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Large Square Bale Biomass Transportation Analysis

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Abstract
Transportation logistics are a critical factor in the optimization of biomass supply chains. A single 25 million gallon per year cellulosic ethanol biorefinery will require 18,500 semi loads of bales to be delivered to the plant. For a typical corn stover biomass supply chain, baled corn stover must be transported in two phases. The first phase is from the field to a storage site while the second is from the storage site to the biorefinery. All activities in-between these two points are connected and together they form the biomass supply chain. The goal of supply chain optimization is to minimize the total cost of these activities (transportation cost per unit, inventory cost per unit etc.) while satisfying the supply demands of a biorefinery. This paper will report on a recent analysis of production scale biomass transportation. Intensive GIS tracking and videocapture of the loading, securement, hauling, and unloading events of industrially produced large square bales of corn stover were collected and results were summarized. Specific results including; metrics for measuring supply chain efficiency, current capability of biomass supply chains, and sensitivity analysis to improvements in future supply chains will be presented. The outcomes of this work will help in forming more efficient biofuel production process and improve biofuel life cycle as well.

Keywords
Transportation, Corn Stover, Supply Chain, Logistics, Cycle Time, Efficiency, Biomass

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Large Square Bale Biomass Transportation Analysis

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Abstract.

Transportation logistics are a critical factor in the optimization of biomass supply chains. A single 25 million gallon per year cellulosic ethanol biorefinery will require 18,500 semi loads of bales to be delivered to the plant. For a typical corn stover biomass supply chain, baled corn stover must be transported in two phases. The first phase is from the field to a storage site while the second is from the storage site to the biorefinery. All activities in-between these two points are connected and together they form the biomass supply chain. The goal of supply chain optimization is to minimize the total cost of these activities (transportation cost per unit, inventory cost per unit etc.) while satisfying the supply demands of a biorefinery. This paper will report on a recent analysis of production scale biomass transportation. Intensive GIS tracking and videocapture of the loading, securement, hauling, and unloading events of industrially produced large square bales of corn stover were collected and results were summarized. Specific results including; metrics for measuring supply chain efficiency, current capability of biomass supply chains, and sensitivity analysis to improvements in future supply chains will be presented. The outcomes of this work will help in forming more efficient biofuel production process and improve biofuel life cycle as well.

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Introduction

Because of its positive influence on environment, economy and society production of bioenergy is a main focus of researchers in United States [United States Department of Energy, 2006]. Transportation logistics are one of such factors that can provide successful and efficient recovering of energy from biomass [Searcy et al. 2007]. Optimal biomass energy production is directly connected with optimal transportation and supply chain parameters. The loading point in a corn stover supply chain is always located in the corn field while the unloading point is located either at a satellite storage facility or the central biorefinery [Sokhansanj et al 2006]. All activities in-between these two points are connected and together they form the biomass supply chain. One biomass supply chain normally includes several hundred corn fields within a system. A single 25 million gallon per year cellulosic ethanol biorefinery will require 18,500 semi loads of corn stover bales to be delivered to the plant [Darr et al. 2012] which is indicator of large transportation savings potential. Especially if we take in consideration, that transportation is followed by several energy and time-consuming activates such as loading and unloading, stacking and securing [Hess et al 2007].

Finely adjusted supply chain parameters are an essential part of efficient exploitation of corn stover. Especially if we take in consideration that loading transporting and unloading process can achieve more than 13% of overall delivery costs [Sokhansanj and Turhollow 2004].

In this paper, we are introducing relations between transportation team optimization, trucking productivity, bale handling equipment efficiency, location of storage sites and transportation time window. As one of the most important parameters we introduce optimal number of road vehicles and loading/unloading machines, considering biomass bales as a basic transportation unit [Darr et al. 2012]. The aim of this paper is to more descriptively present key factors that affect transportation efficiency and cycle time optimization. According to that, transportation system optimization was divided into several optimization categories:

1) *Optimal number of loading/unloading units and road vehicles*.

By successfully adjusting the optimization of these physical resources idle operation of either transportation vehicle or loading/unloading machine, can be decreased to a reasonable level.

2) *Storing and securing time optimization, using satellite storages rather than single central storage.* This type of organization allows shorter time window for transportation since transportation network is divided into several subsystems.

3) *Optimal transportation team that will yield the highest possible equipment utilization and the shortest transportation time window.* Transportation team is defined as number of semi-trailers and loaders/unloaders that operate within certain radius. Optimization goals are to reduce the total number and cost of transportation resources.

Therefore, the cycle time optimization can be achieved by soliciting needs of all three optimization categories from above. Methods to collect important data and make correct decisions will be presented in this paper.

In order to correctly estimate influence of the factors, several methods such as GPS vehicle tracking, GIS data processing, supply chain computer modeling and video capture of the loading and unloading activities were employed.

Methodology

Making appropriate decisions inside of the system requires accurate information on system parameters. GPS tracking, GIS data processing and system modeling were conducted in order to collect this important information. Credibility of the model is directly connected with reliability of the model inputs. Therefore model inputs such as vehicle speed distribution on different road surface types, typical transportation distance distribution, loading and unloading times were collected from the realistic biomass supply chain. The supply chain operated in central Iowa during the fall of 2011.

Biomass Handling Systems

During corn stover transportation two types of bale handling systems were used (Figures 1 and 2):

- Squeeze Loader (loading capacity 6 bales per cycle)
- Telehandler (loading capacity 3 bales per cycle)

Those two systems has different loading capacities per hour. While the squeeze loader can handle six bales in a single cycle, a telehandler typically obtains lower values of turnaround time (cycle time). According to experimental observations squeeze loader system has higher loading productivity (typically around 30% higher).

Figure 1. John Deere Payload with Six-Bale Squeeze Loader Attachment

Figure 2. Three-Bale Telehandler

Bale Hauling Systems

Bale hauling was conducted using two sytems:

1. Truck Tractor / 53 ft semi-trailer combination (flatbed trailers)
2. Hauserbuilt Truck

Semi-trailer capacity was 36 bales per load using flatbed trailers. This system is adequate for long distances because of its high productivity rate. Transportation of biomass must meet state guidelines for vehicle weight. The restriction for Gross Vehicle Weight (GVW) on primary highways (i.e. state highways, federal highways, and interstate highways) consider weight limit of 80,000 lbs. Typically, the average Truck Tractor or Flatbed combination will weight approximately 30,000 lbs. Load weight for 36 bale trailers can vary depending on moisture content, but in most cases is below 50,000 lb for 36 bales, which comply with the weight limitation.

On flatbed trailers or trailers without sides cargo must be secured using tiedown or ratchet straps. The straps used must be of the proper strength. The combined strength of the all the straps must be equal to one and a half times that of the load. In case of securing a load of bales that weighs 50,000 lbs. straps must be rated at 75,000 lbs. of breaking strength. More advanced and automated load securement can be achieved with Automatic Load Securement System (ALSS) that will be explained in more details later.

Hauserbuilt system does not include loading and offloading equipment since this system is self-loading/unloading. The vehicle weight is 5850 lbs. and GVW is approximately 26,000 lbs. with hauling capacity of 12 bales per load. Securement is automated and does not include manual strapping.

Image 3. Bale Hauling equipment (Hauserbuilt truck on the left, flatbed semi on the right) *Source: www.houserbuilt.com*

Road Vehicle Parameters and GIS Analysis

GIS methods can be successfully employed in order to evaluate time, distance and transport costs involved in the road transportation of biomass [Perpina et al 2009] To properly represent road vehicle in the model, two basic parameters were determined: vehicle speed distribution and travel distance distribution. This was relevant information related to truck team optimization and trucking productivity that was one of the major goals of this project. The data set was formed using GPS receiver connected to a CAN (controller area network) data logger with a memory card. Described equipment collected important spatial information: vehicle position, vehicle speed and UTC time stamp that were crucial in distinguishing different vehicle activates.

To properly process the data Ag Leader SMS 11.50 software that works on GIS platform was utilized. Once raw data from the data logger was loaded into Ag Leader SMS 11.50 it was easy to create spatial map comprised of several transportation cycles. Each transportation cycle was presented as a consecutive data point array (figure 4.) where each data point contains attributes such as vehicle position, vehicle speed and UTC time stamp. The data set allowed reconstructing vehicle activities during the working hours and collecting information described above.

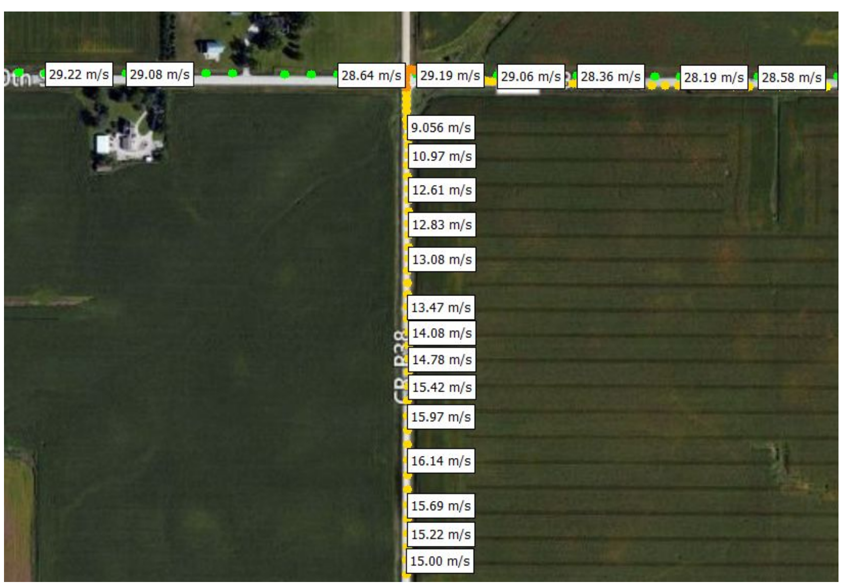


Figure 4. Ag Leader SMS 11.50 Spatial Map Detail

As a result of GIS data processing three data types were obtained:

1) Transportation distance distribution for various road surfaces (gravel, pavement, and highway)

2) Biomass transportation speed distribution for various road surfaces (gravel, pavement, highway)

3) Road Winding Factor

Loading/Unloading Process Parameters

The loading/unloading dataset was obtained using on-field video captures. Several dedicated cameras were positioned on the loading/unloading points of the supply chain. After processing video captures in video editing software it was easy to determine following data types:

1) Loading/ unloading time distribution

   To obtain relevant data on loading process from video captures this operation was observed in cycles. Each cycle consisted several operations such as: bale pick up and lift, full loader travel, bale drop and empty loader travel. Time duration of the loader turnaround for each loading cycle was measured and implemented into the model.

2) Securing the load- strapping time distribution

   Strapping process typically starts after first bale is loaded. From that point truck operator works on strapping until all bales are completely secured. In some cases strapping procedure duration can exceed loading procedure so truck is additionally delayed. Strapping procedure was observed along with loading procedure and loading+strapping time was implemented in the model to represent true delay of the truck.

3) Vehicle dwelling (unproductive work) time distribution

   Vehicle dwelling distribution was obtained from the surveillance captures. Basically queuing time of trucks was measured and summarized.

Same data types were obtained for two different loading/unloading systems(Figure 5):

1) Classic Strapping System

2) Hydraulic ALSS (Automatic Loading Strapping System)

This allowed two different load securing systems to be compared in terms of time efficiency.

Figure 5. Classic and Hydraulic ALSS Bale Strapping Systems

Supply Chain Modeling Method

In order to make proper assessment of the supply chain system performance ExtendSim 8 was used for discrete modeling task. The supply chain model was a representation of realistic biomass transportation cycle between a single corn field and biomass storage. The transportation cycle model was consisted of several components that simulate real activities during transportation (Figure 6). By modeling realistic transportation cycle activities it is possible to estimate impact of key factors (number of trucks, number of loaders, gravel and paved road segment length etc.) on overall performance of the system which was main tool in making final conclusions and recommendations. Model inputs were inserted as distributions with standard deviation and mean values since almost all collected data sets demonstrated normal distribution. In this paper model of a single transportation cycle will be described

Components of the Single Transportation Cycle Model

As outlined before, all datasets from the video captures and GIS maps were used in order to adjust model in the most realistic fashion. Following parameters were inserted:

- Number of truck inside of the system
- Loading/unloading time
- Gravel, pavement and highway travel distance
- Gravel, pavement and highway average speed for full vehicle
- Gravel, pavement and highway average speed for empty vehicle
- Random delay (due to unpredicted events)

It is important to note that randomly distributed truck travel time was derived from the speed and distance distribution using appropriate equation, where inputs are normally distributed and randomly generated (figure 6).

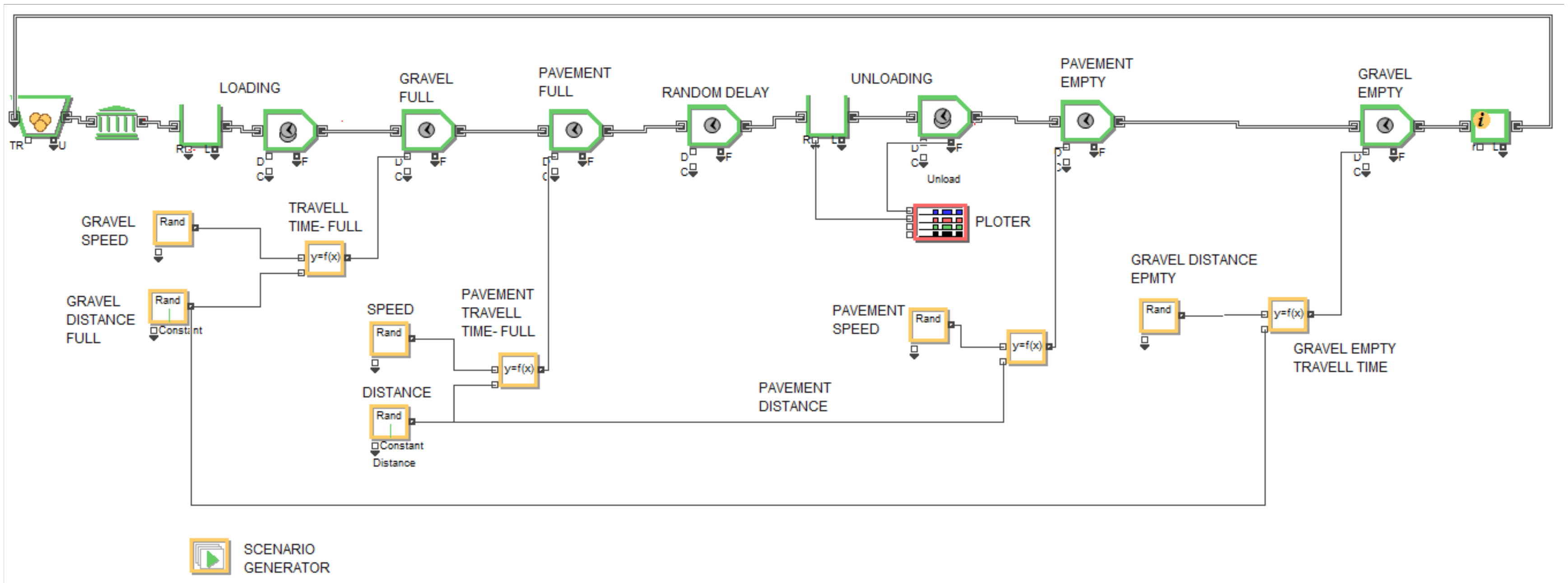
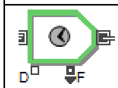
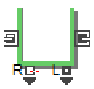
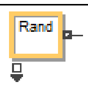
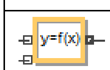
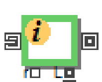


Figure 6 ExtendSim Model of a Single Transportation Cycle

ExtendSim model components are presented as follows:

	Model Component Name	Description
	Resource component	Generates initial number of items that are representation of biomass transportation vehicles. Once items are generated they stay in the system until the end of modeling scenario.
	Process component	Represent activities such as truck travelling on various road surfaces. Input denoted as D receives values from the formula component made to calculate travel time for given speed and distance distribution. Item that is representation of truck in the model, will be delayed for the travel time inputted on connector D.
	Queue component	Simulates queuing behavior of trucks. Queuing follows first in, first out sort method and it is directly connected with loading activity. In the moment when loader becomes available, the item leaves queue component and starts being processed by the loading component.
	Random number component	Generates random numbers according to data distribution that is inserted. Almost all data distribution included in corn stover supply chain modeling had normal distribution shape and were presented using average value and standard deviation.
	Equation component	Calculates an equation and outputs the results that are inputs for the next component in the loop. For instance, travel time is calculated using following formula: Delay_min = Distance*60/Speed; where distance is variable introduced as distribution and takes different values in different moments.
	Information component	Keeps record about item arrival time and helps determining overall processing duration for each vehicle in the system.
	Scenario manager	Component that configures and runs multiple simulation model scenarios.

ExtendSim Scenario Manager Tool

Including scenario manager in the modeling allows creating multiple simulations with different model factors that affect final model responses. By using this component it is possible to make assessment of various treatment factors and treatment levels on the system productivity measured in number of loads or tons per hour delivered. In this paper several treatment factors were examined:

1) Number of trucks in the system

2) Number of loaders in the system

3) Number of unloaders in the system

4) Gravel distance length

5) Paved distance length

By including those factors in the model we allow scenario manager to control components and provide full factorial of inputs in order to examine every combination of input factors.

Using this tool it is also possible to choose several factor properties such as:

1) Minimum and maximum value of the factor
2) Step associated in creating combination (i.e step =2 will generate 2,4,6 trucks in three different scenarios)

In the sample of model iterations presented below alteration of pavement distance is visible. However there were more than 6 iterations for this specific model in which rest of factors will be altered in the same manner. More details about scenario manager setup will be provided in the results section.

Scenario name	Trucks	Loaders	Unloaders	Gravel	Pavement	Total Loads/10Hr
Scenario 0001	1	1	1	1	1	28.4
Scenario 0002	1	1	1	1	3	28.2
Scenario 0003	1	1	1	1	5	28.7
Scenario 0004	1	1	1	1	7	28.5
Scenario 0005	1	1	1	1	9	28.4
Scenario 0006	1	1	1	1	11	29.2

As response number of truck loads delivered in 10 hour working period was selected. Using this dataset it was easy to derive number of truck loads per hour and number of loads/hour/truck for each possible scenario of the model. Entire model was replicated ten times per iteration. This yielded certain variability within the response since every input can take different value for the same scenario depending on data distribution characteristics.

Results

Using described methods, several data categories were obtained:

Road Winding Factor

The winding factor is a coefficient used in order to estimate real travel distance using vector distance between two points on the road network. It is basically overall road mileage between two spots divided by vector distance between them. Using GIS data that included GPS tracking of semi-trucks during corn stover transportation, winding factor distribution was obtained (Figure 7.) By using winding factor we include more accurate values for travel distances in case when we observe the distance in vector format.

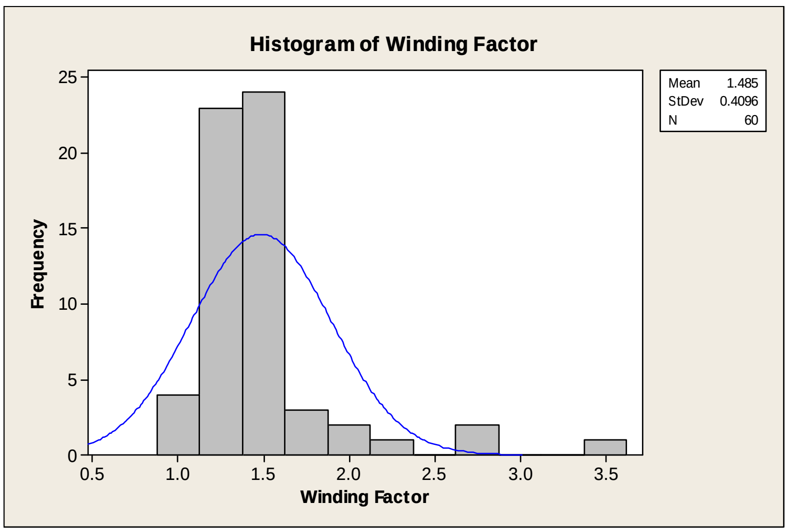


Figure 7. Road Winding Factor Distribution

The average winding factor for this production data set was 1.48, based on 60 different transportation cycles. Mean values for transportation parameters can be considered as a representative values for Story County, IA road network since those values were obtained by observation of the real biomass transportation conditions. Using data distribution implemented in the model makes model output values closer to the real conditions on the field. Speed and distance values may deviate only in unpredicted circumstances (severe weather conditions, long truck detours or traffic flow congestions). Having such abrupt changes in the transportation conditions would normally require additional over the road data analysis and model update.

Winding factors that were calculated to be greater than 2.0 where generally associated with a truck driver becoming lost or following a very inefficient path to the satellite storage facility. This is a real response during industrial scale biomass harvesting and should be considered as part of an accurate supply chain model.

Performance of Classic and Automatic Load Securement System (ALSS)

Classic load securing operation typically comprises of the following activities:

1) Placing strapping belt over the load

2) Attaching and preparing the belt for tensioning

3) Belt tensioning and checking

All activities from above yield significant truck delay, typically around 15 minutes.

The ALSS is automatic system with hydraulic elements for belt tensioning that eliminates classic strapping activates (belt placement, attachment and manual tensioning). By using ALSS significant time savings can be achieved since average truck delay approximately decreases from 16 to 12 minutes. The magnitude of overall time savings will be achieved depends on overall transportation quantity. Since overall loading time is comprised of loading and strapping this time is typically longer than strapping itself. Main reason for this is strapping latency. The latency is present because strapping usually starts after first bale is placed on the trailer, which can take several minutes.

When considering loading and strapping as simultaneous operations, the ALSS trailer provides a 4 minute per cycle savings. Although this saving is significant, much greater time efficiencies are generated if loading and strapping are not allowed to operation simultaneously. This would typically be the case for industrially managed biomass which follows strict safety requirements around truck loading and securement. In this case, both strapping systems will require 12 minutes to load the truck, but the classic manual strapping system will require another 15 minutes to secure the load. Under this scenario, the 15 minute per truck savings is very significant when applied across an industrial supply chain.

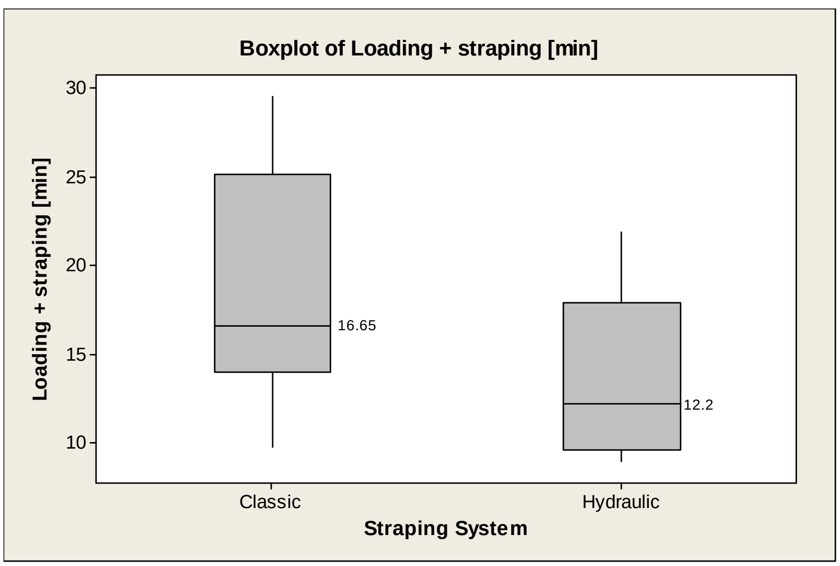


Figure 8. Advantages of the Automatic Load Securement System

In addition to time savings, using ALSS can improve overall safety. When using classic strapping system, truck operators spend significant amount of time on the road exposed to possible car accident that is arising from bypassing vehicles. In addition to reduced traffic risk, ALSS can reduce liability from employee injury and lower insurance costs due to lower employee risk. For more detailed information about advantages of the ALSS, a simple benefit–cost analysis can be employed. This analysis should take in consideration injury and fatal accident possibility rates, costs per single fatal or injury accident and ALSS equipment cost [Sinha et al 2007].

Corn Stover Supply Chain Model Outputs

ExtendSim Scenario Manager Tool gives opportunity to alter selected inputs in terms of quantity, speed and time. By changing input parameters it is possible to estimate their influence on the model outputs such as, truck productivity in bales/hour, or vehicle utilization in bales/hour/truck.

Truck Productivity and Team Optimization

Hauserbuilt System provides advantage of self-loading/unloading operation with no loader/unloader involved. The Hauserbuilt system modeling was conducted taking in consideration truck speed and distance distribution as well as loading/unloading time distribution. Speed probability distribution was obtained using GPS tracking and recording, while loading/unloading time distribution was determined by observation on the field.

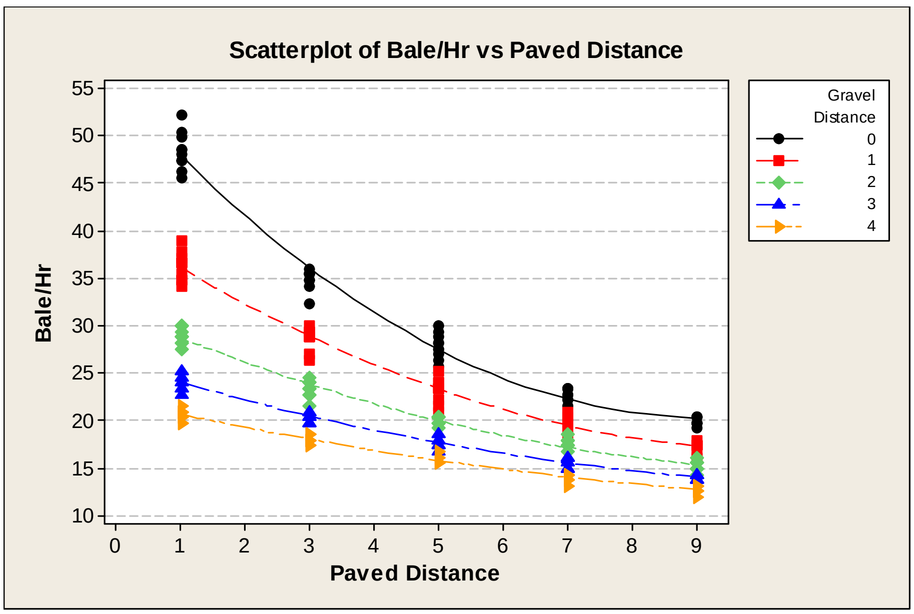


Figure 9. Hauserbuilt Truck Productivity

The Hauserbuilt productivity result was based on a load factor equal to 1 (12 bales per load). For an average road travel of 5 paved miles with a 1 mile gravel field entrance, the Hauserbuilt system is likely to retrieve and stack 23 bales per hour. However Hausebuilt productivity will decrease by increasing gravel distance (see Figure 9). This scatterplot is result of ExtendSim Scenario manager with gravel distance as a treatment factor and productivity as a system response.

Semi-Trailer (Flatbed) System

This system was modeled taking in consideration scenarios and system setup presented in Table 3. Each simulation case included ten modeling iterations. Hence, each scenario outcome is an average outcome of ten modeling iterations.

Table 3. Semi Truck Modeling Factors

Factor	Type	Levels	Values
Nr.Of Trucks	fixed	6	1,3,5,7,9,11
Nr. Of Loaders	fixed	2	1,2
Nr. Of Unloaders	fixed	2	1,2
Gravel Distance	fixed	2	1,3
Paved Distance	fixed	6	1,4,7,10,13,16
Mean/Median Loading Time	fixed	3	6,12,18
Mean/Median Unloading Time	fixed	3	3, 7.5,12

Effect of Distance on Model Output

Altering road distance and number of trucks within a system can yield different values for the system productivity (bales/hour). Modeling result is presented on the scatterplots below (Figures 10 and 11).

It is important to notice that system performance is presented as a number of bales/hour/truck (direct indicator of truck utilization) and as a number of bales/hour (overall system performance, figure 11). For the paved distances less than 16 miles one truck in the system provides optimal truck utilization, but overall system performance is significantly lower than 3,5,7,9,and 11 truck scenario (see Figure 10).

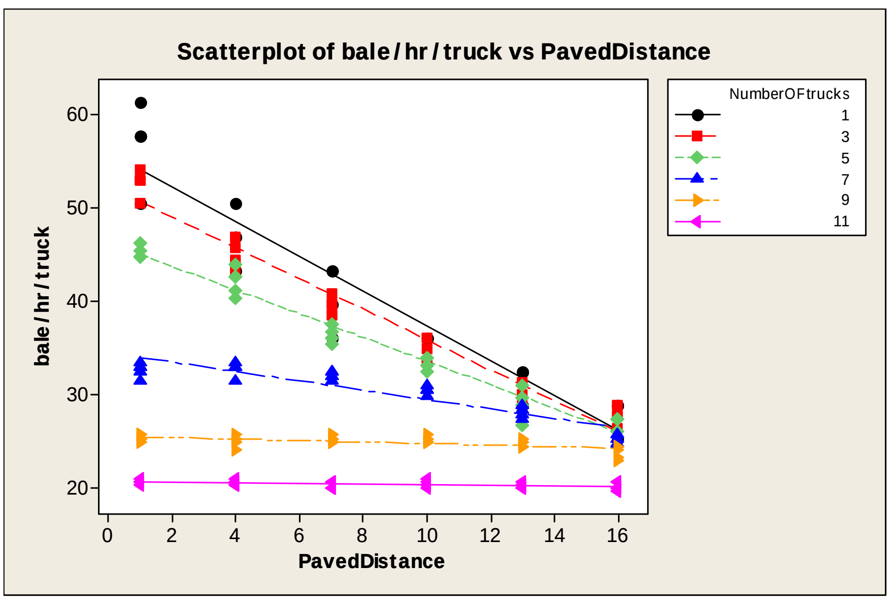


Figure 10. Effect of Distance and Number of Trucks

From the Figure 11 it is obvious that using 11 truck scenario is the most effective in terms of overall system performance (bales/hour) for all travel distance values. However, overall system performance in bales/hour is not the only indicator that has to be considered. Truck utilization in bales/hour/truck is another important factor that needs to be included, when it comes to truck efficiency comparison. In cases when we have 9 and 11 trucks in the system a flat response of overall system productivity to distance will be achieved (Figure 11). This is mainly due to increased system hauling capacity that is not adequately utilized. For distances less than 5 miles seven, nine and eleven trucks have almost similar productivity. In other words, we have more trucks than transportation demand requires, but some of those trucks are not properly utilized. In this case choosing seven trucks seems more reasonable. In case of too many trucks in the system, those trucks spend significant amount of time queuing at the loading/unloading points. To fix truck utilization we simply need to decrease number of truck in the system (Figure 10). By decreasing number of trucks we are decreasing overall capacity in bales/hour but on the other hand, we are increasing truck utilization Therefore, a tradeoff for those two situations should be achieved by using 7 trucks operational setup.

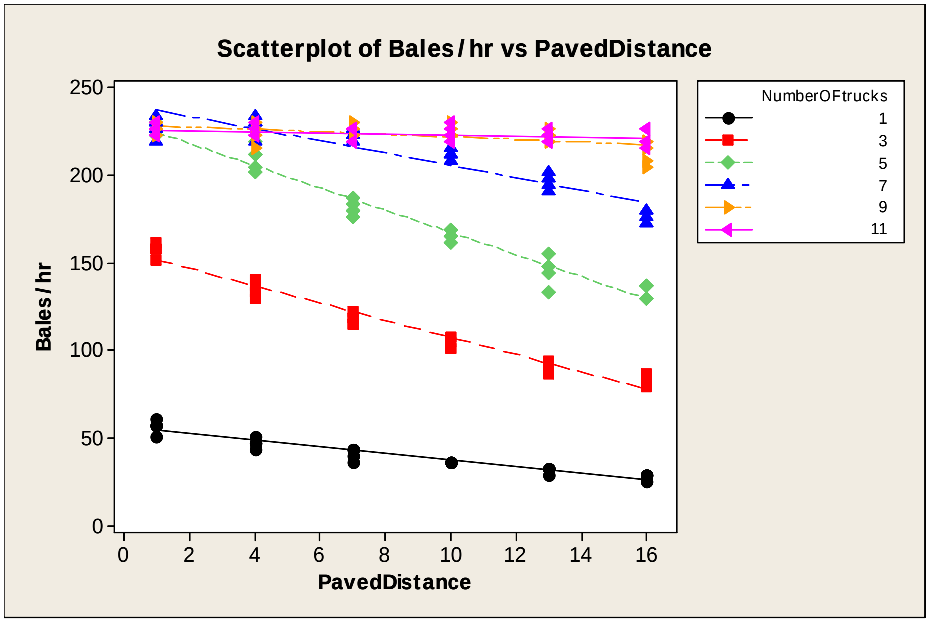


Figure 11. Overall System Productivity (bales/hr)

Effect of Number of Loaders on Model Output

Increased number of loaders inside of the system will result in decreased truck delay on the loading/unloading points and increased truck utilization. Increased number of loaders can have significant impact on truck utilization depending on number of trucks in the system. It can be inferred from Figure 12, that more trucks we have in the system, higher impact of the second loader we attain. For one truck in the system, adding second loader will produce insignificant change in truck utilization. On the other hand, in case of 11 trucks, utilization will rise nearly 65 %. From the aspect of total system performance in bales/hour, for one truck system, there is no change in overall performance after additional loader is employed. However, adding second loader in case of 3 and more truck scenario will result in significant system performance improvement. This is mainly due to elimination of truck dwelling time at the infield loading location. In these cases truck queuing time will be minimized or even totally eliminated for certain transportation cycles. In general, loading makes more influence on model outputs because loading time is significantly higher than unloading time. In some cases loading can be even 50% longer than unloading. Hence, its influence is 50% higher than influence of the unloading time. This increase in loading time is primarily driven by low quality field conditions at the point of loading in agricultural fields versus improved ground conditions at satellite storage facilities.

Adding a second loader has a positive influence on truck utilization. This is mainly due to loader idling in cases when no truck is present at the loading point or because truck is being loaded by second loader. In other words, by employing two loaders in the system, we improve truck utilization, but also we decrease loader utilization. In case of additional unloader, no significant improvement will be achieved.

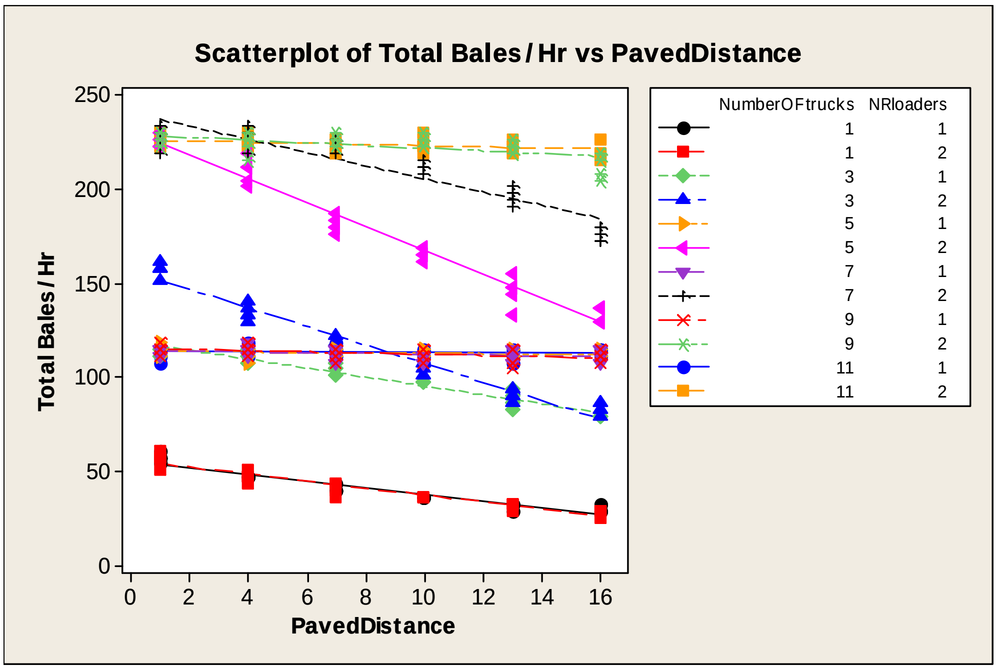


Figure 12. Impact of Number of Loaders on Productivity

Effect of Loading Time on Model Output

It can be inferred from Figure 13 that reduction of loading time results in higher truck utilization. This influence has higher magnitude as number of trucks increase inside of the system.

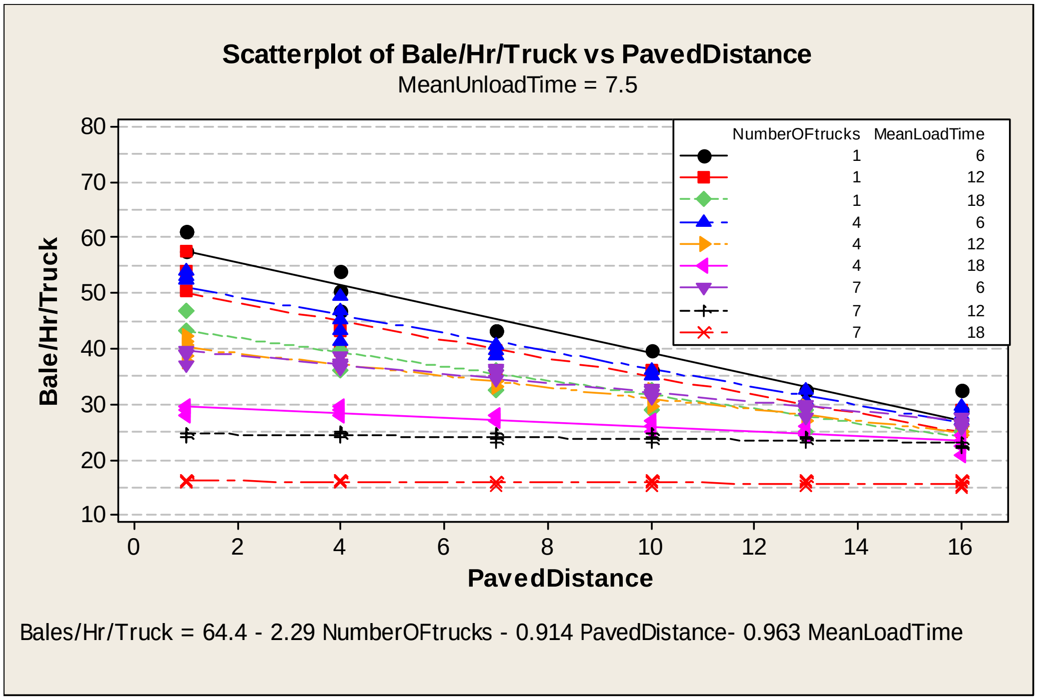


Figure 13. Influence of Loading/Unloading Time on Truck Utilization

Graph from the figure 13 has regression equation that can describe effect of distance, loading time, and number of trucks on truck utilization is presented below:

Bales/Hr/Truck = 64.4 - 2.29 NumberOFtrucks - 0.914 PavedDistance- 0.963 MeanLoadTime

Following standard error and R-squared values were obtained:

S = 38.6721 R-Sq = 80.6%

It can be inferred from the equation that truck utilization decreases with increasing number of trucks and loading time.

Similarly, total number of bales per hour increases as loading/unloading time declines (figure 12). On the other hand, influence of unloading time on system performance has lower magnitude compared with loading time influence. As outlined before, this is mainly due to nature of unloading process that takes less time than loading. This can generally result in lower unloader utilization but also higher unloader availability, which again reduced truck queuing on the unloading point of the supply chain.

Conclusion

1) Prioritize Hauserbuilt trailer based on:
    a. Small fields or low bale count stacks.
    b. Fields within 3 mile radius of storage sites.

Hauserbuilt system's overall productivity in bales/hour is highly sensitive on transportation distance. Productivity significantly decreases for distances longer than three miles due to low truck capacity.

2) Utilize semis for longer hauls. Max utilization with 2 loaders and four trucks within a storage radius.

Because of its higher transportation capacity, semi-trailer system productivity is less sensitive on travel distance compared to Hauserbuilt system.

Since effect of adding second loader has significant influence on truck utilization and overall system productivity it is reasonable to conclude that second loader will produce additional benefits and increase overall supply chain productivity.

3) Bale hauling progress should be closely monitored during the season. Any deviation from expected hauling response will require correction.

Productivity of the supply chain is key factor for transportation time window estimation. For corn stover feedstock transportation time window is limited due to weather conditions. Therefore, observing overall productivity should be employed in decision making.

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