysis for Biofuel Plant Least-Cost Location Decisions (Frear et al. Data) section introduces the results found by applying the GIS-based methodology for identifying ethanol plant least-cost locations using to Frear et al. (2005) data.

Error! Reference source not found. section develops an economic modeling of cellulosic ethanol plants with different processing capacities. Resulting per-gallon ethanol processing costs were used for the delivered costs derivation.

Distribution Costs section utilizes trucking costs, modified for tanker truck configuration, and GIS methodology to derive ethanol distribution costs.

Delivered Costs section concludes the report by combining the feedstock transportation, processing and distribution costs to derive the delivered cost of ethanol to alternative markets.

Introduction and Background

Over many years of experimental processing, cellulosic ethanol has recently gained significant attention as a next generation of advanced fuels that will partially eliminate environmental and economic consequences of petroleum fuels and corn-based ethanol processing. In addition to considerable environmental benefits, the main advantages of cellulosic feedstocks are their resource abundance, higher energy returns (for several dedicated feedstocks), and competitive production costs (McLaughlin et al. 2002). However, besides the current technological (biomass-to-ethanol conversion) challenges with cellulosic feedstocks processing, there are numerous issues to be investigated. Such considerations include feedstock transportation and ethanol distribution costs, which may influence the viability of the industry through total delivered costs of the final product – the ethanol blend.

Current financial/economic crisis has imposed many obstacles for the effective implementation of the Renewable Fuel Standard (RFS) as mandated by the Energy Independence and Security Act (EISA) of 2007. Nevertheless, according to the recent USDA long-term projections report (USDA 2009) the ethanol industry is projected to expand in 2009. Despite the processing technological barriers (for the cellulosic ethanol) and logistical bottlenecks at feedstock producer level, the U.S. Department of Energy forecasts that 11 billion gallons of ethanol will be produced in 2009 (EIA 2008a). Another source suggests a potential capacity reaching more than 13 billion gallons of processing by the end of 2009 (Ethanol Producer Magazine 2008).

However, with the increasing levels of ethanol processing, the transportation infrastructure that is utilized for both feedstocks transportation and ethanol distribution needs to be improved accordingly. To accommodate the logistics of both corn and cellulose-based feedstocks, considerable improvements are needed for all three modes of transportation – rail, barge and truck. Because cellulosic feedstocks are geographically dispersed, the transportation infrastructure load will need to be adjusted and rebalanced. Given current absence of commercial scale cellulosic biorefineries, and the existing transportation bottlenecks, the ethanol industry expansion forecasts above are conditional on considerable improvements on every segment of the ethanol supply chain.

This report is a component (Objective 4) of the study investigating Washington's bioresources, which is a part of an agreement between Washington State Department of Ecology and the Department of Biological Systems Engineering and the School of Economic Sciences at Washington State University. In this report, as a continuation of the Project 1 (Biomass Inventory Technology and Economics Assessments) under the agreement, the Transportation Research Group (TRG) at WSU School of Economic Sciences analyzed economic feasibility of cellulosic ethanol processing. The analyses include investigation of feedstock harvesting, transportation, processing and distribution costs.

Earlier part of the study (Project 1) had geographically identified and categorized potential biomass sources in the state of Washington at a county level. The sources of biomass for cellulosic ethanol processing included field residue, animal waste, forestry residue, food packing/processing and municipal waste categories. This study expands the previous work by spatially investigating types of available biomass, incorporates geographically varying road infrastructure and hauling distances from fields to prospective biorefineries, as well as from biorefineries to markets throughout the state of Washington.

As an initial step for geographically identifying feedstock transportation and distribution cost-minimizing potential refinery locations, the biomass was mapped in relation to the Washington State highway network using GIS. Considering different harvesting technologies, feedstock collection costs of agricultural crops residue and forest residue were derived. Recovery costs of other sources of biomass, such as animal manure and municipal solid waste

(MSW) were adapted from the recent research literature. Per ton mile hauling costs of feedstocks have been derived using an economic engineering approach that includes both fixed and variable costs of trucking operation for relevant truck configurations. Total trucking costs include expenses, such as fixed vehicle costs (truck and trailer, depreciation and license fees, etc.), fixed business costs (management, insurance, interest, etc.) and variable costs (truck – driver wages, fuel, repairs, maintenance, tires, miscellaneous; trailer – repairs, maintenance, tires, miscellaneous).

Due to the spatially variable availability characteristic, the total biomass that was identified in the first phase of this project cannot be fully utilized at the same expense. To assess the delivered costs of the feedstocks to biorefineries, the farm-gate price of feedstocks, transportation costs, biomass availability and geographic distribution information were integrated. In addition, to avoid inaccurate evaluation of economic feasibility or volumes of cellulosic ethanol processing, we considered the proximity of the processing plants to market locations as well. For that purpose, we have developed a Geographic Information Systems based model to support cellulosic ethanol plant least-cost location decisions by integrating delivery market destinations. After testing the model with the National Renewable Laboratory (NREL) data, we used the data compiled in the first phase of this project (Frear et al. 2005).

Six types of biomass – agricultural crops residue, forest residue, animal waste, food waste, wood residue, and paper waste have spatially been analyzed with the use of GIS Network Analyst toolset to derive the delivered costs (supply curves) of feedstocks to biorefineries in the state. These supply curves were further combined with the internal plant processing costs derived in Objective 3 of this project. From each biorefinery in the study area, per ton mile distribution costs have been calculated for ethanol distribution to alternative markets. To determine distribution costs, GIS methodology similar to the feedstock transportation costs was used by incorporating origin (processing plants/blending terminals) and destination (ethanol fueling station locations in the state) data.

Geographic Distribution of Feedstocks

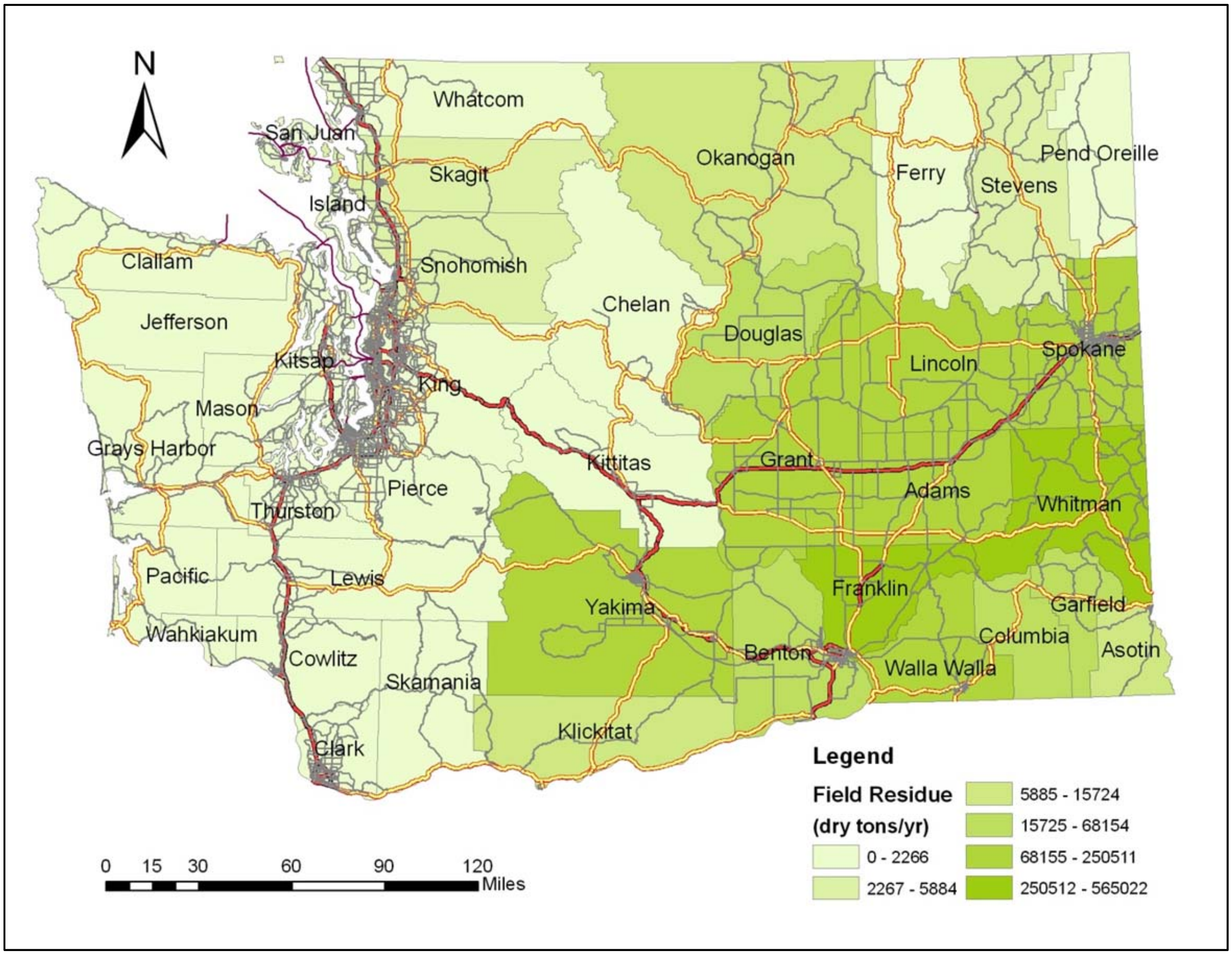
According to biomass inventory assessment findings (Project 1, Frear et al. 2005), Washington's biomass is underutilized by 16.9 million annual tons. Another source, the NREL, had geographically identified forest residue, crops residue, urban wood, primary mill, methane emissions from landfill as the primary sources of biomass in the state. Based on the 75 gallon per dry ton biomass-to-ethanol conversion rate, NREL (2007) data show that only agricultural crops residue category (which is 20% of the state's total biomass available) could support up to 130 million gallons per year (MGY) ethanol processing.

Figure 37 shows the geographic distribution of agricultural crops residue in the state of Washington in relation to the State highway network using Frear et al. 2005 data. Comprising of thirteen counties,[3] the Southwest region produces more than 95% of the State's agricultural crop residues. Considering economically feasible feedstock collection and 75 gallon per dry ton biomass-to-ethanol conversion rate, this reveals underutilization of biomass equivalent to 170 MGY ethanol processing. However, because of an increasing transportation distances (required for larger processing capacities), all of the identified available residue cannot be utilized at the same expense. Consequently, to ensure economically feasible production, processing plants considering crop residue as a feedstock need to optimize their locations or processing capacity based on the "affordable" feedstock distribution. Although, the optimal location is primarily sensitive to feedstock transportation distances, however, the proximity of

[3] Twelve counties include Adams, Asotin, Benton, Columbia, Douglas, Franklin, Garfield, Grant, Lincoln, Spokane, Walla Walla, Yakima and Whitman.

blending terminals and final markets is also important. We analyze the proximity of markets to processing plants in the distribution costs section.

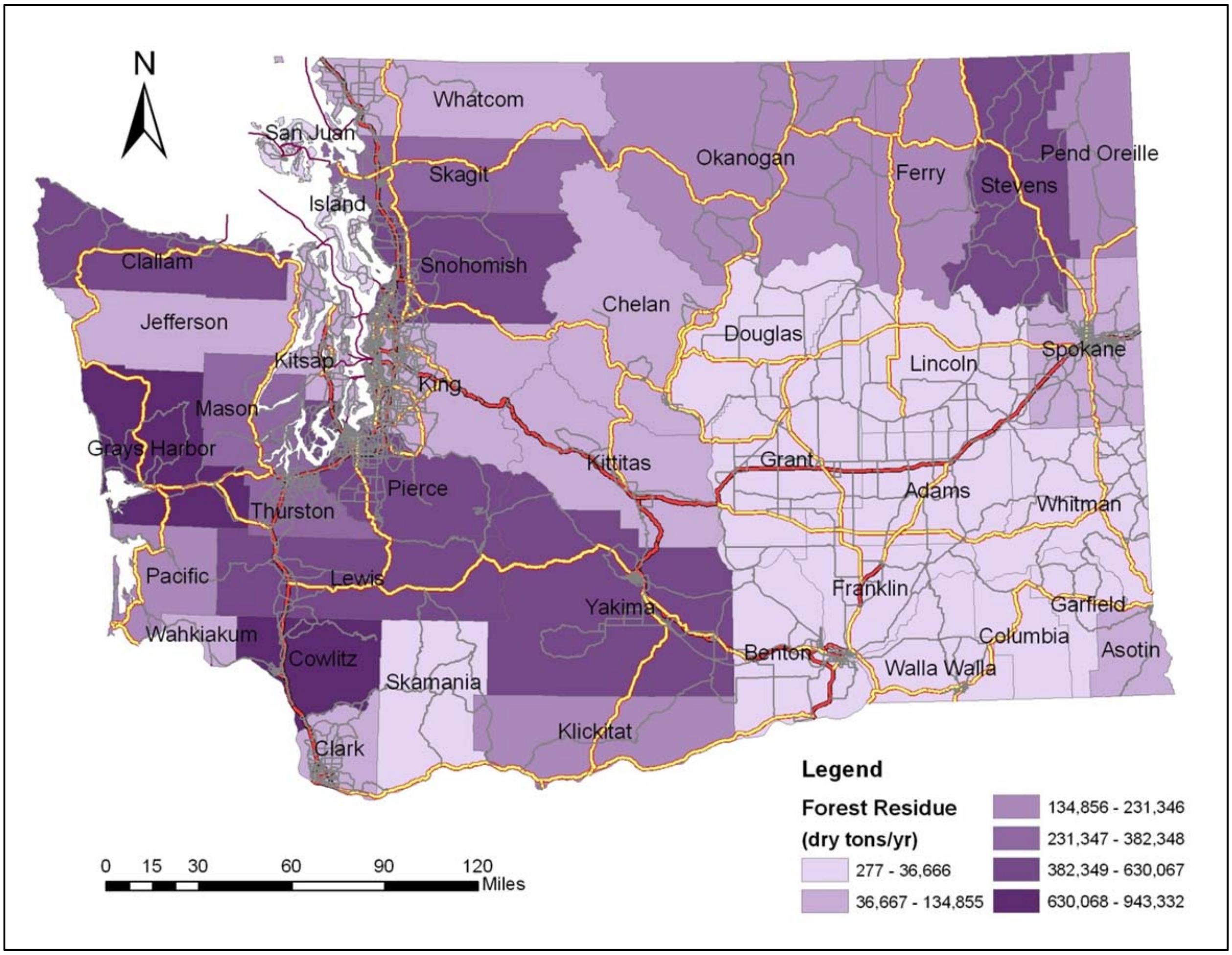
Figure 37: Geographic Distribution of Crop Residue in Relation to the Road Network



For agricultural crop residue in particular, besides the transportation cost component, there are issues concerning soil fertility after the crop residue is harvested. The required quantity of the biomass to be left on the field to ensure soil fertility may adversely impact the delivered costs. By assessing county-level availability of wheat straw and the economics of ethanol processing in the state of Washington, Kerstetter and Lyons (2001) used five-year average of crop yields to develop biomass supply curves for the hypothetical biorefinery location. As a result, considering the 20 MGY capacity ethanol facility, the study found that the price of the delivered straw is highly sensitive to the amount of straw left on the ground to assure soil fertility and sustainable crop production. Additionally, the amount of residue that needs to be left on the field for soil fertility controls may differ according to soil type, crop type and region specific weather conditions.

Next feedstock category, forest residue, includes logging residues and other removals, such as unconsolidated slash, chips, and comminuted or bundled residues. A separation of different parts (sorting) of the three, such as leaves and needles, stumps, etc., is important since depending on its form, pre-processing, drying and storage may influence the quality of the feedstock. As shown in Figure 38, forest residue is mostly distributed throughout the Western, and partially in the Northern part of the state.

Figure 38: Geographic Distribution of Forest Residue in Relation to the Road Network



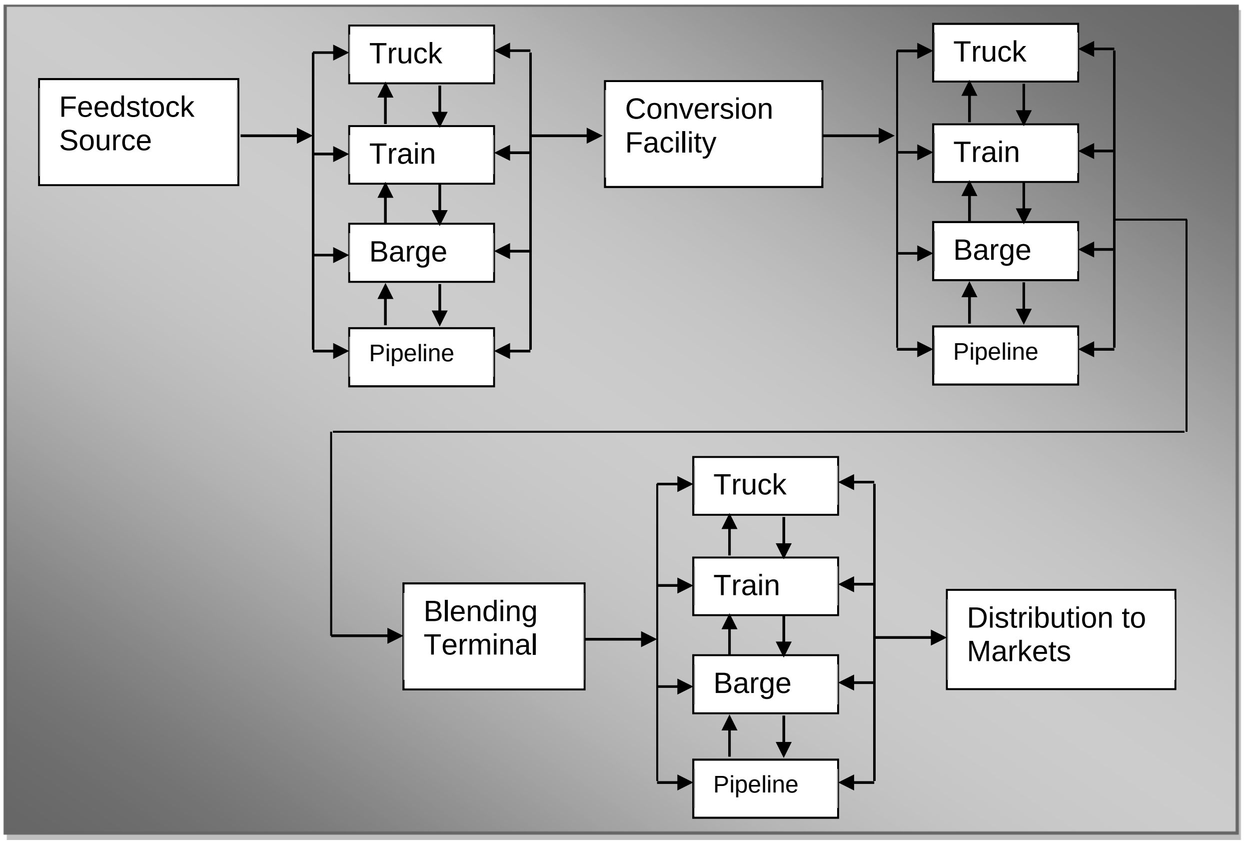
Geographic distributions of different types of biomass, such as animal manure, urban wood residues, primary and secondary mill residues, methane emissions from landfill and domestic wastewater treatment are provided in the Geographic Distribution of Biomass in the State of Washington section.

An Overview of Transportation Modes

Only recently, one of the most important considerations for successful and reliable development of the ethanol industry – the economics of transportation gained proper attention (Morrow et al. 2006). Transportation issues regarding cellulosic feedstock shipments to ethanol processing plants, outbound shipments of ethanol to blending terminals and to the end-users are the key components for cost-competitiveness of the industry [National Association of Development Organization (NADO) Research Foundation 2007].

Depending on numerous factors that vary according to the local transportation infrastructure, the mode of transportation for different segments of the biofuels processing may differ (Figure 39). Among others, the main factors include proximity of feedstock sources to biorefineries and blending terminals to markets, size of the shipments, form of the feedstock, and alternative (rail/barge) modes accessibility.

Figure 39: Modes of Transportation for Different Stages of Biofuels Processing



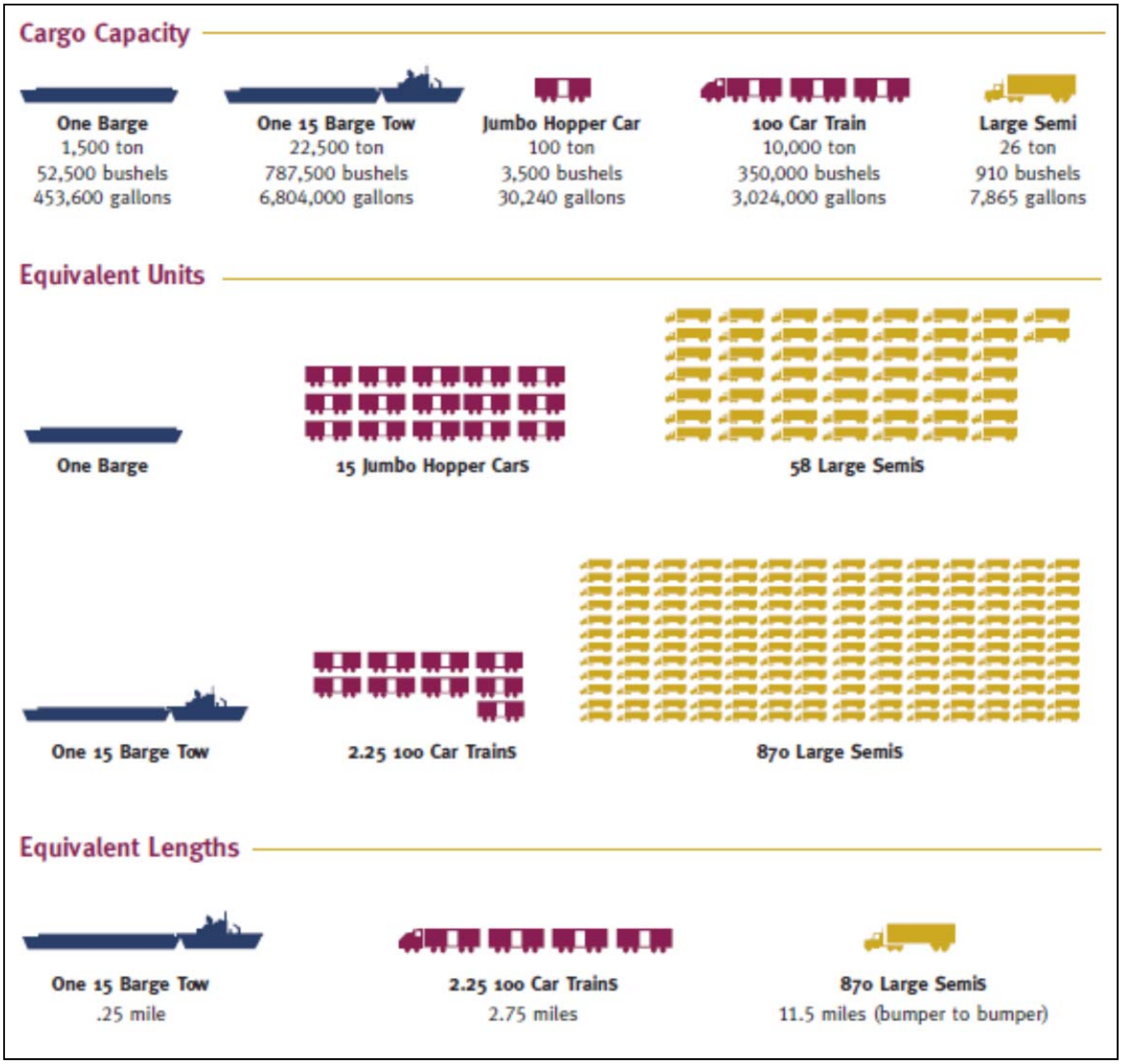
According to the U.S. DOE (2003), all of the current biomass and biofuel transportation efficiencies need considerable improvements. Rail transportation can be more cost-efficient for ethanol transportation when certain conditions are met. Large size processing plants requiring longer-distance shipments (less dependent on time) prefer rail transportation for cost minimization purposes. However, general drawbacks of the rail mode include current shortage of rail tank cars, longer time periods required to fill a unit train (NADO Research Foundation 2007), and high capital costs. Although, the rail option can be more efficient for point to point shipments, its immobility can directly affect the delivery times (reliability issue) of feedstock to conversion facilities, especially for small and mid-size processing plants (Casavant and Jessup 2007).

If accessibility and some additional conditions are met, waterborne transportation, complemented by truck transportation, can be the lowest option for ethanol transportation from processing plant to blending terminal segment. According to Stevens (2008) and Iowa Department of Transportation (2008), one barge tow with capacity of 22,500 tons is equivalent to a 2.25 100-car train or 870 large semi trucks (Figure 40). Nevertheless, even with its large capacity (beneficial for highway congestion issues) and fuel efficiency, barge transportation has numerous limitations concerning accessibility, speed of delivery and its aging infrastructure (Stevens 2008).

Other options, such as pipeline transportation have been investigated as an alternative to reduce traffic congestion created by feedstock hauling trucks, and to minimize processing costs. Most notably among others, Kumar et al. (2005) compared the cost of transporting corn stover by truck and pipeline (on a wet basis) at 20% solids concentration. As suggested by the authors, a wide variation of previously reported trucking costs made the comparison useful only with mid range of variable trucking costs ($0.1167 per dry-ton-kilometer). Under this scenario, pipeline transportation revealed a 20 percent reduction in transportation costs for the plant with the capacity of 1.4 million dry tons per year (~105 MGY). However, transportation modes such as pipelines require more technological investigation (due to ethanol's water attracting characteristic) to make the system operational (McCormick et al. 2003).

Casavant and Jessup (2007) categorized economic attributes including cost, market coverage, degree of competition, traffic/product type, length of haul and capacity of truck transportation.

Figure 40: Truck, Rail and Barge Mode Carrying Capacity Comparisons



Source: Iowa Department of Transportation (2008).

Combined with service attributes that involve speed, availability, consistency/delivery time, loss/damage and flexibility, the truck transportation is by far the most flexible option for feedstock transportation. For the purposes of transportation cost analyses in this study, only truck transportation is considered.

Feedstock Production and Transportation

The delivered cost of feedstocks contains collection and transportation cost components. The collection or harvesting part is a function of several considerations including resource availability, equipments used and harvesting methods. Loading, transporting to a nearby storage facility, and unloading is oftern included in the harvesting costs. The feedstock transportation costs from sources (fields or storage facilities) to conversion facilities is included in the feedstock transportation part of the delivered cost. Because of a variety of factors involved in the process, the previous literature suggests a range of feedstock farm-gate costs.

Given the geographic distribution of the cellulosic biomass, such as crop residue in the state, the marginal delivered cost of the feedstock is expected to increase, for larger capacity processing plants, since the hauling distances become longer. Alghough for a specific feedstock the collection costs may be comparatively similar from one geographic area to another, longer-distance transportation dirrectly affect the delivered cost of the feedstock. This is explained by increasing feedstock demand required to support larger capacity conversion plants.

Feedstock Collection Characteristics

Agricultural Crop Residue

One of the commonly accepted methods to derive feedstock supply curves that include both harvesting and transportation cost calculations is a spreadsheet-based model. Sokhansanj et al. (2006) developed spreadsheet-based IBSAL (Integrated Biomass Supply Analysis and Logistics) that incorporates weather conditions to calculate corn stover collection costs using baling system. Consisting of four-step operation, including combining, shredding, baling and stacking, the overall cost of stover harvesting was found to be $23.27 per dry ton. Assuming flat-bed trailers carrying about 36 rectangular bales, and front-end loaders equipped with special bale grabbers for loading/unloading and stacking the bales, the IBSAL model simulation resulted in $35.76 per dry ton transportation cost for travel distances ranging from 32 to 160 km. Since the distance of feedstock transportation directly influences delivered costs, many spreadsheet-based estimates in the previous research reports were found for only specific haul-destinations.

Sokhansanj and Turhollow (2002) examined two methods to calculate corn stover collection baseline costs. Assuming fully mechanized harvesting and transport system, and five mile distance to the storage, costs for collecting corn stover residue totaled $19.70 and $21.40 per dry ton for round and for rectangular bales respectively. The difference in cost was explained by the additional operation and higher equipment cost for the rectangular baling system.

Another feedstock recovery method that recently gained attention is preprocessing of feedstocks before transporting to processing facility. Atchison and Hettenhaus (2003) introduced innovative methods for harvesting, storage and transportation costs of corn stover. To account for collection delays, feedstock drying and densification methods were investigated, which were found to increase costs from $35 to around $50 per dry ton. In comparison with baling, one-pass harvest method resulted in a significant cost reduction. Depending on the yield, net returns to a farmer were $22-$47 per acre, while baling totaled $16-$22 per acre for the same harvesting area.

Comparing rail and truck efficiencies, Atchison and Hettenhaus (2003) emphasize the limitations of the rail depending on local infrastructure situations/constraints. However, if feedstock supply area is economically expanded (up to 300 mile distance) by locating additional harvesting sites, the collection costs using rail transportation were found to be in $3 to $10 per dry ton range, compared to more than $15 per dry ton for trucking option.

Perlack and Turhollow (2002) investigated the logistics of four different methods to estimate harvesting, handling, and transporting costs of corn stover to a biorefinery. The authors assumed conventional equipment for baling, trucks and flat-bed trailers for the transportation of collected stover to a storage. Large round and large rectangular baling methods resulted in $44 – 49 per dry ton for harvesting, storage and haulage, including procurement costs.

Perlack and Turhollow (2003) introduced an economic-engineering assessment of corn stover harvesting and transportation for 500 to 4,000 tons per day capacity ethanol processing facilities. The study considered fast tractors transferring large bales of corn stover from fields to storage, which then were hauled to a biorefinery using flat-bed trailers carrying 29 large bales. The feedstock costs for several biorefinery capacities were investigated to understand the economies of scale associated with processing costs. However, the feedstock delivery distances were calculated using straight line method from field to a biorefinery with a road winding factor, which partially eliminates local road infrastructure characteristics. According to this study's findings, the delivered cost of stover increased from $44.80 to $53.70 per ton for the 500 and 4,000 tons per day capacity biorefineries respectively.

Another research paper (Sokhansanj and Fenton 2006) developed a dynamic model to simulate harvesting and transportation costs for crop residues and switchgrass incorporating four different collection options. According to Sokhansanj and Fenton (2006), baling is the most common and widely used method for crop residue harvesting.[4] Factors affecting the size and mode of transportation include the frequency of biomass supply to a biorefinery, the density of biomass, proximity of the biomass source to the biorefinery, the transportation infrastructure between biomass sources and processing plants. Sokhansanj and Fenton (2006) found that the biggest impact on the transportation mode decision is ascribed to the physical form and quality of biomass.

Jenkins et al. (2000) used surveys and time-and-motion studies to evaluate performance and economics of rice straw harvest, transport, and storage systems for industrial applications. Analyzing three types of bales, the study found that total harvest costs range from as low as $7.50, reaching up to $42.79 per ton of rice straw. The large bales had an average total harvest cost of $12.77 per dry ton. Transportation costs for the large bales assuming flat-bed trailers with19 tons payload had been estimated as $9.10 per ton for a 32 km one-way haul distance. This cost included loading and unloading costs accounting for $4.58 per ton of straw and a distance-dependent cost of $0.14 per-ton-kilometer.

Switchgrass and Short Rotation Woody Crop

Kumar and Sokhansanj (2007) used the previously developed spreadsheet-based method (Sokhansanj et al. 2006) to model three biomass collection and transportation systems for

[4] A procedure for the crop residue harvesting slightly differs from corn stover operations, since a combine is processing most part of the straw. In case of corn stover, the majority of the corn stalk is left on the ground, which is then shredded and made ready for baling.

switchgrass. Delivered costs to a biorefinery with the capacity of 1,841 dry tons per day totaled $44-$47 per dry ton for both round and square bales. Loafing, chopping-pilling, chopping-ensiling methods resulted in $37, $40 and $48 per dry ton respectively. Comparable results ($40 per dry ton) for the switchgrass farm gate costs were found in McLaughlin et al. (2002). According to the authors, switchgrass is economically feasible feedstock and will significantly contribute to biofuel industry advancements.

Graham et al. (1997) summarized nationwide county-level energy crop yields, acreage of land suitable for energy crops and farm-gate price predictions from the Oak Ridge Energy Crop County-Level (ORECCL) database. The average farm-gate price for a short rotation woody crop (SRWC) production in the state of Washington was predicted $86.13 per dry ton, emphasizing aforementioned variation in research conclusions.

Harvesting and Transportation Costs Comparison

As mentioned eariler, there is a wide disparity in previous research recommendations on the feedstock supply system cost components. In the harvesting component, the variation partially depends on methods and equipment used, and processing plant size assumptions. Generally, comprised of combining, shredding, baling and stacking operations, feedstock harvestings costs were found to be in about $14 to $35 per dry ton range. Table 1 summarizes harvesting costs considering different harvesting methods found in selected papers.

Table 1: Harvesting Costs (per dry ton)

Author/s Name	Feedstock Name	Harvesting Options/Methods				
Kumar and Sokhansanj (2007)[a]	Switchgrass	Square Bales $24.10	Round Bales $22.62	Loafing $13.67	Chopping-Pilling $14.81	Chopping-Ensiling $22.63
Sokhansanj et al. (2006)	Stover	Baling [b] $19.16 [c] (21.12 $ Mg^{-1})				
Sokhansanj and Fenton (2006)	Switchgrass and crop residues	Square bales $23.72	Loafing $19.69	Chopping Dry – Piling $35.71	Chopping Moist - Ensiling $35.12	
Sokhansanj and Turhollow (2002)[d]	Corn Stover	Round Bales $19.70		Rectangular Bales $21.40		
Perlack and Turhollow (2002)[e]	Corn Stover	Large Round Bales $24.80	Large Rectangular Bales $22.25	Unprocessed - Pickup High Cost $26.80	Unprocessed Pickup-Low Cost $21.67	

[a] Calculations did not include production costs such as machinery operations, seeds, fertilizers, lime, herbicides, land charges, reseeding, etc.
[b] Harvesting methods were not specified.
[c] The value was converted from $ Mg^{-1} to $/ton using 1.102 conversion rate.
[d] See the paper for additional assumptions.
[e] Calculations include delivery to a storage for the facility with 4000 dry tons per day processing capacity.

Table 2 provides estimates from recent research literature on transportation costs considering fixed and variable haul distances. Many of these studies estimated the amount of feedstock availability within given straight line radius around biorefineries by assuming average yields and average production costs for the entire study area. The variation in feedstock transportation costs ($/per dry ton) ranging from around $7 – $29 ($/per dry ton) can partially be explained by the different haul distance and truck configuration assumptions.

Table 2: Transportation Costs (per dry ton)

<table>
<tr><th>Author/s Name</th><th>Feedstock Name</th><th colspan="4">Harvesting Options/Truck Configurations</th></tr>
<tr><td>Kumar and Sokhansanj (2007)[a]</td><td>Switchgrass</td><td>Load bale – truck (stationary grinder)
$21.19</td><td colspan="2">Bale or loaf is ground (mobile grinder) – truck
$23.19</td><td>Ground biomass (pile or silage) - truck
$25.32</td></tr>
<tr><td>Sokhansanj et al. (2006)[b]</td><td>Stover</td><td colspan="4">Rectangular bales are placed on the trailers using bale grabbers
$29.45 [c] (32.45 $ Mg^{-1})</td></tr>
<tr><td>Sokhansanj and Fenton (2006)[d]</td><td>Switchgrass and Crop Residues</td><td colspan="2">Large square bale – flat-bed trailer (variable distance: 20-100 km)
$19.41</td><td colspan="2">Large square bale – flat-bed trailer (fixed distance: 100 km)
$25.83</td></tr>
<tr><td>Perlack and Turhollow (2002)[e]</td><td>Corn Stover</td><td>Large Round Bales
$10.06</td><td>Large Rectangular Bales
$10.62</td><td>Unprocessed Pickup – High Cost
$7.32</td><td>Unprocessed Pickup- Low Cost
$7.32</td></tr>
</table>

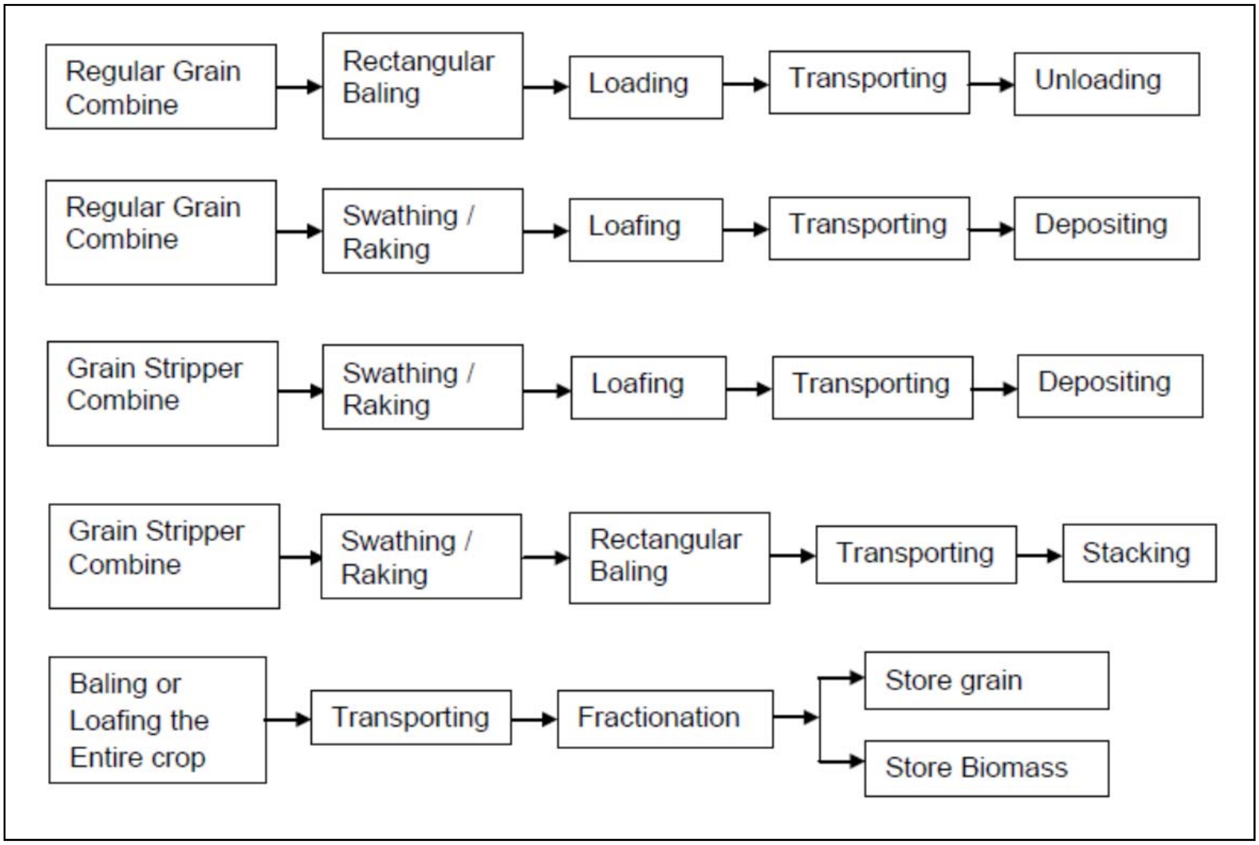
[a] The transportation cost includes loading, traveling and unloading expenses and is averaged over a year.
[b] The transportation cost includes grinding, transporting, loading and unloading.
[c] The value is converted from $/Mg to $/ton using 1.102 conversion rate.
[d] The transport operations used for the cost calculation include loading, traveling, unloading, stacking and grinding.
[e] A facility with 4000 dry ton/day processing capacity was considered.

Factors that influence delivered feedstocks costs, including weather conditions, proximity of feedstock collection area to biorefineries, and road infrastructure, may differ from one geographic region to another. Therefore, an economic evaluation of transportation costs should account for varying haul distances and local transportation infrastructure.

Crop Residue Collection Process and Costs

Feedstock cost is one of the most important components for analyzing the viability of both corn- and cellulose-based ethanol production. To calculate the cost of agricultural residue harvesting, transportation to storage facility, and the transportation costs to biorefineries, several components have to be considered: 1) physical characteristics of residue – form/condition, 2) field operations – swathing, raking, shredding, baling, stacking, loading, transporting to nearby storage facility and unloading, 3) equipment used for field operations, its service life, as well as capital costs and maintenance 4) wages, tax, interest and insurance expenses. Figure 41 shows the feedstock collection process for five different collection methods for agricultural crop residue, modified from Sokhansanj and Fenton (2006).

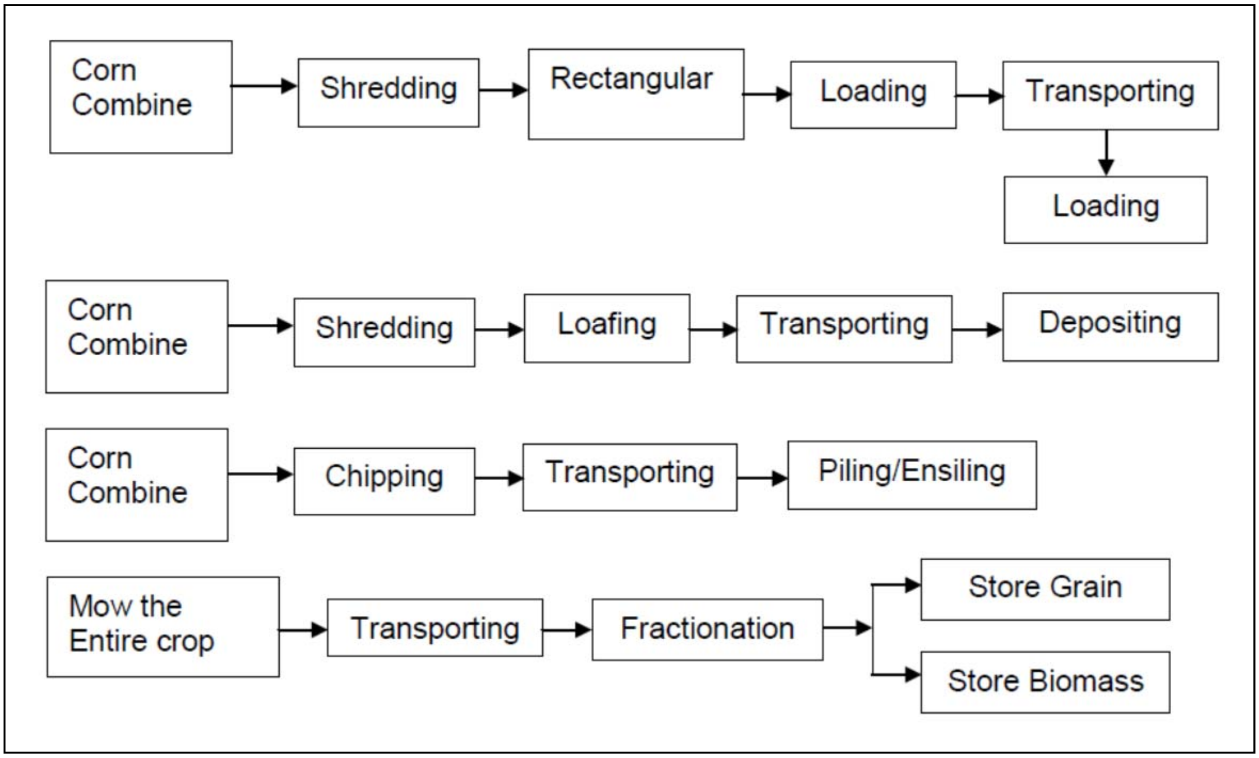
Figure 41: Collection Methods for Agricultural Crops Residue (straw)



The straw is ready for harvesting as a feedstock for biofuel processing after the grain harvest. Using regular grain combine, two methods are presented in the flowcharts – baling and loafing. Similar to the regular grain combine, baling and loafing operations can be performed using grain stripper combine.[5] Raking operation (when applicable) is used before baling when straw height is less than 0.15 m. Raking forms windrows from swathed straw, which allows catching more wind and thus, allows quicker drying. It also increases the volume of straw to be processed by the baling equipment. Figure 42 provides similar flowcharts for four corn stover harvesting methods.

Figure 42: Collection Methods for Agricultural Crops Residue (corn stover)

[5] The grain stripper uses rows of polyurethane plastic teeth to strip grain from stems, and leaves stems rooted in the ground.



Generally, rectangular or round baling option is found to be the most accepted method for straw harvesting (Cundiff 1996). Within those two options, considering an economic feasibility of feedstock transportation to biorefineries, rectangular bales are more convenient for flat-bed trailer loadings. The dimensions of conventional types of bales used for commercial straw harvesting are presented in the Table 3.

Table 3: Predominant Bale Types, Dimensions, Volume and Weight

Bale type	Dimensions (m)	Volume (m^3)	Weight (~kg, dry matter)
Small rectangular	$0.4 \times 0.6 \times 1.2$	0.3	32
Large rectangular (Hesston type)	$1.2 \times 1.2 \times 2.4$	3.5	600
Large rectangular (Freeman type)	$0.9 \times 1.2 \times 2.4$	2.6	450

Source: Jenkins et al. (2000).

Depending on moisture level, speed and capacity of swathing and raking operations may differ. Due to the relatively light weight of the equipment, soil moisture affects the speed of operation less than the straw moisture (Jenkins et al. 2000). The relationship between soil/straw moisture and the speed of different operations, such as raking, swathing, baling is shown in the Table 4.

Table 4: Seasonality Straw/Soil Moisture and Harvesting Operations Speed

Operation	Straw Moisture (% w.b)[1]	Soil Moisture (% w.b)	Average Speed (mile/hour)
Raking			
Fall	19	18	6.96
Spring	11	32	4.47
Swathing			
Fall	29	21	3.35
Spring	12	24	1.5
Baling			
Fall, small bales, $0.4 \times 0.6 \times 1.2$	11	19	2.42
Fall, large bales, $0.9 \times 1.2 \times 2.4$	10	28	3.97
Fall, large bales, $1.2 \times 1.2 \times 2.4$	12	18	4.03
Spring, large bales, $1.2 \times 1.2 \times 2.4$	11	24	5.22
Road-siding			
Fall, small bales, $0.4 \times 0.6 \times 1.2$	9	15	-
Fall, large bales, $0.9 \times 1.2 \times 2.4$	11	29	-
Fall, large bales, $1.2 \times 1.2 \times 2.4$	12	22	-
Spring, large bales, $1.2 \times 1.2 \times 2.4$	11	-	-

Source: Jenkins et al. (2000)
[1] wet basis percentage.

The loafing method shown in the flowcharts above differs from the baling by forming large stacks of straw. One of the advantages with loafing option is that the harvesting, densification and transportation to the storage area is performed with one piece of equipment. Note that if the grain stripper combine is used with baling option, then the loading, transportation and unloading steps are the same as baling with regular grain combine described above.

Simultaneously with the baling operation, a bale accumulator collects the bales in group of four, and transports to the nearby storage facility. Another method used for the bales collection from fields is road-siding, which essentially is a process of moving the bales from the field to the edge of the field. Both of these operations are included in the transporting part depicted in the collection methods flowchart. In the next step of the process, the bales are loaded with front end loader onto flat-bed trucks and transported to the storage facility. Feedstock Harvesting and Transportation Efficiencies includes figures with the equipment discussed in the crop residue harvesting process.

Most common truck configurations used for the bales transportation to storages are trucks with flat-bed or drop-bed trailers. Due to an additional space, drop-bed trailer carry more payload compared to flat-bed trailers. On average, semi-trucks with flat-bed trailers can carry up to 20 tons payload weight with large Freeman-type large bales. At the storage facility, bales are unloaded using loader equipment. Table 5 shows the relationship between bale size and payload, average loading/unloading time, as well as travel speed and time.

Table 5: Characteristics of Bales Transportation to Storage Facility

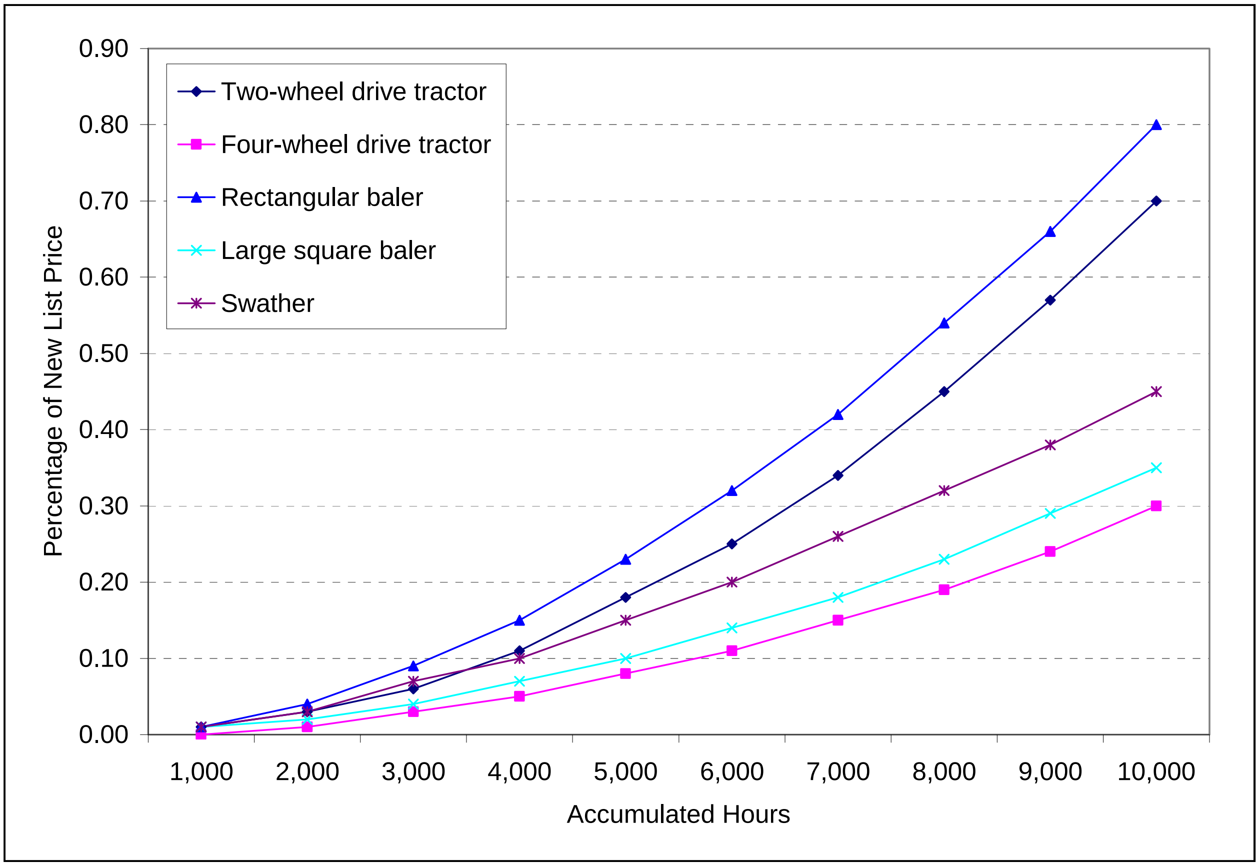
Bale Dimensions (meter)	Number of Bales	Payload (Mg)	Average Loading Time (min)	Average Travel Distance (mile)	Average Travel Time (min)	Average Travel Speed (miles/hour)	Average Unloading Time (min)
Double Flat-bed Trailer							
Small 0.4 × 0.6 × 1.2	460-512	14.5	32	91.3	122	44.7	22
Large 0.9 × 1.2 × 2.4	42-48	18.1	15	8.7	17	31.7	16
Large 1.2 × 1.2 × 2.4	28-30	16.3	21	155.4	188	49.7	14
Double Drop-bed Trailer							
Large 1.2 × 1.2 × 2.4	36-38	19.1	29	28	41	41	31

Source: Jenkins et al. (2000)

A direct relationship exists between farm equipment repair and maintenance costs and their lifetime hours of operation.
Figure 43 shows the relationship between tractor lifetime hours of operation and total repair costs based on Edwards (2002) data. This may suggest that for the short term, new equipment purchase increases capital investments, but for the long run (as shown in Figure 43), significant savings in terms of relatively low repairs costs may be gained.

At a given level of operation hours, four-wheel drive tractor accumulates less repair expenses compared to two-wheel drive tractor. After around 4,500 hours of operation, the rate of repair costs as percentage of a new list price significantly increases for both two- and four-wheel drive tractors, as well as for baling and swathing equipments.

Figure 43: Lifetime Hours of Operation and Repairs Costs as Percentage of New List Price



Field activity average costs were derived using an economic engineering approach, combined with the survey data by Sokhansanj and Turhollow (2002) and Jenkins et al. (2000). The results for both large and small rectangular bales are summarized in Table 6. Images for feedstock harvesting machinery and transportation can be found in Feedstock Harvesting and Transportation Efficiencies section of the supplemental material. Based on our calculations (Table 6) and the estimates found in the recent literature, in this study the agricultural crop residue is considered to be available at $30 per dry ton farm-gate cost.

Table 6: Agricultural Crop Residue Harvesting and Transportation to Storage Facility (Average Costs)

Operation/Activity	**Costs ($/ton)**	
	Large Rectangular Bales	Small Rectangular Bales
Swathing	5.51	4.80
Raking	1.70	1.70
Baling	10.80	9.66
Road-siding	4.54	4.54
Loading/Unloading	3.30	3.30

Transporting (field storage)[6]	3.32	3.32
Storage (under tarp)	2.26	2.26
Total Costs	31.43	29.58

Animal Waste Feedstock Cost

For purposes in this report, animal waste category includes five different manure categories – dairy, cattle, horse, swine, and poultry. Several research papers tried to assess the transportation costs and net benefits of using animal manure for crop production. The potential use of animal waste for ethanol processing purposes may change public opinions about health and environmental degradation from increased geographic concentration of manure stacks and odors (Fleming et al. 1998). However, similar to other commodities with low value-mass ratios, the net benefit of manure utilization is influenced by the haul distance and the nutrient content. High transportation costs limit the distance that the animal waste can be economically hauled (Keplinger and Hauck 2006). Additionally, the transportation costs are also influenced by timeliness of collection and depth of manure scraping (to keep the dirt content below 60 percent and moisture content below 20 percent).

Whittington et al. (2007) conducted an industry survey and reported poultry litter estimates for manure transportation costs in Mississippi. Using the collected data, the authors derived the transportation cost function as follows: $C_m = 0.1 + 0.002 \times D$, where C_m is the per-ton-mile cost of transportation, D is the distance traveled, 0.1 is the fixed costs associated with shipping poultry litter, and $0.002 \times D$ represents the variable costs incurred with the shipment. As mentioned above, manure may be shipped with varying moisture contents.

Table 7 provides a summary of manure transportation cost estimates for different moisture content found in recent literature (Ghafoori et al. 2007; Aillery et al. 2005; and Ribaudo et al. 2003).

Table 7: Manure Transportation Costs

Manure	Moisture Content (%)	Variable Cost ($ per-ton-km)	Fixed Cost ($ per ton)
Lagoon Manure	99	0.22	2.31
Slurry Manure	95	0.22	2.31
Dry Manure	50	0.08	11.57

Estimates in Table 7 suggest that lagoon and slurry forms of manure are suitable for short-haul distances. If this type of feedstock can consistently be produced, and is available for ethanol processing, a localized processing may eliminate high transportation costs. However, moisture reduced from of manure is easier to transport (Goodwin et al. 2007). Considering the time sensitivity of feedstock transportation to support consistent ethanol processing, we use dry manure cost estimates (i.e., $11.5 per dry manure[7]) for purposes in this report. Goodwin et al. (2007) estimated plastic-wrapped bales poultry litter procurement costs similar to those shown in Table 7. For transportation distances below 150 miles, the study reports $3.35 per mile, and $2.70 for distances more than 150 miles.

[6] Transportation cost breakdown/details are provided in the Feedstock Transportation Costs section.
[7] As shown in the Table 7, the dry manure refers to 50% moisture content.

Forest Residue Feedstock Cost

More than 50% of the five main feedstock types (crop, animal waste, MSW, food packing/processing, and forestry) identified in Frear et al. (2005) is the forest residue category. To derive a cost estimate for analysis in this report, we use spreadsheet-based calculator Forest Residues Transportation Costing Model (FRTCM) developed by Rummer (2005). The resulting estimates were compared with estimates published in the recent literature on economic feasibility of forestry residue collection and transportation.

Graf and Koehler (2000) evaluated the potential for ethanol production in Oregon using cellulosic feedstocks. The study reported the cost of removing and delivering forest thinning to a facility within 50-mile radius to be in a range of $28-40 per dry ton. The estimates were partially based on information provided by private mill owners in Oregon ($28-35 per dry ton), and another source (The Quincy Library Group Study) that estimated the “farm-gate” cost of forest residue to be $40 per dry ton.

In this study, we modified the default values of the RFTCM calculator (Rummer 2005) to derive the cost of moving biomass from the forest to a site from where it can be hauled to a biorefinery. The flexibility of this model allows estimating biomass loading and hauling (to a site) costs for different combinations of equipment. The estimates found to be slightly above $40 per dry ton of biomass, if considering haul distance within 25 miles from the site (i.e., from the “farm-gate”). The second stage of the transportation expenses is included in the feedstock transportation to a biorefinery part.

Municipal Solid Waste Feedstock Cost

Three types of feedstocks were considered under the MSW category – paper waste, food waste, and wood residue. According to Frear et al. (2005), paper waste category represents about 14% of the total biomass identified in the state. However, food waste and wood residue categories account for only 1.46% and 4.93% of the total respectively. Because of their relatively low volumes, food waste and wood residue categories will be suitable as supplemental feedstocks. For purposes in this study, we assumed that about $25 tipping fee (Graf and Koehler 2000) will be spend on transporting food waste and wood residues to a site (the first stage of transportation expenses). Therefore, in this study the delivered feedstock cost for these two categories includes only the transportation expenses to the biorefinery.

According to Metro Waste Management Division (as reported in Graf and Koehler 2000) the prices for recycled and mixed paper waste ranges from $60-$125 per dry ton. However, the methodology used to calculate the paper waste availability in the state of Washington considered a combination of the percentage of paper in MSW and recyclables (Frear et al. 2005). Therefore, we assume that the “farm-gate” cost of paper to be lower than the estimates found in Graf and Koehler (2000). Several other sources (Baled Waste Paper Spot Market Prices 2009) reported spot market prices in a range of $22.5/$30 (for mixed paper), $69 (baled corrugated cardboard) to over $200 (for soft white paper) per ton depending on its quality. Based on spot market prices and the estimates found in the literature, in this report we consider $45 feedstock price per dry ton of paper waste.

GIS Studies

Graham et al. (1996) developed a GIS-based modeling system to identify potential and optimal bioenergy feedstock locations. This system was designed to model the supply cost of feedstock (energy crops) taking into account spatial variation of resources. The authors adopted an interdisciplinary approach involving information on land use, soil quality, climate, highway networks, as well as environmental and economic models to determine the marginal cost of feedstock supply from potential locations where energy crops might be grown. As a first step of the four-component modeling, the study mapped the availability of energy cropland in the study area. In the next step, expected yield and a farm gate cost of the energy crops were defined. Further, the potential farm gate feedstock supply was identified and the marginal cost of delivery was mapped to the biorefinery destinations. As a last component, the study mapped and ranked the potential biorefinery locations in the study area based on feedstock delivery costs.

Graham et al. (2000) and Zhan et al. (2005) introduced another GIS approach to map the delivered cost surface for a study area that accounted for spatial variation of the factors affecting collection and transportation costs. The study also identified least cost locations for collecting and transporting biomass to processing plants. Another study involving GIS (Noon et al. 1996) extended and applied GIS-based modeling system to forecast the most promising areas for biofuel processing plants in a specific region. Results revealed considerable correlation between variation of switchgrass costs (throughout the study area) and biorefinery plant sizing, as well as facility location decisions. Considering consistent construction and labor costs across the study area, the authors found that the delivery cost of the feedstock is the main determinant in the variable cost of the ethanol processing.

Langholtz et al. (2007) conducted a woody biomass feasibility study for 27 counties in the US southeastern states. Detailed explanations were provided about the utilization of the GIS Network Analyst tool to assess the economic feasibility of the woody biomass available in the study area. Taking into account the spatial distribution and variability of the biomass resources, transportation costs were combined with the procurement costs in order to derive the delivered costs.

Feedstock Transportation Costs

An Economic Engineering Framework

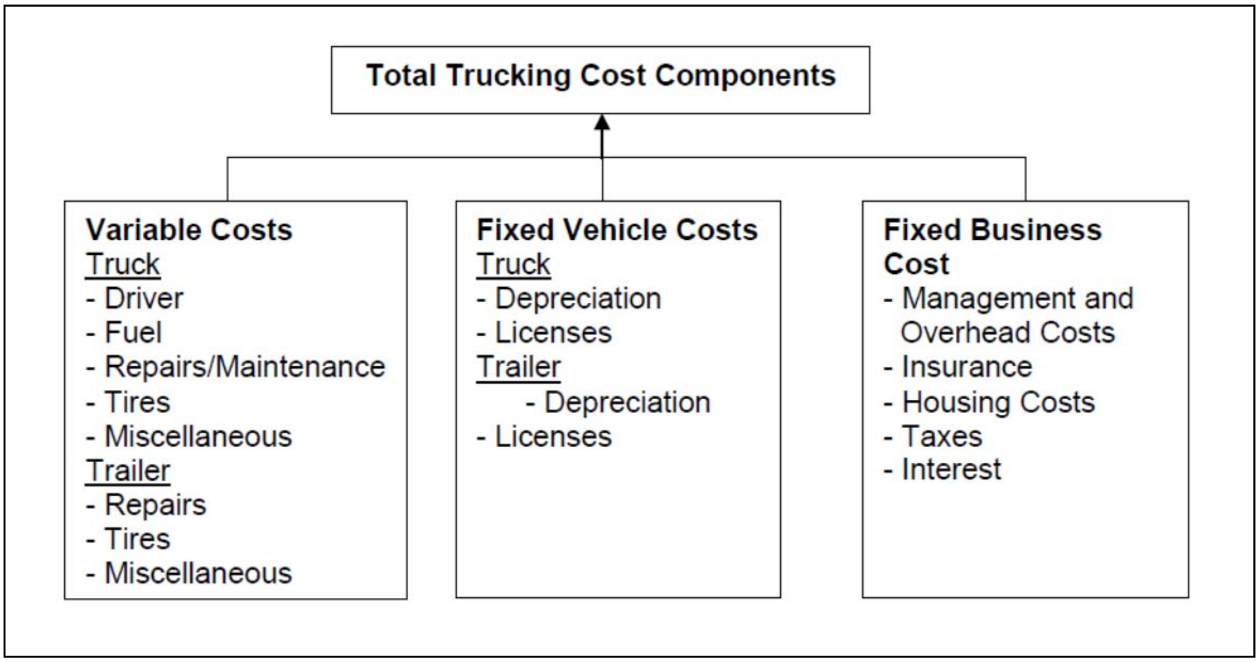
Trucking costs can be derived using several cost measurements, such as cost per ton, cost per mile, or cost per ton mile. Depending on the objective of the study, the type of the cost measurement may vary. For the analysis in this study, cost per ton mile measure is used.

The derivation of feedstock transportation costs requires information on factor prices that determine costs of a typical trucking firm (Casavant 1993). Trucking costs can be separated into categories, such as fixed vehicle costs, fixed business costs and variable costs. Fixed vehicle costs include expenses, such as depreciation and licenses for both truck and trailer. Fixed business costs consist of management, insurance, housing, taxes and interest cost components. Variable costs for a truck include expenses associated with drivers' wages, fuel expense, repair and maintenance, tires; trailer part of the variable costs includes repair, maintenance and tires related expenses (Figure 44). To understand the derivation of the total trucking costs with an economic engineering approach, each of the cost components are briefly discussed in the following paragraphs. Further, these values will be used to derive the total trucking costs, which in turn will be used for the feedstock transportation cost calculations and feedstock supply curve constructions.

Variable Costs

Variable costs vary with the number of trips or distances driven by trucks. For instance, long-destination trips require more fuel, more driver wages, more repair costs and result in quicker tire wear out. The following part of the Variable Costs section provides description for each of the cost components, which are summarized in the Total Cost Per Ton Mile section of this report.

Figure 44: Total Trucking Cost Components



Driver Wages

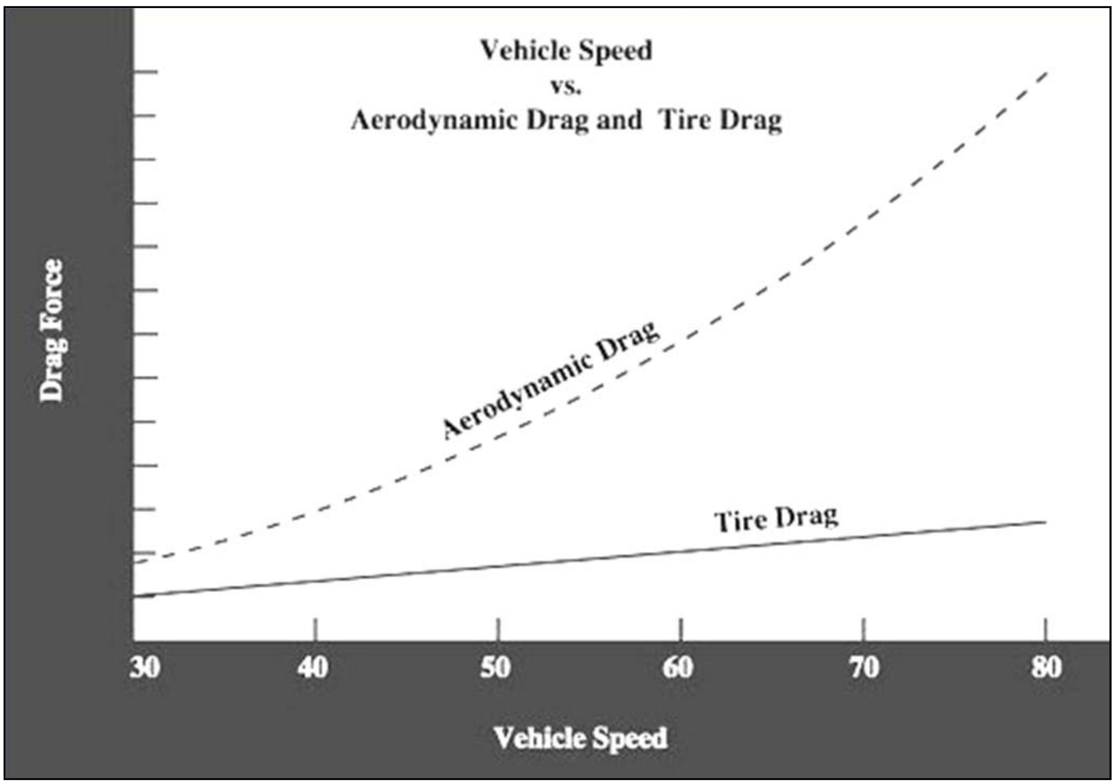
Similar to the various measurements for trucking costs, driver wages may have different forms, such as a percentage of the freight bill, or based on number of trips, hours of drive time or mileage driven (Casavant 1993). The most accepted measure, a time-based wage was considered for the analysis in this study. Driver wages may also vary depending on the type of the haul (short haul - the driver is home every night; long haul – requires overnight trips).

As reported by the U.S. Bureau of Labor Statistics, classified as Truck, and Heavy Truck-Trailer Drivers, the average hourly wage is $17.41 (U.S. Department of Labor 2007). Sometimes, a combination of haul distance and hours of operations are used for determination of driver wages. For instance, in addition to per mile pay, driver wages for the haul distances over 60 miles may include time of loading and unloading activity. According to the findings from a truck costing model for grain transportation reported in Trimac (1999), depending on truck configuration and local infrastructure, per mile wages may range from 18 – 28 cents. Most of per mile driver wages for truck and trailer configurations were observed within the 26 – 28 cents range, occasionally reaching 30 – 32 cents per mile. Considering 45 – 60 mph driving speed, these estimates are closely comparable with the rates provided by the U.S. Department of Labor (2007) reports.

Fuel Cost

With current crude oil prices (EIA 2008c), fuel costs are considered (as shown in the sensitivity analysis part) to be one of the most affecting components of the variable costs. In addition to the fuel price itself, several most important factors affecting trucks' fuel economy include its payload weight, tire pressure (affected by vehicle gross weight and tire rolling resistance), tire type, vehicle aerodynamics (affected by vehicle speed, truck's front area and shape), and traffic congestion. Figure 45 below shows the relationship between the vehicle driving speed and both aerodynamic and tire drag force levels, which (drug forces) may influence/increase the vehicle fuel consumption.

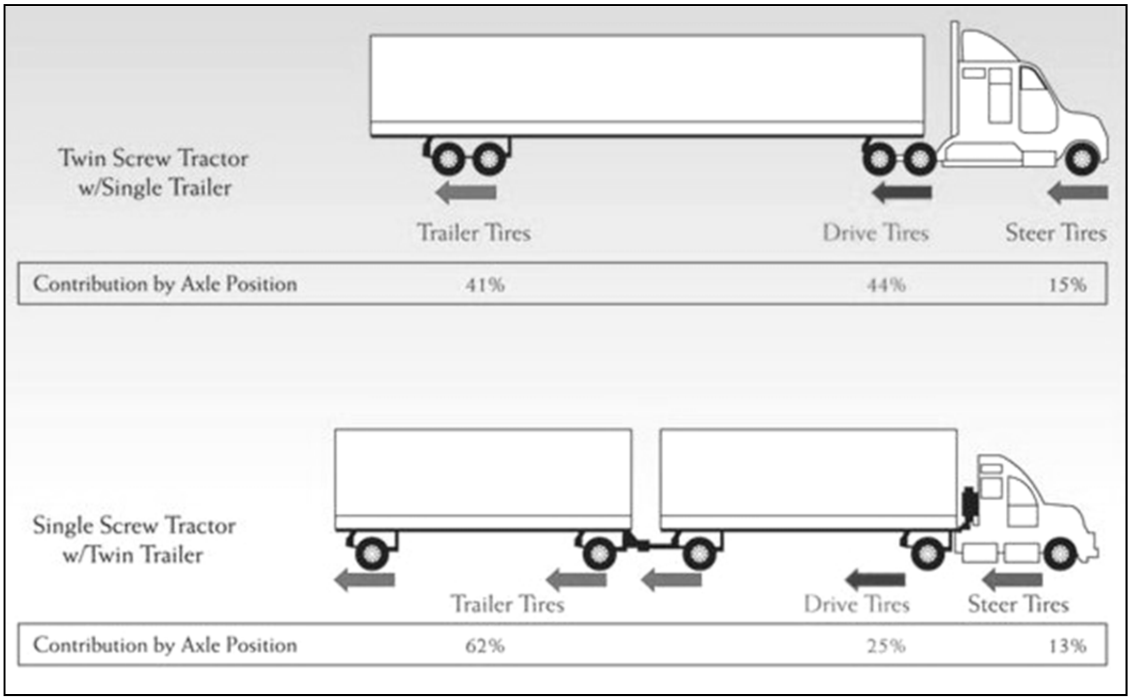
Figure 45: The Relationship between Vehicle Drive Speed and Drag Force



Source: Goodyear Tire & Rubber Company, Commercial Tire Systems (2008)

Depending on different truck configurations, the fuel economy also depends on factors, such as the drag force distribution between steer, drive and trailer tires (Goodyear Tire & Rubber Company 2008). For instance, according to Figure 46, 85 percent of the tire rolling resistance is attributed to drive and trailer tires (truck and trailer configuration), or 87 percent in case of truck and double trailer. Information on tire rolling resistance distribution between steer, drive and trailer tires helps in identifying axle groups that contribute to the vehicle fuel consumption level.

Figure 46: Truck and Trailer Tire Drag Force Distribution



Source: Goodyear Tire & Rubber Company, Commercial Tire Systems (2008)

According to recent U.S. Department of Energy report by Kodjak (2004), as well as the University of Washington & Washington State University Log Trucking Study (2008), trucking firms reported an average of 5.5 miles per gallon fuel efficiency. For time-based trucking cost derivation, fuel costs can be calculated by combining an average price of diesel $4.5 per gallon (EIA 2008c), 45 mph average driving speed, and 5.5 miles per gallon fuel efficiency. Using year to date average diesel prices (EIA 2008c), fuel costs reach $36.8/hour [8].

Figure 47 shows the relationship between weekly diesel prices and per hour diesel costs.

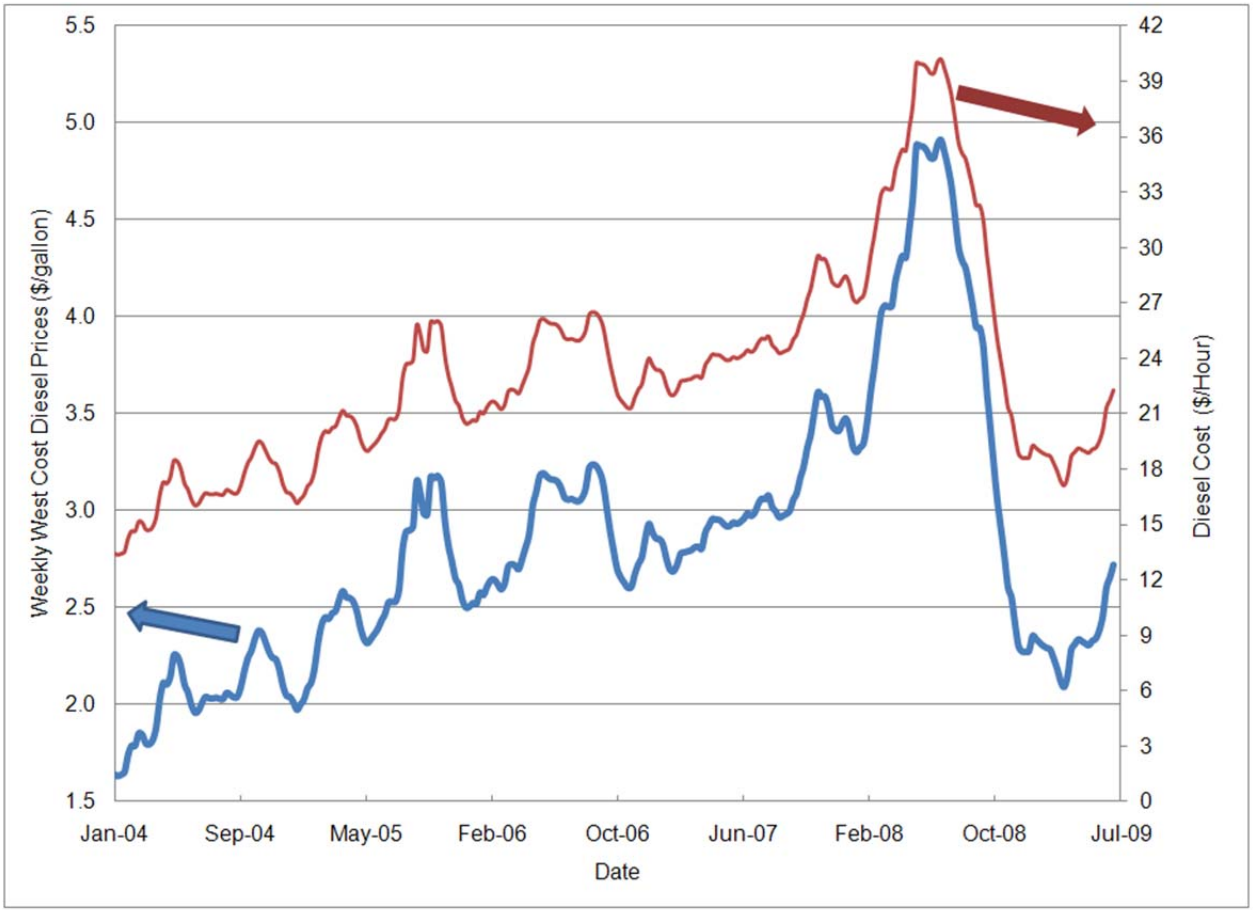
Annual fuel expenses for purposes in this study were calculated using the following formula:

$$Fuel\ Costs = \left(\frac{distance\ driven\ per\ year\ (miles)}{fuel\ efficiency\ (miles/gallon)}\right) \times price\ of\ fuel$$

Further, depending on the necessity, the annual costs can be converted to per mile, per ton, or per ton mile basis.

Figure 47: Weekly West Cost Diesel Prices

[8] Fuel Expense per hour of Drive = [fuel price x (mph / fuel efficiency)] = 4.50 ($/gal) x 45 / 5.5 (gal/hr) = 36.8 $/hr.



To measure the effects of the increasing fuel prices on trucking costs, a diesel price sensitivity analysis was conducted and discussed in the Total Cost Per Ton Mile section. A sensitivity analysis is useful to examine the variation of the delivered cost of a biofuel under investigation based on petroleum fuel price fluctuations.

Repair and Maintenance Cost

Repair and maintenance costs may differ depending on drivers' ability to make part of the repair on their vehicles, which makes the calculation of this cost component difficult. The total repair and maintenance costs include lubrication, engine repairs, tune-ups and other part repairs. There are several factors that may lower repair costs, including relatively flat geography, the initial newer condition of the purchased vehicle, as well as the number of daily operation hours and even different management policies. Repair costs per vehicle are lower for trucking firms owning big fleet of trucks, since labor (repair/maintenance) costs spread over many vehicles, and parts obtained at the wholesale rate. On the contrary, smaller firms may spend more on labor force that serves only few vehicles, and purchase parts at usual commercial rates. The lubrication portion of the repair and maintenance annual costs per truck is calculated considering 10% of fuel costs mentioned earlier:

$$Lubrication\ Costs\ =\left(\frac{distance\ driven\ per\ year\ (miles)}{fuel\ efficiency\ (miles/gallon)}\right)\times fuel\ price\times 0.1$$

The annual repair costs (further converted to per ton mile measure) were calculated using $0.17 per mile repair cost estimate obtained from Trimac (1999), and information on annual miles driven by each truck from the University of Washington & Washington State University Log Trucking 2008 Study:[9]

$$Annual\ Repair\ Costs = \ Annual\ distance\ driven\ (miles) \times Annual\ repair\ cost\ (\$/mile)$$

Tire Cost

Tire cost calculations are relatively straightforward. Although, truck tires lifetime mileage varies depending on the placement – drive, steer and trailer, for purposes in this study an average lifetime per tire was used. Ten tires costing $400 each, with 60,000 average lifetime miles per tire for truck, and 8 tires with the same purchase price with 72,000 average lifetime miles for trailer was considered for the calculation of the tire cost component (University of Washington & Washington State University Log Trucking Study 2008). Further, incorporating 20-ton average payload weights, the tire costs per ton mile were derived:

$$\left(\frac{Number\ of\ Tires \times Replacement\ Cost \times \left(\frac{Annual\ Miles}{Lifetime\ Miles}\right)}{Annual\ Miles}\right)/Payload\ Weight$$
$$= \left(\frac{Number\ of\ Tires \times Replacement\ Cost}{Lifetime\ Miles}\right)/Payload\ Weight$$

Fixed Vehicle and Business Costs

The fixed vehicle costs change with the size of the fleet owned by the trucking firm, while mileage driven doesn't alter them. Expenses such as depreciation and annual license fees increase with the number of trucks in a fleet. Fixed business costs for a typical trucking firm include insurance, housing costs, taxes and interest.

Depreciation

Depreciation is a cost resulting from wear or aging of machinery over time. Trucking firm equipment costs are associated with trucks and trailers. The magnitude of the wear may lower the value of the equipment above or below the current market price of similar equipment. The depreciation cost is significant when equipment with newer technology is introduced in the marketplace (Edwards 2002). An economic engineering approach considers either aging or the estimated useful life years of the equipment as a basis for calculating depreciation costs. For the purposes in this study, 10 years of truck and trailer ownership was considered.

Another component needed to calculate depreciation is a salvage value of the equipment – an estimated value of the truck and/or trailer (in this case) at the end of the useful

[9] 1999 conversion rate for USD – CAD was used for converting into US dollars; the distance measure was converted from kilometer to miles.
Annual miles driven are calculated assuming three relatively short haul trips per day (50 miles one way), or two trips at 75 mile one way per day.

or accounting time. Based on salvage value as percentage of the new list price of machinery (provided in

Table 14 of Trucking Cost Calculation Tables section) and 10 years of equipment ownership, the salvage value was calculated as a 26% of the new list price of truck, and 35% for the trailer. Further, the annual depreciation was calculated as a new list price less the salvage value of the truck and trailer over years of ownership:

$$Depreciation = (New\ List\ Price - Salvage\ Value)/Years\ of\ Ownership$$

License and Tax Fees

License and tax fees differ from state to state, by mileage driven, and by the type of commodities hauled (Casavant 1993). License fee and tax information was obtained from the Washington State Department of Licensing (WADOL).[10] To obtain per mile or per ton expenses, fees can be divided by the average miles driven per truck, or by the annual tons hauled respectively. Alternatively, using both annual miles driven and tons hauled, license fees per ton mile can be derived.

Insurance Fees

Insurance expenses are usually much less then interest costs, but still constitute part of the trucking firms' fixed costs. In addition to cargo insurance, trucking firms usually carry a full insurance on new trucks and trailers to ensure a replacement in case of physical damage. According to the phone interview conducted with Gordon Trucking Inc., the following formula was used to calculate truck and trailer insurance fees:

$$Insurance\ Cost = (\$2 \times Price\ of\ Truck\ or\ Trailer)/1000$$

Interest/ROI

The lender of money for capital investments determines the rate of interest to charge. If the firm is using a combination of borrowed money and own capital, then the average of the opportunity cost for that capital and the interest rate charged by the lender should be calculated. The interest can also be calculated using Return on Investment (ROI) approach. ROI for the trucking firm is considered to be a part of equipment (truck and trailer) costs, which can be calculated using the following formula (Casavant 1993):

$$ROI = [(PP - SV)/2 + SV] \times Interest\ Rate$$

Where *PP* is the purchasing price of the equipment, *SV* is the salvage value (discussed in the Depreciation section).

Total Cost Per Ton Mile

The per ton mile transportation cost of feedstocks to biorefineries can be derived by combining aforementioned fixed and variable cost components for truck and trailer, and fixed (trucking) business costs. Further, the per ton mile transportation costs can be incorporated with the feedstock farm-gate costs and haul distances to derive the delivered feedstock costs. With

[10] In addition estimates provided by Washington State Department of Licensing, phone interview was conducted with the Gordon Trucking Inc. operations management department.

appropriate truck configuration (tanker trailer truck) and hauling origin/destination modifications, trucking costs for ethanol distribution can be derived. Lastly, feedstock transportation and processing costs, combined with the distribution costs will make up the delivered cost of the ethanol to alternative markets.

As mentioned earlier, an economic engineering approach allows combining all of the components that the total trucking costs comprise. Table 8 lists necessary input values and units of measurement for the truck transportation cost calculations.

Table 8: Truck Transportation Cost Calculation Inputs

Component	Units	Truck	Trailer (Flat-bed, Drop bed)
Purchase price	$	110,000	25,000
Time period of ownership	years	10	10
Expected salvage value	$	28,600	8,750
Annual cost of repairs	$	14,005	500
Number of tires	number	10	8
Replacement cost per tire	$	400	400
Lifetime per tire	miles	60,000	72,000
Annual miles driven	miles	80,700	-
Annual tons hauled	tons	16,140	-
Interest rate	%	0.07	-
Price of fuel	$/gallon	4.61	-
Fuel efficiency	miles/gallon	5.5	-
Average hauling speed	miles/hour	45	-
Annual cost of license	$	2,000	-
Annual cost of insurance	$	220	-
Driver labor rate	$/hour	17.41	-

Note: Trailer components that are not applicable for the total cost calculation are not listed.

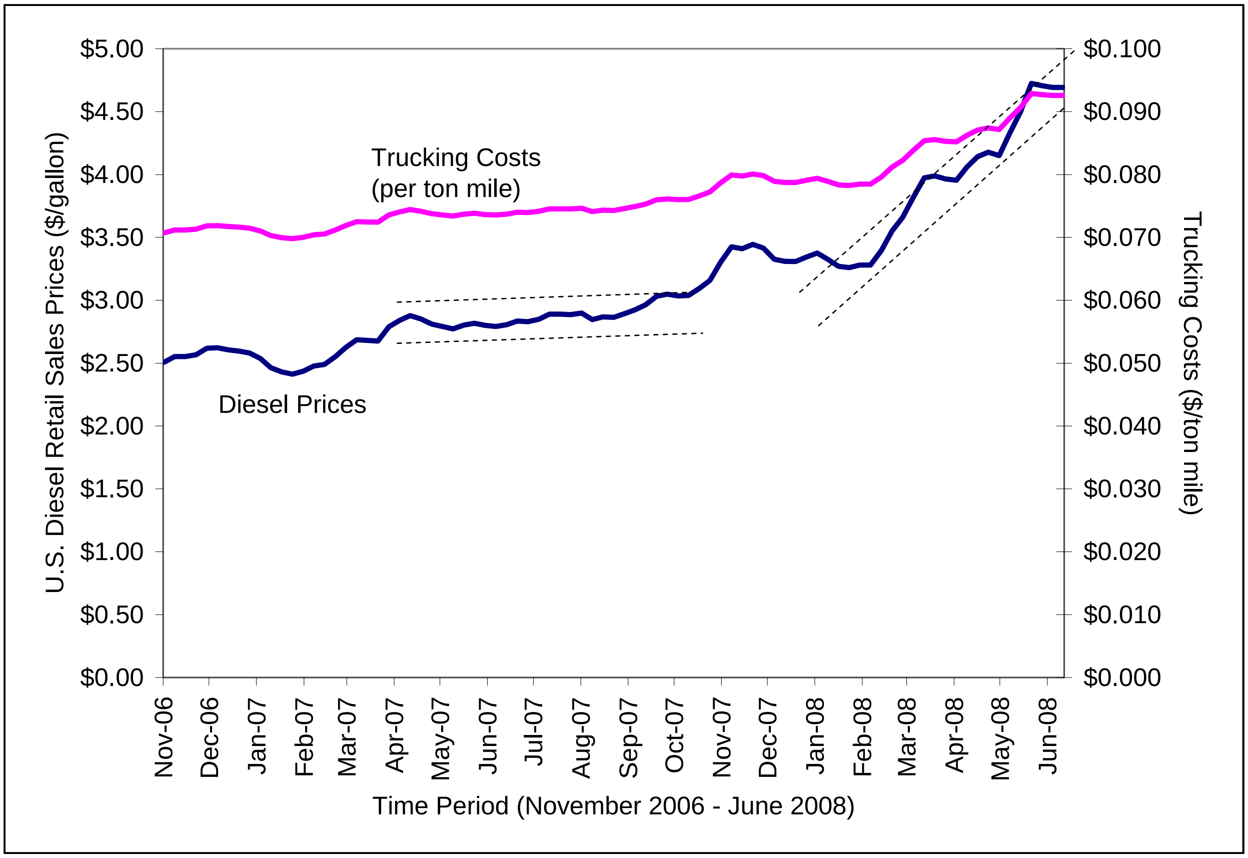
Further, these input values were used for the truck transportation total cost calculations shown in Table 9. Fixed cost calculations require information on interest rate, time period of equipment ownership, equipment purchase price and expected salvage value, as well as information on insurance and license fees. Additionally, costs that vary depending on annual miles driven or annual tons hauled (variable costs), involve repair and maintenance, tire, fuel and labor costs. While trucking costs were derived as both per ton and per mile basis, for the purposes in this study per ton mile measure is utilized for further feedstock transportation and ethanol distribution cost derivations.

Table 9: Truck Transportation Total Costs

Description	Truck ($/year)	Trailer ($/year)	Total Cost ($/year)	Total Cost ($/ton)	Total Cost ($/mile)	Total Cost ($/ton/mile)
Fixed Costs						
Capital recovery (interest and depreciation)	$13,592	$2,926	$16,518	$1.023	$0.205	$0.010
insurance & license	2,220	250	$2,470	$0.153	$0.031	$0.002
Total fixed cost	$15,812	$3,176	$18,988	$1.176	$0.235	$0.012
Variable Costs						
Repair cost	$14,005	$500	$14,505	$0.899	$0.180	$0.009
Tires cost	5,380	3,587	8,967	$0.556	$0.111	$0.006
Fuel cost	67,641		67,641	$4.191	$0.838	$0.042
Lubrication cost	6,764		6,764	$0.419	$0.084	$0.004
Labor cost	31,222		31,222	$1.934	$0.387	$0.019
Total variable cost	$125,012	$4,087	$129,099	$7.999	$1.600	$0.080
Total Costs	**$140,824**	**$7,263**	**$148,086**	**$9.175**	**$1.835**	**$0.092**

In addition to delivered feedstock cost sensitivity to farm-gate costs and haul distances, the feedstock costs at the refinery gate are sensitive to diesel prices. Fluctuations in diesel price may influence the feedstock delivered costs, since the fuel costs constitute about 46% of the per ton mile transportation costs. As illustrated in Figure 48, when diesel prices are in a range, as highlighted with dotted lines (Apr-07 through Oct-07), trucking costs stayed at almost the same level. However, the chart pattern illustrates that the trucking costs significantly increase as diesel prices form a trend, as highlighted with dotted lines (Jan-08 through Jun-08). Not surprisingly, as illustrated in Figure 49, trucking costs are significantly sensitive to fuel prices, which according to the calculations above (Table 9) take up about 46% of the total transportation per ton mile costs.

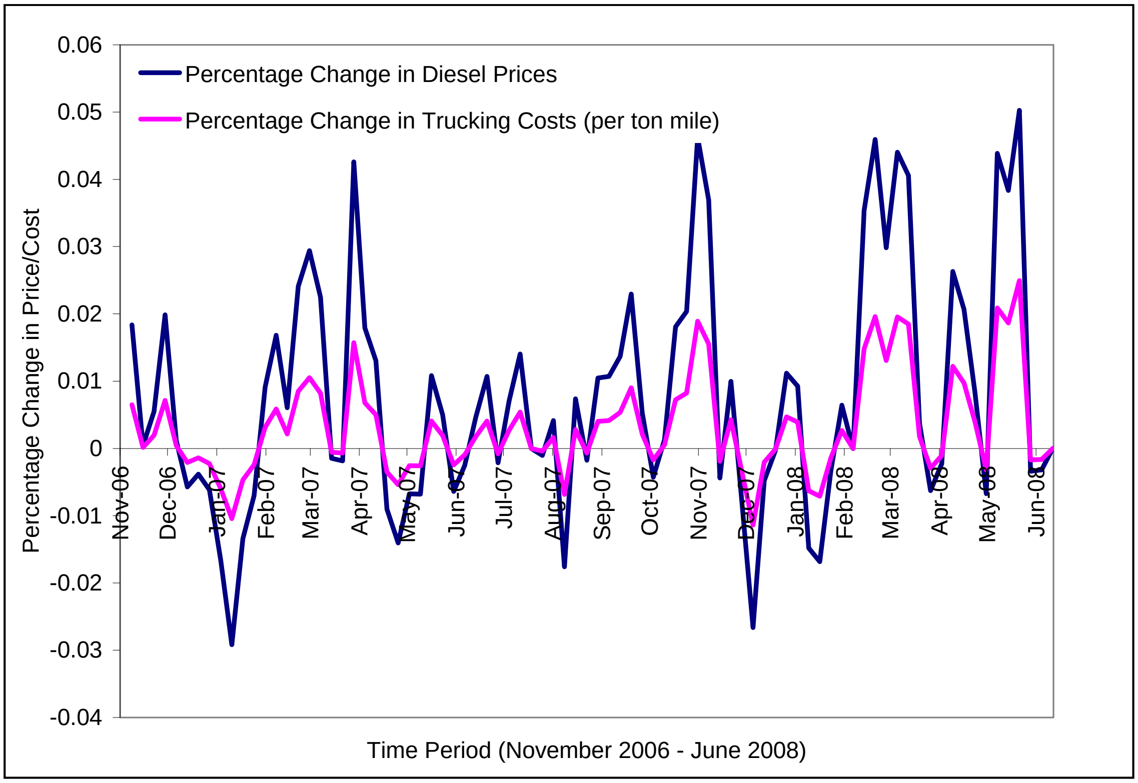
Figure 48: U.S. Diesel Retail Sales Prices and Trucking Cost Sensitivity



Data Source: Diesel prices were obtained from EIA (2008)b.

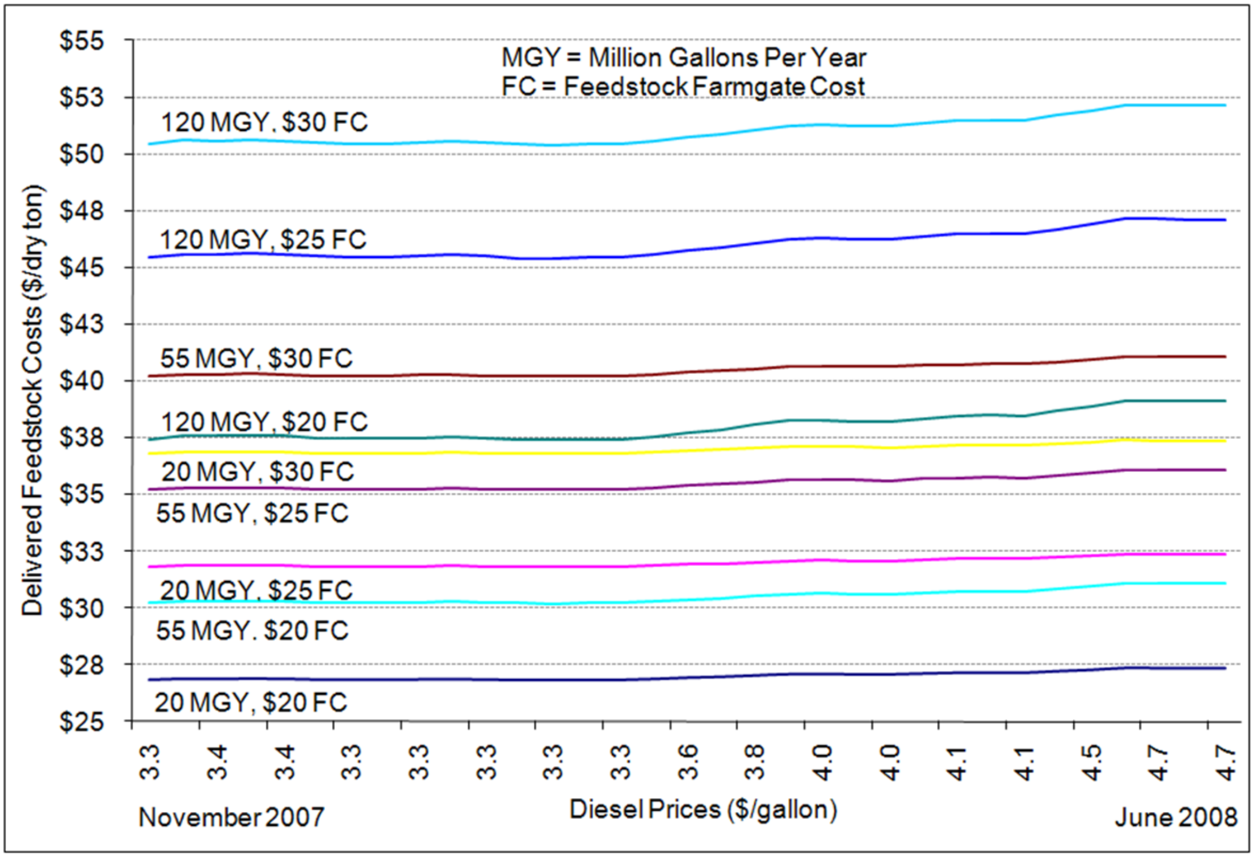
A sensitivity analysis with a range of diesel prices by incorporating different processing plant capacities was used to allow evaluating the delivered feedstock costs in relation to the different ethanol processing plant capacities. Diesel prices from November 2007 to June 2008 (EIA 2008b) were chosen to analyze the variation of feedstock delivered costs with different farm gate costs ($20, $25 and $30) and small, medium and large plant capacities (20 MGY, 55 MGY, and 120 MGY). As shown in Figure 50, small scale processing plants are comparatively less sensitive to diesel price increases in terms of the delivered feedstock costs, for all of the three farm gate cost scenarios.

Figure 49: Percentage Change in Diesel Prices and Trucking Costs



In comparison, the influence of the increasing diesel prices on the delivered feedstock costs for the medium and large processing plants is considerably higher. Particularly, as a result of increasing diesel prices since January 2008 (39% increase from January to June, 2008), the delivered costs of feedstocks for the 55 MGY plant increased by three percent considering $20 farm gate costs, and two percent considering $25 and $30 farm gate costs. Because larger plants involve more transportation activity, the delivered feedstock costs for the 120 MGY capacity plant increased by four percent considering $20 and $25 farm gate costs, and three percent for $30 farm gate cost.

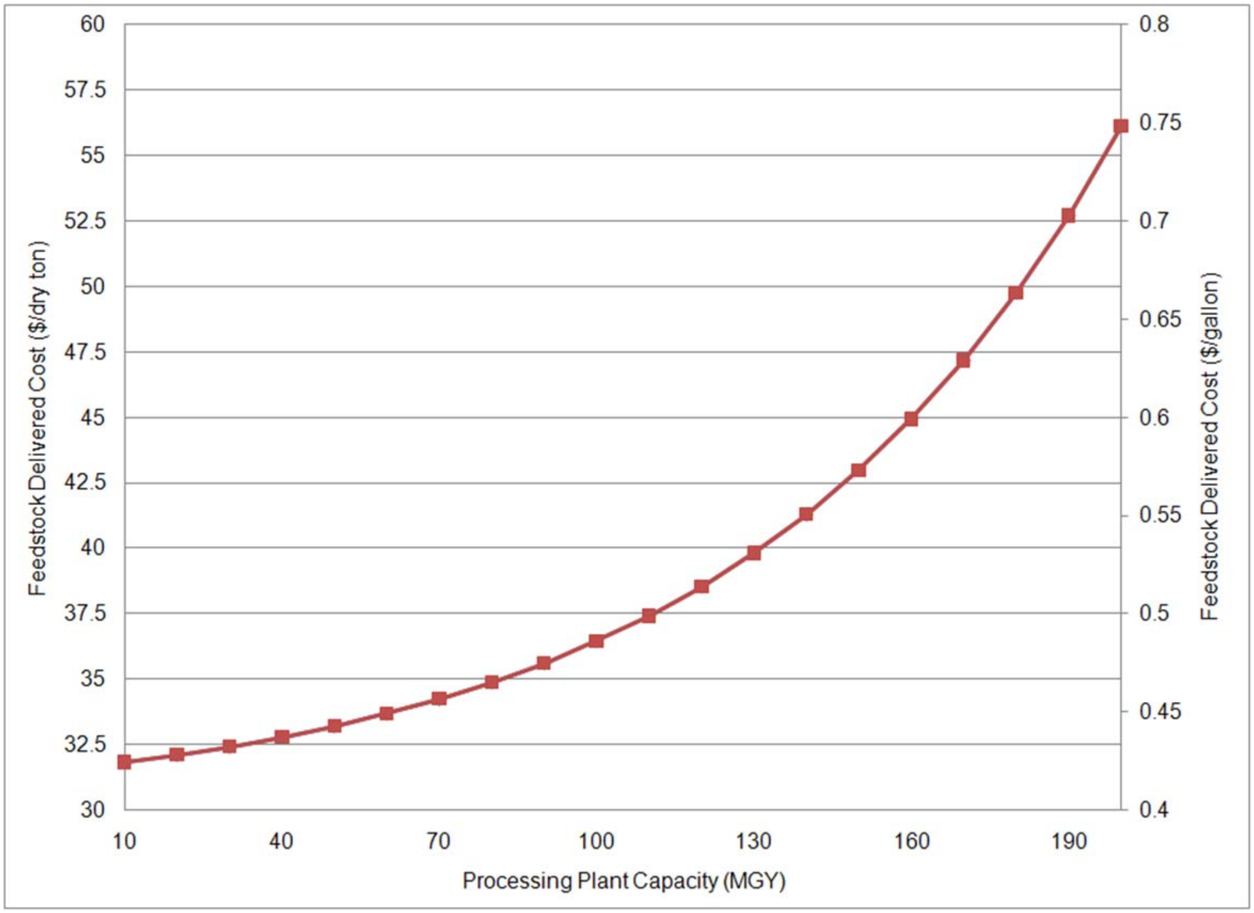
Figure 50: Delivered Feedstock Cost Sensitivity to Diesel Prices



Besides the cost components such as fuel prices, there are other factors that influence the transportation costs. Per ton mile transportation costs may differ depending on plant processing capacity, since larger plants require more feedstock to be processed. Cellulosic feedstocks, such as crop residue are geographically dispersed. Consequently, more feedstock demanded by larger plants requires farther-distance hauling, which consequently increases transportation expenses. As derived earlier in this section, 9.2 cents per ton mile trucking cost was used in combination with the feedstock farm-gate cost (derived in the Error! Reference source not found. section) to calculate the delivered cost of feedstock to biorefineries.

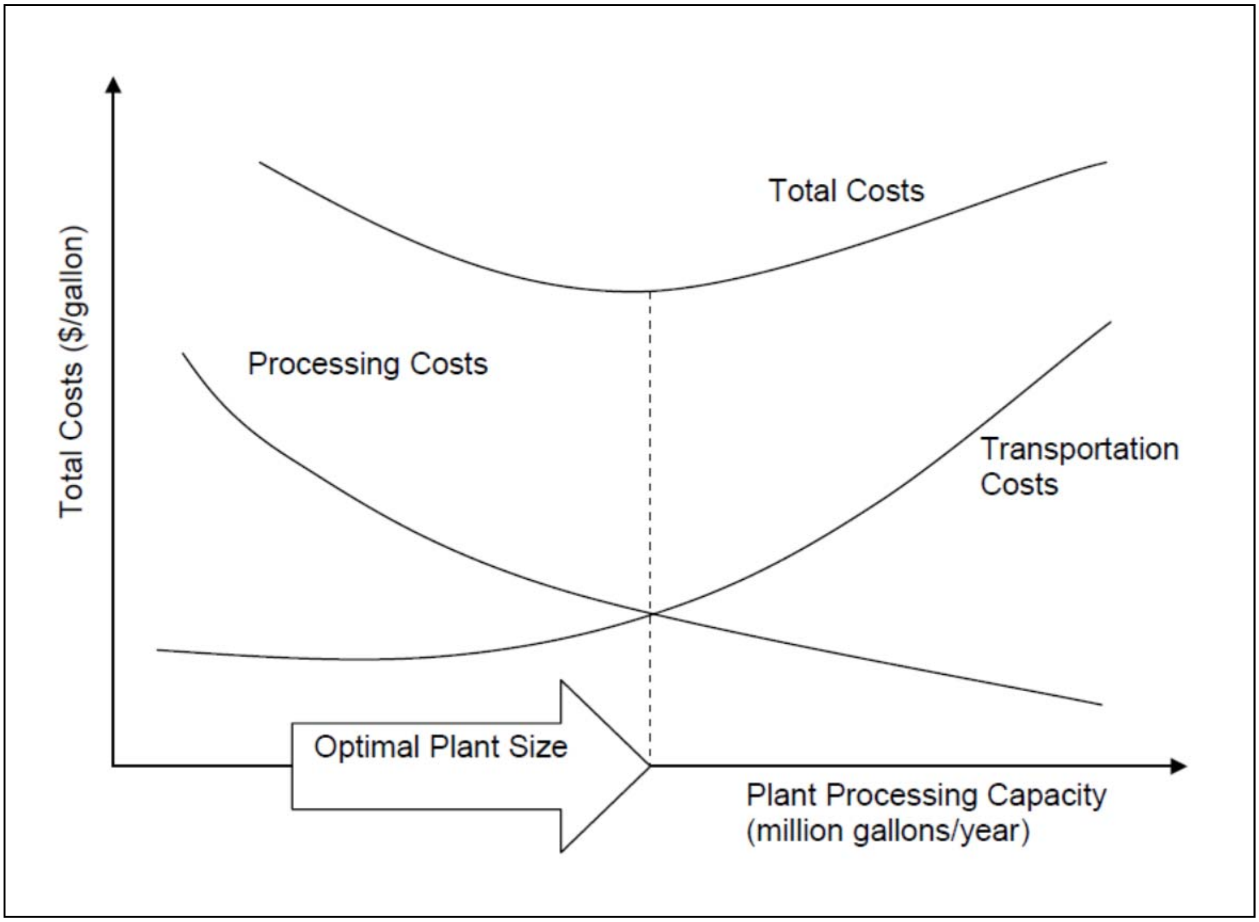
Figure 51 shows the relationship between increasing plant processing capacity and feedstock delivered costs per dry ton and per gallon basis (using NREL data). These costs may also differ by the type of feedstock utilized for the ethanol processing. Nevertheless, the upward sloping delivered cost curves emphasize that the overall amount of the feedstock available in the region cannot be utilized at the same expense. The tradeoff for the economies in scale is the increasing transportation costs. The overall delivered (final) cost dependence on the geographic dispersion of feedstocks and markets, introduces the importance of the optimal processing plant size concept.

Figure 51: Feedstock (crop residue) Delivered Costs to Biorefineries by Processing Capacity



In addition to spatial characteristics, such as feedstock production geography and market locations, optimal plant size decision involves factors, such as alternative transportation mode (rail, barge) accessibility. However, the fundamentals of the processing plant size decision making involve two main components - increasing feedstock transportation costs and economies of scale in the processing segment. As shown in Figure 52 (also discussed in the Error! Reference source not found. section), per gallon processing costs tend to decrease with increasing processing capacity, since capital and operation expenses are spread over more gallons of processing. Economies of scale are large enough to offset the increasing feedstock transportation costs up to the processing capacity where the total cost is at its lowest point (shown with an arrow in Figure 52). The lowest point on the total costs curve determines the optimal capacity for the economically feasible ethanol processing. The transportation cost curve includes both feedstock transportation and ethanol distribution segments.

Figure 52: Total Delivered Costs and Processing Plant Optimal Size



GIS Approach to Delivered Cost of Feedstocks (NREL Data)

In this section, we use GIS with NREL (2007) data to spatially investigate the delivered costs of feedstocks. The methodology is then utilized to analyze the state of Washington biomass data identified in the first phase of this project (Frear et al. 2007). Feedstock transportation costs were derived for multiple processing plant locations in the state. Further, the optimal processing plant locations in terms of least feedstock transportation costs were identified in the GIS Analysis for Biofuel Plant Least-Cost Location Decisions (NREL Data) section.

GIS Analysis for Eastern Washington (Crops Residue)

Introduction

The study area includes twelve counties that produce 93% of the State's agricultural crop residues (shown above, in Figure 37). The annual crop residue available in the study area (roughly 1.6 million dry tons), can support up to 122.5 MGY processing (using 75 gallon per dry ton biomass-to-ethanol conversion rate). However, because of the geographic distribution of the biomass and increasing transportation costs, resulting from longer haul distances, above mentioned capacity can't be supported at the same feedstock expense.

The GIS Network Analyst Extension toolset has been employed to investigate geographic distribution of crop residue in each of the haul areas of the twelve-county study area in relation to the Washington State highway system. Using Census feature classification codes (CFCC)[11], speed limits have been assigned to all segments in the GIS roads shapefile to calculate haul distances and drive times for a specific biorefinery location.[12] Assuming truck transportation, six haul time categories with 30-minute (up to 3-hour haul time) intervals were used to estimate feedstock availability within each county and each haul distance area. Further, the residue physical availability, farm-gate price, transportation costs (from fields to a biorefinery), including loading/unloading, and geographic distribution (accounting for site-specific road infrastructure) information were combined to derive feedstock supply curves. In this case study, truck and flat-bed trailer configuration has been considered for transporting crop residue bales from field facilities (storage) to the ethanol processing plants. We used per ton mile transportation costs derived in the Total Cost Per Ton Mile section.

The results show that there is no fixed price for the delivered cost of feedstocks. Harvesting costs differ by collection methods, transporation rates differ by drive times and haul distances, as well as by truck configuration. Therefore, depending on the processing plant capacity, the feedstock costs will differ accordingly. The subsequent section describes 1) GIS procedures for calculating resource availability by haul distances/times for each county in the state, 2) procedure of converting the GIS road shapefile into a network dataset, and assigning speed limits to the highway network file, and 3) the procedures of generating of spatial data for the supply curves construction.

GIS Data and Procedures

The GIS procedures started with querying out counties in the study area from the state of Washington biomass shapefile, obtained from the NREL GIS Data and Analysis Tools website (NREL 2007). Biomass shapefiles includes counties (depicted as polygons) with attribute information, such as area, boundaries, population, etc., and spatial information, such as latitude, longitude and projection type. The attribute table (that can be exported to a spreadsheet file) of the shapefile contains annual availability for crop and forest residues, animal manure and municipal solid waste feedstock categories. The U.S. Census Topologically Integrated Geographic Encoding and Referencing (TIGER) roads layers for the study area were obtained through the Environmental Systems Research Institute (ESRI) website. County road shapefiles were merged to form one road network for the entire study area. After joining the Census feature classification codes to highway shapefile attribute tables, the length measure of line features was converted from feet into miles. This allowed calculating travel/driving for each road segment (and entire route) using the following formula:

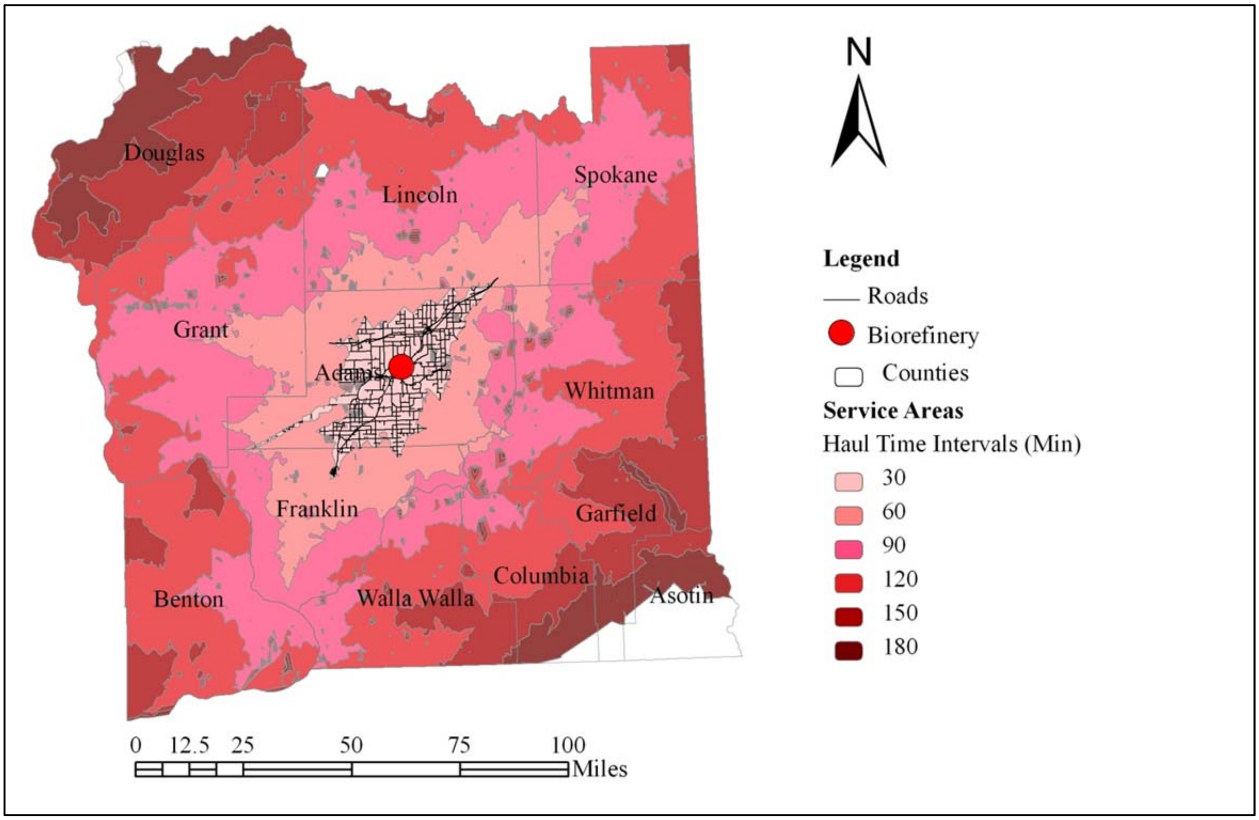
$$\textit{Travel Time (min)} = \textit{Road Segment Length (mile)} \times \frac{60}{\textit{Driving Speed Limit (mph)}}$$

[11] CFCC provides an alphanumeric code for each line feature in the GIS road shapefile. Further, the codes are used to classify roads, railroads, water, and other linear features.

[12] A shapefile is a name of the file used in Geographic Information Systems that contains nontopological geometry and attribute information for the spatial features (roads in our case) in a data set. Feature information such as geometry and attributes (i.e., length of the segment, name, location, etc.) is stored as a shape containing a set of vector coordinates.

Using GIS Network Analyst[13] extension toolset, first the road shapefile was converted into network dataset. Further, the service area layers as shown in Figure 53 were mapped. In the middle of the study area is the geographic location of cellulosic ethanol processing plant, in Ritzville, Washington. Note that in order to keep the map simple, the road layer was made visible only in the 0 – 30 minute haul zone.

Figure 53: Service Areas by Haul Times with Highlighted Roads within 30 Minutes Interval



Hereafter, the term haul zone/s is used to refer to the service area/s mapped by GIS Network Analyst Service Area function as shown in Figure 53. Haul zones were calculated with 30-minute intervals (up to 180 minutes) from the origin (processing plant) using travel time as a cost attribute. For example, in the 30-minute interval zone, all biomass can be transported from the field to the plant within 30 minutes of drive time. The next haul zone is mapped as 31 – 60 minutes haul zone, meaning the amount of feedstock available in that zone takes from 31 to 60 minutes of drive time for transporting to the plant. The same logic applies to 61 – 90 minutes and to the rest of the haul zones.[14]

Haul zones were saved as a separate layer (shapefile), which then was joined with the biomass layer such that for each haul zone the feedstock amount in tons is available. Since the

[13] The Network Analyst extension toolset enables network based spatial analysis, such as finding the closest facility from a particular location, identifying routes, finding driving directions and mapping service areas based on distance (miles) and/or travel time (minutes) from/to specific locations.

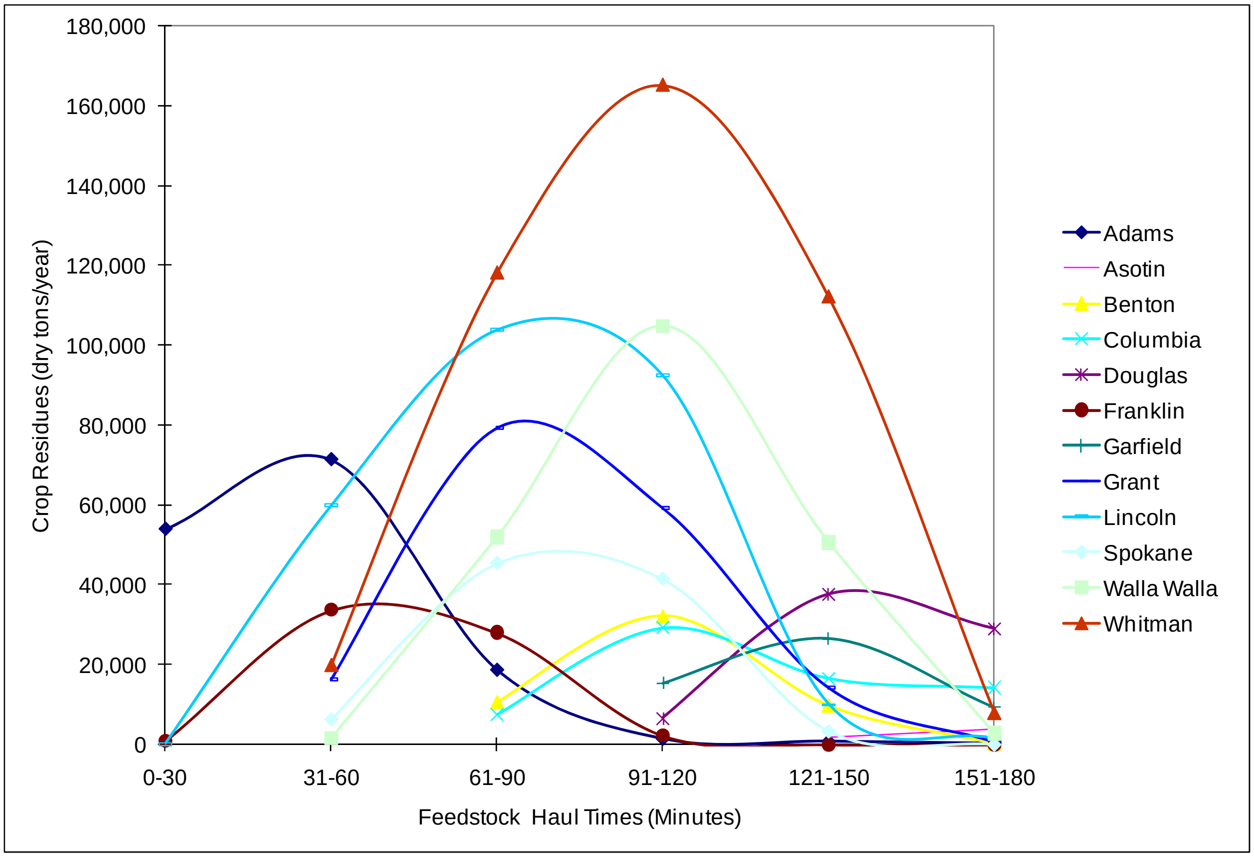
[14] The term haul area differs from the haul zone by including all inner zones. For example, 60-minute haul area includes feedstock available from both 0 – 30 and 31 – 60 minutes haul zones. Similarly, 90-minute haul area includes everything from the origin (processing plant) to the outer boundaries of the 61 – 90 minutes haul zone. The same explanation is applicable to the rest of the haul areas.

biomass data was initially available per county, it is not possible to simply "cookie cut" the biomass layer with the haul zones. Instead, the haul zone layer was first merged with the biomass layer using the ArcMap *Union* spatial analyst function. Then, the areas within the boundaries of haul zones can be selected from the merged layer (biomass and haul zones) and saved as another layer. In this selected layer the areas (in square miles) for each of the haul zones in each county was calculated using ArcMap *Geometry* calculation tool. Finally, the attribute table was exported into the spreadsheet format. Certainly, the spatial manipulation of the data as enabled by the GIS is not conceivable by solely spreadsheet-based models used in many studies investigating feedstock transportation. Based on the GIS-generated data, geographically varying resource availability and the feedstock supply curves are constructed and discussed in the Feedstock Supply Curve Construction (Crops Residue) section.

Feedstock Supply Curve Construction (Crops Residue)

The attribute table of the resulting GIS data layer (which includes feedstock and haul zone information) was summarized by haul distances and exported to a spreadsheet, allowing identification of the feedstock amount available in each haul zone at the county level. Figure 54 depicts resulting crops residue availability by haul time and by county in the study area.
The availability curves can be expressed in two ways. In Figure 54 the amount of feedstock in each haul zone is shown as the amount available only in that zone. Alternatively, the cumulative availability of crop residue in the study area can be depicted, such that increasing haul time results in increasing availability of feedstocks.

Figure 54: Crops Residue Biomass Availability by Haul Times (from a Biorefinery) for the Counties in the Study Area

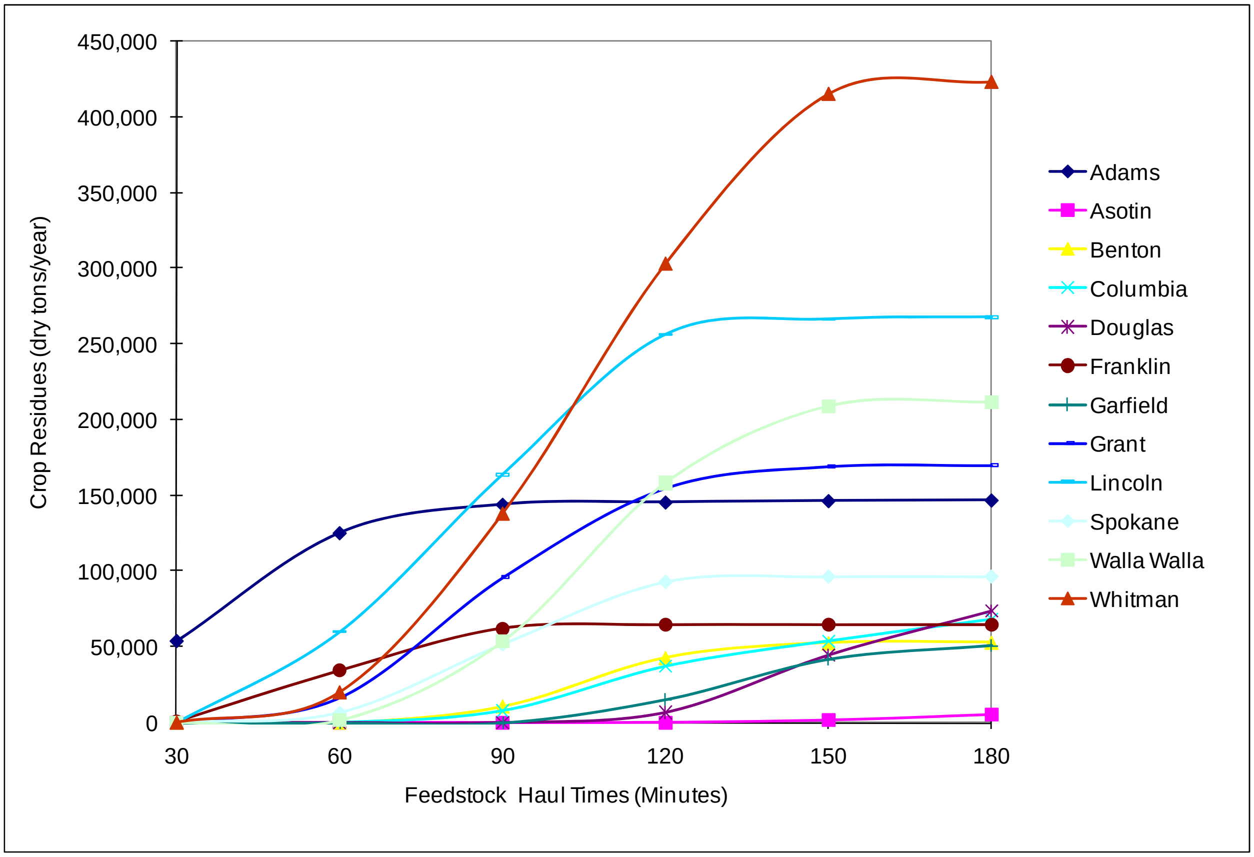


Depending on the specific objective, both methods of expressing feedstock availability can be useful. Suppose, a processing plant can currently “afford” to haul feedstocks from at most two hours of drive time from their location. If for instance, the processing facility operations management is interested in knowing the amount of feedstock that is available within the next (3rd) hour of drive time, then the representation form in the Figure 54 will be more useful. In other words, given the geographic distribution of feedstock, by driving one more hour (to reach more distant areas), Figure 54 shows the resource availability specifically in that new zone. If additional expenses from driving one more hour are considered, the figure can inform the cost of those additional feedstocks.

As shown in Figure 54, the biomass availability sharply increases starting from the 31 – 60 minutes haul zone and reaches its highest levels of availability at the 61 – 90 minutes zone for counties Grant, Lincoln and Spokane. Adams and Franklin counties reach their highest levels within 31 – 60 minutes interval. The availability in the counties Whitman, Walla Walla, Benton and Columbia peaks within the 91 – 120 minutes haul zone. Finally, the availability in the Douglas and Garfield counties starts within 91 – 120 minutes haul zone and reaches its highest level within 121 – 150 minutes haul zone.

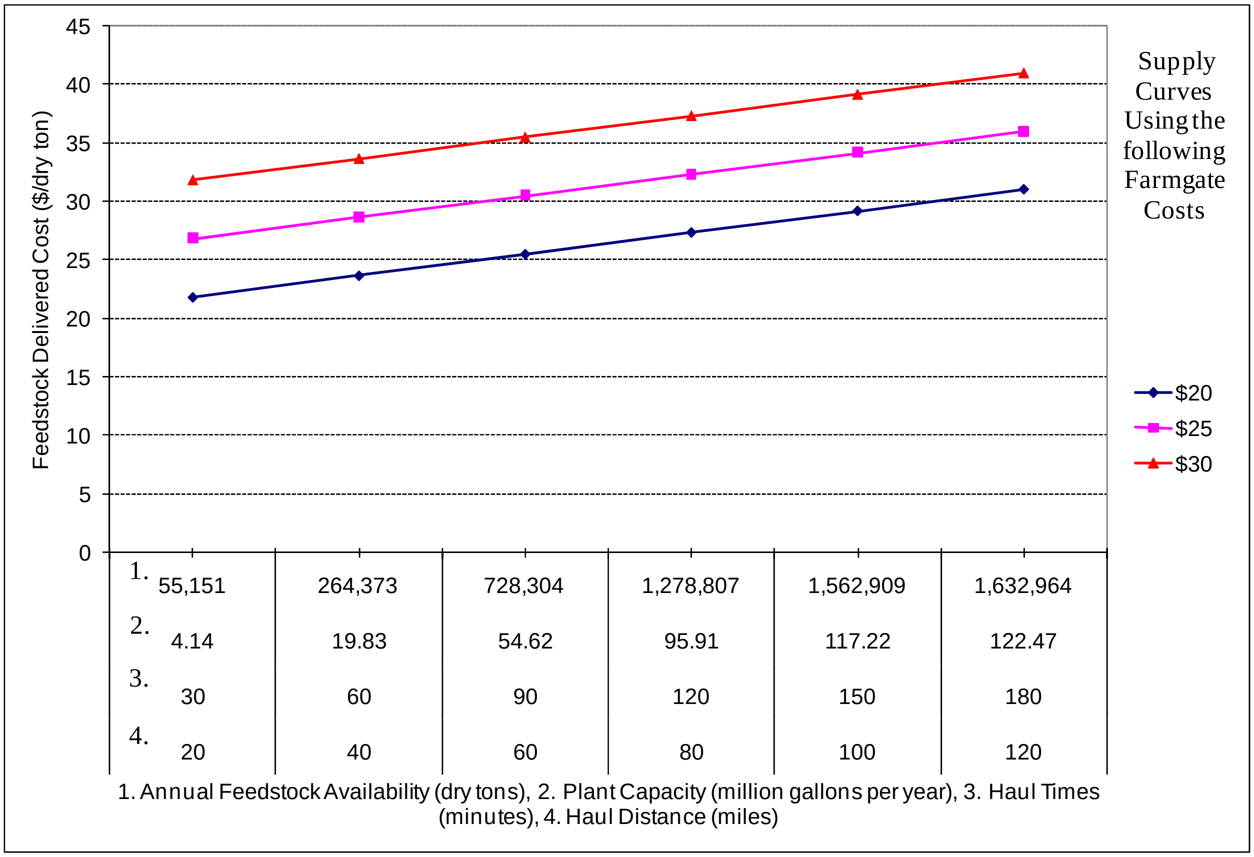
On the other hand, if the interest is in knowing the total supply of the feedstock within certain haul time, Figure 55 will be more useful since it shows cumulative availability of feedstocks. In Figure 55, counties Adams, Lincoln and Whitman reach their maximum cumulative availability within 90, 130 and 160 minutes of drive time respectively. In comparison, feedstocks to be transported from counties Garfield and Douglas require haul distances starting from 120 miles.

Figure 55: Cumulative Crops Residue Biomass Availability by Haul Times (from a Biorefinery) for the Counties in the Study Area



Derivation of feedstock supply curves (Figure 56) involves several components. First, the processing plant capacity that the existing/available feedstock can support was determined using 75 gallons per dry ton biomass-to-ethanol conversion rate. Another important measure is the resource availability within various haul time zones around the biorefinery. Haul times used for the supply curve construction were adjusted for transportation delays, such as stops, turns, and slow speed road segments. The relationship between the delivered cost of a feedstock per dry ton (specifically for the ethanol processing plant depicted in Figure 53) and the annual feedstock availability, processing plant capacity, feedstock haul times (in minutes) and distances (miles) are depicted in Figure 56.

Figure 56: Feedstock Supply Curves Using $20, $25 and $30 per Dry Ton Farm Gate Costs



On the horizontal axis, the first line represents the amount of crop residue available within the boundaries of a specific haul zone. The second line shows an incremental plant capacity in million gallons per year that the feedstock (cumulatively) available in a given haul zone can support. The delay-adjusted distance measure is included in order to fine tune the haul times. The slopes of the curves in the Figure 56 reveal the magnitude of the positive relationship between increasing haul times or increasing feedstock amount required by larger processing plants and the delivered cost of feedstock for all of the three feedstock farm gate cost scenarios. Depending on the plant annual processing capacity, supply curves provide the information on the delivered cost of feedstock. For example, for the geographic location of the 55 MGY proposed plant (mapped in Figure 53), the delivered cost was found to be $25.51 per dry ton considering feedstock farm gate cost of $20. More feedstock, and thus, higher processing capacity (up to 122.47 MGY) could be supported within the area under investigation by increasing haul distances. However, the delivered cost of feedstock will increase accordingly ($31.01 per dry ton).

Supply curves constructed using GIS-generated data help in assessing the optimal size of the plant given not only the feedstock availability in the study area, but also the geographic distribution and local road infrastructure. However, to assess the benefits from the economies of scale, processing costs need to be investigated as well. This may partially alter the delivered cost of the final product – ethanol blend.

Conclusion

Feedstock supply curves suggest that depending on the processing plant capacity, transportation costs may significantly influence the delivered cost of feedstock. Thus, larger capacity plants are not necessarily advantageous from economies of scale as it pertains to the feedstock production costs, because more capacity requires longer feedstock haul destinations. The economic viability of the ethanol processing is partially influenced by the delivered feedstock costs. Due to the spatially variable feedstock availability, the total biomass that is available in any region cannot be fully utilized at the same expense. Therefore, as a part of the interrelated structure of both ethanol processing and distribution, transportation costs prove to be a key component for the feasible feedstock supply system.

<u>GIS Analysis for Western Washington (Forest Residue)</u>

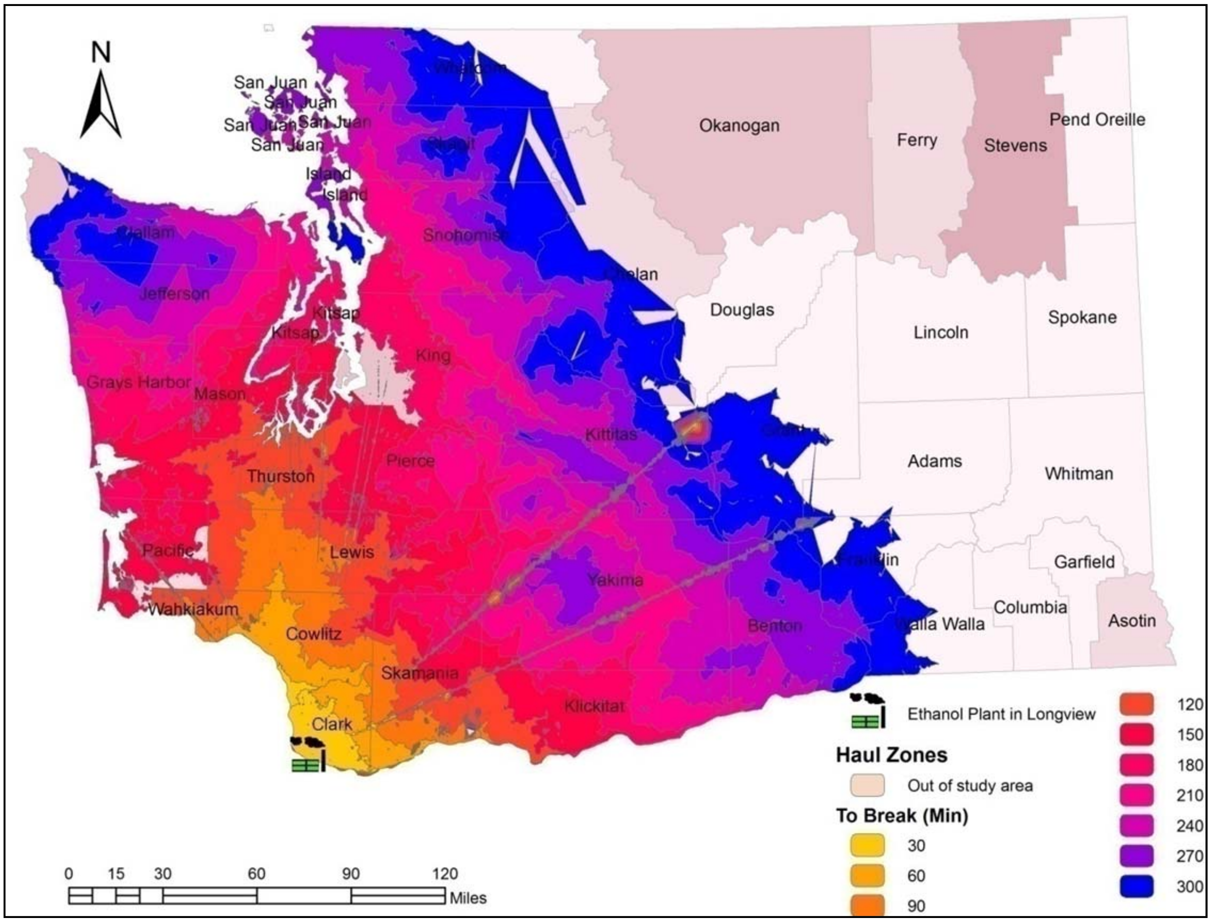
GIS Procedures

The road shapefiles for the study area counties and Census feature classification codes (CFCC) were obtained from the same source described in the GIS Analysis for Eastern Washington (Crops Residue) section. Using the same procedures described in the crop residue analysis part, the CFCC were joined to the roads shapefile attributes table and travel times were calculated using the following formula:

$$\textit{Travel Time (min)} = \textit{Road Segment Length (mile)} \times \frac{60}{\textit{Driving Speed Limit (mph)}}$$

Using GIS Network Analysis toolset, the service area layers (originating from the Southeastern part of the state) have been mapped (Figure 57). The origin is the actual geographic location of currently corn-based ethanol processing plant with the capacity of 55 MGY located in Clark County (Southwestern part of the state). Note that in order to keep the map simple, the road layer was not displayed. Following similar procedures described for crop residue feedstock, haul zones were calculated with 30-minute intervals (up to 300 minutes) from the origin (plant location) using travel time as the primary cost attribute.

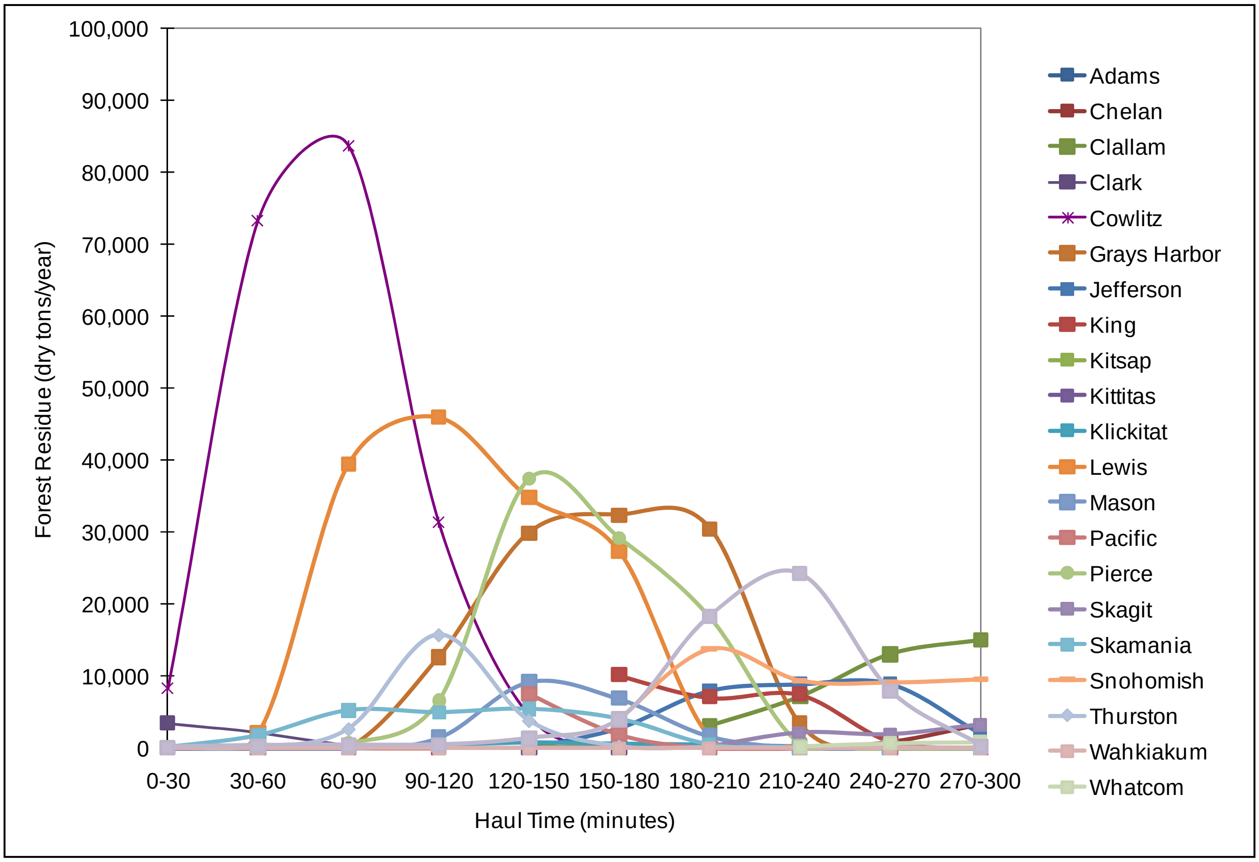
Figure 57: Forest Residue Availability by Haul Times



Feedstock Supply Curve Construction (Forest Biomass)

Feedstock supply curves were constructed following similar procedures described in the GIS Analysis for Crop Residue section. The feedstock availability in each haul zone and the cumulative availability are depicted in Figure 58 and Figure 59 respectively. Figure 58 can be more useful when information on feedstock availability within the next haul time category is needed.

Figure 58: Forest Residue Biomass Availability by Haul Times



As shown in Figure 58, the biomass availability reaches the highest levels of availability at 60 – 90 minutes zone for Cowlitz County, 90-120 minutes zone for Lewis County. Similarly, 120-150 minutes zone for Pierce, 180-210 for Grays Harbor and 210-240 for Yakima Counties. In Figure 59, resource availability in counties Grays Harbor and Pierce reach maximum cumulative availability at around 210 minutes of haul time; counties Cowlitz and Lewis reach maximum resource availability at around 120 and 180 minutes of drive time respectively.

Figure 59: Cumulative Forest Residue Biomass Availability by Haul Times

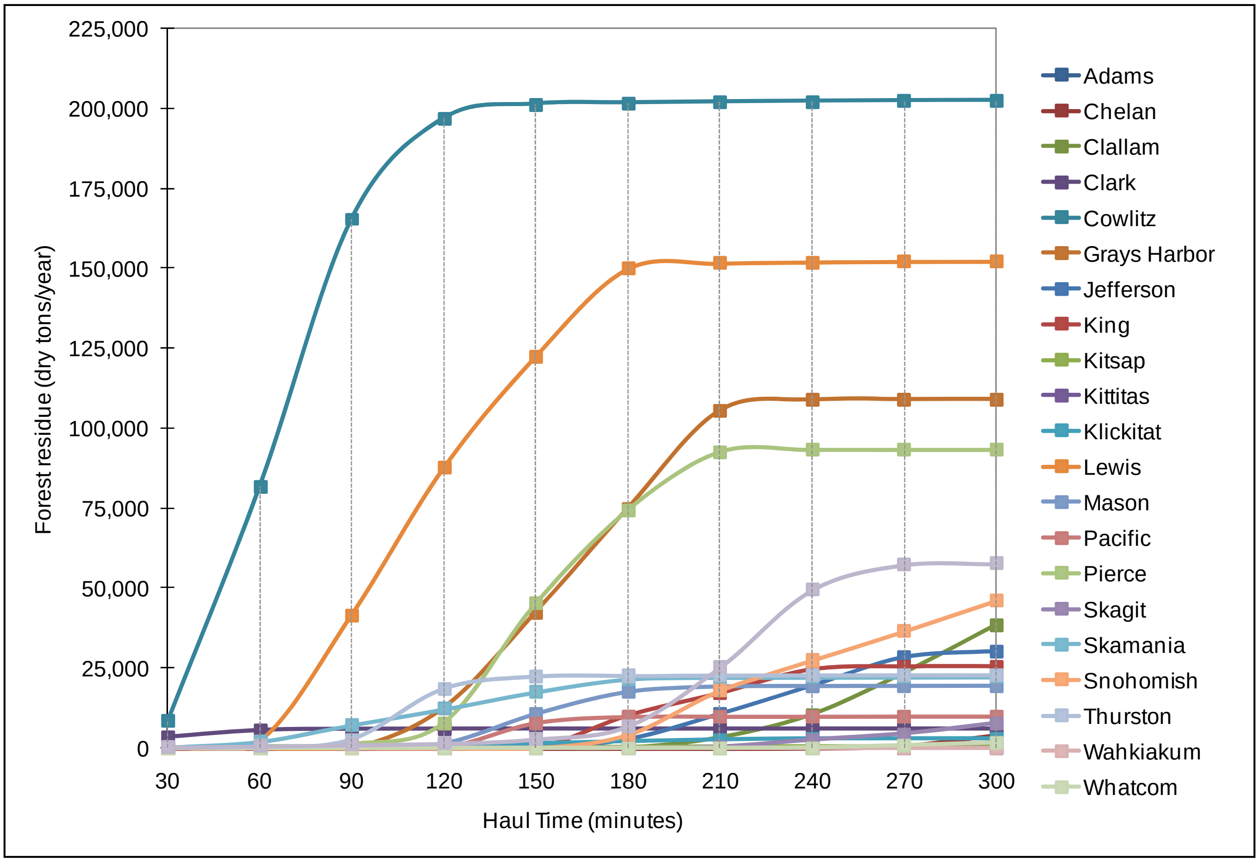
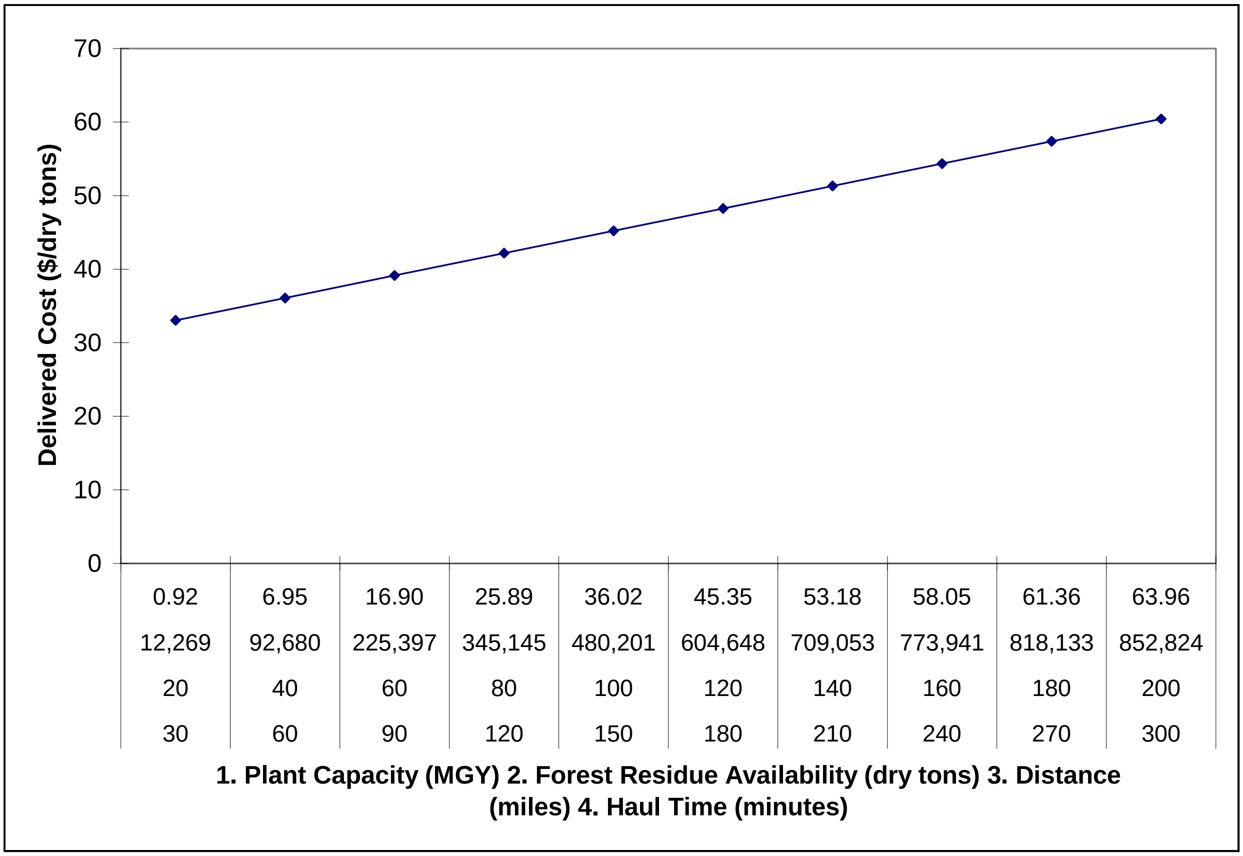


Figure 60 shows the relationship between the delivered cost of feedstock per dry ton and cumulative feedstock availability, as well as cumulative plant capacity, distances and haul times. On the horizontal axis, the first measure shows the plant capacity and the second line represents the amount of forest residue availability. The distance measure was included in order to complement the haul times.

Figure 60: Feedstock Supply Curve (Cumulative)



Conclusion

As with crop residue feedstock, depending on the plant capacity, the delivered cost of forest residue varies. For the geographic location of the operating plant (mapped in Figure 57), the delivered cost of forest residue feedstock that supports (current) 55 MGY ethanol processing capacity was found to be $52.82 per dry ton. By increasing haul distances with consideration of increasing delivered costs, higher processing capacity (up to 64 MGY) can be supported within the area under investigation.

Feedstock supply curves derived for forest residue suggest that processing plant capacity and the geographic distribution of feedstocks may significantly influence the delivered cost of feedstock. Thus, similar to plants utilizing crop residue as a feedstock, the larger capacity plants need (enough) processing cost reductions due to the economies of scale to offset increasing feedstock transportation costs.

GIS Analysis for Biofuel Plant Least-Cost Location Decisions (NREL Data)

In this section we introduce a Geographic Information Systems based model [using NREL (2007) data] to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs. Similar to the feedstock transportation GIS analysis above, the methodology is then utilized to analyze the state of Washington biomass data identified in the first phase of this project (Frear et al. 2005).

As an initial step of a multi-factor spatial optimization problem, including both feedstock transportation and ethanol distribution cost, we investigated the influence of feedstock transportation costs on optimal location decisions. To achieve that purpose, the feedstock resources, in this analysis forest biomass and agricultural crop residue, were spatially investigated relative to the road network and potential cellulosic ethanol plant locations in the state of Washington. The flexibility of the model allows spatial manipulation of the data for the least-cost location identifications considering both cumulative and separate types of feedstock utilization scenarios. Study results show that the ethanol plant transportation cost-minimizing location decisions are significantly influenced by the type of the feedstock utilized, and vary depending on the plants' processing capacities.

GIS Model

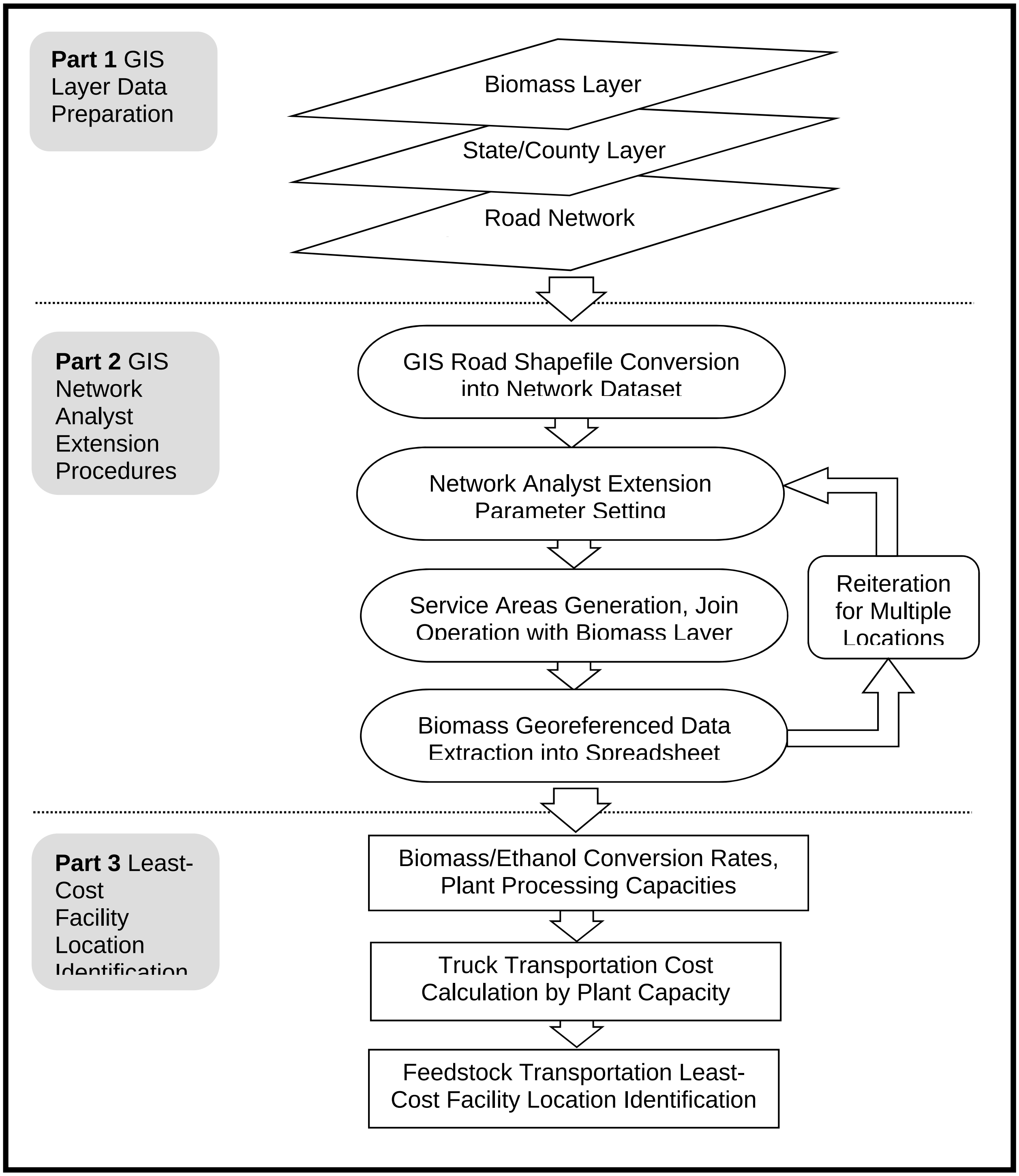
Data

The GIS data have been obtained from the National Renewable Energy Laboratory's Dynamic Maps, GIS Data and Analysis Tools webpage (NREL 2007). According to the same source, the cumulative availability of the forest biomass and agricultural crop residue in the state is over 2.7 million annual dry tons, indicating a potential to process more than 200 million gallons of ethanol annually. Crop residue procurement prices and per ton mile truck transportation costs (for both types of feedstock) have been used as derived in Feedstock Production and Transportation section of this report. For the forest biomass procurement prices, estimates from relatively recent studies have been adapted from recent studies (Gan and Smith 2006; Asikainen et al. 2002; Rummer et al. 2003; and Puttock 1995). Study area road shapefiles have been obtained from the Environmental Systems Research Institute website (ESRI 2007).

Structure

The GIS-based model consists of three main parts. In turn, each of the parts includes several procedures (Figure 61). The first part builds a dataset by layering GIS shapefiles that are necessary for the analysis in this section. The second part involves GIS Network Analyst extension procedures for creating service area (a shapefile of driving zones) around processing plants included in the study area, as well as for joining and relating that new shapefile (service areas) with existing GIS layers. Reiteration of the procedures is undertaken for each of the processing plant locations. The final part of the model incorporates spreadsheet operations for further analysis with the GIS-generated spatial data. In particular, it links steps in which annual ethanol processing capacities (using biomass-to-ethanol conversion rates) and truck transportation per ton mile costs are derived for the least-cost facility location identification.

Figure 61: Flowchart of GIS-based feedstock transportation least-cost facility location decision model.

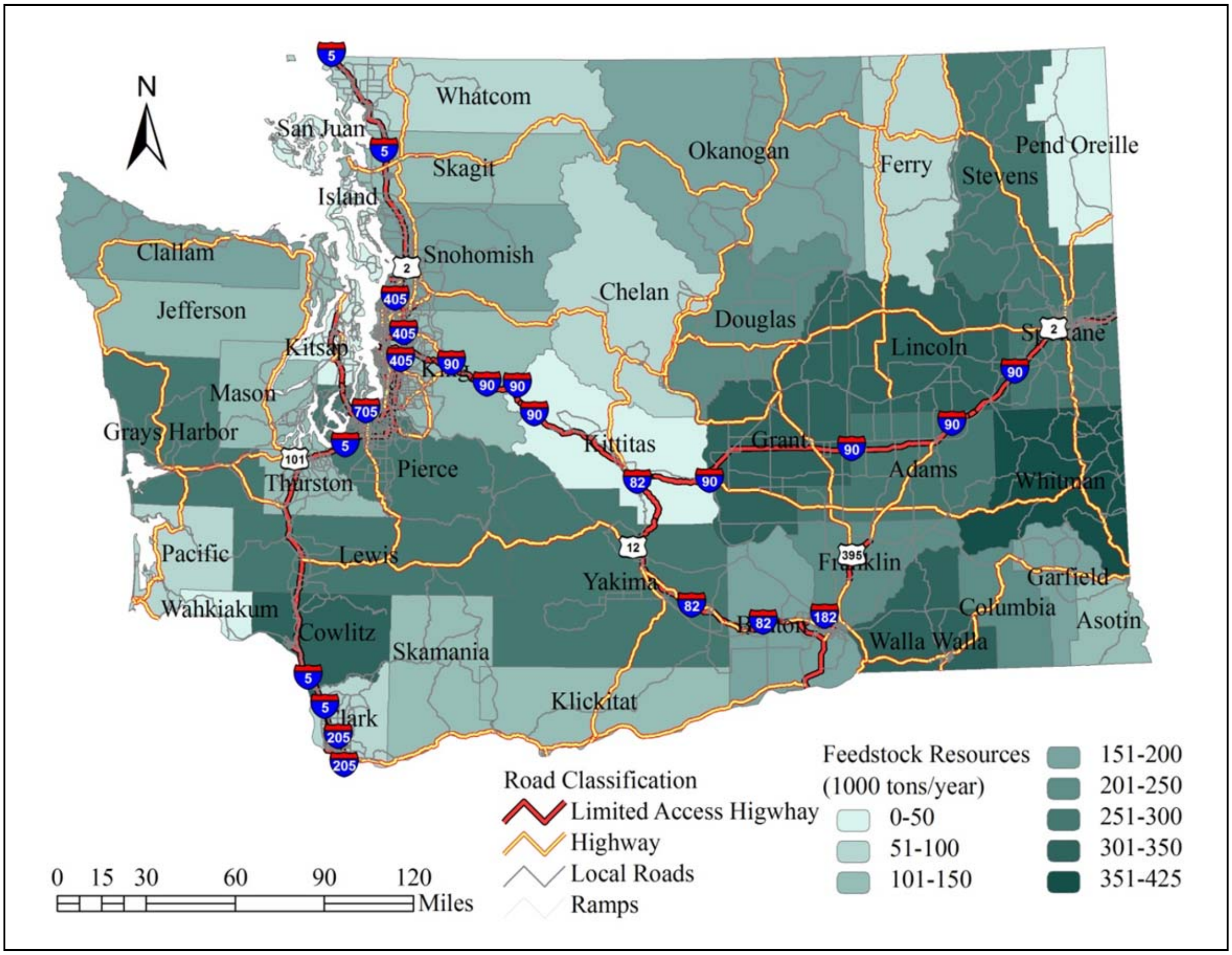


GIS Procedures

This section provides details on the GIS procedures for calculating feedstock resource availability by county, and by specified haul distances. It also describes procedures for assigning driving speed limits to the road segments and for generating datasets for the feedstock transportation costs derivation.

The biomass shapefile, indicated in Part 1 of Figure 61, represents a geographical layer with attribute information, such as area and boundaries of biomass distribution, and spatial information, such as latitude, longitude and type of the map projection (i.e. transformation of spheroid surface to a flat map while maintaining spatial relationships). Integration with the state/county shapefile provides annual availability information for agricultural crops residue and forest biomass by county level (cumulatively mapped in the following Figure 62). Simultaneously census feature classification codes (CFCC) were joined to the GIS roads shapefile's attribute table. This procedure assigns speed limits to each of the road segments, which in turn, allows driving distances from each processing plant to the feedstock sources to be calculated.

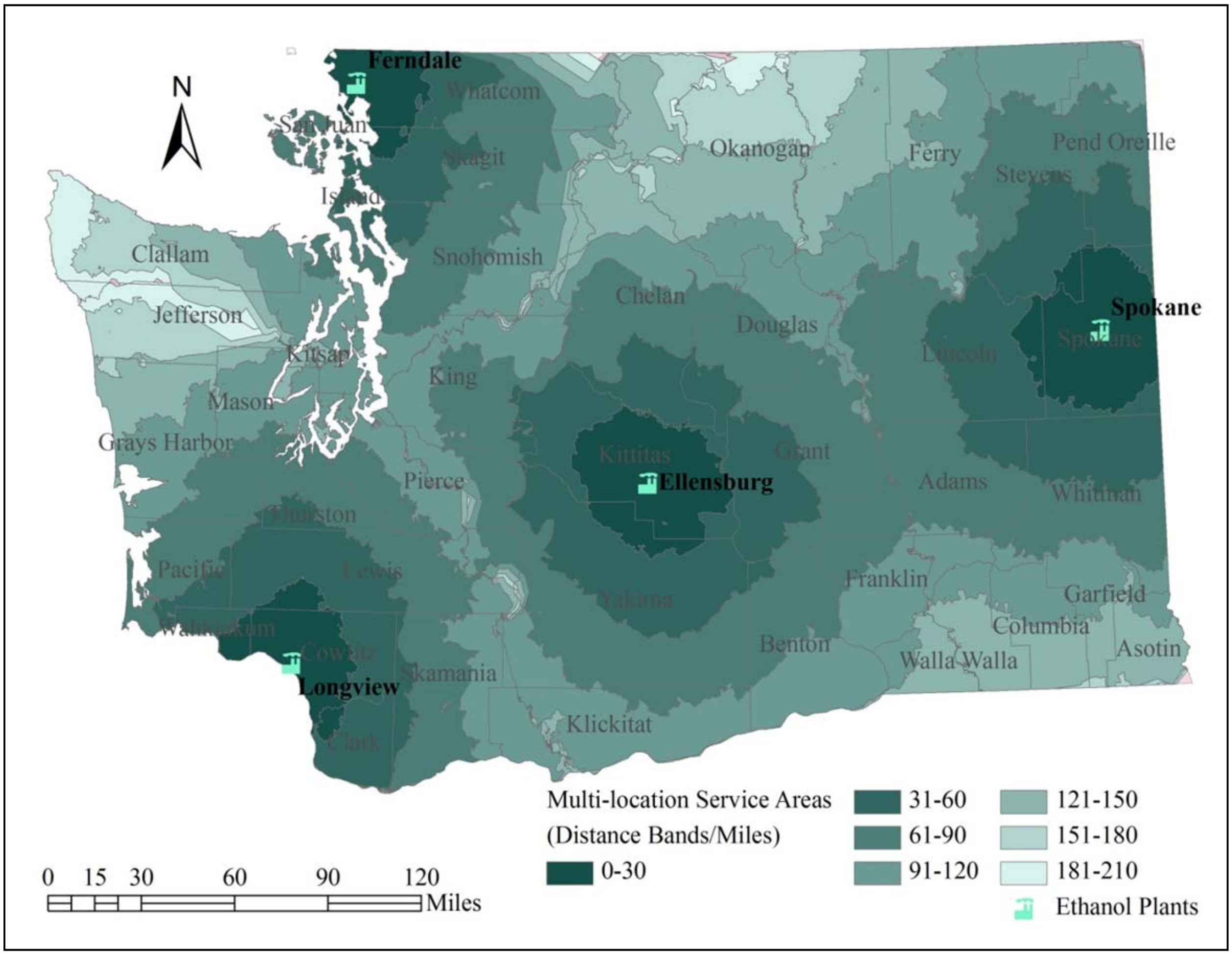
Figure 62: Distribution of forest biomass and agricultural crop residue in the state of Washington



Procedures in Part 2 of the model involve a GIS Network Analyst extension toolset, which enables network based spatial analysis, such as finding the closest facility from a particular location, identifying routes and driving distances to reach specified areas, and generating service areas (distance-based buffer zones) around points of interest. As an initial step, the GIS road shapefile was converted into a network dataset (using GIS ArcCatalog software). GIS network datasets are constructed from spatial features – lines, points and turns, which build an advanced connectivity model for transportation networks. The next step sets parameters for the service area generation, such as driving distance bands (in miles), processing plant locations and cost attributes.

To identify the feedstock resource availability within increasing driving distances around ethanol processing plants, the service areas cover the entire state at 30-mile increments. For instance, within the 30-mile buffer, all available feedstocks will require a 30-mile length haul (maximum) to be transported from the field to the processing plant. The cost attribute for service areas generation was set as a distance in miles, and the four proposed ethanol facility locations have been loaded as points where the feedstock needs to be transported. The rationale for selected processing plant locations is that all of them are currently under planning or feasibility study stage (Lyons 2008). After the generation of service areas, (depicted in Figure 63) the resulting distance based layers were joined with the biomass layer, such that for each service area the available feedstock/biomass amount in annual tons is identified at the county level.

Figure 63: Service areas around four proposed ethanol facilities



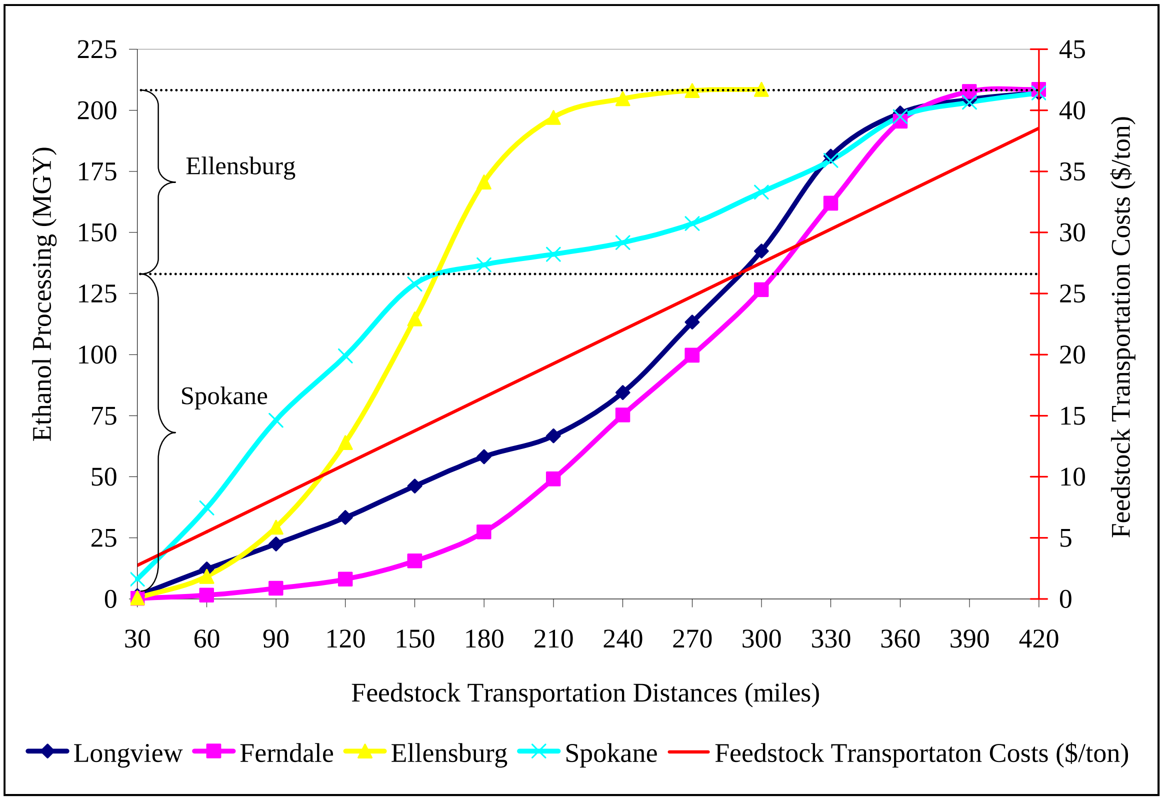
Since the biomass data were available per county, several additional steps were implemented to extract the county availability information, within each driving distance. First, the information within the service area boundaries of the merged (service area with biomass layer) layer was selected and saved as a separate layer. In this selected layer the geographic area (in square miles), for each of the service areas within boundaries of each county was calculated using GIS ArcMap Geometry Calculation tool. As the last step of Part 2, the attribute table of merged shapefile was exported into a spreadsheet. Finally, to specify the availability of biomass in each of the service areas at county level, the service area proportions were calculated by dividing service areas (in square miles, within respective counties) by the area of the county itself. Reiteration of procedures was carried out for all four processing plant locations depicted in Figure 63.

The final part of the model incorporates per ton mile transportation costs, considering loading/unloading delays, physical availability, as well as the geographic distribution of the biomass, allowing delivered feedstock costs to be derived. Using a 75 gallons of ethanol per dry ton of feedstock conversion rate, driving distances varied by different processing plant capacities (reaching to 210 MGY) were identified (U.S. DOE 2007). This finally allowed transportation costs per ton of feedstock by processing plant capacity to be derived. Integration of per ton mile transportation costs, physical availability of feedstock and its distribution enabled identifying least-cost processing plant location, as affected by the feedstock transportation costs. Further as discussed in the Results section, this approach allows ranking plant locations according to the type of feedstock utilized (agricultural crops residue vs. forest biomass) and according to the plant processing capacity.

Results

Analytical results indicate that transportation costs differ according to the processing plant capacity, since the larger plants require more feedstock to support their production level, hence longer haul distances. Figure 64 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the combined (forest biomass and agricultural crop residue) feedstock utilization scenario. The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to 130 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within only 120 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations will need to reach out twice as farther as it is required for the Spokane location.

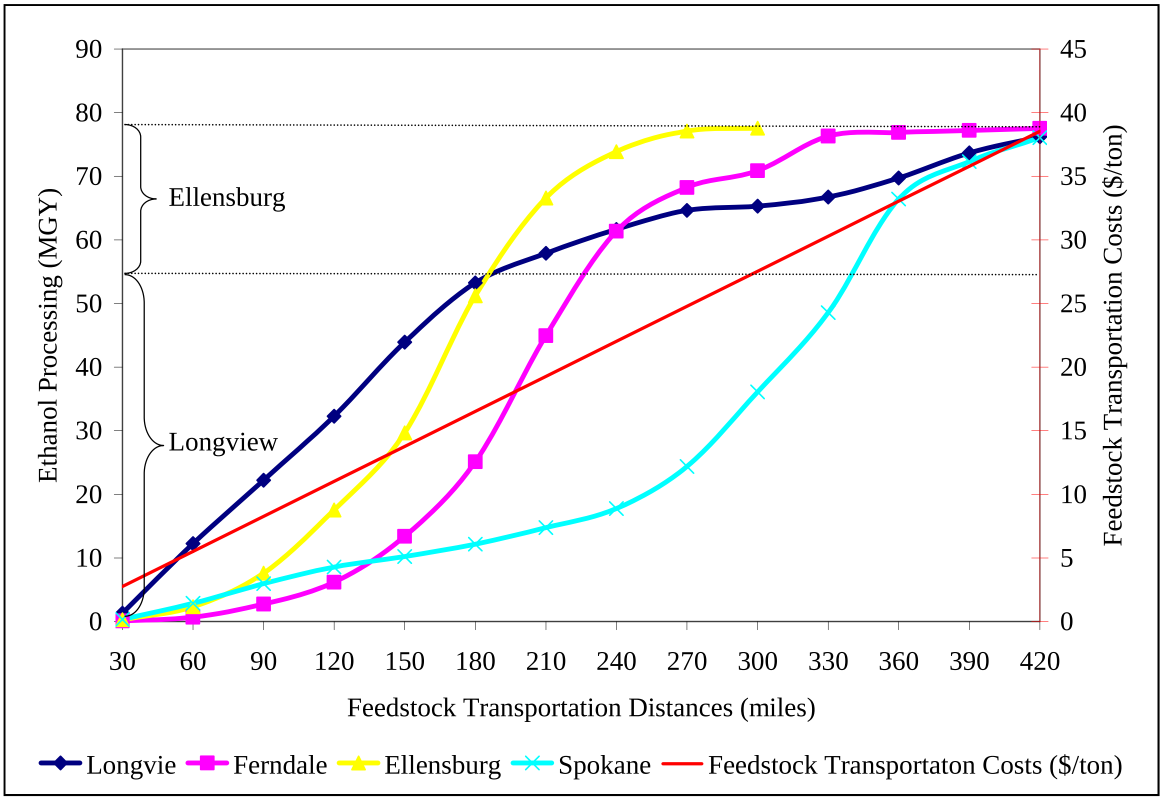
Figure 64: Feedstock transportation costs by processing plant capacity (forest biomass and agricultural crop residue combined).



For the processing capacities over 130 MGY, the location with the lowest feedstock transportation cost is Ellensburg. A maximum of 210 MGY processing can be achieved using resources within 300 miles around the plant. Locations in Longview and Ferndale were not found to be competitive, in this scenario, which considers cumulative (forest and agricultural residue) availability of feedstock resources.

Depending on the type of the feedstock considered for ethanol processing, transportation costs differ, since each type has different geographic distributions in the study area. To compare results with that of the cumulative feedstock utilization scenario, forest biomass was analyzed separately. The relationship between forest biomass transportation costs and an annual ethanol processing for the same plant locations in the study depicted in Figure 65. The previous location (Spokane) does not necessarily sustain its cost competitiveness when considering feedstocks separately. One of the obvious reasons for considering separate feedstock scenario is processing/conversion technology restrictions pertaining to types of feedstocks.

Figure 65: Feedstock transportation costs by processing plant capacity (forest biomass).



As shown in Figure 65, for the processing capacities up to 55 MGY, the Longview location shows the lowest transportation costs when considering forest biomass only. This level of processing capacity can be supported by transporting feedstocks within 180 miles around the plant. For larger capacities (reaching up to 78 MGY at maximum), the Ellensburg location provides the lowest transportation costs. In contrast to the cumulative biomass scenario, the Spokane location is not cost competitive for any of the processing capacities when considering forest biomass only. The Ferndale location has the highest transportation costs for both cumulative and separate feedstock utilization scenarios.

Conclusions

Ethanol processing plant optimal location decisions depend on many factors, including costs associated with feedstock transportation and ethanol distribution. In this section we investigated the least-cost locations in the state of Washington pertaining to the feedstock transportation at different levels of ethanol processing. Because of the spatially variable distribution of the feedstock resources and increasing transportation costs for longer destinations, all of the feedstock deposits cannot be utilized at the same expense. Additionally, it was demonstrated that for different processing capacities, optimal plant locations vary according to the type of the feedstock. The GIS approach discussed in this section allowed spatial manipulation of data considering multiple geographic locations in the study area, which provides more accurate evaluation of available feedstock resources within specified distances from processing plants. Finally, the flexibility of the model enables its application to any geographic area. In further steps, the model will be used to analyze the feedstock types identified in the first phase of this project (Frear et al. 2005).

GIS Approach to Delivered Feedstock Costs (Frear et al. Data)

Using the GIS procedures tested with the NREL data, we estimated the availability and the delivered cost of feedstocks using Frear et al. (2005) data. Figures below show the relationship between feedstock transportation costs and plant processing capacities by haul distances for four potential biorefinery locations in the state. GIS maps with 30-mile increasing service areas (buffer zones) are provided for each of the locations. Considering forest residue feedstock for Vancouver/Longview location (Figure 66), a 100MGY plant requires feedstocks to be transported from about 90 miles of haul distance. To support the same capacity of ethanol processing from animal manure, feedstocks need to be transported from within 240 mile distance from the potential biorefinery location.

Overall, the results show a positive correlation between processing plant capacity and feedstock transportation costs. As discussed in the Economies of Scale section, increasing transportation costs will be offset by economies of scale in the processing section up to the point where the transportation costs start to increase at a higher rate.

Figure 66: Feedstock Transportation Costs by Haul-Distances for Vancouver/Longview Plant

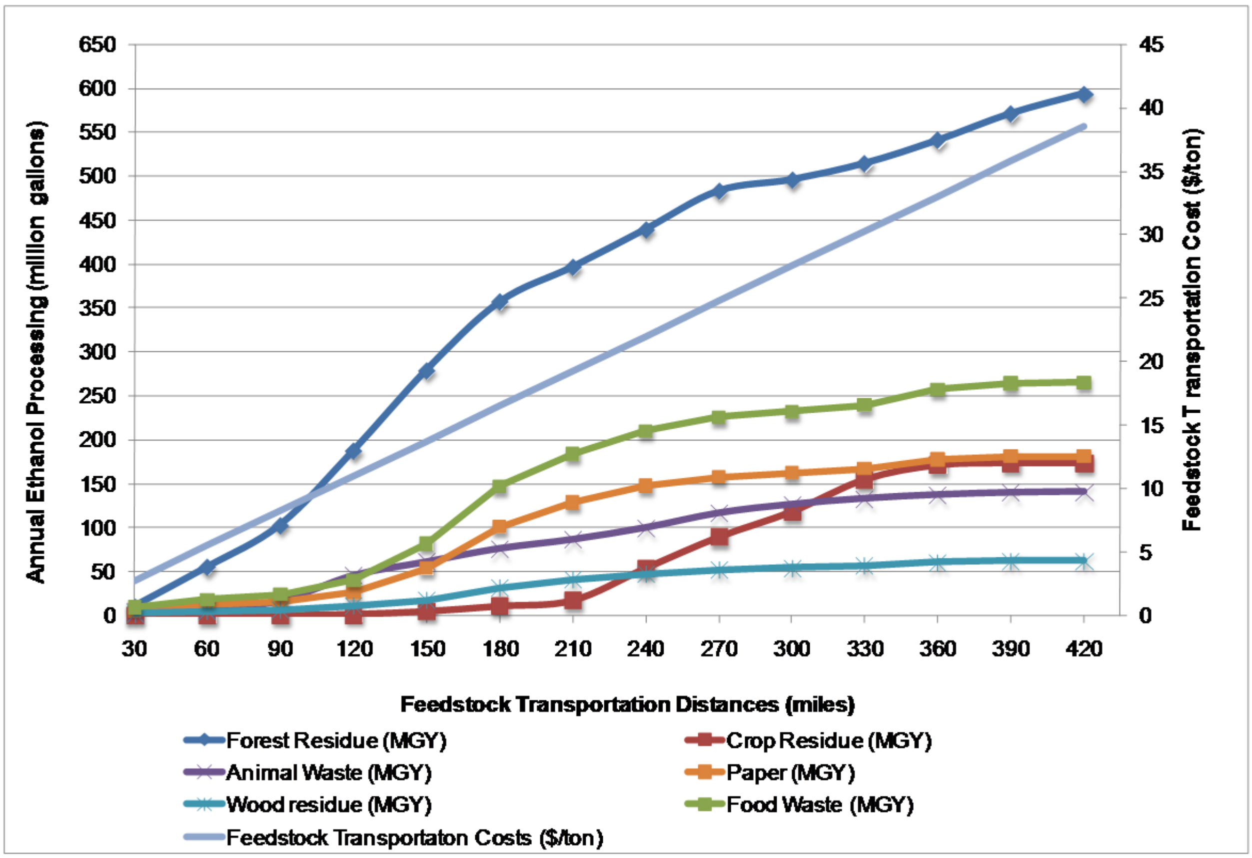
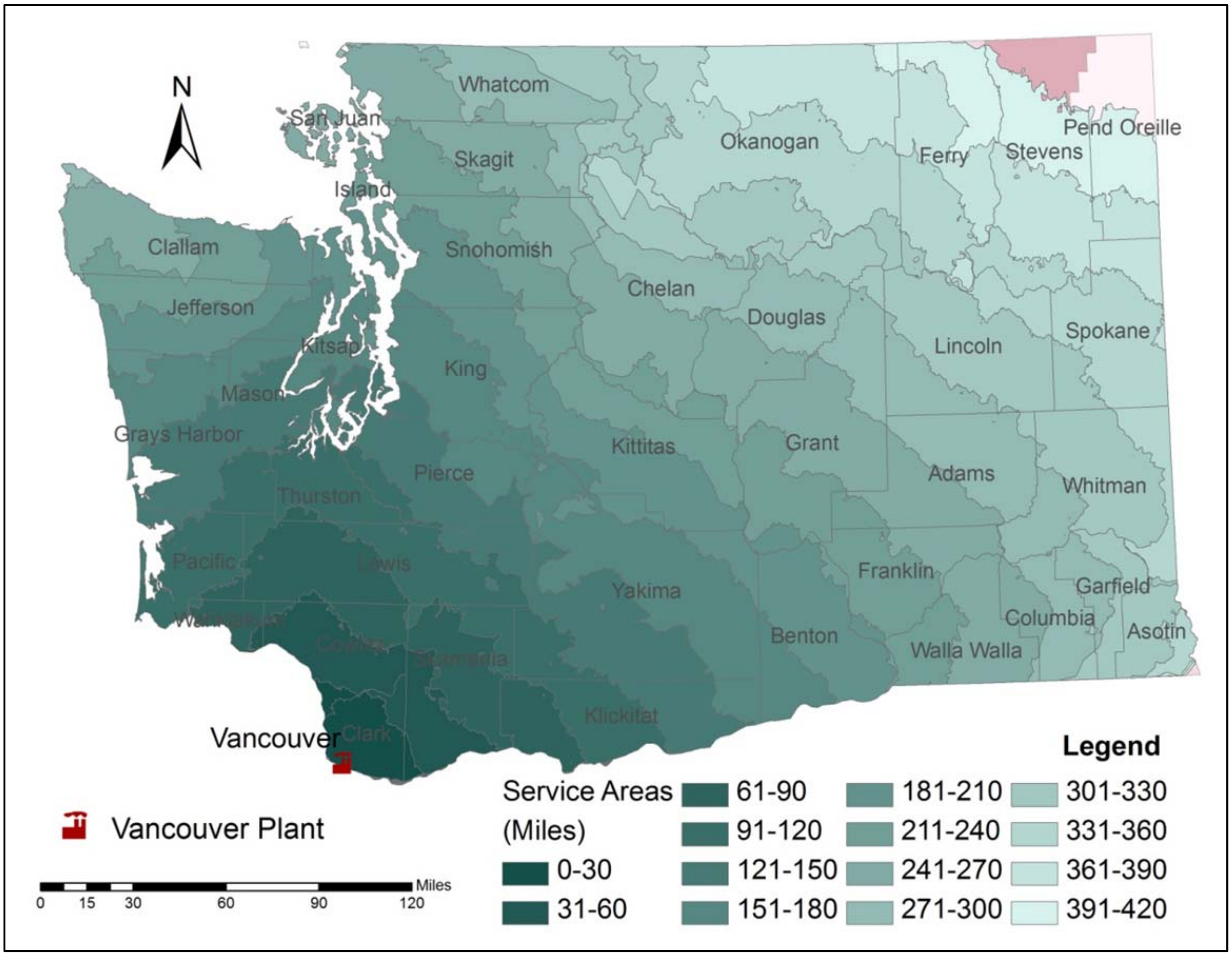


Figure 67: Service Areas for Vancouver/Longview Plant



As shown in Figure 68, considering forest residue feedstock for Ferndale location, a 100MGY plant requires feedstocks to be transported from about 130 miles of haul distance. To support the same capacity of ethanol processing from paper residue (for example), feedstocks need to be transported from within 150 mile distance from the potential biorefinery location, thus increasing transportation costs.

Figure 68: Feedstock Transportation Costs by Haul-Distances for Ferndale Plant

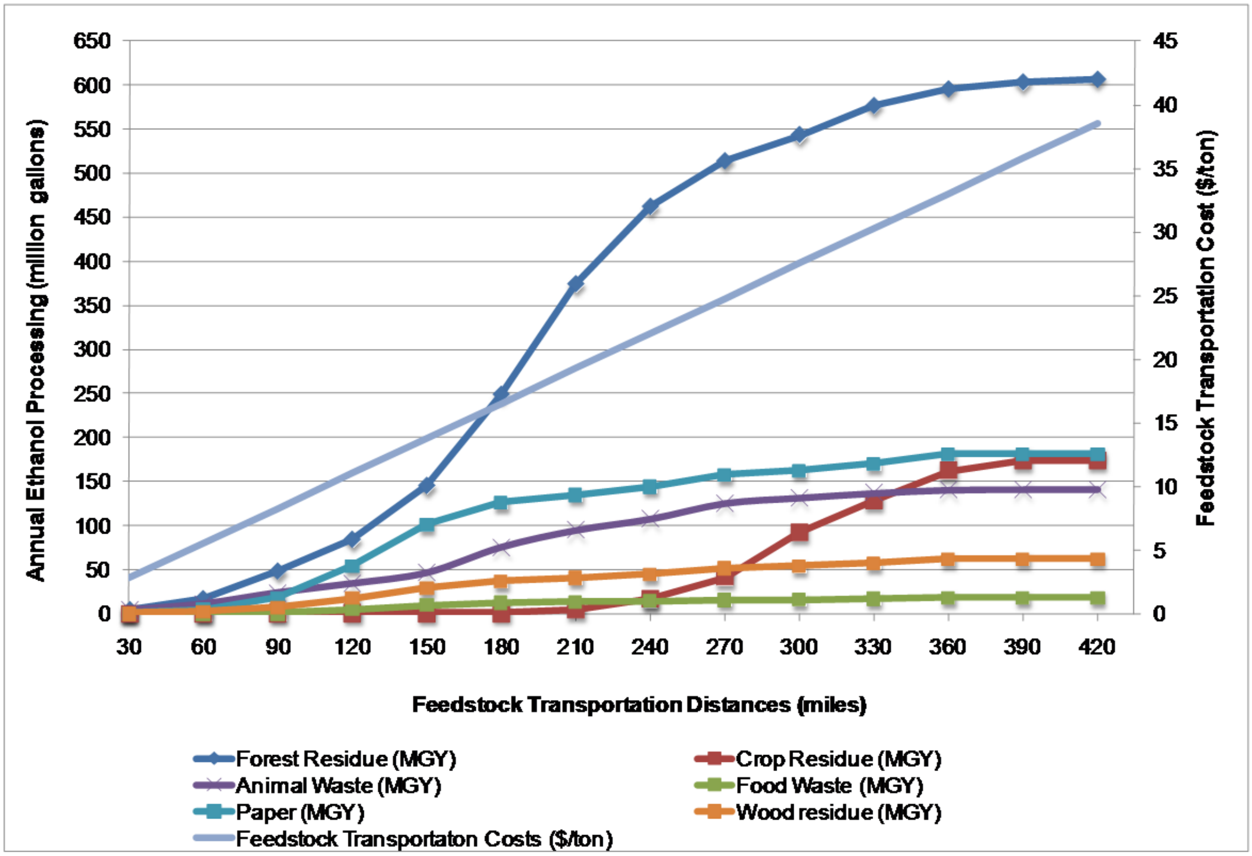
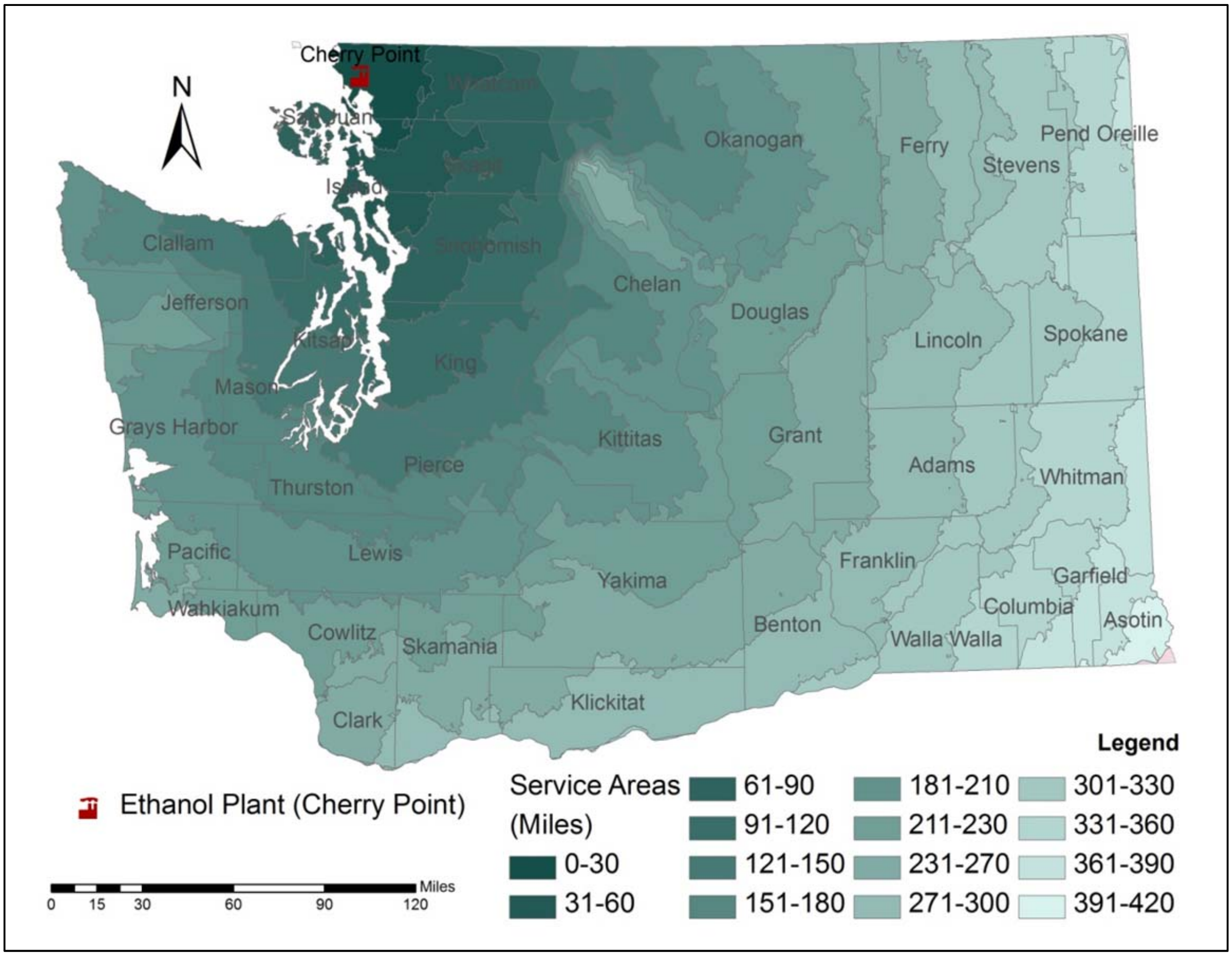


Figure 69: Service Areas for Cherry Point/Ferndale Plant



Based on Figure 70, about 150 MGY processing plant can be supported by feedstocks collection from only 150 mile distance from the potential biorefinery in Spokane. To support the same capacity of ethanol processing from forest residue, feedstocks need to be transported from about 230 mile distance from the biorefinery location. Feedstock transportation costs increase respectively.

Figure 70: Feedstock Transportation Costs by Haul-Distances for Spokane Plant

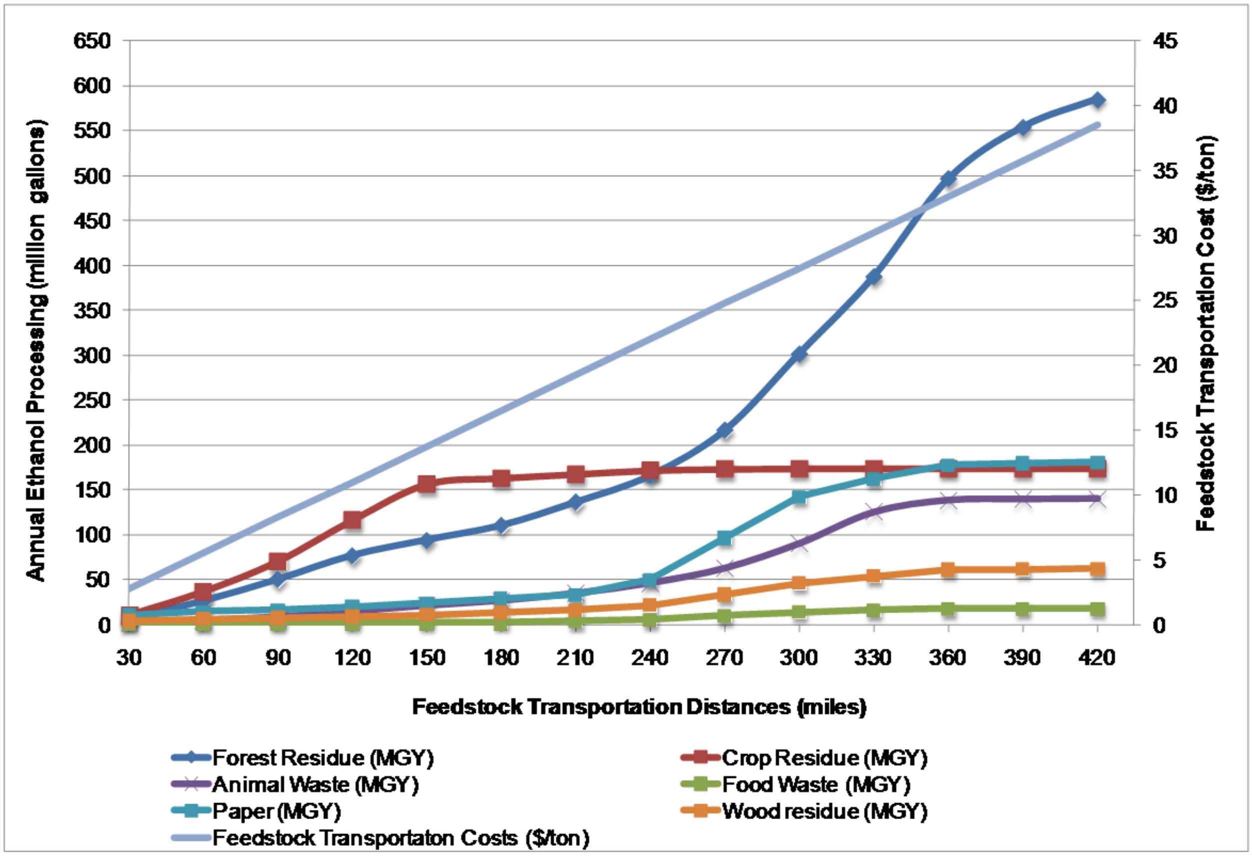
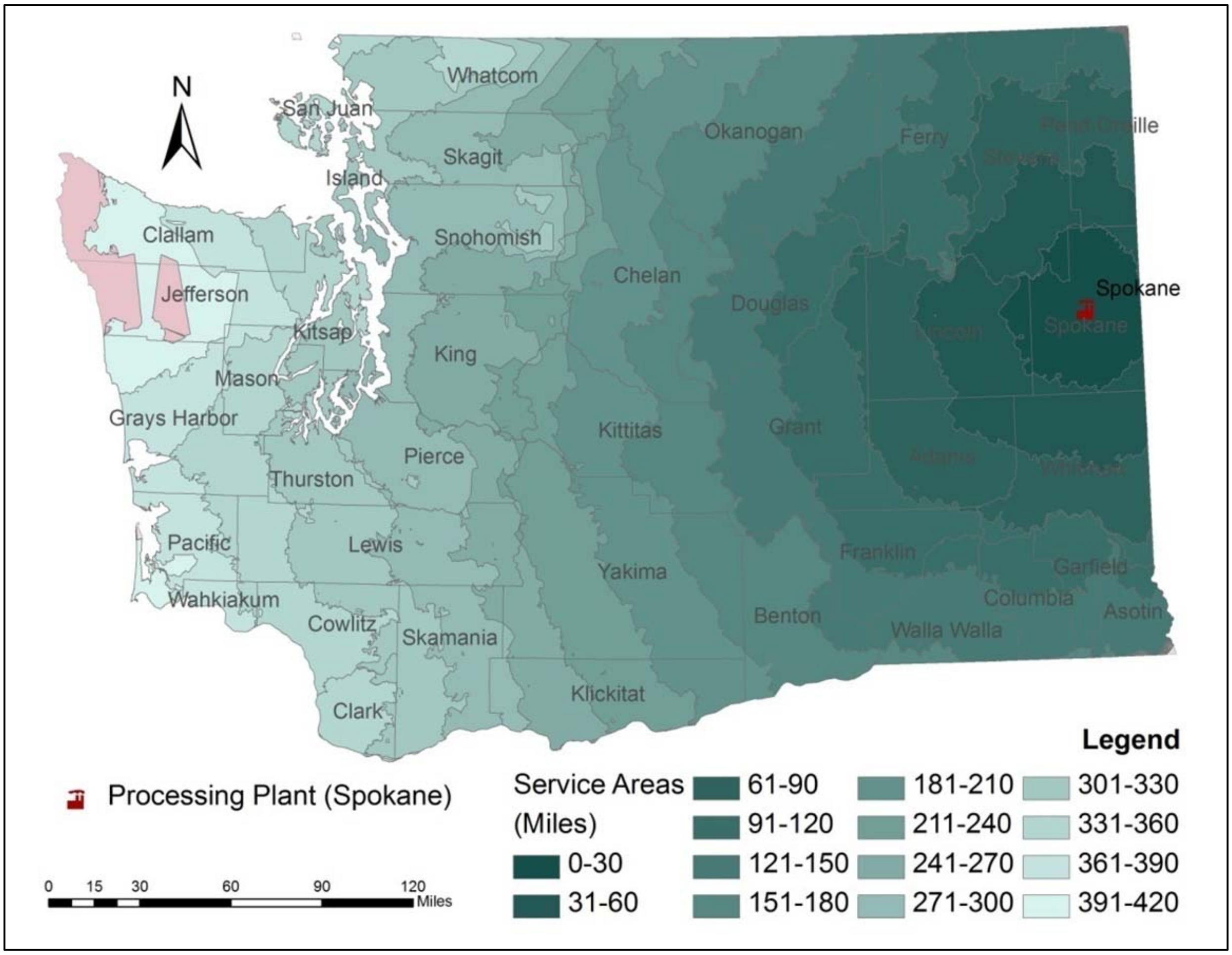


Figure 71: Service Areas for Spokane Plant



According to the results shown in Figure 72, considering forest residue feedstock for Ellensburg location, a 100MGY plant requires feedstocks to be transported from about 100 miles of haul distance. To support the same capacity of ethanol processing from crop or paper residue, the haul distance increases to about 120 miles from the biorefinery location.

Figure 72: Feedstock Transportation Costs by Haul-Distances for Ellensburg Plant

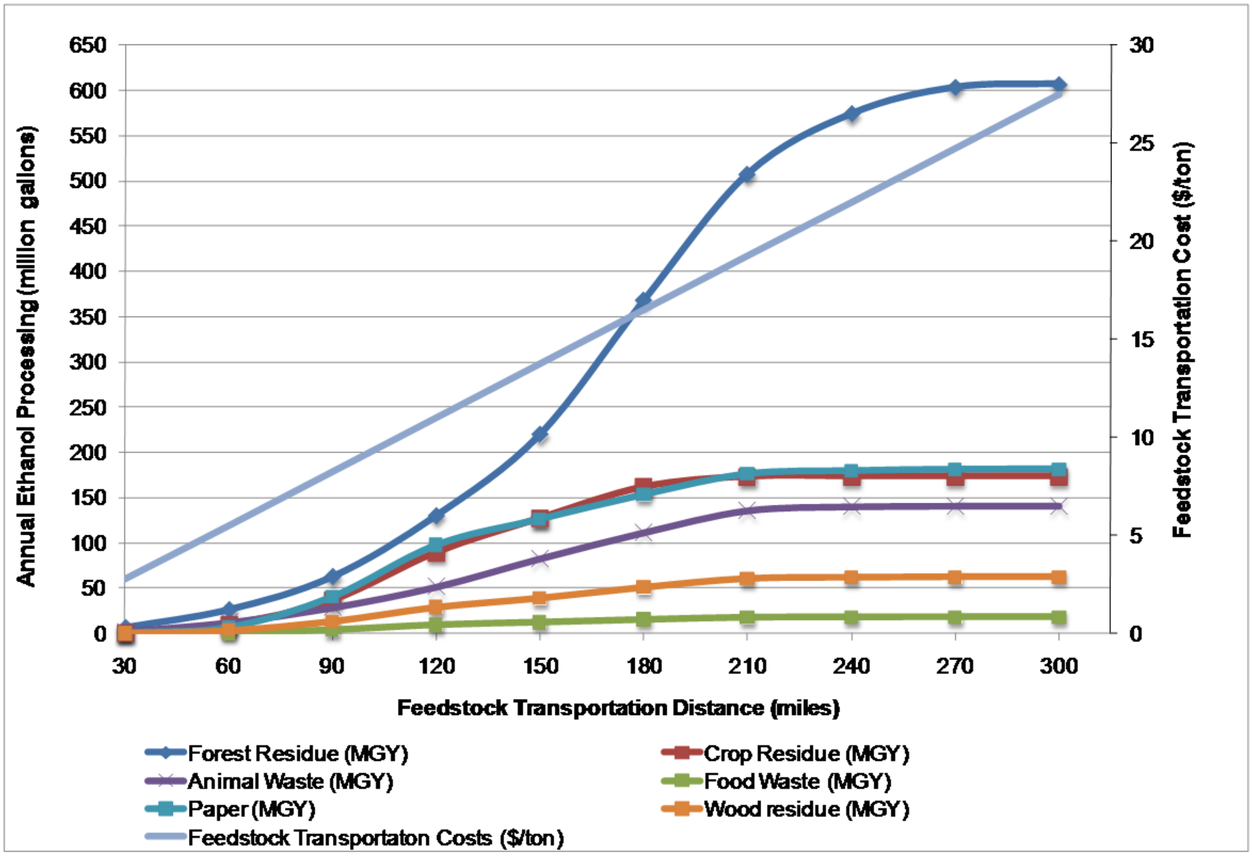
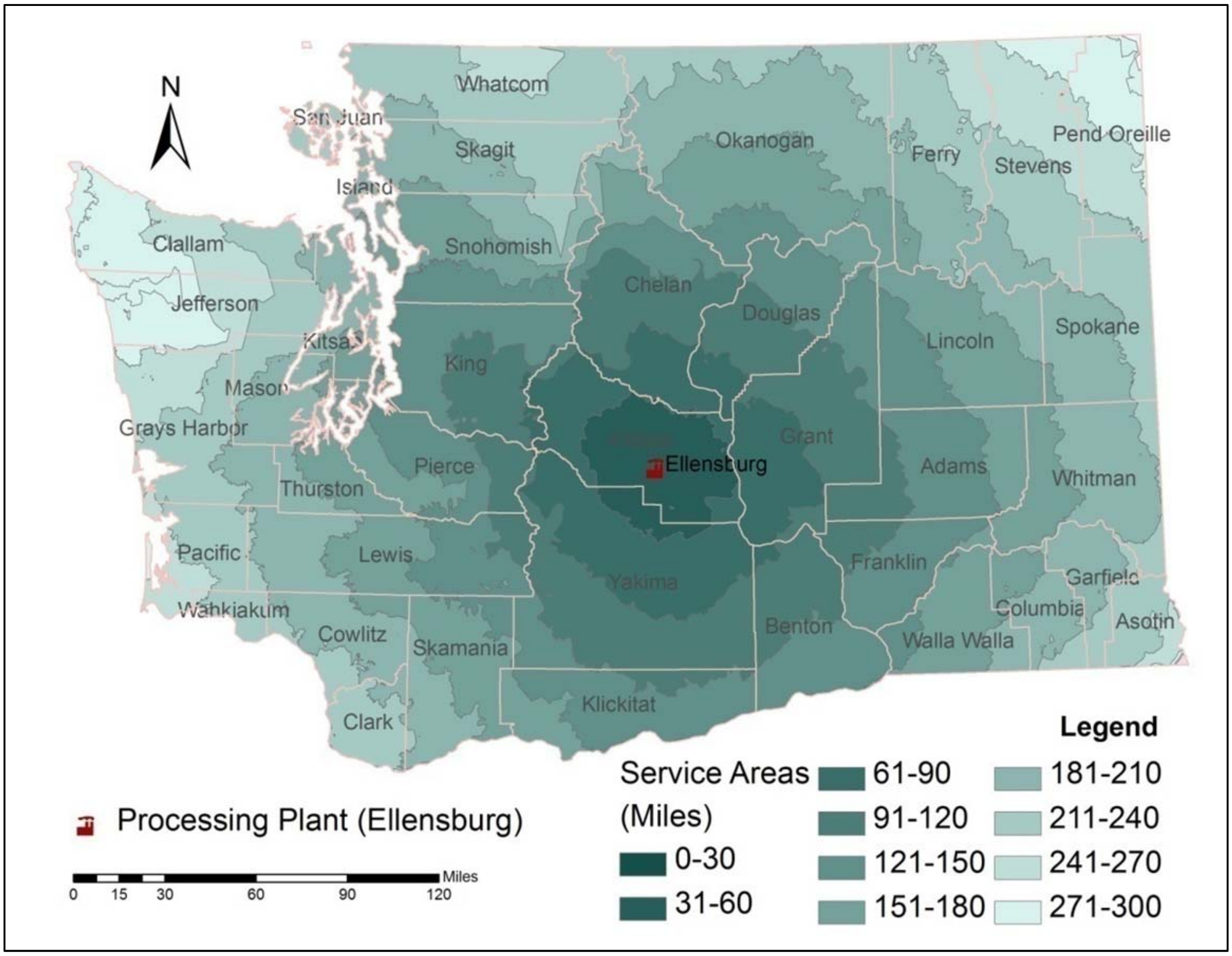


Figure 73: Service Areas for Ellensburg Plant

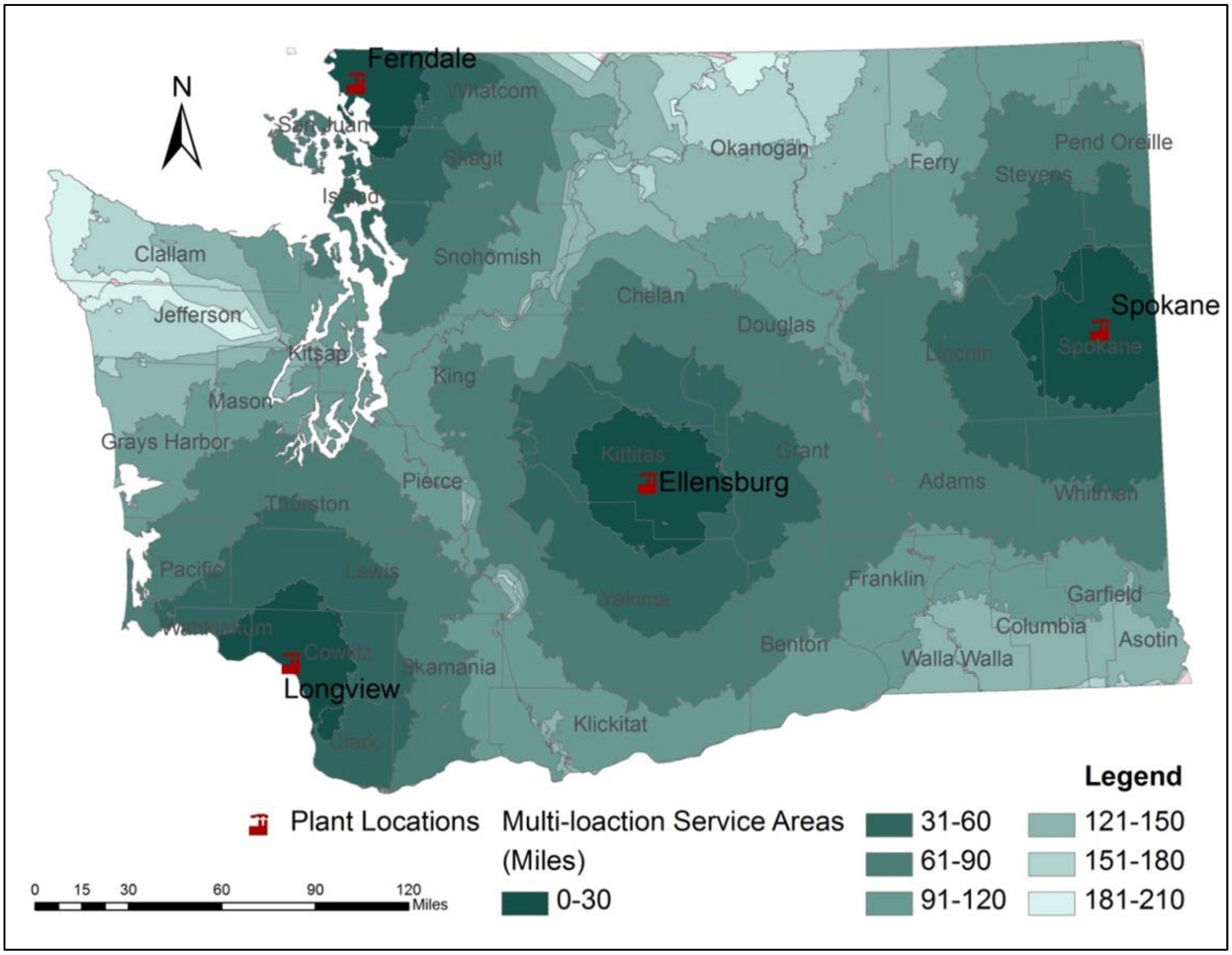


GIS Analysis for Biofuel Plant Least-Cost Location Decisions (Frear et al. Data)

In this section we introduce results using the GIS biofuel plant least-cost location decision model introduced earlier in this report. The model provides information to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs. The GIS procedures are similar to the pilot model tested above. Figure 74 shows feedstock collection service areas the cover the study area with 30-mile increments.

As shown in Figure 75, the results indicate that transportation costs increase with increasing processing plant capacity, since the larger plants require more feedstock to support their production level, hence longer haul distances. Figure 75 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for agricultural crop residue utilization scenario.

Figure 74: Multi-location Service Areas for Four Plants in the State of Washington



The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to 165 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 105 miles from the plant location. To achieve the same level of ethanol processing, plants considering Ellensburg location need to reach out about 120 miles from the plant. Longview and Ferndale locations will require twice as farther as it is required for the Spokane location.

Figure 75: Feedstock Transportation Least-Cost Locations (Crop Residue)

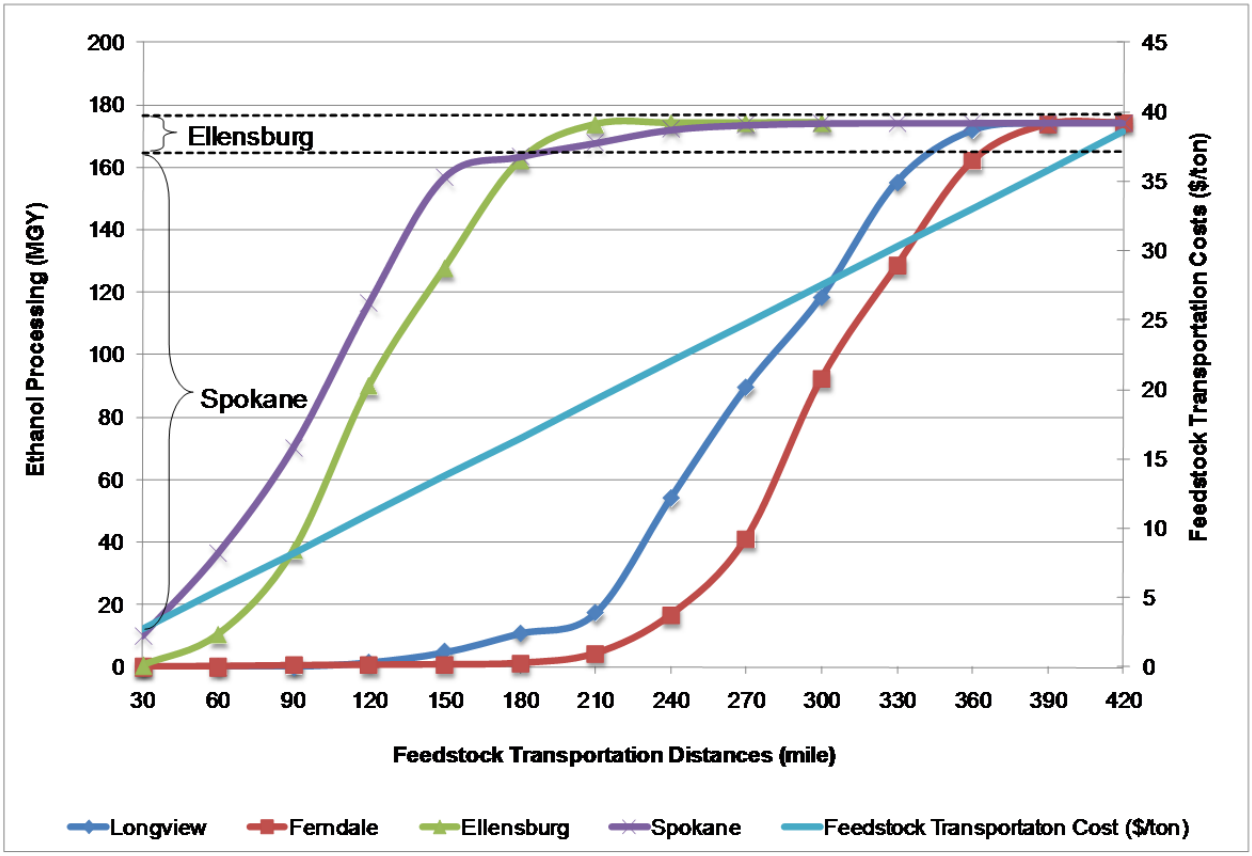


Figure 76 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for forest residue utilization scenario. The location in Longview maintains its least-cost feedstock transportation advantage for all processing capacities up to 350 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 90 miles from the plant location. To achieve the same level of ethanol processing, plants considering Ellensburg location need to reach out about 110 miles from the plant. Ferndale and Spokane locations will require feedstocks to be transported from 130 and 160-mile haul distances.

Figure 76: Feedstock Transportation Least-Cost Locations (Forest Residue)

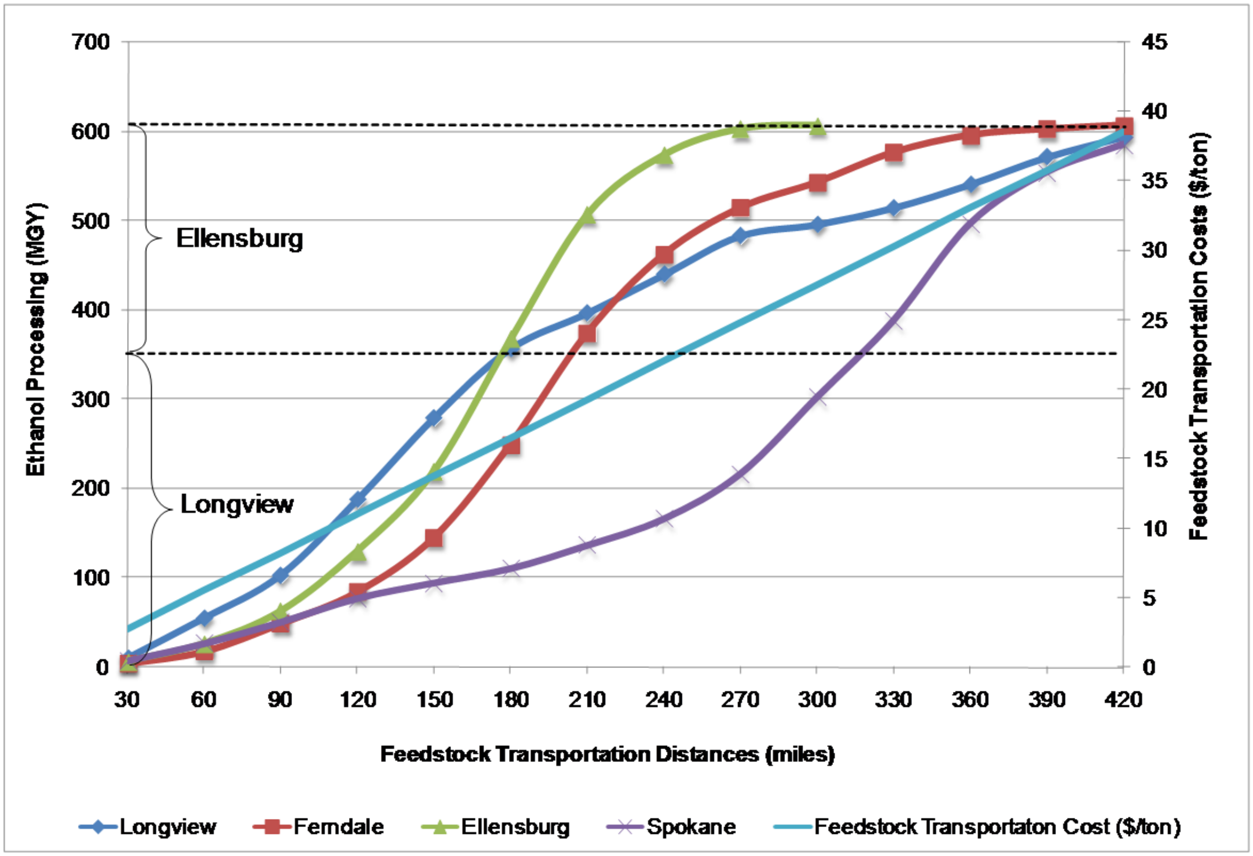


Figure 77 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for animal waste utilization scenario. Given the geographic distribution of animal manure in the state, Ellensburg location has advantage over all three location for all processing scales. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 160 miles from the plant location. To achieve the same level of ethanol processing, plants considering Ferndale and Longview locations need to reach out about 220 and 240 miles from the plant respectively.

Figure 77: Feedstock Transportation Least Cost Locations (Animal Waste)

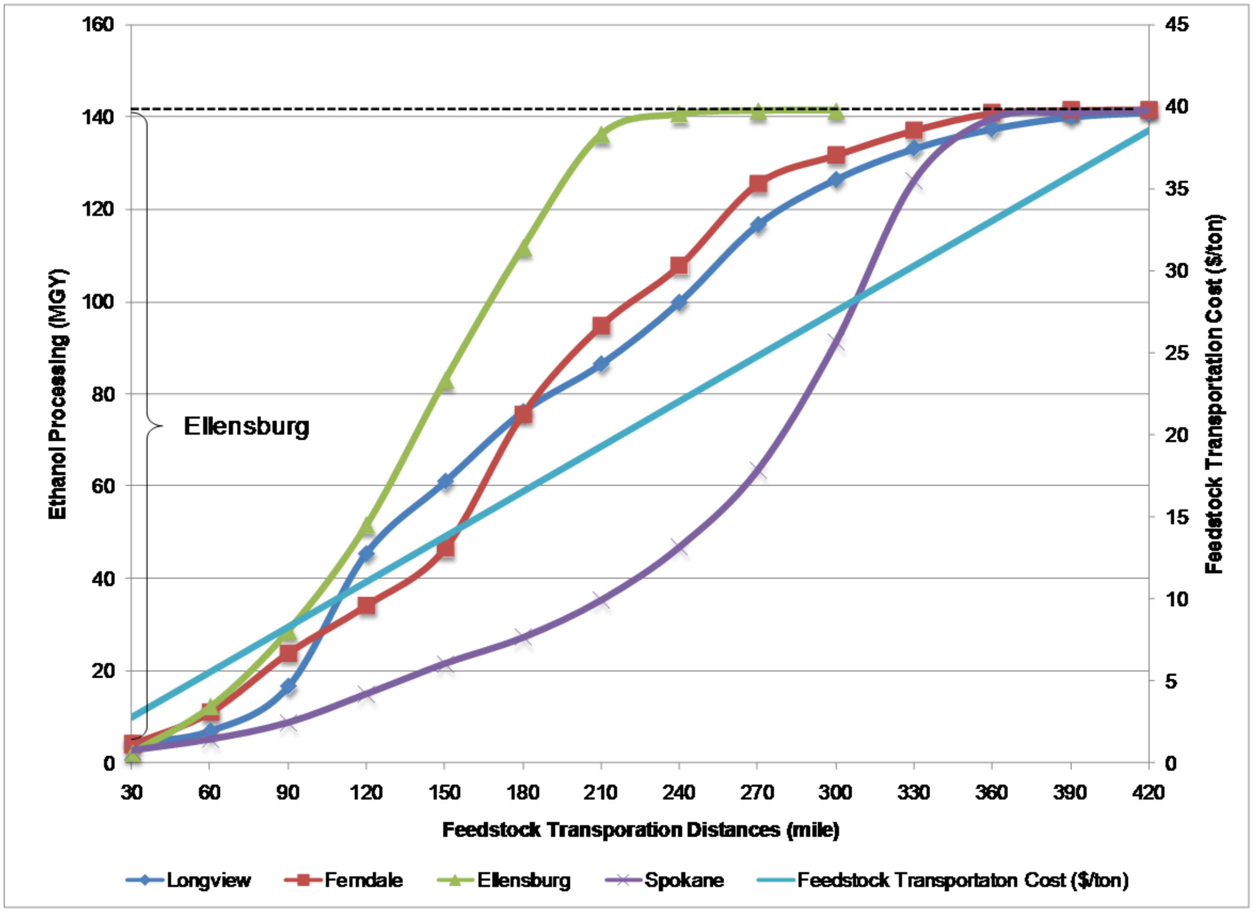


Figure 78 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for food waste utilization scenario. Again, given the geographic distribution of food waste in the state, Ellensburg location has advantage over all three locations for all processing scales. Longview location is cost competitive for only small scale production (under 2 MGY). Feedstocks transported from about 200 miles can support about only 18 MGY processing, respectively increasing the transportation costs.

Figure 78: Feedstock Transportation Least-Cost Locations (Food Waste)

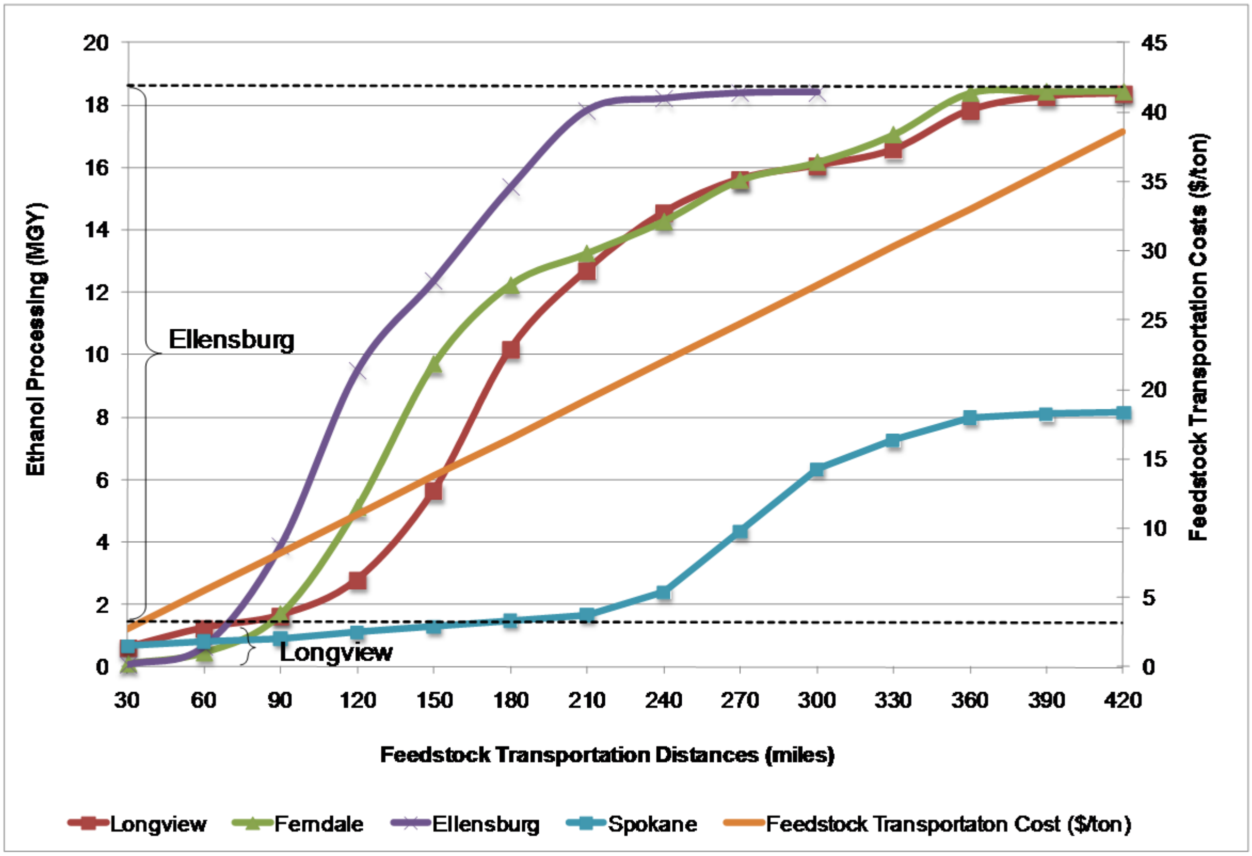


Figure 79 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for paper waste utilization scenario. Similar to the previous two feedstock categories, the Ellensburg location has advantage over all three locations for processing scales above 10MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 110 miles from the plant location. To achieve the same level of ethanol processing, plants considering Ferndale and Longview locations need to reach out about 150 and 180 miles from the plant respectively.

Figure 79: Feedstock Transportation Least-Cost Locations (Paper Waste)

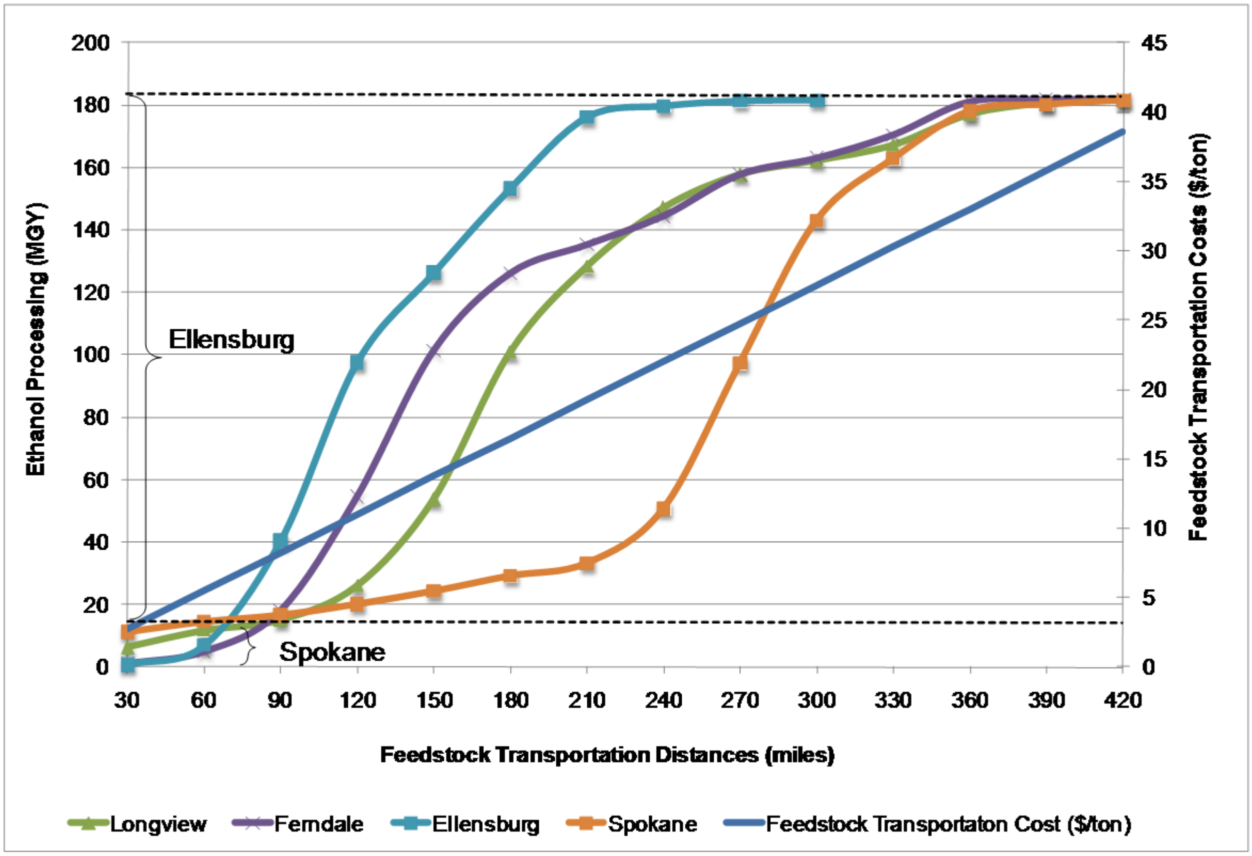


Figure 80 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for wood residue utilization scenario. The location in Ellensburg shows the least-cost feedstock transportation advantage for processing capacities above 7MGY. For this location, a processing capacity of 50 MGY can be supported with the available biomass within about 180 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations need to reach out about 250 miles from the plant.

Figure 80: Feedstock Transportation Least-Cost Locations (Wood Residue)

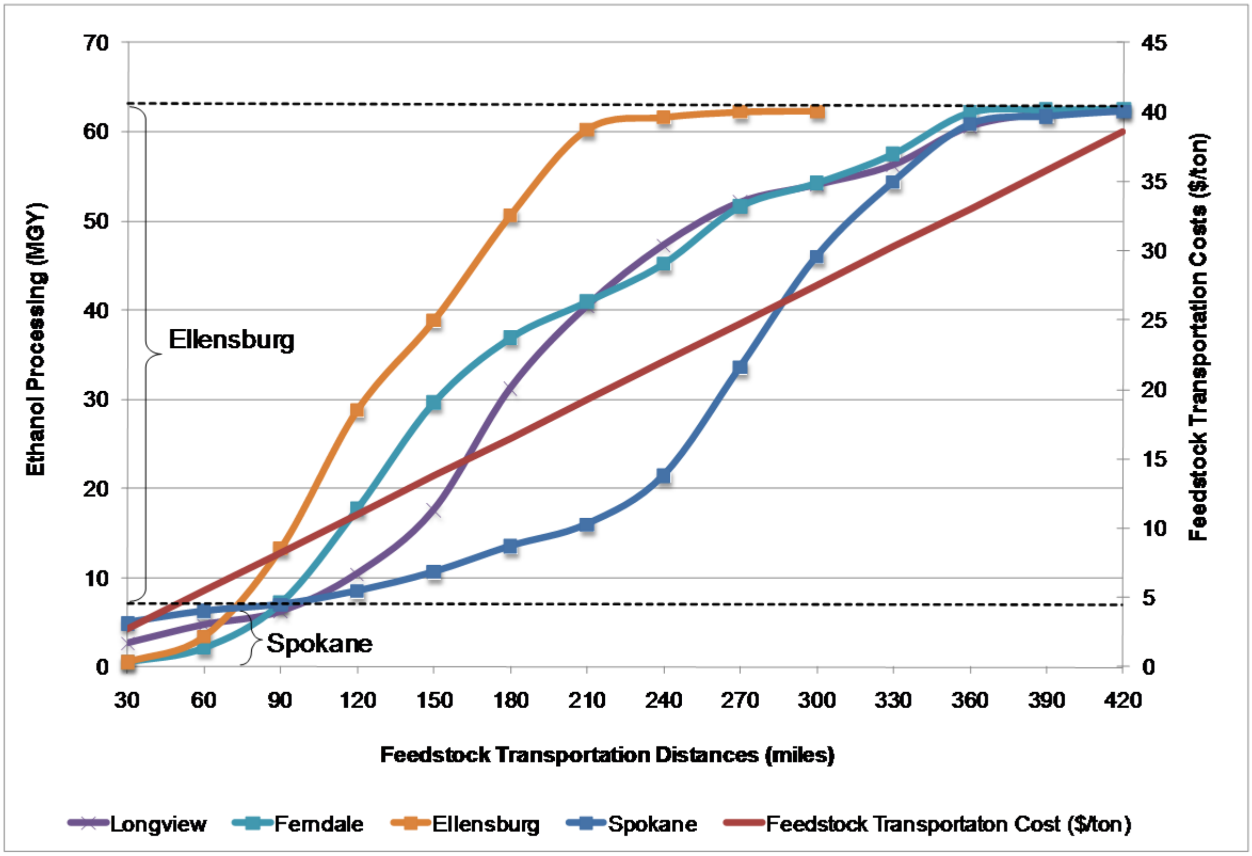


Figure 81 and **Figure 82** show additional results for cumulative feedstocks – crop and forest residues, and animal waste combined with MSW.

Figure 81: Feedstock Transportation Least-Cost Locations (Crop and Forest Residue)

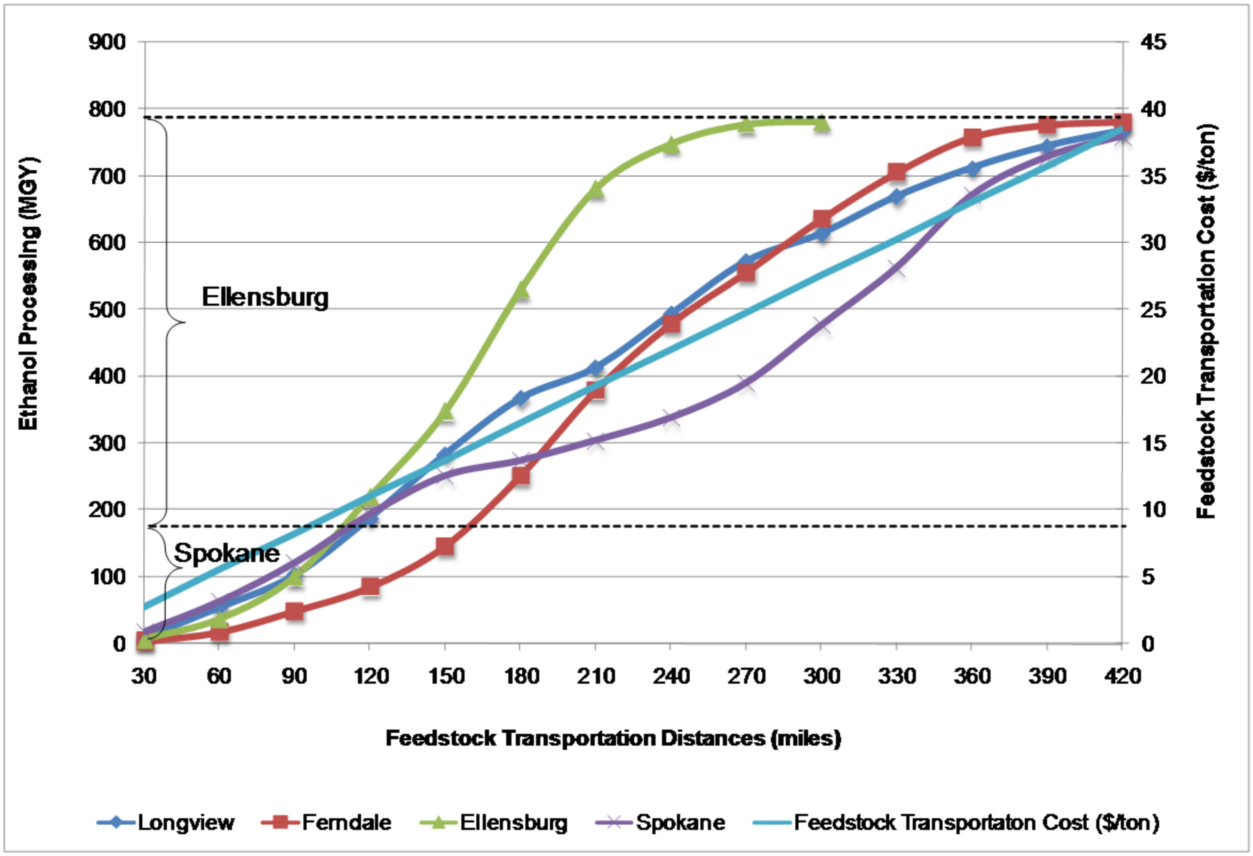
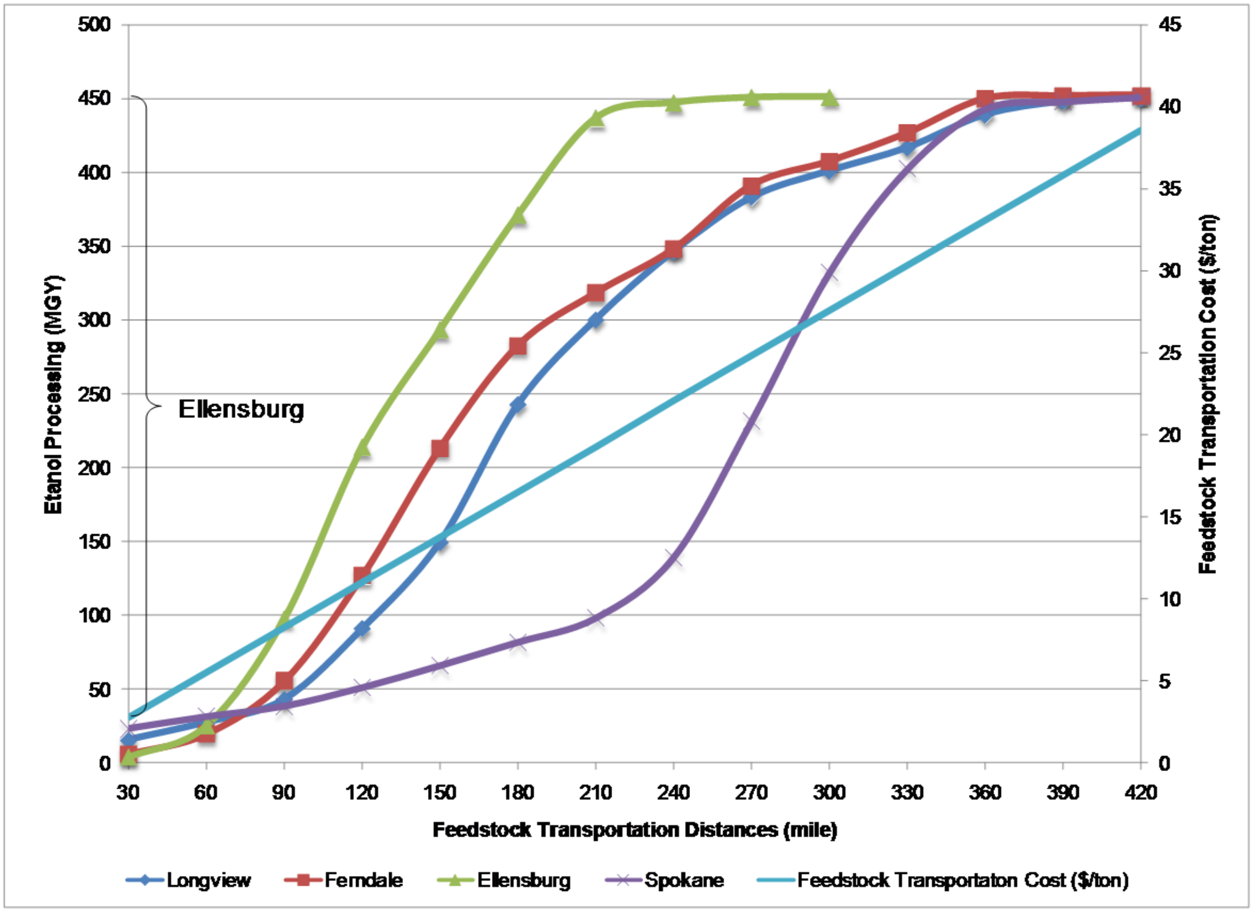


Figure 82: Feedstock Transportation Least-Cost Locations (Animal Waste and MSW)



Distribution Costs

[Distribution Infrastructure Overview]

Depending on market locations, distribution costs may influence the total delivered costs of the ethanol blend. Partially complemented by truck transportation, rail is one of the current primary modes of transportation for ethanol distribution from processing plants to blending terminals. However, limited capacity of current railroad system, combined with increasing mandated levels of biofuel processing (EISA 2007), suggests immediate need for considerable improvements, both in terms of transportation capacity and its economic feasibility [U.S. GAO (2007)].

Despite the pipeline transportation's economic and environmental promising benefits, such as traffic congestion and emissions reductions, thus far, no dedicated networks exist for ethanol shipments via pipelines neither to blending terminals nor to final markets. Additionally, due to the number of problems, including ethanol's moisture attracting characteristic, existing gasoline pipelines are not suitable for ethanol distribution. While this mode of transportation needs further technological investigation, an improvement of existing railroad infrastructure, and further investigation of the cost-competitiveness of truck transportation mode remains critical.

The distribution infrastructure improvements include capital investments associated with ethanol fueling stations as well. According to U.S. GAO (2007), in 2007, only about one percent of fueling stations in the U.S. had capacity/efficiency to offer E85 fuel.[15] Given mandated levels

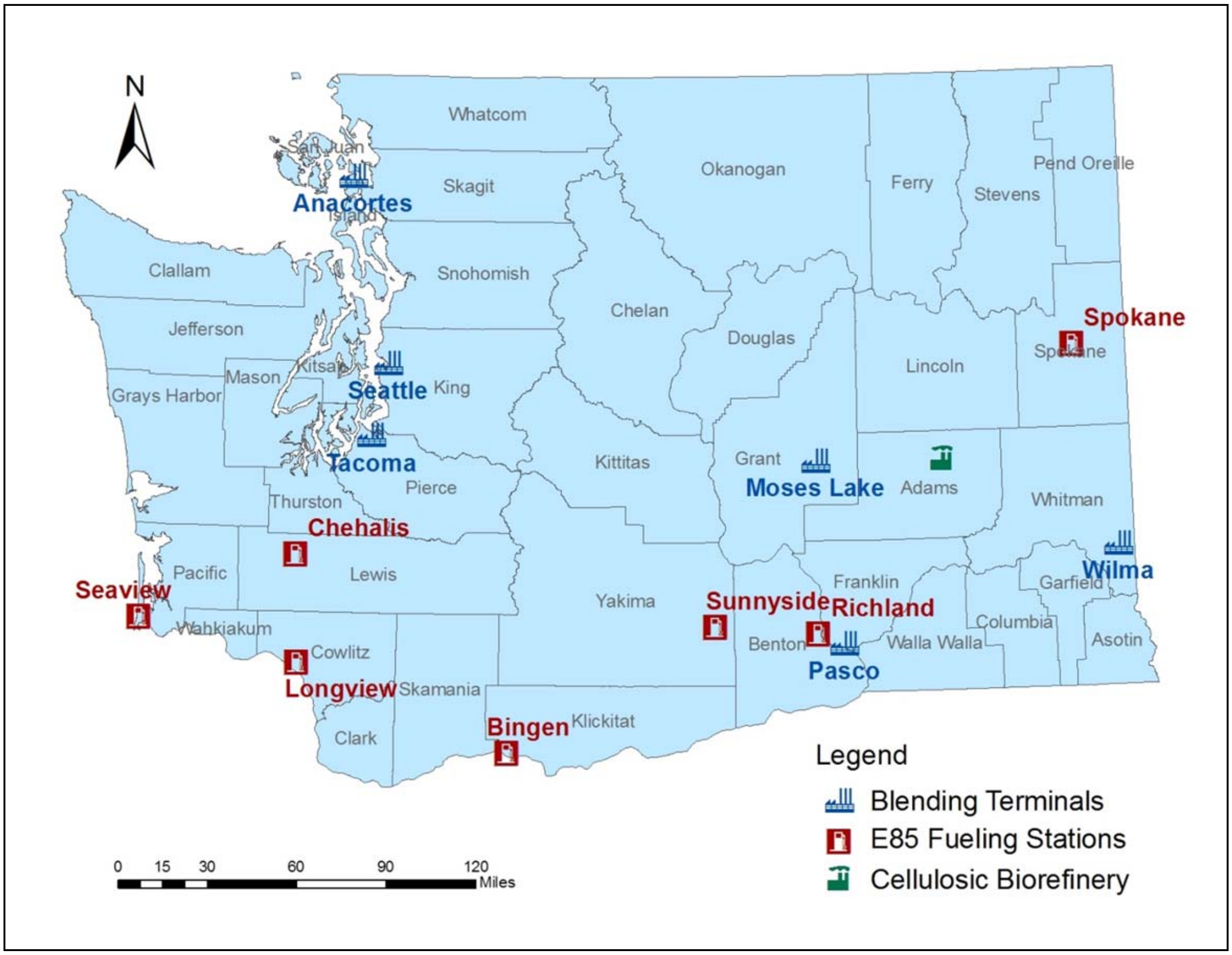
[15] Blend of 85 percent ethanol and 15 percent gasoline.

of cellulosic ethanol processing for the next decade, this limited capacity of the existing distribution infrastructure, including transportation efficiency and existing E85 fueling stations availability, may create considerable obstacles for the development of the emerging cellulosic ethanol industry. Therefore, further economic feasibility investigation of modes, such as truck transportation is critical in increasing the number of gas stations (at "least-cost" locations) offering ethanol blend, since efficient operation of retail stations partially depends on steady supply system.

The ethanol distribution system consists of two segments. First, the processed ethanol is shipped to blending/distribution terminals (also known as racks). Racks also serve as storage facilities that the conventional gasoline is transported to, through pipelines, barge, truck or railroad modes. At the blending terminals the pure ethanol is blended into E10 or E85 (depending on the demand), which is then distributed by tank trailer trucks to the fueling stations offering E85 or E10 ethanol blend. According to Johnson and Melendez (2007), terminal shipment and storage costs add about $0.04 per gallon to the cost of gasoline. U.S. GAO (2007) estimated the overall cost of ethanol distribution, including shipments to blending terminals and distribution to gas stations, to $0.13 – 0.18 per gallon range depending on the proximity of markets from processing plants.

Distribution costs derived in this report include both shipment costs to the blending terminals in the state (using least-cost/distance approach), and to the E85 fueling stations, with spatially optimized routes using GIS. Figure 83 shows the distribution of existing blending terminals and E85 fueling stations in the state of Washington. The map includes only publicly accessible E85 fueling stations, leaving out three private or government-only facilities.

Figure 83: State of Washington Blending Terminals (Racks) and E85 Fueling Station Locations



Data Source: E85 fueling station location information - National Ethanol Vehicle Coalition webpage (NAVC 2008); Blending Terminal location information - OPIS Rack Cities (2008).

An Economic Engineering Construction of Trucking Costs for Distribution

The economic engineering approach to calculating trucking costs used earlier in this report was modified to include tank trailers (different from flat bed or drop bed trailers considered for feedstock transportation). Table 10 provides modified input values needed for both fixed and variable cost components of trucking costs. Descriptions provided in An Economic Engineering Framework section are correspondingly applicable to the fixed and variable cost components shown in Table 11. First, trucking cost per gallon of ethanol has been derived, which was further converted into per mile and per gallon mile measures needed for the ethanol distribution cost derivations.

Table 10: Truck (Tank Trailer) Transportation Cost Calculation Inputs

Component	Units	Truck	Tank Trailer
Purchase price	$	110,000	50,000
Time period of ownership	years	10	10

Expected salvage value	$	28,600	17,500
Annual cost of repairs	$	9,336	1,000
Number of tires	number	10	8
Replacement cost per tire	$	400	400
Lifetime per tire	miles	60,000	72,000
Annual miles driven	miles	53,800	-
Annual gallons hauled	tons	2,690,000	-
Interest rate	%	0.07	-
Price of fuel	$/gallon	4.61	-
Fuel efficiency	miles/gallon	5.5	-
Average hauling speed	miles/hour	45	-
Annual cost of license	$	2,000	-
Annual cost of insurance	$	220	-
Driver labor rate	$/hour	17.41	-

Table 11: Truck and Tank Trailer Transportation Total Costs

Description	Truck ($/year)	Trailer ($/year)	Total Cost ($/year)	Total Cost ($/gallon)	Total Cost ($/mile)	Total Cost ($/gallon/mile)
Fixed Costs						
Capital recovery (interest and depreciation)	$13,592	$5,852	$19,444	$0.007	$0.361	$0.00007
Taxes, insurance & license	2,220	500	$2,720	$0.001	$0.051	$0.00001
Total fixed cost	$15,812	$6,352	$22,164	$0.008	$0.412	$0.00008
Variable Costs						
Repair cost	$9,336	$1,000	$10,336	$0.004	$0.192	$0.00004
Tires cost	3,587	2,391	5,978	$0.002	$0.111	$0.00002
Fuel cost	45,094		45,094	$0.017	$0.838	$0.00017
Lubrication cost	4,509		4,509	$0.002	$0.084	$0.00002
Labor cost	20,815		20,815	$0.008	$0.387	$0.00008
Total variable cost	$83,341	$3,391	$86,732	$0.032	$1.612	$0.00032
Total Costs	**$99,153**	**$9,743**	**$108,896**	**$0.040**	**$2.024**	**$0.00067**

Per Gallon Mile Costs

As mentioned earlier, the basics of deriving the total distribution costs, involves two parts – distribution to blending terminals (racks), followed by the distribution to final markets (E85 or E10 fueling stations in the state). Because longer destinations increase transportation costs, the same logic as with the transportation of feedstocks can be applied to understand the relationship between distribution costs and haul distances. To support larger capacity processing plant operations, feedstocks need to be transported from longer destinations, consequently increasing transportation costs. Alternatively, since fueling stations have limited storage capacity, the larger the volume of the processing plant, the longer are the destinations that the ethanol needs to be distributed to reach out more fueling stations.

If we consider ethanol shipments from one processing plant, the cost of the distribution to blending terminals (first segment) is relatively fixed, since the distances from processing plants to the terminals are constant. However, the distribution distances from the blending terminals to E85 fueling stations (second segment) are increasing as soon as stations in the vicinity from the rack receive their full capacity volumes of ethanol blend (E85 or E10).

Total distribution costs can be derived by combining shipment costs to terminals and distribution costs to E85 stations. It should be noted, however, that depending on the business structure, ethanol plants may chose to ship (sell) their production to blending terminals, leaving the rest of the costs to other businesses, called jobbers or middleman (Johnson and Melendez 2007). Alternatively, terminals that are owned by independent companies may purchase the ethanol from refineries, blend, and distribute the fuel themselves. Regardless of the business structure, the delivered costs to final markets still include costs associated with both segments – shipment costs to terminals, and distribution costs to ethanol blend fueling stations.

At each level of processing capacity, transportation costs from processing plants to blending terminal can be added to costs accrued from terminals to E85 stations to derive the total distribution costs. Applying per gallon mile truck transportation costs to increasing distances, distribution costs resulted an upward sloping curve ranging from $0.013 – 0.138 per gallon for 100 – 200 MGY processing plants respectively (Figure 84). E85 fueling stations (shipment destination) were assumed to have a tank/storage capacity of 8000 gallons on average, dispensing 8 gallons per minute, 10 hours a day, and 300 days a year, based on gas stations study conducted by Geyer (2008). The sequence of ethanol distribution to E85 stations was assumed to be ranked according to the proximity to the blending terminals (origin). In other words, E85 stations that are within boundaries of first distance band from the distribution terminal (created using GIS, refer to Figure 85) are served first. Once the capacity of stations in the first distance band is filled, stations in the second distance band are supplied, etc.

Figure 84: Distribution Costs per Gallon of Ethanol by Processing Plant Capacity

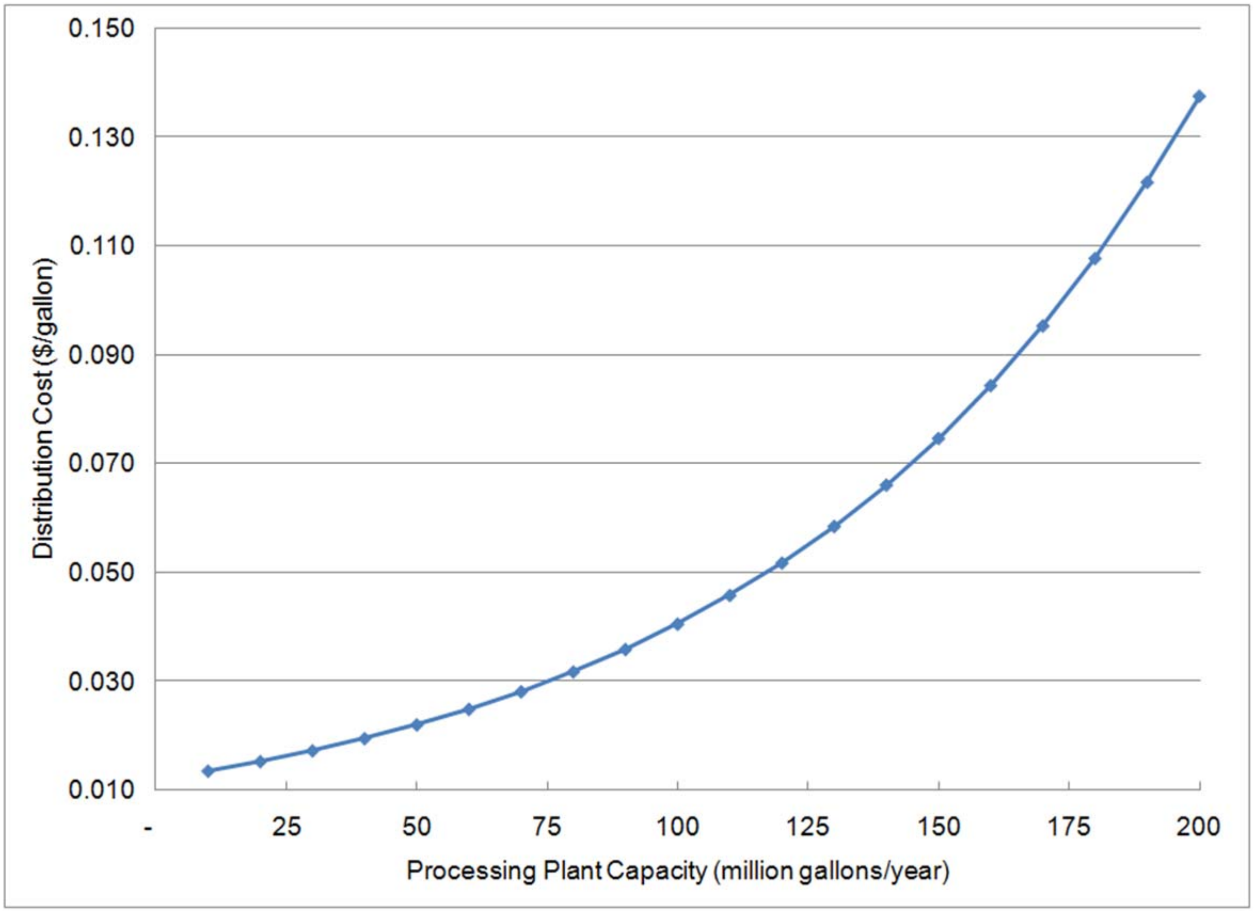
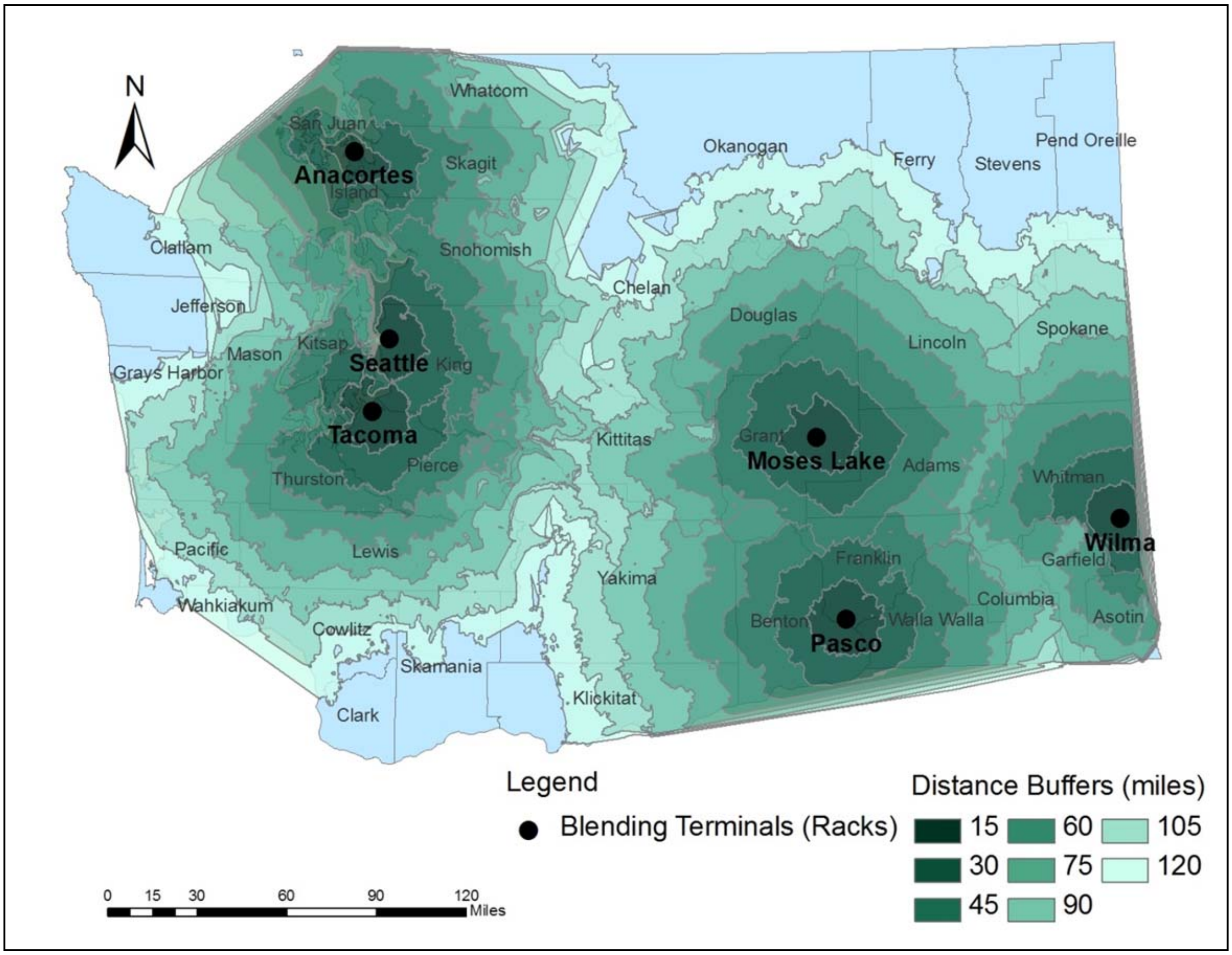


Figure 85 shows the map of state's current blending terminals surrounded with 15, 30, 45, 60, 75, 90, 105, and 120 mile distance buffers, which were created with the ArcGIS Network Analyst Service Area tool. The outer boundary of each distance band represents the maximum distance from the blending terminal. For example, all E85 fueling stations that are within the first distance buffer have maximum distance of 15 mile from a given blending terminal. To avoid multiple use of the same E85 station in the overlapping distance band areas, the GIS Network Analyst Service Area tool eliminates points (E85 stations) that were once considered to be supplied from a blending terminal.

Figure 85: Blending Terminals with 15, 30, 45, 60, 75, 90, 105, and 120-mile Distance Buffers



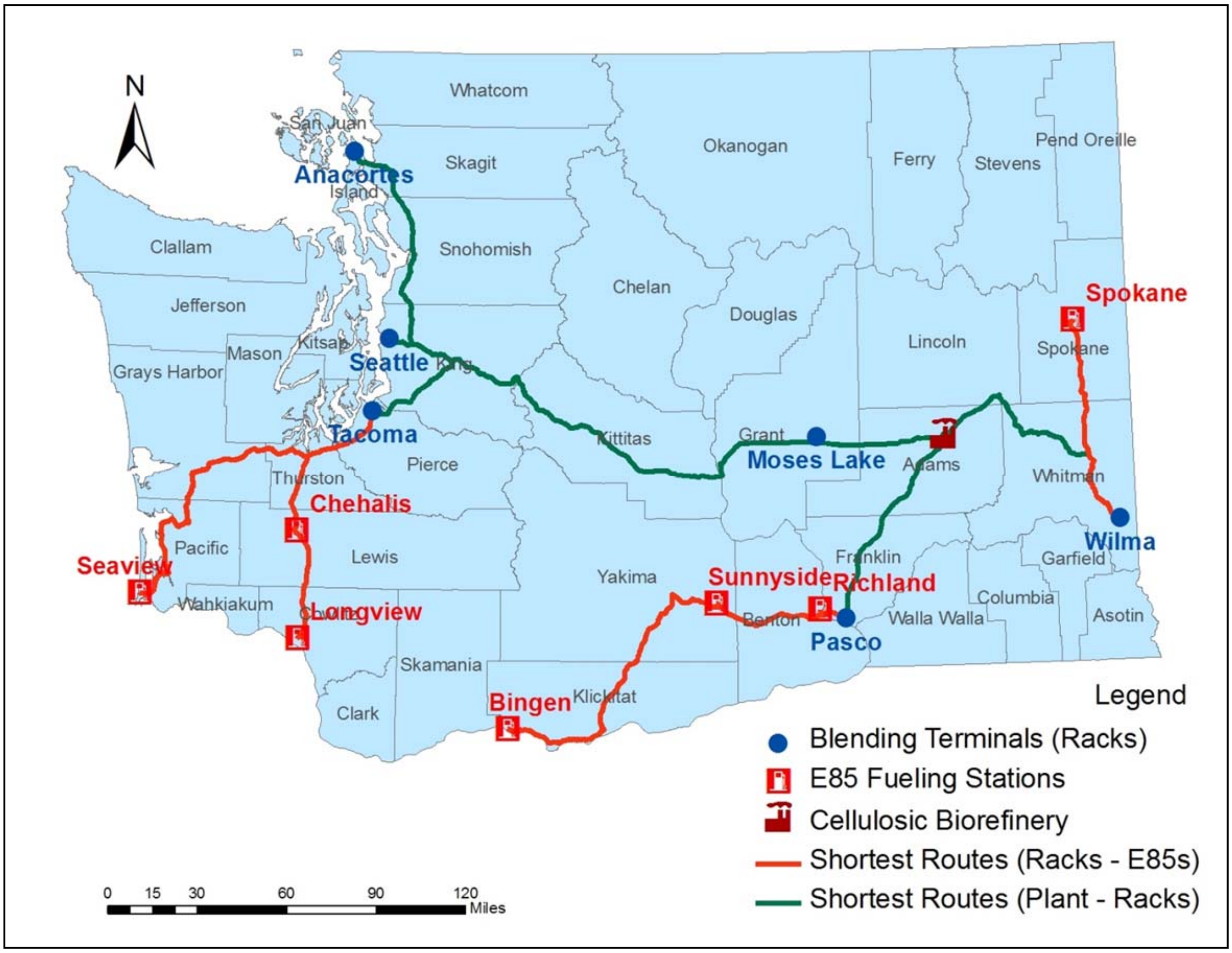
GIS Investigation of Distribution Costs for Existing Infrastructure

This section presents a case study in which the distribution costs are calculated for the existing E85 fueling stations in the state. As with feedstock transportation, ethanol distribution costs can be spatially investigated with the use of GIS. Particularly, GIS least-cost or shortest route identification tools were used to find optimal routes from an ethanol processing plant to existing blending terminals, and further, to fueling stations in the state of Washington. For this part of the spatial analysis, location information of a cellulosic biorefinery, existing blending terminals and E85 stations (depicted in Figure 83) was considered. For the second part, distribution routes from blending terminals to E85 fueling stations were identified with the use of GIS Network Analyst Origin-Destination Cost Matrix solver.

The concept of shortest route has different interpretations. The cost attribute for optimal route calculation can be set as drive time (minutes), since same-distance routes can have different speed limits, resulting different drive times. Alternatively, GIS can incorporate driving distance (miles) as cost attribute for optimal route calculations. For purposes in this part of the report, distance information was used as a cost attribute for the GIS optimal route, as well as origin-destination cost ranking calculations.

First, the processing plant, blending terminals and E85 fueling stations were mapped as shown in Figure 86. The GIS Network Analyst Closest Facility toolset was utilized to solve for optimal routes identification that originate from one processing plant in the Eastern Washington and reach all existing E85 stations in the state through six blending terminals. After the optimal route determination, spatial information regarding distances and drive times, facility (plant) and object (blending terminal) ID and other route details can be extracted into spreadsheet. Part of the extracted attribute table information regarding processing plant to blending terminal segment is summarized in Table 15, Trucking Cost Calculation Tables section.

Figure 86: Shortest Routes from Processing Plant to Blending Terminals and E85 Fueling Stations



To derive the distribution costs, per gallon mile trucking rates found in An Economic Engineering Construction of Trucking Costs for Distribution section were utilized. The resulting least-cost destinations (blending terminals) from the cellulosic biorefinery are as follows: Moses Lake ($0.03/gallon), Pasco ($0.05/gallon), Wilma ($0.07/gallon), Seattle ($0.15/gallon), Tacoma ($0.16/gallon), and Anacortes ($0.20/gallon) [Figure 87]. The consideration of only one processing plant and six blending terminal locations makes the computation of optimal routes relatively straightforward. However, with the growing ethanol industry that will eventually result in increasing number of processing plants and E85 fueling stations, the route optimization can be complicated. Therefore, this methodology is useful for the route optimization and distribution costs derivation with multiple ethanol processing plants serving hundreds of fueling stations in the state.

Figure 87: Ethanol Distribution Costs from Processing Plant to Washington's Blending Terminals

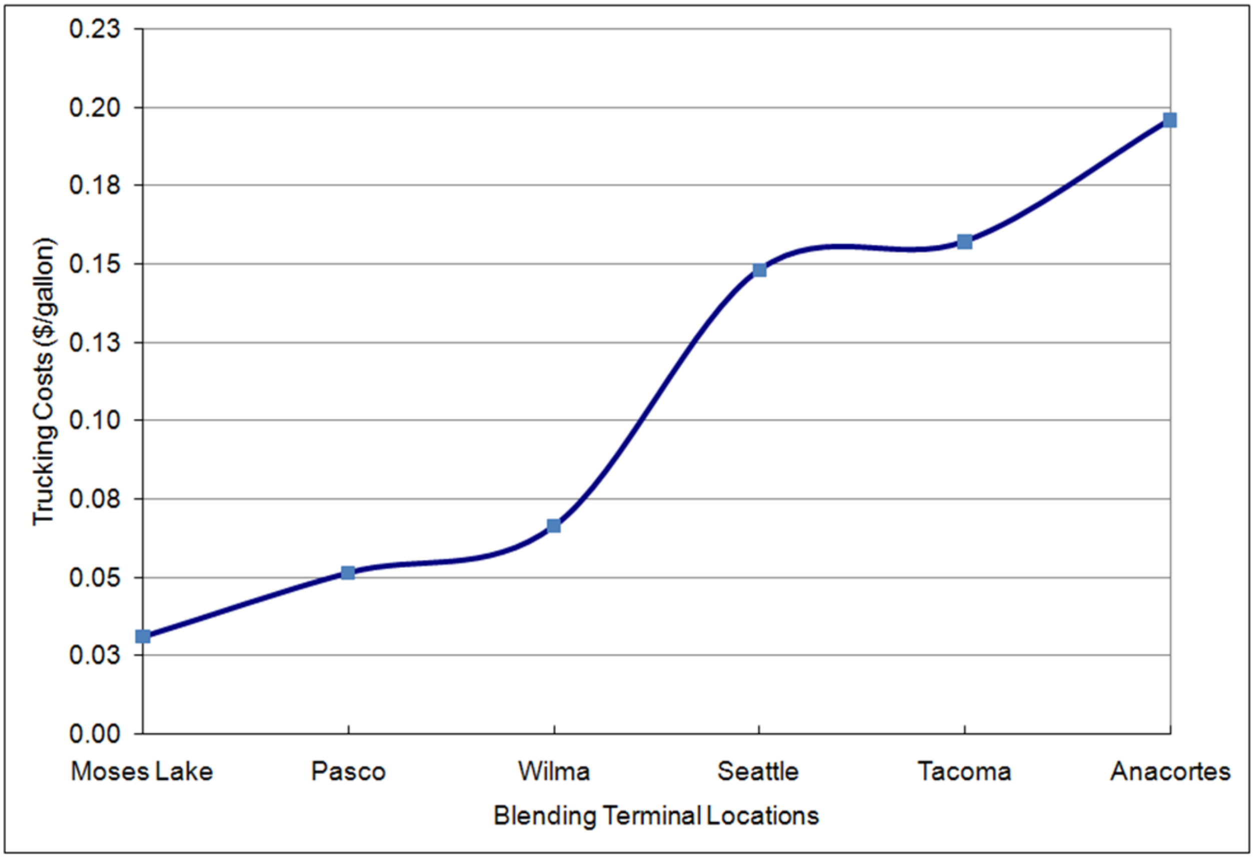
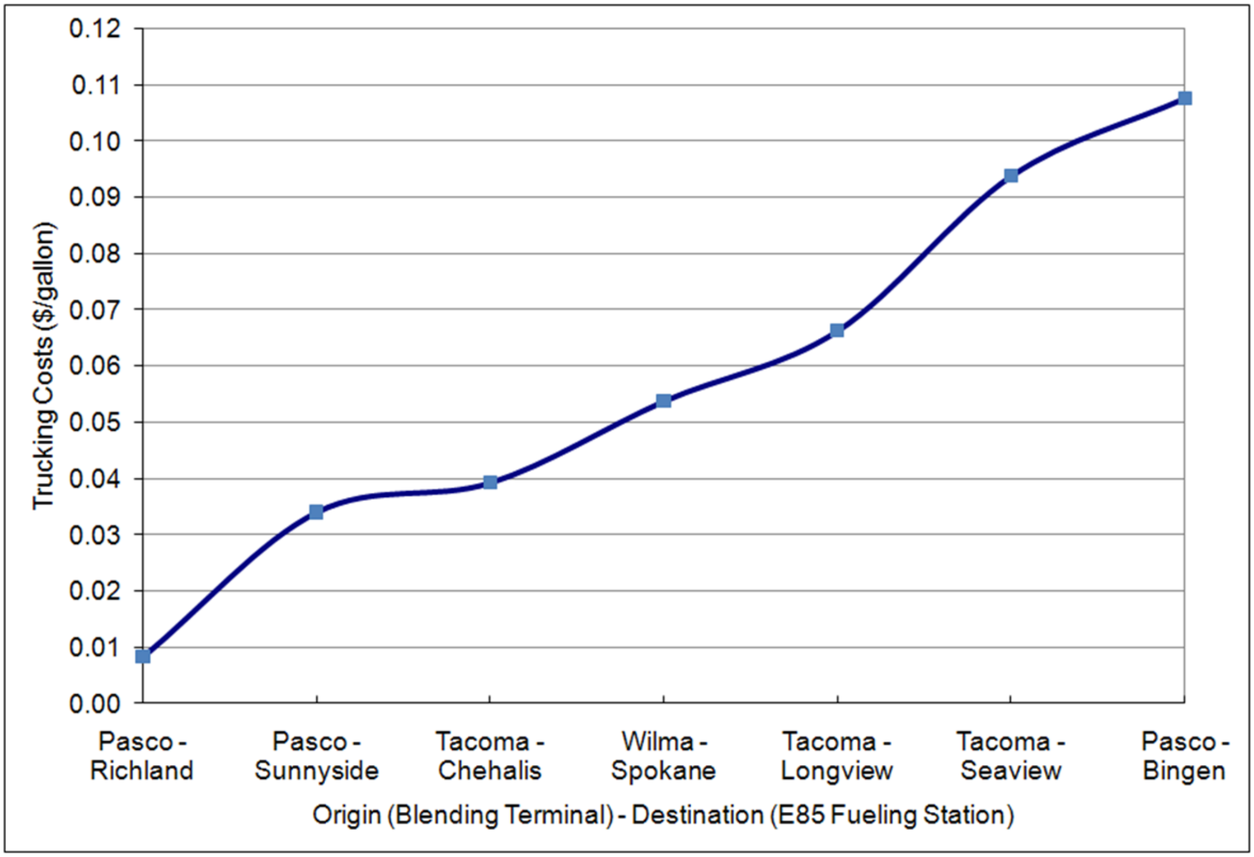


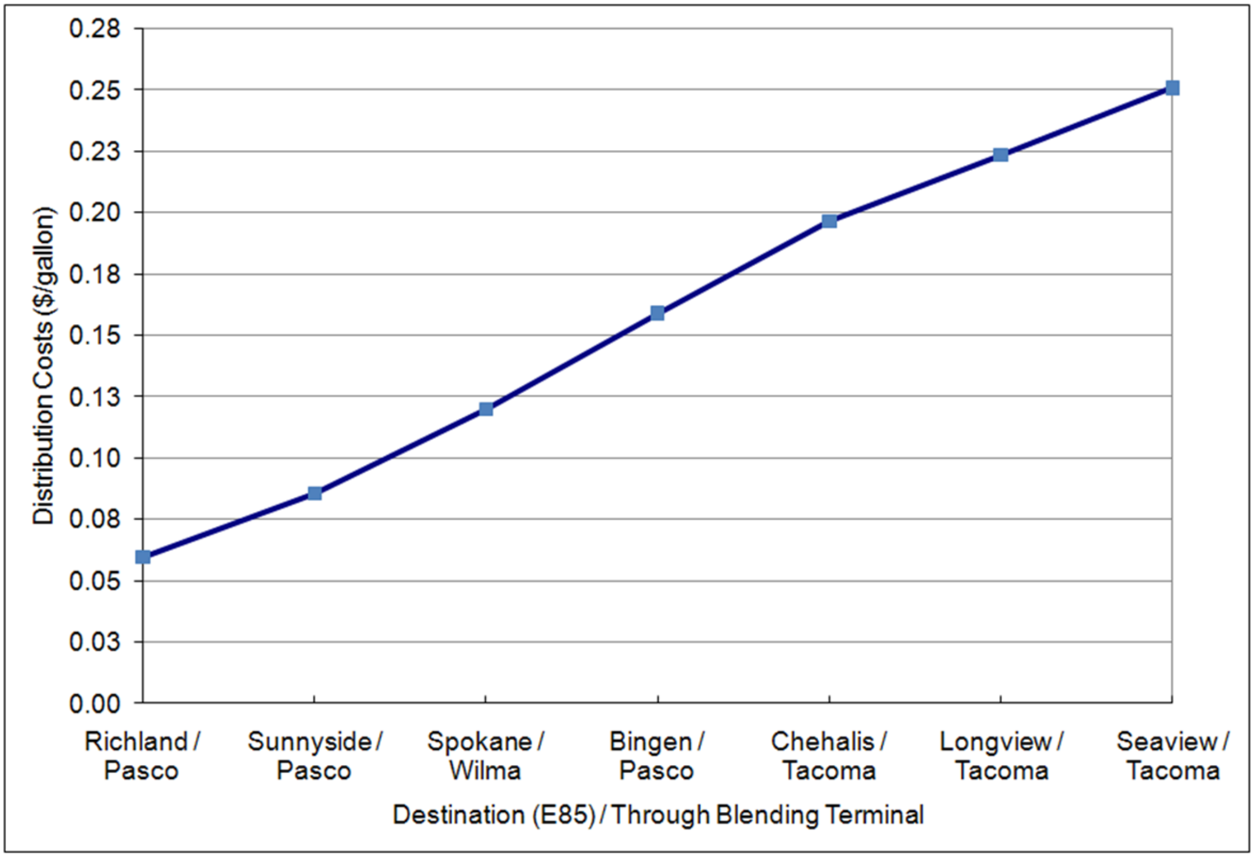
Figure 88 shows per gallon trucking costs associated with the final segment - the distribution of ethanol from blending terminals to existing E85 fueling stations (also in Table 16, Trucking Cost Calculation Tables section). Note that only three blending terminals (in Tacoma, Pasco and Wilma) were plotted as origins against all seven E85 fueling stations. Terminals in Seattle, Anacortes and Moses Lake are relatively further away, and therefore, were dropped by the GIS Network Analyst Closest Facility toolset.

Figure 88: Ethanol Distribution Costs from Washington's Blending Terminals to E85 Fueling Stations



To finalize the distribution cost calculations for the entire distribution path, starting from the processing plant in the Eastern Washington to all E85 fueling stations through three closest blending terminals, costs for the both segments were combined (Figure 89). Resulted transportation costs for the ethanol distributed through the terminal in Pasco increase as $0.06, $0.09, and $0.16 per gallon for E85 stations in Richland, Sunnyside and Bingen respectively. Per gallon costs for the distribution through the Tacoma terminal start with $0.20 in Chehalis, and increase to $0.22 and $0.25 for the E85 destinations in Longview and Seaview. Given current geographic distribution of E85 fueling stations, only one distribution route was identified for the fueling station in Spokane through the terminal in Wilma, resulting $0.12 per gallon transportation costs.

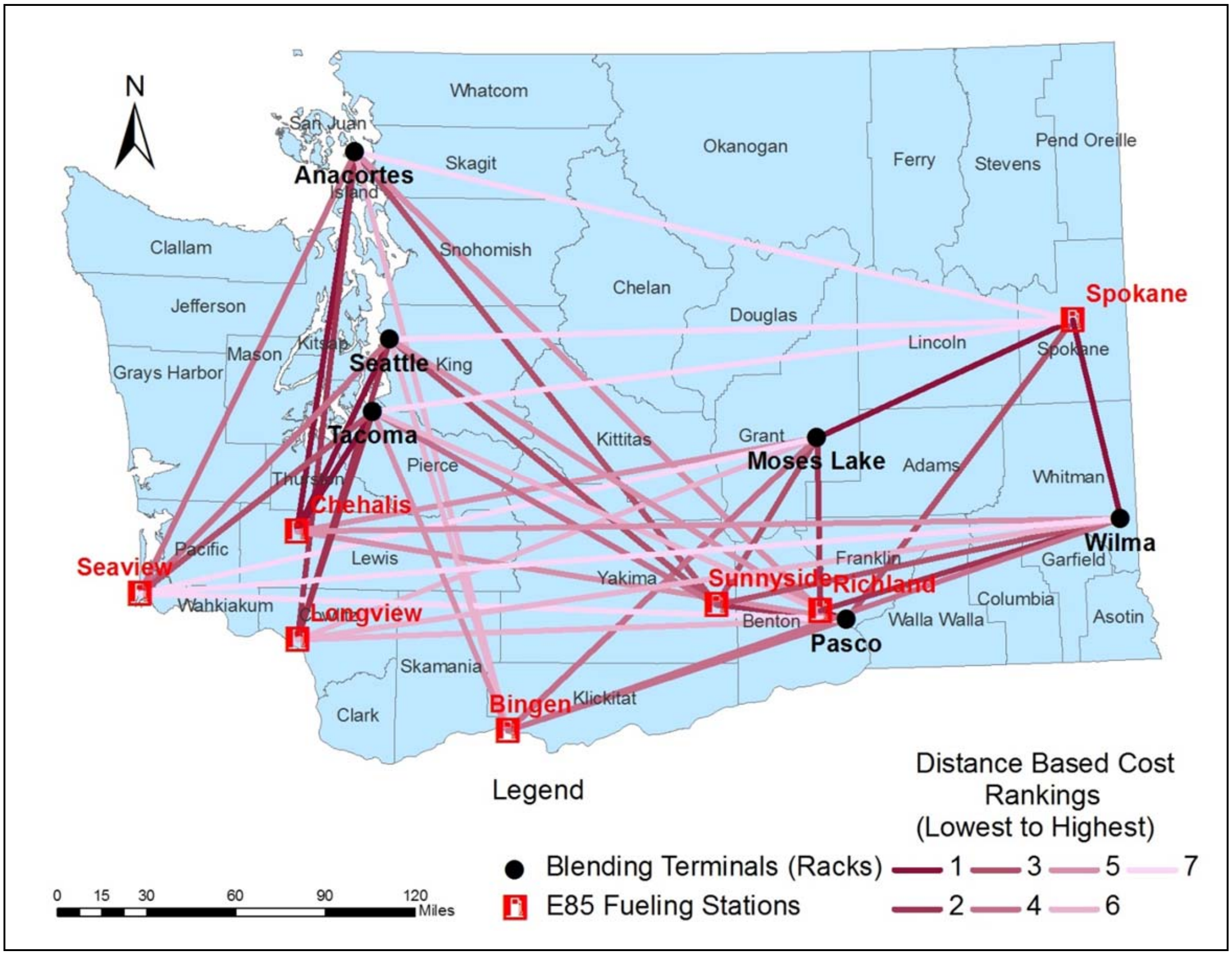
Figure 89: Distribution Costs from the Processing Plant through Three Blending Terminals to All E85 Fueling Stations in the State



As mentioned earlier, for the second part of the spatial investigation, an origin-destination cost matrix was created to rank the least cost distribution routes from blending terminals to the state's E85 gas stations. For this part of the analysis, the GIS Network Analysis toolset uses location information to rank distribution routes according to the lowest to highest transportation costs. Currently, with only six origins (blending terminals) and seven destinations (E85 stations (resulting 6×7 cost matrix), the current computation is relatively easy. However, with the development of the industry, the methodology may be useful to include hundreds of trips originating from existing blending terminals to future E85 stations in the state. Figure 90 shows a map with connection lines[16] illustrating the distance based cost ranking for the routes from the blending terminal to E85 fueling stations in the state. For each of the blending terminal location, route information was considered for calculating the closest E85 station location, and to rank according to the transportation costs.

Figure 90: Map for GIS Origin (Blending Terminal) Destination (E85 Fueling Station) Distance Based Cost Matrix

[16] Despite the lines in the map are shown as straight lines, the information they provide is based on origin-destination highway distances. To keep the map clear, the Washington's highway layer was not included.



To make this cost matrix useful for any biorefinery location considering existing six blending terminals for the ethanol distribution, the specific cellulosic biorefinery location (discussed above) was not included as an origin. Similar to the Closest Facility calculation used for optimal route identification (described above), the attribute information regarding origin-destination matrix can be extracted into spreadsheets. The summary of the origin-destination attribute table data is provided in Table 17 (Trucking Cost Calculation Tables).

Delivered Costs

Figure 91: Delivered Cost of Bio-ethanol Using Crop Residue (Longview)

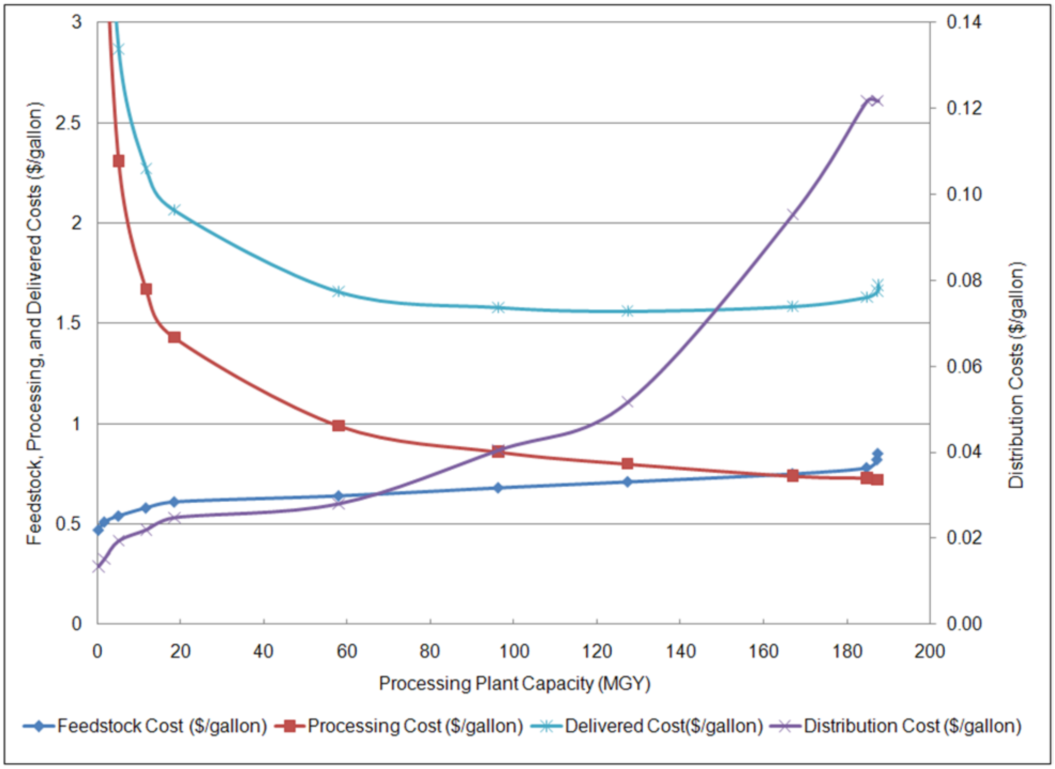


Figure 92: Delivered Cost of Bio-ethanol Using Crop Residue (Ferndale)

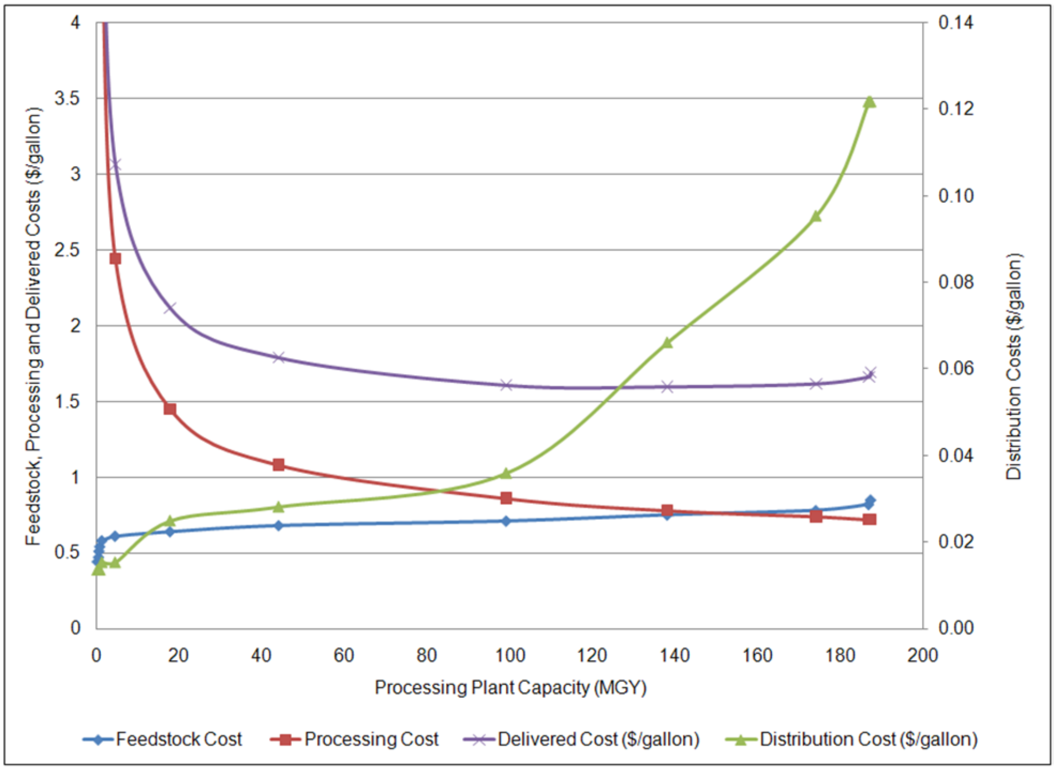


Figure 93: Delivered Cost of Bio-ethanol Using Crop Residue (Ellensburg)

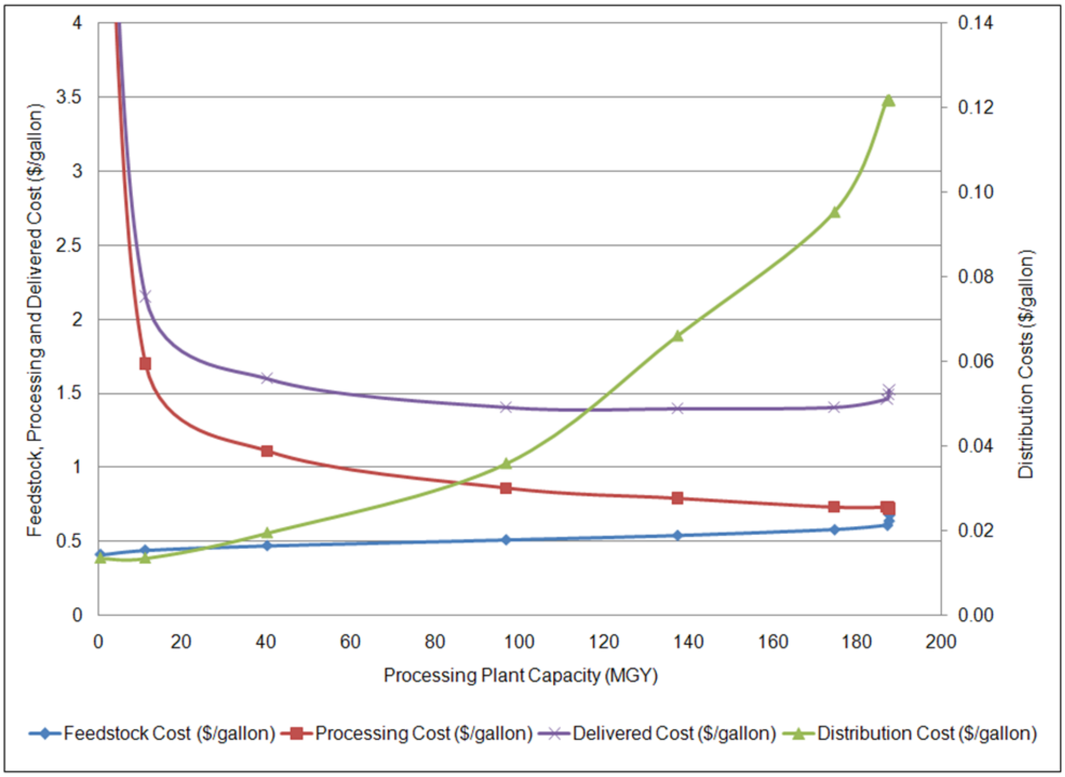


Figure 94: Delivered Cost of Thermo-ethanol Using Crop Residue (Longview)

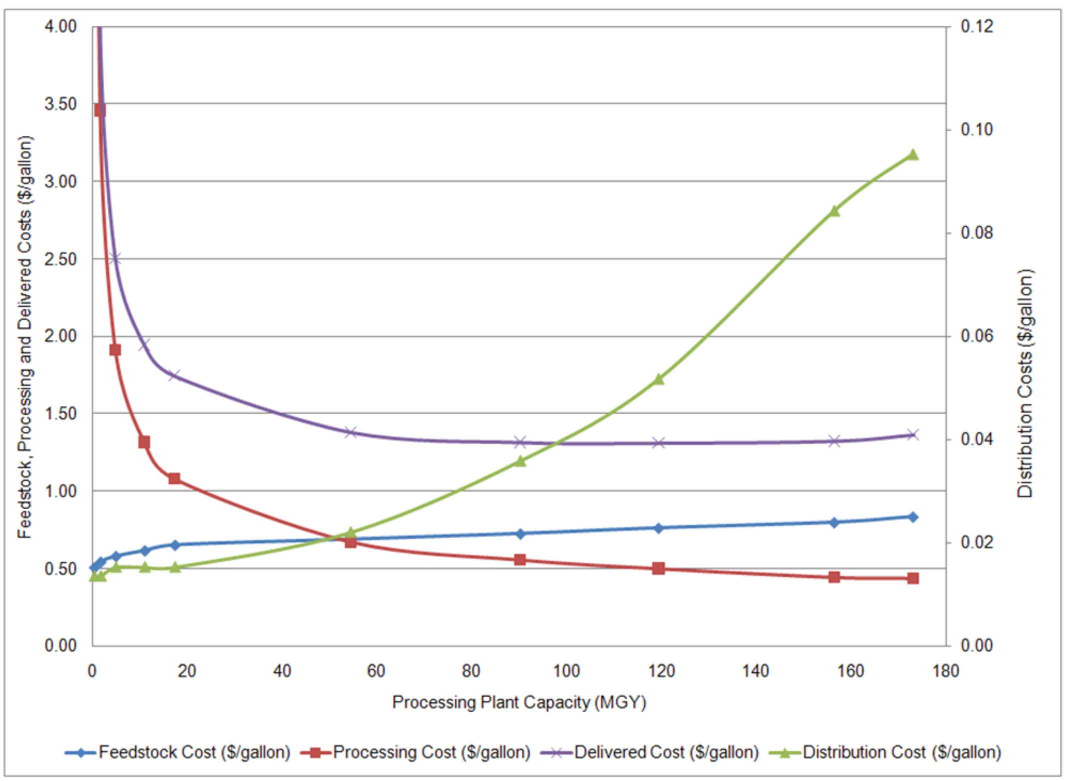


Figure 95: Delivered Cost of Thermo-ethanol Using Crop Residue (Ferndale)

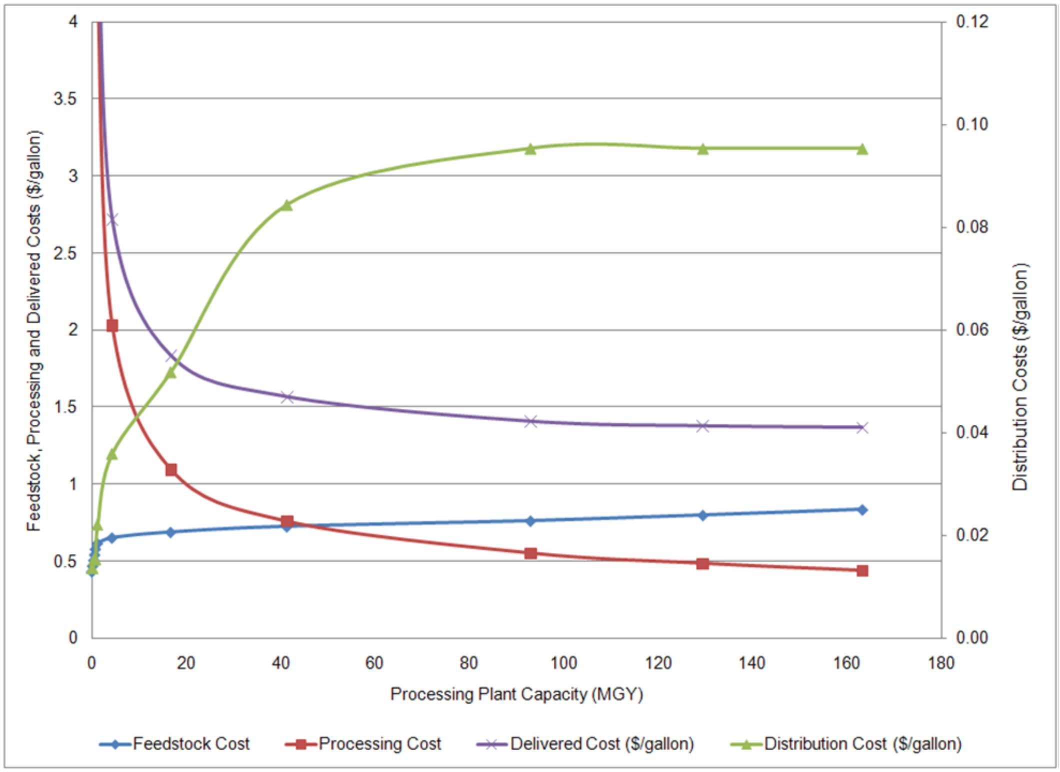


Figure 96: Delivered Cost of Thermo-ethanol Using Forest Residue (Longview)

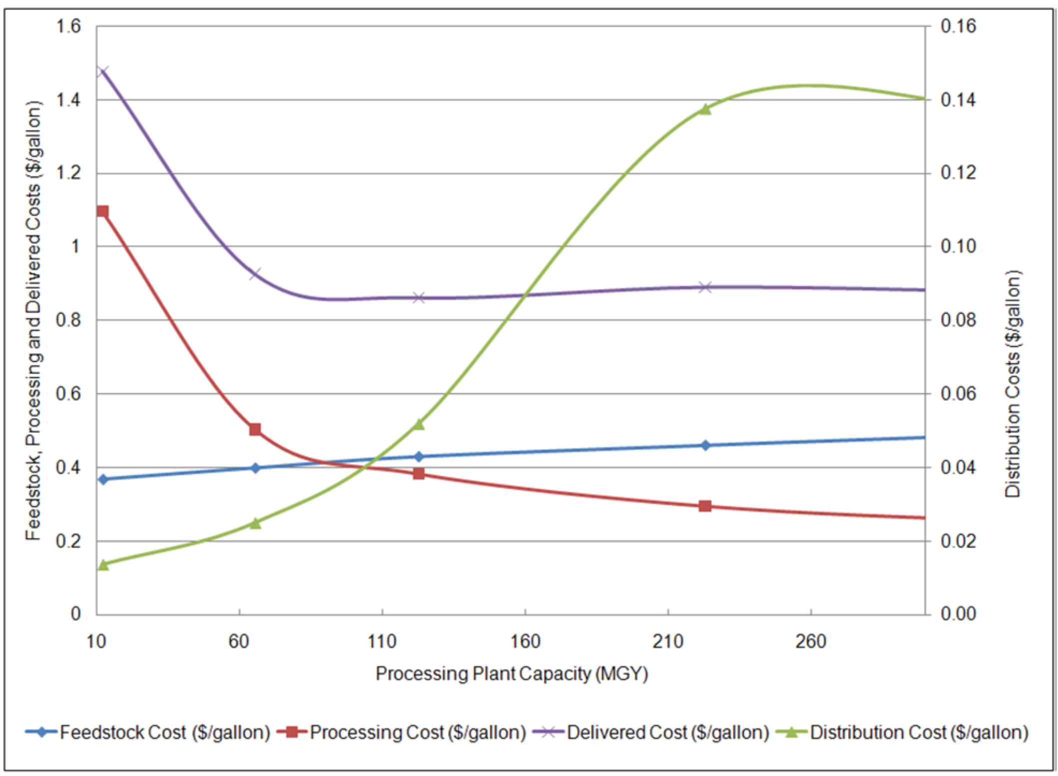


Figure 97: Delivered Cost of Thermo-ethanol Using Forest Residue (Ferndale)

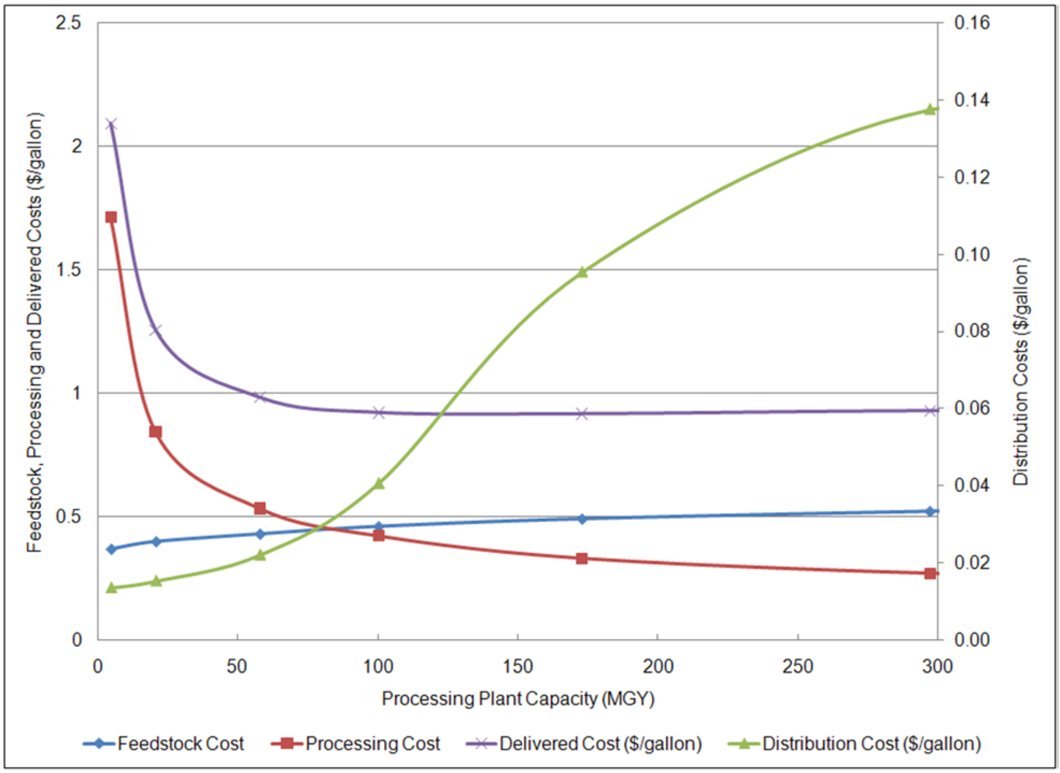
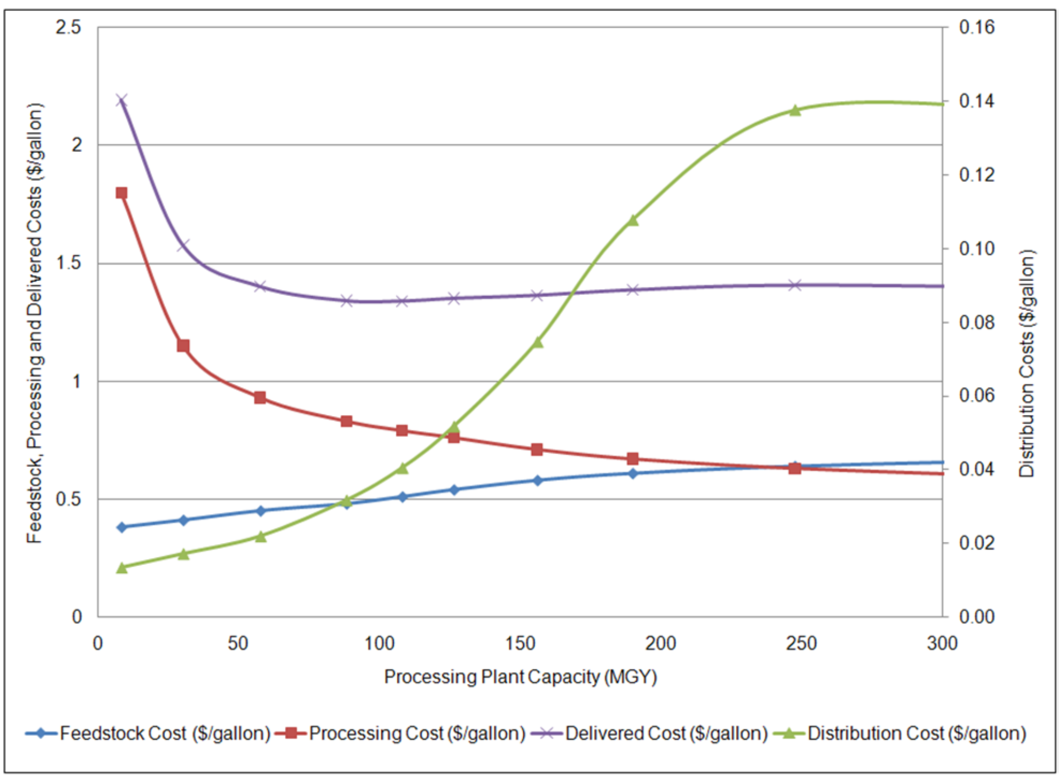


Figure 98: Delivered Cost of Thermo-ethanol Using Forest Residue (Spokane)



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Supplemental Materials

<u>Geographic Distribution of Biomass in the State of Washington</u>

Figure 99: Geographic Distribution of Animal Waste Residue in Relation to the Road Network

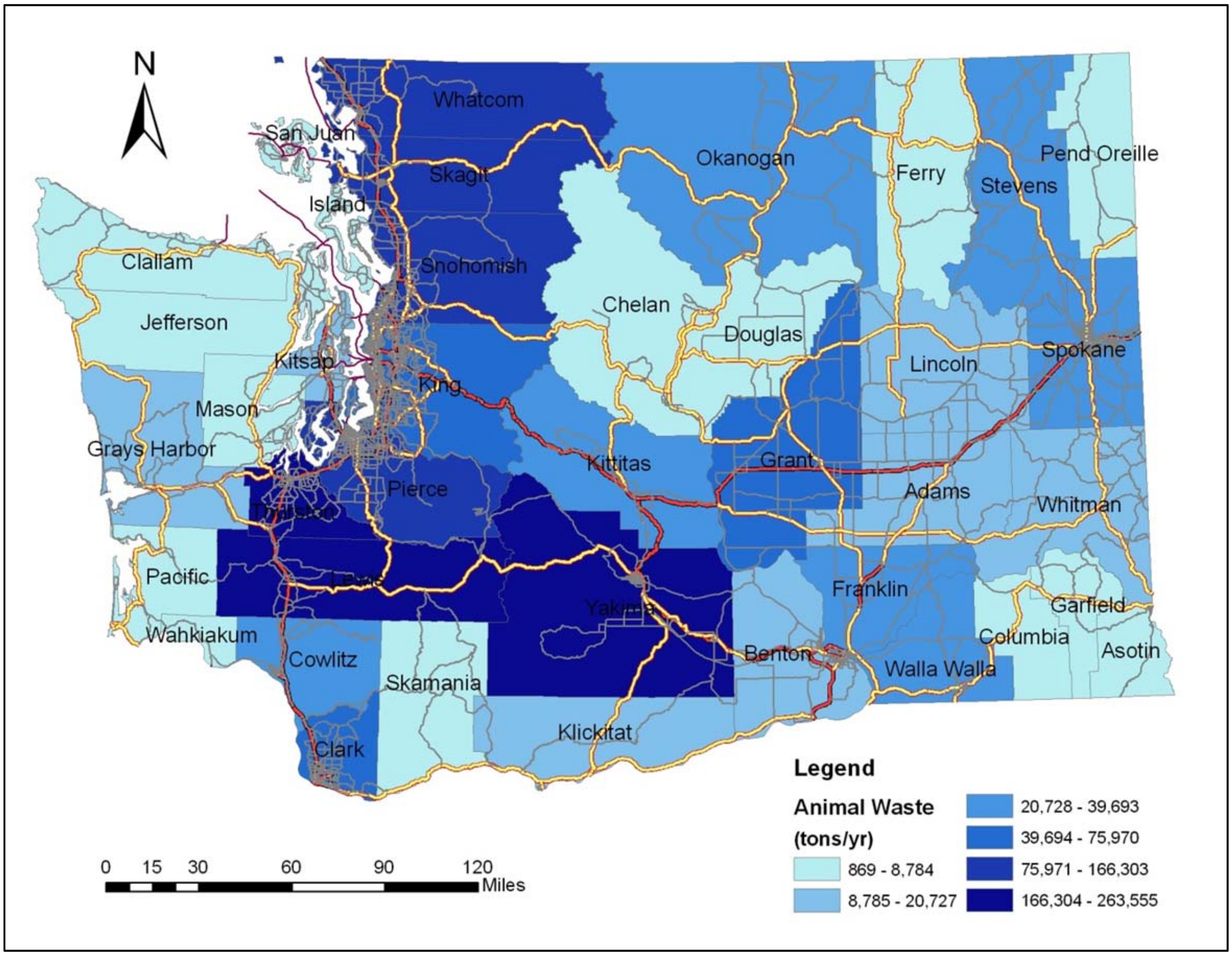


Figure 100: Geographic Distribution of Municipal Solid Waste in Relation to the Road Network

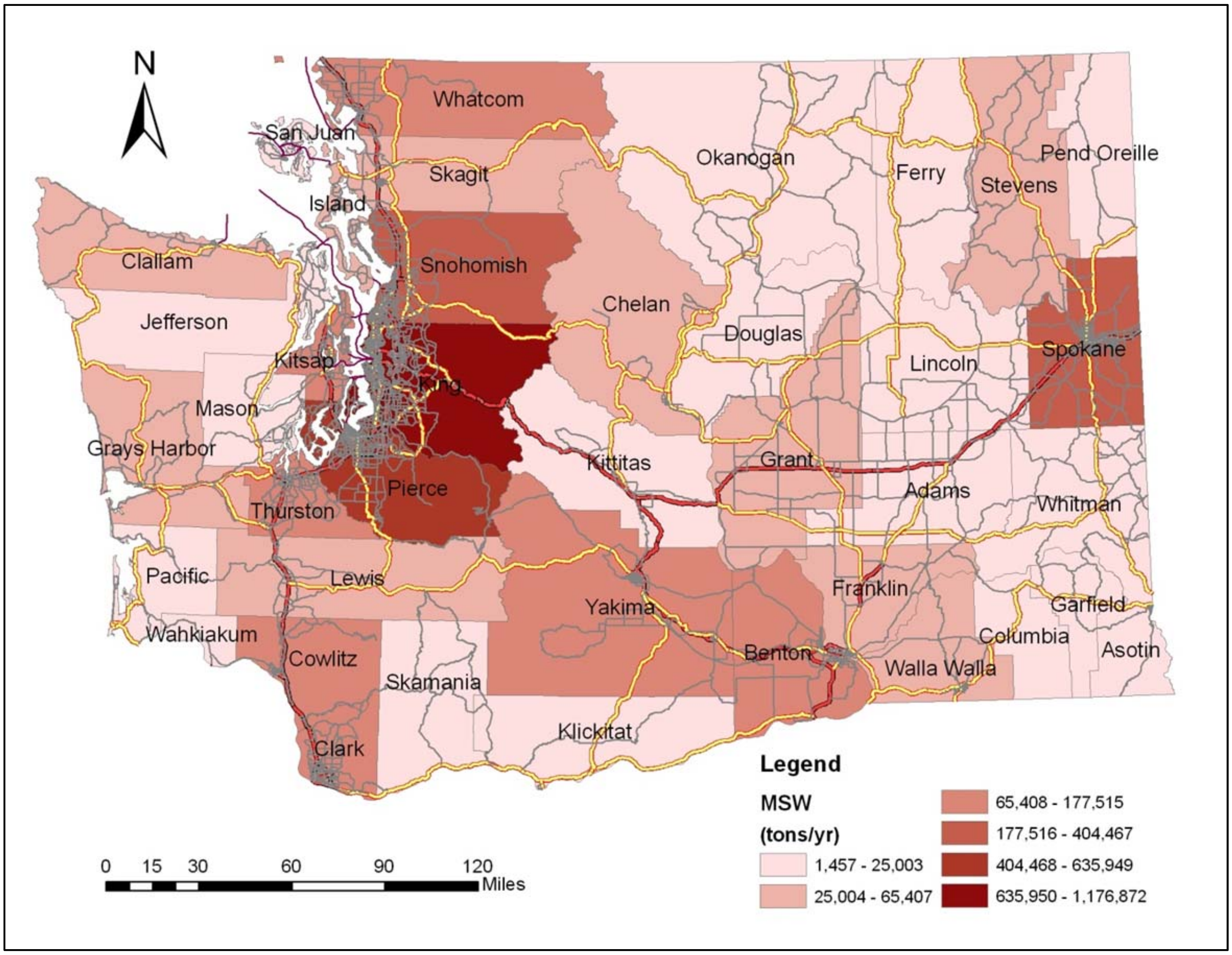


Figure 101: Geographic Distribution of Urban Wood Residue in Relation to the Road Network **(NREL Data)**

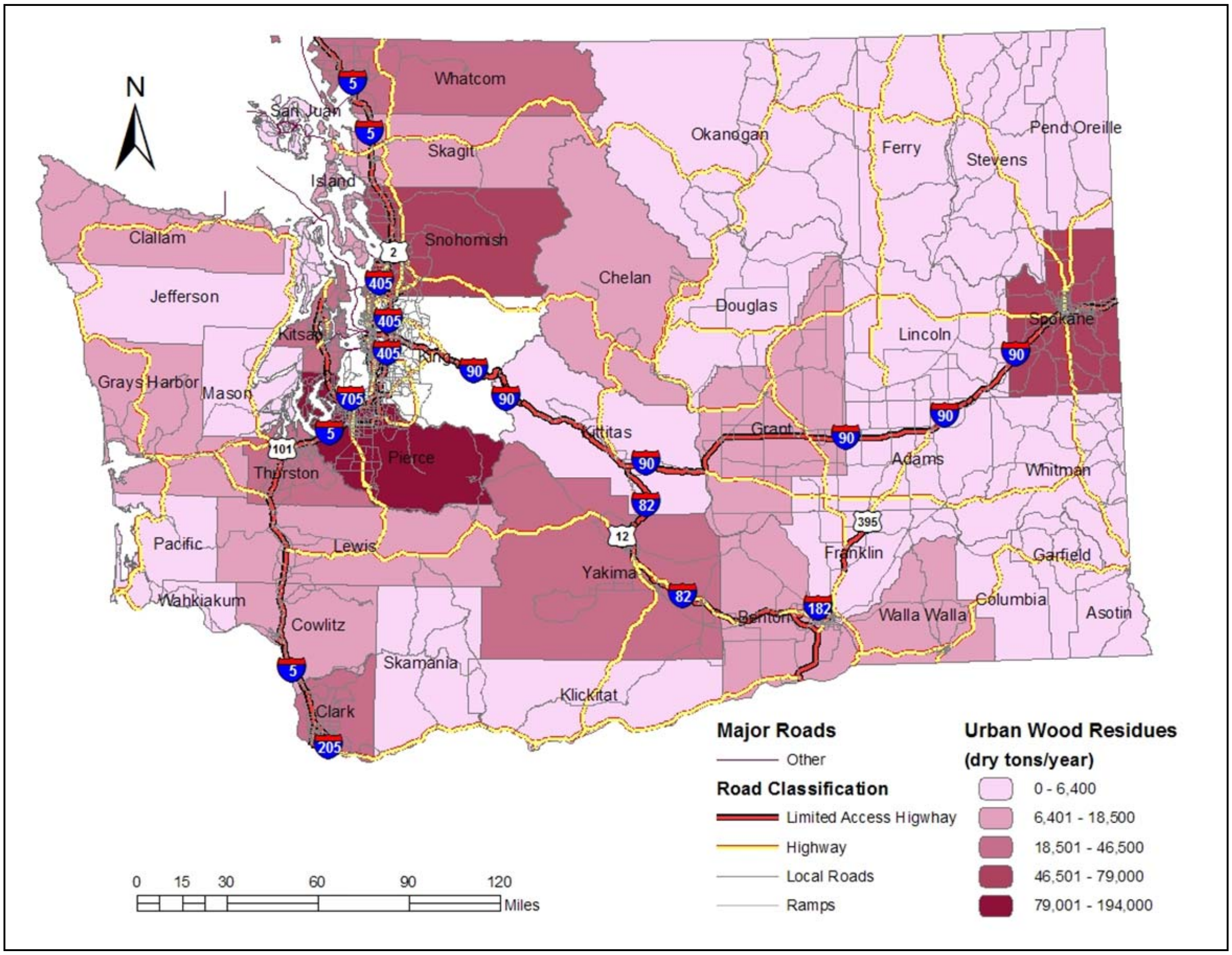


Figure 102: Geographic Distribution of Primary Mill Residue in Relation to the Road Network **(NREL Data)**

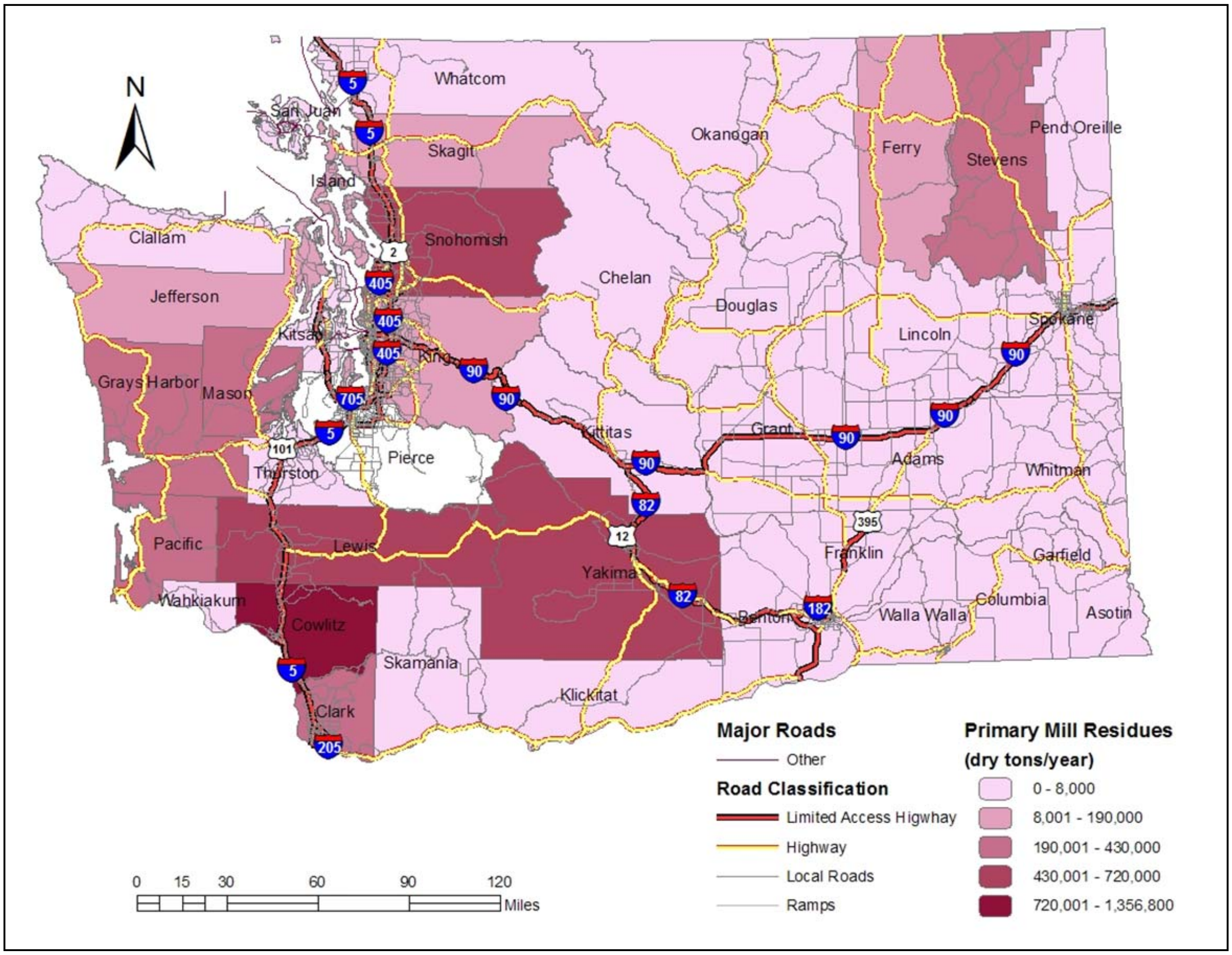


Figure 103: Geographic Distribution of Secondary Mill Residue in Relation to the Road Network **(NREL Data)**

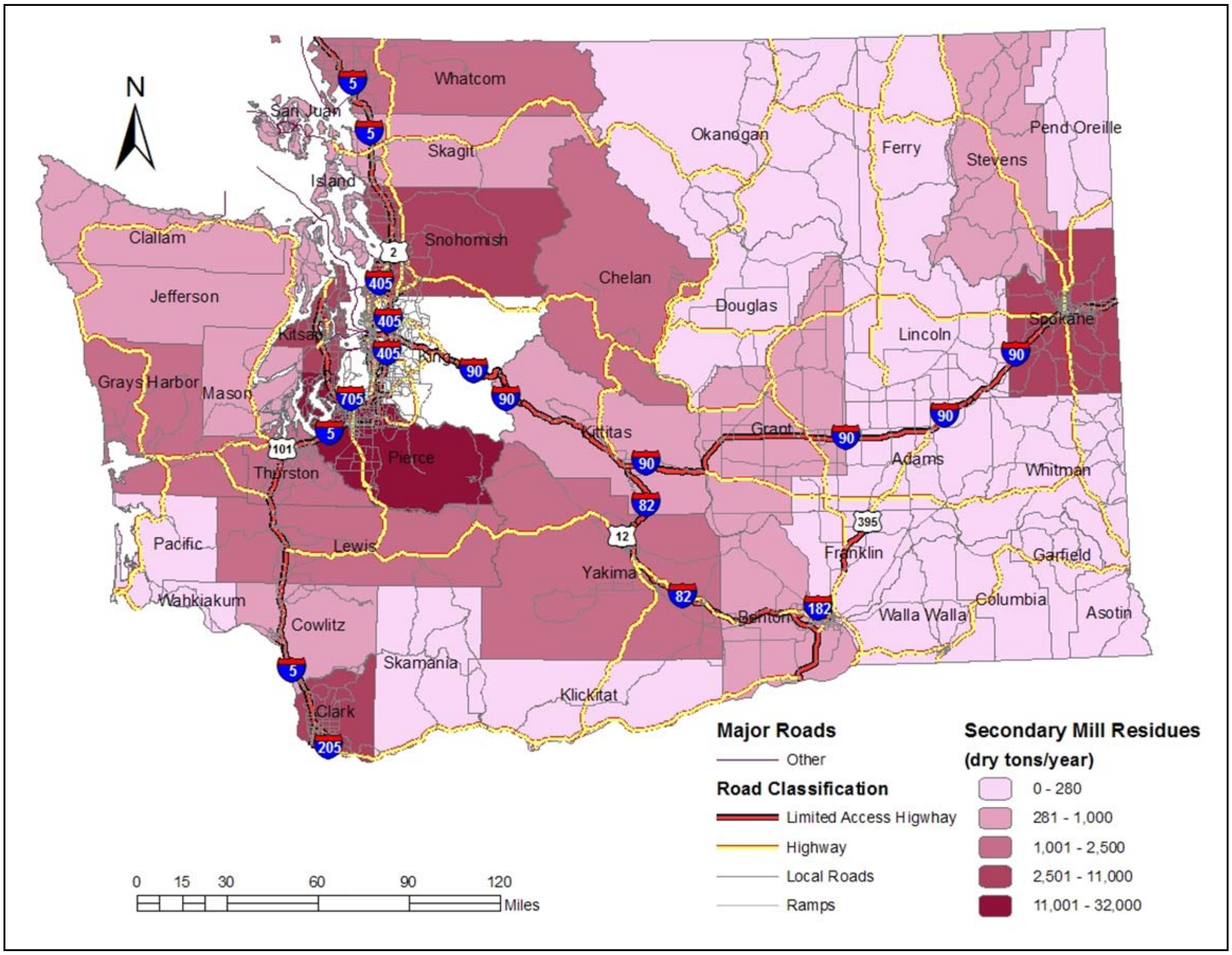
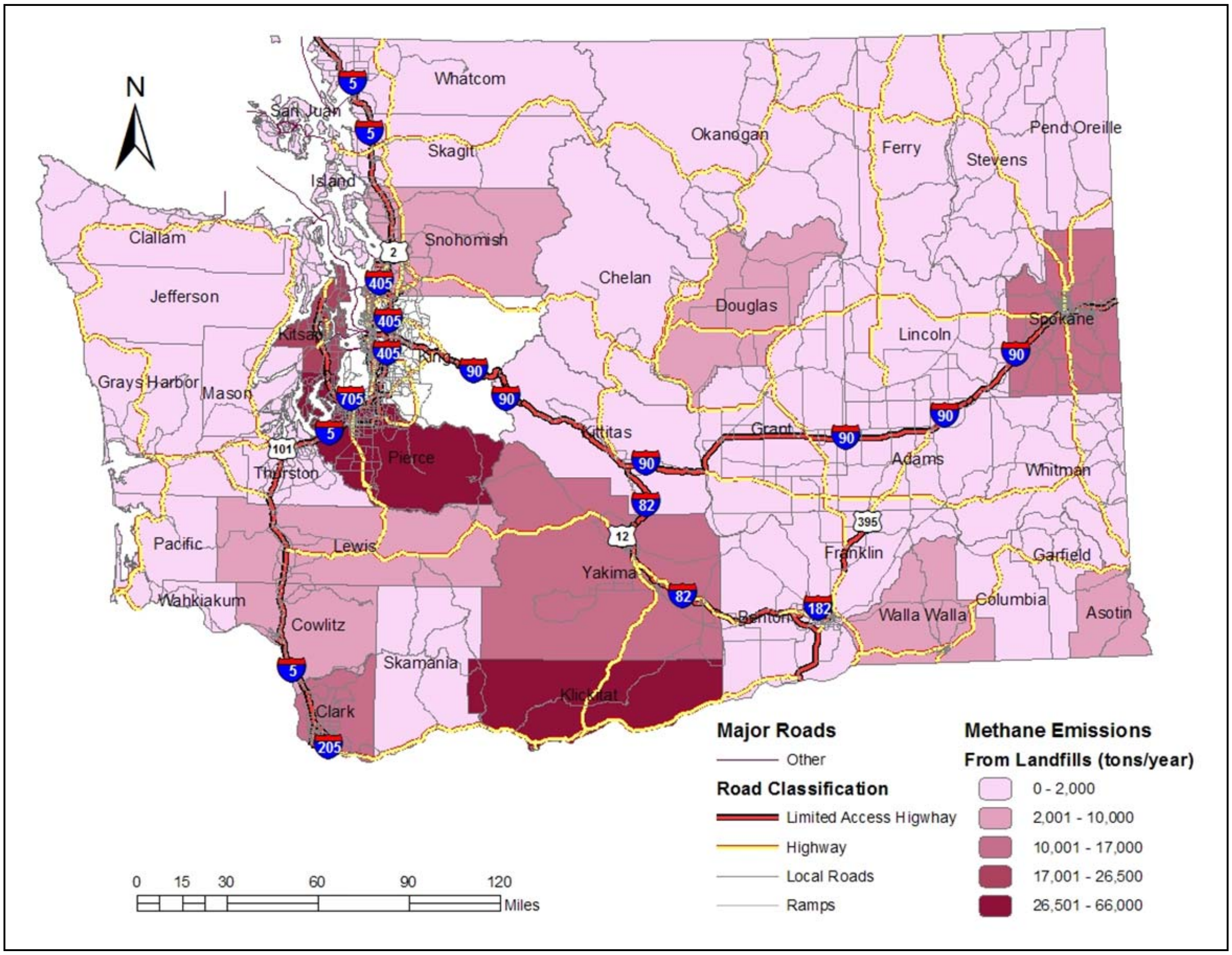


Figure 104: Geographic Distribution of Methane Emissions from Landfills in Relation to the Road Network **(NREL Data)**



Feedstock Harvesting and Transportation Efficiencies

Figure 105: Raking Process

Figure 106: Raking Equipment

Source: www.truckpaper.com

Figure 107: Swathing Process

Figure 108: Baling Process (Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 109: Baling Process (Small Bales: 0.4 x 0.6 x 1.2 m)

Figure 110: Road-siding Process (Large Bales: 1.2 $\times$ 1.2 $\times$ 2.4 m)

Figure 111: Road-siding Process (Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 112: Loading Drop Bed Trailer Truck (Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 113: Transporting Large Bales with Double Flat-bed Trailer

Figure 114: Drop Bed Trailer

Source: www.truckpaper.com

Figure 115: Flat-bed Trailer

Source: www.truckpaper.com

Trucking Cost Calculation Tables

Table 12: Lifetime Hours of Machinery Operation and Repairs Costs as Percentage of New List Price

	Accumulated hours									
	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
Type of Machinery										
Two-wheel drive tractor	1%	3%	6%	11%	18%	25%	34%	45%	57%	70%
Four-wheel drive tractor	0%	1%	3%	5%	8%	11%	15%	19%	24%	30%
	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
Moldboard plow	2%	6%	12%	19%	29%	40%	53%	68%	84%	101%
Heavy-duty disk	1%	4%	8%	12%	18%	25%	32%	40%	49%	58%
Tandem disk	1%	4%	8%	12%	18%	25%	32%	40%	49%	58%
Chisel plow	3%	8%	14%	20%	28%	36%	45%	54%	64%	74%
field cultivator	3%	7%	13%	20%	27%	35%	43%	52%	61%	71%
Harrow	3%	7%	13%	20%	27%	35%	43%	52%	61%	71%
Roller-packer, mulcher	2%	5%	8%	12%	16%	20%	25%	29%	34%	39%
Rotary hoe	2%	6%	11%	17%	23%	30%	37%	44%	52%	61%
Row crop cultivator	0%	2%	6%	10%	17%	25%	36%	48%	62%	78%
	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
Corn picker	0%	2%	4%	8%	14%	21%	30%	41%	54%	69%
Combine (pull)	0%	1%	4%	7%	12%	18%	26%	35%	46%	59%
Potato harvester	2%	5%	9%	14%	19%	25%	30%	37%	43%	50%
Mower-conditioner	1%	4%	8%	13%	18%	24%	31%	38%	46%	55%
Mower-conditioner (rotary)	1%	3%	6%	10%	16%	23%	31%	41%	52%	64%
Rake	2%	5%	8%	12%	17%	22%	27%	33%	39%	45%
Rectangular baler	1%	4%	9%	15%	23%	32%	42%	54%	66%	80%
Large square baler	1%	2%	4%	7%	10%	14%	18%	23%	29%	35%
Forage harvester (pull)	1%	3%	7%	10%	15%	20%	26%	32%	38%	45%
	300	600	900	1,200	1,500	1,800	2,100	2,400	2,700	3,000
Forage harvester (SP)	0%	1%	2%	4%	7%	10%	13%	17%	22%	27%
Combine (SP)	0%	1%	3%	6%	9%	14%	19%	25%	32%	40%
Windrower (SP)	1%	2%	5%	9%	14%	19%	26%	35%	44%	54%
Cotton picker (SP)	1%	4%	9%	15%	23%	32%	42%	53%	66%	79%
	100	200	300	400	500	600	700	800	900	1,000
Mower (sickle)	1%	3%	6%	10%	14%	19%	25%	31%	38%	46%
Mower (rotary)	0%	2%	4%	7%	11%	16%	22%	28%	36%	44%
Large round baler	1%	2%	5%	8%	12%	17%	23%	29%	36%	43%
Sugar beet harvester	3%	7%	12%	18%	24%	30%	37%	44%	51%	59%

Rotary tiller	0%	1%	3%	6%	9%	13%	18%	23%	29%	36%
Row crop planter	0%	1%	3%	5%	7%	11%	15%	20%	26%	32%
Grain drill	0%	1%	3%	5%	7%	11%	15%	20%	26%	32%
Fertilizer spreader	3%	8%	13%	19%	26%	32%	40%	47%	55%	63%
	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
Boom-type sprayer	5%	12%	21%	31%	41%	52%	63%	76%	88%	101%
Air-carrier sprayer	2%	5%	9%	14%	20%	27%	34%	42%	51%	61%
Bean puller-windrower	2%	5%	9%	14%	20%	27%	34%	42%	51%	61%
Stalk chopper	3%	8%	14%	20%	28%	36%	45%	54%	64%	74%
Forage blower	1%	4%	9%	15%	22%	31%	40%	51%	63%	77%
Wagon	1%	4%	7%	11%	16%	21%	27%	34%	41%	49%
Forage wagon	2%	6%	10%	14%	19%	24%	29%	35%	41%	47%

Source: Edwards (2002)

Table 13: Salvage Value as a Portion of New List Price of Field Machinery

	30-79 hp Tractor			80-149 hp Tractor			150+ hp Tractor			Combine, Foreage Harvester		
Annual Hours	200	400	600	200	400	600	200	400	600	200	400	600
Age												
1	65%	60%	56%	69%	68%	68%	69%	67%	66%	79%	69%	63%
2	59%	54%	50%	62%	62%	61%	61%	59%	58%	67%	58%	52%
3	54%	49%	46%	57%	57%	56%	55%	54%	52%	59%	50%	45%
4	51%	46%	43%	53%	53%	52%	51%	49%	48%	52%	44%	39%
5	48%	43%	40%	50%	49%	49%	47%	45%	44%	47%	39%	34%
6	45%	40%	37%	47%	46%	46%	43%	42%	41%	42%	35%	30%
7	42%	38%	35%	44%	44%	43%	40%	39%	38%	38%	31%	27%
8	40%	36%	33%	42%	41%	41%	38%	36%	35%	35%	28%	24%
9	38%	34%	31%	40%	39%	39%	35%	34%	33%	31%	25%	21%
10	36%	32%	30%	38%	37%	37%	33%	32%	31%	28%	23%	19%
11	35%	31%	28%	36%	35%	35%	31%	30%	29%	26%	20%	17%
12	33%	29%	27%	34%	34%	33%	29%	28%	27%	23%	18%	15%
13	32%	28%	25%	33%	32%	32%	27%	26%	25%	21%	16%	13%
14	30%	27%	24%	31%	31%	30%	25%	24%	24%	19%	14%	12%
15	29%	25%	23%	30%	29%	29%	24%	23%	22%	17%	13%	10%
16	28%	24%	22%	28%	28%	27%	22%	21%	21%	16%	11%	9%
17	26%	23%	21%	27%	27%	26%	21%	20%	19%	14%	10%	8%
18	25%	22%	20%	26%	25%	25%	20%	19%	18%	13%	9%	7%
19	24%	21%	19%	25%	24%	24%	19%	18%	17%	11%	8%	6%
20	23%	20%	18%	24%	23%	23%	17%	17%	16%	10%	7%	5%

Source: Edwards (2002)

Table 14: Salvage Value as a Portion of New List Price of Machinery

Machine Age	Plows	Other Tillage	Planter, Drill, Sprayer	Mower, Chopper	Baler	Swather, Raker	Vehicle	Other
1	47%	61%	65%	47%	56%	49%	42%	69%
2	44%	54%	60%	44%	50%	44%	39%	62%
3	42%	49%	56%	41%	46%	40%	36%	56%
4	40%	45%	53%	39%	42%	37%	34%	52%
5	39%	42%	50%	37%	39%	35%	33%	48%
6	38%	39%	48%	35%	37%	32%	31%	45%
7	36%	36%	46%	33%	34%	30%	30%	42%
8	35%	34%	44%	32%	32%	28%	29%	40%
9	34%	31%	42%	31%	30%	27%	27%	37%
10	33%	30%	40%	30%	28%	25%	26%	35%
11	32%	28%	39%	28%	27%	24%	25%	33%
12	32%	26%	38%	27%	25%	23%	24%	31%
13	31%	24%	36%	26%	24%	21%	24%	29%
14	30%	23%	35%	26%	22%	20%	23%	28%
15	29%	22%	34%	25%	21%	19%	22%	26%
16	29%	20%	33%	24%	20%	18%	21%	25%
17	28%	19%	32%	23%	19%	17%	20%	24%
18	27%	18%	30%	22%	18%	16%	20%	22%
19	27%	17%	29%	22%	17%	16%	19%	21%
20	26%	16%	29%	21%	16%	15%	19%	20%

Source: Edwards (2002)

Table 15: Plant to Blending Terminal Optimal Route Attribute Table

Object ID (Blending Terminal)	Facility ID (Ethanol Plant)	Facility Rank	Object Name (Blending Terminal)	Total Drive Time (minutes)	Total Distance (miles)	Trucking Costs ($/gallon)
27	11	1	Moses Lake	45.85	45.93	0.03
28	11	1	Pasco	77.26	76.18	0.05
31	11	1	Wilma	118.81	98.25	0.07
29	11	1	Seattle	201.64	219.36	0.15
30	11	1	Tacoma	222.75	232.75	0.16
26	11	1	Anacortes	272.48	290.27	0.20

Table 16: Blending Terminal to E85 Fueling Station Optimal Route Attribute Table

Object ID (E85)	Facility ID (Racks)	Name (Rack - E85)	Total Minutes	Total Distance	Trucking Costs ($/gallon)
35	14	Pasco - Richland	15.4	12.4	0.01
38	14	Pasco - Sunnyside	49.6	50.4	0.03
33	16	Tacoma - Chehalis	53.3	58.2	0.04
37	17	Wilma - Spokane	96.4	79.7	0.05
34	16	Tacoma - Longview	91.0	98.2	0.07
36	16	Tacoma - Seaview	144.9	139.0	0.09
32	14	Pasco - Bingen	175.6	159.4	0.11

Table 17: GIS Origin-destination Cost Matrix Data in Relation to per Gallon Trucking Costs

Object ID	Name (From - To)	Origin ID (Rack)	Destination ID (E85)	Destination Rank by Shortest Drive Time	Total Minutes	Total Distance	Trucking Costs ($/gallon)
1	Anacortes - Chehalis	1	2	1	157.4	165.4	0.11
2	Anacortes - Longview	1	3	2	195.0	205.5	0.14
3	Anacortes - Sunnyside	1	7	3	234.6	248.5	0.17
4	Anacortes - Seaview	1	5	4	249.0	246.3	0.17
5	Anacortes - Richland	1	4	5	271.4	287.9	0.19
6	Anacortes - Bingen	1	1	6	306.8	305.4	0.21
7	Anacortes - Spokane	1	6	7	325.6	349.3	0.24
8	Moses Lake - Spokane	2	6	1	98.9	105.0	0.07
9	Moses Lake - Richland	2	4	2	101.2	82.7	0.06
10	Moses Lake - Sunnyside	2	7	3	121.3	101.5	0.07
11	Moses Lake - Bingen	2	1	4	219.2	212.7	0.14
12	Moses Lake - Chehalis	2	2	5	232.3	245.0	0.17
13	Moses Lake - Longview	2	3	6	265.6	264.7	0.18
14	Moses Lake - Seaview	2	5	7	323.9	325.8	0.22
15	Pasco - Richland	3	4	1	15.4	12.4	0.01
16	Pasco - Sunnyside	3	7	2	49.6	50.4	0.03
17	Pasco - Spokane	3	6	3	130.2	135.0	0.09
18	Pasco - Bingen	3	1	4	175.6	159.4	0.11
19	Pasco - Chehalis	3	2	5	235.7	231.0	0.16
20	Pasco - Longview	3	3	6	255.8	251.9	0.17
21	Pasco - Seaview	3	5	7	351.4	326.4	0.22
22	Seattle - Chehalis	4	2	1	80.7	88.2	0.06

23	Seattle - Longview	4	3	2	118.4	128.2	0.09
24	Seattle - Sunnyside	4	7	3	163.8	177.6	0.12
25	Seattle - Seaview	4	5	4	172.3	169.0	0.11
26	Seattle - Richland	4	4	5	200.6	217.0	0.15
27	Seattle - Bingen	4	1	6	230.1	228.2	0.15
28	Seattle - Spokane	4	6	7	254.7	278.4	0.19
29	Tacoma - Chehalis	5	2	1	53.3	58.2	0.04
30	Tacoma - Longview	5	3	2	91.0	98.2	0.07
31	Tacoma - Seaview	5	5	3	144.9	139.0	0.09
32	Tacoma - Sunnyside	5	7	4	184.9	191.0	0.13
33	Tacoma - Bingen	5	1	5	202.7	198.2	0.13
34	Tacoma - Richland	5	4	6	221.7	230.4	0.16
35	Tacoma - Spokane	5	6	7	275.8	291.8	0.20
36	Wilma - Spokane	6	6	1	96.4	79.7	0.05
37	Wilma - Richland	6	4	2	179.5	148.6	0.10
38	Wilma - Sunnyside	6	7	3	213.7	186.7	0.13
39	Wilma - Bingen	6	1	4	339.7	295.7	0.20
40	Wilma - Chehalis	6	2	5	386.5	384.8	0.26
41	Wilma - Longview	6	3	6	419.9	404.5	0.27
42	Wilma - Seaview	6	5	7	478.1	465.6	0.31