Grain and Soybean Industry Dynamics and Rail Service

Analytical Models of Rail Service Operations

Final Report

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Executive Summary

To remain globally competitive, the United States' grain industry and associated transportation services underwent significant restructuring over the past fifteen years. New technologies, helped by weather changes, led to sustained yield volume increases in the Upper Midwest. To move larger volumes faster and at lower cost, the railroad industry introduced shuttle train service. Traveling as a unit to the same destination, shuttle trains save considerable time in transit and potential delay, bypassing intermediate classification yards. Grain shippers concurrently began consolidating and storing grain in larger, more efficient terminal elevators (shuttle loaders) instead of country elevators. This report examines the effectiveness of shuttle train service and the terminal elevators supporting the shuttle train system, under different demand levels, through the formulation of simple mathematical models. In order to compare shuttle and conventional rail service, this paper introduces three distinct models. The first model, referred to as the 'time model', determines the time it takes to transport grain from the farm to a destination (e.g. an export elevator). The second model, referred to as the 'engineering cost model', determines the aggregate variable costs of transporting grain from the farm to an export elevator. The third model, referred to as the 'capacity model', determines the maximum attainable capacity (i.e. throughput) of a rail network as a function of demand for rail transport and the percentage of railcars on the network being moved via shuttle service and conventional service.

Because the introduction of shuttle train service was accompanied by the prominence of terminal elevators, the scope of the analysis extends upstream of the rail transportation network to encompass the following three phases of the grain logistical supply chain:

- Transport from farm to local terminal or country elevator via truck
- Handling and storage of grain at terminal or country elevators
- Transport of grain from local elevator to export elevator via conventional or shuttle service

The 'time model' determines the total time to transport grain from farm to export elevator. The time model incorporates the following components:

- Travel time from farm to grain elevator via truck
- Truck unloading time at elevator
- (Short-term) storage time of grain at elevator

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- o We assume that grain remains in storage until enough grain is consolidated to fill an entire shuttle train (110 railcars) or conventional train (24 railcars)
- Railcar loading time at grain elevators
- Rail transport time from local elevator to export elevator
  - o Conventional service: we capture the time spent in classification yards
  - o Shuttle service: we capture the time lost due to mandatory crew changes

The time to truck grain from farm to elevator and unload the truck is small compared with elevator storage time and rail transport time. The storage time of grain is a function of the demand for grain rail transport service in the region surrounding an elevator. The higher the demand, the more grain entering an elevator per unit of time, and therefore the shorter the time grains spend in storage. The results of the time model suggest that shuttle train service is significantly faster than conventional rail service at moderate to high demand levels. The reason for this outcome is due to the fact that shuttle trains bypass classification yards and transport grain directly from origination to termination point. In contrast, conventional rail service requires grain railcars to enter classification yards. At very low demand levels (<250 tons per day), conventional service is comparable to shuttle service in terms of total time due to the fact that it takes a longer time to consolidate enough grain to fill an entire shuttle train at a terminal elevator than a conventional train at a country elevator. However, as the demand rate increases, shuttle service quickly begins to outperform conventional service in terms of travel time. The model results suggest that at demand rates greater than 2,500 tons of grain per day, conventional service takes twice as long as shuttle service (12 days vs. 6 days) to transport grain from eastern North Dakota to the Pacific Northwest. We conducted a number of sensitivity analyses on the model results with respect to different parameter values. The sensitivity analyses strengthen the initial time model results: shuttle train service is faster than conventional service at moderate to high demand levels

The engineering cost model captures each of the variable logistical supply chain costs of moving grain between the farm and the export elevator. The model excludes the capital costs of country and terminal elevators, classification yards, and rolling stock equipment. Similar to the time model, the cost model components include: a trucking cost model, an elevator cost model, and a rail transportation cost model. Note that engineering costs are different from "accounting" costs, intended for tax and financial reporting, in that they refer to direct costs actually incurred in providing the service in question.

The cost to transport grains via truck from farm to terminal elevator is larger than the cost to truck the grain to country elevators due to the fact that there are fewer terminal elevators; therefore, on average the distance from farm to terminal elevator is greater than the distance from farm to country elevator. The storage, or inventory costs, of terminal elevators are higher than country elevators because terminal elevators need to store larger volumes of grain to fill 110 railcar shuttle trains. Despite the increased upstream logistics costs associated with shuttle train service relative to the upstream costs of conventional service, the cost efficiencies associated with shuttle train

transportation over the rail network outweigh the increased upstream costs. Transporting the grain faster via shuttle service reduces in-vehicle inventory costs. Moreover, bypassing classification yards reduces labor costs, as does always having the optimal number of railcars on a train.

The results of the cost model suggest that at demand rates greater than 500 tons per day, shuttle service is approximately 16% cheaper than conventional service ($21 per ton vs. $25 per ton). These values include trucking and elevator storage costs as well as rail transportation engineering costs. A deeper analysis reveals that for both shuttle train service and conventional service, rail transportation costs account for a significant portion of the total logistical supply chain costs, approximately, 70% for shuttle service and 85% for conventional service. Once again we performed a number of sensitivity analyses on the cost model results with respect to model parameters including trucking costs, the price of grain and the handling costs of grain elevators.

The capacity model differs considerably from the time and cost models. The geographical scope of the capacity model is considerably larger than that of the time and engineering cost models. Rather than modelling the demand for a local terminal or country elevator, the capacity model incorporates all the demand for a rail classification yard. Additionally, the capacity model includes non-grain demand for rail service. Lastly, unlike the time and engineering cost models that compare shuttle service with conventional service as if the two service types could not exist simultaneously in the same region, the capacity model varies the percentage of demand served by conventional service and shuttle train service.

The capacity model is essentially a queuing model designed to evaluate the throughput of a section of track that includes a rail classification yard. All conventional service railcars, both grain and non-grain, enter the classification yard and are 'served' at a fixed rate. The shuttle trains, both grain and non-grain trains, bypass the classification yard unless the classification yard queue exceeds the capacity of the yard's receiving tracks and spills over onto the mainline.

As mentioned previously, we vary both the total demand for grain rail transportation and also the percentage of grain served via conventional and shuttle service. Demand is varied in small increments, whereas, we include four different percentages of demand served by shuttle service: 0%, 25%, 50% and 75%. We assume the number of non-grain railcars is fixed. A series of interesting results were obtained from the capacity model. First and foremost, if demand is low enough switching grain railcars from conventional service to shuttle service has no effect on throughput, as expected. As demand increases the throughput of the network is constrained by the service rate of the classification yard. The larger the percentage of grain served by shuttle service the higher the demand rate at which the classification yard constrains total throughput. In the 0% case and the 25% case, at high demand rates, the classification yard queue spills onto the rail network and prevents shuttle trains from bypassing the classification yard unimpeded. The results of the capacity model are quite clear, switching grain railcars to shuttle service from conventional service never decreases the throughput of the rail network and at high rail transport demand levels it can significantly increase the throughput of the rail transportation network.

The time, cost, and capacity models presented in this report allow for a comprehensive comparison of shuttle train service and conventional train service. The results of each model illustrate that shuttle train service offers meaningful advantages relative to conventional service under most realistic demand scenarios. The more grain demand that railroads can switch from conventional service to shuttle service the greater the overall operational and economic benefits. The cost, time and throughput advantages of shuttle train service all stem from its ability to bypass classification yards. Bypassing classification yards reduces travel time, decreases labor costs, and increases the capacity of rail transport networks. Each of these advantages benefit not only railroads but also grain shippers and grain producers. Grain producers and shippers require fast transport times and low transport costs to compete in global markets. Moreover, increased rail network throughput allows grain shippers (i.e. grain elevators) and producers to sell more grain when prices are at attractive levels.

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1. Introduction

Over the past fifteen years, grain production and the logistics of grain distribution, especially in the corridor from the Upper Midwest to the Pacific Northwest, underwent significant restructuring driven by the desire to achieve economies of scale in reaching export markets. Consolidation occurred in both production of grains and the logistics of moving grains to market. New technologies and weather changes led to sustained yield volume increases in the Upper Midwest, which subsequently increased the demand for grain transportation considerably. The railroad industry responded to the yield volume increase by introducing shuttle train service, while grain shippers concurrently began consolidating and storing grain in larger, more efficient terminal elevators (also known as shuttle loaders), as opposed to less efficient country elevators. Shuttle trains travel as a single block of railcars from origin to destination, with no need for processing (disassembling inbound trains and reassembling outbound trains) at classification yards. Terminal elevators typically have higher storage and handling capacity than country elevators.

Freight rail transportation is most cost efficient when a large number of railcars move together on a single train. As the number of railcars on a train increases, the fixed costs of rail transportation are spread over more railcars, resulting in a lower cost per railcar; hence, railroads aim to move as many railcars as possible on a single train. In order to obtain the cost efficiencies associated with large trains, railroads have historically consolidated railcars at classification yards. Under conventional rail service, single or multiple railcars are typically moved from their origin to a nearby classification yard where they are grouped with other railcars traveling to a similar destination. Railcars often travel through multiple classification yards before reaching their destination. Unfortunately, the disassembly and reassembly of railcars at classification yards is a time and resource consuming process. Railroads accepted the inefficiencies of classification yards as the price they needed to pay in order to obtain the benefits of railcar consolidation[1]. However, the introduction of unit and shuttle train service allowed railroads to move a large number of railcars directly from origin to destination without having to enter a classification yard.

This report examines the factors that contribute to the relative operational and cost performance of different types of rail service under different demand levels through the formulation of simple mathematical models ('demand' refers to the demand for rail transportation). In order to compare the two types of rail transportation services, this paper introduces three distinct models. The first model, referred to as the 'time model', determines the amount of time necessary to transport grain from the farm to a destination (e.g. an export elevator). The second model, referred to as the 'engineering cost model', determines the aggregate variable costs of transporting grain from the farm to an export elevator. The time and engineering cost models include the components of the grain supply chain upstream of the rail transportation because shuttle trains necessitated the introduction and use of terminal grain elevators. The third model, referred to as the 'capacity model', determines the maximum

attainable capacity (i.e. throughput) of a rail network as a function of the percentage of railcars on the network being moved via shuttle trains and conventional service.

The three models address three distinct performance dimensions of a rail service network, namely time, cost, and throughput. These allow us to explore the potential trade-offs associated with different types of service features, and how these might vary under different rail transportation demand levels. The next section presents a conceptual model of a typical grain supply chain. Sections 3, 4 and 5 present the time, cost and throughput models, respectively. In each of these three sections, the mathematical model, base parameter values, numerical results and sensitivity analyses are presented. The final section presents conclusions along with potential extensions to the capacity model.

2. Modelling a Grain Supply Chain
2.1. Conceptual Model

Grain moving from the Upper Midwest to the Pacific Northwest travels a long distance (e.g. 1,500 miles from Fargo, ND to Portland, OR). The route and distance that the grain travels make Class I railroads the best mode for moving grain to export markets. There is no feasible waterway between North Dakota and the Pacific Northwest for barge transportation; moreover, trucking low value commodities such long distances is prohibitively expensive. Figure 1 presents a conceptual model of the grain logistical supply chain. Trucks are used for the initial leg of grain transport from farm to elevator. After the grain is transported from the farm to an elevator via truck, the grain remains in storage until the elevator consolidates enough grain to fill an 'order'. A shuttle service order is typically between 90 and 120 carloads of grain, whereas, a conventional service order ranges from 1 single carload to 55 carloads. After the elevator consolidates enough grain to fill an order, railcars arrive and move the grain from the elevator to the export destination over the rail network. Despite being shown in the diagram, the model does not explicitly capture truck/rail transport between country and terminal elevators.
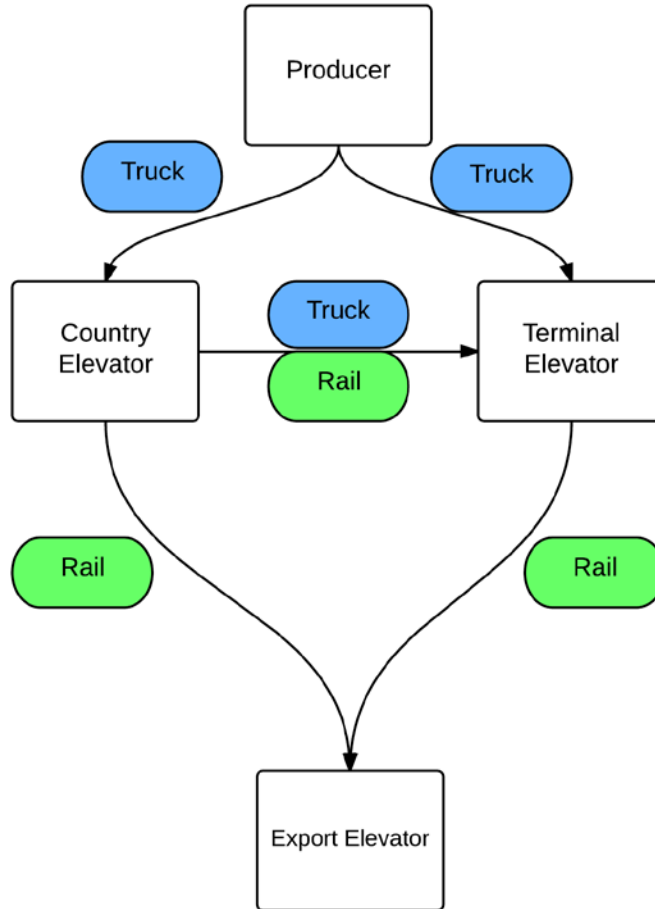
Figure 1: Conceptual Model of the Logistics of Grain Transportation

In the grain transportation network displayed in Figure 1, there are essentially five different stages, each with different costs, speeds, capacities, etc. The five stages are as follows:

- Production of grain on farms
- Transport, via truck, from the farm to country elevator or terminal elevator
- Consolidation and storage at country and terminal elevators
- Transport, via rail, from country or terminal elevator to export terminal
- Consolidation and storage at export terminal

Grain production, export elevator operations and oversea transportation via ship are beyond the scope of this analysis (these components are not examined further).

2.2. Network Representation

To further conventionalize the logistics supply chain of grain from production to export, the model's network representation, presented in Figure 2, includes the links and nodes that handle grain. In Figure 2, links represent the actual movement of grain, and nodes represent points at which the grain is stationary, such as production nodes (farms) and elevators. The red triangle-shaped production nodes represent farms, which produce grain at a given rate. The red curved

(black straight) trucking links connect production nodes to terminal (country) elevators. The green pentagon-shaped terminal elevator node and the blue diamond-shaped country elevator nodes serve as consolidation points for grain. A rail link is then used to either transport grain via shuttle service or conventional service to export terminals. While shuttle trains run from terminal elevator to export elevator with no need for processing, grain traveling via conventional service is processed at classification yards (white hexagons). The bottom portion of Figure 2 includes a detailed representation of a classification yard. The green triangle labeled 'Hump' is analogous to a server in a queueing model. Each of the links and nodes in Figure 2 have different time, cost and capacity elements; these links and nodes are described in detail in the following sections.

Figure 1 and Figure 2 refer to export elevators as the final destination of grain. It is important to note that the models developed in this report are valid independent of the grain's destination, assuming that at the destination, the facility can unload shuttle trains. For example, another possible destination for grain might be a grain feedlot in Texas or California.
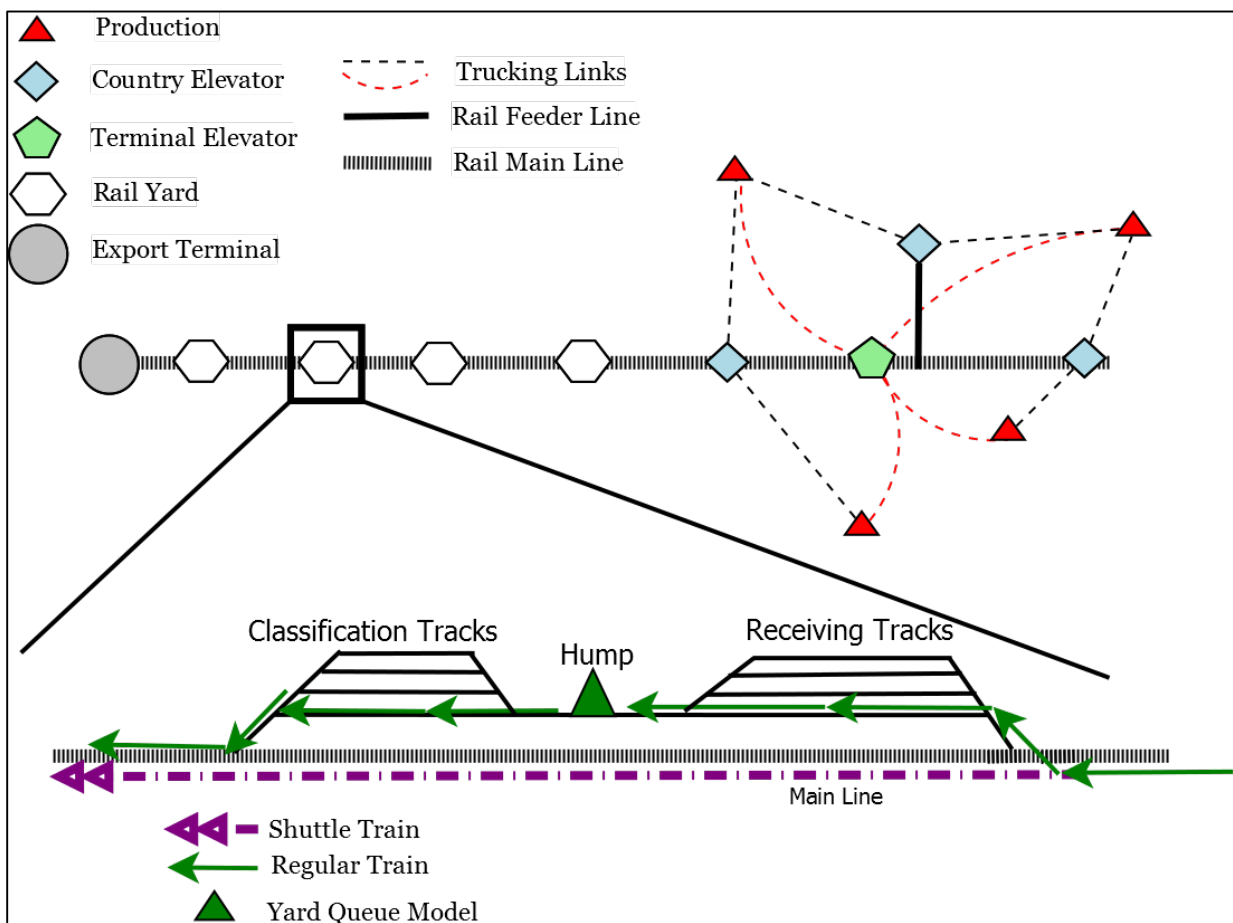

Figure 2: Model of Grain Transportation Network

2.3. Model Inputs

The principal input to the time and engineering cost models is the grain rail transportation demand rate, which has units of tons per day. For simplicity, the model includes a demand rate that is temporally and spatially uniform. The demand rate depends on a number of factors including the number of farms served by an elevator, the production rate of the farms during the current season, the percentage of farms selling their yield to an elevator (as opposed to selling it to other entities, e.g. flour mill or ethanol plant, or storing it and waiting for a better price). Capturing all of these factors is beyond the scope of this analysis; therefore, rather than assuming a fixed demand rate, we vary the demand rate between 50 tons per day and 5,000 tons per day, an extremely large range. The Alton Grain terminal, for example, handles 25 million bushels of grain per year which is approximately 2,000 tons per day on average.

The capacity model includes a second input in addition to the demand rate: the percentage of rail transport demand served by shuttle trains. The analysis varies percentage of demand served by shuttle service between 0% and 75% in increments of 25%. Naturally, the percentage of demand served by conventional service is equal to 100% minus the percent served by shuttle service. The capacity model also includes background traffic representing other commodities moving through the network.

2.4. Modelling Assumptions and Unit Conversions

The following assumptions hold for all three models. First, the following unit conversions are assumed:

- 1 bushel of grain = 55 pounds = 0.0275 tons
- 1 jumbo hopper = 286k pounds (220k pounds of grain + 66k tare) = 110 tons of grain
- 1 shuttle train = 110 railcars = 12,100 tons of grain
- 1 conventional train = 24 railcars = 2,640 short tons of grain

Due to the fact that country elevators are sometimes located off of the mainline track, bridges on some branch lines have weight restrictions that prevent railcars from being loaded with 110 tons of grain. However, we make the conservative assumption[a] that conventional train railcars, as well as those on shuttle trains, hold 110 tons of grain. Additionally, we assume that 1 terminal

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[a] Throughout the paper we refer to a number of assumptions as 'conservative'. The results presented in this paper suggest that shuttle train service is superior to conventional service across all three performance dimensions. A 'conservative' assumption implies that the assumption is making shuttle train service look worse or conventional service look better than what a deeper analysis would likely suggest.

elevator replaces 3 country elevators (i.e. in a situation where either only terminal elevators operate or only country elevators operate, one terminal elevator would serve the rail transport demand of three country elevators).

The term shuttle train is used rather than unit train because railcars on shuttle trains do not detach from the locomotive; whereas, the locomotive often detaches from the railcars on a unit train[2]. Twenty-four railcar units are associated with conventional service in this paper because, according to the USDA[3], shuttle service is disproportionately replacing 6-26 railcar blocks.

3. Time Model

The 'time model' presented in this section measures the amount of time it takes for a unit of grain to move from a production node (i.e. a farm) to the export terminal. The time model is subdivided into three components: the time it takes to truck grain from a farm to the nearest country or terminal elevator for consolidation and temporary storage; the time that the grain remains in storage before a train arrives to pick up the grain; and the time that the grain takes to travel from the local country or terminal elevator to the export elevator over the rail network. The ability of shippers to transport their goods to market quickly is essential[4], especially in a competitive global market wherein customers are located all over the world.

3.1. Time Model Parameter Values and Mathematical Formulation

Each of the three components of the time model are presented in this section. For the variables that have different base values for shuttle and conventional service, the base value for shuttle service is presented first, followed, in parenthesis, by the base value for conventional service.

Trucking and Unloading

Presented below are the variables – including their meanings and base values – used to determine trucking and unloading time.

Parameter	Symbol	Value	Units
Truck Speed	v_{truck}	35	MPH
Farm to Elevator Distance	$dist_{truck}$	30 (15)	miles
Truck Unloading Time	$time_{unload}$	10	minutes

Mathematical formulation of truck in-transit and unloading time:

$$Time_{truck} = \frac{dist_{truck}}{v_{truck}} + time_{unload} \approx 1\ hour \qquad \text{Equation 2.1}$$

The trucking and unloading times make up a miniscule portion of the total time to move grain from farm to export elevator. We include Equation 2.1, which determines trucking and

unloading time, for completeness. If Equation 2.1 is rounded to the nearest hour for either conventional or shuttle service, the value for $Time_{truck}$ is approximately equal to 1 hour.

Elevator Storage and Handling Time

The amount of time that a ton of grain spends at an elevator depends on a number of factors including the demand rate (a model input), the minimum amount of grain needed to fill a railcar order, and the handling rate at which grain is loaded onto a train. Each of these factors are considered in the elevator time model component presented in this section. Long-term storage is implicitly captured in this model through the demand rate. A farmer's decision to either sell grain to an elevator or put it in long-term storage directly affects the demand rate for grain transportation.

Presented below are the variables – including their meanings and base values – used to determine elevator storage and handling time.

Parameter	Symbol	Value	Units
Elevator Loading Minimum	L_{min}	12,100 (2,640)	tons
Demand Rate	d_{rate}	input	tons/day
Handling Time	$time_{handling}$	13 (24)	hours

The loading minimum is the amount of grain that must be consolidated at an elevator before a train can pick-up and transport the grain. For shuttle trains the loading minimum is equal to 110 railcars or 12,100 tons. The loading minimum for a country elevator is 24 railcars or 2,640 tons. Railroads typically incentivize terminal elevators to load shuttle trains as quickly as possible. The incentive includes rate discounts if elevators load railcars in under 15 hours[5]. A value of 13 hours is used because grain shuttle loading elevators typically load grain shuttle trains in significantly less than 15 hours. In contrast, multi-car (6-30 railcars) trains are typically loaded in one day[6].

As mentioned previously, the demand rate is the amount of grain produced in the geographical area surrounding an elevator, per unit of time, that is to be served via rail transport. This analysis assumes that the demand rate of a terminal elevator is three times higher than the demand rate of a country elevator; i.e. assuming a region wherein only terminal or country elevators are allowed to operate, not both, a terminal elevator would serve the same demand as three country elevators. The 3:1 ratio used in this analysis is a conservative assumption; terminal elevators typically replace more than three country elevators.

Mathematical formulation of elevator storage and handling time:

Equation 2.2 determines the amount of time a ton of grain spends at an elevator. In order for a fair comparison between shuttle and conventional service, in terms of storage time, the analysis

assumes that as soon as a terminal (country) elevator consolidates enough grain to fill a shuttle (conventional) train, the train arrives and picks up the grain.

$$Time_{elevator} = \frac{L_{min}}{d_{rate}*2} + time_{handling}$$

Equation 2.2

The first term on the right-hand side of Equation 2.2 represents the average time a ton of grain spends in storage. $\frac{Lmin}{d_{rate}}$ is the total time needed to accumulate enough grain at an elevator to fill a train. Assuming a uniform arrival rate of grain into an elevator, dividing the total time needed to accumulate enough grain to fill an entire train by two gives the average time a ton of grain spends in storage. The research team interviewed a number of grain industry stakeholders in the Upper Midwest. One farmer stated that he typically waits until he knows a shuttle train is coming before selling his grain to, and dropping his grain off at, an elevator. We asked three terminal elevator operators whether or not this was common practice. Each of the three elevators operators denied that farmers are typically notified when shuttle trains are coming to pick-up grain.

Rail Transportation

The two models presented in this section determine the time to transport grain from a terminal (country) elevator to an export elevator. This section presents two distinct rail transport time models because the factors influencing rail transportation time for shuttle and conventional service are different.

Shuttle Rail Transportation:

Presented below are the variables – including their meanings and base values – used to determine the time to transport grain over the rail network via shuttle train service.

Parameter	Symbol	Value	Units
Distance (ND to PNW)	$dist_{PNW}$	1400	miles
Shuttle Train Speed[78]	$v_{shuttle}$	22	MPH
Frequency of Crew Changes[9]	f_{crew}	1/7	changes/hour
Crew Change Delay	$delay_{crew}$	1	hours/change

The 1400 miles value is approximately the distance from Fargo, North Dakota to the Ports in the Pacific Northwest (PNW). A 2008 Bureau of Transportation Statistics report[7] shows that the quarterly average line-haul speed between 1999 and 2008 ranged from 21 to 25 miles per hour. The STB now requires railroads to report on performance metrics every week[8]. According to BNSF's self-reported performance metrics the average line-haul speed for unit grain trains over the past 52 weeks was 22 miles per hour[8]. Line-haul speed is a measure of the over-the-rail train speed and does not include the time trains and/or railcars spend at classification yards or at origination or termination points. According to a GAO report[9], railroad train crews typically

switch every 7 hours. This paper assumes that the delay per crew change is 1 hour – this is an upper bound (i.e. a conservative value) on the time required for a rail crew change.

Mathematical formulation of shuttle train service in-transit time:

Equation 2.3a determines the amount of time that a ton of grain spends on the railroad network when travelling via shuttle train service. The first term on the right-hand side of the equation represents the 'in-transit' time wherein the train is moving over the rail network. The second term represents the lost time due to mandatory crew changes. Using the parameter values from the table above, Equation 2.3a returns a value 71 hours.

$$Time_{shuttle-rail} = \frac{dist_{PNW}}{(v_{shuttle})} + \frac{dist_{PNW}}{(v_{shuttle})} * f_{crew} * delay_{crew}$$ Equation 2.3a

Conventional Rail Transportation:

Presented below are the variables – including their meanings and base values – used to determine the time to transport grain over the rail network via conventional service.

Parameter	Symbol	Value	Units
Distance (ND to PNW)	$dist_{PNW}$	1400	miles
Conventional Train Speed	v_{conven}	21	MPH
Distance between Classification Yards[6]	$dist_{yards}$	250	miles/yard
Delay Per Classification Yard	$delay_{yard}$	30	hours/yard

The distance between classification yards depends on a number of factors. Railcars travelling between two major rail hubs usually do not have to travel through many classification yards, in contrast, railcars travelling between two low density points usually travel through many classification yards. The other key determinant is the number of railcars travelling together; as the number of railcars travelling together increases the number of inter-train and intra-train switches typically decreases[6]. Tolliver and Bitzan[6] mention that the average distance between classification yards for single car shipments is 200 miles. The value is typically larger for multi-car (~24 railcar) shipments; hence a reasonable value of 250 miles is used in this analysis. A sensitivity analysis on the model results is performed with respect to the average distance between classification yards.

According to BNSF's self-reported performance metrics the average speed for conventional trains over the past 52 weeks was 21 miles per hour[8]. Additionally, BNSF self-reported that the average time a railcar spent in the Pasco, WA classification yard over the past 52 weeks was 31.2 hours[8]. The average time in the Northtown, MN classification yard was 34.7 hours[8]. These two classification yards are located on the BNSF's northern corridor. We use a value of 30 hours,

representing a lower bound (i.e. a conservative parameter value), for the average dwell time of a conventional train at a classification yard.

Mathematical formulation of conventional train service in-transit time:

Equation 2.3b determines the amount of time that a ton of grain spends on the rail network when travelling via conventional train service. The second term on the right-hand side represents the time that conventional train railcars spend in classification yards. Using the parameter values from the table above, Equation 2.3a returns 206 hours.

$$Time_{conven-rail} = \frac{dist_{PNW}}{(v_{conven})} + \frac{dist_{PNW}}{dist_{yards}} \, delay_{yard} \qquad \text{Equation 2.3b}$$

Total Travel Time – Farm to Export Elevator

This section presents the abbreviated mathematical formulation used to calculate the total logistical supply chain time between farm and export elevator. The only remaining variable in these two equations is the demand rate.

Shuttle Rail Service

$$Total\ Time_{shuttle} = Time_{truck} + Time_{elevator} + \ Time_{shuttle-rail} \quad \text{Equation 2.4a}$$

$$Total\ Time_{shuttle} = (1\ hour) + \left(\frac{6050}{d_{rate}} + 13 hours\right) + (71\ hours)$$

Conventional Rail Service

$$Total\ Time_{conventional} = Time_{truck} + Time_{elevator} + \ Time_{conven-rail} \quad \text{Equation 2.4b}$$

$$Total\ Time_{conventional} = \ (1\ hour) + \left(\frac{1320*3}{d_{rate}} + 24 hours\right) + (206\ hours)$$

3.2. Time Model Results

Figure 3 displays the results of the time model described in Section 3.1. The figure shows that shuttle service is faster than conventional service when the rail transport demand rate is greater than 350 tons per day – a relatively low rate. As the demand rate increases to values greater than 2,500 tons per day, shuttle train service transports grain nearly 50% (12 days vs. 6 days) faster than conventional service. The reason for this discrepancy is because grain travelling via shuttle train moves directly from origin to destination without entering classification yards; whereas, conventional service railcars spend 30 hours in classification yards. The reason why conventional service is comparable/slightly faster at low demand levels is because at low demand levels it takes a long time to consolidate enough grain at a terminal elevator to fill an entire 110 railcar shuttle train; therefore, the average grain spends a long time in storage at a terminal elevator. The main takeaway from the time model presented in Section 3 is that at moderate and high demand levels, the total time it takes for grain to travel from the farm to the export elevator is significantly lower when it travels via shuttle train service.
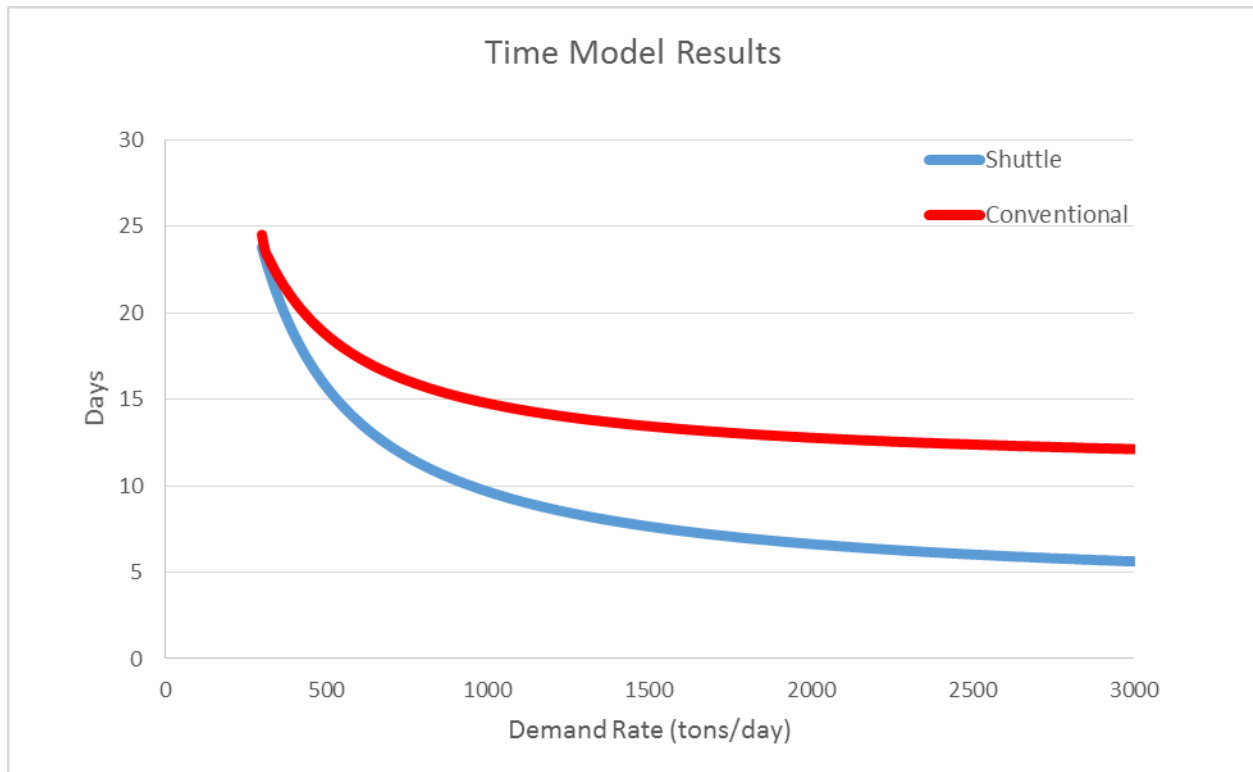
3.3. Sensitivity Analyses on Time Model Results with Respect to (WRT) Key Parameter Values

The purpose of this section is to analyze how the results displayed in Figure 3 would change if the parameter values listed in Section 3.1 were different. The sensitivity analyses presented here strengthen the key result of Section 3.2: shuttle train service is faster than conventional service at moderate and higher demand levels.

Average Distance between Classification Yards

Figure 4 displays the results of a sensitivity analysis on the time model results with respect to changes in the average distance between classification yards. The results displayed in Figure 3 assume that the average distance between classification yards is 250 miles; whereas, Figure 4 displays the results as the parameter value ranges from 200 miles, to 400 miles. Figure 4 shows that as the average distance between classification yards increases, the time for conventional service decreases; however, the reduction in time is subject to decreasing marginal returns. As the distance between classification yards increases from 200 miles to 300 miles, the associated total time at 2,500 tons per day for conventional service decreases from 14 days to 11 days. However, as the distance between classification yards increases from 300 miles to 400 miles, the associated total time at 2,500 tons per day for conventional service only decreases from 11 days to 10 days. It is important to note that the average distance between classification yards parameter value is a proxy for the number of times that a conventional train must stop at

classification yards. There are numerous factors that influence how frequently railcars stop at classification yards; hence the sensitivity analysis on this parameter is very important.
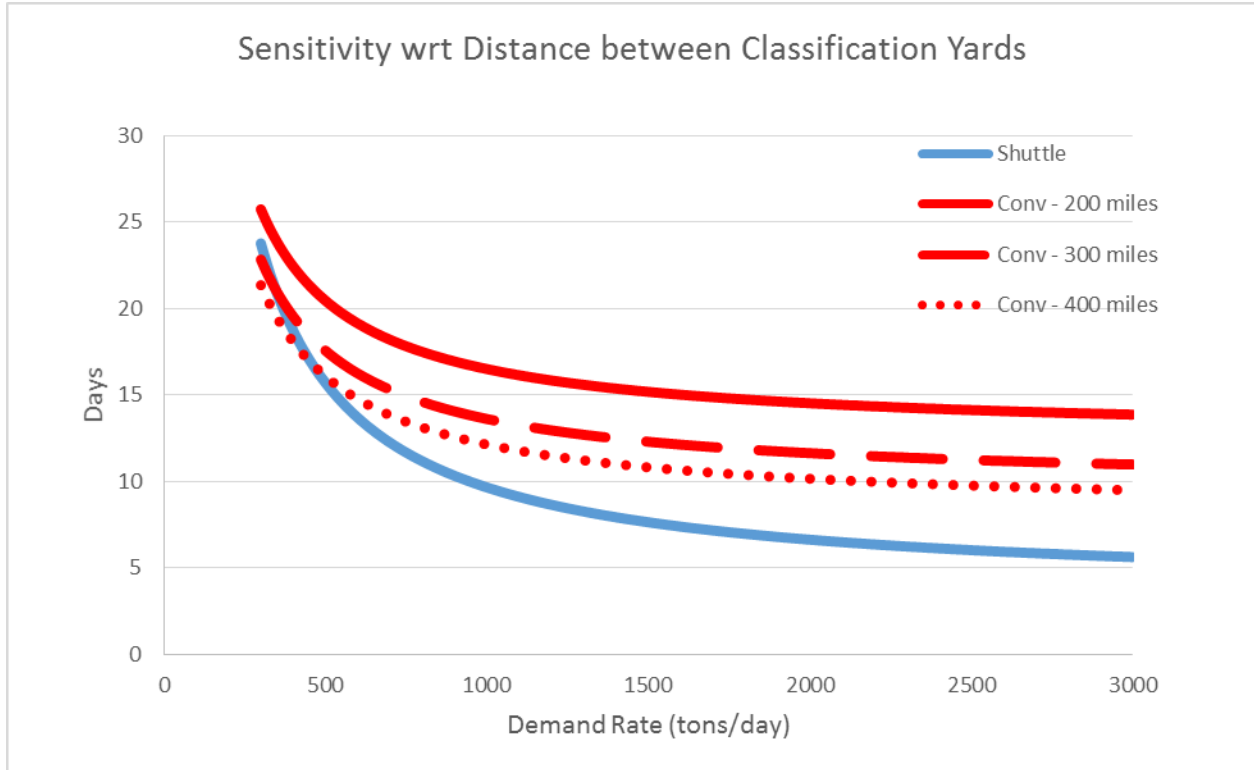

Figure 4: Sensitivity analysis on the time model results with respect to the average distance between classification yards.

Figure 4 shows that the average distance between classification yards significantly impacts the travel time of conventional rail service. However, given that a shuttle train takes approximately 5 days to travel from farm to export elevator at demand levels greater than 3000 tons per day, every day that a conventional train sits in a classification yard increases its total travel time significantly relative to shuttle service. Therefore, even with the most beneficial assumptions on the average distance between classification yards, the fact that conventional trains travel through at least one classification yard means that at demand levels greater than 2000 tons per day, shuttle train service is always be faster than conventional service. Figure 4 also shows that even as the average distance between classification yards increases, the 'breakeven' point between conventional and shuttle service only moves slightly to the right.

Total Distance between Farm and Export Elevator

Figure 5 displays the results of a sensitivity analysis performed on the total rail distance, $dist_{PNW}$. The figure shows that as rail distance decreases, the total travel time of conventional service decreases faster than the total travel time of shuttle service. The reason for the larger decrease in travel time under conventional service is due to the assumption that the number of classification yards a conventional train visits is dependent on the total distance the grain travels

and the distance between classification yards. Figure 5 shows that as total distance decreases, the gap between shuttle service and conventional service decreases at all demand levels, but the 'breakeven' point between shuttle and conventional shifts only slightly to the right; albeit more so than in Figure 4.
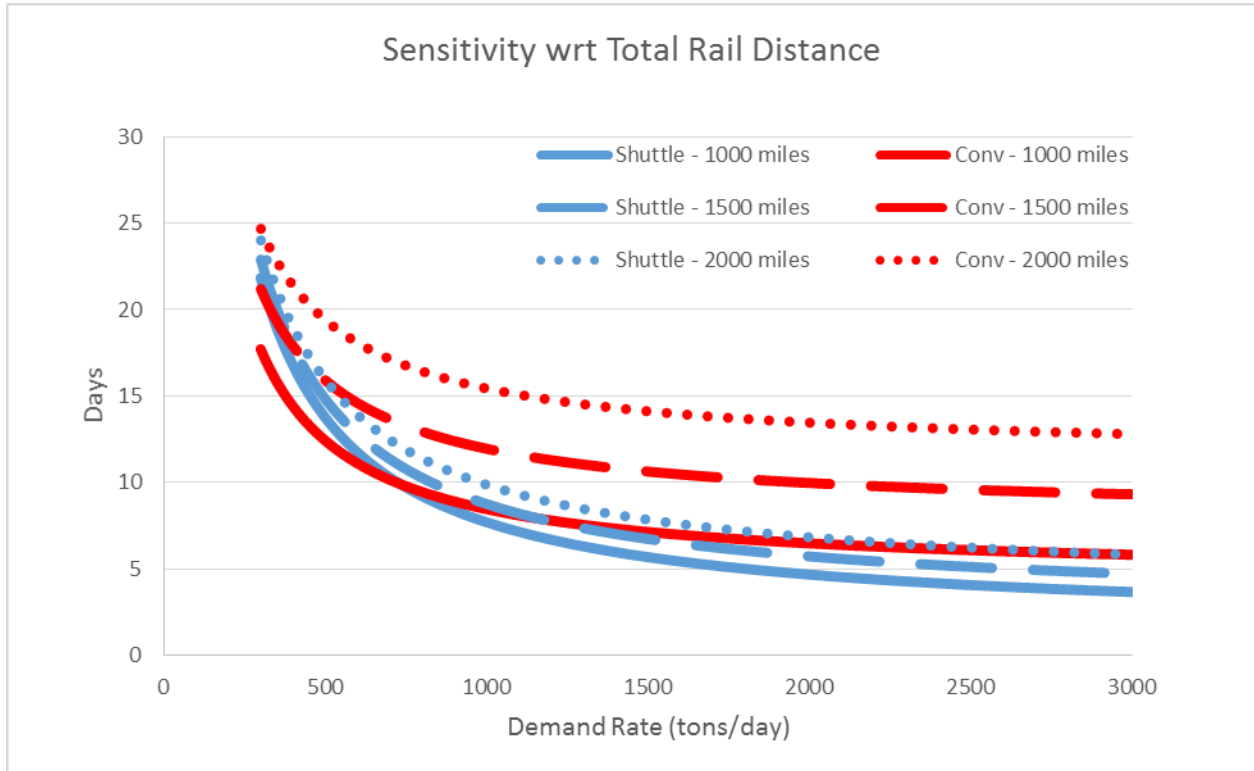

Figure 5: Sensitivity analysis on the time model results with respect to the total distance between the farm and an export terminal (or domestic termination point).

Dwell Time at Classification Yards

Figure 6 displays the results of the sensitivity analysis conducted on the time model with respect to the dwell time of railcars at classification yards. The results show a linear decrease in total time with the time a railcar spends in a classification yard. However, once again we see that eventhough total time decreases with railcar dwell time, shuttle trains do not need to stop at all; therefore, the general result still holds true: shuttle service is faster than conventional service.
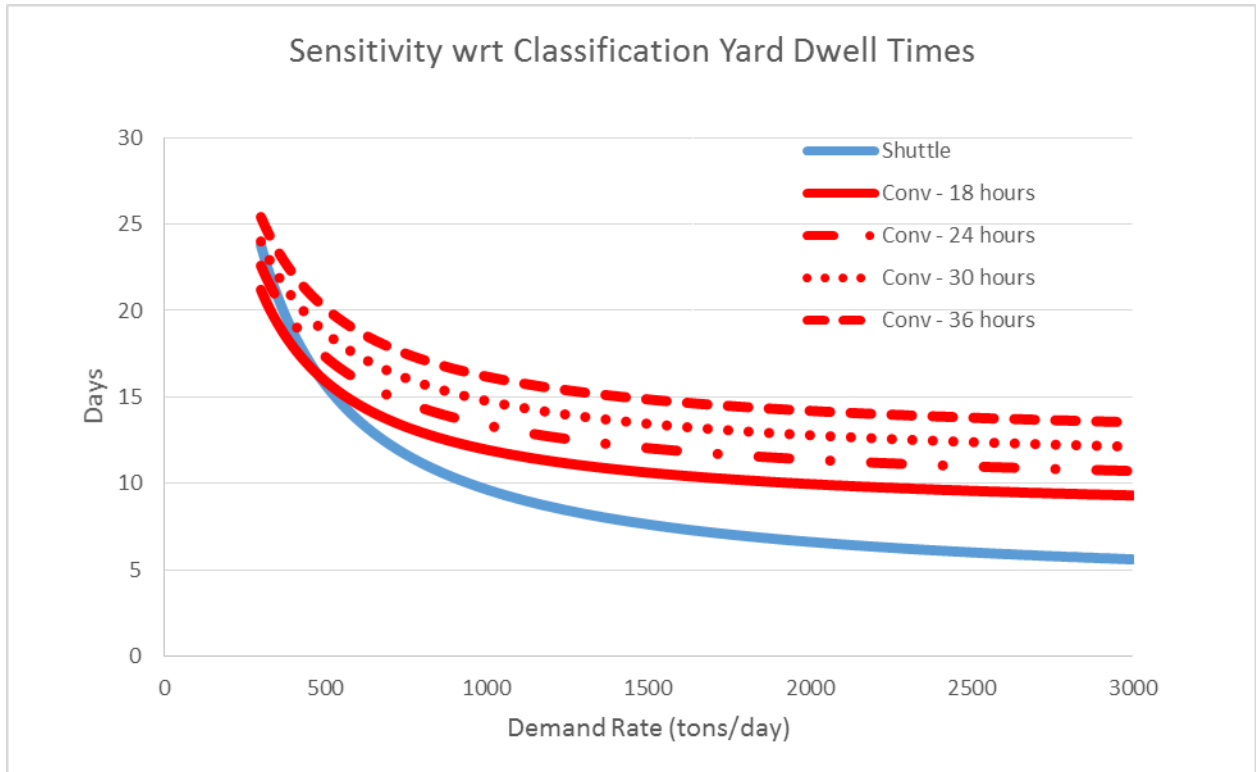
Figure 6: Sensitivity analysis on the time model results with respect to the average dwell time of railcars in a classification yard.

4. Engineering Cost Model

The engineering cost model presented in this section aims to capture each of the variable logistical supply chain costs of moving grain between the farm and the export elevator. The model excludes the capital costs of country and terminal elevators, classification yards, and rolling stock equipment. Excluding the rolling stock costs is a very conservative assumption because the utilization of shuttle train assets is significantly higher than the utilization of conventional train assets.[10]

Similar to the time model, there are three cost model components including a trucking cost model, an elevator cost model, and a rail transportation cost model. Note that engineering costs are different from "accounting" costs, intended for tax and financial reporting, in that they refer to direct costs actually incurred in providing the service in question. The model captures the aggregate variable costs per unit of grain transported in order to compare shuttle train service and conventional service. By capturing all of variable costs we are able to determine which variable costs contribute the most to the aggregate variable cost per unit of grain transported.

4.1. Cost Model Parameter Values and Modelling Assumptions

The mathematical models for each of the three cost model components are presented below. The costs obtained in each of the three components are additive.

Trucking Costs

Presented below are the variables – including their meanings and base values – used to determine trucking costs.

Parameter	Symbol	Value	Units
Trucking Cost per Mile**	$rate_{truck}$	**$1.60	$/mile
Farm to Elevator Distance	$dist_{truck}$	30 (15)	miles
Truck Capacity	cap_{truck}	20^{11}	tons
Length of Analysis Period	$time$	1	days
Demand Rate	d_{rate}	input	tons/day

**Truck Rate Details[12]	
Fuel Costs	$0.641/mile
Lease/Purchase Payment	$0.174/mile
Repair and Maintenance	$0.138/mile
Insurance	$0.063/mile
Tires	$0.019/mile
Labor	$0.533/mile

Fender and Pierce[12] report a trucking cost rate of $1.60 per mile. They break the cost down into six components, each of which is shown in the table above. As expected, the fuel and labor costs are the largest two cost components. To clarify, $1.60 per mile is not the cost of purchasing truck service; it is the cost of moving grain from farm to elevator. We assume that farmers truck their own grain from farm to elevator. The model results are independent of the length of the analysis period. Due to the fact that each terminal elevator replaces three country elevators, the average trucking distance from farm to a terminal elevator is considerably farther than from farm to country elevator[3].

Mathematical formulation of trucking costs:

Equation 3.1 presents the mathematical formulation used to determine the cost of trucking grain from farm to export elevator. The term on the right-hand side of Equation 3.1 includes a two in order to account for the round-trip distance between farm and elevator.

$$Cost_{truck} = \frac{d_{rate}*time}{cap_{truck}} * rate_{truck} * dist_{truck} * 2 \qquad \text{Equation 3.1}$$

Elevator Storage and Handling Costs

Presented below are the variables – including their meanings and base values – used to determine terminal (country) elevator storage and handling costs.

Parameter	Symbol	Value	Units

Elevator Loading Minimum	L_{min}	12,100 (2,640)	tons
Demand Rate	d_{rate}	input	tons/day
Handling Cost[13]	c_{hand}	$0.76 ($0.84)	$/ton
Annual Interest Rate	I_{rate}	6.0%[14]	%
Price of Grain	P_{grain}	$170	$/ton
Length of Analysis Period	$time$	1	days

The handling cost value of $0.76 per ton was obtained from a study by Kenkel et al.[13] The study reports an aggregate terminal elevator variable cost of $0.60 per ton in 2004 dollars ($0.76 per ton in 2015 dollars – CPI indexed (10)). The $0.60 per ton variable cost is comprised of labor overtime ($0.041 per ton), grain inspection ($0.073 per ton), grain inspection overtime ($0.061 per ton), electricity ($0.33 per ton) and grain cleaning ($1.833 per ton). However, Kenkel et al.[13] assume that only 5% of the grain is cleaned which equates to an average grain cleaning cost of $0.091 per ton. A 10% increase in terminal handling cost ($0.84 per ton) was assigned to country elevators because no analysis comparable to Kenkel et al.[13] study was conducted for country elevators. A later study by Kenkel[15] determines the handling and storage costs of grain in country elevators but the breakdown of costs is not consistent with Kenkel et al.[13]. Because a reliable estimate is not available for the grain handling costs at country elevators, a sensitivity analysis is performed in Section 4.3 with respect to country elevator handling costs. The results clearly show that the relative handling cost difference between shuttle and country elevators has an insignificant effect on the cost model results.

As mentioned previously, the model assumes that as soon as enough grain is consolidated to fill either an entire shuttle train or set of conventional train railcars, the grain exits the elevator. Hence, the cost of long-term storage is not accounted for in the engineering cost model. However, the model includes the inventory costs associated with storing grain in the short term.

Mathematical formulation of elevator storage and handling costs:

Equation 3.2 determines the storage and handling costs of grain at an elevator. The first term in parenthesis determines the handling costs and the second term determines the inventory cost of the grain sitting in storage. The model assumes that a terminal elevator needs to have the financing to store an entire shuttle train full of grain – independent of the production (arrival) rate of grain. The country elevator, which serves 24 railcar trains, has lower inventory costs because it only needs to store 24 carloads full of grain. However, because 1 terminal elevator replaces 3 country elevators, the aggregate inventory costs are relatively close.

$$Cost_{elevator} = time * \left(d_{rate} * c_{handle} + P_{grain} * L_{min} * I_{rate} \right) \qquad \text{Equation 3.2}$$

Rail Transportation Costs

The final component of the engineering cost model, relating to rail transport costs, is presented in this section. Presented below are the variables – including their meanings and base values – used to determine shuttle (conventional) rail transportation costs.

Parameter	Symbol	Value	Units
Distance (ND to PNW)	$dist_{PNW}$	1400	miles
Labor Cost	c_{crew}	$60	$/hour
Workers per train	w_{train}	2 (1.5)	workers/train
Fuel Consumption Rate	r_{fuel}	470	ton-miles/gallon
Fuel Cost per Gallon	c_{fuel}	$4.0	$/gallon
Time on Rail Network	$Time_{rail}$	71 (206)[b]	hours
Annual Interest Rate	I_{rate}	6.0%	%
Price of Grain	P_{grain}	$170	$/ton
Workers per yard	w_{yard}	NA (0.5)	workers/yard
Delay per classification yard	$time_{yard}$	NA (30)	hours
Distance between classification yards	$dist_{yards}$	NA (250)	Miles
Line-haul speed	v_{rail}	22 (21)	MPH
Elevator Loading Minimum	L_{min}	12,100 (2,640)	tons

Shuttle trains do not enter classification yards, by definition; therefore, the delay per classification yard for shuttle trains and the number of classification yard workers per shuttle train are not applicable (NA). The time that a conventional service railcar spends in a classification yard is highly variable and dependent on a number of factors. A reasonable, yet conservative, value of 30 hours is used in this model.

In recent years, the Federal Railroad Administration (FRA) tried to implement regulations requiring all trains to have at least two persons on each train. Two crew members per train is currently the unofficial standard for nearly all railroads[16]; hence, we assume that each 110 railcar shuttle train employs 2 crew members. In terms of conventional trains, we also assume 2 crew members on each of these trains. However, conventional service typically involves the multi-car grain shipments (e.g. 24 railcars) being combined with other railcars; therefore we assume, on average, each set of 24 railcars requires 1.5 crew members. The fuel consumption rate of 470 ton-miles per gallon was obtained from CSX's website[17]. The $4.0 per gallon fuel cost rate comes from a 2015 U.S. Energy Information Administration report[18].

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[b] Values come directly from the sub-section entitled "Rail Transportation" from Section 3 in the time model

The Bureau of Labor Statistics reports that the mean hourly wage for locomotive engineers, firers, and rail yard engineers are $27.41, $25.81, and $21.54 respectively[19]. However, the wage received by an employee is significantly less than the cost incurred by an employer. The employer also pays social security/FICA taxes (6.2 percent of income), unemployment (6.2 percent), Medicare (1.45 percent), workmen's compensation (a non-miniscule amount for railroad workers), and benefits (25%)[20]. Moreover, employees are not actively working on trains 100% of the time; therefore, in a cost model, their costs to the employer during downtime need to be spread over the time they spend working on trains. Hence, the $60 per hour value for labor is a reasonable, albeit slightly inflated assumption (this is not a 'conservative' parameter value because higher labor rates drive conventional rail transport costs higher than shuttle transport costs).

Mathematical formulation of rail transportation costs:

Equation 3.3a determines the cost of railcars travelling through a classification yard, which only applies to conventional service railcars. Equation 3.3b determines the inventory cost incurred during the rail transportation portion of the supply chain. Equation 3.3c is the summation of (a) Equation 2.3.1, (b) Equation 2.3.2, (c) fuel costs and (d) labor costs and it determines the total rail transportation cost.

$$c_{labor_{yard}} = \frac{d_{rate}*time}{L_{min}} * time_{yard} * w_{yard} * c_{crew} * \frac{dist_{PNW}}{dist_{yards}} \quad \text{Equation 3.3a}$$

$$c_{inventory} = P_{grain} * d_{rate} * time * I_{rate} * Time_{rail} \quad\quad \text{Equation 3.3b}$$

$$Cost_{rail} = dist_{PNW} * \left(d_{rate} * time * \frac{1}{r_{fuel}} * c_{fuel} + c_{crew} * w_{train} * \frac{1}{v_{rail}} * \frac{d_{rate}*time}{L_{min}} \right) +$$
$$c_{labor_{yard}} + c_{inventory} \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \text{Equation 3.3c}$$

Total Logistical Supply Chain Costs

Equation 3.4 displays the abbreviated total supply chain engineering cost of transporting grain between farm and export elevator.

$$Cost(d_{rate}) = Cost_{truck} + Cost_{elevator} + Cost_{rail} \quad\quad \text{Equation 3.4}$$

4.2. Cost Model Results

Figure 7 illustrates that the aggregate variable costs per unit of grain transported from farm to export elevator via shuttle service are significantly lower than conventional service. At demand levels greater than 800 tons per day, the aggregate variable cost per unit of grain transported via shuttle service is approximately $21 per ton and under conventional service the cost is approximately $25 per ton. This 16% decrease in cost is quite significant in the rail transportation and grain production industries.

There are only two components of the cost model presented in Section 4.1 in which conventional service has a cost advantage over shuttle service: trucking costs and inventory costs. Trucks have to travel nearly twice as far to access a terminal elevator (30 miles) compared with country elevators (15 miles); therefore, the trucking costs are twice as high under shuttle service. However, Figure 8 below shows that trucking makes up a relatively small portion of the total logistical supply chain costs compared with rail transport costs. Conventional service's elevator inventory cost advantage over shuttle service is also relatively small. Whereas one terminal elevator needs to finance 110 railcars worth of grain, it takes 3 country elevators to replace a terminal elevator; therefore, 3 country elevators need to finance 72 railcars (24 * 3) worth of grain.
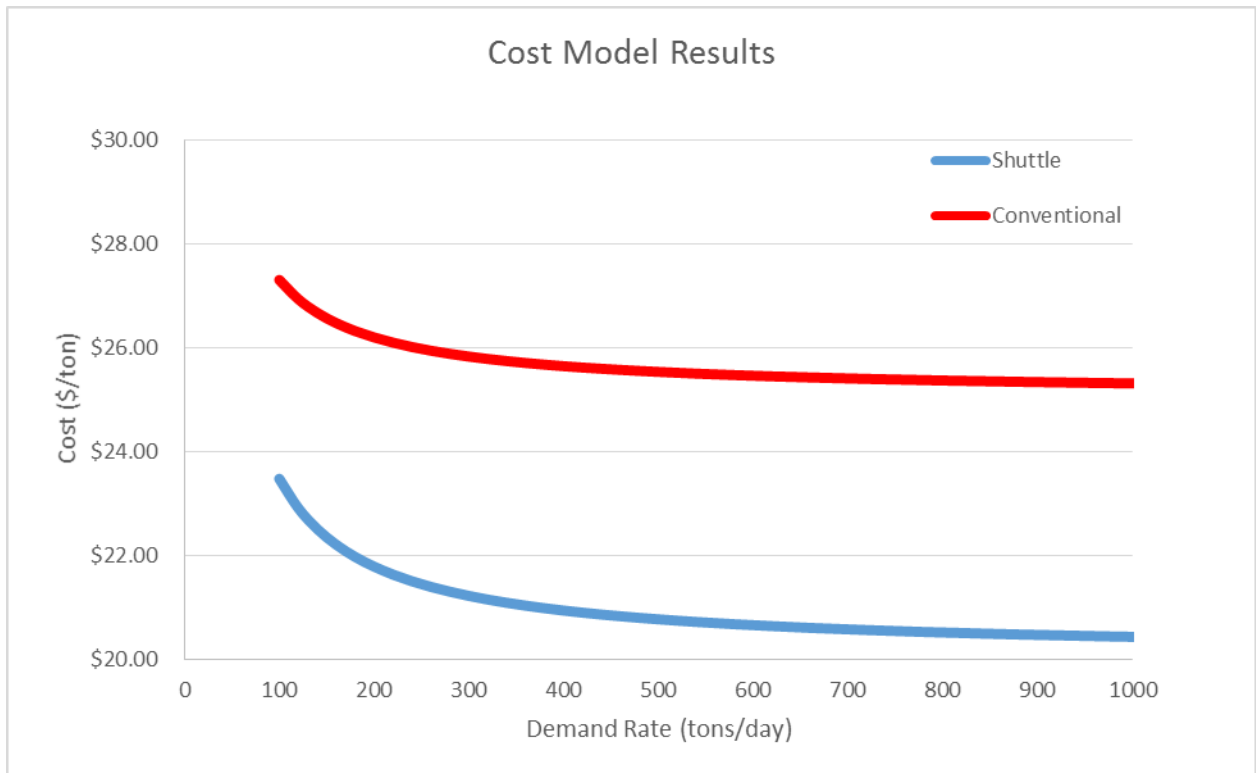

Figure 7: Engineering cost model results using the base values presented in Section 4.1.

In contrast to conventional services two minor cost advantages, shuttle train service has a number of major cost advantages, including: lower elevator handling and storage costs, lower rail transport labor costs, no classification yard costs, and lower in-transit inventory costs. The summation of all of these cost advantages is displayed in Figure 7; moreover, Figure 8 shows that the rail transport portion of the logistical supply chain is where shuttle service has a significant advantage over conventional service in terms of costs. The values in Figure 8 are based on a demand of 500 tons of grain. Of the three grain supply chain components modeled in this report, railroad transportation is the largest contributer to total costs and shuttle service has numerous per unit rail transportation cost advantages over conventional service.
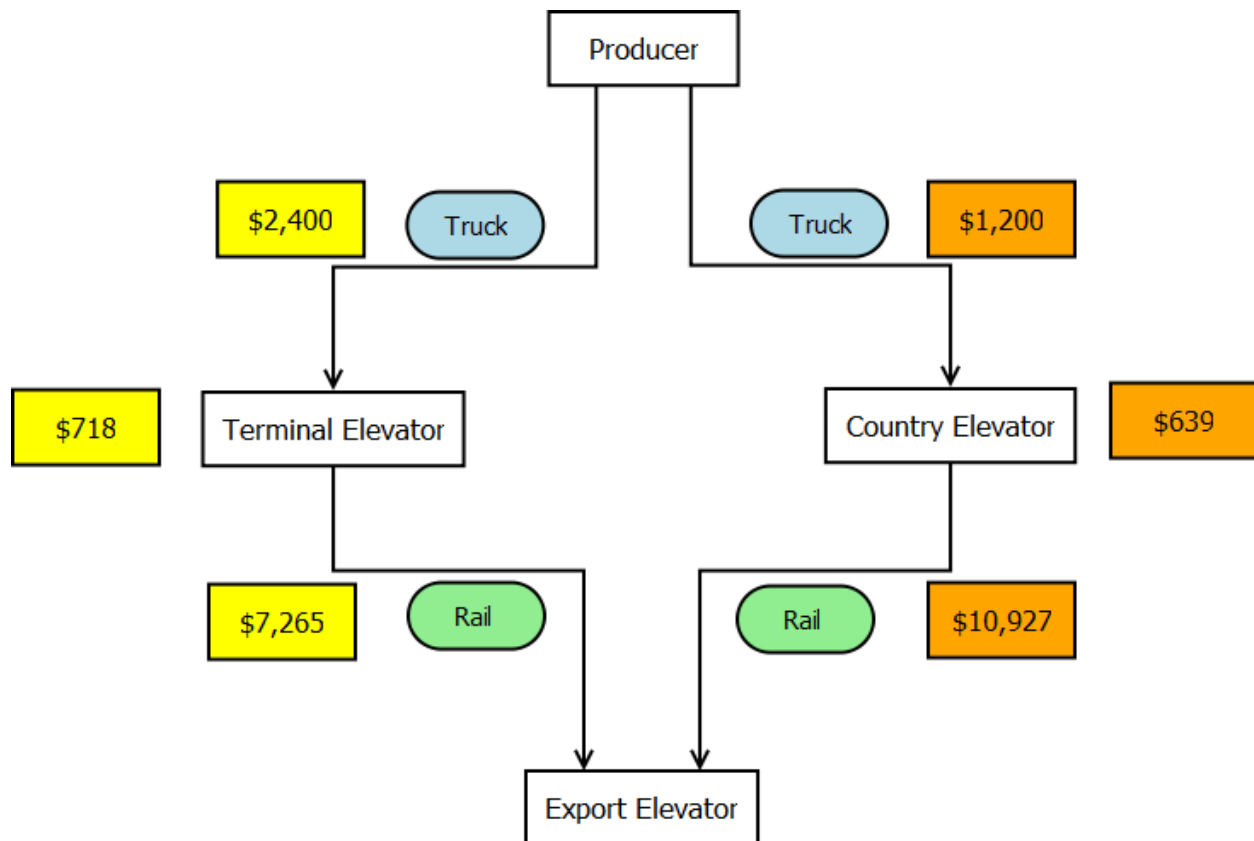
Figure 8: Comparison of the logistical costs of trucking grain, storing grain, and transporting grain via shuttle train service (left-hand side – yellow) and conventional service (right-hand side – orange). The logistical cost values are based on a demand of 500 tons of grain.

4.3. Sensitivity Analyses on Cost Model Results WRT Key Parameter Values

In order to capture how some of the key parameter values, listed in Section 4.1, affect the aggregate variable costs per unit of grain transported via shuttle and conventional service, we performed sensitivity analyses. The sensitivity analyses are presented in this section.

Trucking Costs

Figure 9 displays the results of a sensitivity analysis performed with respect to trucking costs. The value used for the trucking cost per mile was $1.6 per mile in the analysis in Section 4.2. In order to determine the sensitivity of the cost model results to the trucking cost per mile, we vary the parameter value between $2.0 per mile and $5.0 per mile. Figure 9 shows that the aggregate variable costs of grain transport are sensitive to trucking costs. However, even if trucking costs increase by 200% (from $1.6 per mile to $5.0 per mile) shuttle train service is still approximately the same as conventional service.

$5.0 per mile was chosen as an upper bound because this rate is comparable to what trucking companies charge to pick-up and move grain distances of around 25 miles[21]. However, most farmers own and drive their own semi-trucks; therefore, the costs are lower than the prices charged by truck operators. Once again, the cost model presented in Section 4 is an engineering

cost model of the logistical grain supply chain; therefore, the model aims to capture all of the engineering costs of the supply chain not the rates charged by trucking companies, elevator operators or railroad companies.
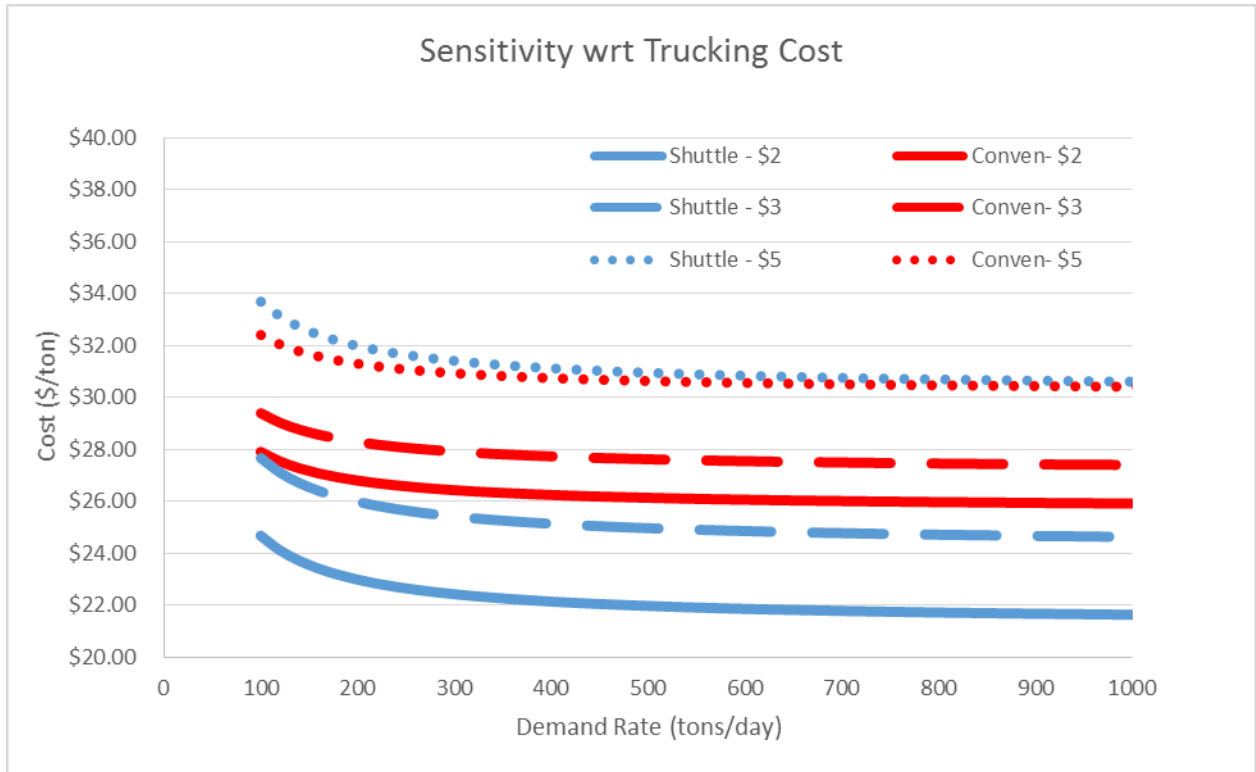

Figure 9: Sensitivity of the cost model results with respect to trucking costs.

Price of Grain

In this sub-section we aim to analyze the effect that the value (i.e. the market price) of grain has on the aggregate variable costs of grain transport. The value used in the base analysis presented in Section 4.2 for the price of grain was $170 per ton or approximately $5 per bushel. In Figure 10, the price of grain varies between $140 per ton and $200 per ton. As the price of grain increases, elevator inventory costs increase and shuttle train inventory costs also increase. An increase in the price of grain makes country elevators more appealing for storage, but the increase makes shuttle trains more appealing for rail transportation. Figure 10 shows that an increase (decrease) in the market price of grain favors shuttle (conventional) service.
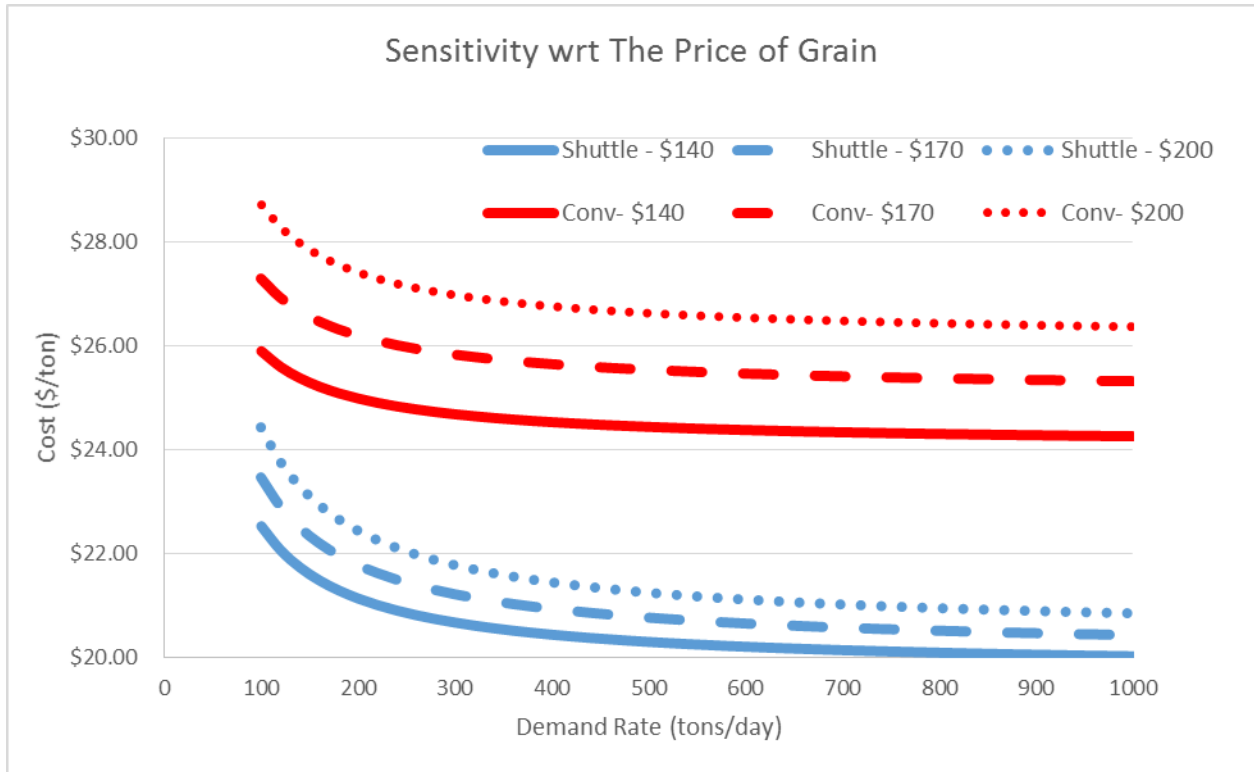
Figure 10: Sensitivity of the cost model results with respect to the price of grain.

Handling Cost of Grain

In the base model we assume that terminal elevators are 10% more cost effective. This estimate is a conjecture; therefore we perform a sensitivity analysis with respect to this parameter value. Figure 11 displays the results of the sensitivity analysis. We vary the percent difference between the handling cost of terminal and country elevators between -50% (i.e. country elevator handling costs are half the costs of terminal elevators) and +25%. The figure clearly shows that the the handling cost of grain at elevators has minimal impact on aggregate variable cost.
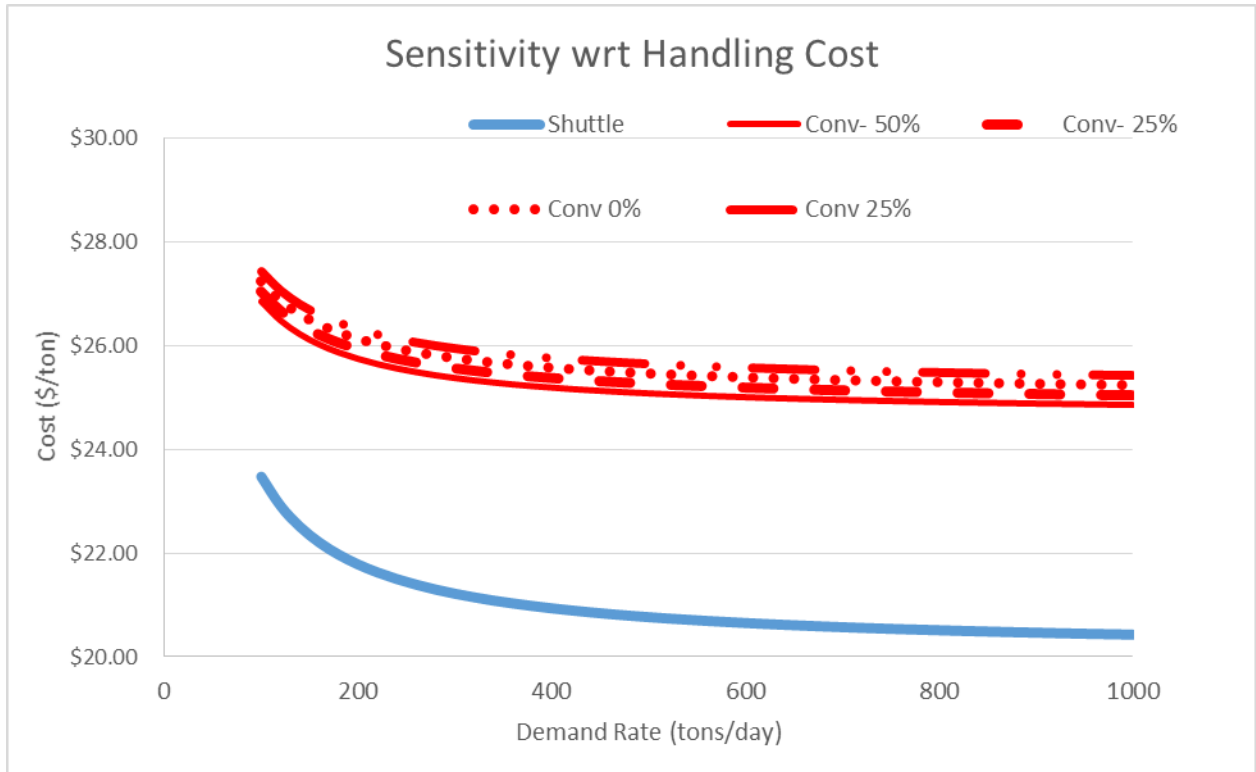
Figure 11: Sensitivity of the cost model results with respect to elevator handling costs.

5. Capacity Model

Measuring the capacity of a rail network is complicated. There are three broad categories to measure level of service or capacity of a rail network: throughput, asset utilization and reliability. The first, throughput, measures the quantity of goods that the transportation network serves per unit of time. Asset utilization measures the percentage of time assets are being utilized in the manner in which they were intended to be used. Reliability is a broad term that, in transportation, generally refers to on-time performance. Our understanding of the dynamics of the grain and grain transportation industries in the Upper Midwest leads us to believe that throughput is the most relevant level of service/capacity measure to examine. Two important facts lead us to believe that reliability is not as important as throughput in terms of level of service: (1) the region's grain storage capacity is very high and (2) grain does not lose its value quickly. Also, because the utilization of assets is highly correlated with throughput (e.g. given x number of assets, a higher throughput necessitates higher utilization rates of the x assets), the results of our throughput model provide a proxy for asset utilization.

There are two main factors that restrict capacity in rail networks: mainline rail capacity and rail classification yard capacity. Some mainlines are single track, meaning that two trains moving in different directions both have to travel over the same rail track to get to their respective destinations. In single track operation, the width of the train speed distribution increases with traffic density due to the increased likelihood of crossing paths with another train. A rail line that is double tracked allows trains to travel uninhibited by trains moving in the

opposite direction. The speed distribution for double track lines should remain narrow as trains do not need to stop as frequently. The rail network capacity model presented below assumes double track configurations.

Train movements on sections of the railroad network are controlled by rail classification yards. As discussed previously, classification yards allow railroads to consolidate railcars, travelling in similar directions, in order to transport more railcars per train and reduce costs. The model assumes that classification yards along the rail network are large enough to both maintain optimal mainline flow, by holding back trains, while also completing their necessary functions such as sorting, re-fueling, and inspections. However, the model does capture queue spillbacks upstream from the classification yards.

It is possible to model network capacity using either the mainline or the classification yard as the bottleneck. Because we assume a double track configuration, our model treats the classification yard as the network bottleneck. Moreover, previous research[22] suggests that classification yards are the major source of delays in rail networks.

The classification yard 'hump' acts as the server in the queuing model presented in this section. The classification yards are modeled using a simple queue-based simulation, where the rate of sorting, fueling, and inspections is fixed. Conversely, the input (i.e. arrival rate of trains) to the classification yard depends on the total demand for grain rail transportation, the percentage of that demand served by shuttle trains and conventional service, and also non-grain railcar demand.

Unlike the time model and engineering cost model presented in Sections 3 and 4, respectively, the capacity model excludes the trucking and elevator storage components of the grain supply chain. Trucking capacity is nearly unlimited because grain trucks travel on the road network, which is relatively uncongested in most parts of the Upper Midwest. While trucking companies do face driver shortages, this issue can be overcome without capital investments. Elevator storage capacity is excluded because land and storage capacity is cheap in the Upper Midwest. There is currently a significant amount of long and short term storage capacity and if the need for more storage presented itself, the cost to increase capacity would be relatively small compared with increasing capacity via capital investments in the rail network. Bunge[23] implies that rail network congestion is disproportionately impacting grain throughput in many parts of the United States.

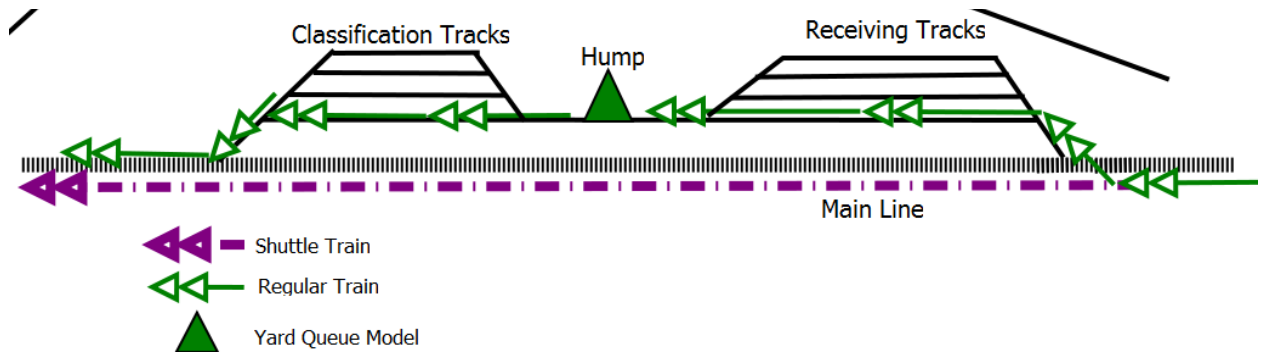## 5.1. Conceptual Model and Input Parameters

Figure 12: Classification yard queuing model used to analyze network capacity

Figure 12 displays a physical representation of the classification yard queuing model. Conventional grain trains and non-grain trains enter the classification yards. From the conventional trains, each individual railcar is processed and passes over the hump before being attached to a departing train. As long as the queue does not exceed the capacity of the receiving tracks at the classification yard, grain and non-grain shuttle trains simply bypass the classification yard without stopping.

The following assumptions and parameter values are used in the queueing model:

- Service Rate (μ) = 3.0 railcars per minute = 4,320 railcars per day
- The capacity of the receiving tracks upstream of the hump in the queuing model is 5,000 railcars.
    - Existing classification yards range widely in terms of receiving track capacity
- The model only includes one classification yard. This classification yard theoretically represents the most congested classification yard between the Upper Midwest and the PNW.
- The arrival rate of trains, λ, is based on a Poisson process
    - $\lambda = f(demand, \%shuttle)$
- The simulation is run for approximately 3 days. The length of the simulation only effects the potential for queue spillback.

Additionally, whereas, the time and cost models examine the geographical area around one terminal elevator (500 - 5,000 tons per day), the capacity model examines a much broader geographical area (e.g. Western North Dakota). Once again, because demand for grain rail transportation varies considerably depending on a number of exogenous factors, we vary the demand rate in the analysis between 1 and 30 shuttle train equivalents (110 railcars) per day. We also vary the percentage of grain demand served by shuttle between 0% and 75% in increments of 25%.

Because railcars carrying grain make up only a portion of the traffic on the rail transportation network, we assume a fixed level of background traffic. The model assumes 50 shuttle train

equivalents per day of non-grain rail transport. We initially assume that 25% of the non-grain demand is served by shuttle service. We also present results assuming that 35% of the non-grain demand is served by shuttle service. All of the conventional background railcars and grain railcars travel through a single classification yard.

5.2. Rail Network Capacity Model Results

The queueing model presented in the previous section is simple yet realistic for the purpose of this analysis. A more elaborate bulk (batch) queueing model of classification yard operations with multiple commodities and destinations (e.g. Mahmassani et al. analysis[24]) may also be used. However, the simplified model presented in this section provides the necessary level of detail to illustrate the effects of shifting demand to shuttle train service. Both the input and the output (displayed in Figure 13) of the model are easy to interpret. The input represents the total number of railcars (conventional and shuttle, grain and background) attempting to pass through, or by, the classification yard. In Figure 13, the demand for grain transportation varies (along the x-axis); the demand for non-grain transportation remains constant. The output represents the total number of railcars that are actually able to pass through, or by, the classification yard.

Figure 13 displays the advantages of shuttle service over conventional service in terms of network capacity and throughput. The graph on the left-hand side of Figure 13 assumes that 25% of background traffic is served by shuttle service. The graph on the right-hand side assumes 35% of background traffic is served by shuttle service. As demand for grain rail transportation increases, the throughput of the network is constrained by the amount of demand served by conventional service; the more grain that is served by shuttle service, the higher the potential throughput. The left-hand graph of throughput as a function of demand in Figure 13 shows that after a certain demand breakpoint (~5,600 railcars per day) conventional service (red line – '0% shuttle') is no longer able to increase throughput. In contrast, if demand is served by 50% conventional service and 50% shuttle service (green line), throughput is only partially constrained at approximately 6,100 railcars per day. At demand levels higher than 6,100 railcars per day, the 50% of grain demand served by conventional service, along with conventional background railcars, exceed the capacity of the classification yard; however, the 50% of grain served by shuttle service is still able to bypass the classification yard. Hence, throughput still increases with demand for rail transport.

Looking at Figure 13, the 0% grain shuttle and 25% grain shuttle lines have two distinct breakpoints; whereas, the 50% and 75% grain shuttle lines have one distinct breakpoint. The first breakpoint for each of the four levels simply represents the point at which the classification yard throughput is maximized (i.e. even as the rate of railcars entering the classification yard increases, the rate of railcars exiting the classification yard cannot increase). For the 0% case, all of the grain railcars need to pass through the classification yard; therefore, as demand increases past 5,600 railcars per day, throughput is capped at 5,600 railcars per day. The second

breakpoint, for the 0% and 25% cases, represents the demand rate at which the receiving tracks overflow onto the mainline. Receiving tracks overflow onto the mainline restricts the flow of the mainline, including shuttle trains. In the 0% case, the spillback prevents the non-grain shuttle trains from bypassing the classification yard. This is why the throughput decreases with more demand.

The model currently assumes unlimited mainline capacity downstream of the classification yard. A more realistic network model would include mainline capacity restrictions – limiting the throughput of shuttle train service. However, this limitation does not take away from the main result illustrated by the queueing model: shuttle train service provides significant capacity advantages compared with conventional service when demand is high. Including a mainline capacity restriction would only cap the potential advantage of switching railcars from conventional service to shuttle service.
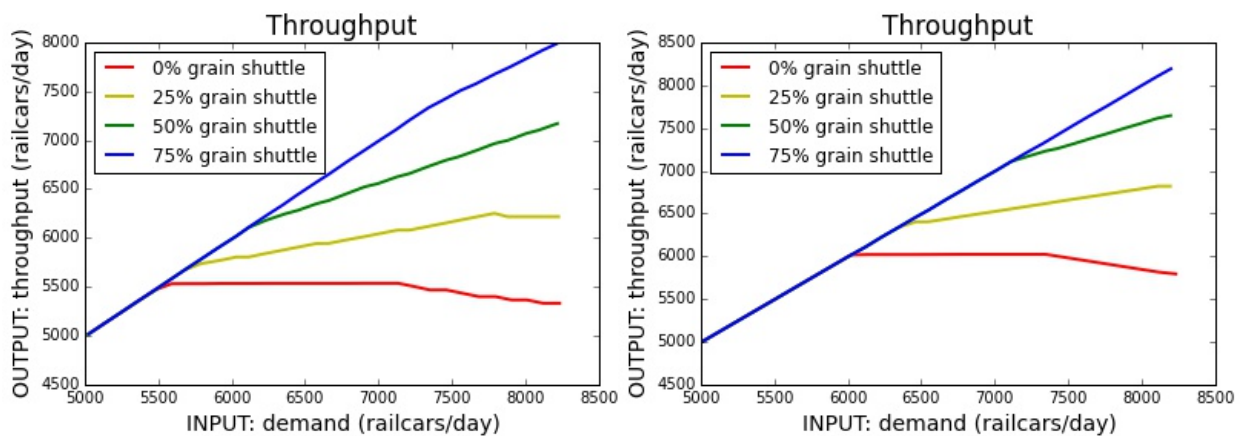

Figure 13: Rail Network Capacity Model Results. In the figure on the left (right), 25% (35%) of the background traffic is served via shuttle train service.

Increased network capacity and throughput benefits railroads, elevator operators, and farmers. Higher throughput, by definition, means more railcars travelling over the rail network. The more railcars moving through the network the more revenue opportunities for railroads. Elevator operators typically buy and sell grain at small margins; therefore, increased throughput implies a potential for increased revenues and profits. Moreover, increased throughput on the rail network allows farmers to sell more of their grain when market prices are attractive. Lastly, not only do large-volume shuttle train shippers benefit from the network capacity improvements associated with switching railcars to shuttle service, small-volume conventional service shippers of grain and other commodities also benefit from the reduced classification yard and mainline congestion.

6. Conclusions and Future Extensions and Capabilities of the Capacity Model

This paper presents three models of grain rail transportation service, introduced to compare shuttle and conventional rail service. The first model measures the time it takes to move grain from farm to export elevator. For shippers, travel time is an important consideration when choosing modes; hence, as service providers, railroads are also interested in reducing travel time. The second model determines the aggregate variable cost of moving grain from the farm to an export elevator. The third model determines rail network capacity as a function of the demand for rail service and the percentage of railcars that are travelling via shuttle service and conventional service. Together, the three models allow for a comprehensive comparison of grain rail transportation by service type. The results of each model presented in this paper show that shuttle train service offers meaningful advantages relative to conventional service under most realistic demand scenarios. The more freight that railroads can switch from conventional service to shuttle service the greater the overall operational and economic benefits. The research team believes that the key benefit of shuttle train service over conventional service is the increased network capacity that shuttle service provides.

Traveling in a single block from origin to destination reduces transit times by eliminating intermediate stops and their associated delays. Additionally, under shuttle service, rail assets are 'turned around' faster to maintain higher service rates and deliver greater capacity. Shuttle train service allows rail companies to increase capacity without having to invest in infrastructure. Increasing capacity has major implications not just for rail companies but also for grain producers and elevator operators. Increased rail network capacity allows farmers and elevators to sell and move more of their product when prices are at attractive levels. The need for higher capacity on the rail network in the Upper Midwest has increased in recent years as a direct result of increased demand for rail transportation from both grain and other commodities – the 'other commodities' mainly being oil and coal.

The three models in this paper are built on flexible frameworks that may be scaled up in terms of scope and/or complexity. Including additional variable costs and time components to the first two models is relatively straightforward. Similarly, in the capacity model, the classification yard service and/or arrival rates may be readily adjusted. However, while the capacity model effectively illustrates the benefits of shuttle service over conventional service, added complexity would allow end-users to compare different operational scenarios more effectively and completely. Future extensions and capabilities of the capacity model include:

- A non-uniform demand rate: The model in this paper assumes demand is uniform and constant over time. This assumption is likely unrealistic given the cyclicality of grain production and fluctuations in grain prices. Although farmers and elevators increased their storage capacities in recent years to handle increased price volatility in the market, demand for rail transportation still varies with yield seasonality.

- Capacity restrictions on tracks: In addition to the classification yard capacity restriction, the model could also handle track capacity restrictions that occur on track segments between yards.
- Resiliency: Incorporating a non-uniform demand distribution would allow us to measure: how demand peaks affect queue length and how long it takes to reach full throughput after demand normalizes again. It would be especially interesting to model and analyze the effects of system disruptions (e.g. bad weather events, track maintenance, labor shortages, etc.) when the system is operating close to maximum capacity.
- Reliability: With the additional capabilities and model relaxations suggested above, the model could measure the reliability of conventional and shuttle services. The model could produce transit time distributions under various scenarios. This could help operators and managers better understand what factors affect the predictability of the rail service. In addition, we could also study the effects of a more uniform grain demand distribution on rail service reliability.

[1] Keaton, M. Service-Cost Tradeoffs for Carload Freight Traffic in the US Rail Industry. *Transportation Research Part A: General,* Vol. 25, No. 6, 1991, pp. 363-374.

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