Liquid Manure Hauling Capacity of Custom Applicators Using Tank Spreader Systems

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Abstract. *In the last several years livestock farms in the Great Lakes Region have expanded and increased in size. With more livestock comes more manure handling and a greater transport distance to reach the expanding land base needed for land application. Because hauling and spreading large volumes of manure can greatly impact peak labor demand and the timeliness of tillage and planting, many farm managers are using custom hire of manure hauling and land application. A time-and-motion study of 13 liquid manure hauling systems on 10 farms using custom hauling services in Michigan, Ohio, and Ontario, Canada was done in 2006-2008. Representative time and material flow rates were used to model the hauling capacity of tank spreader systems as a function of spreader tank volume and transport distance. Simulated hauling rates were fit to a general model to develop machinery system-specific coefficients to predict an effective hauling capacity of tractor-drawn and truck-drawn spreader tanks, and hauling systems using truck-drawn nurse tanks for over-the-road transport to tractor-drawn spreader tanks for field spreading. The machinery-system specific coefficients are presented in a convenient reference table and can be used to estimate liquid manure hauling capacity over a range of tank volume and travel distance. Compared to standard tractor-drawn tank spreaders, spreaders drawn with high-speed tractors and truck-drawn spreaders had an advantage with longer hauls. Compared to injection with a 6-shank injector a broadcast application with a 26495-L (7000-gal) high-speed tractor-drawn spreader increased the hauling rate 25% near storage and 17% with a 3.2-km (2-mile) haul. The hauling rate of tank spreader systems was most sensitive to an increase in tank volume and travel speed. A 20% increase in tank volume increased the effective hauling rate about 8% with a 0.16-km (0.1-mile) haul and more than 16% with a 16-km (10-mile) haul. A 20% increase in travel speed had little effect when hauling near storage, but increased the hauling rate more than 7% with a 3.2-km (2-mile) haul, and more than 14% with a 16-km (10-mile) haul.*

Keywords. Manure, Tank spreader, Land application, Time-and-motion, Machinery management, Custom applicator.

On most livestock farms in the Great Lakes region, daily hauling of manure has been replaced by long-term storage and handling of liquid slurries. Manure from long-term storage is usually more uniform in nutrient content than manure spread daily, and this manure is often spread and incorporated within a few days time. This allows for timely use of manure as fertilizer and reduces nutrient loss to the environment. In Michigan, manure application on frozen or snow-covered ground is discouraged as a threat to water quality (Michigan Agricultural Commission, 2009). Compared to daily hauling, long-term storage and slurry spreading requires a higher initial investment in structures and equipment and may greatly impact the timeliness of tillage and planting (Harrigan et al., 1996), but these systems are preferred because they are easily mechanized and a range of equipment options are available.

Travel distance can greatly influence labor requirements and costs and is often the most variable factor affecting manure hauling rate (Welty et al., 1986). Scarborough et al. (1978) evaluated spreader tank costs and reported that selection of a larger than optimal spreader tank was generally more economical than a smaller than optimal tank, and optimal tank volume increased as transport distance increased. Truck-mounted and truck- and tractor-drawn spreader tanks and systems using truck-drawn nurse tanks capable of transporting 45420 L (12,000 gal) or more of liquid slurry are being used by livestock producers to spread manure in a timely and cost-efficient manner. Livestock producers can recover manure storage and handling costs by accounting for manure nutrients and reducing the purchase of commercial fertilizer. A break-even hauling distance over which the value of manure nutrients applied will equal the ownership and operating costs of transport and land application is a function of the machinery set and nutrient content of the manure. A break-even hauling distance of 12.9 km (8 miles) was reported when using solid beef manure as a crop nutrient source in Idaho (Araji and Stodick, 1990) and 16 km (10 miles) when using solid dairy manure as a nutrient source for corn production in Texas (Adhikari et al., 2005).

Accurate estimates of the hauling capacity of spreader tank systems are needed to create valid models which give meaningful comparisons between system alternatives. Motion-and-time studies have been used to document the productivity of specific manure handling systems (Sweeten and Reddell, 1979; Phillips, 1980; Welty et al., 1986). Welty et al. (1986) reported that total cycle time for a tractor-drawn spreader tank was typically 7 to 10 min plus travel time, but cycle time varied with spreader tank volume, manure application rate, machinery set, and other farm-specific

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factors (Phillips, 1980; Maschhoff and Meuhling, 1985; Welty et al., 1986; Harrigan, 1997).

Farm system computer models using linear programming (Coote et al., 1976; Safley et al., 1977), mixed integer programming (Amir and Ogilvie, 1977), cost analysis (Scarborough et al., 1978; Bennett et al., 1991) network analysis (Safley et al., 1976; Burney et al., 1980), and simulation (Borton et al., 1995; Harrigan et al., 1996) have been used to select machinery and evaluate the economics and performance of manure management systems. Harrigan (1997) developed a general model with machinery system-specific coefficients to predict the effective hauling capacity of commonly used spreader tank systems as a function of spreader tank volume and distance hauled. Harrigan (2001) provided a format for linking the hauling capacity of spreader tank systems with machinery data to evaluate farm-specific transport and land application costs. Hadrich et al. (2008) developed a modified linear program to balance least-cost rations that included manure transport and disposal cost. Incorporating the excess phosphorus disposal cost increased feed cost by 1% but decreased disposal costs and resulted in a cost savings of $4,883 per year for a 200-cow dairy.

Livestock operations in the Great Lakes region are consolidating and increasing in size. Because more animals are housed at a single location there is a greater volume of manure to handle and the transport distance has increased because a larger land base is needed for land application. Rising costs for commercial fertilizer have created an incentive for crop producers to use manure as a major nutrient source. Brokering of manure between livestock and crop farms is being promoted in several states (Cabot et al., 2004). A small fraction of liquid manure is applied on hay ground during the growing season, but most is applied in the spring prior to planting, in late summer after small grain harvest, or in the fall after corn harvest so there are generally few suitable days for manure application. Custom haulers typically have the specialized, high-capacity equipment needed to complete hauling and land application within the time available. There is a need for current estimates of the hauling capacity of liquid manure transport and land application systems used by custom haulers.

Objectives

Specific objectives of this work were to:

- Identify representative material flow rates, travel, and support time for loading, transport, and unloading of spreader tank and spreader tank/nurse tank systems used by custom liquid manure applicators in the Great Lakes region.
- Simulate the hauling rate of commonly used spreader tank systems and develop a reference table of machinery system-specific coefficients for use with a general model whereby the hauling rate is a function of spreader tank volume and hauling distance.
- Compare the hauling capacity of commonly used tank spreader systems over a range of tank volumes and distance hauled.

Procedure

Farm managers, consultants, and others working with machinery management data use equipment capacity information to estimate costs and select machinery to complete field operations within the time available. A major effort in determining hauling rates for custom applicators using liquid manure systems was in determining representative loading and unloading rates, time for maneuvering in the field and near the storage structure, and over-the-road travel time. A time-and-motion study of 13 hauling systems on 10 farms using custom hauling services in Michigan, Ohio, and Ontario, Canada was completed in 2006-2008 (table 1). The manure hauling cycle was divided into discrete time units for data collection: 1) loading the spreader, 2) maneuvering the spreader near the storage structure, 3) transporting the spreader to the field, 4) maneuvering the spreader in the field, 5) unloading the spreader, and 6) transporting the spreader back to the storage structure. At least six complete hauling cycles were observed for each system at each farm to determine representative rates and times. Time required for each activity was logged by the researcher and recorded to the nearest second.

The time and material flow rates identified in the motion-and-time study were used to determine representative parameters. Parameters selected were approximate median values (table 2). These parameters were used to create a static, spreadsheet-based model to estimate a theoretical hauling capacity for commonly used spreader tank systems using broadcast and injection application over a range of tank volume and distance hauled. The systems modeled were: 1) tractor-drawn spreader tank, 2) high-speed tractor-drawn spreader, 3) truck-drawn spreader tank, broadcast application, 4) two truck-drawn, over-the-road nurse trucks in parallel with a tractor-drawn spreader tank of equal volume, and 5) two truck-drawn, over-the-road nurse trucks in parallel with a spreader tank with one-half the volume of the nurse tanks.

Representative material flow rate, travel, and support time for loading, transport, and unloading of spreader tank and spreader/nurse tank systems were used with the spreadsheet model to estimate a theoretical hauling capacity for spreader tank systems over a range of tank volume and distance hauled. The simulated data revealed an exponential decay in hauling rate as transport distance increased. Logarithmic transformation of the simulated hauling rate (L/h, gph) and tank volume (L, gal) was used to create a linear relationship among variables. Multiple regression of the simulated data was used to identify coefficients for each machinery set with manure hauling rate (L/h, gph) as the dependent variable and spreader tank volume (L, gal) and travel distance (km, mile) as independent variables (Harrigan, 1997). The equation with machinery system-specific coefficients can be used to generate data suitable for a specific farm, or can be used in a more generalized way to evaluate and compare alternative manure hauling systems.

Results

The objective of the motion-and-time study was to identify representative material flow rates, travel and support time for loading, transport and unloading of spreader tank

Table 1. Summary of representative time and material flow rates identified in a motion- and-time study of livestock farms in the Great Lakes Region.

	Mean	Range	Median	Selected[a]
Spreader loading				
At the storage pit (L/min)	6968	3997-9341	7350	7190
(gpm)	1841	1056-2468	1942	1900
In-field, nurse to spreader (L/min)	4856	2865-7036	5144	4920
(gpm)	1283	757-1859	1359	1300
Spreader unloading				
Broadcast, tank spreader (L/min)	9489	5787-11487	9557	9465
(gpm)	2507	1529-3035	2525	2500
Broadcast, truck-mount (L/min)	4856	2865-7036	5144	4920
(gpm)	1283	757-1859	1359	1300
Injection, 6-pt. injector (L/min)	5102	3414-6336	4860	5110
(gpm)	1348	902-1674	1284	1350
Injection, per injector (L/min)	814	568-1033	783	850
(gpm)	215	150-273	207	225
Maneuvering and positioning				
Tank spreader, over-the-road (min)	6.8	5.2-7.6	6.9	6.8
In-field tank spreader (min)	4.5	2.8-6.1	4.1	4.5
Nurse truck/truck-mounted (min)	7.4	4.3-9.4	7.6	7.5
Travel and transport				
High-speed tractor to field (km/h)	34.9	30.6-39.4	35.7	35
(mph)	21.7	19.0-24.5	22.2	22.0
High-speed tractor to storage (km/h)	41.8	34.9-46.3	42.2	42
(mph)	26.0	21.7-28.8	26.2	26.0
Standard tractor to field (km/h)	29.9	27.4-33.3	29.9	30
(mph)	18.6	17.0-20.7	18.6	18.5
Standard tractor to storage (km/h)	30.9	29.0-32.5	30.9	31
(mph)	19.2	18.0-20.2	19.2	19.0
Nurse/truck-mount to field (km/h)	50	38.3-57.3	51.5	50
(mph)	31.1	23.8-35.6	32.0	31.0
Nurse/truck-mount to pit (km/h)	56.3	40.4-68.7	59.2	56
(mph)	35.0	25.1-42.7	36.8	35.0

[a] Indicates representative values used with the hauling rate model to determine machinery system-specific coefficients.

and spreader tank/nurse tank systems used by custom liquid manure applicators in the Great Lakes region.

Motion-and-Time Study

Hauling distance was measured from the point a spreader or nurse tank entered the county road near the storage structure to the point it exited the road near the spreading site. An average speed was calculated based on travel time and distance. Time loading the tank at the storage structure and unloading in the field were based on tank volume and pump flow rate. Time spent positioning the spreader at the storage pit maneuvering between the storage structure and the public road, and in the field positioning the spreader between the public road and the start of spreading site were measured and reported as maneuvering time.

Most custom applicators evaluated in this work used tractors designed for rapid (40 km/h; 25 mph and greater) over-the-road transport. The JCB Fastrac 8250 had a rated road speed of 64 km/h (40 mph). The Fendt 926 was rated at 50 km/h (31 mph). The Challenger MT665B, Case-IH 305 Magnum and Ag Chem Terra Gator 9105 were rated at 40 km/h (25 mph). These ‘high-speed’ tractors averaged 35 km/h (21.7 mph) with a full tank over a mix of paved and unpaved roads with hauling distances ranging from 3.5 to 6.1 km/h (2.2 to 3.8 miles). The return trip with an empty spreader averaged 42 km/h (26 mph). Representative transport speeds of 35 km/h (22 mph) with a loaded spreader and 42 km/h (26 mph) with an empty spreader were used in developing the machinery system-specific coefficients for the ‘high-speed’ tractor-drawn spreaders (table 2).

Several tractors were rated in the 32- to 35-km/h (20- to 22-mph) range (Case-IH STX 380, Case-IH MX 285 and the JD 9200). An average transport speed with these ‘standard’ tractors (rated at less than 40 km/h; 25 mph) over 3.5 to 5.8 km (2.2 to 3.6 mile) averaged 30 km/h (18.6 mph) with a loaded spreader and 31 km/h (19.2 mph) with an empty spreader (table 2). Representative transport speeds used in developing the machinery system-specific coefficients were 30 and 31 km/h (18.5 and 19 mph) for loaded and empty tractor-drawn spreaders, respectively.

Truck travel speeds were greater than tractor speeds. Average truck travel speeds with a full tank ranged from 38.3 to 57.8 km/h (23.8 to 35.9 mph) with travel distances of 4.3 to 14.5 km (2.7 to 9 miles). The return trip with an empty tank ranged from 40.4 to 68.7 km/h (25.1 to 42.7 mph). Representative transport speeds selected for truck-drawn/mounted spreaders were 50 km/h (31 mph) loaded and 56 km/h (35 mph) empty (table 2).

Reported on-farm slurry tank loading rates for top-loaded spreader tanks ranged from 3596 to 9084 L/min (950 to 2400 gpm; Maschhoff and Muehling, 1985; Welty et al., 1986; Brown et al., 1994; Harrigan, 1997). Manure pumps

Table 2. Manure hauling motion-and-time study farm and machine performance data.

Farm	1	2	3	4	5	6	7
Livestock	Dairy	Dairy	Dairy	Dairy	Dairy	Dairy	Swine
Manure storage	In-ground pit	In-ground pit	In-ground pit	In-ground pit	In-ground pit	In-ground pit	Concrete tank
Hauling distance (km)[a]	8.4	11.3-14.5	5.8	4.7	3.5	6.1	5.8
Hauling method	Truck-drawn nurse to spreader	Truck-drawn nurse to spreader	Truck-drawn nurse to spreader	Tractor-drawn	Tractor-drawn	Tractor-drawn	Tractor-drawn
Application method	Inject, 6-pt	Broadcast	Broadcast	Inject, 6-pt	Inject, 5-pt	Broadcast	Broadcast
Machinery used							
Spreader tractor[b]	Challenger MT665B	Fendt 926	Case-IH MX285	JCB 8250	JD 9200	Challenger MT665B	Case-IH STX380
Tractor-drawn spreader (L)[a]	34065	35958	35958	37850	22710	35958	37850
Truck-drawn spreader (L)	---	---	---	---	---	---	---
Truck-mounted spreader (L)	---	---	---	---	---	---	---
Truck-drawn nurse tank (L)	2-22710	3-30280	3-8000	---	---	---	---
Pump/agitator	Trailer	Trailer	Trailer	Trailer	Trailer	Trailer	Wall-mount
Machine performance							
Pit loading (L/min)[a]	9341	5144	4826	8668	5273	3217	5579
Spreader unloading (L/min)	3414	10836	9209	6200	4860	8255	5787
Transfer, nurse to spreader (L/min)	2865	4663[c]	7188	---	---	---	---
Truck/tractor travel to field (km/h)[a]	48	55	38	33	31	31	28
Truck/tract. travel to storage (km/h)	53	59	40	43	32	35	30
Maneuvering and positioning							
Tractor-spreader, in-field (min.)	5.4	2.6	4.1	---	---	---	---
Tractor-spreader (min.)	---	---	---	7.3	6.9	6.4	6.9
Truck-drawn/mounted (min.)	---	---	---	---	---	---	---
Nurse tank (min.)	6.4	4.3	9.1	---	---	---	---

are seldom used at full capacity because high flow rates can cause foaming in the spreader tank and limit usable tank volume, and pipe stands may become unstable at high flow rates. Spreader loading rates measured in this study ranged from 3997 to 9341 L/min (1056 to 2468 gpm; table 2). The lower rate was recorded with a self-propelled manure pump when removing swine manure from a below-ground concrete tank. Higher pumping rates were possible but the storage pit was nearly empty and the pump would draw air at greater pumping rates. The higher pumping rate was attained when filling from a clay-lined pit with an 8-in. pump agitator. A representative loading rate of 7192 L/min (1900 gpm) was used in developing the machinery system-specific coefficients.

Reported on-farm slurry unloading rates ranged from 473 to 1067 L/min (125 to 282 gpm) per injector shank for subsurface injection (Scarborough, 1978; Welty et al., 1986; Harrigan, 1997), and 2952 to 5946 L/min (780 to 1571 gpm) for surface spreading (Phillips, 1980; Welty et al., 1986; Harrigan, 1997). Spreader unloading rates in this study ranged from 3414 to 11487 L/min (902 to 3035 gpm; table 2). The lower rate was observed with a 6-pt injector when the flow rate was controlled with a hydraulically-driven pump to achieve a target application rate of 65478 L/ha (7000 gpa). The higher rate was attained with a broadcast application with a large tractor-drawn spreader tank. A representative unloading rate of 9463 L/min (2500 gpm) for broadcast application was used in developing the machinery system-specific coefficients (table 2). Five to nine injector shanks were used on the spreader tanks evaluated in this study. The unloading rate with slurry injection ranged from 568 to 1033 L/min (150 to 273 gpm) per injector shank. A representative injection rate of 852 L/min (225 gpm) per injector was used in developing the machinery system-specific coefficients.

Welty et al. (1986) reported that 10% to 12% percent of total hauling time was spent mounting/dismounting the tractor and maneuvering the spreader tank under the pump spout. When manure was transferred from nurse- to spreader-tank, about 1.5 additional minutes was needed to connect the nurse tank to the spreader tank (Maschhoff and Muehling, 1985). Harrigan (1997) reported maneuvering times ranging from 4.5 to 11.7 min for spreader tank systems. Time maneuvering in the field varied with distance from the county road. Near the storage pit, maneuvering time varied with the time needed to position the spreader at the pump. Over-the-road transport with a nurse tank to a spreader tank for field application involved an additional step; transfer of the manure slurry from the nurse tank to a spreader tank. Total time needed to maneuver and position the spreader tank ranged from 2.8 to 6.1 min for tractor-drawn spreaders in the field when serviced by nurse trucks, and 5.2 to 7.6 min when hauling over-the-road from the storage pit to the field. Nurse trucks and truck-drawn spreader tanks required more time for maneuvering and positioning, 4.3 to 9.4 min. Representative maneuvering times were 4.5 min for tank spreaders in-the-field, 6.8 min for tank spreaders over-the-road, and 7.5 min for nurse tanks and truck-drawn spreaders (table 2).

Efficiency factors are frequently used in machinery management to estimate the ratio of the time a machine is effectively operating to the total time the machine is committed to an operation (Hunt, 1995; *ASABE Standards,* 2007). Phillips (1980) reported a functional efficiency for

Table 2. Continued

Farm	8	9	10	11	12	13
Livestock	Dairy	Dairy	Dairy	Swine	Dairy	Dairy
Manure storage	In-ground pit	In-ground pit	In-ground pit	Concrete tank	In-ground pit	In-ground pit
Hauling distance (km)	3.5-4.3	4.7	5.0	7.1	5.1	5.6
Hauling method	Tractor-drawn	Tractor-drawn	Truck-drawn nurse to spreader	Truck-drawn nurse to spreader	Tractor-drawn	Truck-drawn nurse to spreader
Application method	Broadcast	Inject, 6-pt	Surface placement	Inject, 9-pt	Broadcast	Broadcast
Machinery used						
Spreader tractor	Fendt 926, Case-IH MX285	Challenger MT665B	Ag-Chem Terragator	JCB 8250	MT665B	Case-IH 305 Magnum
Tractor-drawn spreader (L)	27631, 35958	28388	2-17033	35958	35958	35958
Truck-drawn spreader (L)	---	---	---	---	---	---
Truck-mounted spreader (L)	---	---	---	---	---	---
Truck-drawn nurse tank (L)	---	---	3-34065[c]	3-30280	---	3-34065
Pump/agitator	Trailer	Trailer	Trailer	Trailer	Trailer	Trailer
Machine performance			[c]Frac tank			
Pit loading (L/min)	6457	8391	9035	3997	9864	Did not record
Spreader unloading (L/min)	9557	4705	3747	6340	11283	11487
Transfer, nurse to spreader (L/min)	---	---	4277	5469	---	4451
Truck/tractor travel to field (km/h)	36	36	52	58	39	---
Truck/tract. travel to storage (km/h)	41	42	60	69	44	---
Maneuvering and positioning						
Tractor-spreader, in-field (min.)	---	---	3.5	5.8	---	2.8
Tractor-spreader (min.)	5.2	6.8	---	---	7.2	---
Truck-drawn/mounted (min.)	---	---	---	---	---	---
Nurse tank (min.)	---	---	9.4	8.0	---	---

[a] km × 0.62 equals miles; L × 0.264 equals gallons.
[b] Tractor power ratings: JCB Fastrac 8250, 168 pto-kW (225 pto-hp); Fendt 926, 197 pto-kW (265 pto-hp); Challenger MT665B, 197 pto-kW (265 pto-hp); Case-IH 305 Magnum, 224 pto-kW (300 pto-hp); Case-IH STX 380, 261 pto-kW (350 pto-hp); Case-IH MX 285, 179 pto-kW (240 pto-hp); JD 9200, 220 pto-kW (295 pto-hp).
[c] In-field manure transfer from an over-the-road nurse truck to a stationary frac tank.

manure hauling and land application of about 0.93 when allowing time for equipment repair and maintenance; 0.83 to 0.86 when allowing additional time for personnel breaks. Sweeten and Reddell (1979) reported functional efficiencies for manure collection equipment ranging from 0.79 to 0.90. Harrigan (1997) proposed an efficiency range of 0.85 to 0.95 for surface spreading to allow for machine preparation and adjustment time, repair and maintenance, and operator personal time.

Short-term efficiencies observed in this work ranged from 66% when two nurse trucks were delayed by slow pump performance to 100% when an in-the-field tractor-spreader refilled from a frac tank. A functional efficiency ranging from 0.85 to 0.95 is proposed for tractor-drawn, truck-drawn, or truck-mounted spreaders hauling over-the-road for broadcast applications. Efficiencies ranging from 0.80 to 0.90 are proposed for slurry injection, or when in-field tractor-drawn spreaders work in parallel with nurse trucks for over-the-road transport. The upper limit of this range applies to well-maintained equipment where little time is generally needed for unexpected maintenance or personal time, and where transport conditions would be expected to cause few delays. The lower limit applies to older or poorly maintained equipment; where field shape or access may increase off-road transport time; or when time for breaks and other personal time are included. The lower efficiencies are proposed for slurry injection to account for additional downtime for injector repair and maintenance.

Hauling Rate Model

The simulated hauling rates based on the parameters selected for custom hauling were fit to the general model developed by Harrigan (1997) for spreader tank systems. Material capacity was defined as the volume of liquid manure (L/h, gph) removed from storage and applied to the land by tractor- or truck-drawn spreader tanks, or spreader tanks in combination with truck-drawn nurse tanks. An exponential function with base *e* and exponent a composite of machinery system-specific parameters and coefficients (tables 3 and 4) was used to model the effective hauling capacity of tractor- and truck-drawn spreader tanks as a function of spreader tank volume and transport distance:

$$H = Ee^{(T-UD+V \ln C)} \tag{1}$$

or alternatively,

$$H = Ee^{T} \cdot e^{-UD} \cdot C^{V} \tag{2}$$

where

H is manure hauling rate; L/h (gal/h)

E is a dimensionless efficiency factor for manure application method; 0.85 to 0.95 for surface application and

0.80 to 0.90 for subsurface injection or systems using tank spreaders in combination with nurse trucks.

T[Ln(L$^{(1-V)}$/h), Ln(gal$^{(1-V)}$/h)],U (1/km, 1/mile) and V (dimensionless) are machinery system-specific coefficients (tables 3 and 4).

D is transport distance (km, mile); 0.16 to 16 km (0.1 to 10 mile)

C is the spreader tank volume (L, gal); 9464 to 37850 L (2500 to 10000 gal)

When a truck-drawn nurse tank is used in parallel with a tractor-drawn spreader tank and the field is close to storage, the system hauling capacity will be nearly constant, limited by the spreader tank capacity. An alternative set of equations is proposed to model the effective hauling capacity of nurse

Table 3. Liquid manure transport machinery system-specific regression coefficients.

Hauling Method	Transport Distance	Machinery Set Regression Coefficients T	U	V	R^2 [A]	W	X	R^2	Y	Z	R^2
Tractor-drawn spreader tank, high-speed tractor[a]											
Broadcast	<6.4 km	4.33	0.127	0.706	0.980	---	---	---	---	---	---
	<4 mile	3.94	0.205	0.706	0.980	---	---	---	---	---	---
Broadcast	≥6.4 km	2.48	0.070	0.852	0.992	---	---	---	---	---	---
	≥4 mile	2.28	0.113	0.852	0.992	---	---	---	---	---	---
Injection	<6.4 km	4.84	0.115	0.641	0.982	---	---	---	---	---	---
	<4 mile	4.36	0.186	0.641	0.982	---	---	---	---	---	---
Injection	≥6.4 km	2.83	0.067	0.808	0.992	---	---	---	---	---	---
	≥4 mile	2.57	0.107	0.808	0.992	---	---	---	---	---	---
Tractor-drawn spreader tank, standard tractor[b]											
Broadcast	<6.4 km	4.08	0.146	0.728	0.977	---	---	---	---	---	---
	<4 mile	3.72	0.235	0.728	0.977	---	---	---	---	---	---
Broadcast	≥6.4 km	2.14	0.075	0.874	0.991	---	---	---	---	---	---
	≥4 mile	1.97	0.121	0.874	0.991	---	---	---	---	---	---
Injection	<6.4 km	4.57	0.133	0.666	0.978	---	---	---	---	---	---
	<4 mile	4.12	0.215	0.666	0.978	---	---	---	---	---	---
Injection	≥6.4 km	2.44	0.072	0.835	0.991	---	---	---	---	---	---
	≥4 mile	2.22	0.116	0.835	0.991	---	---	---	---	---	---
Truck-drawn/truck mounted spreader tank[b]											
Broadcast	<6.4 km	4.99	0.090	0.642	0.984	---	---	---	---	---	---
	<4 mile	4.49	0.145	0.642	0.984	---	---	---	---	---	---
Broadcast	≥6.4 km	3.35	0.058	0.766	0.994	---	---	---	---	---	---
	≥4 mile	3.04	0.093	0.766	0.994	---	---	---	---	---	---
Nurse truck volume equals spreader tank volume[c]											
1 spreader tank, 2 nurse trucks											
Broadcast	≤W+XC, km	---	---	---	---	-0.415	0.00012	1.0	73227	1.78	0.986
	≤W+XC, mile	---	---	---	---	-0.260	0.00028	1.0	19360	1.78	0.986
Broadcast	>W+XC, km	4.10	0.061	0.761	0.986	---	---	---	---	---	---
	>W+XC, mile	3.78	0.099	0.761	0.986	---	---	---	---	---	---
Injection	≤W+XC, km	---	---	---	---	-0.401	0.00020	0.999	68006	1.28	0.985
	≤W+XC, mile	---	---	---	---	-0.253	0.00046	0.999	17967	1.28	0.985
Injection	>W+XC, km	3.97	0.060	0.771	0.985	---	---	---	---	---	---
	>W+XC, mile	3.67	0.096	0.771	0.985	---	---	---	---	---	---
Nurse truck volume equals two times spreader tank volume[c]											
1 spreader tank, 2 nurse trucks											
Broadcast	≤W+XC, km	---	---	---	---	1.93	0.00017	1.0	46164	3.31	0.999
	≤W+XC, mile	---	---	---	---	1.20	0.00040	1.0	12197	3.31	0.999
Broadcast	>W+XC, km	3.16	0.048	0.747	0.994	---	---	---	---	---	---
	>W+XC, mile	4.15	0.077	0.747	0.994	---	---	---	---	---	---
Injection	≤W+XC, km	---	---	---	---	1.72	0.00030	0.993	44991	2.58	1.0
	≤W+XC, mile	---	---	---	---	1.07	0.00070	0.993	11887	2.58	1.0
Injection	>W+XC, km	3.12	0.045	0.744	0.996	---	---	---	---	---	---
	>W+XC, mile	4.11	0.072	0.744	0.996	---	---	---	---	---	---

[a] R^2 is the square of the correlation coefficient between the simulated value of the dependent variable (H in eqs. 1, 2, and 4, D in eq. 3) and the predicted value from the fitted line.
[b] Coefficients T, U, and V apply to equation 1 and 2.
[c] Coefficients T, U, and V apply to equation 1 and 2; W and Y to equation 3; Y and Z to equation 4.

Table 4. Machinery system-specific regression coefficients derived from the sensitivity analysis of liquid manure transport.

Hauling Method	Transport Distance	Machinery Set Regression Coefficients									
		T	U	V	R^2 [a]	W	X	R^2	Y	Z	R^2
Tractor-drawn spreader tank, high-speed tractor[b]											
Pit loading, 8630 L/min	<6.4 km	4.72	0.118	0.657	0.980	---	---	---	---	---	---
2280 gpm	<4 mile	4.26	0.191	0.657	0.980	---	---	---	---	---	---
8630 L/min	≥6.4 km	2.74	0.068	0.820	0.991	---	---	---	---	---	---
2280 gpm	≥4 mile	2.50	0.109	0.820	0.991	---	---	---	---	---	---
6-pt. injection, 6132 L/min	<6.4 km	4.22	0.120	0.709	0.980	---	---	---	---	---	---
1620 gpm	<4 mile	3.83	0.193	0.709	0.980	---	---	---	---	---	---
6132 L/min	≥6.4 km	2.14	0.068	0.881	0.991	---	---	---	---	---	---
1620 gpm	≥4 mile	1.98	0.109	0.881	0.991	---	---	---	---	---	---
Nurse tank equals spreader tank volume[c]											
In-field transfer,5905 L/min	≤W+XC km	---	---	---	---	-0.333	0.00018	0.998	70166	1.44	0.962
1560 gpm	≤W+XC mile	---	---	---	---	-0.207	0.00042	0.998	18538	1.44	0.962
5905 L/min	>W+XC km	3.90	0.061	0.782	0.986	---	---	---	---	---	---
1560 gpm	>W+XC mile	3.61	0.098	0.782	0.986	---	---	---	---	---	---
Maneuvering, 6 min	≤W+XC km	---	---	---	---	0.236	0.00020	0.999	68006	1.28	0.970
	≤W+XC mile	---	---	---	---	0.147	0.00046	0.999	17967	1.28	0.970
	>W+XC km	3.97	0.060	0.775	0.988	---	---	---	---	---	---
	>W+XC mile	3.67	0.096	0.775	0.988	---	---	---	---	---	---
Nurse tank equals 2× spreader tank volume[c]											
In-field transfer,5905 L/min	≤W+XC km	---	---	---	---	1.93	0.00026	1.0	45344	2.83	1.0
1560 gpm	≤W+XC mile	---	---	---	---	1.20	0.00060	1.0	11980	2.83	1.0
5905 L/min	>W+XC km	4.35	0.046	0.758	0.996	---	---	---	---	---	---
1560 gpm	>W+XC mile	4.03	0.074	0.758	0.996	---	---	---	---	---	---
Maneuvering, 6 min	≤W+XC km	---	---	---	---	3.06	0.00026	1.0	44991	2.58	1.0
	≤W+XC mile	---	---	---	---	1.90	0.00060	1.0	11887	2.58	1.0
	>W+XC km	4.53	0.045	0.739	0.996	---	---	---	---	---	---
	>W+XC mile	4.18	0.072	0.739	0.996	---	---	---	---	---	---

[a] R^2 is the square of the correlation coefficient between the simulated value of the dependent variable (H in eqs. 1, 2 and 4, D in eq. 3) and the predicted value from the fitted line.
[b] Coefficients T, U, and V apply to equation 1 and 2.
[c] Coefficients T, U, and V apply to equation 1 and 2; coefficients W and Y to equation 3; Y and Z to equation 4.

tank/spreader tank systems when the spreading site is within a few kilometers (miles) of storage:
if

$$D \leq W + XC \tag{3}$$

then

$$H = E(Y + ZC) \tag{4}$$

where

D is transport distance; 0.16 to 16 km (0.1 to 10 mile)

W(km, mile), X(km/L, mile/gal),Y(L/h, gal/h),and Z (L/h) are machinery system-specific coefficients (tables 3 and 4).

H is manure hauling rate (L/h, gph);

C is spreader tank volume (L, gal).

Equation 3 defines the range of over-the-road transport distance where spreader tank capacity will likely limit system capacity. Equation 4 estimates an effective hauling capacity of nurse tank/spreader tank systems which use two nurse tanks in parallel with a spreader tank within a few kilometers (miles) of storage. When hauling within the distance defined by equation 3, equation 4 can be used to evaluate an effective hauling capacity.

The hauling rate equations and proposed machinery system-specific coefficients provide a useful tool for comparing the effective hauling capacity of commonly used spreader tank systems. These equations and coefficients were used with a hauling efficiency of 0.85 for injection and nurse/spreader tank systems and 0.90 for truck- and tractor-drawn broadcast applications to compare the effects of tank volume, transport distance, and machinery set on the effective hauling capacity of tractor- and truck- drawn spreaders, and systems using truck-drawn nurse tanks for over-the-road transport.

Tractor and Nurse Truck Travel Speed

The hauling capacity of tractor- and truck-drawn spreaders increased as travel speed increased. There was little advantage for high-speed tractors when hauling near storage, but they had an advantage with longer hauls. Compared to a standard tractor, a 26495-L (7000-gal) spreader drawn with a high-speed tractor had 8% greater hauling capacity with a 1.6-km (1-mile) haul, 14% greater capacity with a 4.8-km (3-mile) haul, and 21% greater capacity with a 16-km (10-mile) haul (fig.1). A truck-drawn spreader traveled faster than a tractor-drawn spreader, but truck-drawn spreaders unloaded at a lower rate and required more time for maneuvering. Compared to truck-drawn spreaders, tractor-drawn spreaders had 20% greater hauling capacity near storage, but truck-drawn spreaders had 8%

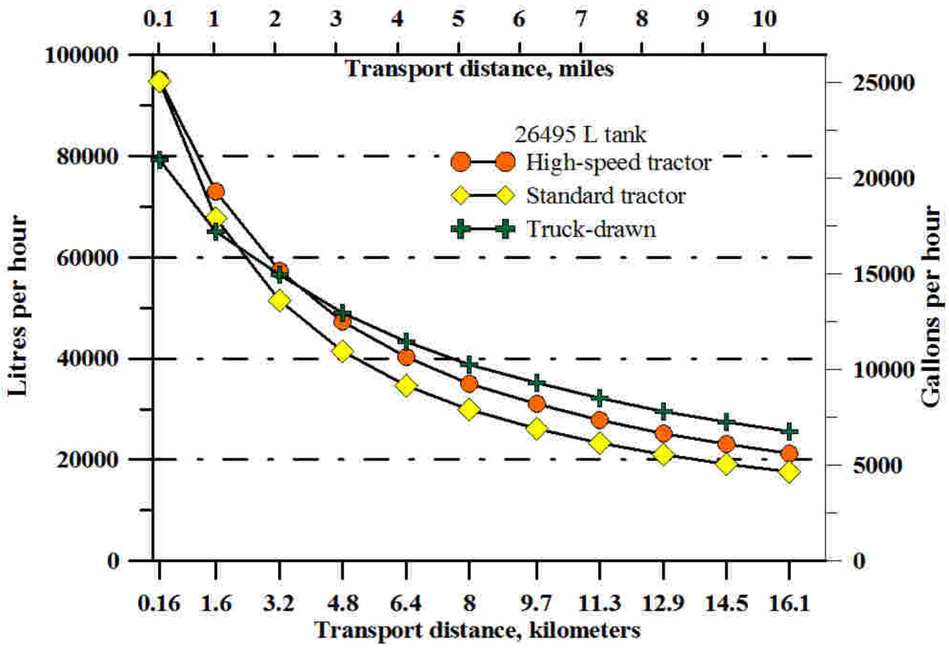

Figure 1. Hauling capacity of a 26495-L (7000-gal) tank spreader drawn with a high-speed or standard tractor, or truck-drawn with broadcast application.

greater capacity with a 6.4-km (4-mile) haul and 20% greater capacity with a 16-km (10-mile) haul. The cycle time when hauling near storage was 0.239 h with the standard tractor, 0.238 h with the high-speed tractor, and 0.286 h with the truck-drawn spreader. The cycle time when hauling 16 km (10 miles) increased to 1.294 h with a standard tractor, 1.067 h with a high-speed tractor, and 0.888 h with a truck-drawn spreader.

Tank Volume

Increasing tank volume increased the hauling rate, but because loading and unloading time increased with tank volume, hauling capacity did not increase in direct proportion to tank volume. A 40% increase in tank volume (from 18925 to 26495 L; 5000 to 7000 gal) increased hauling capacity about 26% with a 1.6-km (1-mile) haul and 37% with a 16-km (10-mile) haul (fig. 2). The cycle time for an 18,925-L (5,000-gal) tractor-drawn spreader ranged from 0.21 h for a 0.16-km (0.10-mile) haul to 1.26 h for a 16-km (10-mile) haul. A somewhat longer cycle time was needed for a 9,000-gal spreader; 0.27 h for a 0.16-km (0.10-mile) haul and 1.33 h for a 16-km (10-mile) haul.

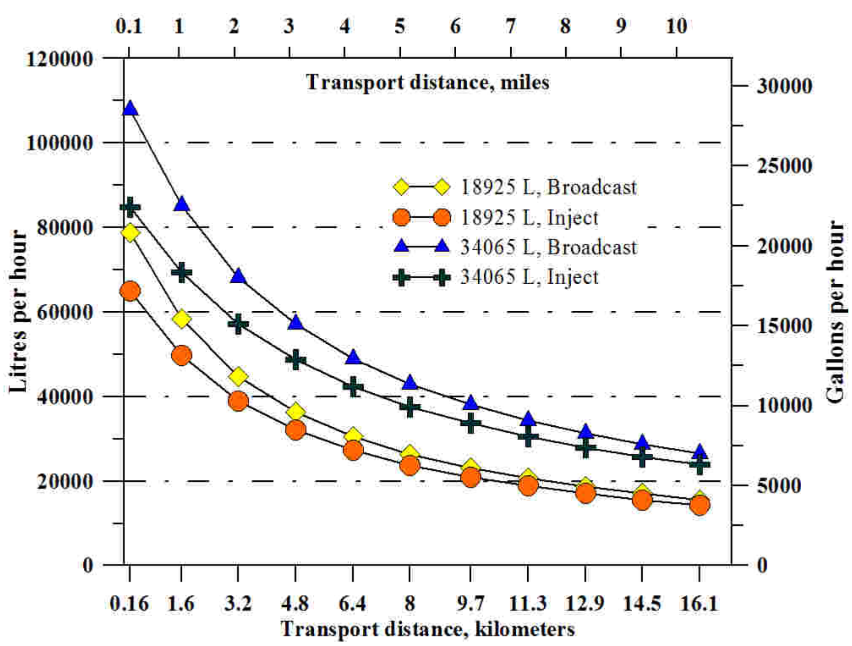

Figure 2. Hauling capacity with high-speed tractor-drawn 18925-km (5000-gal) and 34065-L (9000-gal) spreaders with surface broadcast or subsurface injection.

Broadcast vs. Injection

A representative unloading rate was 9463 L/min (2500 gpm) for a broadcast application with a splash plate and 852 L/min (225 gpm) per injector for slurry injection. Compared to injection with a 6-shank injector (5110 L/min; 1350 gpm) a broadcast application with a 26495 L (7000 gal) high-speed tractor-drawn spreader increased the hauling rate 25% near storage, 17% with a 3.2 km (2 mile) haul, and 10% with a 16 km (10 mile) haul (fig 2). Broadcast cycle times were 0.238, 0.478, and 1.067 h over 0.16, 4.8, and 16 km (0.1, 3, and 10 mile), respectively. Injection cycle times were 0.28, 0.52, and 1.109 h over the same distances.

Nurse Trucks in Parallel with a Spreader Tank, Nurse Truck Volume Equal to Spreader Vo1ume

Two nurse trucks are often used for over-the-road transport to a tractor–drawn spreader in the field. When the nurse trucks and spreader tank held an equal volume the tractor-spreader had no idle time near storage. When two 18925-L (5000-gal) nurse trucks were used in parallel with an 18925-L (5000-gal) tractor-spreader for slurry injection, the tractor-spreader had no idle time within 3.4 km (2.1 miles) of storage (fig. 3). Beyond this distance the tractor-spreader had to wait for a nurse truck because it applied the manure faster than the two nurse trucks were able to deliver it. A 26495-L (7000-gal) machinery set had no idle time within 4.8 km (3 miles) of storage, and a 34065-L (9000-gal) machinery set had no idle time within 6.3 km (3.9 miles). The tractor-spreader cycle times (with no idle time) were 0.194 h with 18925-L (5000-gal) tanks, 0.243 h with 26495-L (7000-gal) tanks, and 0.29 h with 34065-L (9000-gal) tanks. When hauling 16 km (10 miles), cycle times were 0.435, 0.455, and 0.475 h for the 18925, 26495, and 34065 L (5000, 7000, and 9000 gal) machinery sets, respectively.

Nurse Trucks in Parallel with a Spreader Tank, Nurse Truck Volume Equal to Spreader Volume, Broadcast vs. Injection

Nurse truck and tractor–spreader systems had greater hauling capacity with broadcast than injection because tractor-drawn spreaders unloaded faster with a broadcast application. Compared to injection, the no-idle-time hauling rate with a broadcast application increased 16% with a 18925-L (5000-gal) machinery set and 20% with a 34065-L (9000-gal) machinery set (fig. 4). The lower unloading rate with injection reduced the overall hauling capacity, but increased the hauling distance over which tractor-spreader had no idle time. Compared to a broadcast application, injection increased the no-idle-time hauling distance from 1.9 to 3.4 km (1.2 to 2.1 miles) with a 18925-L (5000-gal) machinery set, 2.7 to 4.8 km (1.7 to 3 miles) with a 26495-L (7000-gal) machinery set, and 3.7 to 6.3 km (2.3 to 3.9 miles) with a 34065-L (9000-gal) machinery set. Once the hauling distance exceeded the point where the tractor-spreader incurred idle time with injection, there was no difference in the hauling rate between broadcast and injection because nurse truck capacity limited system capacity. The broadcast no-idle cycle time when hauling close to storage was 0.167 h for the 18925-L (5000-gal) machinery set and 0.29 h for the 34065-L (9000-gal) machinery set.

Nurse Trucks in Parallel with a Spreader Tank, Spreader Tank Volume Equals One-Half Nurse Truck Volume

Some custom haulers use nurse tanks two times larger than the spreader tank. Such a machinery set is generally limited to spreader tanks of 18925 L (5000 gal) or less. Smaller spreader-tanks require less power, improve maneuverability, and may decrease the potential for soil compaction. When a 13248-L (3500-gal) tractor-spreader (broadcast application) was used with two 26495-L (7000-gal) nurse tanks, the tractor-spreader had no idle time within 4.2 km (2.6 miles; fig. 5). When a 13248-L (3500-gal) spreader was

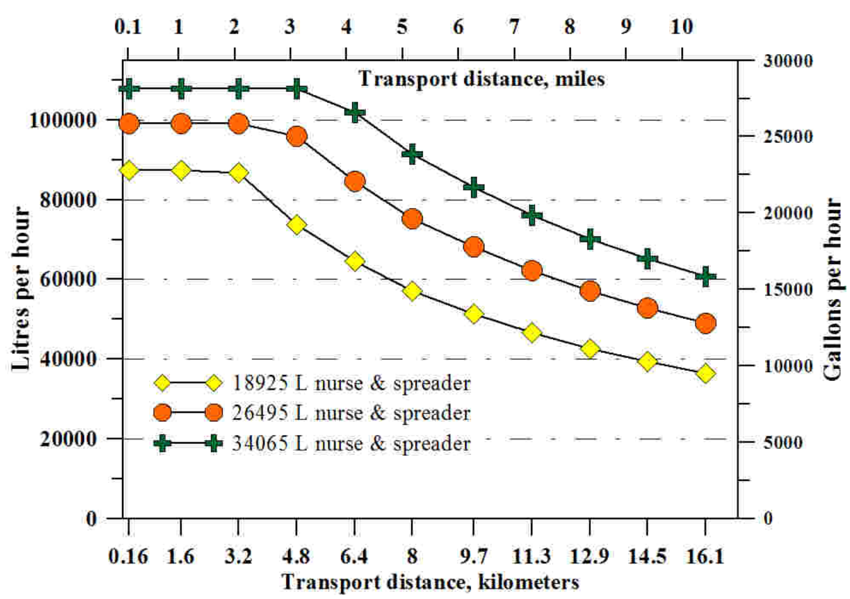

Figure 3. Hauling capacity of 18925-L (5000-gal), 26495-L (7000-gal) and 34065-L (9000-gal) tank-spreaders with two nurse trucks of equal volume with subsurface injection.

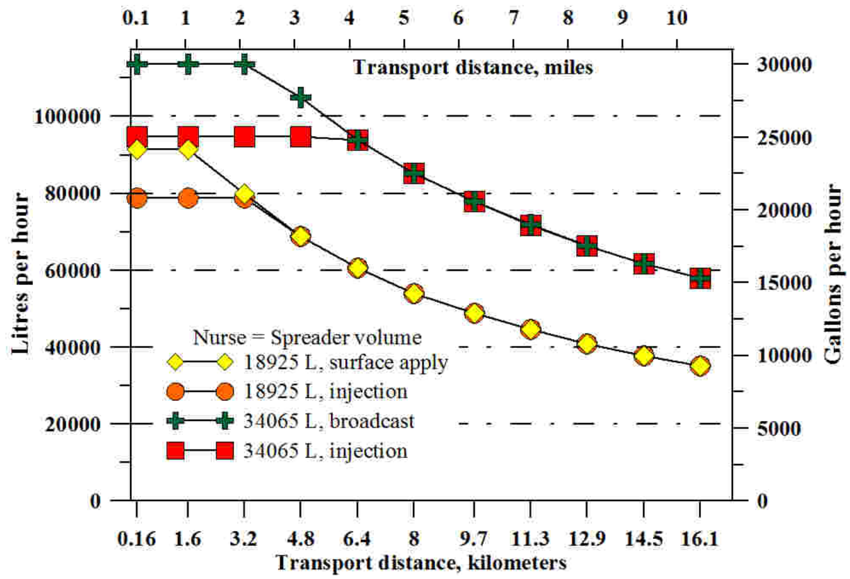

Figure 4. Hauling capacity of two 18925-L (5000-gal) or 34065-L (9000-gal) nurse tanks with a tractor-drawn spreader of equal volume, surface broadcast or subsurface injection.

used with two 13248-L (3500-gal) nurse tanks, the no-idle time distance was reduced to 1.3 km (0.8 miles). The hauling rates was the same for each system near storage, but with a 4.8-km (3-mile) haul the 26495-L (7000-gal) nurse tanks had 42% greater hauling capacity, and 66% more capacity with a 16-km (10-mile) haul. A 26495-L (7000-gal) tractor-spreader with two 26495-L (7000-gal) nurse tanks had 37% greater capacity than a 13248-L (3500-gal) tractor-spreader with two 26495-L (7000-gal) nurse tanks within 1.6 km (1 mile) of storage, 20% more capacity with a 4.8-km (3-mile) haul, and 11% with a 16-km (10-mile) haul. The no-idle cycle time was 0.14 h for the 13248-L (3500-gal) tractor-spreader and 0.205 h for the 26495-L (7000-gal) spreader.

Sensitivity Analysis

A sensitivity analysis was done to examine the response of the simulated hauling rate to changes in key parameters. This analysis was done by changing each parameter by 20% and noting the effect on the hauling rate of the machinery set chosen. Three representative hauling systems using slurry injection with a six-point injector were selected: (1) a high-speed tractor-drawn spreader with a 26495-L (7000-gal) spreader tank, (2) two nurse trucks (26495 L; 7000 gal) in parallel with a tractor-drawn spreader (26495 L; 7000 gal), and (3) two nurse trucks (26495 L; 7000 gal) in parallel with a tractor-drawn spreader (13248 L; 3500 gal). Transport distance varied from 0.16 to 16 km (0.1 to 10 miles). An efficiency of 0.85 was used to estimate an effective hauling rate for each method. Regression coefficients derived from the simulated data are listed in table 4.

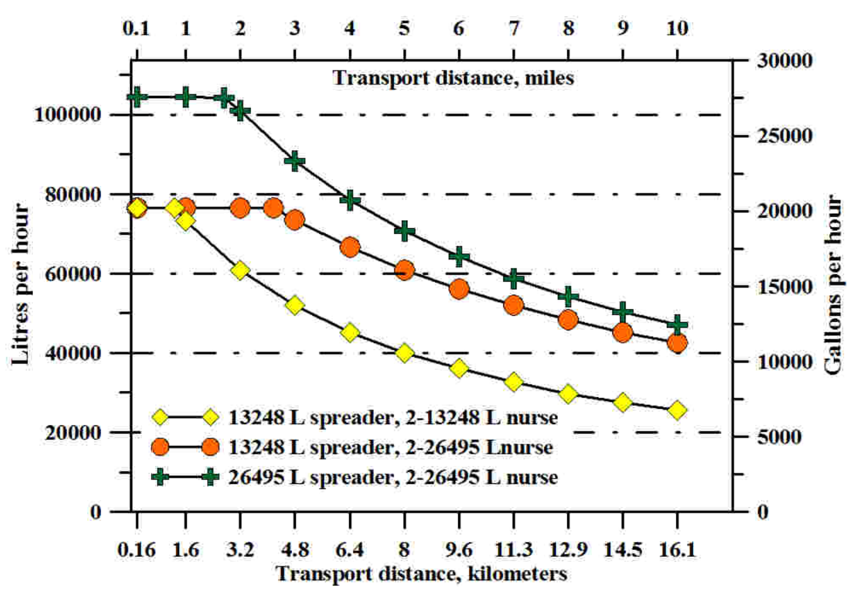

Figure 5. Hauling capacity with broadcast application of a 13258-L (3500-gal) spreader with two 13258-L (two 3500-gal) or two 26495-L (two 7000-gal) nurse trucks, and a 26495-L (7000-gal) spreader with two 26495-L (two 7000-gal) nurse trucks.

The hauling rate of the tractor-drawn spreader tank was compared to hauling rates of the same machinery set with a 20% increase in: (1) the loading rate at the storage pit (from 7192 to 8630 L/min; 1900 to 2280 gpm), (2) the injection flow rate (from 852 to 1022 L/min; 225 to 270 gpm) per injector shank, (3) over-the-road travel speed, and (4) spreader tank volume (from 26495 to 31794 L; 7000 to 8400 gal). A 20% increase in tank volume increased the effective hauling rate about 8% with a 0.16-km (0.1-mile) haul and more than 16% with a 16-km (10-mile) haul (fig. 6). An increase in travel speed had little effect when hauling near storage, but increased the hauling rate more than 7% with a 3.2-km (2-mile) haul and more than 14% with a 16-km (10-mile) haul. An increase in the injector flow rate or the pump flow rate at the storage pit had the greatest effect when hauling near storage. Increasing the injector flow rate increased the effective hauling rate about 6% near storage, less than 4% with a 3.2-km (2-mile) mile haul, and less than 2% with a 16-km (10-mile) haul (fig. 6). Increasing the spreader loading rate increased the hauling rate about 4% with a 0.16 km (0.1 mile) haul and less than 1% with a 16-km (10-mile) hauls.

The hauling rate of nurse tank/spreader tank systems was compared to rates with a 20% increase in: (1) the in-field slurry transfer rate from nurse tank to spreader tank (from 4921 to 5905 L/min; 1300 to 1560 gpm), (2) over-the-road nurse truck travel speed, (3) nurse tank and spreader tank volume, and (4) a 20% decrease in nurse tank maneuvering time (from 7.5 to 6 min per load). When the nurse tank and spreader tank volume were equal, neither increasing nurse tank travel speed nor decreasing nurse tank maneuvering time had an impact on the hauling rate near storage because the spreader tank rather than the nurse tanks limited the hauling rate (fig. 7). When hauling a greater distance, increasing travel speed had a significant effect on the hauling rate; an 8% increase with a 6.4-km (4-mile) haul and a 12% increase with a 16-km (10-mile) haul.

Decreasing maneuvering time 20% increased the hauling rate about 5% with a 6.4-km (4-mile) haul and about 3% with a 16-km (10-mile) haul (fig. 7). Increasing the in-field nurse tank-to-spreader tank flow rate and the nurse tank/spreader tank volume increased the hauling capacity of the spreader tank and thereby the hauling capacity near storage. Increasing the nurse tank volume increased the effective hauling rate about 6% within 4.8 km (3 mile) of storage, 14% with a 6.4-km (4-mile) haul, and more than 16% with a 16-km (10-mile) haul. An increase in in–field manure slurry transfer rate increased the hauling rate more than 6% when hauling near storage, but the increase diminished to about 3% with a 6.4-km (4-mile) haul and less than 2% with a 16-km (10-mile) haul.

When using nurse tanks with twice the volume of the spreader tank, increasing tank volume by 20% increased the hauling rate more than 8% near storage, and about 16% with a 16-km (10-mile) haul (fig. 8). Increasing the nurse tank travel speed had no effect when hauling near storage, but increased the hauling rate about 4% with a 6.4-km (4-mile) haul and 11% with a 16-km (10-mile) haul. Increasing the in-field nurse-to-spreader slurry transfer rate and decreasing the nurse tank maneuvering time increased the productivity of the in-field tank spreader. Each change increased the hauling rate about 4% near storage with a diminishing effect as the hauling distance increased.

Conclusions

- Representative time and rates for loading and unloading, maneuvering and road travel were developed for custom liquid manure application with tank-spreader systems based on a time-and-motion study of 13 hauling systems on 10 farms in Michigan, Ohio, and Ontario, Canada.
- Representative manure slurry flow rates were: 1) 7192 L/min (1900 gpm) for loading at the storage structure, 2) 4921 L/min (1300 gpm) for in-field, nurse truck-to-spreader tank transfer, 3) 852 L/min (225 gpm) per injector shank for subsurface injection, 4) 9463 L/min (2500 gpm) for a broadcast application from a

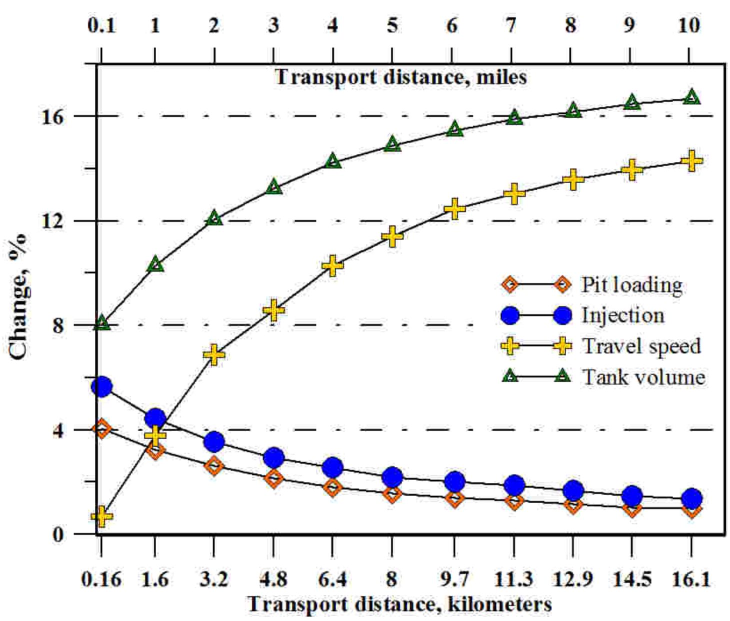

Figure 6. Percent change in the hauling capacity of a 26495-L (7000-gal) tractor-drawn spreader with a 20% increase in pit loading rate, injector flow rate, travel speed, or tank volume.

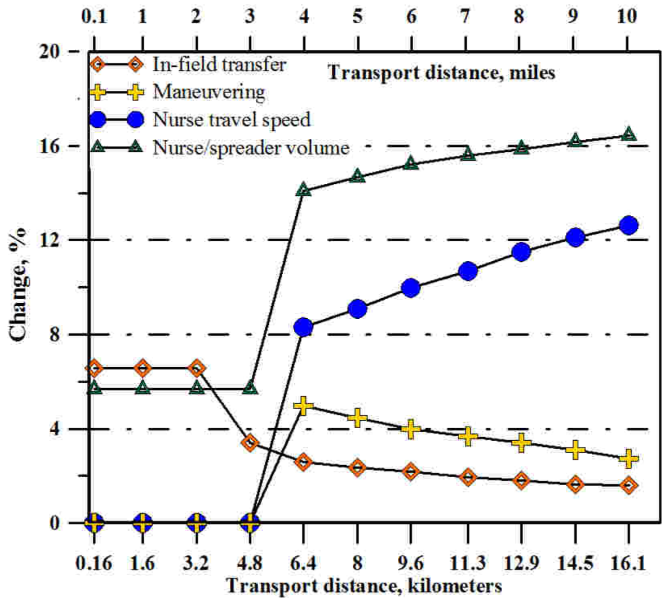

Figure 7. Percent change in the hauling capacity of a 26495-L (7000-gal) tractor-drawn spreader in parallel with two 26495-L (two 7000-gal) nurse tanks with a 20% increase in in-field manure transfer rate, nurse tank travel speed, or nurse tank/spreader tank volume, or a 20% decrease in maneuvering time.

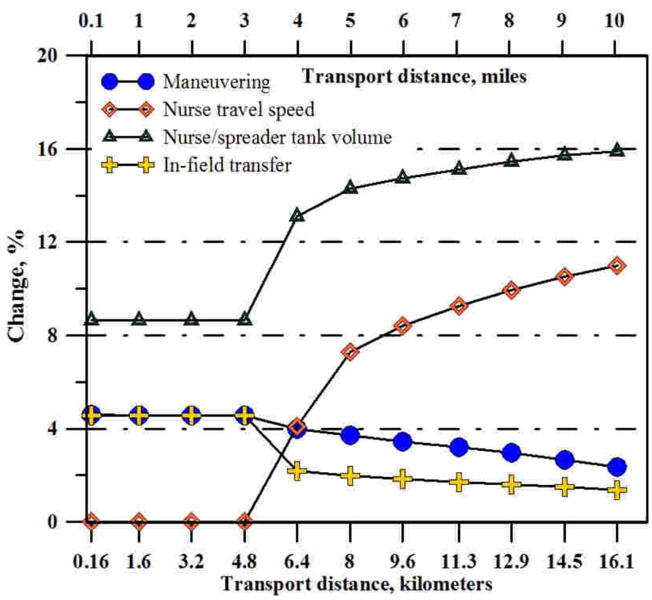

Figure 8. Percent change in the hauling capacity of a 13248-L (3500-gal) tractor-drawn spreader in parallel with two 26495-L (two 7000-gal) nurse tanks with a 20% increase in in-field manure transfer rate, nurse truck travel speed, nurse tank/spreader tank volume, or a 20% decrease in maneuvering time.

tractor-drawn spreader tank, and 5) 4921 L/min (1300 gpm) for a broadcast application from a truck-drawn spreader tank.

- Representative time for maneuvering and positioning the spreader tank or nurse truck were: 1) 4.5 min for a tractor-drawn spreader serviced in-field by nurse trucks, 2) 6.8 min for tractor-drawn spreaders over-the-road, and 3) 7.5 min for nurse trucks and truck-drawn spreaders.
- Representative road travel to the field with a loaded tank for standard tractors, high-speed tractors and truck-drawn spreader/nurse trucks were 30, 35, and 50 km/h (18.5, 22, and 31 mph), respectively. Travel speeds returning to the storage structure with an empty tank were 31, 42, and 56 km/h (19, 26, and 35 mph), respectively.
- Machinery-specific coefficients are proposed for a general model to estimate the effective hauling capacity of spreader tank systems whereby hauling capacity is a function of spreader tank volume and travel distance. Machinery system coefficients developed from the motion-and-time study are presented in a convenient reference table.
- There was little advantage with a high-speed tractor when hauling near storage, but they had an advantage with longer hauls. Compared to a standard tractor, a 26495-L (7000-gal) spreader tank drawn with a high-speed tractor had 8% greater hauling capacity with a 1-mile haul, 14% greater capacity with a 4.8-km (3-mile) haul, and 21% greater capacity with a 16-km (10-mile) haul.
- Compared to a truck-drawn spreader, a standard tractor-drawn spreader had 20% greater hauling capacity near storage, but a truck-drawn spreader had 8% greater capacity with a 6.4-km (4-mile) haul and 20% greater capacity with a 16-km (10-mile) haul.
- Compared to injection with a 6-shank injector (5110 L/min; 1350 gpm) a broadcast application with a 26495-L (7000-gal) high-speed tractor-drawn spreader increased the hauling rate 25% near storage, 17% with a 3.2-km (2-mile) haul, and 10% with a 16-km (10-mile) haul.
- Compared to the nurse truck/spreader tank machinery set where the nurse tanks were two times the volume of the spreader tank, a larger spreader tank with tank volume equal to nurse tank volume increased the hauling rate. A 26495-L (7000-gal) tractor-spreader with two 26495-L (7000-gal) nurse tanks had 37% greater capacity than a 13248-L (3500-gal) tractor-spreader with two 26495-L (7000-gal) nurse tanks with a 1.6-km (1-mile) haul and 20% greater capacity with a 4.8-km (3-mile) haul.
- The hauling rate of tank spreader systems was most affected by an increase in tank volume and travel speed.

A 20% increase in tank volume increased the effective hauling rate about 8% with a 0.16-km (0.1-mile) haul, 12% with a 3.2-km (2-mile) haul, and more than 16% with a 16-km (10-mile) haul. A 20% increase in travel speed had little effect when hauling near storage but increased the hauling rate more than 7% with a 3.2-km (2-mile) haul, and more than 14% with a 16-km (10-mile) haul.

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