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# Parameters Used to Simulate the Spread of FMD in Texas Using the North American Animal Disease Spread Model (NAADSM) for use in FMD Response Workforce Requirement Estimates



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## Version History

This section provides the history of revisions to this document. Additional versions will be created if errors are found in this document. The current version number is 2.0.

Version 1.0 (04/2012) First draft completed.

Version 2.0 (04/2013) Second draft completed. This version includes the revision of herd-level disease state durations, within-herd prevalence, and detection.

## The North American Animal Disease Spread Model

The North American Animal Disease Spread Model (NAADSM) was used to simulate the beginnings of a foot-and-mouth disease (FMD) outbreak in Texas (NAADSM Development Team, 2011). NAADSM is a stochastic, state-transition simulation model designed to simulate the spread and control of highly contagious diseases in a population of susceptible animals. NAADSM is a spatially explicit, herd-based model that simulates disease spread among herds. User-established parameters define model behavior in terms of disease progression; disease spread by direct contact, indirect contact, and airborne dissemination; and the application of control measures such as movement restrictions, depopulation, and vaccination. Resources available to implement depopulation and vaccination programs, as well as the calculation of estimates for direct government costs associated with control strategies, are also taken into consideration. The model records detailed and summary statistics which can be used to reconstruct and analyze the simulated outbreaks. The following sections describe in detail the parameters used in NAADSM for this study.

### Production Types

Herds may be classified as user-defined production types in NAADSM. A production type is a collection of herds with similar disease transmission probabilities, disease manifestation, disease detection probabilities, and control strategies. Production types are typically defined by animal species and/or management practices applied to each herd. The 12 production types used in the model were derived from 2 surveys of livestock producers in Texas and a published study set in the Texas Panhandle (Dominguez, 2007a; Dominguez, 2007b; Ward, Highfield, Vongseng, & Garner, 2009) (Table 1).

**Table 1. Production types used in NAADSM scenarios**

<b>Production type</b>	<b>Description</b>	<b>Size (number of head)</b>
Company feedlot	Cattle feeding operation comprised of company-owned cattle	>50,000
Stockholder feedlot	Cattle feeding operation where individual cattle owners contract the feedlot to produce pre-specified product for processing	20,000–50,000
Custom feedlot	Cattle feeding operation where lots of purchased cattle are fed to pre-specified criteria	5,000–20,000
Yearling-pasture feedlot	Cattle feeding operation where cattle <12 months of age that were raised on pasture are accustomed to feedlot rations	<5,000
Large cow-calf	Permanent herd of cattle, extensively managed, that is kept to produce calves for sale. Herd population can include breeding cows, calves, heifers, steers, and bulls	≥100
Small cow-calf	Permanent herd of cattle, extensively managed, that is kept to produce calves for sale. Herd population can include breeding cows, calves, heifers, steers, and bulls	<100
Stockers	Cattle operations that receive recently weaned animals that are raised on grass for a period of time prior to shipping to a feedlot	<35,000
Large dairy	Cattle operation that can consist of calves, heifers, lactating cows, and non-lactating cows	≥2,000 head
Small dairy	Cattle operation that can consist of calves, heifers, lactating cows, and non-lactating cows	<2,000 head

Large swine	Swine operation that consists of one or more production phases (gestation, farrowing, nursery, grower/finisher)	≥200 head
Small swine	Swine operation that consists of one or more production phases (gestation, farrowing, nursery, grower/finisher)	<200 head
Small ruminants	Sheep and/or goat operations consisting of animals of all ages for production of meat or dairy	All sizes

## Disease States

There are seven discrete disease states used in NAADSM (Table 2). During a simulation, herds transition through these disease states according to user-defined parameters. All animals within a herd are assumed to exist in the same disease state.

**Table 2. Description of disease states used by NAADSM**

Disease state	Description
Susceptible	Healthy herds without immunity to infection. Susceptible herds become infected upon effective contact.
Latent	Herds which are infected, but not yet shedding the disease agent.
Subclinically infectious	Herds which are infected and shedding the disease agent, but not yet showing clinical signs of disease.
Clinically infectious	Herds which are infected, shedding the disease agent, and showing clinical signs.
Naturally immune	Herds which have progressed through the disease cycle and are immune from further infection.
Vaccine immune	Herds which are immune by virtue of vaccination.
Depopulated	Herds which have been depopulated.

Distributions were used in NAADSM to determine the time that a herd would spend in a particular disease state. A separate model framework of within-herd disease spread (WH version 0.9.7) was used to determine the distributions for the herd-level state durations applied in NAADSM (Reeves, Talbert, Salman, & Hill, 2013).

Animal-level disease data were obtained from published studies involving experimental infection with FMD. These data were used to develop animal-level disease state distributions by resampling data and generating best-fit distribution curves. This was done using Microsoft Excel (2007), the Solver add-in for Microsoft Excel (2007), @Risk, SAS 9.2, and EasyFit 5.5 (Mathwave, 2010; Mathwave, 2010; Microsoft Corporation, 2007; Palisade Corporation, 2008; SAS Institute Inc, 2008). The resulting distributions were reviewed for epidemiological application by analytical epidemiologists at USDA–APHIS–VS–CEAH. The animal-level disease state distributions were then entered into the within-herd model (WH version 0.9.7) and a separate scenario was run for each of the 12 production types listed in Table 1. The parameters used in each of the 12 within-herd scenarios and their justifications are described in Table 3 - Table 14.

**Table 3. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for company feedlots**

<b>Parameter</b>	<b>Distribution</b>	<b>References</b>
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (3, 4.85, 5, 900)	USDA–NAHMS, pers. comm., 2012
Population	Beta (2, 2, 50000, 126000)	TX population file
Latent period	Weibull (1.782, 3.974)	Mardones et al., 2010
Subclinical period	Gamma (1.222, 1.672)	Mardones et al., 2010
Clinical period	Gamma (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 4. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for stockholder feedlots**

<b>Parameter</b>	<b>Distribution</b>	<b>References</b>
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (3, 4.85, 5, 900)	USDA–NAHMS, pers. comm., 2012
Population	Beta (0.75, 2.3, 20000, 28000)	TX population file
Latent period	Weibull (1.782, 3.974)	Mardones et al., 2010
Subclinical period	Gamma (1.222, 1.672)	Mardones et al., 2010
Clinical period	Gamma (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 5. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for custom feedlots**

<b>Parameter</b>	<b>Distribution</b>	<b>References</b>
Initially latent individuals	Uniform (1,5)	NA

Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (3, 4.85, 5, 900)	USDA–NAHMS, pers. comm., 2012
Population	Lognormal (9521, 3437)	TX population file
Latent period	Weibull (1.782, 3.974)	Mardones et al., 2010
Subclinical period	Gamma (1.222, 1.672)	Mardones et al., 2010
Clinical period	Gamma (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 6. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for yearling-pasture feedlot operations**

Parameter	Distribution	References
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (2.5, 4.75, 5, 900)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	Weibull (1.78, 3.97)	Mardones et al., 2010
Subclinical period	Gamma (1.22, 1.67)	Mardones et al., 2010
Clinical period	Gamma (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 7. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for large cow-calf operations**

Parameter	Distribution	References
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (1.5, 6.5, 5, 199)	USDA–NAHMS, pers. comm., 2012
Population	Beta (0.88, 54.76, 100, 23932)	TX population file

Latent period	Weibull (1.78, 3.97)	Mardones et al., 2010
Subclinical period	Gamma (1.22, 1.67)	Mardones et al., 2010
Clinical period	Gamma (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 8. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for small cow-calf operations**

Parameter	Distribution	References
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (9, 5.25, 5, 99)	USDA–NAHMS, pers. comm., 2012
Population	Weibull (1.614, 40.827)	USDA–APHIS–VS–CEAH Small-Scale Operations, 2011, unpubl. data
Latent period	Weibull (1.782, 3.974)	Mardones et al., 2010
Subclinical period	Gamma (1.222, 1.672)	Mardones et al., 2010
Clinical period	Gamma (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 9. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for stocker operations**

Parameter	Distribution	References
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Beta (1.75, 6, 5, 900)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	Weibull (1.78, 3.97)	Mardones et al., 2010
Subclinical period	Gamma (1.22, 1.67)	Mardones et al., 2010
Clinical period	Exponential (4.75, 0.74)	None

Immune period	Gaussian (1095, 180)	None
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**Table 10. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for large dairy operations**

Parameter	Distribution	References
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Lognormal (3533.21, 3044.99)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	Weibull (1.78, 3.97)	Mardones et al., 2010
Subclinical period	Gamma (1.22, 1.67)	Mardones et al., 2010
Clinical period	Exponential (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 11. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for small dairy operations**

Parameter	Distribution	References
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Lognormal (77.78, 200)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	Weibull (1.78, 3.97)	Mardones et al., 2010
Subclinical period	Gamma (1.22, 1.67)	Mardones et al., 2010
Clinical period	Exponential (4.75, 0.74)	None
Immune period	Gaussian (1095, 180)	None

**Table 12. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for large swine operations**

Parameter	Distribution	References
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Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Weibull (5, 200)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	Gamma (1.62, 1.91)	Alexandersen et al., 2012; Mardones et al., 2010
Subclinical period	Inverse Gaussian (2.3, 3.05)	Alexandersen et al., 2012; Mardones et al., 2010
Clinical period	Gaussian (4.33, 1.34)	Aggarwal et al., 2002; Alexandersen, Zhang, Donaldson, & Garland, 2003
Immune period	Gaussian (360, 90)	(Alexandersen et al., 2012)

**Table 13. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for small swine operations**

<b>Parameter</b>	<b>Distribution</b>	<b>References</b>
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA
Adequate exposures per time step	Weibull (5, 200)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	Gamma (1.62, 1.91)	Alexandersen et al., 2012; Mardones et al., 2010
Subclinical period	Inverse Gaussian (2.3, 3.05)	Alexandersen et al., 2012; Mardones et al., 2010
Clinical period	Gaussian (4.33, 1.34)	Aggarwal et al., 2002; Alexandersen, Quan, Murphy, Knight, & Zhang, 2003
Immune period	Gaussian (360, 90)	Alexandersen et al., 2012

**Table 14. Parameters used to generate herd-level disease state durations and within-herd prevalence curves for small ruminant operations**

<b>Parameter</b>	<b>Distribution</b>	<b>References</b>
Initially latent individuals	Uniform (1,5)	NA
Initially subclinical individuals	Point (0)	NA
Initially clinical individuals	Point (0)	NA

Adequate exposures per time step	Beta (3, 5, 75, 300)	USDA–NAHMS, pers. comm., 2012
Population	Empirical histogram	TX population file
Latent period	BetaPERT (0, 3.96, 13.98)	Mardones et al., 2010
Subclinical period	Gamma (2.4, 0.90)	Mardones et al., 2010
Clinical period	Exponential (1.52)	None
Immune period	Gaussian (1095, 90)	None

#### Justification for assumptions

Daily output resulting from 1,000 iterations of a within-herd model of disease spread (WH version 0.9.7) was collected.

The herd-level duration of the **latent period** is defined as the time from when the first animal in a herd becomes infected to the time when the first animal in the herd becomes subclinical. The herd-level duration of the **subclinically infectious period** is defined as the time from when the first animal in a herd becomes subclinical and infectious to the time when the first animal in the herd becomes clinically infectious. The herd-level duration of the **clinically infectious period** is defined as the time from when the first animal in a herd shows clinical signs to the time when the last animal becomes immune (Table 16). Charts of herd-level disease durations are shown in Appendix I. The parameters described in Table 15 and Table 16 were input into NAADSM for simulation.

**Table 15. Herd-level disease durations**

<b>Company feedlot</b>	<b>Distributions for the durations of the latent, subclinical and clinical periods (days)</b>
Latent	gamma (alpha=3.24, beta=0.70)
Subclinical	log-logistic (alpha=4.48, beta=0.95)
Clinical	gamma (alpha=216.62, beta=0.15)
<b>Stockholder feedlot</b>	
Latent	gamma (alpha=3.27, beta=0.70)
Subclinical	log-logistic (alpha=4.37, beta=0.95)
Clinical	log-logistic (alpha=24.05, beta=30.58)
<b>Custom feedlot</b>	
Latent	gamma (alpha=2.97, beta=0.77)
Subclinical	log-logistic (alpha=4.13, beta=0.96)
Clinical	log-logistic (alpha=134.02, beta=0.22)
<b>Yearling-pasture feedlot</b>	
Latent	gamma (alpha=2.97, beta=0.80)
Subclinical	log-logistic (alpha=3.54, beta=0.99)

Clinical	beta (alpha1=7.52, alpha2=458.54, min=13.12, max=506.88)
<b>Large cow-calf</b>	
Latent	Weibull (alpha=1.84, beta=2.52)
Subclinical	logistic (mu=1.18, sigma=0.44)
Clinical	beta (alpha1=14.26, alpha2=78.03, min=10.5, max=93.75)
<b>Small cow-calf</b>	
Latent	gamma (alpha=3.14, beta=0.72)
Subclinical	Weibull (alpha=2.26, beta=1.87)
Clinical	logistic (mu=16.22, sigma=1.93)
<b>Stocker</b>	
Latent	gamma (alpha=2.19, beta=0.94)
Subclinical	normal (mu=1.10, sigma=0.74)
Clinical	logistic (mu=20.0, sigma=1.87)
<b>Large dairy</b>	
Latent	gamma (alpha=2.11, beta=1.03)
Subclinical	logistic (mu=0.86, sigma=0.23)
Clinical	lognormal (mu=3.25, sigma=0.09)
<b>Small dairy</b>	
Latent	gamma (alpha=2.09, beta=1.09)
Subclinical	gamma (alpha=1.68, beta=1.26)
Clinical	logistic (mu=16.97, sigma=2.89)
<b>Large swine</b>	
Latent	log-logistic (alpha=2.18, beta=1.19)
Subclinical	gamma (alpha=6.10, beta=0.21)
Clinical	log-logistic (alpha=4.10, beta=10.63, location=25.04)
<b>Small swine</b>	
Latent	log-logistic (alpha=2.28, beta=1.21)
Subclinical	gamma (alpha=3.32, beta=0.48)
Clinical	gamma (alpha=10.73, beta=1.43)
<b>Small ruminant</b>	
Latent	Weibull (alpha=1.71, beta=3.57)
Subclinical	Weibull (alpha=2.58, beta=2.30)
Clinical	lognormal (mu=2.91, sigma=0.13)

Justification for assumptions

Herd-level disease state durations from 1,000 iterations of the within-herd model were used to develop probability distributions to define the duration of each disease state. These probability distributions were developed to match the shape, mean values, and standard deviations of the observed distributions of disease state durations from the 1,000 iterations. Goodness-of-fit was evaluated using the Anderson-Darling, Kolmogorov-Smirnov, and Chi-squared tests.

The herd-level **immune period** represents the duration of immunity following natural infection (Table 16).

**Table 16. Duration of the naturally immune period by livestock species**

<b>Production type</b>	<b>Duration of the <i>immune period</i> (days)</b>	<b>References</b>
Cattle	Gaussian ( $\mu=1095$ , $\sigma=180$ )	Cunliffe, 1964; Moonen et al., 2004
Swine	Weibull ( $\alpha=5$ , $\beta=985$ )	None available
Small ruminant	Gaussian ( $\mu=930$ , $\sigma=90$ )	None available

#### Justification for assumptions

Eighty percent of the cattle reported by Cunliffe (1964) retained immunity over a period of 4.5 years. Sixty percent of the cattle reported by Moonen et al. (2004) retained immunity for 609 days following inoculation with FMD virus.

Swine have shorter immune periods than cattle; however, unlike the studies reported for cattle, there are no long-term studies available in the peer-reviewed literature that define the duration of the immune period for swine (Bachrach, 1968; Cunliffe, 1964). Given this limitation, the Weibull distribution was chosen as an approximation in order to account for the shorter immune period. There are no long-term studies available in the peer-reviewed literature that define the duration of the immune period for small ruminants. Given this limitation, it was assumed that the duration of the immune period in small ruminants is roughly equivalent to that of swine. Additionally, in order to account for an increase in the quantity of antibodies detected in sheep after vaccination a Gaussian distribution was chosen as an approximation of the duration of the immune period in small ruminants (Patil et al., 2002).

## Within-herd Prevalence

While a herd is in the latent, infectious subclinical and infectious clinical disease states, a chart may be used to determine the prevalence or proportion of animals infected on a given day. When a latent, subclinical, or clinical herd ships animals to a susceptible herd, the probability that the susceptible herd becomes infected is determined by the within-herd prevalence of the source herd (direct contacts in NAADSM). The within-herd prevalence also affects the probability of infection for airborne/local area spread.

The within-herd model of disease transmission (WH 0.9.7 described by Reeves et al. in preparation) was used to generate distributions of within-herd prevalence for each production type (Table 1) for import into

NAADSM. The within-herd model estimates within-herd prevalence over time as a function of herd size, contact rates among animals within a herd, the probability of infection given contact, and disease state parameters of individual animals. The parameters used in the within-herd model are listed in Table 3 - Table 14. The medians of the daily prevalence values obtained from the within-herd model were calculated and plotted on a time series axis to produce the within-herd prevalence charts for input into NAADSM (Appendix II).

## Direct Contact

NAADSM simulates herd-to-herd movements. Direct contact involves the shipment of one or more animals from one herd to another. Herd-to-market and market-to-herd movements have not been factored into these scenarios.

It was assumed that the shipment of animals from a latently infected herd to a susceptible herd can spread disease. Animals do not shed virus while in the latent state, but shipment of a latently infected animal to a susceptible herd introduces FMD virus (FMDV) into that herd which will be transmitted to susceptible animals once the latent animal become infectious.

The probability of infection given exposure is determined using the prevalence of the source herd according to the specified within-herd prevalence charts.

Movement controls, expressed as a reduction in direct contact rates among herds can be applied universally to an entire production type to represent a stop-movement order, or they can be applied only within zones (see section on Zones). Subject matter experts from the National Center for Animal Health Emergency Management (NCAHEM) recommended that a 24-hour stop-movement order would be implemented upon initial detection with effectiveness equivalent to a 50-percent reduction in direct contacts. Therefore, the relational function describing the effect of production-type-wide movement controls on the baseline contact rate is set to 50 percent on the day following initial detection and returned to 100 percent 2 days following initial detection for all production types.

Overall direct contact rates and distance distributions of direct contacts were obtained from two studies: a survey of 77 livestock producers in 8 counties located in the Texas Panhandle and another survey of 156 livestock producers in 9 counties in southwest Texas (Dominguez, 2007a; Dominguez, 2007b). A matrix was created with marginal row and column values equal to the estimates of overall direct contacts onto and off of premises reported by the two surveys. The contact rates of individual cells in the matrix were distributed so that the sums of the rows and columns were as close to the marginal values as possible. Relative differences in direct contact rates between production-type combinations were guided by estimates from the National Animal Health Monitoring System (NAHMS) reports (USDA-APHIS-VS, CEAH, Fort Collins, CO, 2000; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2001; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007a; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007b; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2008; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2009; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2010). The sum of all production-type contact rates off of premises was 0.07/day less than the sum of contact rates onto premises. Therefore, it was not possible to perfectly reconcile the marginal totals. These discrepancies were distributed among the feedlot production types which had the highest onto-premises contact rates, and therefore the discrepancies resulted in the lowest percentage of onto-premises contact rates. The distances travelled by contacts were reported as minimum, most likely

and maximum values in the two Texas studies. These reported values were used to assign BetaPERT distance distributions for direct contacts (Tables 17–19).

**Table 17. Direct contact originating from a cattle production type**

<b>Production type combination</b>	<b>Contact rate<sup>1</sup></b> (shipments from/day)	<b>Movement distance (km)</b> (min, mode, max) <sup>2</sup>
Yearling-pasture feedlot to company feedlot	0.150	BetaPERT (20, 175, 1,480)
Yearling-pasture feedlot to stockholder feedlot	0.050	BetaPERT (20, 175, 1,480)
Yearling-pasture feedlot to custom feedlot	0.010	BetaPERT (20, 175, 1,480)
Large dairy to company feedlot	0.035	BetaPERT (1, 30, 90)
Large dairy to stockholder feedlot	0.035	BetaPERT (1, 30, 90)
Large dairy to custom feedlot	0.010	BetaPERT (1, 30, 90)
Large dairy to large dairy	0.005	BetaPERT (1, 30, 90)
Large dairy to small dairy	0.005	BetaPERT (1, 30, 90)
Small dairy to company feedlot	0.025	BetaPERT (1, 30, 90)
Small dairy to stockholder feedlot	0.010	BetaPERT (1, 30, 90)
Small dairy to custom feedlot	0.005	BetaPERT (1, 30, 90)
Small dairy to large dairy	0.005	BetaPERT (1, 30, 90)
Small dairy to small dairy	0.005	BetaPERT (1, 30, 90)
Stocker to company feedlot	0.150	BetaPERT (13, 376, 805)
Stocker to stockholder feedlot	0.050	BetaPERT (13, 376, 805)
Stocker to custom feedlot	0.010	BetaPERT (13, 376, 805)
Large cow-calf to company feedlot	0.100	BetaPERT (5, 32, 805)
Large cow-calf to stockholder feedlot	0.060	BetaPERT (5, 32, 805)
Large cow-calf to custom feedlot	0.010	BetaPERT (5, 32, 805)
Large cow-calf to yearling-pasture feedlot	0.025	BetaPERT (5, 32, 805)
Large cow-calf to stockers	0.090	BetaPERT (5, 32, 805)

Large cow-calf to large cow-calf	0.020	BetaPERT (5, 32, 805)
Large cow-calf to small cow-calf	0.010	BetaPERT (5, 32, 805)
Large cow-calf to small ruminant	0.005	BetaPERT (5, 32, 805)
Small cow-calf to company feedlot	0.060	BetaPERT (4, 26, 153)
Small cow-calf to stockholder feedlot	0.030	BetaPERT (4, 26, 153)
Small cow-calf to custom feedlot	0.005	BetaPERT (4, 26, 153)
Small cow-calf to yearling-pasture feedlot	0.015	BetaPERT (4, 26, 153)
Small cow-calf to stockers	0.060	BetaPERT (4, 26, 153)
Small cow-calf to large cow-calf	0.020	BetaPERT (4, 26, 153)
Small cow-calf to small cow-calf	0.005	BetaPERT (4, 26, 153)
Small cow-calf to small ruminant	0.005	BetaPERT (4, 26, 153)

<sup>1</sup> A contact rate is used to indicate the average number of contacts (shipments of animals) that are generated by each herd on each day.

<sup>2</sup> This variable defines the distance between a herd of the source production type and its contact with herds of the recipient production type.

### Justification for assumptions

#### *All Feedlots*

It was assumed that all cattle leaving company feedlots, stockholder feedlots, and custom feedlots were consigned to slaughter and had no direct contacts shipped to other production types (Dominguez, 2007b). All cattle leaving yearling-pasture feedlots were assumed to go to one of the other three feedlot types (Dominguez, 2007b). To reflect the variability in feedlot direct contacts observed in that study, it was assumed that contact rates increased with increasing feedlot capacity (Dominguez, 2007b). Using the numbers of each feedlot category that participated in the Texas Panhandle study, weighted average daily contact rates were calculated so that the combined total for all categories equaled 0.27. According to the Texas Panhandle study, yearling-pasture feedlots and stocker operations shipped animals to other feedlots at the same rate. Therefore, direct contacts off of yearling-pasture feedlots were assumed to be the same as those reported for stocker operations (0.21/day; see below).

#### *Cow-calf and stocker operations*

According to the southwest Texas survey, there was an average of 0.32 direct contacts/day originating from large cow-calf operations, 0.20 direct contacts/day originating from small cow-calf operations, and 0.21 direct contacts/day originating from stocker operations (Dominguez, 2007a). It was assumed that all contacts from large and small cow-calf operations were to other beef operations, feedlots, or small ruminants (see below), and all contacts from stocker operations were to feedlots only (Dominguez, 2007a).

### *Dairy*

The Texas Panhandle study surveyed 21 dairy operations (4 small and 17 large) (Dominguez, 2007b). It was assumed that the destinations of all animal shipments from dairies were to other dairies or to feedlots. According to the NAHMS Dairy 2007 study, approximately three times as many dairies shipped animals directly to feedlots than shipped directly to other dairies (USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007a). Therefore, the assigned contact rates between dairies and feedlots were higher than the contact rates between dairies. All dairy production types were assumed to have direct contacts with each other at equal rates.

**Table 18. Direct contact originating from swine operations**

<b>Production type combination</b>	<b>Contact rate</b> (shipments from/day)	<b>Movement distance (km)</b> (min, mode, max)
Large swine to large swine	0.030	BetaPERT (1, 50, 1,500)
Small swine to small swine	0.005	BetaPERT (1, 50, 1,500)

### Justification for assumptions

The Texas panhandle study surveyed 16 swine producers (7 small and 9 large) and estimated the average daily rate of direct contacts off of all swine premises to be 0.01/day (sd=0.02) (Dominguez, 2007b). The average reported direct contact rate onto swine premises was rounded to 0 (sd=0.01). According to the NAHMS Swine 2007 study, 8 percent of large swine operations in the southern region (including Texas) had a combination of all phases of swine production present, indicating that most large swine premises specialized in one or more production phases such as farrowing or finishing (USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007b). According to the NAHMS Small-Enterprise Swine 2007 study, 67 percent of small swine operations shipped one or more pigs off their premises in the previous 12 months but only 22 percent of these shipments were to other swine premises (USDA-APHIS-VS, CEAH, Fort Collins, CO, 2009). The remaining removals were sold directly to commercial or custom slaughter, or were sold via auction. Based on this information, it was assumed that large swine premises had more frequent shipments of pigs off premises to other specialty operations than did small swine operations. It was also assumed that small and large swine operations had direct contact only within their respective production types.

**Table 19. Direct contact originating from small ruminant operations**

<b>Production type combination</b>	<b>Contact rate</b> (shipments from/day)	<b>Movement distance (km)</b> (min, mode, max)
Small ruminant to company feedlot	0.075	BetaPERT (3, 29, 129)
Small ruminant to stockholder feedlot	0.025	BetaPERT (3, 29, 129)
Small ruminant to custom feedlot	0.025	BetaPERT (3, 29, 129)
Small ruminant to yearling-pasture feedlot	0.010	BetaPERT (3, 29, 129)

Small ruminant to stockers	0.020	BetaPERT (3, 29, 129)
Small ruminant to large cow-calf	0.010	BetaPERT (3, 29, 129)
Small ruminant to small cow-calf	0.005	BetaPERT (3, 29, 129)
Small ruminants to small ruminants	0.030	BetaPERT (3, 29, 129)

#### Justification for assumptions

According to the southwest Texas survey, 79 percent of sheep operations also owned cattle and 67 percent of goat operations owned cattle (Dominguez, 2007a). Therefore, small ruminant production types were allowed to have direct contact with other nondairy, cattle production types. The southwest Texas study reported direct contact rates for mixed small ruminant/cattle operations as 0.20/day off of premises and 0.04/day onto premises.

## Indirect Contact

The movement of people, materials, vehicles, equipment, etc. among herds is simulated in the same manner as direct contact, except that only infectious subclinical and infectious clinical herds can be a source of infection. The parameters for indirect contact are similar but independent of those for direct contact. The probability of infection given exposure by indirect contact does not depend on within-herd prevalence of the source herd; rather, it is determined by a fixed probability of infection (Table 20).

**Table 20. Indirect contact by source production type**

<b>Production type combination</b>	<b>Contact rate (shipments from/day)</b>	<b>Movement distance (km) (min, mode, max)</b>	<b>Probability of infection given adequate exposure</b>
Company feedlot to company feedlot	0.4401	0, 20, 2,600	0.1263
Company feedlot to stockholder feedlot	0.3301	0, 20, 2,600	0.1263
Company feedlot to custom feedlot	0.2200	0, 20, 2,600	0.1263
Company feedlot to yearling-pasture feedlot	0.1100	0, 20, 2,600	0.1263
Company feedlot to large cow-calf	0.2606	0, 20, 2,600	0.1263
Company feedlot to small cow-calf	0.1737	0, 20, 2,600	0.1263
Company feedlot to stocker	0.0212	0, 20, 2,600	0.1263
Company feedlot to large dairy	0.3764	0, 20, 2,600	0.2795
Company feedlot to small dairy	0.2523	0, 20, 2,600	0.2795
Company feedlot to large swine	0.2162	0, 20, 2,600	0.5937
Company feedlot to small swine	0.1081	0, 20, 2,600	0.5937
Company feedlot to small ruminant	0.0212	0, 20, 2,600	0.4286

Stockholder feedlot to company feedlot	0.4157	0, 20, 2,600	0.1384
Stockholder feedlot to stockholder feedlot	0.3118	0, 20, 2,600	0.1384
Stockholder feedlot to custom feedlot	0.2079	0, 20, 2,600	0.1384
Stockholder feedlot to yearling-pasture feedlot	0.1039	0, 20, 2,600	0.1384
Stockholder feedlot to large cow-calf	0.2462	0, 20, 2,600	0.1263
Stockholder feedlot to small cow-calf	0.1641	0, 20, 2,600	0.1263
Stockholder feedlot to stocker	0.0201	0, 20, 2,600	0.1263
Stockholder feedlot to large dairy	0.3556	0, 20, 2,600	0.2795
Stockholder feedlot to small dairy	0.2383	0, 20, 2,600	0.2795
Stockholder feedlot to large swine	0.2042	0, 20, 2,600	0.5937
Stockholder feedlot to small swine	0.1021	0, 20, 2,600	0.5937
Stockholder feedlot to small ruminant	0.0201	0, 20, 2,600	0.4286
Custom feedlot to company feedlot	0.3479	0, 20, 2,600	0.1384
Custom feedlot to stockholder feedlot	0.2609	0, 20, 2,600	0.1384
Custom feedlot to custom feedlot	0.1740	0, 20, 2,600	0.1384
Custom feedlot to yearling-pasture feedlot	0.0870	0, 20, 2,600	0.1384
Custom feedlot to large cow-calf	0.2060	0, 20, 2,600	0.1263
Custom feedlot to small cow-calf	0.1373	0, 20, 2,600	0.1263
Custom feedlot to stocker	0.0168	0, 20, 2,600	0.1263
Custom feedlot to large dairy	0.2975	0, 20, 2,600	0.2795
Custom feedlot to small dairy	0.1995	0, 20, 2,600	0.2795
Custom feedlot to large swine	0.1709	0, 20, 2,600	0.5937
Custom feedlot to small swine	0.0854	0, 20, 2,600	0.5937
Custom feedlot to small ruminant	0.0168	0, 20, 2,600	0.4286
Yearling-pasture feedlot to company feedlot	0.3253	0, 20, 2,600	0.1384
Yearling-pasture feedlot to stockholder feedlot	0.2440	0, 20, 2,600	0.1384
Yearling-pasture feedlot to custom feedlot	0.1626	0, 20, 2,600	0.1384
Yearling-pasture feedlot to yearling-pasture feedlot	0.0813	0, 20, 2,600	0.1384
Yearling-pasture feedlot to large cow-calf	0.1926	0, 20, 2,600	0.1263
Yearling-pasture feedlot to small cow-calf	0.1284	0, 20, 2,600	0.1263
Yearling-pasture feedlot to stocker	0.0157	0, 20, 2,600	0.1263
Yearling-pasture feedlot to large dairy	0.2782	0, 20, 2,600	0.2795
Yearling-pasture feedlot to small dairy	0.1865	0, 20, 2,600	0.2795
Yearling-pasture feedlot to large swine	0.1598	0, 20, 2,600	0.5937

Yearling-pasture feedlot to small swine	0.0799	0, 20, 2,600	0.5937
Yearling-pasture feedlot to small ruminant	0.0157	0, 20, 2,600	0.4286
Large cow-calf to company feedlot	0.0522	0, 20, 2,600	0.1384
Large cow-calf to stockholder feedlot	0.0391	0, 20, 2,600	0.1384
Large cow-calf to custom feedlot	0.0261	0, 20, 2,600	0.1384
Large cow-calf to yearling-pasture feedlot	0.0130	0, 20, 2,600	0.1384
Large cow-calf to large cow-calf	0.0309	0, 20, 2,600	0.1263
Large cow-calf to small cow-calf	0.0206	0, 20, 2,600	0.1263
Large cow-calf to stocker	0.0025	0, 20, 2,600	0.1263
Large cow-calf to large dairy	0.0446	0, 20, 2,600	0.2795
Large cow-calf to small dairy	0.0299	0, 20, 2,600	0.2795
Large cow-calf to large swine	0.0256	0, 20, 2,600	0.5937
Large cow-calf to small swine	0.0128	0, 20, 2,600	0.5937
Large cow-calf to small ruminant	0.0025	0, 20, 2,600	0.4286
Small cow-calf to company feedlot	0.0365	0, 20, 2,600	0.1384
Small cow-calf to stockholder feedlot	0.0274	0, 20, 2,600	0.1384
Small cow-calf to custom feedlot	0.0183	0, 20, 2,600	0.1384
Small cow-calf to yearling-pasture feedlot	0.0091	0, 20, 2,600	0.1384
Small cow-calf to large cow-calf	0.0216	0, 20, 2,600	0.1263
Small cow-calf to small cow-calf	0.0144	0, 20, 2,600	0.1263
Small cow-calf to stocker	0.0018	0, 20, 2,600	0.1263
Small cow-calf to large dairy	0.0312	0, 20, 2,600	0.2795
Small cow-calf to small dairy	0.0209	0, 20, 2,600	0.2795
Small cow-calf to large swine	0.0179	0, 20, 2,600	0.5937
Small cow-calf to small swine	0.0090	0, 20, 2,600	0.5937
Small cow-calf to small ruminant	0.0018	0, 20, 2,600	0.4286
Stocker to company feedlot	0.0087	0, 20, 2,600	0.1384
Stocker to stockholder feedlot	0.0065	0, 20, 2,600	0.1384
Stocker to custom feedlot	0.0043	0, 20, 2,600	0.1384
Stocker to yearling-pasture feedlot	0.0022	0, 20, 2,600	0.1384
Stocker to large cow-calf	0.0051	0, 20, 2,600	0.1263
Stocker to small cow-calf	0.0034	0, 20, 2,600	0.1263
Stocker to stocker	0.0004	0, 20, 2,600	0.1263
Stocker to large dairy	0.0074	0, 20, 2,600	0.2795
Stocker to small dairy	0.0050	0, 20, 2,600	0.2795

Stocker to large swine	0.0043	0, 20, 2,600	0.5937
Stocker to small swine	0.0021	0, 20, 2,600	0.5937
Stocker to small ruminant	0.0004	0, 20, 2,600	0.4286
Large dairy to company feedlot	0.4853	0, 36, 1,880	0.1384
Large dairy to stockholder feedlot	0.3640	0, 36, 1,880	0.1384
Large dairy to custom feedlot	0.2427	0, 36, 1,880	0.1384
Large dairy to yearling-pasture feedlot	0.1213	0, 36, 1,880	0.1384
Large dairy to large cow-calf	0.2874	0, 36, 1,880	0.1263
Large dairy to small cow-calf	0.1916	0, 36, 1,880	0.1263
Large dairy to stocker	0.0234	0, 36, 1,880	0.1263
Large dairy to large dairy	0.4151	0, 36, 1,880	0.2795
Large dairy to small dairy	0.2782	0, 36, 1,880	0.2795
Large dairy to large swine	0.2384	0, 36, 1,880	0.5937
Large dairy to small swine	0.1192	0, 36, 1,880	0.5937
Large dairy to small ruminant	0.0234	0, 36, 1,880	0.4286
Small dairy to company feedlot	0.1818	0, 36, 1,880	0.1384
Small dairy to stockholder feedlot	0.1363	0, 36, 1,880	0.1384
Small dairy to custom feedlot	0.0909	0, 36, 1,880	0.1384
Small dairy to yearling-pasture feedlot	0.0454	0, 36, 1,880	0.1384
Small dairy to large cow-calf	0.1076	0, 36, 1,880	0.1263
Small dairy to small cow-calf	0.0718	0, 36, 1,880	0.1263
Small dairy to stocker	0.0088	0, 36, 1,880	0.1263
Small dairy to large dairy	0.1555	0, 36, 1,880	0.2795
Small dairy to small dairy	0.1042	0, 36, 1,880	0.2795
Small dairy to large swine	0.0893	0, 36, 1,880	0.5937
Small dairy to small swine	0.0446	0, 36, 1,880	0.5937
Small dairy to small ruminant	0.0088	0, 36, 1,880	0.4286
Large swine to company feedlot	0.0066	0, 24, 1,135	0.1186
Large swine to stockholder feedlot	0.0050	0, 24, 1,135	0.1186
Large swine to custom feedlot	0.0033	0, 24, 1,135	0.1186
Large swine to yearling-pasture feedlot	0.0017	0, 24, 1,135	0.1186
Large swine to large cow-calf	0.0039	0, 24, 1,135	0.1083
Large swine to small cow-calf	0.0026	0, 24, 1,135	0.1083
Large swine to stocker	0.0003	0, 24, 1,135	0.1083
Large swine to large dairy	0.0057	0, 24, 1,135	0.2396

Large swine to small dairy	0.0038	0, 24, 1,135	0.2396
Large swine to large swine	0.0032	0, 24, 1,135	0.3299
Large swine to small swine	0.0016	0, 24, 1,135	0.3299
Large swine to small ruminant	0.0003	0, 24, 1,135	0.4286
Small swine to company feedlot	0.0042	0, 24, 1,135	0.1186
Small swine to stockholder feedlot	0.0031	0, 24, 1,135	0.1186
Small swine to custom feedlot	0.0021	0, 24, 1,135	0.1186
Small swine to yearling-pasture feedlot	0.0010	0, 24, 1,135	0.1186
Small swine to large cow-calf	0.0025	0, 24, 1,135	0.1083
Small swine to small cow-calf	0.0016	0, 24, 1,135	0.1083
Small swine to stocker	0.0002	0, 24, 1,135	0.1083
Small swine to large dairy	0.0036	0, 24, 1,135	0.2396
Small swine to small dairy	0.0024	0, 24, 1,135	0.2396
Small swine to large swine	0.0021	0, 24, 1,135	0.3299
Small swine to small swine	0.0010	0, 24, 1,135	0.3299
Small swine to small ruminant	0.0002	0, 24, 1,135	0.4286
Small ruminants to company feedlot	0.0209	0, 20, 2,600	0.1384
Small ruminants to stockholder feedlot	0.0157	0, 20, 2,600	0.1384
Small ruminants to custom feedlot	0.0104	0, 20, 2,600	0.1384
Small ruminants to yearling-pasture feedlot	0.0052	0, 20, 2,600	0.1384
Small ruminants to large cow-calf	0.0124	0, 20, 2,600	0.1263
Small ruminants to small cow-calf	0.0082	0, 20, 2,600	0.1263
Small ruminants to stocker	0.0010	0, 20, 2,600	0.1263
Small ruminants to large dairy	0.0179	0, 20, 2,600	0.2795
Small ruminants to small dairy	0.0120	0, 20, 2,600	0.2795
Small ruminants to large swine	0.0103	0, 20, 2,600	0.5937
Small ruminants to small swine	0.0051	0, 20, 2,600	0.5937
Small ruminants to small ruminant	0.0010	0, 20, 2,600	0.2143

#### Justification for assumptions

Both the Texas Panhandle survey and the southwest Texas survey reported indirect contacts as either high risk or low risk (Dominguez, 2007a; Dominguez, 2007b). High-risk indirect contacts are those that involve contact with animals, whereas low-risk indirect contacts were defined as vehicles and people who came onto a premises but did not have contact with animals. All premises in the two studies reported having high-risk indirect contacts during the previous year, but only some of the premises reported having low-risk indirect contact. NAADSM does not

differentiate between high-risk and low-risk contacts, so these two types of indirect contact were combined into averages that were weighted by the proportion of premises in each production type that reported those contacts.

The indirect contact rates reported by the Texas Panhandle study were for broad production type classes, such as feedlots and dairy and swine operations (Dominguez, 2007b). The southwest Texas study reported one combined indirect contact rate for all premises (Dominguez, 2007a). These rates were applied to the specific production types in our study by using the 50- and 75-percent confidence limits of the production-type classes. For example, for the four feedlot production types, it was assumed that indirect contacts increase with increasing feedlot capacity. The indirect contact rate for company feedlots was assumed to be the upper 75-percent confidence limit for all feedlots reported in the Texas Panhandle study. However, the indirect contact rate was assumed to be the upper 50-percent confidence limit for stockholder feedlots, the lower 50-percent confidence limit for custom feedlots, and the lower 75-percent confidence limit for yearling-pasture feedlots. For the four production types represented in the southwest Texas study, it was assumed that the indirect contact rates were highest for large cow-calf operations followed by small cow-calf, small ruminant, and stocker operations. Upper and lower 50- and 75-percent confidence limits were applied to these four production types in the same way they were for the feedlots.

To estimate the contact rates between production-type combinations, the sources of indirect contact were classified into eight groups (veterinarians/extension, feed trucks, drug sales, nutritionists, external processors, milk trucks, neighbors, and contract haulers). The proportions of visits collectively made by each of these eight sources to each production type were estimated from NAHMS reports and expert opinion (Mike Sanderson, pers. comm., 5/4/2011; (USDA-APHIS-VS, CEAH, Fort Collins, CO, 2000; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2001; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007a; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007b; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2008; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2009; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2010). From these estimates, normalized proportions of overall contact visits for each production type were calculated. The contact rate from one production type to another was the product of the contact rate for the source production type and the normalized proportion of visits by all contact sources to the recipient production type.

The distance distributions of indirect contacts were reported in the Texas Panhandle study for each type of indirect contact as minimum, most likely, and maximum distances. The software package DistMixer (v1.01) was used to combine the distance distributions for individual sources into one histogram for each production-type class (Animal Population Health Institute at Colorado State University, 2011). Three histograms were estimated: one for all beef and small ruminant production types, one for all swine, and one for all dairy production types. The histograms were highly skewed right, with at least 95 percent of the mass below 700 km and maximum values as high as 2,600 km.

In order to determine the probability of infection given adequate exposure, laboratory transmission data were obtained from published studies involving experimental infection with FMD. In cases where no empirical disease transmission data were published, the probability of disease transmission was assumed to be 1.0 (100 percent). The data collected from the literature were used to calculate the probability of infection given exposure for each production-type combination. To account for a variety of biosecurity measures implemented by various livestock sectors, an average reduction factor was calculated using published NAHMS data (USDA-APHIS-

VS, CEAH, Fort Collins, CO, 2000; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2001; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007a; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007b; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2008; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2009; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2010). This reduction factor was then multiplied by the probability of indirect disease transmission for each livestock sector (cattle, swine, and small ruminants).

## Local Area Spread

Local area spread, defined as the transmission of virus via local aerosols and mechanical transmission (rodents, birds, pets, etc.), is thought to be a contributor of disease spread. Local spread may affect the size, duration, and extent of an FMD outbreak in the proximity of each infected herd. Of particular concern is that, unlike movements of animals, products, and people, this form of spread cannot be controlled by the usual quarantines and movement restrictions that animal health authorities apply to affected regions (Table 21).

**Table 21. Local area spread parameters**

<b>Production type combination</b>	<b>Probability of spread between two herds of average size located 1 km apart</b>	<b>Maximum distance of spread (km)</b>	<b>Range of direction (deg)</b>	<b>Airborne transport delay (days)</b>
All production type combinations	0.008	3	0–360	0

### Justification for assumptions

After movement controls had been imposed in Cumbria, U.K., during the 2001 FMD outbreak, disease spread continued. This continued spread may have been due to direct fence-line contact between contiguous premises, spread by fomites or illegal movements of animals, or close proximity aerosol spread. Disease spread that occurred over short distances (<3 km) where no source was identified was referred to as local spread. A study using data from the 2001 Cumbria outbreak estimated the cumulative 17-day risk of infection by local spread to be 14 percent at a distance of 1.5 km and 3 percent at a distance of 3 km after movement controls had been imposed (Taylor, Honhold, Paterson, & Mansley, 2004). Therefore, the assumed daily probability of local spread infection for all production type combinations at a distance of 1 km was estimated to be 0.008 ( $0.14/17=0.008$ ).

## Detection and Reporting

Disease detection refers to the identification and reporting of infected herds based on the appearance of clinical signs. Two probabilities affect the overall chance that an infected herd will be detected: (1) the probability of observing clinical signs in a herd given the number of days that a herd has been exhibiting clinical signs and (2) the probability that the owner or veterinarian will report disease to the animal health authorities given the number of days since disease was first detected and reported anywhere in the

population. Both of these probabilities are represented as relational functions (Tables 22–34). The rationale for having the probability of detection be a function of these two individual probabilities is that, as disease progresses through a herd, the owner will be more likely to observe sick animals, and once disease has been observed and reported somewhere in the study population, awareness and alertness is likely to increase among livestock producers and veterinarians.

**Table 22. Probability of observing clinical signs in a company feedlot given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Company feedlots</b>								
Day	0	2	4	6	8	10	12	14
Probability	0.17	1.0	1.0	1.0	1.0	1.0	1.0	1.0

**Table 23. Probability of observing clinical signs in a stockholder feedlot given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Stockholder feedlots</b>								
Day	0	2	4	6	8	10	12	14
Probability	0.19	1.0	1.0	1.0	1.0	1.0	1.0	1.0

**Table 24. Probability of observing clinical signs in a custom feedlot given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Custom feedlots</b>								
Day	0	2	4	6	8	10	12	14
Probability	0.22	1.0	1.0	1.0	1.0	1.0	1.0	1.0

**Table 25. Probability of observing clinical signs in a yearling-pasture feedlot given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Yearling-pasture feedlots</b>								
Day	0	2	4	6	8	10	12	14
Probability	0.48	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Justification for assumptions – all feedlots

The parameters for probability of observing clinical signs were derived from simulations that were run for each production type using the R software environment (R Development Core Team, 2011). These simulations calculated the probability of observing clinical signs as a function of the within-herd prevalence of clinically infectious animals, the herd size, and the hypergeometric probability of observing at least one clinically infectious

animal from a random sample of animals each day. The daily within-herd prevalence of clinically infectious animals was obtained from the within-herd model (Reeves et al., 2013). The herd size for each production type followed BetaPERT distributions with minima, modes, and maxima obtained from the TX population file. The number of animals observed per day followed a Poisson distribution with a mean of 20. In conversations with commodity experts, it was determined that management practices of feedlot operations generally confine groups of animals within pens, limiting the degree of commingling among animals. It was assumed that FMDV would be introduced to a single pen and spread throughout that pen before spreading to neighboring pens. Maximum pen size was assumed to be 300 animals. A sample size of 20 animals was chosen as a reasonable number of animals easily observed if one were to approach a confinement area. Each simulation was run for 1,000 iterations to obtain distributions of the daily probability of observing clinical signs. The parameter values used in NAADSM were the medians of those distributions.

**Table 26. Probability of observing clinical signs in a large cow-calf operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Large cow-calf operations</b>						
Day	0	4	8	12	16	20
Probability	0.04	0.97	1.0	1.0	1.0	1.0

**Table 27. Probability of observing clinical signs in a small cow-calf operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Small cow-calf operations</b>				
Day	0	4	8	12
Probability	0.41	1.0	1.0	1.0

**Table 28. Probability of observing clinical signs in a stocker operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Stocker operations</b>			
Day	0	4	8
Probability	0.16	1.0	1.0

Justification for values—large cow-calf, small cow-calf, and stocker operations

The parameters for the probability of observing clinical signs were derived from simulations that were run for each production type using the R software environment (R Development Core Team, 2011). These simulations calculated the probability of observing clinical signs as a function of the within-herd prevalence of clinically infectious animals, the herd size, and the hypergeometric probability of observing at least one

clinically infectious animal from a random sample of animals each day. The daily within-herd prevalence of clinically infectious animals was obtained from the within-herd model (Reeves et al., 2013). The herd size for each production type followed BetaPERT distributions with minima, modes, and maxima obtained from the TX population file. The number of animals observed per day followed a Poisson distribution with a mean of 20. In conversations with commodity experts, it was determined that cattle on large cow-calf, small cow-calf, and stocker operations were generally grazed in pastures of larger area with limited observation potential. This limited observation potential leads to a longer lead time to observation than other production types. A random sample of 20 animals from a grazing herd was chosen as a reasonable number of animals easily observed when visually scanning the herd. Each simulation was run for 1,000 iterations to obtain distributions of the daily probability of observing clinical signs. The parameter values used in NAADSM were the medians of those distributions.

**Table 29. Probability of observing clinical signs in a large dairy operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Large dairy operations</b>								
Day	0	2	4	8	8	10	12	14
Probability	0.05	0.97	1.0	1.0	1.0	1.0	1.0	1.0

**Table 30. Probability of observing clinical signs in a small dairy operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Small dairy operations</b>							
Day	0	2	4	6	8	10	10
Probability	0.07	0.94	1.0	1.0	1.0	1.0	1.0

Justification for values—large dairy and small dairy operations

The parameters for the probability of observing clinical signs were derived from simulations that were run for each dairy production type using the R software environment (R Development Core Team, 2011). These simulations calculated the probability of observing clinical signs as a function of the within-herd prevalence of clinically infectious animals, the herd size, and the hypergeometric probability of observing at least one clinically infectious animal from a random sample of animals each day. The daily within-herd prevalence of clinically infectious animals was obtained from the within-herd model (Reeves et al., 2013). The herd size for each production type followed BetaPERT distributions with minima, modes, and maxima obtained from the TX population file. The number of animals observed per day followed a Poisson distribution with a mean of 20. In conversations with commodity experts, it was determined that management practices of dairy operations generally confined animals within pens limiting the degree of comingling among animals, and animals are observed on a daily basis. It was assumed that FMDV would be introduced to a single pen and spread throughout that pen before spreading to neighboring pens. Maximum pen size was assumed to be 300

animals. A sample size of 20 animals was chosen as a reasonable number of animals easily observed if one were to approach a confinement area. Each simulation was run for 1,000 iterations to obtain distributions of the daily probability of observing clinical signs. The parameter values used in NAADSM were the medians of those distributions.

**Table 31. Probability of observing clinical signs in a large swine operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Large swine operations</b>									
Day	0	2	4	6	8	10	12	14	18
Probability	0.87	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

**Table 32. Probability of observing clinical signs in a small swine operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Small swine operations</b>							
Day	0	2	4	6	8	10	
Probability	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Justification for values—large swine and small swine operations

The parameters for the probability of observing clinical signs were derived from simulations that were run for each swine production type using the R software environment (R Development Core Team, 2011). These simulations calculated the probability of observing clinical signs as a function of the within-herd prevalence of clinically infectious animals, the herd size, and the hypergeometric probability of observing at least one clinically infectious animal from a random sample of animals each day. The daily within-herd prevalence of clinically infectious animals was obtained from the within-herd model and multiplied by 0.9 to reflect that clinical signs are less apparent in swine than in cattle (Reeves et al., 2013). The herd size for each production type followed BetaPERT distributions with minima, modes, and maxima obtained from the TX population file. The number of animals observed per day followed a Poisson distribution with a mean of 20. In conversations with commodity experts, it was determined that management practices of swine operations were generally confined within pens, limiting the degree of commingling among animals. It was assumed that FMDV would be introduced to a single pen and spread throughout that pen before spreading to neighboring pens. Maximum pen size was assumed to be 300 animals. A sample size of 20 animals was chosen as a reasonable number of animals easily observed if one were to approach a confinement area. Each simulation was run for 1,000 iterations to obtain distributions of the daily probability of observing clinical signs. The parameter values used in NAADSM were the medians of those distributions.

**Table 33. Probability of observing clinical signs in a small ruminant operation given the number of days that a herd has been showing clinical signs of disease** (Day 0 represents the first day that a herd is showing clinical signs of disease.)

<b>Small ruminant operations</b>							
Day	0	2	4	6	8	10	12
Probability	0.05	0.53	0.63	0.55	0.38	0.21	0

Justification for values

The probability of observing clinical signs in small ruminants was derived from a simulation that was run using the R software environment (R Development Core Team, 2011). This simulation calculated the probability of observing clinical signs as a function of the within-herd prevalence of clinically infectious animals, the herd size, and the hypergeometric probability of observing at least one clinically infectious animal from a random sample of animals each day. The daily within-herd prevalence of clinically infectious animals was obtained from the within-herd model and multiplied by 0.25 to reflect that clinical signs are less apparent in small ruminants than in cattle and swine (Reeves et al., 2013). The herd size for each production type followed BetaPERT distributions with minima, modes, and maxima obtained from the TX population file. The number of animals observed per day followed a Poisson distribution with a mean of 20. A sample size of 20 animals was chosen as a reasonable number of animals easily observed if one were to approach a confinement area. The simulation was run for 1,000 iterations to obtain distributions of the daily probability of observing clinical signs. The parameter value used in NAADSM was the median of that distribution.

**Table 34. Probability of reporting clinical signs for all production types given the number of days since the initial detection in the entire population** (Day 0 represents the day of initial detection.)

<b>All production types</b>			
Day	0	2	4
Probability	0.20	1.0	1.0

Justification for assumptions

The assumed probability of reporting clinical animals was based on the study by Delgado et al., 2012, which states that less than 20 percent of cattle operation managers would be able to identify FMD in the event of an outbreak and that others may be reluctant to report their findings to veterinarians during that time (Delgado, Norby, Dean, McIntosh, & Scott, 2012). Additional challenges in reporting and diagnosis include the misdiagnosis of FMDV as other diseases have similar clinical signs (Kitching & Alexandersen, 2002; Kitching & Hughes, 2002; Kitching, 2002).

## Tracing

Herds that have had contact with diseased herds within a given number of days prior to detection of the diseased herd may be identified by trace investigations. In NAADSM, trace investigations may be immediate or there may be a delay in results. Trace investigations are simulated to identify premises that were recipients of direct or indirect contact from infected, detected premises (referred to as “trace out” or “trace forward”), or premises that were sources of direct or indirect contact to infected, detected premises (“trace in” or “trace back”) (Table 35).

**Table 35. Trace parameters by production type**

<b>Production type</b>	<b>Probability of direct contact trace-forward/back investigations succeeding</b>	<b>Probability of indirect contact trace-forward/back investigations succeeding</b>	<b>Delay in obtaining results (both direct and indirect) (min, mode, max)</b>	<b>Period of interest for trace-out investigations (days)</b>
Company feedlot	0.86	0.70	BetaPERT (0, 7.38, 14)	28
Stockholder feedlot	0.86	0.70	BetaPERT (0, 7.38, 14)	28
Custom feedlot	0.86	0.70	BetaPERT (0, 7.38, 14)	28
Yearling-pasture feedlot	0.86	0.70	BetaPERT (0, 7.38, 14)	28
Large dairy	0.93	0.70	BetaPERT (0, 3.63, 14)	28
Small dairy	0.93	0.70	BetaPERT (0, 3.63, 14)	28
Large swine	0.91	0.70	BetaPERT (0, 3.72, 14)	28
Small swine	0.91	0.70	BetaPERT (0, 3.72, 14)	28
Large cow-calf	0.86	0.70	BetaPERT (0, 5.97, 14)	28
Small cow-calf	0.86	0.70	BetaPERT (0, 5.97, 14)	28
Stockers	0.86	0.70	BetaPERT (0, 5.97, 14)	28
Small ruminants	0.87	0.50	BetaPERT (0, 5.57, 14)	28

Justification for assumptions

Federal and State FMD response plans dictate that trace-forward and trace-back investigations should be conducted for premises where FMD infection is detected. A survey of 19 Federal animal health managers, evaluating traceability of slaughter cattle and swine to the last herd of ownership under different animal identification scenarios, reported probabilities of trace success and delay in obtaining trace results (Disney, Green, Forsythe, Wiemers, & Weber, 2001). The probabilities of success and delays in obtaining results varied by species and by animal identification method. Results reported from that survey and estimates of percentages of operations that use individual-animal identification (or group/lot ID for swine) were used to

calculate weighted averages of the probability of direct contact trace success and the delay in obtaining trace results. Percentages of operations that use individual-animal ID were obtained from NAHMS reports, a National Scrapie Eradication Program report, the National Pork Board, and the American Sheep Industry Association (American Sheep Industry Association, 2011; The National Pork Board, 2010; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2000; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2001; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007a; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2007b; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2008; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2009; USDA-APHIS-VS, CEAH, Fort Collins, CO, 2010). The results reported in the study by Disney and others (2001) for the delay in obtaining trace results were reported as averages. To reflect variability in the delay in obtaining trace results, these parameters follow BetaPERT distributions in which the minimum assumed delay is 0 days, the maximum assumed delay is 14 days, and most likely delay is equal to the weighted average delay for each production type. A minimum of 0 days was used to allow for the possibility that some direct contacts could be identified the same day that an infected herd is detected and reported. The maximum delay was chosen in consultation with subject matter experts from NCAHEM who considered it unlikely that tracing would be continued for more than 14 days because contact herds would likely be showing clinical signs by that time. A survey of 11 traceability experts in California found that the maximum delay in obtaining trace results from dairies during a bovine tuberculosis investigation was 28 days (unpublished data). Therefore, this value was chosen as the maximum tracing delay.

Information on the probability of trace success of indirect contacts was not available in the published literature but was assumed to be lower than the probability of success of direct traces. Based on NAHMS data of record-keeping practices, small ruminants were given a lower probability of indirect trace success than all cattle and swine production types (USDA-APHIS-VS, CEAH, Fort Collins, CO, 2009). Parameters for the delay in obtaining indirect trace results were assumed to be the same as the delay in obtaining direct trace results. The number of days prior to detection that trace investigations were to be conducted reflects two times the incubation period, as stated in Federal and State FMD response plans (USDA-APHIS-VS-NCAHEM, 2011a).

## Exam and Diagnostic Testing

Herds that are directly or indirectly traced to an infected herd that has been detected can be examined for clinical signs. Traced herds that are not detected by examination may still be tested for FMD infection. The outcome of the exam depends on the disease state of the examined herd, the probability of observing clinical signs, and an exam multiplier. The outcome of the diagnostic test depends on the disease state of the tested herd and the sensitivity and specificity of the diagnostic test. There may also be a delay in obtaining test results (Table 36).

**Table 36. Exam and diagnostic testing parameters by production type**

<b>Production type</b>	<b>Exam multiplier</b>	<b>Test sensitivity</b>	<b>Test specificity</b>	<b>Delay in obtaining test results (min, mode, max)</b>
Company feedlot	4.47	0.90	0.98	BetaPERT (0, 1, 2)
Stockholder feedlot	4.00	0.90	0.98	BetaPERT (0, 1, 2)

Custom feedlot	3.45	0.90	0.98	BetaPERT (0, 1, 2)
Yearling-pasture feedlot	1.58	0.90	0.98	BetaPERT (0, 1, 2)
Large cow-calf	19.0	0.90	0.98	BetaPERT (0, 1, 2)
Small cow-calf	1.85	0.90	0.98	BetaPERT (0, 1, 2)
Stockers	4.75	0.90	0.98	BetaPERT (0, 1, 2)
Large dairy	15.2	0.90	0.98	BetaPERT (0, 1, 2)
Small dairy	10.86	0.90	0.98	BetaPERT (0, 1, 2)
Large swine	0	0.90	0.98	BetaPERT (0, 1, 2)
Small swine	0	0.90	0.98	BetaPERT (0, 1, 2)
Small ruminants	15.2	0.90	0.98	BetaPERT (0, 1, 2)

#### Justification for assumptions

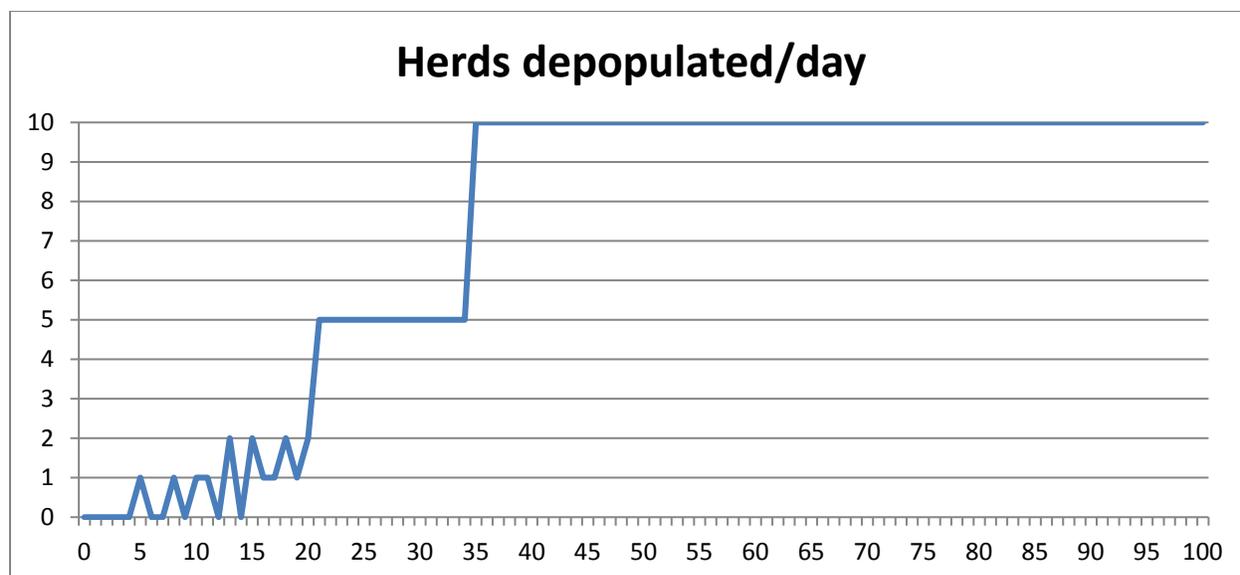
A study of the 2001 U.K. outbreak estimated that the diagnostic sensitivity of routine examination for clinical signs was 76 percent (McLaws, Ribble, Stephen, McNab, & Barrios, 2007). For production types that have probabilities of observing clinical signs parameters below 76 percent on the first day of clinical illness, the exam multiplier was set to raise those probabilities to 76 percent. Small ruminants require a longer time period to reach 76 percent probability of observing clinical signs. The exam multipliers for that production type were chosen to strike a balance between underestimating the probability of observing clinical signs during the early days of clinical illness and overestimating the probability later.

FMD infection can be confirmed by enzyme-linked immunosorbent assay (ELISA), virus isolation, or reverse transcription polymerase chain reaction (RT-PCR) (World Organization for Animal Health (OIE), 2009). The NVS Countermeasures Working Group recommended in 2007 that commercial AG-ELISA tests be stockpiled for detection of FMD during an outbreak with no vaccination and the 3ABC commercial test kits (Cedi-diagnostics) be stockpiled to detect cases during an outbreak with vaccination (USDA Agricultural Research Service, 2007). A comparative study of six ELISA tests using cattle, swine, and sheep sera found the Cedi-diagnostic test to have a specificity of 98.1 percent. Sensitivity varied by vaccination status, experimental exposure status, and number of days post infection but generally approached 90 percent. Results were similar across species (Brocchi et al., 2006). Therefore sensitivity and specificity parameters are assumed to be the same for all species. ELISA assay results can be obtained within hours of sample delivery. However, there may be a delay depending on herd distance from the nearest testing facility, time of day, or day of the week that samples are collected. Therefore, it is assumed that the delay in obtaining results follows a BetaPERT distribution with a minimum of 0 days, a mode of 1 day, and a maximum of 2 days.

## Depopulation

When the first detection occurs in the study population, the affected premises will be quarantined the following day and all livestock movement to or from that premises will be prohibited. Additionally, movement restrictions will be implemented in order to reduce the amount of movement between herds. Authorities may also initiate a depopulation program. It can take several days before the authorities are ready to begin depopulating. The delay before implementing a depopulation program was assumed to be 1 day (Ward et al., 2009).

There is a limit (depopulation capacity) to how many herds can be depopulated per day. Depopulation capacity does not consider herd size (i.e., the number of animals in each herd) and a single depopulation capacity applies to all production types. It was assumed that depopulation capacity follows the pattern in Figure 1 below.



**Figure 1. Depopulation capacity in herds per day as a function of number of days since initial detection of disease**

### Justification for assumptions

A modeling study set in the Texas Panhandle used expert opinion obtained from local industry personnel to estimate depopulation capacity. From those meetings it was assumed that one depopulation team would be available on the first day post-detection and would increase linearly until reaching a maximum on day 21 post-detection (Ward et al., 2009). These meetings also gathered information that was used to estimate the time required to depopulate one herd of each production type and to prioritize according to risk category (Table 37). Depopulation capacity in NAADSM is a global parameter that applies equally to all herds regardless of production type or herd size. Therefore, a weighted average time requirement was calculated from the number of herds of each production type and the time required to depopulate a herd in each production type. For this calculation all feedlots were collapsed into one category requiring 14 days for

depopulation because only 7 percent of herds with cattle on feed had more than 2,500 head. Stockers and large cow-calf operations were combined into a large beef category requiring 10 days for depopulation. The average estimated time required for depopulation was 5.11 days, reflecting the fact that small beef operations comprised 69 percent of the herds in the calculation (Table 38).

**Table 37. Depopulation priorities and time requirements by production type**

<b>Production type</b>	<b>Depopulation, disposal and decontamination time (days) per herd</b>	<b>Depopulation priority</b>
Company feedlot	28	3
Stockholder feedlot	28	4
Custom feedlot	21	5
Yearling pasture feedlot	14	6
Large cow-calf	10	9
Small cow-calf	5	11
Stocker	10	10
Large dairy	7	7
Small dairy	5	8
Large swine	7	1
Small swine	5	2
Small ruminant	3	12

Assuming that a depopulation program begins with 1 team 1 day after initial detection, depopulation of the first herd would be completed 5 days after initial detection. It is assumed that the number of depopulation teams available increases by 1 team every 2 to 3 days until reaching a maximum of 10 teams 21 days after the initiation of the depopulation campaign. Assuming a time requirement of 5 days/herd results in an irregular pattern of depopulation capacity ranging from 0 to 2 herds/day until 21 days after the initiation of the depopulation campaign. Beginning 21 days after initiation of the depopulation campaign, a repetitive 5-day pattern emerges of 2, 1, 3, 1, 3 herds/day. These depopulation capacity estimates were adjusted after consultation with subject matter experts from NCAHEM who recommended that the vaccination capacity from day 21 to day 34 be 5 herds/day and 10 herds/day after day 35.

If a herd is marked for depopulation but cannot be depopulated immediately, it is quarantined and goes onto the following prioritized waiting list: **reason for depopulation** (detection of disease > identification of

a direct contact with a detected herd by trace investigation) > **production type** (following the order in Table 37 above) > **days holding**.

Justification for assumptions

The depopulation priorities ensure that all detected herds will be depopulated before traced herds. Detected high-priority production types will be depopulated before detected low-priority production types regardless of the length of time that herds have been waiting for depopulation. This setting follows from the assumption that the highest priority production types are at risk of contributing to airborne spread after quarantine has been imposed and should be depopulated before lower risk production types that have been waiting longer but are at lower risk of contributing to airborne spread.

All detected herds are marked for depopulation. Herds that have had contact with diseased herds within a given number of days prior to detection of the diseased herd (found through trace investigations) and herds within a given distance of diseased herds may also be marked for depopulation. The depopulation of these herds associated by trace or distance is called pre-emptive depopulation.

**Table 38. Depopulation parameters by production type**

<b>Production type</b>	<b>Depopulate detected disease herds</b>	<b>Detection triggers a depopulation ring</b>	<b>Radius of depopulation ring (km)</b>	<b>Pre-emptively destroy direct contacts</b>	<b>Pre-emptively destroy indirect contacts</b>	<b>Pre-emptively destroy herds within ring</b>
Company feedlot	Yes	No	NA	Yes	No	No
Stockholder feedlot	Yes	No	NA	Yes	No	No
Custom feedlot	Yes	No	NA	Yes	No	No
Yearling-pasture feedlot	Yes	No	NA	Yes	No	No
Large dairy	Yes	No	NA	Yes	No	No
Small dairy	Yes	No	NA	Yes	No	No
Large swine	Yes	No	NA	Yes	No	No
Small swine	Yes	No	NA	Yes	No	No
Large cow-calf	Yes	No	NA	Yes	No	No
Small cow-calf	Yes	No	NA	Yes	No	No
Stockers	Yes	No	NA	Yes	No	No
Small ruminants	Yes	No	NA	Yes	No	No

Justification for assumptions

According to the USDA FMD disease response plan, four control strategies will be considered in the event of the outbreak (USDA-APHIS-VS-NCAHEM, 2011a). Three of these four strategies involve slaughter of all clinically affected herds and herds that have had direct or indirect contact with detected premises. The fourth strategy is a vaccination-to-live policy without stamping out where no slaughter of direct or indirect contact premises identified by tracing takes place. Following the three strategies that involve slaughter, it was assumed that all detected and traced herds will be depopulated and ring depopulation will not be implemented. Subject matter experts from NCAHEM recommended that herds traced by indirect contact should not be depopulated in these simulations.

## Vaccination

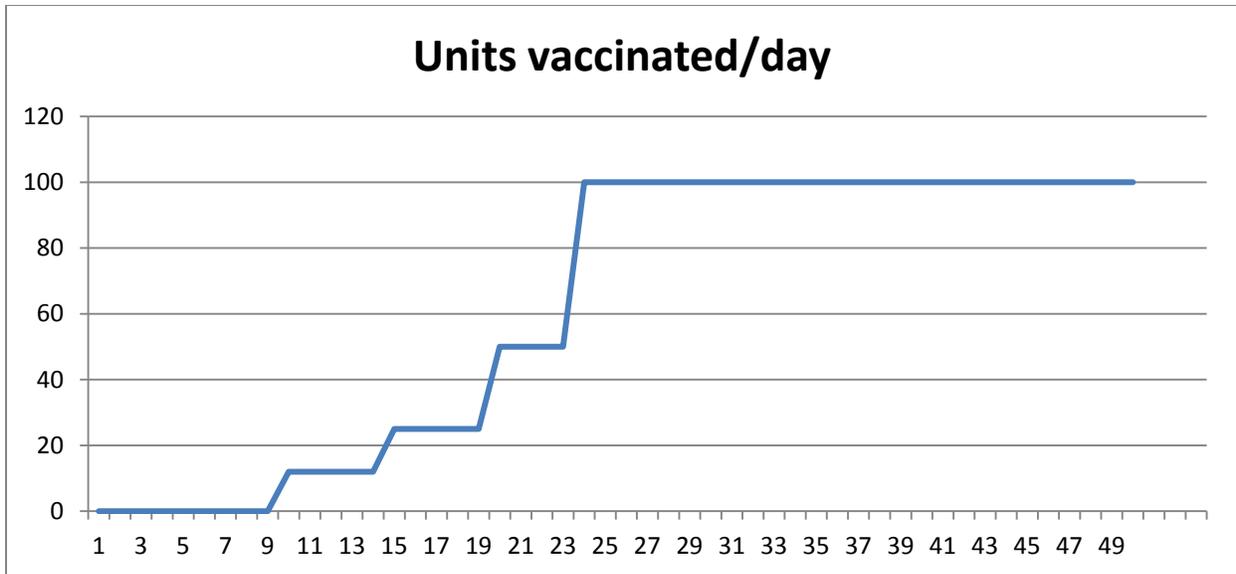
When disease is detected, authorities may also initiate a vaccination campaign. This consists of vaccinating units within a specified distance of the detected units.

A vaccination program is initiated when the user-specified number of infected units has been detected. Until or unless this number is reached, units are not marked for vaccination. Once this critical number has been reached, units within the specified vaccination circle surrounding detected units are marked for vaccination.

### Justification for assumptions

Subject matter experts with NCAHEM recommended that the vaccination campaign should start 10 days after initial detection of FMD regardless of the number of detected herds. Therefore, the number needed to initiate a vaccination campaign is one herd.

Vaccination capacity (the number of units that can be vaccinated per day) is specified as a relational chart of the number of units which can be vaccinated per day versus the number of days since the first detection of disease. Vaccination capacity does not consider unit size (i.e., the number of animals in each unit) and a single vaccination capacity applies to units of all production types. It was assumed that vaccination capacity follows the pattern in Figure 2.



**Figure 2. Number of herds that can be vaccinated per day as a function of time since initial FMD detection**

Justification for assumptions

It was assumed that the North American Foot-and-Mouth Disease Vaccine Bank will be activated immediately after the first detection occurs. Vaccine capacity over time is a function of the time required for the first batch of vaccine doses to be produced and delivered, the number of vaccine doses available over time, and the logistical resources available to administer vaccine. A published review of vaccine bank technical requirements stated that the time between the receipt of an order by a manufacturer and delivery of the vaccine on site can vary between 4 and 13 days depending on distance and flight availability (Lombard & Fussel, 2007). A survey of 8 vaccine bank organizations reported that the shortest time needed for delivery of 100,000 doses was 3 to 4 days, 2 days if required quality control tests were waived (Proceedings of the first workshop of workpackage 4 of the FMD-European Union, CSF coordination action held as IAH-Pirbright, U.K., 2006). The most likely time period required for vaccine production and delivery is 6 to 10 days (USDA-APHIS-VS-NCAHEM, 2011b).

In NAADSM, vaccine capacity is defined as the number of units that can be vaccinated per day given the number of days since *first* detection. It is assumed that 0 units/day can be vaccinated during the first 10 days after initial detection while the vaccine is matched, produced, and delivered. A study that modeled FMD spread in the Texas Panhandle surveyed local industry representatives to determine the vaccination capacity in that region (Ward et al., 2009). According to that study, once vaccine became available, 12 herds/day could be vaccinated during the first 7 days (days 11–17 post initial detection), 25 herds/day during the next 7 days (days 18–24), and 50 herds/day for the remainder of the vaccination campaign. The vaccination capacity was adjusted to that shown in Figure 2 after consultation with subject matter experts from NCAHEM who thought that vaccination capacity would be higher than estimates from the Texas Panhandle study.

If a unit is marked for vaccination but cannot be vaccinated immediately, it goes onto the following prioritized waiting list: production type > days holding > reason for vaccination – ring.

Justification for assumptions

Vaccination is limited to units that have not been identified as infected and are located within a vaccination ring. Among production types, swine operations will receive highest priority followed by dairy operations, feedlots, cow-calf operations, and stocker operations. Among herds of the same production type, priority is given to herds that have spent the most time in holding. In consultation with subject matter experts from NCAHEM, it was decided that small ruminant operations would not be vaccinated.

**Table 39. Vaccination parameters by production type**

<b>Production type</b>	<b>Vaccinate detected units of this production type</b>	<b>Immune period (days)</b>	<b>Delay in immunity (days)</b>	<b>Time between vaccination (days)</b>	<b>Radius of vaccination ring (km)</b>
Company feedlot	No	BetaPERT (28, 180, 220)	7	180	10
Stockholder feedlot	No	BetaPERT (28, 180, 220)	7	180	10
Custom feedlot	No	BetaPERT (28, 180, 220)	7	180	10
Yearling-pasture feedlot	No	BetaPERT (28, 180, 220)	7	180	10
Large dairy	No	BetaPERT (28, 180, 220)	7	180	10
Small dairy	No	BetaPERT (28, 180, 220)	7	180	10
Large swine	No	BetaPERT (28, 180, 220)	14	180	10
Small swine	No	BetaPERT (28, 180, 220)	14	180	10
Large cow-calf	No	BetaPERT (28, 180, 220)	7	180	10
Small cow-calf	No	BetaPERT (28, 180, 220)	7	180	10
Stocker	No	BetaPERT (28, 180, 220)	7	180	10
Small ruminants	No	NA	NA	NA	NA

Justification for assumptions

According to the USDA Foot-and-Mouth Disease Response Plan (USDA-APHIS-VS-NCAHEM, 2011a), a modified stamping out strategy with emergency vaccination to slaughter will involve slaughter of detected and contact premises and vaccination of at-risk premises (i.e., susceptible premises within a vaccination zone surrounding detected premises). A vaccination-to-live

strategy, with or without stamping out, involves forming vaccination zones outside of the FMD containment area (control zone). NAADSM allows vaccination zones to be formed only around detected units. Therefore, simulations are assumed to follow a modified stamping out strategy with emergency vaccination to slaughter of all at-risk premises in a 10-km zone around infected premises eligible for vaccination.

Vaccine parameters (Table 39) were developed under the assumption that high-potency emergency vaccines ( $PD_{50} \geq 6$ ) would be used. NAADSM assumes that vaccination is 100-percent effective. Therefore, the delay in immunity parameter should be selected to reflect the time required for a herd to become completely protected from clinical disease/virus shedding. Experimental studies have shown that vaccinated cattle and sheep are partially protected as early as 4 days post vaccination but may take up to 14 days for complete protection (Barnett & Carabin, 2002; Barnett et al., 2004; Cox & Barnett, 2009; Madhanmohan, Nagendrakumar, Narasu, & Srinivasan, 2010; Orsel, Dekker, Bouma, Stegeman, & de Jong, 2005; Orsel, Dekker, Bouma, Stegeman, & de Jong, 2007; Orsel, de Jong, Bouma, Stegeman, & Dekker, 2007a; USDA-APHIS-VS-NCAHEM, 2011b). Results varied by study design, species, challenge strain, and vaccine. Onset of immunity in pigs generally takes longer to achieve than for other species, usually requiring at least 21 to 28 days for complete protection (Doel, Williams, & Barnett, 1994; Orsel, de Jong, Bouma, Stegeman, & Dekker, 2007b; Parida et al., 2007). In consultation with subject matter experts from NCAHEM, a value of 14 days was chosen for swine and 7 days for non-swine species.

Experimental studies on the duration of immunity using single-dose, high-potency emergency vaccines have generally shown that titers remain high 6 months after vaccination (Cox & Barnett, 2009); (USDA-APHIS-VS-NCAHEM, 2011b). One study showed titers in cattle peaked at 2 months and remained high, declining slightly up to 6 months (Cox et al., 2010). Another study showed waning titers in vaccinated cattle 43 days after vaccination (Barnett, Pullen, Williams, & Doel, 1996). There are few challenge studies available beyond 28 days post vaccination. One challenge study in cattle showed protection from clinical disease and high titers at 6 months (Cox et al., 2010). Another challenge study in pigs showed protection at 7 months (Cox, Aggarwal, Statham, & Barnett, 2003). To reflect the uncertainty due to the lack of experimental data available and the fact that immunity generally lasts at least 6 months, the duration of immunity for all species is assumed to follow a BetaPERT distribution with a minimum of 28 days, a maximum of 220 days, and a mode of 180 days.

The size of a vaccination ring zone should be the smallest area necessary to control the outbreak, taking into consideration geographical barriers, climatic conditions, the number and distribution of detected FMD infected herds, the density of farms, and species present. Therefore, the optimal ring size will vary by location. However, for the purposes of this study, a vaccine ring with a radius of 10 km is assumed to be triggered following the detection of infected herds.

Revaccination in NAADSM can occur in situations where a new vaccination ring is created around herds that had also been located within an older vaccination ring and were previously vaccinated. The OIE Manual of Diagnostic Tests and Vaccines for Terrestrial Animals (2010) recommends that revaccination occur at 4 to 12 months and we have assumed that the duration of immunity for most herds will last approximately 6 months (World Organization for Animal Health (OIE), 2010). We have assumed that, under conditions of limited vaccination resources, decision makers would not elect to revaccinate a herd unless at least 6 months had elapsed since the prior vaccination.

## Zones

Circular zones can be created to simulate enhanced movement restrictions in a Control Area and enhanced detection in a Surveillance Zone. Zone formation can be triggered by and established around any herd that is detected as diseased. Zones can also be triggered by and established around any direct or indirect contact herd that has been discovered through tracing (Table 40).

Some types of movement controls are imposed automatically by NAADSM when a zone is created. Detected herds that trigger a zone are automatically quarantined. Movement from a herd located in a zone with less restrictive parameters to an adjacent zone with more restrictive parameters (e.g., from a Surveillance Zone to a Control Area) is allowed, but the reverse is not allowed. In addition to these automatic movement controls built into NAADSM, movement among herds located within the same zone can be reduced. Zone parameters for movement control override “global” movement control parameters that apply to all herds of a given production type. (See explanation provided in the Direct Contact and Indirect Contact sections.)

**Table 40. Zone parameters**

	<b>Control Area</b> (Infected Zone + Buffer Zone)	<b>Surveillance Zone</b>
Trigger by detection	Yes	Yes
Trigger by direct trace	Yes	Yes
Trigger by indirect trace	Yes	Yes
Radius (km)	10	20
Reduction of baseline direct contact rate within the zone	90%	No additional reduction
Reduction of baseline indirect contact rate within the zone	50% for the first 3 days then 70%	No additional reduction
Multiplier for probability of detection	Same as the exam multiplier for each production type (Table 36)	Same as the exam multiplier for each production type (Table 36)

### Justification for assumptions

All zone parameters, except the multiplier for probability of detection (see exam parameters above), are assumed to apply equally to all production types. According to the APHIS Framework for Foreign Animal Disease Preparedness and Response, Control Areas with minimum radii of 10 km (comprised of an Infected Zone surrounded by a Buffer Zone) will be designated around infected premises and direct and indirect contact premises traced to infected premises (USDA-APHIS-VS-NCAHEM, 2010). Each Control Area will be surrounded by a Surveillance Zone with a minimum width of 10 km. Therefore, the total combined zone size around detected and contact premises is assumed to be 20 km. All premises within a Control Area will be subject to movement controls, strict biosecurity measures, and surveillance requirements, resulting in reduced direct

and indirect contact rates and an increased probability of detection. All herds within a Surveillance Zone will be subject to surveillance requirements but no additional movement controls within the Surveillance Zone.

A group of 10 experts with experience in FMD control were surveyed to elicit parameters for a hypothetical FMD outbreak set in the Texas Panhandle (Ward et al., 2009). Based on this survey, movement controls were assumed to reduce the direct contact rate by 80 percent and reduce the indirect contact rate by 50 percent in the Control Area 1 day after detection. Subject matter experts from NCAHEM recommended that the reduction in the direct contact rate in the Control Area should be increased to 90 percent and the reduction in the indirect contact rate should be increased from 50 to 70 percent 3 days after the creation of the Control Area.

Zone parameters for enhanced detection include a “multiplier” that alters the baseline probability of observing clinical signs. A study of the 2001 U.K. outbreak estimated that the herd diagnostic sensitivity of examination for clinical signs was 76 percent (McLaws et al., 2007). The multiplier for probability of detection parameter for each production type depends on the baseline probability of detection. For production types with a baseline probability of detection <76 percent, the multiplier for probability of detection will be such that the probability of detection equals 76 percent.

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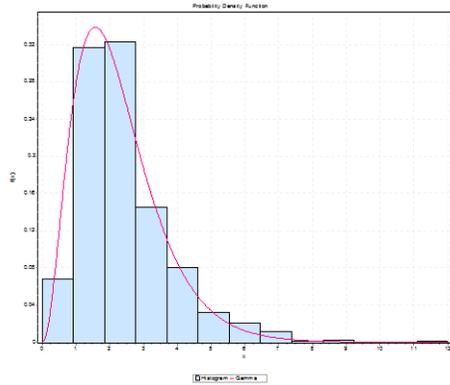
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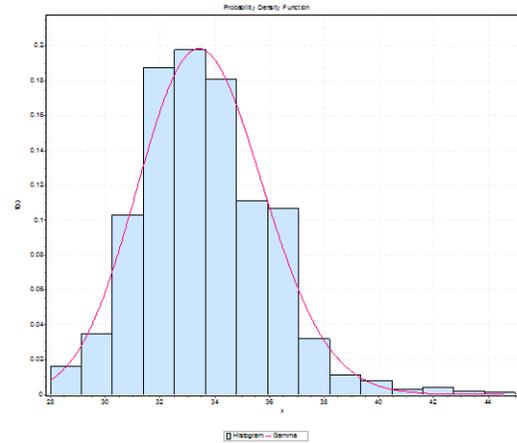
## Appendix I: Herd-level Disease State Charts

### Company feedlot—latent



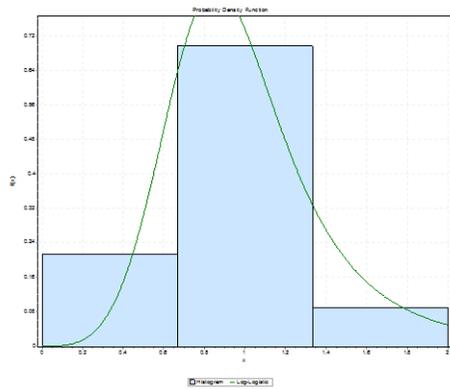
gamma (alpha=3.24, beta=0.70)

### Company feedlot—clinical



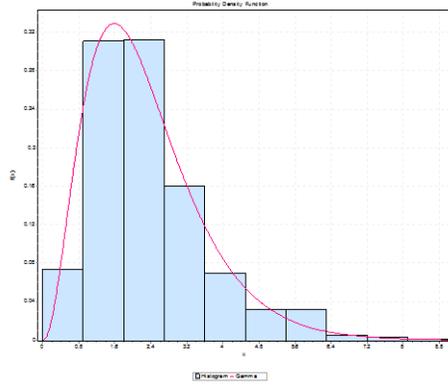
gamma (alpha=216.62, beta=0.15)

### Company feedlot—subclinical



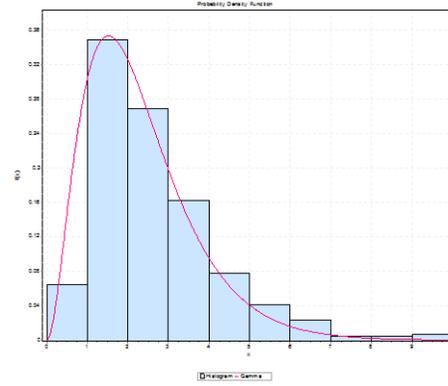
log-logistic (alpha=4.48, beta=0.95)

### Stockholder feedlot—latent



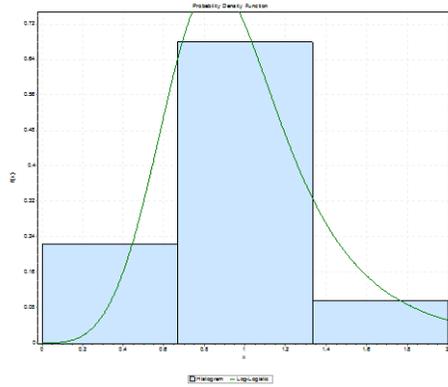
gamma (alpha=3.27, beta=0.70)

### Custom feedlot—latent



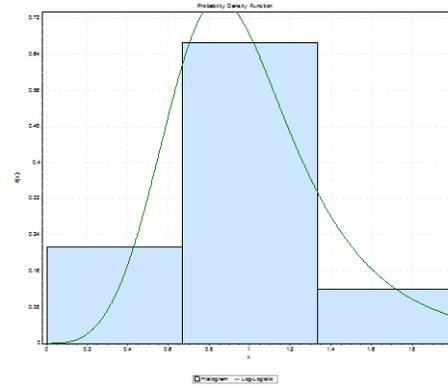
gamma (alpha=2.97, beta=0.77)

### Stockholder feedlot—subclinical



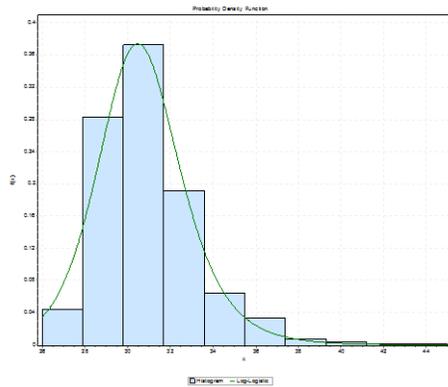
log-logistic (alpha=4.37, beta=0.95)

### Custom feedlot—subclinical



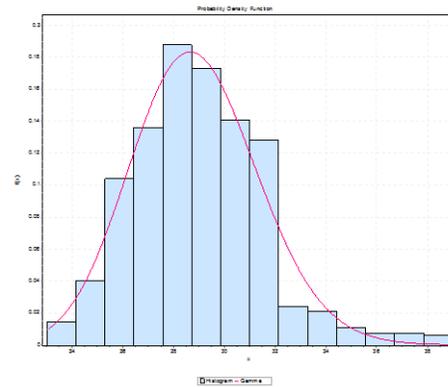
log-logistic (alpha=4.13, beta=0.96)

### Stockholder feedlot—clinical



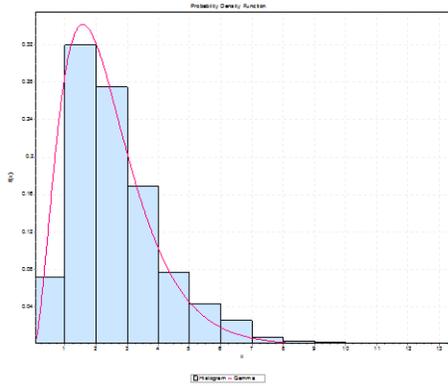
log-logistic (alpha=24.05, beta=30.58)

### Custom feedlot—clinical



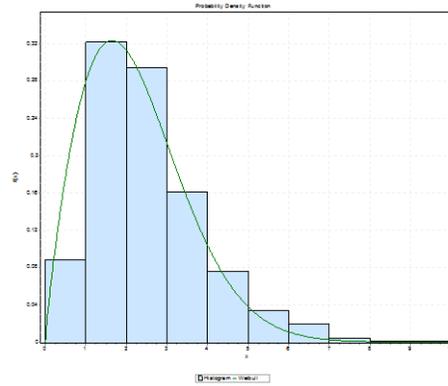
gamma (alpha=134.02, beta=0.22)

**Yearling-pasture feedlot—latent**



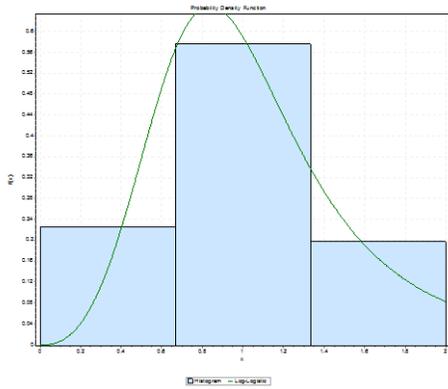
gamma (alpha=2.97, beta=0.80)

**Cow-calf large—latent**



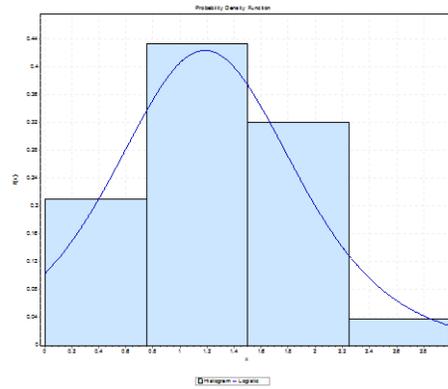
Weibull (alpha=1.84, beta=2.52, Y=0)

**Yearling-pasture feedlot—subclinical**



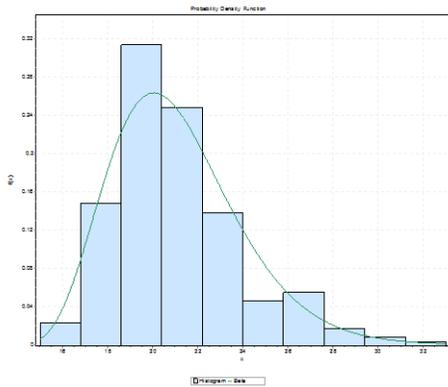
log-logistic (alpha=3.54, beta=0.99)

**Cow-calf large—subclinical**



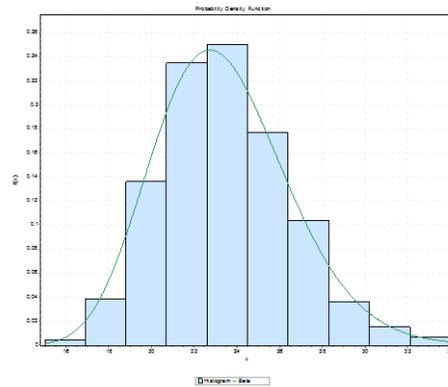
logistic (mu=1.18, sigma=0.44)

**Yearling-pasture feedlot—clinical**



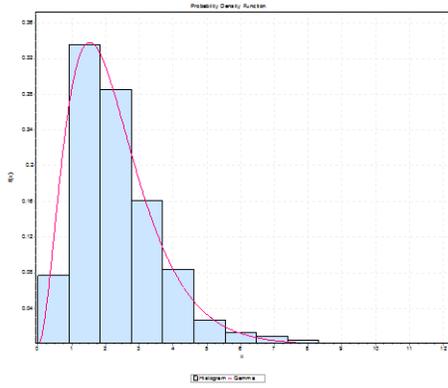
beta (alpha1=7.52, alpha2=458.54, min=13.12, max=506.88)

**Cow-calf large—clinical**



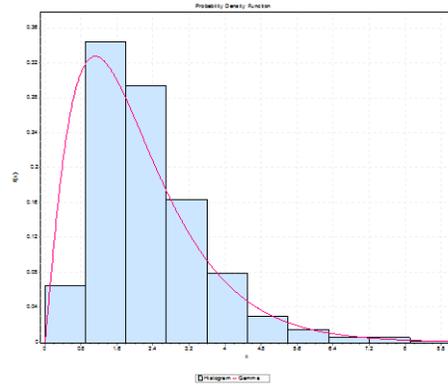
beta (alpha1=14.26, alpha2=78.03, min=10.5, max=93.75)

### Cow-calf small—latent



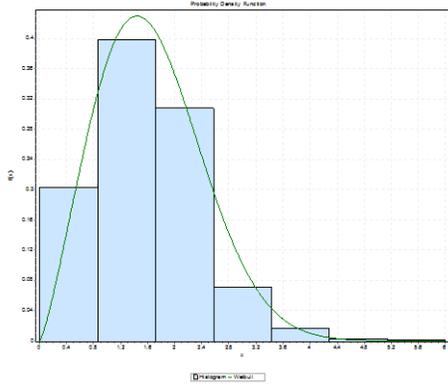
gamma (alpha=3.14, beta=0.72)

### Stocker—latent



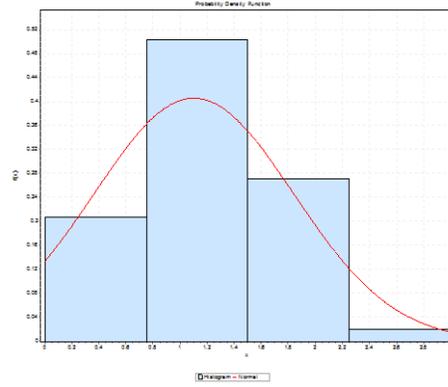
gamma (alpha=2.19, beta=0.94)

### Cow-calf small—subclinical



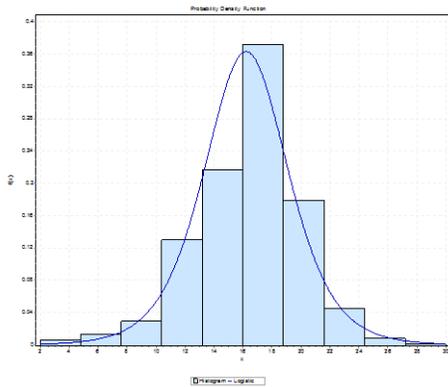
Weibull (alpha=2.26, beta=1.87)

### Stocker—subclinical



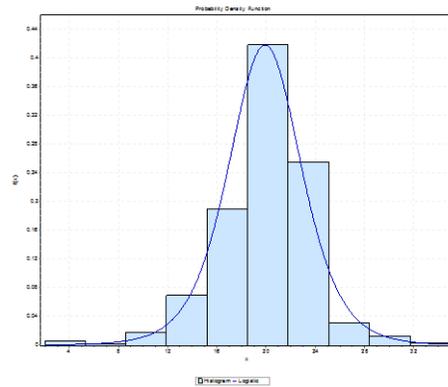
normal (mu=1.10, sigma=0.74)

### Cow-calf small—clinical



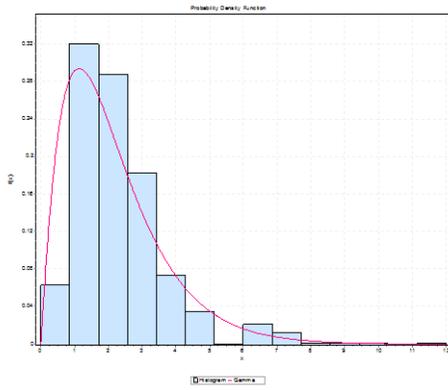
logistic (mu=16.22, sigma=1.93)

### Stocker—clinical



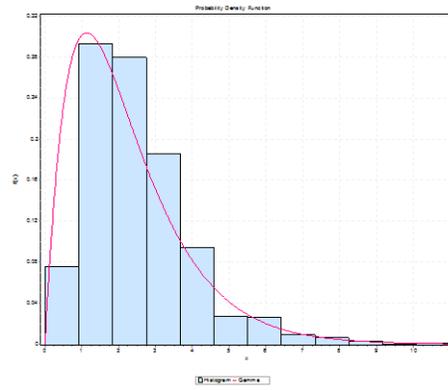
logistic (mu=20.0, sigma=1.87)

### Large dairy—latent



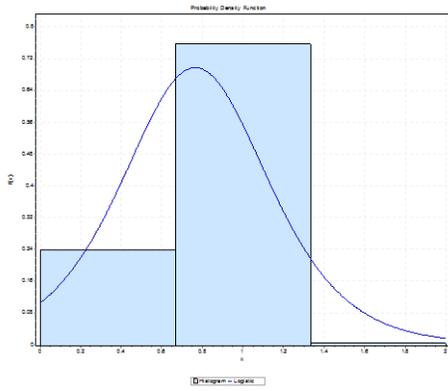
gamma (alpha=2.11, beta=1.03)

### Small dairy—latent



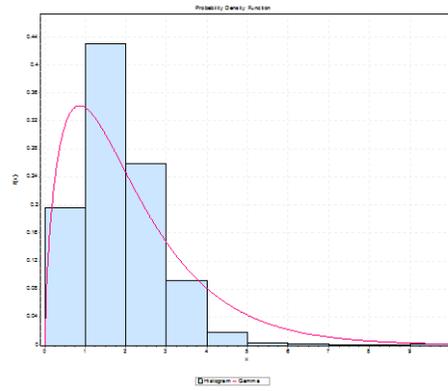
gamma (alpha=2.09, beta=1.09)

### Large dairy—subclinical



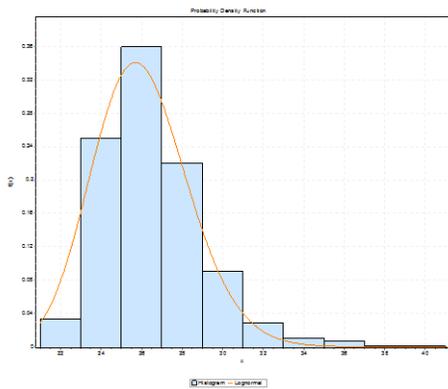
logistic (mu=0.86, sigma=0.23)

### Small dairy—subclinical



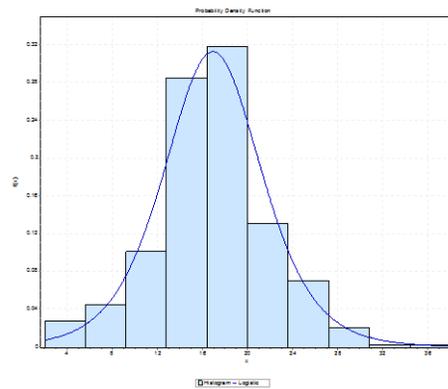
gamma (alpha=1.68, beta=1.26)

### Large dairy—clinical



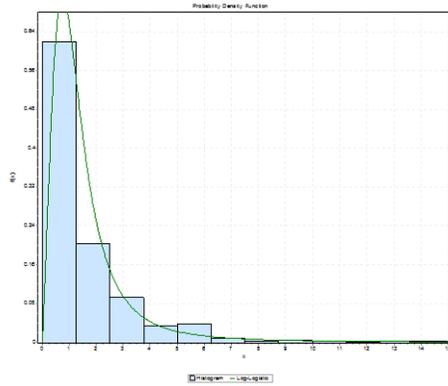
lognormal (mu=3.25, sigma=0.09)

### Small dairy—clinical



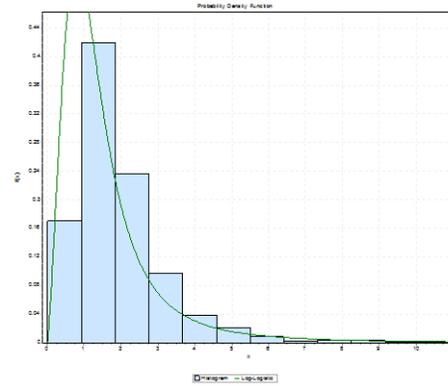
logistic (mu=16.97, sigma=2.89)

### Large swine—latent



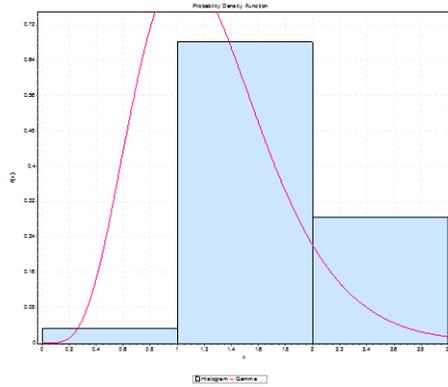
log-logistic (alpha=2.18, beta=1.19)

### Small swine—latent



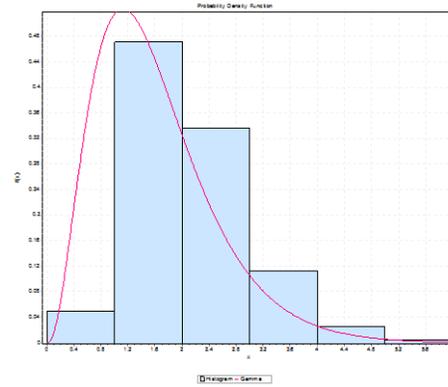
log-logistic (alpha=2.28, beta=1.21)

### Large swine—subclinical



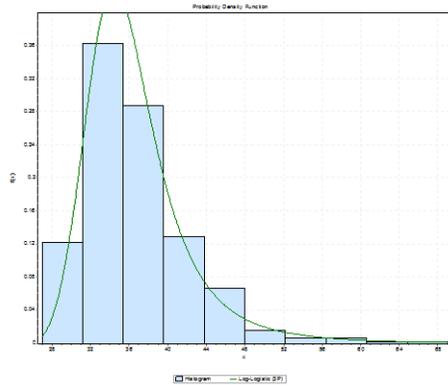
gamma (alpha=6.10, beta=0.21)

### Small swine—subclinical



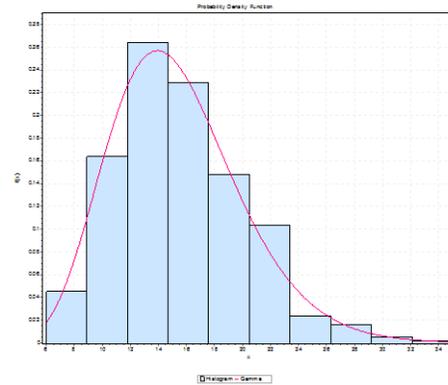
gamma (alpha=3.32, beta=0.48)

### Large swine—clinical



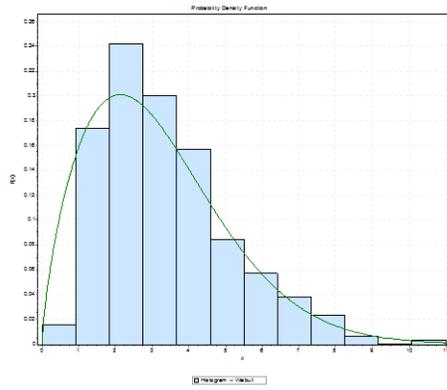
log-logistic (alpha=4.10, beta=10.63, location=25.04)

### Small swine—clinical



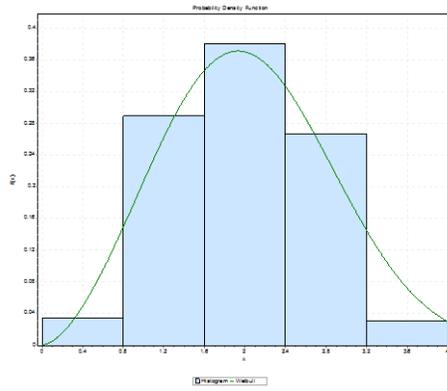
gamma (alpha=10.73, beta=1.43)

### Small ruminant—latent



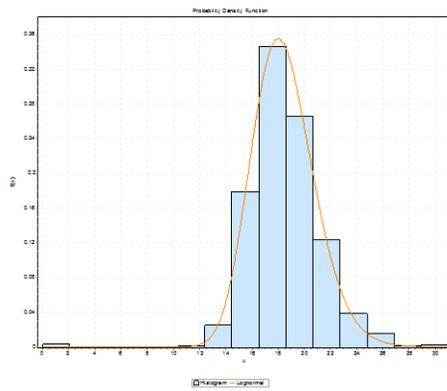
Weibull (alpha=1.71, beta=3.57)

### Small ruminant—subclinical



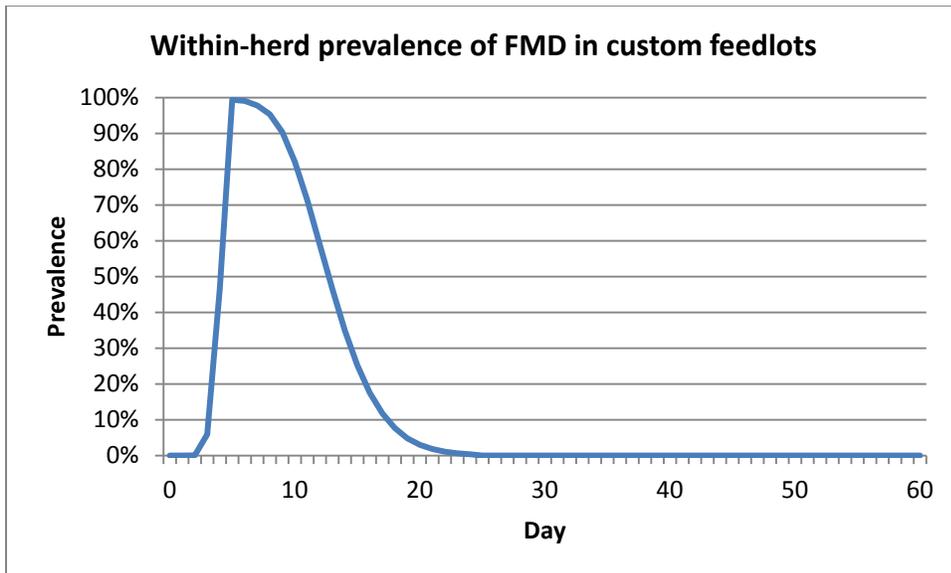
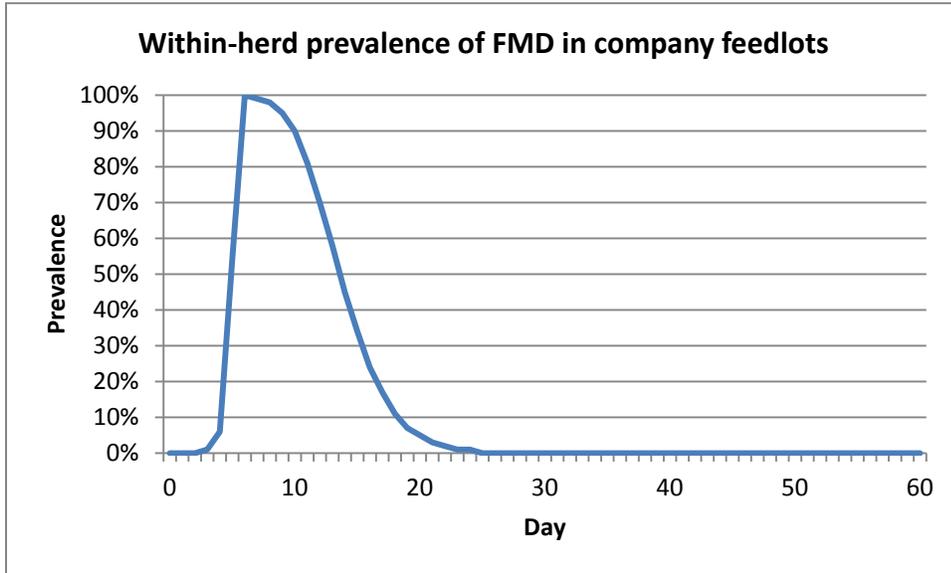
Weibull (alpha=2.68, beta=2.30)

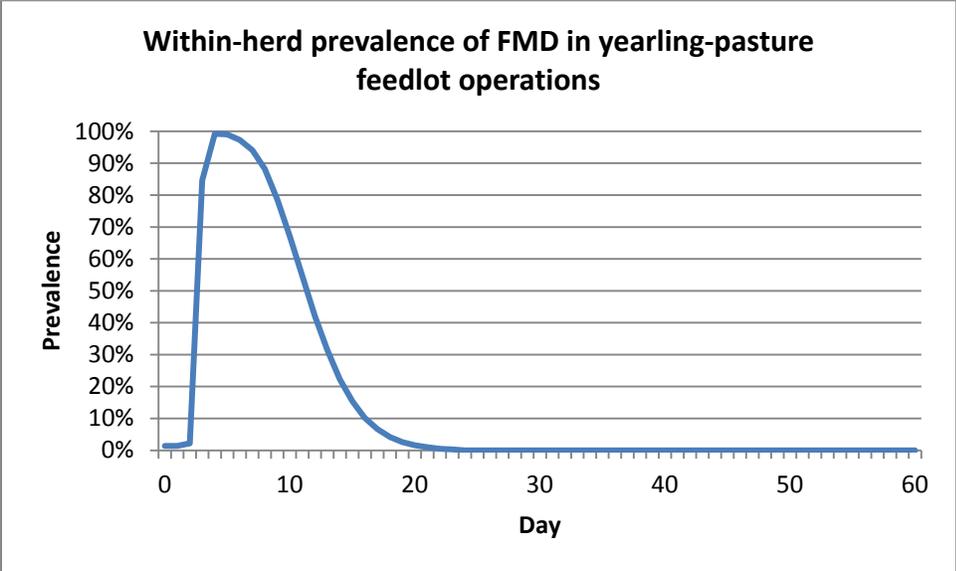
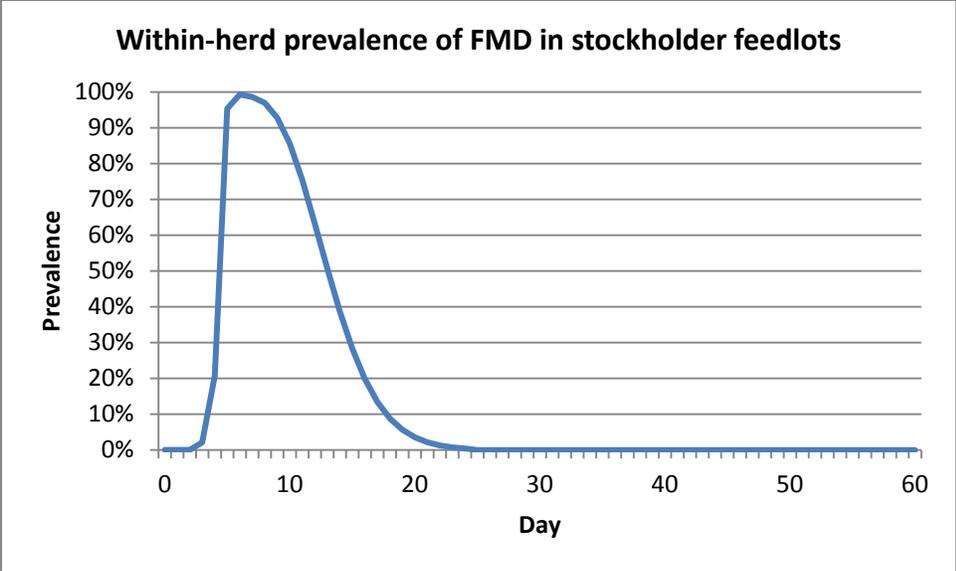
### Small ruminant—clinical



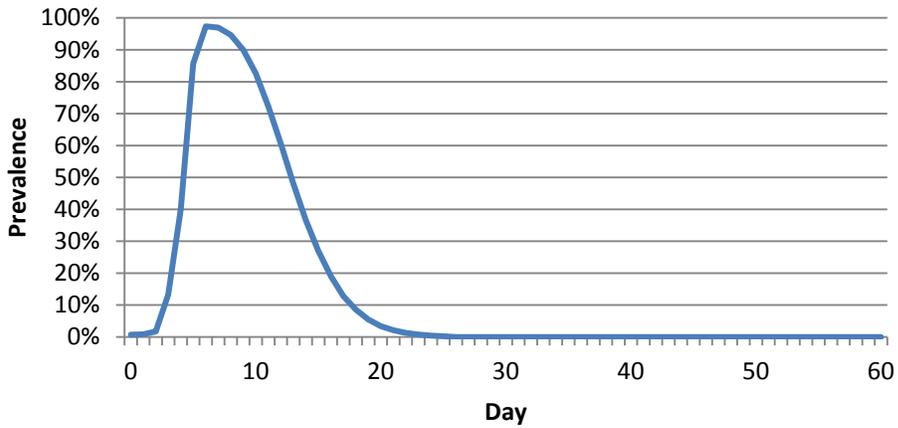
lognormal (mu=2.91, sigma=0.13)

## Appendix II: Within-herd Prevalence Curves

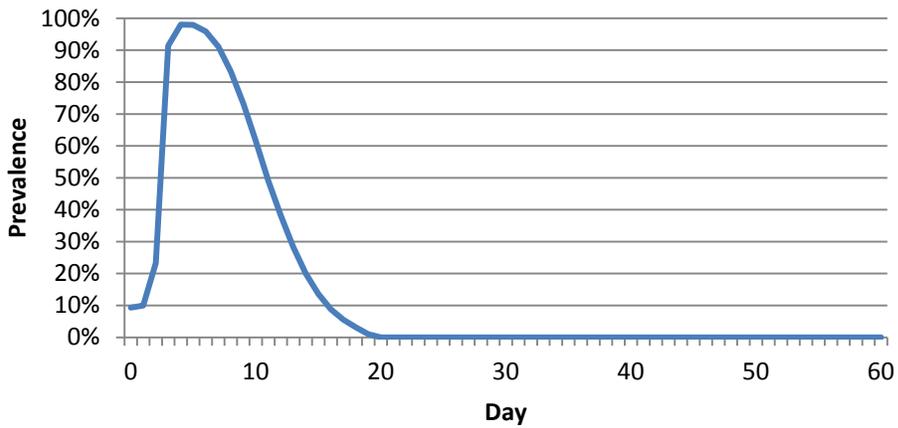


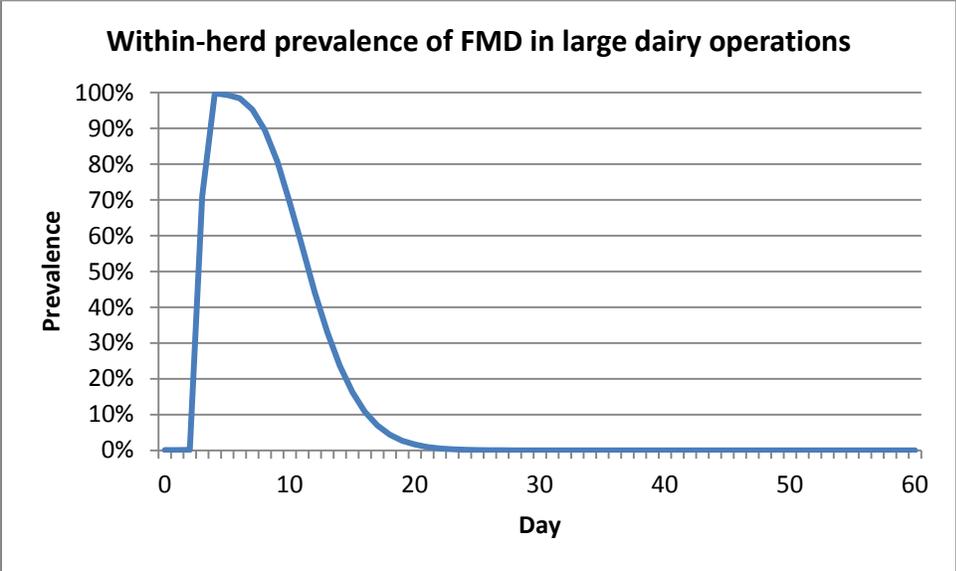
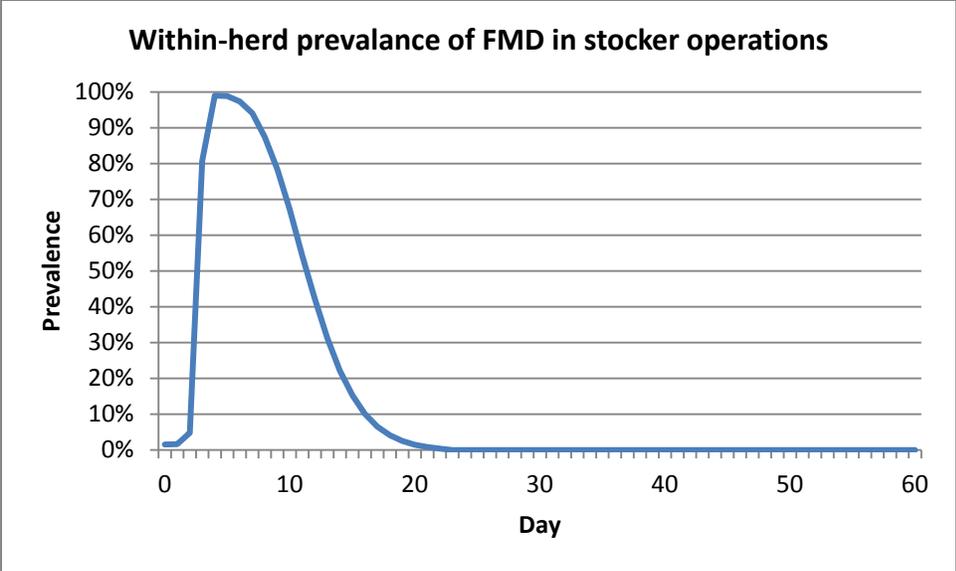


**Within-herd prevalence of FMD in large cow-calf operations**

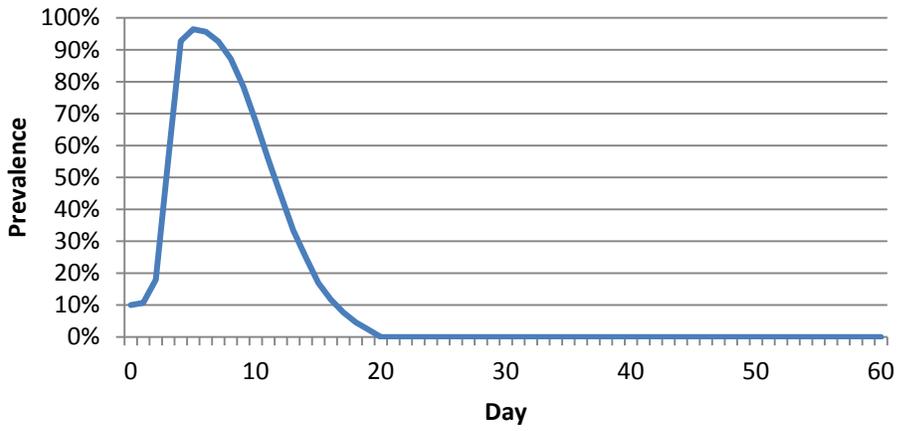


**Within-herd prevalence of FMD in small cow-calf operations**





**Within-herd prevalence of FMD in small dairy operations**



**Within-herd prevalence of FMD in large swine operations**

