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Truck versus pipeline transportation cost analysis of wastewater sludge

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ABSTRACT

Domestic and industrial sludge generated at wastewater treatment facilities is considered a potential biomass source for producing biodiesel. However, transportation of large amounts of sludge from wastewater treatment facilities to a biorefinery is expensive. The objective of this paper is to identify the proper transportation mode to use as a function of the volume shipped and transportation distances. Currently, sludge is mainly shipped by truck and pipeline. We estimated that the fixed and variable cost components of pipeline transportation for a volume such as 480 m^3/day and a distance of 100 miles are \$0.116/m^3 and \$0.089/m^3/mile, respectively. We estimated the biomass (sludge) transportation cost per gallon of biodiesel, and observed the changes in these costs as a function of distance traveled and volume shipped. The outcomes of this study have the potential to help biofuel plants make better biomass transportation decisions, and consequently reduce the price of biodiesel significantly.

1. Introduction

In recent years there has been an increasing interest in biofuels as a source of energy that has the potential to replace fossil fuels. For example, the production of biodiesel in the USA has increased from 75 million gallons in 2005 (National Biodiesel Board, 2007) to 678 million gallons in 2009 (US Energy Information Administration, 2009). This number is expected to increase to over 1 billion gallons per year (BGY) in the next few years (Kargbo, 2010). The increased interest in biofuels has been somewhat overshadowed by concerns related to the economics of transporting biomass and producing biofuels, as well as the national debate over food versus fuel. For example, the main feedstock sources for production of biodiesel are lipids extracted from soybean, canola, sunflower, palm and coconut oil. These feedstock sources are not only expensive for fuel production, as the cost of pure vegetable and seed oils constitute 70% to 85% of the overall biodiesel production cost (Haas and Foglia, 2005), but in addition, increased demand for these products impact their consumer price.

The biofuel research community has responded to these concerns by developing models that optimize the transportation (Kumar et al., 2003, 2004, 2005) and the overall performance of the supply chain for biofuels (Ribaudo et al., 2003; Ekşioğlu et al., 2011), as well as by identifying alternative sources of biomass feedstock (Foidl et al., 1996; Lee et al., 2002; Kulkarni and Dalai, 2002; Nelson and Schrock, 2006; Lu et al., 2009; Mondala et al., 2009). For example, several studies have already been conducted to identify alternative lipid feedstock for production of biodiesel, such as non-edible crops (i.e. *Jatropha*

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curcas (Foidl et al., 1996; Lu et al., 2009)); animal fats, such as lard (Lee et al., 2002) and beef tallow (Nelson and Schrock, 2006)); waste cooking oil (Kulkarni and Dalai, 2002); and municipal wastewater sludge (Dufreche et al., 2007; Mondala et al., 2009). Using municipal and industrial wastewater sludge is a very attractive option for a number of reasons. First, significant amounts of wastewater sludge are available in the USA. For example, municipal wastewater treatment (WWT) facilities in the US produce approximately 6.2 million dry metric tons of sludge annually. This amount is expected to increase in the near future due to the expected growth in urbanization and industrialization (Water Environment Federation, 2002). Note that, with the technology proposed by Mondala et al. (2009) it would be possible to produce 1.34 million tons of biodiesel annually in Mississippi using wastewater sludge (Marufuzzaman et al., 2014). The authors derived this number based on an analysis of the amount of wastewater generated by wastewater treatment facilities, pulp and paper plants, poultry slaughtering and processing plants, and fresh and frozen fish processing plants in Mississippi. Second, municipal sewage sludge contains significant concentration of lipids (Kargbo, 2010). The work by Mondala et al. (2009) indicates that the majority of the fatty acids from sludge fall in the range of C_{10} to C_{18} which favors the production of biodiesel. Finally, using municipal sewage sludge has the potential to solve some environmental issues associated with sludge treatment and disposal.

Let us consider the scenario in which industrial and municipal wastewater sludge is used to produce biodiesel. Under this scenario, sludge would be transported from WWT facilities to a biorefinery. The two major modes of transportation that can be used are truck and pipeline. Truck transportation is favored for low volume and short distances. Truck costs rapidly increase for large scale transportation of wastewater sludge. On the other hand, pipeline transportation is favored for large volumes and long travel distances. Achieving economies of scale by using pipelines for large scale transportation of liquids is not a new concept. Most crude oil is transported by pipeline.

In order to identify whether truck or pipeline should be used for transporting wastewater sludge, a biorefinery needs to research the different costs that occur when using either mode of transportation. It is also important to study how these costs change as a function of product type, amount shipped, and distance traveled. Similar studies have already been conducted for bio-oil (Pootakham and Kumar, 2010a,b), beef cattle manure (Ribaudo et al., 2003; Ghafoori and Flynn, 2006; Ghafoori et al., 2007), and other types of biomass (Kumar et al., 2003, 2004, 2005). Based on this literature, the variable and fixed transportation cost components depend on the type of product shipped. For example, design requirements for pipelines depend on the density, pH level, viscosity, and total solid (TS) content of the product shipped. The literature indicates that carbon steel and high density polyethylene (Menon, 2005; Badger and Fransham, 2006; Pootakham and Kumar, 2010a,b) are used to build pipelines for carrying bio-oil due to the low pH level (2.8) of this product. Carbon steel pipelines are also used for shipping crude oil. The use of these expensive materials impacts pipeline transportation costs. We note that wastewater sludge has a pH level of 7.0 ± 0.1 (Mondala et al., 2011); and therefore, low cost PVC pipe can be used. On the other hand, wastewater sludge is a highly viscous material, and therefore, has a higher friction factor. As a result, powerful pumps and more energy (as compared to less viscous materials) are required to move this material through a pipeline (Ghafoori and Flynn, 2006; Pootakham and Kumar, 2010a,b). These requirements increase capital and electricity costs.

Finally, pipeline transportation costs are impacted by design requirements and other decisions related to facility planning. For example, a company may decide to store the product for a few days in order to increase the volume shipped by pipeline. This could be the case for many wastewater treatment plants in Mississippi since these plants do not generate enough volume of wastewater on a daily basis. Therefore, it makes economical sense to store wastewater for a few days until enough deposits are accumulated. This practice ensures that pump transportation costs are optimized. Otherwise, costs would increase due to pressure loss and frictional loss. The amount necessary to optimize the use of the pump is a function of the pipeline capacity. This practiced does, however, increase inventory holding costs. A study by Badger and Fransham (2006) indicates that the investment costs for a three-day storage capacity of bio-oil using stainless steel tanks at a capacity of 9400 m^3 is \$2 million. Another study by Pootakham and Kumar (2010a,b) shows that storing bio-oil for a single day reduces these investment costs drastically.

To our knowledge, there exist no studies in the literature that explore the cost of shipping wastewater sludge. Table 1 summarizes the existing literature on transportation cost analysis. We have compared this current research with the

Table 1
Transportation cost analysis literature.

Research component	Current paper	Kumar et al. (2005)	Ghafoori et al. (2007)	Pootakham and Kumar (2010a,b)	Luk et al. (2014)
Product considered	Wastewater Sludge	Corn stover	Beef Cattle Manure	Bio-oil	Wheat straw slurry
Transportation modes used	Owned Truck, Rented Truck, Pipeline	Rented Truck, Pipeline	Rented Truck, Pipeline	Rented Truck, Pipeline	Pipeline
Models developed are product specific	Yes	Yes	Yes	Yes	Yes
Relationship between cost components established	Yes	Yes	Yes	Yes	No
Real world application	Yes	No	Yes	No	No

literature and found that the work presented in this paper is unique and makes a contribution to the literature by presenting a techno-economic assessment of pipeline and truck transportation of wastewater sludge. This research identifies the fixed and variable cost components associated with using pipeline and trucks to deliver wastewater sludge. We identify the following factors that impact wastewater sludge transportation costs: truck ownership, pipeline capacity, distance traveled, volume shipped, and the physical properties of the product (e.g., viscosity, density, etc.). This study identifies the optimum design slurry velocity which minimizes the variable transportation cost (in $/m^3/mile) for pipelines of different capacity.

The state of Mississippi is used as the testing grounds for this analysis. The knowledge created is used to identify the appropriate mode of transportation for a particular municipal WWT facility in Mississippi that plans to ship wastewater sludge to a biorefinery. We also estimate transportation costs per unit (gallon) of biodiesel produced using wastewater sludge.

2. Truck transportation costs

2.1. Properties of wastewater sludge

Table 2 presents a summary of the key parameters for activated sludge (with 20% solid content). The properties of enhanced activated sludge are provided by Hernandez et al. (2011). The wastewater used in their analyses is collected from a municipal WWT plant located in Tuscaloosa; AL. Other properties of raw activated sludge are provided by Tchobanoglous et al. (2003). The pH value of sludge as reported by Mondala et al. (2011) is 7.0 ± 0.1. We concentrate this analysis on enhanced activated sludge as it can further be treated to produce biocrude.

2.2. Methodology used for calculating unit transportation cost

This study analyses the unit transportation costs for two types of truck: single trailer truck with load capacity of 30 m^3 and tandem trailer truck with load capacity of 40 m^3. These two truck types are often used to transport liquid manure (Ghafoori et al., 2007). The major components of truck transportation costs are: the fixed cost ($/m^3) which is independent of distance traveled, and the variable distance-dependent cost ($/m^3/mile). We use Eq. (1) to calculate the total annual transportation costs, C_{tr} ($/m^3) (Pootakham and Kumar, 2010a,b; Ghafoori et al., 2007; Searcy et al., 2007).

$$C_{tr} = FC_{tr} + d_{tr} * VC_{tr} \tag{1}$$

where, FC_{tr}, d_{tr} and VC_{tr} represent the fixed transportation cost ($/m^3), the one-way trip distance (mile), and the variable transportation cost ($/m^3/mile), respectively.

This study estimates the costs of using rented and facility-owned trucks. Based on discussions with experts, a rented vehicle is used when shipping in small volumes. We estimate the corresponding annual costs and compare these costs based on the volume shipped and distance traveled.

Case 1: Facility owned truck costs.

The fixed transportation cost components include the cost of ownership, annual sale tax, license fees and taxes, management & overhead cost and insurance cost (Berwick and Farooq, 2003). We consider fixed costs all the cost components that occur whether the truck is moving or not. The total cost of ownership, OC_{tr} ($/year), is calculated by using Eq. (2) (Berwick and Farooq, 2003). Depreciation and return on investment are used to calculate an equivalent annual cost of ownership.

$$OC_{tr} = \left(\frac{P_{tr} - S_{tr}}{EUL}\right) + \left[\left(\frac{P_{tr} - S_{tr}}{2}\right) + S_{tr}\right] * I \tag{2}$$

where P_{tr}, S_{tr}, I and EUL are the purchase price, salvage value, interest rate and estimated useful life of a truck. Then, the total annual fixed cost, FC_{tr} ($/m^3), is calculated as follows.

$$FC_{tr} = \frac{(OC_{tr} + AS_{tr} + MO_{tr} + LT_{tr} + IC_{tr})}{cap_{tr} * n} \tag{3}$$

where AS_{tr}, MO_{tr}, LT_{tr}, IC_{tr}, cap_{tr} and n are the corresponding annual sales tax, management and overhead cost, license fees & taxes, insurance cost, truck capacity, and the expected number of trips per year. The denominator of Eq. (3) calculates the total annual amount of wastewater sludge transported by a truck.

License fees and insurance costs depend on the trade area, distance traveled, product weight and other product characteristics. Most of the components of license fees and insurance costs are fixed in nature, with minor exceptions (Casavant, 1993). Management and overhead costs include costs of management and administrative help. Technology advancements have impacted management and overhead cost. The reduction of these costs due to technology depends on the truck ownership (Berwick and Farooq, 2003; Dooley et al., 1988). The amount of sales tax paid varies on a per state basis. In this study we have accounted for 3% sales tax which is posted by the department of revenue in Mississippi (Department of revenue: State of Mississippi, 2011).

The variable transportation cost components are fuel cost, labor cost, cost for tires, and repair and maintenance cost. Fuel price varies by geographical location, and season. Fuel prices are usually higher in the summer since people travel more in this season. Fuel costs are a function of fuels price, engine horsepower, terrain, wind speed, and product weight. In this study we have considered an average transportation speed of 40 miles/h. Average fuel cost per mile, F_{tr} (\$/mile) is calculated using Eq. (4) (Ryder, 1994):

$$F_{tr} = \left(\frac{f_{tr}}{E_{jL}}\right) * TL + \left(\frac{f_{tr}}{E_{jE}}\right) * TE \tag{4}$$

where f_{tr}, TL, TE, E_{jL} and E_{jE} represent the fuel price (\$), time loaded, time empty, fuel efficiency of truck type j in loaded and unloaded condition (miles/gallon), respectively.

Labor cost per mile, L_{tr} (\$/mile) can be calculated by using Eq. (5) (Berwick and Farooq, 2003):

$$L_{tr} = LM + \left[\left(\left(\frac{d_{tr}}{v_{tr}}\right) + w_{tr}\right) * LH\right] \Big/ d_{tr} \tag{5}$$

where LM, v_{tr}, w_{tr} and LH represent the labor rate per mile (\$/mile), transport speed (mile/h), waiting time (h) and labor rate per hour (\$/h), respectively.

We use the method proposed by Faucett and Associates (1991) to calculate repair and maintenance costs. The formula is weight sensitive, and the calculations are based on a gross shipment weight (GVW) of 58,000 lbs. The service cost is estimated \$0.097 for each 1000 lbs above or below 58,000 lbs. Maintenance and repair cost vary with truck usage, shipment weight, and operating conditions (Berwick and Dooley, 1997). The base maintenance and repair cost is estimated using figures given in an earlier study by Barnes and Langworthy (2003) and is adjusted for inflation.

$$M_{tr} = Base_M + [(((GVW_L - 58,000)/1000) * ad_{tr} * TL) + (((58,000 - GVW_E)/1000) * ad_{tr} * TE)] \tag{6}$$

where $Base_M$, GVW_L, GVW_E and ad_{tr} represent the base repair and maintenance cost (\$/mile), gross vehicle weight at loaded condition (lb), gross vehicle weight at unloaded condition (lb), and adjustment cost (\$/1000 lb), respectively.

Tire cost per mile, T_{tr} (\$/mile) is calculated using Eq. (7) (Berwick and Farooq, 2003):

$$T_{tr} = C^L_{tire} * m * TL + C^E_{tire} * m * TE \tag{7}$$

where C^L_{tire} and C^E_{tire} represents tire cost per mile and unit of time at loaded and empty condition, respectively; m denotes the number of tires required by truck. Faucett and Associates (1991) show that when a truck is used for shipments that weight less than 3500 lbs/tire, the life of a tire is independent of shipment weight. However, for shipments that weight over 3500 lbs/tire, there is a 0.7% increase in cost for each 1% percent increase in shipment weight.

Total variable cost, VC_{tr} (\$/m^3/mile) of transportation can be calculated as:

$$VC_{tr} = \frac{(F_{tr} + L_{tr} + M_{tr} + T_{tr})}{cap_{tr}} \tag{8}$$

Substituting Eqs. (3) and (8) into Eq. (1) yields the total annual truck transportation cost of wastewater sludge, C_{tr} (\$/m^3) for facility owned truck.

$$C_{tr} = \left(\frac{OC_{tr} + AS_{tr} + MO_{tr} + LT_{tr} + IC_{tr}}{cap_{tr} * n}\right) + d_{tr} * \left(\frac{F_{tr} + L_{tr} + M_{tr} + T_{tr}}{cap_{tr}}\right) \tag{9}$$

Note that, all cost figures in this paper are adjusted for inflation and are brought to the same base year, 2013.

Several studies have analyzed transportation related costs for rented trucks. Such an analysis has been conducted for bio-oil (Pootakham and Kumar, 2010a,b), beef cattle manure (Ghafoori et al., 2007), and biomass (Kumar et al., 2004). These studies use the following approach to determine the annual fixed and variable truck transportation costs. Eq. (10) is used to calculate the fixed annual transportation cost, FC_{tr} (\$/m^3).

$$FC_{tr} = \left(\frac{CO_{tr}}{cap_{tr}}\right)\left(\frac{T_{lu}}{60}\right) \tag{10}$$

where CO_{tr} (\$/h) is the truck charge out rate. This is the weighted average hourly rate charged by engineering services. T_{lu} is the total loading and unloading time (min).

Total annual variable cost, VC_{tr} (\$/m^3/mile) is calculated using Eq. (11) (Pootakham and Kumar, 2010a,b):

Table 2
Key properties of wastewater sludge.

Parameter	Raw activated sludge	Enhanced activated sludge	Unit
Density	1100 @ 22 °C	1200 @ 25 °C	kg m^{-3}
Viscosity	1.0 @ 22 °C	1.5 @ 25 °C	cp
Total solids	0.5%	5.0%	Of total waste water

$$VC_{tr} = \frac{CO_{tr}}{v_{tr}cap_{tr}} \tag{11}$$

Substituting Eqs. (10) and (11) into Eq. (1) yields the total wastewater sludge transportation cost for rented truck, C_{tr} ($/m^3).

$$C_{tr} = \left(\frac{CO_{tr}}{cap_{tr}}\right)\left(\frac{T_{lu}}{60}\right) + d_{tr} \times \left(\frac{CO_{tr}}{v_{tr}cap_{tr}}\right) \tag{12}$$

2.3. Summary of data used to estimate fixed and variable truck transportation costs

Table 3 summarizes the key financial and operational parameters we have used to estimate the fixed truck transportation costs for wastewater sludge. We use these parameters in Eq. (3). Our calculations indicate that the fixed transportation cost for facility owned trucks with capacity 30 m^3 and 40 m^3 are $3.42/m^3 and $3.62/m^3 respectively. We use Eq. (10) to calculate the fixed transportation costs for rented trucks of similar capacities. These costs are $4.56/m^3 and $4.76/m^3.

Table 4 presents a summary of fixed and variable truck cost for shipping wastewater sludge. We estimate that the variable transportation cost component of wastewater sludge using a truck with capacity 30 m^3 and 40 m^3 are $0.058/m^3 and $0.047/m^3, respectively. These estimates are made for facility-owned trucks. For rented trucks, these costs are $0.072/m^3 and $0.059/m^3, respectively.

3. Pipeline transportation costs

It is expected that enhanced activated wastewater sludge will be shipped from a WWT facility to the biorefinery. Therefore, we estimate costs related to installing and operating a one way pipeline transportation system. Table 5 presents key financial and operational parameters that we use to estimate the fixed and variable pipeline transportation costs.

The fixed pipeline transportation costs include the capital cost to install inlet and outlet stations. An inlet station refers to the terminal that pumps wastewater sludge into the pipeline. The terminal which collects wastewater sludge is referred to as the outlet station. The costs incurred when installing inlet and outlet stations are: purchase cost of the storage tank, building & foundation cost, fitting & valve cost, inlet pump cost and road access cost (Pootakham and Kumar, 2010a,b). Since these costs occur only once at the beginning of the project, we calculate the corresponding equivalent annual costs over project's lifetime (Liu et al., 1998). Table 6 summarizes the capital costs for an inlet and an outlet station facility with daily operating capacity of 480 m^3 wastewater sludge with 5% solid concentration.

Variable transportation cost includes pipeline construction costs, operating costs, and the costs of operating booster stations. Note our definition of variable cost: these costs are variable with respect to the distance traveled (not the volume shipped). As such, we consider pipeline construction costs variable, as the longer the distances traveled, longer pipelines should be installed. Similarly, the longer the distance traveled, more booster stations are required. Table 7 gives a detailed breakdown of pipeline variable costs. This table also presents cost estimates for transportation of wastewater sludge along 100 miles-long pipeline at a capacity of 480 m^3/day of wastewater sludge at 5% solid concentration.

We consider that PVC plastic pipe is used for pipelines dedicated to wastewater sludge. Other works that studied the movement of dairy and pig manure (such as, Howard, 1979; and Patni, 1980) have also used PVC pipes. Our decision for considering PVC pipe was motivated by the low cost of PVC, and by the fact that wastewater sludge is not corrosive (pH value 7.0 ± 0.1) and has relatively low total solid content.

We consider that transportation velocity of sludge along a pipeline is 2.7 ms^{-1} (Ghafoori and Flynn, 2006). An increase in velocity (due to using more powerful pumps) initially decreases the unit variable transportation cost (in $/m^3/mile). However, as we further increase the velocity, the unit variable cost increases. Fig. 1 presents the relationship that exists between the unit variable transportation cost and velocity of movement of sludge along pipelines of different capacity. The results of this graph suggest that the diameter of the pipeline should be selected in such a way that the variable unit transportation cost is minimized.

We use the results from Fig. 1 to identify the corresponding pipeline diameters that maintain sludge velocity at the level required to minimize the variable transportation costs. Fig. 2 summarizes our findings. In this figure, we present pipeline diameters required for shipping (o) 150 m^3/day, (□) 320 m^3/day, (Δ) 480 m^3/day, (+) 1000 m^3/day, and (◇) 2000 m^3/day of sludge. Some inflections in the curve arise due to considering standard PVC sizes in defining pipeline diameters.

Table 8 presents the formulae for calculating the variable pipeline transportation costs of wastewater sludge as a function of the shipment distance. We present formulas for different pipeline capacities and pipeline diameters. It has been observed that higher the capacity of a pipeline, shorter the distance between the booster stations. For a given pipeline capacity, the corresponding pipeline diameter and distance between booster stations is defined in such a way that the slurry velocity of sludge is maintain at 2.7 ms^{-1} and unit variable costs are minimized.

Finally, we use Eq. (1) to calculate the total transportation cost ($/m^3) of sludge for pipelines of different capacity. Appendixes A.1 and A.2 summarize the costing parameters considered by truck and pipeline transportation. In our costing approach, we do not consider the details of obstacle layers (e.g., terrain, river, road, rail crossings, national and state parks, and populated areas) that pipelines experience. Instead, we multiplied the base cost by a factor (e.g., 1.2) to accommodate for these factors.

4. Result and discussions

4.1. Truck transportation costs

Based on our experimental results, the following is a breakdown of facility-owned fixed truck transportation costs. About 53% of the fixed transportation cost is due to the cost of ownership, 25% is due to management and overhead costs, 17% is due to insurance costs, 4% is due to license fees and taxes, and 1% is due to annual sale taxes (see Fig. 3a). About 41% of the variable cost is due to fuel consumption, 47% is due to labor, 10% is due to maintenance and repair, and 2% is due to tire consumption (see Fig. 3b). Note that fuel and labor costs constitute 82% of variable transportation costs, and therefore, any increase in fuel price and labor cost will greatly impact variable transportation costs. For example, the price of diesel increased 172% from 2003 to 2011 (US Energy Information Administration, 2009). Such an increase greatly impacts transportation costs.

Fixed transportation cost is a function of truck utilization (Berwick and Dooley, 1997). The results presented in Table 4 assume that: the total number of trips made by a single trailer truck in a year is 500; the amount of sludge transported per trip is 30 m^3. Using these parameters we estimated the fixed transportation cost for a single trailer truck as \$3.42/m^3. This cost could however be as high as \$5.71/m^3 or as low as \$2.14/m^3 if the total number of trips per year changes from 300 and 800, respectively. Fig. 4a presents the relationship that exists between the number of trips per year (n) and the fixed costs for a single trailer truck, DFC_{WWS} (\$/m^3). We fitted the following equation to this relationship. This equation is used to forecast fixed transportation costs per number of trips. The value of R^2 is 1.

$$DFC_{WWS} = 1644.5n^{-0.993} \tag{13}$$

The rate of loading and unloading wastewater sludge depends on the viscosity of the product. Highly viscous products, such as gasoline and diesel fuel, are loaded at a rate between 0.9 and 1.3 m^3/min. Pootakham and Kumar (2010a,b) consider that the loading rate for bio-oil is 0.6 m^3/min since its viscosity level is higher than crude oil. In this study, we consider the

Table 3
Financial and operational parameters required to calculate wastewater sludge truck transportation costs.

Parameter	Value	Units	Comments/remarks
Truck owned	100	%	Assumed
Truck leased	0	%	Assumed
Estimated useful truck life	5	Years	Assumed
Purchase tax rate	3	%	Department of revenue: State of Mississippi (2011)
Interest rate	11	%	Assumed
Salvage price	30	% of purchase price	Berwick and Farooq (2003)
Miles driven per year[a]	100,000	Miles/year	Berwick and Farooq (2003)
Miles driven per year[b]	80,000	Miles/year	Assumed
Number of trips per year[a]	500	Trips/year	Assumed
Number of trips per year[b]	400	Trips/year	Assumed
Average transport speed	40	Miles/h	Assumed
Fuel price	4.08	\$/gallon	US Energy Information Administration (2009)
Percent loaded	50	%	Assumed
Percent empty	50	%	Assumed
Fuel efficiency for loaded truck	5.1	Miles/gallon	US Department of Commerce: Bureau of the Census (2004b)
Fuel efficiency for unloaded truck	6.6	Miles/gallon	Calculated by using a conversion factor of 0.78 based on the values from Tchobanoglous et al. (2003)
Regular labor wages[a]	16.0	\$/h	US Department of Commerce: Bureau of the Census (2004a)
Regular labor wages[b]	17.8	\$/h	Calculated by using a conversion factor of 0.90 based on the values from Kulkarni and Dalai (2002)
Labor rate per mile	0.34	\$/mile	Berwick and Farooq (2003)
Base maintenance and repair cost	0.12	\$/mile	Barnes and Langworthy (2003)
Tire cost	480	\$/tire	Assumed
Life of tire	270,000	Miles/tire	Assumed
Truck charge out rate[b]	95.1	\$/h	Ghafoori et al. (2007)
Truck charge out rate[a]	86.4	\$/h	Ghafoori et al. (2007)

[a] 30 m^3 single trailer truck.
[b] 40 m^3 tandem trailer truck.

Table 4
Fixed and variable costs for truck transportation of wastewater sludge.

Items	Single trailer truck	Tandem trailer truck
Capacity (m^3)	30	40
Loading and unloading rate (m^3/min)	0.8	0.8
Loading time (min)	37.5	50
Unloading time (min)	37.5	50
Additional time for set up during loading and unloading time (min)	20	20
Total time for loading and unloading (min)	95	120
Case 1: Truck is owned by the WWT facility		
Fixed cost component:		
Cost of ownership	26,810	32,172
Annual sale taxes	720	864
License fees and taxes	2086	2295
Management and overhead cost	13,020	13,020
Insurance cost	8726	9599
Total fixed cost of transportation of wastewater sludge ($/mile)	0.51	0.72
Total fixed cost of transportation of wastewater sludge ($/$m^3$)	3.42	3.62
Variable cost component:		
Fuel cost ($/mile)	0.71	0.77
Labor cost ($/mile)	0.82	0.87
Maintenance and repair cost ($/mile)	0.17	0.18
Tire cost ($/mile)	0.04	0.05
Total variable cost of transportation of wastewater sludge ($/mile)	1.74	1.87
Total variable cost of transportation of wastewater sludge ($/$m^3$/mile)	0.058	0.047
Case 2: Truck is rent by the WWT facility		
Total fixed cost of transportation of wastewater sludge ($/$m^3$)	4.56	4.76
Total variable cost of transportation of wastewater sludge ($/$m^3$/mile)	0.072	0.059

Table 5
Financial and operational parameters required to calculate wastewater sludge pipeline transportation costs.

Parameter	Value	Units	Comments/remarks
Pipeline operating life	30	Years	Ghafoori et al. (2007)
Pipeline operating days	350	Days	Time (days) plant is running in a year
Slurry design velocity	2.7	ms^{-1}	Ghafoori and Flynn (2006)
Pump efficiency	80%	–	Assumed
Discount rate	10%	–	Assumed
Labor cost	29.20	$/h	Pootakham and Kumar (2010a,b)
Labor hour requirement	8400	h $year^{-1}$	Based on pipeline operating days a year
Electricity cost	60.0	$ MW h^{-1}	Pootakham and Kumar (2010a,b)
Pipeline maintenance cost	0.5%	Of its capital cost	Ghafoori and Flynn (2006)
Pump station maintenance cost	3.0%	Of its capital cost	Ghafoori and Flynn (2006)
Engineering cost	10%	Of its capital cost	Assumed
Contingency	10%	Of its capital cost	Assumed

total solid content of sludge shipped by truck to be 20%, and by pipeline 5%. The loading equipment is assumed to operate at a volume flow rate of 0.8 m^3/min; and loading/unloading times are assumed equal. An additional 20 min is added to the loading/unloading time to capture the time it takes to perform other related activities in support of loading/unloading.

Fig. 4b presents the relationship that exists between the loading/unloading rate and the direct transportation fixed cost. Given the operating pressure of the pump used for loading/unloading, as the viscosity of the wastewater sludge increases, the loading/unloading rate decreases, and vice versa. Fixed cost components are affected by the increase of the loading/unloading rate since higher viscous products take a longer time to load/unload. In summary, fixed transportation costs increase with the increase of loading/unloading time since the charge out rate of transportation companies is made on an hourly basis.

4.2. Identifying the minimum economic pipeline capacity

Fig. 5 shows the relationship that exists between the variable transportation cost ($/$m^3$/mile) and pipeline capacity. It is clear that, as pipeline capacity increases, the variable transportation cost decreases. For example, the variable unit transportation cost along a pipeline with a capacity of 480 m^3/day is estimated to be $0.09/$m^3$/mile. This amount reduces to $0.04/$m^3$/mile for a pipeline with a capacity of 1500 m^3/day. This scale dependent behavior can be fitted to the following equation. Note that, R^2 is equal to 0.991.

Table 6
Capital cost components for inlet and outlet station facilities.

Items	Cost ($/year)
Inlet station	
Storage tank cost[a]	7390
Building and foundation cost[b]	1110
Fitting and valve cost[c]	260
Inlet pump cost[d]	1790
Road access cost[e]	320
Total inlet station cost	10,870
Outlet station	
Storage tank cost[a]	7390
Building and foundation cost[b]	1110
Fitting, valve and pump cost[c]	355[f]
Total outlet station cost	8855

[a] Costs were estimated based on the values reported by Pootakham and Kumar (2010a,b) using the conversion equation of capacity: $\text{Cost}_B = \text{Cost}_A(\text{Capacity}_B/\text{Capacity}_A)^{0.65}$.
[b] Building and foundation cost is estimated from the study of Liu et al. (1995) and was adjusted for inflation.
[c] Fitting and valve cost is estimated from the study of Liu et al. (1995): Cost($) = 13,220 * $D^{1.05}$, where D is the diameter of the pipe in ft. For transporting 480 m^3 of wastewater sludge at a velocity of 2.7 ms^{-1}, the diameter of the pipe was calculated as 6.3 cm.
[d] Pump cost is estimated from the study of Liu et al. (1995): Cost($) = 1322 * $(\text{Power})^{0.8}$, where power of pump is in hp. Pump power was calculated as 24 hp based on the determination of friction factor suggested by Chen (1986) for beef cattle manure.
[e] Assumed.
[f] For distribution purposes within the plant a pump size of 5 hp is assumed and the cost is incorporated along with the fitting and valve cost.

$$DVC_{WWS} = 5.27C^{-0.658} \tag{14}$$

where C is pipeline capacity (in m^3/day).

The pipeline capacity breakeven point is the capacity at which the variable transportation costs for pipeline and for truck intercept. This means that when the volume of sludge shipped to be greater than the breakeven point, then the transportation of wastewater sludge becomes more economical using pipeline than using truck. Conversely, when the volume of sludge to be shipped is lower than the breakeven point, truck transportation is more economical. In this study, the minimum economic pipeline capacity is estimated at: 700 m^3/day for rented single trailer trucks; 800 m^3/day for rented tandem trailers and facility-owned single trailer trucks; and 1200 m^3/day for facility-owned tandem trailer trucks. Therefore, WWT facilities that process up to 700 m^3/day of sludge should use a rented single trailer truck. WWT facilities that process more than 1200 m^3/day should use a pipeline.

4.3. The relationship between total transportation costs and distance

Fig. 6 presents the relationship that exists between the total transportation costs and distance traveled for pipelines of different capacity and for trucks. This figure indicates that the total transportation costs increase with the increase in pipeline capacity. This is mainly due to the increase of fixed cost component such as storage tank cost and pump power cost. The total variable costs (including costs related to the pipeline system and the booster stations) also increase. Variable costs increase with the distance traveled. For example, the number of booster stations required by pipelines increases with distance. But this incremental cost is offset by the economies of scale achieved from the pipeline transportation of wastewater sludge. Fuel consumption and labor required by trucks also increases with distance traveled. However, the rate of increase is higher for trucks than for pipelines.

4.4. The relationship between pipeline capital costs and distance traveled

Pipeline capital costs, represented by pipeline material and construction costs, constitute 62% of the total pipeline variable costs. These costs depend on pipe material, insulation requirements and construction rate charged by the engineering firm. For example, Pootakham and Kumar (2010a,b) report that a bio-oil plant spends $1,073,180/year on pipeline capital costs to transport 560 m^3/day of bio-oil for 100 km. Based on the analysis presented in this study, it is expected that $730,932/year will be spent on pipeline capital costs to ship wastewater sludge along pipelines with similar pipeline capacity and transportation distance. Fig. 7a presents the relationship that exists between total pipeline transportation costs and distance traveled as the value of the pipeline capital cost (in $/$m^3$) increases by 5%, 10%, 15% and 20%, and decreases by 5% and 10%. Note that the lines are close to each-other for shorter distances. The gap between these lines widens as the transportation distance increases. Our analysis indicates that a 10% increase in the pipeline capital cost will increase the total

Table 7
Variable cost components for pipeline transportation of wastewater sludge.

Items	Cost ($/year)
Pipeline construction and operating related costs	
Construction cost[a]	792,748
Pipe material cost[b]	296,750
Road access cost[c]	17,780
Pipeline maintenance cost[d]	1490
Pump maintenance cost[e]	1075
Labor cost[f]	245,280
Electricity cost[g]	126,750
Total construction and operating cost	1,481,873
Booster station cost	
Building and foundation cost[h]	1110
Booster pump cost[i]	1790
Booster pump installation cost[i]	3253
Road access cost[j]	320
Power line cost[k]	13,759
Total booster station cost	20,232

[a] Construction cost is estimated based on a rate of $31,037.1 per mile per inch from the study of Pootakham and Kumar (2010a,b).
[b] Pipe material cost is estimated based on the formula: Cost($) = $28.2(D_o - T)TLC$ where D_o is outer diameter in inch, T is pipe wall thickness in inch, L is length of pipe in mile and C is pipe material cost in $/ton (Menon, 2005).
[c] Assumed.
[d] Based on 0.5% of pipeline capital costs (Ghafoori and Flynn, 2006).
[e] Based on 3% of pump and pump station capital costs (Ghafoori and Flynn, 2006).
[f] Based on 8400 man-hour per year at $29.2 h^{-1}.
[g] Based on $60.0 MW h^{-1}.
[h] Building and foundation cost is estimated from the study of Liu et al. (1995) and was adjusted for inflation.
[i] Estimation of pump cost is explained earlier. Booster pump installation cost is assumed to be 10% of the capital cost (Menon, 2005).
[j] Assumed.
[k] Power line cost is estimated from the study of Liu et al. (1995): Cost($) = 1.32 * ((8400 * N) + 8400), where N is the number of booster station for transporting wastewater sludge for 100 miles.

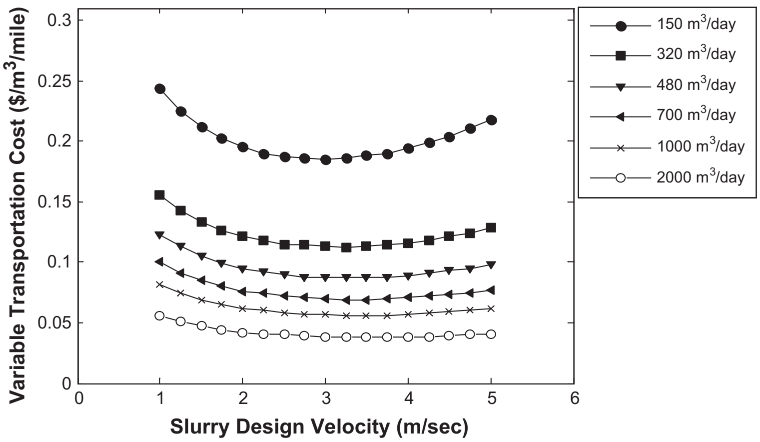

Fig. 1. The effect of slurry design velocity (ms^{-1}) on the variable transportation cost of wastewater sludge ($/m^3/mile).

variable cost of shipping 480 m^3 of sludge for 100 m from $9.01/m^3 to $9.72/m^3. A 10% decrease in these costs decreases the total variable cost from $9.01/m^3 to $8.42/m^3.

It is estimated that the economic lifetime of a pipeline is 30 years. We conducted a sensitivity analysis to see the impact of project lifetime on the total transportation costs with respect to distance traveled. The results of the sensitivity analysis are shown in Fig. 7b. Each line on this figure represents the total transportation cost ($/m^3) considering a 30-year project lifetime. The markers along each line (o 150 m^3/day, □ 250 m^3/day, Δ 400 m^3/day, x 500 m^3/day, + 700 m^3/day, ∗ 1000 m^3/day, ◇ 1500 m^3/day, • 2000 m^3/day) represent the corresponding total transportation cost, assuming a project lifetime of

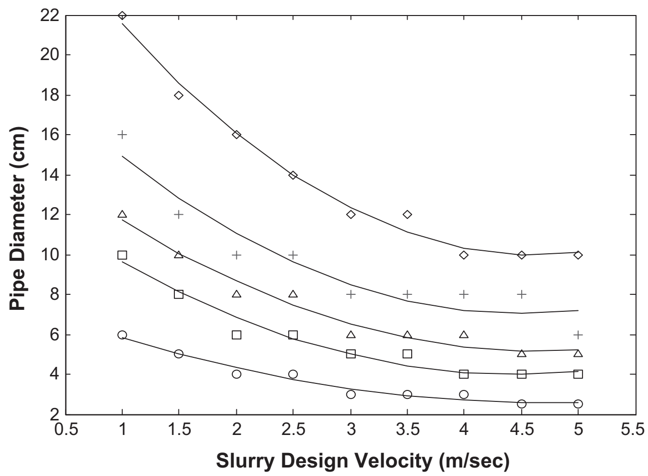

Fig. 2. Slurry design velocity versus pipe diameter for wastewater sludge.

Table 8
Formulae for calculating pipeline transportation cost of wastewater sludge.

Capacity (m^3/day)	Diameter of pipeline (cm)	Velocity of sludge (ms^{-1})	Formulae for calculating total transportation cost	Distance between booster station (miles)
150	4.0[a]	2.7	$0.184 + 0.213d$[b]	5.5
200	4.0	2.7	$0.161 + 0.159d$	5.0
350	6.0	2.7	$0.132 + 0.119d$	8.9
450	6.0	2.7	$0.119 + 0.093d$	8.1
550	7.0	2.7	$0.111 + 0.085d$	10.6
700	8.0	2.7	$0.102 + 0.073d$	12.5
800	8.0	2.7	$0.097 + 0.065d$	11.3
1000	9.0	2.7	$0.090 + 0.056d$	14.3

[a] Rounded to next standard pipe size available in the market.
[b] d is distance in miles.

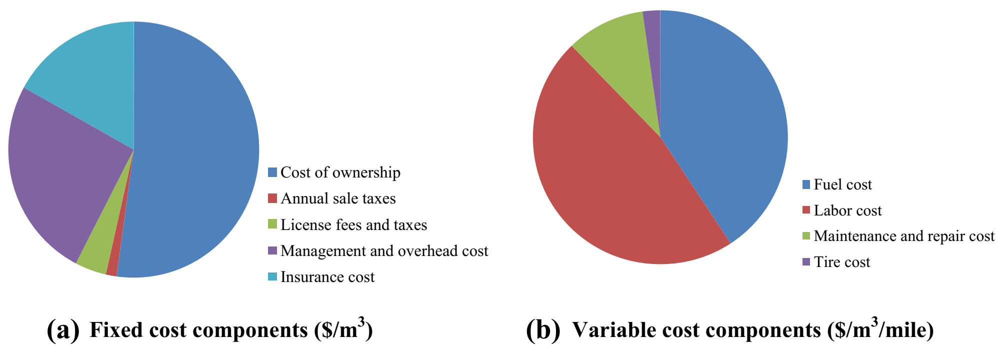

Fig. 3. Distribution of wastewater sludge transportation costs for a single trailer truck with a capacity of 30 m^3.

20 years. As expected, the total transportation cost for projects with a lifetime of 20 years are higher than for projects with a lifetime of 30 years. Another important observation is that the gap between these costs increases with pipeline capacity. For example, the gap in the total transportation costs, when the distance traveled is 100 miles and pipelines capacities are 150 m^3/day, 400 m^3/day and 700 m^3/day, are \$0.215/m^3, \$0.611/m^3 and \$0.709/m^3 respectively.

5. A case study

We used the models presented above to identify the best transportation mode to ship wastewater sludge from 66 different WWT facilities in Mississippi. The maximum amount of water treated in these facilities varies between 0.35 million

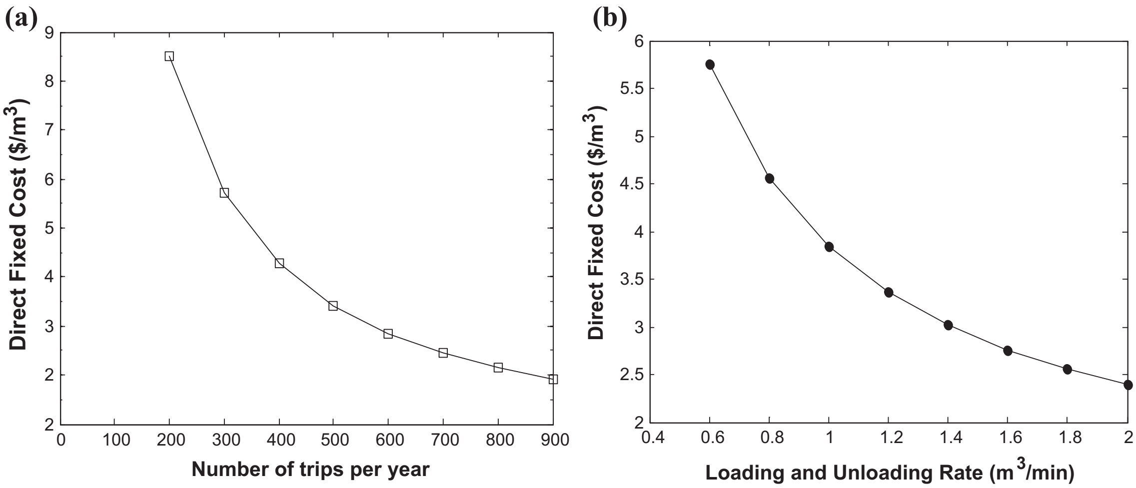

Fig. 4. Impact of (a) number of trips per year and (b) loading and unloading rate (m^3/min) on direct fixed cost ($/$m^3$) for a 30 m^3 single trailer truck.

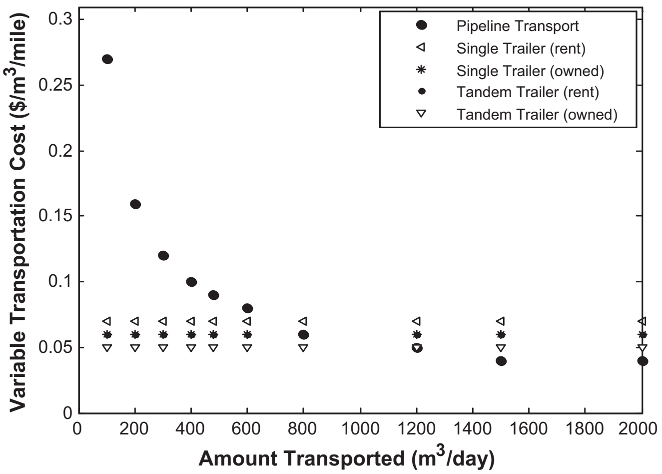

Fig. 5. Amount transported versus variable transportation cost of wastewater sludge.

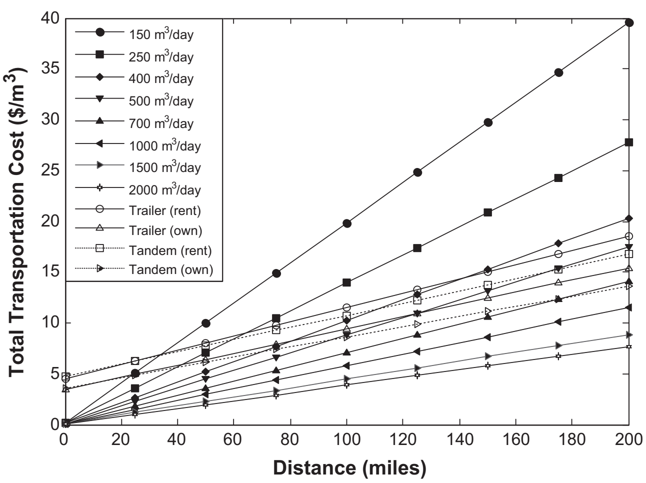

Fig. 6. The relationship between distance traveled and total transportation costs for different modes of transportation.

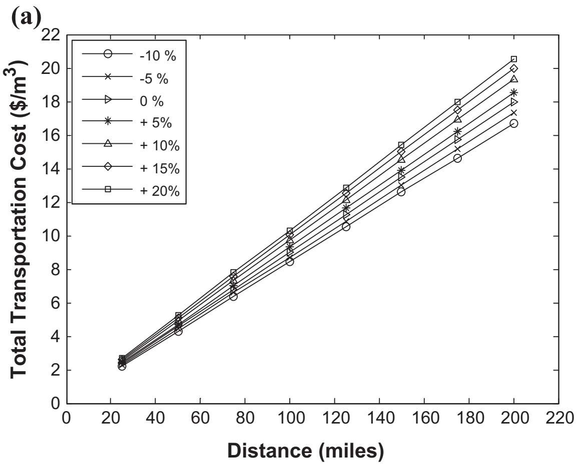

Fig. 7. The relationship between total transportation costs and distance traveled on (a) different pipeline capital costs, and (b) pipeline capacities and project lifetimes.

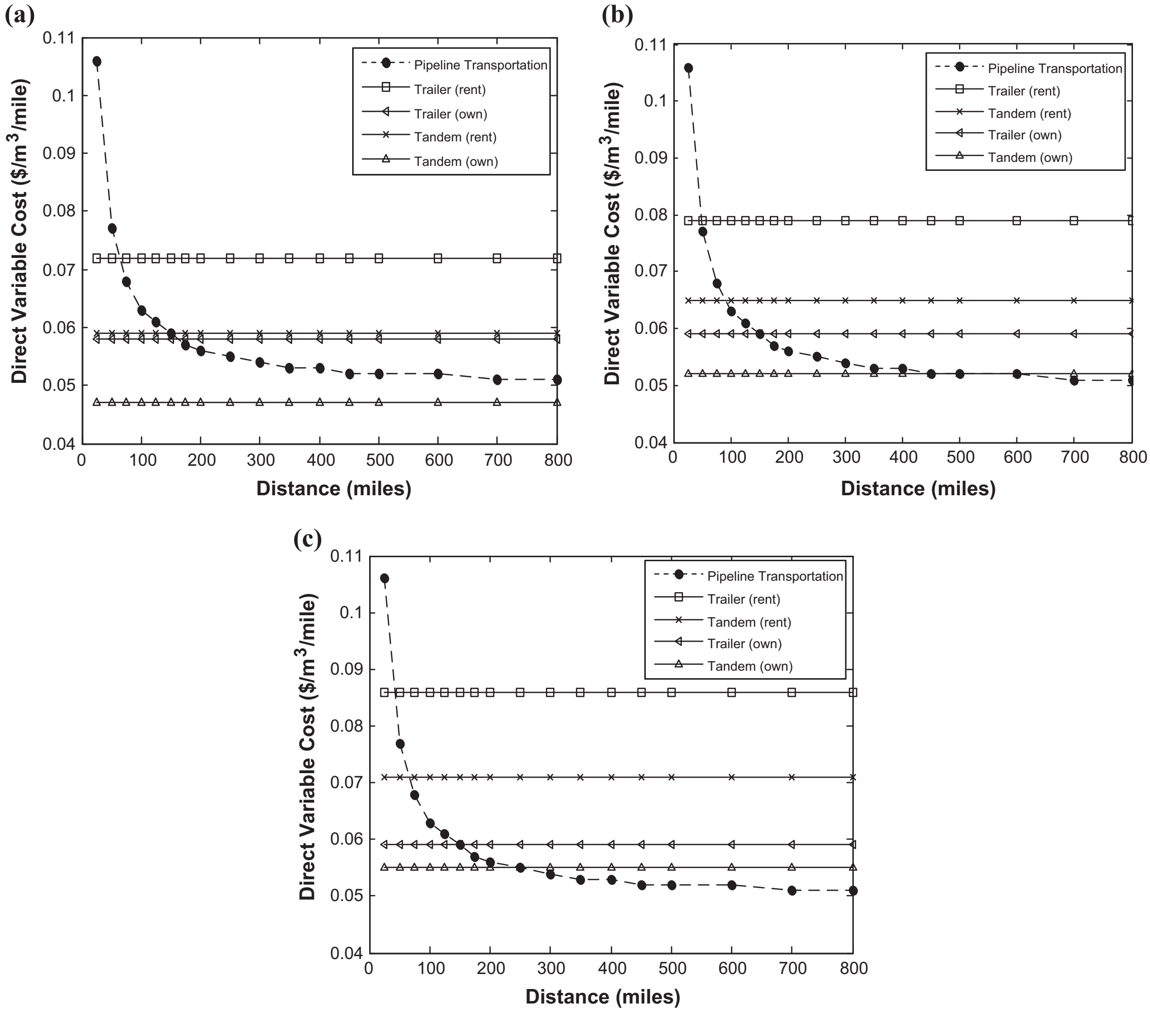

Fig. 8. The relationship between distance traveled and direct variable cost of different modes of transportation for scenario (a), (b) and (c).

Table 9
Total transportation cost per gallon of biodiesel versus volume transported.

Mode	Volume Shipped (m^3/day)					
	150	250	350	480	700	1000
	$ amount per gallon of biodiesel					
Single trailer (own)	0.101	0.103	0.103	0.101	0.103	0.103
Single trailer (rent)	0.131	0.131	0.133	0.131	0.133	0.133
Tandem trailer (own)	0.098	0.098	0.098	0.096	0.098	0.096
Tandem trailer (rent)	0.125	0.125	0.125	0.123	0.125	0.123
Pipeline	0.152	0.109	0.089	0.073	0.058	0.047

Table 10
Transportation cost per gallon of biofuel as a function of distance traveled.

Mode	Distance (miles)							
	25	50	75	100	125	150	175	200
	$ amount per gallon of biofuel							
Corn stover – Ethanol[a]	0.052	0.079	0.105	0.131	0.159	0.186	0.213	0.240
Sludge – Biodiesel (owned TT truck)	0.077	0.096	0.114	0.133	0.152	0.171	0.191	0.208
Sludge – Biodiesel (pipeline) [b]	0.077	0.152	0.226	0.301	0.375	0.449	0.524	0.598
Sludge – Biodiesel (pipeline) [c]	0.037	0.073	0.109	0.144	0.180	0.216	0.251	0.287
Sludge – Biodiesel (pipeline) [d]	0.024	0.047	0.070	0.093	0.115	0.138	0.161	0.184

[a] The distance fixed and variable parameters for truck transportation come from Mahmudi and Flynn (2006). The conversion rate for corn stover comes from Ekşioğlu et al. (2009).
[b] Calculated based on pipeline capacity of 150 m^3/day.
[c] Calculated based on pipeline capacity of 480 m^3/day.
[d] Calculated based on pipeline capacity of 1000 m^3/day.

Table 11
Distance fixed and variable transportation parameters.

Mode	Item transported	DVC	Units	DFC	Units
Truck	Straw/Stover (Mahmudi and Flynn, 2006)	0.14	\$/Actual t/km	5.25	\$/Actual t
	Wastewater sludge (owned) [this study]	0.04	\$/Actual t/km	3.42	\$/Actual t
Pipeline	Wastewater sludge (rented) [this study]	0.05	\$/Actual t/km	4.56	\$/Actual t
	Wastewater sludge [this study]	$3.27C^{-0.658}$	\$/t sludge/km	1574[a]	\$/t sludge

[a] Calculated based on pipeline capacity of 480 ton/day.

gallons of water a day (MGD) to 120 MGD (Mississippi Departmental of Environmental Quality, 2011). The corresponding amount of sludge generated varies between 2.5 tons/day and 843.5 tons/day.

Initially, we analyzed transportation costs for the WWT facility with the highest capacity. Based on our model, this facility would use trucks to ship sludge to a biorefinery when the distance traveled is less than 154 miles. For longer distances, pipeline transportation makes more economic sense. It is of interest to note that assuming a 10% or a 20% increase in the price of fuel, labor cost and truck charge out rate had a great impact on the transportation mode selection for this facility. When these costs increased by 10%, it is more economical for a WWT facility to use trucks when the distance traveled is less than 100 miles. When costs increased by 20%, trucks are found to be economical for distances less than 74 miles. The motivation for performing this sensitivity analysis is the steady increase of the price of gasoline we have observed in the recent years. Obviously, this increase has a greater impact on truck rather than pipeline transportation costs.

Fig. 8 presents the relationship that exists between variable transportation costs and distance traveled for different modes of transportation using 3 scenarios: (a) current fuel price, labor cost and truck charge-out rate; (b) a 10% increase in fuel price, labor cost and truck charge-out rate; and (c) a 20% increase in fuel price, labor cost and truck charge-out rate.

Table 9 presents the relationship that exists between the volume shipped and transportation cost per gallon of biodiesel. We assume that the distance traveled is 50 miles. Two important observations are made from these results. First, facility-owned tandem trailer trucks are the most cost efficient transportation mode for volumes up to 300 m^3/day. Beyond this point, pipeline transportation is the most cost efficient mode of transportation. Second, truck transportation cost per gallon of biodiesel does not change with the volume transported. On the other hand, pipeline transportation cost per gallon of biodiesel decreases as the volume shipped increases. Table 10 compares the cost of transporting biomass (per gallon of biofuel) for different types of biofuels. Table 11 summarizes the parameters used to calculate these costs.

We extended this analysis to other WWT facilities in Mississippi. Our analysis indicates that at the current level of gasoline price and labor cost, WWT facilities will not find the use of pipelines for sludge transportation economical. However, we believe that in the long run, investing in pipelines would be beneficial. We came to this conclusion by looking at the impact that fuel price and labor costs have on transportation costs, as well as by considering the positive impacts that pipeline transportation have on the environment. Obviously, the amount of carbon released during pipeline transportation is negligible compared to during truck transportation. In addition, there is far less noise associated with pipeline transportation than with truck movement.

6. Conclusion

This study presents a techno economic analysis of pipeline and truck transportation of wastewater sludge. The key conclusions from this study are:

- We estimate the fixed and variable costs for a facility-owned single trailer truck with a capacity of 30 m^3 to be \$3.42/m^3 and \$0.058/m^3/mile, respectively. Similarly, these costs were calculated for a rented single trailer truck (\$4.56/m^3, \$0.072/m^3/mile), a facility-owned tandem trailer truck of 40 m^3 capacity (\$3.62/m^3, \$0.047/m^3/mile), and a rented tandem trailer truck of 40 m^3 capacity (\$4.76/m^3, \$0.059/m^3/mile). Based on our model, the direct fixed cost components for truck transportation depend on the loading/unloading rate and the level of utilization of the truck.
- Similarly, we estimate the fixed and variable cost components for pipeline transportation of wastewater sludge. Our analysis indicates that pipeline capacity and transportation distance greatly impact transportation costs. We also identified the optimal pipeline capacity (diameter) given the daily volume, density, and viscosity of sludge. We estimated that it is more economical to use a pipeline rather than a rented single trailer truck if the volume shipped is greater than 700 m^3/day. It is more economical to use a pipeline rather than a rented tandem trailer or a facility-owned single trailer truck when the volume shipped is 800 m^3/day. And, it is more economical to use a pipeline than a facility-owned tandem trailer truck when the volume shipped is more than 1200 m^3/per day. The transportation distance is assumed to be 100 miles.
- We use the models developed to gain an understanding of the cost structure for truck and pipeline transportation of sludge. In Figs. 1 and 2, we identify the corresponding pipeline diameters that maintain sludge velocity at the level required to minimize the variable transportation costs. Eq. (14) presents the relationship that exists between pipeline capacity and variable transportation cost. We performed sensitivity analysis to see the impact of different fixed and variable cost components on total transportation cost. The results of this analysis are summarized in Figs. 5–8. Tables 9 and 10 provide information which helps decision makers (e.g., supply chain managers of biofuel plants) to estimate biomass transportation costs based on information about the vicinity of suppliers and sludge availability. For example, let assume that a wastewater treatment plant generates 350 m^3 of sludge per day, and it is located further than 100 miles away. Then, a biofuel plant would rather use pipeline rather than a facility-owned tandem trailer truck to receive shipments from this supplier since pipeline transportation is more economical in this case. In the case when, the wastewater treatment plant generates 480 m^3 of sludge per day and is located further than 75 miles away; the biofuel plant would rather use pipeline than a facility-owned tandem trailer truck. These examples indicate that, both, the amount available and the distance traveled impacts biofuel plant supplier selection decisions.
- Finally, we use these models to identify the best mode of transporting sludge from WWT facilities located in Mississippi. We came to the conclusion that, given the current level of fuel price and labor cost, none of the facilities would consider building a pipeline for sludge transportation to a biorefinery. However, pipeline transportation costs – as compared to truck transportation costs – are less sensitive to the highly fluctuating fuel prices and the increasing labor costs (US Energy Information Administration, 2014; United States Department of Labor, 2014). The results of Fig. 8 support this statement. Pipeline transportation uses less fuel than trucks to deliver a unit of product for one mile. Thus, using pipelines can have a positive impact in reducing greenhouse gas emissions. Using pipelines also reduces noise, reduces highway traffic and improves highway safety.

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Appendix A

Appendix A.1 and A.2 include the summary of costing parameters considered and ignored by truck and pipeline transportation.

A.1. Summary of parameters considered in calculating Truck Transportation Cost

Truck Transportation Cost:

Fixed cost components:

1. Cost of ownership
   - Return on investment
   - Equipment depreciation
2. Annual Sales Tax
   - Purchase price for trucks and trailers
   - Estimated useful truck and trailer life
   - Number of trips per year
   - Sales tax rate
3. License fees and taxes
4. Management and overhead cost
5. Insurance cost

Variable cost components[a]:

1. Fuel cost
   - Fuel price
   - Percent loaded and empty factor
   - Fuel efficiency of loaded and unloaded trucks
2. Labor cost
   - Transport distance and speed
   - Labor rate
   - Waiting time
3. Maintenance and repair cost
   - Percent loaded and empty factor
   - Base repair and maintenance cost
   - loaded and empty gross vehicle weight (GVW)
4. Tire cost
   - Percent loaded and empty factor
   - Tire cost and useful tire life
   - Number of tires used each year

[a] All the variable cost components are dependent on transportation distance.

A.2. Summary of parameters considered in calculating Pipeline Transportation Cost

Pipeline Transportation Cost:

Fixed cost components:

1. Fitting and valve cost (inlet and outlet)
   - Estimated life of pipeline
2. Building and foundation cost (inlet and outlet)
   - Capacity of pipeline
3. Storage tank cost (inlet and outlet)
   - Capacity of storage tank
4. Road access cost
5. Pump cost (inlet and outlet)
   - Pump power and efficiency
   - Pressure gradient, friction factor, viscosity of sludge

Variable cost components[a]:

1. Labor cost
   - Total man-hour per year
   - Labor rate per hour
2. Electricity cost
   - Pump power
3. Power line cost

- Estimated life of pipeline
- Power line cost

4. Road access cost (Pipeline and Booster System)
5. Building and foundation cost (Booster System)
5. Booster pump cost
6. Pipe material cost
   - Pipe material cost
   - Pipe diameter and thickness
7. Pipeline and pump maintenance cost

[a] All the variable cost components are dependent on transportation distance.

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