LACTATION CURVES OF MONTBELIARDE-SIRED AND VIKING RED-SIRED CROSSBRED COWS AND THEIR HOLSTEIN HERDMATES IN 7 COMMERCIAL DAIRIES USING RANDOM REGRESSION AND BEST PREDICTION

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ABSTRACT

Lactation curves were estimated for Montbéliarde (**MO**) × Holstein (**HO**) and Viking Red (**VR**) × HO 2-breed crossbred cows and for MO × VR/HO and VR × MO/HO 3-breed crossbred cows and their HO herdmates from test-day observations in 7 high-performance dairies that participated in a designed research study. Cows calved from 2010 to 2017. Test-day observations from milk recording for the first 3 lactations were used to fit the lactation curves. Lactations of cows were required to have at least 250 days in milk (**DIM**) and to have at least 6 test days ≤ 265 DIM. Lactation curves from random regression (**RR**) functions were compared: 1) Ali-Schaeffer, 2) Wilmink, and 3) Third-order Legendre polynomial. Lactation curves from RR were also compared to lactation curves from Best Prediction (**BP**). The alternative RR functions and BP were compared for the lactation curve characteristics of 305-d production (kg), peak production (kg), peak d of production, and production from 4 to 103 DIM (kg), from 104 to 205 DIM (kg), and from 206 to 305 DIM (kg) for milk, fat, and protein production. Primiparous and multiparous cows were analyzed separately. Furthermore, two alternative measures of persistency of production were developed for each of the alternative RR functions and BP. The 2-breed and 3-breed crossbred cows and their respective HO herdmates were analyzed separately. For primiparous cows, Legendre polynomial RR best fit the actual test-day observations for milk, fat, and protein production among the alternative RR functions as well as BP for each breed group separately and across breed groups for both 2-breed and 3-breed crossbreds and their HO herdmates. For multiparous cows, BP best fit the actual test-day observations for milk and fat production for each breed group separately and across breed groups for both 2-

breed and 3-breed crossbreds. However, Legendre polynomial RR best fit the actual test-day observations for protein production in all cases.

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INTRODUCTION

The Dairy Herd Improvement (**DHI**) Association was established in 1927 to standardize on-farm production, reproduction, and health data collection in the United States (Voelker, 1981). Either a DHI employee or someone on a farm records milk weights of individual cows and collects milk samples to determine milk components on a day that is called a "test day". A computer backup of herd-management software is also collected on the same day for all non-production data. A test day typically occurs monthly, but alternative intervals such as bi-monthly or custom interval testing also exist. Custom interval testing has test days with frequency determined by the dairy farmer. Computerization of DHI production data in the 1950s paved the way for other data such as parentage, breedings, and health events to be collected alongside production. The data collected was used by the USDA, previously, but by the Council of Dairy Cattle Breeding, currently, for genetic evaluation of dairy cattle in the United States.

The United States used the test interval method (**TIM**) to estimate 305-day production of milk, fat, and protein from test-day observations from 1969 to 1999. The 305-day production was also used for genetic evaluation of production of dairy cattle (Voelker, 1981). The TIM divided the time between DHI test days into 2 equal periods. Production from the previous test day was assigned to the first period, and production from the current test day was assigned to the later period (Sargent et al., 1968). The TIM was improved on with the supplementation of Shook factors (Shook et al., 1980), which were scaling factors used to adjust the production of the first test-day of lactation and to project production for lactations shorter than 305 d. However, the Shook factors required lactation curves to conform to a standardized curve, and this caused atypical lactation curves of individual cows to be biased (Schaeffer, 2016).

Lactation curves

In a Missouri study, Turner et al. (1923) compared Holstein (**HO**) cows from a university herd that were milked twice daily to HO cows that were milked three and four times daily. The HO cows that were milked four times daily had later peak milk production on a single day compared with cows milked two and three times daily. Turner et al. (1923) also concluded that a typical lactation curve of a dairy cow is divided into three periods: a period of increasing production after calving, peak production, and a period of decreasing production after peak production. Furthermore, the effect of pregnancy had a large effect on the decline of milk production during the final 2 and 3 months of lactation (Turner et al., 1923).

Wood (1970) studied over 1,500 lactations of British Friesian cows to determine differences in shapes of lactation curves in regard to the effects of parity, herd, and season and year of calving. The lactation records originated from 10 herds, but the lactation curve shape of the cows was not affected by herd variation. Wood (1970) reported parity and season of calving had the largest effects on shape of lactation curves, and also reported these two effects accounted for 77.4% of the variation in shapes of lactation curves.

Wood's Curve

One of the most notable research papers on lactation curves was Wood's (1967) study of the shape and estimation of lactation curves presented in equation form. Wood described the shaped of the lactation curve and expressed the shape as a gamma equation that included the following parameters 1) a scaling factor that is linked to production during early lactation "a", 2) increasing production "b", 3) decreasing production "c", for production on a given day of lactation. The equation is

$$y_t = \mathrm{a}t^b e^{-ct}$$

where t represents production at day t (Wood, 1967). The parameters of Wood's curve can be estimated for individual cows by performing a logarithmic transformation on the original equation (Wood, 1967).

Best Prediction versus random regression

In 2000, a random regression (**RR**) test-day model was implemented for the genetic evaluation of production traits in Canada, this RR test-day model based on Schaeffer and Dekkers (1994). Canada was the first country to use a RR test-day model for genetic evaluation; however, test-day models using RR have now been adopted by most countries globally. Before using RR, Canada used TIM to estimate 305-d production from test-day observations for genetic evaluation. In the United States, Best Prediction (**BP**) replaced TIM for genetic evaluation of production traits since 1999 (VanRaden, 1997). Estimates of daily production from both RR and BP can be plotted for individual cows to examine lactation curve characteristics such as persistency, DIM of peak production, peak production, and total 305-d production of milk, fat, and protein.

The BP has separate and fixed lactation curve parameters for each of the six major dairy breeds in the United States. To estimate production, BP uses Wood's (1967) curve for interpolation between test-day observations (Cole and VanRaden, 2009). The BP estimates 305-d production by adding a cow's estimated production with that cow's deviation from a herd-specific lactation curve. Therefore, BP has a small number of breed-specific lactation curves as options, and pregnancy status is not taken into consideration. Furthermore, the HO lactation curve parameters were lasted updated in 2009 (Cole and VanRaden, 2009), from cows that calved from 1997 to 2003 (Cole et al., 2009). The cows that calved from 1997 to 2003 were from a period of time when many herds used rBST, which now has plummeted in use, and the cows had a lower production level at that time compared with cows today.

The RR is currently the most popular method used globally to estimate 305-d production from test-day observations and to estimate growth rates and other non-linear records. Schaeffer and Dekkers (1994) developed RR to fit test-day observations of production to allow the shape of lactation curves to differ for individual cows. The RR has been adopted in much of the world to estimate 305-d production for genetic evaluation since its inception over 20 years ago.

The RR considers covariances among test-day observations of milk, fat, and protein production for estimation. Variance of test-day observations are included in the estimation of standard lactation curves with RR, because a test-day observation is weighted by its relative variance. Cows of the same breed, herd, parity, and calving season are used to estimate lactation curve parameters for each individual cow (Schaeffer and Jamrozik, 1996). The RR enables 305-d production to be estimated based on a single test-day observation and for accurate estimation of 305-d production with test-day intervals that exceed the typical 30 days in length (Schaeffer and Jamrozik, 1996). Numerous methods of estimating lactation curves use Wood’s curve, but RR allows for alternative functions to be used that are less rigid than Wood’s curve.

Ali and Schaeffer function

Ali and Schaeffer (1987) developed a new RR function and compared it with Wood's gamma function and an inverse quadratic polynomial for estimation of 305-d production. The new Ali and Schaeffer function included effects of days in milk, regression coefficients associated with peak production, and factors associated with increasing and decreasing production during lactation. The three models were compared using percentage squared bias, which is the squared difference of actual and estimated production and the correlation of estimated versus actual milk production. The Ali and Schaeffer RR function performed best based on percentage squared bias and correlation of actual and predicted yields, followed in order by Wood's gamma function and the inverse quadratic polynomial (Ali and Schaeffer, 1987).

Wilmink function

National data of Dutch Friesian cows were used to estimation production using the Wilmink function and to adjust test-day observations of milk, fat, and protein production to account for age at calving, month of calving, and stage of lactation (Wilmink, 1987). The Wilmink function included factors for production level, increasing production before peak production, the day of peak production, and decreasing production after peak production (Wilmink, 1987). After adjusting the test-day observations, month of calving had an effect on estimated protein production, and age at calving had an effect on estimated milk, fat and protein production (Wilmink, 1987). The Wilmink function has been used in numerous studies to estimate daily production from test-day observations and in some countries for genetic evaluation.

Legendre polynomial function

Strabel et al. (2005) compared different RR functions to determine a suitable test-day model for genetic evaluation of Polish dairy cattle. Test-day observations for first-lactation cows of the Polish Black and White breed were used to determine the RR function that would be used for genetic evaluation. A RR model using Legendre polynomials of order 3, 4, and 5 was used to estimate daily production from test-day observations. The different Legendre polynomial functions were evaluated for accuracy of estimation with percentage of squared bias, which is the squared difference between actual and estimated test-day production (Strabel et al., 2005). Due to the low milk production and early peak milk production of Polish Black and White cows, a fifth-order Legendre polynomial best described the lactation curve of these cows. However, a third-order polynomial still adequately estimated daily milk production for cows of the Polish Black and White breed (Strabel et al., 2005).

Macciotta et al. (2005) estimated lactation curves for Simmental cows from test-day observations using Wood's function, the Wilmink function, the Ali and Schaeffer function, and a Legendre polynomial function. The functions were compared for goodness of fit based on adjusted R-squared and the ability to estimate non-traditional shapes of lactation curves (Macciotta et al., 2005). The Legendre polynomial function performed best for goodness of fit compared to the Wood's and Wilmink functions. The Legendre polynomial function had 70% of lactations with an adjusted R-squared value greater than 0.80 compared to 54.6% for Wood's function, and 56.3% for the Wilmink function (Macciotta et al., 2005).

Persistency

Persistency of production, which is defined as the ability of a cow to maintain production after peak production (Wood, 1967) has been of long-term interest to dairy producers. Cows with more persistency have a slower rate of production decline after peak production compared to cows with lower persistency. A review by Gengler (1996) of measures of persistency reported the measures can be categorized into three types: (1) ratios between total or partial production, (2) variation of test-day observations throughout lactation, and (3) estimated by mathematical models. Sanders (1930) defined persistency as average daily production divided by peak production and was the first to report a measure of persistency that used ratios between total or partial production. Johansson and Hansson (1940) were the first to introduce a measure of persistency with ratios of partial production periods. Two different ratio measures were calculated by dividing production from 101 to 200 DIM and from 201 to 300 DIM by production from 1 to 100 DIM (Johansson and Hansson, 1940). This approach was also used as a measure of persistency by Solkner and Fuchs (1987) and more recently by Hickson et al. (2006).

The Wilmink function (1987) has a measure of persistency as a parameter “b” of the function, which is defined as the decrease of production (slope) after peak production. Although provided for each cow, this measure of persistency is not easily understood and is heavily dependent on peak production.

Nearly all measures of persistency are dependent on total production of lactation. The ratio measures of persistency are positively correlated with production, whereas measures of persistency based on deviations of test-day production are negatively correlated with production (Gengler, 1996). However, ratio measures of persistency are more intuitive and easier to explain to dairy producers than measures of persistency based on variation of test-day observations throughout lactation and mathematical models (Gengler, 1996).

Economic benefits of persistency

In the Austrian study of Solkner and Fuchs (1987) the national production data of Simmental cows was used to compare feed efficiency of cows with high and low persistency of milk production. Persistency of milk production was measured by two ratios of partial production, two ratios of peak milk production, and two measures using the standard deviation of test-day observations throughout lactation. Solkner and Fuchs (1987) reported Simmental cows that had greater persistency of milk production required 161 kg less concentrates to produce 5,500 kg of milk compared to cows with lower persistency of milk production. Furthermore, persistency measured by the standard deviation of test-day observations or the ratio of milk production during the final 100 DIM of lactation divided by the milk production during the initial 100 DIM of lactation were recommended by Solkner and Fuchs (1987).

National production data of Canadian HO cows was used by Muir et al. (2004), who estimated the genetic relationship between persistency of milk production and reproductive performance for first-lactation HO cows. Persistency of milk production was measured by the “b” parameter from Wilmink’s function, which measured decline of milk production after peak milk production. First-lactation cows were more persistent if they had calving difficulty and conceived successfully at first insemination (Muir et al., 2004). These results suggested a relationship between reproductive performance and persistency for first-lactation cows.

Harder et al. (2006) used data from 3,200 HO cows in 3 German herds to determine the correlation between disease and persistency. Correlations of udder health, fertility, metabolic diseases, and claw and leg diseases with persistency were estimated. Only metabolic diseases had a significant correlation (unfavorable) with persistency (Harder et al., 2006).

More recently, Appuhamy et al. (2007) compared the relationship of disease incidence and persistency for HO cows. Total production, peak production, and persistency were estimated using Wood's function. Cows that had an incidence of mastitis had less persistency compared to cows that did not have mastitis. Additionally, metritis, displaced abomasum, and metabolic diseases had negative effects on peak production and persistency in second and later lactations. Conversely, lower incidence of mastitis was associated with increased persistency (Appuhamy et al., 2007).

Crossbreeding with Montbeliarde (MO) and Viking Red (VR)

For crossbreeding in confinement herds, a 3-breed rotation of HO × Alpine dairy breed × Red dairy cattle was suggested by Dechow and Hansen (2017) as the ideal dairy crossbreeding rotation for commercial dairy herds. The Alpine dairy breeds consist of Brown Swiss, Montbeliarde (**MO**), and Fleckvieh. Red dairy cattle breeds include Aussie Red, German Angler, Norwegian Red, and Viking Red (**VR**). In a 3-breed crossbreeding rotation, HO provides production, while the Alpine breeds and Red dairy cattle provide milk components, health, and fertility. In the United States, a popular 3-breed rotation is HO × MO × VR, which is marketed as ProCROSS. ProCROSS dairy cows have grown in number over the past 20 years because HO cows have had increasing stature, rising inbreeding levels, and declining health and fertility.

Crossbreeding with MO and VR in California

Heins et al. (2006) compared MO × HO and Scandinavian Red (**SR)** × HO 2-breed crossbred cows with their HO herdmates in 7 commercial dairies in California. The SR sires were a mixture of VR and Norwegian Red bulls. The HO herdmates had higher milk and protein production than MO × HO 2-breed crossbreds. However, the SR × HO 2-breed crossbreds did not differ from their HO herdmates for milk or for fat plus protein production (Heins et al., 2006). The MO × HO 2-breed crossbreds were lower for fat and fat plus protein production compared to HO cows (Heins et al., 2006). However, the MO sires of cows were inferior within breed for production than the HO and SR sires of cows. In a later study, Heins and Hansen (2012) compared MO × HO and SR × HO 2-breed crossbreds with their HO herdmates for production during their first 5 lactations. The MO × HO and SR × HO 2-breed crossbreds were 3 and 4% lower, respectively than their HO herdmates for 305-day projected fat plus protein production for the first 5 lactations.

Crossbreeding with MO and VR in Minnesota

Hazel et al. (2014) compared MO × HO 2-breed crossbred cows with HO cows from two research herds for fat plus protein production in their first 5 lactations at the University of Minnesota in a low-input grazing system and a confinement system. The MO × HO 2-breed crossbreds were not different from HO cows for fat plus protein production during any of the 5 lactations (Hazel et al., 2014).

A 10-year designed study compared rotational crossbreds of MO, VR, and HO cows to their HO herdmates for survival, production, fertility, and conformation for 8 high-performance dairy herds in Minnesota. Hazel et al. (2017) found MO × HO 2-breed crossbred cows in their first lactation had 3% higher 305-d fat plus protein production than their HO herdmates. Also, VR × HO 2-breed crossbred cows had similar fat plus protein production compared with their HO herdmates during first lactation. In terms of milk volume, the MO × HO 2-breed crossbred cows were not different from HO cows, but the VR × HO 2-breed crossbreds produced 3% less milk volume (Hazel et al., 2017).

More recently, Shonka-Martin et al. (2018) compared 3-breed rotational crossbreds of MO, VR, and HO to their HO herdmates for production, dry matter intake, and body traits during the first 150 days of lactation. MO-sired and VR-sired 3-breed crossbred cows were compared to HO cows in a combined crossbred group. The combined crossbred cows had lower milk volume than their HO herdmates but were not different from their HO herdmates for fat plus protein production (Shonka-Martin et al., 2018).

Lactation curves and persistency of dairy crossbred cows

Two-breed crossbred cows of the HO and Ayrshire were analyzed for differences in lactation shape using an inverse polynomial approach by Batra (1986). Breed of sire had a significant effect on the rate of increased production for first lactation cows, the rate of decline of production after peak in third lactation cows, and for the average slope of the lactation curve in first and third lactation cows. However, heterosis was not significantly associated with the lactation curve parameters (Batra, 1986).

More recently, Blöttner et al. (2009) compared Brown Swiss × HO crossbreds with their HO herdmates from a German experiment station for milk, fat, and protein production from weekly test days. Production traits analyzed were total production and production during three periods of lactation (5-100 DIM, 101-200 DIM, and 201-300 DIM) for first and second lactation cows. The Brown Swiss × HO cows did not differ from HO cows for milk, fat, and protein production during either first or second lactation. The crossbred cows produced less milk volume during the beginning of lactation, but had higher milk volume during the final 100 DIM of lactation compared with their HO herdmates (Blöttner et al., 2009).

Hypotheses and Objectives

Our hypothesis was that a RR function would more accurately estimate production compared to actual test-day observations than BP. Furthermore, both Montbéliarde-sired and Viking Red-sired crossbred cows were hypothesized to have more persistency of milk, fat, and protein production than their Holstein herdmates.

The objective of this thesis was to compare the lactation curve parameters of crossbred cows and HO herdmates during their first three lactations. The lactation curve characteristics of milk, and protein were compared for 305-d production, production during three periods of lactation, peak production, DIM of peak production, and persistency of production. Furthermore, RR functions and BP were compared for breed groups.

MANUSCRIPT

Lactation curves of Montbéliarde-sired and Viking Red-sired crossbred cows and their Holstein herdmates in 7 commercial dairies using random regression and Best Prediction.

INTERPRETIVE SUMMARY

Test-day observations from milk recording of crossbred and Holstein cows in a designed study were used to estimate lactation curves with random regression and Best Prediction. Montbéliarde × Holstein 2-breed crossbred cows had more persistency of milk, fat, and protein production than their Holstein herdmates for primiparous cows, but they were not different from their Holstein herdmates for persistency of milk, fat, and protein production for multiparous cows. However, for both primiparous and multiparous cows, Viking Red × Holstein 2-breed crossbred cows were not different from their Holstein herdmates for persistency of fat and protein production.

INTRODUCTION

For many years, the test interval method (**TIM**) was used to estimate 305-d production from test-day observations of milk, fat, and protein for genetic evaluation of production in the United States (Voelker, 1981). The TIM divided the time between DHI test days into 2 periods with an equal number of DIM. Production from the previous test day was assigned to the first period, and production from the subsequent test day was assigned to the later period (Sargent et al., 1968). The TIM was improved upon through the use of Shook factors (Shook et al., 1980), which are scaling factors to adjust the production surrounding the first test day of lactation and to project production for lactations shorter than 305 d. However, the Shook factors assume lactation curves conform to a standardized curve, and this assumption results in bias for atypical lactation curves of cows (Schaeffer, 2016). Furthermore, the use of Shook factors often overestimates 305-d production for less persistent cows with test days only during early lactation and underestimates 305-d production for cows with more persistency (Jamrozik et al., 1997).

In the 1990s, extensive research was conducted to improve the estimation of 305-d production for use in genetic evaluation. In particular, Schaeffer and Dekkers (1994) developed a test-day model using random regression (**RR**) that replaced TIM for Canadian genetic evaluations in 2000. Many countries globally followed the lead of Canada and have continued to use RR for estimating lactational production from test-day observations. A RR function permits the estimation of a unique lactation curve for each cow (Schaeffer, 2016).

VanRaden (1997) developed Best Prediction (**BP**), which has been used in the

United States for genetic evaluation of production traits since 1998. The BP estimates a unique lactation curve for each cow. Also, BP uses variances and co-variances between test days for estimation that are specific to each of the 6 pure breeds of dairy cattle in the United States. However, the breed-specific lactation curves of BP closely resemble those of a Wood's curve (Wood, 1967) and permit less variation of lactation curves for cows than with the more flexible RR. Estimates of daily production from TIM, RR, and BP for cows may be used to compare lactation curve characteristics such as 305-d production (kg), peak production (kg), peak d of production, production from 4 to103 DIM (kg), from 104 to 205 DIM (kg), and from 206 to 305 DIM (kg).

Persistency measures the ability of a cow to maintain daily production following peak production (Wood, 1967). Gengler (1996) categorized the 3 most common measures of persistency of production as 1) ratios of partial or total production, 2) variation of test-day observations, or 3) mathematical models of lactation curves. Despite the measure of persistency, a cow with more persistency of production will have a more horizontal lactation curve compared with a cow with less persistency of production (Togashi and Lin, 2003). Other studies have reported cows with more persistency of production have improved feed efficiency when fed roughages (Solkner and Fuchs, 1987), less incidence of disease (Appuhamy et al., 2007), and improved reproductive performance (Muir et al., 2004) compared with cows with less persistency of production. Therefore, selection for more persistency of production within or across breeds could result in improved profitability of dairy cattle. Comparison of RR and BP for estimation of lactational production is limited in the literature, but a recent Iranian study (Torshizi and Mashhadi, 2018) recommended genetic evaluation of persistency of production should be estimated with RR instead of BP, because RR provides for increased flexibility of shape of lactation curves and provides a higher heritability of persistency of production than BP.

Dechow and Hansen (2017) recommended a 3-breed rotation of Alpine, Nordic Red, and Holstein (**HO**) breeds for commercial dairy producers who implement a crossbreeding program in high-input, temperate environments. In recent years, the Montbéliarde (**MO**), Viking Red (**VR**), and HO breeds have been marketed for 3-breed rotational crossbreeding (ProCROSS) by Coopex Montbéliarde (Roulans, France) and Viking Genetics (Randers, Denmark), and this 3-breed rotation continues to grow in popularity globally. The MO and VR breeds have placed more selection emphasis on fertility, health, and longevity for decades compared with the HO breed while maintaining substantial emphasis on increased milk solids.

Hazel et al. (2017) reported MO × HO 2-breed crossbreds had higher fat plus protein production (kg) and VR × HO 2-breed crossbreds had similar fat plus protein production (kg) compared with their HO herdmates during first lactation. In a more recent study, Shonka-Martin et al. (2018) reported 3-breed crossbreds of the MO, VR, and HO breeds did not differ from their HO herdmates for fat plus protein production (kg) from 4 to 150 DIM. Research on lactation curve characteristics of crossbred dairy cows is limited. Batra (1986) did not find meaningful heterosis for lactation curve characteristics of Ayrshire × HO 2-breed crossbred cows in Canada. The persistency of MO-sired and VR-sired crossbred cows versus their HO herdmates has not been studied.

The objective of this research was to compare the lactation curve characteristics and persistency of production of MO-sired and VR-sired crossbred cows with their HO herdmates using alternative RR functions and BP estimated from test-day observations.

MATERIALS AND METHODS

Description of Cows and Herds

Two generations of crossbred cows and their HO herdmates from 7 high-production herds in Minnesota were available from a 10-yr field study (Hazel et al., 2017). Cows were housed in either 4- or 6-row freestall barns and fed a TMR. At the conclusion of the study in December 2017, the mean herd size was 982 ± 203 cows and weighted production means for cows across breed groups was 13,587 ± 353 kg of milk, 512 ± 9 kg of fat, and 426 ± 10 kg of protein.

Cows and heifers were individually mated by 2 genetic advisors employed by Minnesota Select Sires Co-Op, Inc. (St. Cloud, MN). The crossbred cows and their HO herdmates were both correctively mated for conformation, and virgin heifers were correctively mated based on their dam's conformation when available. Foundation HO females were enrolled in 2008 and paired for mating by AI to either MO, VR, or HO bulls. The HO cows and heifers bred to HO bulls were provided inbreeding protection. For HO service sires, dairy producers used only progeny-proven bulls marketed by Select Sires Inc. (Plain City, OH), and the dairy producers were asked to choose HO bulls that ranked in the top 10% for Net Merit (VanRaden et al., 2018) at the time of selection. The MO and VR progeny-proven bulls were imported to the United States by Creative Genetics of California and ranked highly on the French ISU index (O.S. Montbéliarde, 2019) or the Nordic Total Merit index (Nordic Cattle Genetic Evaluation, 2019), which are the national selection indices for the MO and VR breeds, respectively.

The MO × HO and VR × HO 2-breed crossbred cows and their HO herdmates initiated first lactation from January 2011 to April 2017. The MO × VR/HO and VR ×

MO/HO 3-breed crossbred cows were daughters of the 2-breed crossbred cows. The 3-breed crossbred cows and their HO herdmates initiated first lactation from November 2012 to April 2017.

Data

The test-day observations from DHI of crossbred cows and their HO herdmates were analyzed for first, second, and third lactations. The initial data included 9,749 lactations (4,583 first, 3,285 second, and 1,881 third) of cows. Cows that calved with less than a 260-d gestation period were removed (n = 110). All lactations of cows were required to have completed at least 250 DIM to remove abnormal cows with short or incomplete lactations (n = 1,619). Cows were also required to have at least 6 test days from 4 to 265 DIM to avoid lengthy sampling intervals across the range of days in 305-d lactations. Test days at fewer than 4 DIM or greater than 305 DIM were excluded, and each test day was required to have an observation for milk, fat, and protein production. Test-day observations were also required to have at least 1.0% and no greater than 9.0% fat and at least 1.0% and no greater than 6.0% protein.

Data were assigned to a herd-year-season (**HYS**) of calving within each lactation number. The HYS were 4-month periods (January to April, May to August, and September to December) within each herd. Lactations of cows were edited so that at least 3 crossbred and 3 HO herdmates were available within each HYS for comparison of breed groups in the same herd by lactation number. Also, any HYS that had fewer than 3 cows of either crossbred breed group were combined with the contiguous HYS within herd and lactation number that had the fewest number of cows in a breed group. Following HYS edits, the cows in second and third lactation were combined to create a multiparous group. After all edits for 2-breed crossbred cows, 524 MO × HO and 548 VR × HO primiparous lactations were compared with 1,073 lactations of their primiparous HO herdmates, and 650 MO × HO and 633 VR × HO multiparous lactations were compared with 1,223 lactations of their multiparous HO herdmates. For 3-breed crossbred cows, 430 MO × VR/HO and 479 VR × MO/HO primiparous lactations were compared with 1,043 lactations of their primiparous HO herdmates, and 399 MO × VR/HO and 431 VR × MO/HO multiparous lactations were compared with 827 lactations of their multiparous HO herdmates.

Estimation of Production

The 305-d lactation curves for milk, fat, and protein of each cow were estimated at the phenotypic level with 3 alternative RR functions: 1) Ali-Schaeffer, 2) Wilmink, and 3) Legendre polynomial of the third-order. The Ali-Schaeffer RR function was developed by Ali and Schaeffer (1987) and included coefficients for peak production, increasing production during lactation, and decreasing production during lactation. The Wilmink (1987) RR function used adjustment factors for level of production, increasing production before peak, the day of peak production, and decreasing production after peak. The Legendre polynomial RR function was described by Macciotta et al. (2005) in linear form as

$$Y_t = \alpha_0 \times P_0 + \alpha_1 \times P_1 + \alpha_2 \times P_2$$

where (P_i) represents the function of time (DIM) calculated by Schaeffer (2004), Y_t represents milk production on a given day (t), and α represents a polynomial order. A major difference between the 3 alternative RR functions is the number of parameters within each function. The Wilmink function has only 3 parameters compared with the 5 parameters of the Ali-Schaeffer and Legendre polynomial functions. The larger number of parameters for the Ali-Schaeffer and Legendre polynomial functions allow them to estimate a wider range of shapes of lactation curves than the Wilmink function (Macciotta et al., 2005). The Legendre polynomial function has been more widely used than the Ali-Schaeffer function for genetic evaluations globally because of lower correlations among parameter estimates (Schaeffer, 2016). In this study, lactation curves for each of the 5 breed groups (MO × HO, VR × HO, MO × VR/HO, VR × MO/HO, and HO) were estimated separately for each parity group with each of the 3 RR functions as well as BP.

The BP estimates lactation curves for each combination of breed and parity group (primiparous or multiparous) for the 6 traditional breeds of dairy cows that obtain genetic evaluations in the United States and not for MO, VR, or crossbred cows. Therefore, both the crossbred cows and their HO herdmates in this study were estimated with BP using the default HO lactation curves. The BP was estimated separately for each of the 7 herds in this study. With BP, a cow's daily production is the sum of the mean production on each day of the herd-specific lactation curve (standardized for age at calving, breed, and parity) and the cow's deviation from the mean production on each day of the herd-specific lactation curve (Cole and VanRaden, 2009). The outcome is a regression of a cow's production record on the herd-specific lactation curve, and this lowers the SD of estimates compared with the TIM (Cole et al., 2009).

Goodness of Fit for Alternative RR and BP Across Breed Groups

Three different measures of goodness of fit were used to determine which of the 3 RR functions and BP best estimated daily production of milk, fat, and protein compared with actual test-day observations of milk, fat, and protein. Firstly, the error of estimated production compared with test-day observations was measured by the mean square prediction error (**MSPE**):

$$\text{MSPE} = \sum_{i=1}^{n} (O_i - E_i)^2 / n$$

where $i = 1, 2, \ldots n$, and n is the number of test-day observations, and O_i and E_i represent the observed and estimated production, respectively (Val-Arreola et al., 2004). The second measure of goodness of fit was mean prediction error (**MPE**), which was the square root of MSPE (Fuentes-Pila et al., 1996). The third measure of goodness of fit was the mean difference (**MD**) of test-day observations and estimated production. A lower MSPE, MPE, or MD indicated a better fit among the 3 RR functions and BP for estimation of production. The specific RR function that had the best goodness of fit was then compared with BP for all subsequent analysis comparing RR and BP.

Description of Comparative Traits

Lactation Curve Characteristics. Analysis of 305-d production (kg), peak production (kg), and DIM of peak production for milk, fat, and protein used daily production from either the alternative RR or BP based on DHI test-day observations. In each case, 305-d production was the sum of estimated daily production of milk, fat, and protein. Peak production was the maximum of estimated daily production of milk, fat, or protein. Milk, fat, and protein production was stratified into 3 periods of lactation, 1) the initial 100 DIM (4 to 103 DIM), 2) the middle 102 DIM (104 to 205 DIM), and 3) the final 100 DIM (206 to 305 DIM), to determine if breed groups differed for production during these 3 stratified periods.

Comparison of alternative RR and BP within Breed and Lactation Groups. Difference between the estimates (**DE**) of RR minus BP for each cow was compared for 305-d production (kg), peak production (kg), DIM of peak, and during the 3 stratified periods of lactation for milk, fat, and protein production. For the production traits (kg), a positive DE indicated higher production was estimated with RR compared with BP, and a negative DE indicated lower production was estimated with RR compared with BP. For DIM of peak production, a positive DE indicated DIM of peak production occurred earlier with RR than BP and a negative DE indicated DIM of peak production occurred later with RR than BP.

Persistency of Production. A persistency ratio (**PR**) developed by Johansson and Hansson (1940) was defined as production from 206 to 305 DIM divided by the production from 4 to 103 DIM for each lactation. A PR of 1 indicated a cow had equal production during the initial and final 100 DIM of lactation. A PR greater than 1 indicated more persistency of production, and a PR less than 1 indicated less persistency of production.

Another measure of persistency of production, persistency difference (**PD**), was production during the final 100 DIM subtracted from the production during the initial 100 DIM. A negative PD indicated a cow had lower production during the initial 100 DIM compared with the final 100 DIM, and a positive PD indicated a cow had higher production during the initial 100 DIM compared with the final 100 DIM. Therefore, a negative PD indicated more persistency of production.

Statistical Analysis

Primiparous and multiparous cows were analyzed separately for both 2-breed and 3-breed crossbred cows and their respective HO herdmates. Estimates of lactation curve characteristics and persistency of production for the RR function that best estimated daily production were analyzed separately from the estimates of lactation curve characteristics for BP. The 2-breed crossbred cows were compared only with their HO herdmates that calved during the same lactation and HYS and, likewise, 3-breed crossbred cows were compared only with their HO herdmates that calved during the same lactation and HYS. Most of the HO herdmates for the 3-breed crossbred cows were from a subsequent generation of those used for comparison with 2-breed crossbred cows; however, 23% of the primiparous HO herdmates that were compared with 2-breed crossbred cows were also compared with 3-breed crossbred cows.

Independent variables for the statistical analysis of 305-d milk (kg), fat (kg), and protein (kg), peak production (kg), DIM of peak production, DE, PR, and PD for primiparous cows included the fixed effects of HYS and breed group of cow (MO × HO, VR × HO, MO × VR/HO, VR × MO/HO, or HO cows). Analysis of multiparous cows included the fixed effects of lactation number (2 or 3), HYS nested within lactation number, breed group of cow, interaction of lactation number and breed group, and the random effect of cow nested within breed group of cow. The MIXED procedure of SAS 9.4 (SAS Institute Inc., Cary, NC) was used to conduct the ANOVA and to obtain least squares solutions. Multiple comparisons by breed group were performed with the Tukey's Honest Significant Differences test.

RESULTS AND DISCUSSION

Goodness of Fit for Alternative RR and BP Across Breed Groups

Results for the comparison of alternative estimation functions for goodness of fit of test-day observations are in Table 1. For primiparous cows, Legendre polynomial RR had the lowest MSPE among all RR functions with 63.73 for milk, 0.23 for fat, and 0.07 for protein production. The Legendre polynomial RR also had a better fit than BP, which had MSPE of 91.33, 0.28 and 0.09 for milk, fat, and protein production, respectively. Additionally, MPE and MD for milk, fat, and protein production was the lowest for Legendre polynomial RR compared with the other two RR and with BP. Furthermore, for primiparous cows, the Ali-Schaeffer RR also had lower MSPE, MPE, and MD of milk, fat, and protein production than BP. However, BP had lower MSPE and MPE compared with the Wilmink RR for milk, fat, and protein production, but the Wilmink RR had lower MD for milk, fat, and protein production.

For multiparous cows, BP had the lowest MSPE and MPE for milk and fat production; however, Legendre polynomial RR had the lowest MSPE, MPE, and MD for protein production. The Wilmink RR had the lowest MD for fat production, and Legendre polynomial had the lowest MD for milk production. Although BP had lower MSPE for milk (105.51) and fat (0.41) production for multiparous cows, Legendre polynomial RR had the second lowest MSPE compared to BP for milk (112.32) and fat (0.45) production. Furthermore, Legendre polynomial RR had lower MSPE, MPE, and MD (0.11, 0.33, and -0.007 kg, respectively), for protein production of multiparous cows compared with BP (Table 1). In summary, Legendre polynomial RR best fit lactation curves for the test-day observations of milk, fat, and protein production across all breed groups for primiparous cows and of protein production for multiparous cows. Therefore, Legendre polynomial RR was used for comparison with BP for all the results that follow.

The reduced goodness of fit for BP was possibly due to its use of the breed-specific lactation curves for HO cows as a default for the crossbred cows. Lactation curves for crossbred cows are not available with BP (Cole and VanRaden, 2009), and the use of HO lactation curves as a default may not accurately approximate the typical lactation curve of crossbred cows. The breed-specific lactation curves for BP have not been updated since 2007, and those lactation curves were estimated from cows that calved from 1997 to 2003 (Cole et. al, 2009). Also, the HO lactation curves would have been estimated from cows during a time when up to 22.3% of all dairy herds in the United States used bST (USDA, 2008). Furthermore, the cows used by Cole et al. (2009) to estimate breed-specific lactation curves for BP had lower production than more recent dairy cows and substantially lower production than the cows in this study. The superior goodness of fit for Legendre polynomial RR compared with BP could be because it provides for more flexible shapes of lactation curves for individual cows (Macciotta et al., 2005 and Schaeffer, 2016) rather than the more rigid Wood's curve that is used for interpolation between test-day observations by BP (Cole and VanRaden, 2009).

Two-Breed Crossbred Cows Compared With Their HO Herdmates

Lactation Curve Characteristics. The effect of HYS and breed group significantly ($P < 0.01$) explained variation for all of the lactation curve characteristics for milk, fat, and protein production of both primiparous and multiparous cows. Furthermore, the effect of lactation number and the interaction of breed group and lactation number also significantly ($P < 0.01$) explained variation for lactation curve characteristics of milk, fat, and protein production for multiparous cows.

For primiparous cows, MO × HO 2-breed crossbreds were not different from their HO herdmates for any lactation curve characteristics for milk production with Legendre polynomial RR and with BP, except for DIM of peak milk production with BP (Table 2). With BP, MO × HO 2-breed crossbreds had DIM of peak milk production 8 d later ($P < 0.01$) than their primiparous HO herdmates. With both Legendre polynomial RR and BP, the VR × HO 2-breed crossbreds had lower ($P < 0.01$) milk production than their HO herdmates during all 3 periods of lactation, and this contributed to lower 305-d milk production than their primiparous HO herdmates. Additionally, VR × HO 2-breed crossbreds had 2 kg lower ($P < 0.01$) peak milk production than their HO herdmates with Legendre polynomial RR and had 1 kg lower ($P < 0.01$) peak milk production than their HO herdmates with BP. However, the VR × HO 2-breed crossbreds did not differ from their HO herdmates for DIM of peak milk production with Legendre polynomial RR and with BP. The results in this study for 305-d milk production of primiparous cows agreed with Hazel et al. (2017), who reported MO × HO 2-breed crossbred cows did not differ from their HO herdmates for milk production, but VR × HO 2-breed crossbred cows had 4% lower fluid milk production than their HO herdmates in first lactation. Hazel et al. (2017) used similar data from the same 7 herds; however, that study included cows that completed fewer than 250 DIM and those cows were projected to 305 d using BP.

For multiparous cows, MO × HO 2-breed crossbreds did not differ from their HO herdmates for milk production during any of the 3 periods of lactation and, therefore, did not differ for 305-d milk production with either Legendre polynomial RR or BP (Table 2). The results for 305-d milk production for MO × HO 2-breed crossbreds and their multiparous HO herdmates agreed with those of Hazel et al. (2014), who found MO ×

HO 2-breed crossbred cows did not differ from their HO herdmates for milk production of multiparous cows in 2 institutional herds. Similar to the primiparous cows, VR × HO 2-breed crossbreds had lower milk production during all 3 periods of lactation, and this led to lower 305-d milk production than their HO herdmates with both Legendre polynomial RR and BP (Table 2).

Although milk production (kg) had historically been the prevalent measure of productivity, in recent years production of fat and protein (kg) has become the superior measure of production revenue for dairy producers. For primiparous cows, MO × HO 2-breed crossbreds had higher ($P < 0.01$) fat production during the middle 102 DIM and final 100 DIM periods of lactation than their HO herdmates with both Legendre polynomial RR and BP (Table 3). The higher production of MO × HO 2-breed crossbreds during the latter two-thirds of lactation contributed to higher 305-d fat production than their HO herdmates with Legendre polynomial RR and BP. Similarly, VR × HO 2-breed crossbreds had significantly higher fat production during the middle 102 DIM period of lactation than their HO herdmates with both Legendre polynomial RR and BP. The advantage of fat production for VR × HO 2-breed crossbreds during the middle 102 DIM period of lactation resulted in higher ($P < 0.05$) 305-d fat production (+5 kg) than their primiparous HO herdmates with Legendre Polynomial RR (Table 3). The VR × HO 2-breed crossbreds were not different from their HO herdmates for 305-d fat production with BP.

For multiparous cows, neither MO × HO nor VR × HO 2-breed crossbreds were different from their HO herdmates for fat production during the initial 100 DIM or final 100 DIM periods of lactation with Legendre polynomial RR and with BP (Table 3).

However, MO × HO and VR × HO 2-breed crossbreds had higher (*P* < 0.05) fat production (+3 kg) during the middle 102 DIM period of lactation with Legendre polynomial RR, although both crossbred groups were not different from their HO herdmates for fat production during the middle 102 DIM period of lactation with BP. However, across the 3 periods of lactation, MO × HO and VR × HO 2-breed crossbreds did not differ from their HO herdmates for fat production with Legendre polynomial RR or with BP.

For primiparous cows, MO × HO 2-breed crossbreds had higher (*P* < 0.01) protein production during all 3 periods of lactation than their HO herdmates (Table 4), and this resulted in +14 kg and +10 kg, respectively, higher 305-d protein production with Legendre polynomial RR and BP, respectively. Moreover with Legendre polynomial RR, VR × HO 2-breed crossbreds had significantly higher protein production than their primiparous HO herdmates during the middle 102 DIM and final 100 DIM periods of lactation, and this led to +4 kg higher (*P* < 0.05) 305-d protein production. On the other hand, with BP, VR × HO 2-breed crossbreds were not different from their HO herdmates for protein production during the middle 102 DIM and final 100 DIM periods of lactation and for 305-d protein production. Additionally, MO × HO 2-breed crossbreds had +0.06 kg and +0.04 kg significantly higher peak protein production than their HO herdmates with Legendre polynomial RR and with BP, respectively. The VR × HO 2-breed crossbreds had higher (*P* < 0.05) peak protein production (+0.03 kg and +0.02 kg, respectively) than their HO herdmates with both Legendre polynomial RR and BP (Table 4).

For multiparous cows, MO × HO 2-breed crossbreds also had higher (*P* <0.01) protein production during all 3 periods of lactation than their HO herdmates with both Legendre polynomial RR and BP. The higher production for MO × HO 2-breed crossbreds during all 3 periods of lactation resulted in higher (*P* < 0.01) 305-d protein production than their HO herdmates with both Legendre polynomial RR and BP (Table 4). Furthermore, the MO × HO 2-breed crossbreds had significantly higher peak protein production than their HO herdmates and a higher level of protein production was maintained throughout lactation than their HO herdmates when lactation curves were estimated by both Legendre polynomial RR and BP. The VR × HO 2-breed crossbreds were not different from their multiparous HO herdmates for any of the lactation curve characteristics for protein production with either Legendre polynomial RR or BP.

The results for 305-d production of fat and protein for primiparous cows align with other studies for the comparison of MO × HO 2-breed crossbreds with their HO herdmates. Hazel et al. (2017) reported MO × HO 2-breed crossbred cows had 3% higher fat plus protein production in first lactation. Malchiodi et al. (2014) reported equal protein production and a 5% advantage of fat production for MO × HO 2-breed crossbred cows compared with their HO herdmates during first lactation. The results from BP in this study agree with Hazel et al. (2017), who reported VR × HO 2-breed crossbred cows were not different from their HO herdmates for 305-d production of fat, protein, or fat plus protein production, but had lower 305-d milk production during first lactation. In a German study, Blöttner et al. (2009) reported Brown Swiss × HO 2-breed crossbred cows had higher milk production than their HO herdmates during the final 100 d of lactation. Brown Swiss is an Alpine breed as is the MO breed, and the results of this study may suggest crossbreds of Alpine breeds and HO may have higher production later in lactation than HO cows.

Comparison of Legendre polynomial RR and BP for Breed and Lactation Groups. The effects of HYS and breed group significantly ($P < 0.01$) explained variation of DE (Legendre polynomial RR minus BP) for milk, fat, and protein production of primiparous cows. For multiparous cows, the effects of lactation number and HYS nested within lactation number significantly ($P < 0.01$) explained variation of DE for milk, fat, and protein production of multiparous cows.

Most DE for production during the initial 100 DIM were significantly negative (Table 5), which indicated Legendre polynomial RR estimated lower production than BP for production during the initial 100 DIM period of lactation. Furthermore, all DE for production during the middle 102 DIM and final 100 DIM periods of lactation as well as 305-d production were positive, which indicated Legendre polynomial RR estimated higher production than BP for production during those periods of lactation and for 305-d production.

For primiparous cows, MO × HO 2-breed crossbreds had significantly less DE than their HO herdmates for fat production during the initial 100 DIM period of lactation, which indicated Legendre polynomial RR estimated lower fat production than BP for the MO × HO 2-breed crossbreds than their HO herdmates during that period of lactation. However, MO × HO 2-breed crossbreds had higher ($P < 0.01$) DE than their HO herdmates for fat and protein production during the middle 102 DIM and final 100 DIM periods of lactation, and this indicated Legendre polynomial RR estimated higher fat and protein production than BP for the MO × HO 2-breed crossbreds than their HO herdmates during these 2 periods of lactation. The higher ($P < 0.01$) DE of the MO × HO 2-breed crossbreds for both 305-d fat and protein production than HO herdmates indicated Legendre polynomial RR estimated +1.7 kg higher 305-d fat production and +4.0 kg higher 305-d protein production for the MO × HO 2-breed crossbreds than their HO herdmates. Although VR × HO 2-breed crossbreds had significantly lower (–0.6 kg) DE than their HO herdmates for fat production during the initial 100 DIM period of lactation, the significantly higher (+1.6 kg) DE during the middle 102 DIM period of lactation contributed to significantly higher (+1.2 kg) DE than their HO herdmates for 305-d fat production (Table 5), and this indicated Legendre polynomial RR estimated higher fat production than BP for VR × HO 2-breed crossbreds than their HO herdmates. Similarly, VR × HO 2-breed crossbreds had and significantly higher DE than their HO herdmates for protein production during the middle 102 DIM (+0.9 kg) and final 100 DIM (+0.8 kg) periods of lactation, and these differences contributed to a significantly higher DE than their HO herdmates for 305-d protein production (+1.7 kg). The results indicated Legendre polynomial RR estimated higher 305-d protein production than BP for VR × HO 2-breed crossbreds than their HO herdmates (Table 5).

Our results suggest Legendre polynomial RR estimated lower fat and protein production than BP during the initial 100 DIM period of lactation for the primiparous cows of all breed groups. These findings, coupled with the results that Legendre polynomial RR more accurately estimated production compared with test-day observations (Table 1) suggests BP did not properly characterize the lactation curve of primiparous cows for all 3 of the breed groups. The BP inflated fat and protein production during the initial 100 DIM period of lactation. Both MO × HO and VR× HO

2-breed crossbreds had significantly (P < 0.05) higher DE for 305-d fat and protein production than their HO herdmates, and this indicated Legendre polynomial RR estimated higher 305-d fat and protein production than BP for the MO × HO and VR × HO 2-breed crossbreds than their HO herdmates. The additional fat and protein production with Legendre polynomial RR compared to BP for the 2-breed crossbreds was during the middle 102 DIM and final 100 DIM periods of lactation. This result indicated BP discounted the production of MO × HO and VR × HO 2-breed crossbreds during first lactation compared with their HO herdmates. Furthermore, the use of Wood's curve for interpolation by BP (Cole and VanRaden, 2009) may underestimate production near the end of lactation for all primiparous cows. Our results demonstrate the breed-specific lactation for HO cows with BP are not well-suited for the primiparous 2-breed crossbreds in this study.

For multiparous cows, MO × HO (–14 kg) and VR × HO (–30.5 kg) 2-breed crossbreds had significantly less DE than their HO herdmates for milk production during the initial 100 DIM period of lactation (Table 5), and this indicated Legendre polynomial RR estimated lower milk production than BP for both groups of 2-breed crossbreds than their HO herdmates. Likewise, a portion of the lower milk production (kg) of VR × HO 2-breed crossbreds compared with their HO herdmates resulted from the consistently lower DE during the middle 102 DIM and final 100 DIM periods of lactation as well as 305-d milk production rather than reflecting the true shape of lactation curves for VR × HO 2-breed crossbreds compared with their HO herdmates. For 305-d fat production, MO × HO 2-breed crossbreds had significantly higher DE (+2.7 kg) and VR × HO 2-breed crossbreds had significantly higher (+4.1 kg) DE than their HO herdmates, which indicated Legendre polynomial RR estimated higher fat production than BP for both crossbred groups than their HO herdmates. During the middle 102 DIM and final 100 DIM periods of lactation, the MO × HO 2-breed crossbreds had significantly higher DE (+1.7 kg and +0.9 kg respectively), which indicated higher fat production was estimated by Legendre polynomial RR than BP for the MO × HO 2-breed crossbreds than their HO herdmates. Likewise, VR × HO 2-breed crossbreds had significantly higher DE (+3.2 kg) for fat production during the middle 102 DIM period of lactation and significantly higher DE (+0.9 kg) for fat production during the final 100 DIM period of lactation than their HO herdmates, which indicated Legendre polynomial RR estimated higher fat production during these periods of lactation than BP for the VR × HO 2-breed crossbreds than their HO herdmates. For protein production, MO × HO 2-breed crossbreds had higher ($P < 0.01$) DE than their HO herdmates for production during the middle 102 DIM and final 100 DIM periods of lactation. The higher DE during all 3 periods of lactation contributed to a significantly higher DE (+4.2 kg) for MO × HO 2-breed crossbreds than their HO herdmates for 305-d protein production. The VR × HO 2-breed crossbreds had higher ($P < 0.01$) DE for protein production during the last 2 periods of lactation, and this resulted in a significantly higher DE (+3.9 kg) for 305-d protein production for the VR × HO 2-breed crossbreds than their HO herdmates.

Similar to primiparous cows, the results for multiparous cows indicated Legendre polynomial RR estimated higher fat and protein production than BP during the middle 102 and final 100 DIM periods of lactation and this, in turn, resulted in higher 305-d production for both groups of 2-breed crossbreds than their HO herdmates. Although Legendre polynomial RR estimated higher 305-d fat and protein production than BP for the HO herdmates, even higher 305-d fat and protein production was estimated for both groups of 2-breed crossbreds by Legendre polynomial RR than by BP (Table 5). Similar to the primiparous cows, BP may not have accurately approximated fat and protein production of MO × HO and VR × HO 2-breed crossbreds, especially during the middle 102 DIM and final 100 DIM periods of lactation, because higher fat and protein production was estimated for both crossbred groups than their HO herdmates during these periods of lactation. Perhaps, the use of HO lactation curves as the default by BP for both primiparous and multiparous crossbred cows may not be appropriate.

Persistency of Production. The effect of HYS significantly ($P < 0.01$) explained variation for both measures of persistency of production (PR and PD), and breed group significantly ($P < 0.01$) explained variation for both PR and PD of primiparous cows, except for PR of fat and protein production estimated by BP. For multiparous cows, the effect of lactation number and HYS nested within lactation number significantly ($P < 0.01$) explained variation for both PR and PD for milk, fat, and protein production.

For primiparous cows, MO × HO 2-breed crossbreds had significantly more persistency (both PR and PD) of milk, fat, and protein production than their HO herdmates with both Legendre polynomial RR and BP (Table 6), except for fat production with BP. The VR × HO 2-breed crossbreds did not differ from their primiparous HO herdmates for persistency (both PR and PD) of milk, fat, and protein production for either Legendre polynomial RR or BP (Table 6), except the VR × HO 2-breed crossbreds had significantly more PD of protein production than their HO herdmates with Legendre polynomial RR.

For multiparous cows, MO × HO 2-breed crossbreds did not differ from their HO herdmates for PR of milk, fat, and protein production with either Legendre polynomial RR or BP. Also, MO × HO 2-breed crossbreds did not differ from their HO herdmates for PD of milk and fat production, but they had less ($P < 0.05$) PD of protein production than their HO herdmates with both Legendre polynomial RR and BP (Table 6). The VR × HO 2-breed crossbreds had lower ($P < 0.05$) PR of milk production than their HO herdmates but did not differ from their HO herdmates for PR of fat and protein production with Legendre polynomial RR. The VR × HO 2-breed crossbreds had significantly less PR of milk, fat, and protein production than their HO herdmates with BP (Table 6). However, the VR × HO 2-breed crossbreds did not differ from their HO herdmates for PD of milk, fat, and protein production with either Legendre polynomial RR or BP. The difference in results for PR and PD as measures of persistency of production is because PR is reliant on the relative difference in production for the initial and final periods of lactation, whereas PD is an absolute difference in production for the initial and final periods of lactation.

These results suggest MO × HO 2-breed crossbreds may have a flatter lactation curve than their primiparous HO herdmates with more fat and protein production after peak production than their HO herdmates. Persistency of production has been associated with numerous beneficial attributes of dairy cows. Solkner and Fuchs (1987) found cows with more persistency of production were more feed efficient than cows with less persistency. Muir et al. (2004) reported more persistency of production was positively correlated with more success of insemination at first service for primiparous cows. Appuhamy et al. (2007) reported cows with more persistency of production had lower incidence of mastitis and metabolic disease than cows with less persistency. Therefore, the results for persistency of production in this study were not surprising because crossbred cows of the MO, VR, and HO breeds have been reported to be superior to HO cows for feed efficiency (Shonka-Martin et al., 2018), fertility (Hazel et al., 2017), and cost of health treatments (Hazel et al., 2018). Furthermore, the higher 305-d fat and protein production of MO × HO 2-breed crossbreds provides more production revenue of the MO × HO 2-breed crossbreds than their HO herdmates. Our results suggested VR × HO 2-breed crossbreds were mostly similar to their HO herdmates for persistency of production, and this agreed with a Canadian study (Batra, 1986) of the lactation curve characteristics of 2-breed crossbred cows of HO and Ayrshire that reported heterosis had no effect on shape of lactation curves for crossbreds of those 2 breeds. The advantages for persistency of production for MO × HO 2-breed crossbreds in this study could potentially be explained by heterosis, but their advantages may also be an additive genetic effect from the 50% MO content of the 2-breed crossbreds. Purebred MO and VR cows were not available in this study to estimate heterosis for persistency of production.

Three-breed Crossbred Cows Compared With Their HO Herdmates

Lactation Curve Characteristics. The effect of HYS significantly ($P < 0.01$) explained variation for all lactation curve characteristics of primiparous cows. Breed group significantly explained variation for all lactation curve characteristics except for DIM of peak production and milk production during the initial 100 DIM period of lactation. The effects of lactation number, HYS nested within breed group, and breed group significantly ($P < 0.01$) explained variation for all lactation curve characteristics of multiparous cows.

For primiparous cows, MO × VR/HO 3-breed crossbreds had significantly lower milk (Table 7), fat (Table 8), and protein (Table 9) production during the initial 100 DIM and final 100 DIM periods of lactation than their HO herdmates with both Legendre polynomial RR and BP. As a consequence, MO × VR/HO 3-breed crossbreds had significantly lower 305-d milk, fat, and protein production than their HO herdmates with both Legendre polynomial RR and BP. Conversely, MO × VR/HO 3-breed crossbreds did not differ from their HO herdmates for fat and protein production during the middle 102 DIM period of lactation with Legendre polynomial RR, but they had lower ($P < 0.05$) fat and protein production during the middle 102 DIM period than their HO herdmates with BP.

The MO × VR/HO 3-breed crossbreds had lower ($P < 0.01$) peak milk production in first lactation than their HO herdmates, but they were not different from their HO herdmates for peak fat and protein production with both Legendre polynomial RR and BP. The VR × MO/HO 3-breed crossbreds had lower ($P < 0.01$) milk, fat, and protein production during all 3 periods of lactation and, therefore, had significantly lower 305-d milk, fat, and protein production in first lactation than their HO herdmates with both Legendre polynomial RR and BP. Furthermore, the VR × MO/HO 3-breed crossbreds had significantly lower peak milk, fat, and protein production than their HO herdmates with both Legendre polynomial RR and BP in first lactation.

For multiparous cows, MO × VR/HO 3-breed crossbreds had significantly lower milk (Table 7) and fat (Table 8) production during the initial 100 DIM and final 100 DIM periods of lactation than their HO herdmates, and this contributed to significantly lower 305-d milk and fat production than their HO herdmates with both Legendre polynomial

RR and BP. The MO × VR/HO 3-breed crossbreds had significantly lower milk and fat production during the middle 102 DIM period of lactation than their HO herdmates with both Legendre polynomial RR and BP, except the MO × VR/HO 3-breed crossbreds did not differ from their HO herdmates for fat production during the middle 102 DIM period of lactation with Legendre polynomial RR. Furthermore, MO × VR/HO 3-breed crossbreds were not different from their HO herdmates for protein production during all 3 periods of lactation and for 305-d protein production with both Legendre polynomial RR and BP (Table 9). On the other hand, the VR × MO/HO 3-breed crossbreds had significantly lower milk (Table 7) and fat (Table 8) production during all 3 periods of lactation than their HO herdmates with both Legendre polynomial RR and BP. The VR × MO/HO 3-breed crossbreds did not differ from their HO herdmates for protein production during the initial 100 DIM or the middle 102 DIM periods of lactation, but they had significantly lower protein production than their HO herdmates during the final 100 DIM period of lactation with Legendre polynomial RR (Table 9). For, BP the VR × MO/HO 3-breed crossbreds significantly had lower protein production during all 3 periods of lactation than their HO herdmates. The VR × MO/HO 3-breed crossbreds had significantly lower 305-d milk (Table 7), fat (Table 8), and protein (Table 9) production than their HO herdmates with either Legendre polynomial RR or BP.

The MO × VR/HO 3-breed crossbreds of both parity groups were similar to their respective HO herdmates for fat and protein production during the middle 102 DIM period of lactation. The difference between MO × VR/HO and VR × MO/HO 3-breed crossbreds and their HO herdmates for fat and protein production during the middle 102 DIM period of lactation could potentially be explained by the MO content. The MO-sired

2-breed and 3-breed crossbreds had equal or higher fat and protein production during the middle 102 DIM period of lactation than their respective HO herdmates, whereas the VR × MO/HO 3-breed crossbreds contain 25% MO on average.

The lower production for 3-breed crossbreds compared with their HO herdmates in this study could be due to the individual sires of cows that were used. However, further research may be warranted on the lactation curve characteristics of MO × VR/HO and VR × MO/HO 3-breed crossbreds. The 2-breed and 3-breed crossbreds in this study are unique generations at the beginning of a 3-breed crossbreeding rotation that is continuous. The HO-sired third generation and subsequent generations are expected to have somewhat higher production of milk, fat, and protein (kg) because of the somewhat higher HO content on average, despite the reduction in heterosis as the rotation reaches a plateau for heterosis of 86% compared with a first-generation 2-breed or second-generation 3-breed crossbred.

Comparison of Legendre polynomial RR and BP for Breed and Lactation Groups. The effects of HYS and breed group significantly ($P < 0.01$) explained variation of DE for primiparous cows. Lactation number, HYS nested within lactation number, and breed group significantly ($P < 0.01$) explained variation of DE for multiparous cows.

For primiparous cows, MO × VR/HO 3-breed crossbreds had higher ($P < 0.01$) DE than their HO herdmates for fat (+3.3 kg) and protein (+1.9 kg) production during the middle 102 DIM period of lactation, and this indicated Legendre polynomial RR estimated higher fat and protein production than BP for the MO × VR/HO 3-breed crossbreds than their HO herdmates during that period of lactation (Table 10). Conversely, MO × VR/HO 3-breed crossbreds had a lower ($P < 0.01$) DE than their HO herdmates for fat and protein production during the final 100 DIM period of lactation, and this indicated Legendre polynomial RR estimated higher fat and protein production than BP during that period of lactation for the HO herdmates than the MO × VR/HO 3-breed crossbreds. Finally, the MO × VR/HO 3-breed crossbreds had significantly lower DE than their HO herdmates for 305-d fat production (Table 10). Likewise, VR × MO/HO 3-breed crossbreds had significantly higher DE (+1.1 kg) than their HO herdmates for fat and protein production during the middle 102 DIM period of lactation, which indicated Legendre polynomial estimated higher fat and protein production than BP during that period of lactation for the VR × MO/HO 3-breed crossbreds than their HO herdmates. The VR × MO/HO 3-breed crossbreds had significantly lower DE compared with their HO herdmates for fat and protein production during the final 100 DIM period of lactation, and this indicated Legendre polynomial RR estimated higher fat and protein production than BP during that period of lactation for the HO herdmates than for the VR × MO/HO 3-breed crossbreds. Overall, VR × MO/HO 3-breed crossbreds had significantly lower DE than their HO herdmates for 305-d fat (–4.4 kg) and protein (–2.1 kg) production (Table 10), and this indicated Legendre polynomial RR estimated higher 305-d fat and protein production than BP for the HO herdmates than the VR × MO/HO 3-breed crossbreds (Table 10).

For multiparous cows, MO × VR/HO 3-breed crossbreds had higher ($P < 0.01$) DE than their HO herdmates for fat and protein production during the middle 102 DIM period of lactation (Table 10), and this indicated Legendre polynomial RR estimated higher fat and protein production than BP during that period of lactation for the MO × VR/HO 3-breed crossbreds than their HO herdmates. Likewise, MO × VR/HO 3-breed crossbreds had significantly higher DE than their HO herdmates for 305-d fat and protein production, which indicated Legendre polynomial RR estimated higher 305-d fat and protein production than BP for the MO × VR/HO 3-breed crossbreds than their HO herdmates. The VR × MO/HO 3-breed crossbreds had significantly higher DE than their HO herdmates for fat and protein production during the middle 102 DIM period of lactation, and this indicated Legendre polynomial RR estimated higher fat and protein production than BP during that period of lactation for the VR × MO/HO 3-breed crossbreds than their HO herdmates. However, VR × MO/HO 3-breed crossbreds had significantly lower DE than their HO herdmates for fat (–5.2 kg) and protein (-2.9 kg) production during the final 100 DIM period of lactation, and this indicated Legendre polynomial RR estimated less fat and protein production than BP during this period of lactation for the VR × MO/HO 3-breed crossbreds than their HO herdmates. The VR × MO/HO 3-breed crossbred had significantly lower DE (-2.0 kg) than their HO herdmates for 305-d fat production and significantly higher DE (+1.1 kg) than their HO herdmates for 305-d protein production. The results for DE indicated the HO herdmates of the VR × MO/HO 3-breed crossbreds had higher 305-d fat production from Legendre polynomial RR than from BP compared with the VR × MO/HO 3-breed crossbreds, but Legendre polynomial RR had higher 305-d protein production than BP for the VR × MO/HO 3-breed crossbreds than for their HO herdmates (Table 10).

Much like the differences of the 2-breed crossbreds, MO × VR/HO and VR × MO/HO 3-breed crossbreds of both parity groups had significantly higher DE for fat and protein production during the middle 102 DIM period of lactation than their HO herdmates, and this indicated that Legendre polynomial RR estimated significantly higher fat and protein production than BP during that period of lactation for both MO × VR/HO and VR × MO/HO 3-breed crossbreds than their HO herdmates. Legendre polynomial RR estimated numerically higher fat and protein production than did BP for all breed groups during the middle 102 DIM period of lactation; however, the higher fat and protein production for both MO × VR/HO and VR × MO/HO 3-breed crossbreds was significantly higher during that period of lactation than for their HO herdmates. Unlike the results for the 2-breed crossbreds, Legendre polynomial RR estimated higher 305-d fat and protein production than BP for the primiparous HO herdmates than for both groups of 3-breed crossbreds in first lactation. Nonetheless, the results of this study suggest that BP did not properly characterize the lactation curves of primiparous cows for any of the breed groups. The BP inflated production during the initial 100 DIM period of lactation and underestimated production during the latter two-thirds of lactation compared with Legendre polynomial RR similar to the results of 2-breed crossbreds and their HO herdmates (Table 5).

Persistency of Production. For primiparous cows the effects of HYS and breed group significantly ($P < 0.01$) explained variation of both PR and PD of milk, fat, and protein production. For multiparous cows, the effects of HYS nested within lactation and breed group significantly ($P < 0.01$) explained variation for both PR and PD of milk, fat, and protein production.

For primiparous cows, MO × VR/HO 3-breed crossbreds had significantly more PR of milk and protein production than their HO herdmates (Table 11), but did not differ from their HO herdmates for PR of fat production with Legendre polynomial RR. The MO × VR/HO 3-breed crossbreds had significantly ($P < 0.05$) more PD of milk production and did not differ from their HO herdmates for PD of fat and protein production with Legendre polynomial RR. The MO × VR/HO 3-breed crossbreds were not different from their HO herdmates for PR and PD of milk, fat, and protein production with BP (Table 11), except the MO × VR/HO 3-breed crossbreds had more ($P < 0.05$) PR of protein production than their HO herdmates with BP. The VR × MO/HO 3-breed crossbreds had significantly less PR and PD of milk, fat, and protein production than their HO herdmates with both Legendre polynomial RR and BP (Table 11), except the VR × MO/HO 3-breed crossbreds did not differ from their HO herdmates for PD of fat production with BP.

For multiparous cows, MO × VR/HO did not differ from their HO herdmates for PR of milk, fat, or protein production with both Legendre polynomial RR and BP (Table 11). Additionally, MO × VR/HO 3-breed crossbreds had more ($P < 0.05$) PD of milk production than their HO herdmates with both Legendre polynomial RR and BP. However, the MO × VR/HO 3-breed crossbreds did not differ from their HO herdmates for PD of fat production with Legendre polynomial RR, but the PD indicated more ($P < 0.05$) persistency of fat production than their HO herdmates with BP (Table 10). The MO × VR/HO 3-breed crossbreds did not differ from their HO herdmates for PD of protein production with either Legendre polynomial RR or BP. The PR results for VR × MO/HO 3-breed crossbreds indicated less ($P < 0.01$) persistency of milk, fat, and protein production than their HO herdmates with Legendre polynomial RR and BP. Likewise, VR × MO/HO 3-breed crossbreds had less ($P < 0.01$) PD of milk, fat, and protein production than their HO herdmates with Legendre polynomial RR. Finally, VR × MO/HO 3-breed crossbreds did not differ from their HO herdmates for PD of milk and fat production with BP, but the VR × MO/HO 3-breed crossbreds had less ($P < 0.01$) PD of protein production than their HO herdmates with BP (Table 11).

Similar to the MO × HO 2-breed crossbreds, MO × VR/HO 3-breed crossbreds had significantly higher PR of milk and protein production than their primiparous HO herdmates. These results further suggest primiparous crossbreds with 50% MO content may have similar or more persistency of milk, fat, and protein production compared with their primiparous HO herdmates. The lower persistency of the VR × MO/HO 3-breed crossbreds compared with their HO herdmates could be a consequence of the lower 305-d production of VR × MO/HO 3-breed crossbreds compared with their HO herdmates because both measures of persistency (PR and PD) are dependent on total production. Gengler (1996) reported persistency measures based on ratios, such as PR, have a positive relationship with total production. Moreover, the production traits were not adjusted for the fertility status of cows in this study. If production had been adjusted for days open, the reduced persistency of the VR × MO/HO 3-breed crossbreds compared with their HO herdmates may have been less pronounced because the effect of pregnancy has a substantial effect on production in the later stages of pregnancy (Batra, 1986).

CONCLUSIONS

For the past 20 yr, BP has been used for genetic evaluation in the United States, whereas most other countries globally have used a RR function for genetic evaluation. Because Legendre polynomial RR was superior to BP for estimation of production from test-day observations across all breed groups in this study, Legendre polynomial RR should be further explored across a larger number of herds for the potential use for genetic evaluation in the United States. In particular, Legendre polynomial RR more accurately estimated milk, fat, and protein production of primiparous cows as well as protein production of multiparous cows compared with BP in this study. The large difference between Legendre polynomial RR and BP estimates of 305-d production for MO × HO and VR × HO 2-breed crossbreds suggested the estimates from BP, especially during the latter two-thirds of lactation, were not optimal compared with the estimates from Legendre polynomial RR. Furthermore, 305-d production from BP using the breed-specific lactation curves that are potentially outdated may not be well-suited for today's high-producing dairy cows. The MO × HO and VR × HO 2-breed crossbreds in this study had similar or higher fat and protein production compared to their HO herdmates during 305-d lactations. However, the 2-breed crossbreds generally had more persistency of production than their HO herdmates, and more persistency of production is often preferred by dairy producers. This study considered only the first 2 generations of a continuous 3-breed rotation for crossbreeding. However, our results suggest crossbred cows of the MO, VR, and HO breeds may have advantages over HO cows for persistency of production for high-performance dairy herds.

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Table 1. Comparison of estimation functions[1] for test-day observations based on mean square prediction error (MSPE), mean prediction error (MPE), and the mean difference (MD) of actual and estimated test-day observations across breed groups.

Item	Function	MSPE	MPE	MD
				(kg)
Primiparous				
Milk	Wilmink RR	97.18	9.86	-0.183
	Ali-Schaeffer RR	78.98	8.89	-0.198
	Legendre polynomial RR	**63.73**	**7.98**	**-0.141**
	BP	91.33	9.60	0.926
Fat	Wilmink RR	0.29	0.54	-0.005
	Ali-Schaeffer RR	0.27	0.52	-0.005
	Legendre polynomial RR	**0.23**	**0.48**	**-0.004**
	BP	0.28	0.53	0.052
Protein	Wilmink RR	0.10	0.32	-0.006
	Ali-Schaeffer RR	0.08	0.28	-0.006
	Legendre polynomial RR	**0.07**	**0.26**	**-0.005**
	BP	0.09	0.31	0.025
Multiparous				
Milk	Wilmink RR	157.35	12.54	-0.227
	Ali-Schaeffer RR	133.30	11.55	-0.267
	Legendre polynomial RR	112.32	10.59	**-0.170**
	BP	**105.51**	**10.27**	0.638
Fat	Wilmink RR	0.56	0.75	**-0.006**
	Ali-Schaeffer RR	0.53	0.73	-0.007
	Legendre polynomial RR	0.45	0.67	-0.007
	BP	**0.41**	**0.64**	0.022
Protein	Wilmink RR	0.17	0.42	-0.007
	Ali-Schaeffer RR	0.13	0.37	-0.008
	Legendre polynomial RR	**0.11**	**0.33**	**-0.007**
	BP	0.12	0.34	0.016

[1]RR = random regression, BP = Best Prediction

Bold type = lowest value (most desirable) among the estimation functions for each production trait.

Table 2. Least squares estimates of lactation curve characteristics for milk production of 2-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression				Best Prediction			
Item	HO	MO×HO	VR×HO	Range of SEM	HO	MO×HO	VR×HO	Range of SEM
Primiparous								
n	1,073	524	548		1,073	524	548	
305-d milk (kg)	11,657	11,669	11,098**	45–65	11,219	11,257	10,864**	35–50
Peak milk/d (kg)	43	43	41**	0.16–0.22	42	42	41**	0.14–0.19
DIM of peak milk (d)	150	153	152	1.7–2.4	139	147**	141	1.6–2.3
Initial 100 DIM (kg)	3,626	3,577	3,458**	15–21	3,625	3,618	3,519**	11–16
Middle 102 DIM (kg)	4,246	4,268	4,051**	16–23	4,017	4,036	3,893**	12–18
Final 100 DIM (kg)	3,785	3,823	3,589**	17–25	3,577	3,603	3,452**	13–19
Multiparous								
n	1,223	650	633		1,223	650	633	
305-d milk (kg)	14,147	14,086	13,312**	69–95	13,908	13,847	13,158**	64–88
Peak milk/d (kg)	55	55	52**	0.24–0.33	56	56	53**	0.24–0.33
DIM of peak milk (d)	96	96	95	0.9–1.2	88	90	86	1.4–1.8
Initial 100 DIM (kg)	5,102	5,077	4,838**	24–33	5,139	5,128	4,906**	22–30
Middle 102 DIM (kg)	5,141	5,142	4,850**	25–34	4,939	4,923	4,681**	23–32
Final 100 DIM (kg)	3,909	3,867	3,629**	28–38	3,835	3,796	3,576**	25–34

[1]MO×HO = Montbéliarde × HO, VR×HO = Viking Red × HO.
*$P < 0.05$, ** $P < 0.01$ for difference of crossbred from Holstein cows.

Table 3. Least squares estimates of lactation curve characteristics for fat production of 2-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression				Best Prediction			
Item	HO	MO×HO	VR×HO	Range of SEM	HO	MO×HO	VR×HO	Range of SEM
Primiparous								
n	1,073	524	548		1,073	524	548	
305-d fat (kg)	431	440**	436*	1.6–2.2	414	421**	418	1.4–1.9
Peak fat/d (kg)	1.53	1.57**	1.57**	0.005–0.008	1.55	1.58**	1.58**	0.006–0.009
DIM of peak fat (d)	178	183	178	2.1–3.0	153	160	154	2.2–3.2
Initial 100 DIM (kg)	135	136	136	0.6–0.8	136	138*	137	0.5–0.7
Middle 102 DIM (kg)	152	156**	155**	0.6–0.8	143	146**	145*	0.5–0.7
Final 100 DIM (kg)	144	148**	145	0.6–0.8	134	137**	136	0.5–0.7
Multiparous								
n	1,223	650	633		1,223	650	633	
305-d fat (kg)	501	507	501		496	500	493	
Peak fat/d (kg)	1.86	1.88	1.88	0.009–0.012	2.02	2.04	2.01	0.011–0.015
DIM of peak fat (d)	81	83	89**	1.6–2.2	87	89	90	2.1–2.8
Initial 100 DIM (kg)	179	181	179	0.9–1.2	185	186	184	0.9–1.2
Middle 102 DIM (kg)	176	179*	179*	0.9–1.2	170	172	170	0.9–1.2
Final 100 DIM (kg)	146	147	144	0.9–1.3	142	142	139	0.9–1.3

[1]MO×HO = Montbéliarde × HO, VR×HO = Viking Red × HO.

*$P < 0.05$, ** $P < 0.01$ for difference of crossbred from Holstein cows.

Table 4. Least squares estimates of lactation curve characteristics for protein production of 2-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression				Best Prediction			
Item	HO	MO×HO	VR×HO	Range of SEM	HO	MO×HO	VR×HO	Range of SEM
Primiparous								
n	1,073	524	548		1,073	524	548	
305-d protein (kg)	351	365**	355*	1.2–2.0	343	353**	346	1.0–1.6
Peak protein/d (kg)	1.27	1.33**	1.30*	0.004–0.007	1.28	1.32**	1.30*	0.004–0.006
DIM of peak protein (d)	189	194	190	1.7–2.4	179	181	181	1.8–2.7
Initial 100 DIM (kg)	106	108**	106	0.4–0.5	107	110**	108	0.3–0.4
Middle 102 DIM (kg)	126	132**	128**	0.4–0.6	121	125**	122	0.3–0.5
Final 100 DIM (kg)	119	125**	121*	0.5–0.7	115	118**	116	0.4–0.5
Multiparous								
n	1,223	650	633		1,223	650	633	
305-d protein (kg)	428	445**	429	0.6–0.8	426	438**	423	1.8–2.5
Peak protein/d (kg)	1.58	1.64**	1.59	0.006–0.008	1.64	1.70**	1.64	0.007–0.009
DIM of peak protein (d)	109	111	110	1.5–2.0	102	103	102	1.9–2.5
Initial 100 DIM (kg)	149	155**	149	0.6–0.8	152	157**	152	0.6–0.8
Middle 102 DIM (kg)	153	160**	154	0.7–0.9	149	153**	148	0.6–0.9
Final 100 DIM (kg)	126	130**	126	0.8–1.1	125	128*	123	0.7–1.0

[1]MO × HO = Montbéliarde × HO, VR × HO = Viking Red × HO.

*$P < 0.05$, ** $P < 0.01$ for difference of crossbred from Holstein cows.

Table 5. Difference of the least squares estimates (random regression minus Best Prediction) for the lactation curve characteristics presented in Tables 2 to 4 of the 2-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Milk			Fat			Protein		
Item	HO	MO×HO	VR×HO	HO	MO×HO	VR×HO	HO	MO×HO	VR×HO
<u>Primiparous</u>									
305-d production (kg)	438	412	233**	17.1	18.8**	18.3*	8.1	12.1**	9.8**
Peak production (kg/d)	0.4	0.4	0.0**	-0.02	-0.01	-0.01	-0.01	0.01**	0
DIM of peak	11	6	11	-25	-23	-24	10	13	9
Initial 100 DIM (kg)	0.9	-40.5**	-60.7**	-1.2	-1.7**	-1.8**	-1.8	-1.3*	-1.8
Middle 102 DIM (kg)	228.4	232.2	157.4**	8.8	10.0**	10.4**	5.2	6.8**	6.1**
Final 100 DIM (kg)	208.8	220.2	136.4**	9.5	10.6**	9.7	4.7	6.7**	5.5**
<u>Multiparous</u>									
305-d production (kg)	243	242	160**	4.5	7.2**	8.6**	2.1	6.3**	6.0**
Peak production (kg/d)	-1.2	-1.3*	-1.4**	-0.16	-0.15	-0.14	-0.06	-0.06	-0.05**
DIM of peak	7	6	9	-6	-6	-1	7	8	8
Initial 100 DIM (kg)	-36.2	-50.2**	-66.7**	-5.0	-5.1	-5.1	-3.5	-2.0**	-2.4**
Middle 102 DIM (kg)	205.4	221.1	173.2**	5.6	7.3**	8.8**	4.5	6.3**	5.7**
Final 100 DIM (kg)	75.0	72.6	55.9**	4.0	4.9**	4.9**	1.2	2.0**	2.7**

[1]MO × HO = Montbéliarde × HO, VR × HO = Viking Red × HO.

*$P < 0.05$, ** $P < 0.01$ for difference of crossbred from Holstein cows.

Table 6. Measures of persistency for 2-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression			Best Prediction		
Item	HO	MO×HO	VR×HO	HO	MO×HO	VR×HO
Primiparous						
n	1,073	524	548	1,073	524	548
Final 100 DIM divided by initial 100 DIM						
Milk	1.049	1.074**	1.042	0.989	0.998*	0.983
Fat	1.071	1.085*	1.076	0.990	0.994	0.989
Protein	1.138	1.159**	1.148	1.073	1.083*	1.075
Initial 100 DIM minus final 100 DIM						
Milk (kg)	-159.6	-246.4**	-130.5	48.3	14.2*	66.6
Fat (kg)	-8.8	-11.0**	-9.7	1.8	1.3	1.8
Protein (kg)	-14.1	-16.8**	-15.2*	-7.6	-8.8**	-7.9
Multiparous						
n	1,223	650	633	1,223	650	633
Final 100 DIM divided by initial 100 DIM						
Milk	0.769	0.765	0.754*	0.749	0.743	0.732**
Fat	0.816	0.814	0.806	0.774	0.769	0.760*
Protein	0.851	0.838	0.843	0.823	0.816	0.812*
Initial 100 DIM minus final 100 DIM						
Milk (kg)	1,187.8	1,208.4	1,199.8	1,299.5	1,331.8	1,323.5
Fat (kg)	33.6	33.6	34.6	42.7	43.6	44.6
Protein (kg)	22.7	25.4*	23.5	27.4	29.4*	28.6

[1]MO × HO = Montbéliarde × HO, VR × HO = Viking Red × HO.
*P < 0.05, ** P < 0.01 for difference of crossbred from Holstein cows.

Table 7. Least squares estimates of lactation curve characteristics for milk production of 3-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression				Best Prediction			
Item	HO	MO×VR/HO	VR×MO/HO	Range of SEM	HO	MO×VR/HO	VR×MO/HO	Range of SEM
Primiparous								
n	1,043	479	430		1,043	479	430	
305-d milk (kg)	12,037	11,019**	10,754**	49–75	11,567	10,854**	10,656**	38–57
Peak milk/d (kg)	44	41**	40**	0.17–0.26	44	42**	41**	0.15–0.22
DIM of peak milk (d)	149	149	140**	1.5–2.3	138	141	138	1.5–2.3
Initial 100 DIM (kg)	3,745	3,349**	3,379**	16–25	3,728	3,477**	3,460**	12–19
Middle 102 DIM (kg)	4,397	4,115**	3,977**	17–26	4,156	3,921**	3,840**	13–20
Final 100 DIM (kg)	3,895	3,555**	3,398**	19–29	3,683	3,456**	3,356**	14–22
Multiparous								
n	827	431	399		827	431	399	
305-d milk (kg)	14,309	13,264**	12,860**	78–120	14,097	13,156**	12,847**	72–110
Peak milk/d (kg)	56	52**	52**	0.27–0.41	57	54**	53**	0.28–0.42
DIM of peak milk (d)	95	98	96	1.0–1.6	88	92	91	1.5–2.3
Initial 100 DIM (kg)	5,180	4,772**	4,756**	27–42	5,224	4,852**	4,831**	25–38
Middle 102 DIM (kg)	5,210	4,880**	4,787**	28–43	5,020	4,718**	4,626**	26–40
Final 100 DIM (kg)	3,924	3,613**	3,324**	32–49	3,855	3,588**	3,395**	28–43

[1] MO × VR/HO = Montbéliarde × Viking Red/HO, VR × MO/HO = Viking Red × Montbéliarde /HO.
**P* < 0.05, ** *P* < 0.01 for difference of crossbred from Holstein cows.

Table 8. Least squares estimates of lactation curve characteristics for fat production of 3-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression				Best Prediction			
Item	HO	MO×VR/HO	VR×MO/HO	Range of SEM	HO	MO×VR/HO	VR×MO/HO	Range of SEM
Primiparous								
n	1,043	479	430		1,043	479	430	
305-d fat(kg)	442	431**	420**	1.7–2.7	426	417**	409**	1.5–2.2
Peak fat/d (kg)	1.57	1.58	1.52**	0.006–0.010	1.60	1.59	1.56**	0.007–0.010
DIM of peak fat (d)	160	157	149**	1.9–2.8	150	149	146	2.2–3.3
Initial 100 DIM (kg)	139	133**	132**	0.6–0.9	141	137**	135**	0.5–0.8
Middle 102 DIM (kg)	156	157	152**	0.6–1.0	148	146*	143**	0.5–0.8
Final 100 DIM (kg)	147	141**	136**	0.6–1.0	138	135**	132**	0.5–0.8
Multiparous								
n	827	431	399		827	431	399	
305-d fat (kg)	509	494**	478**	2.8–4.3	506	488**	477**	2.8–4.3
Peak fat/d (kg)	1.90	1.83**	1.84**	0.009–0.015	2.06	1.99**	1.97**	0.012–0.019
DIM of peak fat (d)	78	92**	83	1.8–2.8	84	89	88	2.3–3.5
Initial 100 DIM (kg)	183	176**	174**	1.0–1.5	189	181**	179**	1.0–1.6
Middle 102 DIM (kg)	179	176	173**	1.0–1.5	174	169**	165**	1.0–1.6
Final 100 DIM (kg)	147	141**	131**	1.0–1.6	144	139**	132**	1.0–1.6

[1]MO × VR /HO = Montbéliarde × Viking Red/HO, VR × MO/HO = Viking Red × Montbéliarde/HO.
*$P < 0.05$, ** $P < 0.01$ for difference of crossbred from Holstein cows.

Table 9. Least squares estimates of lactation curve characteristics for protein production of 3-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression				Best Prediction			
Item	HO	MO×VR/HO	VR×MO/HO	Range of SEM	HO	MO×VR/HO	VR×MO/HO	Range of SEM
Primiparous								
n	1,043	479	430		1,043	479	430	
305-d protein (kg)	364	358**	350**	1.3–2.0	356	350**	344**	1.1–1.6
Peak protein/d (kg)	1.32	1.32	1.29**	0.005–0.007	1.33	1.32	1.30**	0.004–0.006
DIM of peak protein (d)	183	172**	170**	1.6–2.4	172	173	168	1.8–2.7
Initial 100 DIM (kg)	110	106**	106**	0.4–0.6	111	108**	108**	0.3–0.5
Middle 102 DIM (kg)	132	132	128**	0.5–0.7	126	124*	122**	0.4–0.6
Final 100 DIM (kg)	123	120**	116**	0.6–0.8	119	117*	114**	0.4–0.6
Multiparous								
n	827	431	399		827	431	399	
305-d protein (kg)	432	435	420**	2.2–3.4	431	430	419**	2.1–3.2
Peak protein/d (kg)	1.61	1.62	1.61	0.007–0.011	1.68	1.66	1.67	0.008–0.012
DIM of peak protein (d)	106	106	105	1.7–2.6	100	104	102	2.0–3.0
Initial 100 DIM (kg)	151	153	150	0.7–1.1	155	154	152*	0.7–1.0
Middle 102 DIM (kg)	155	157	155	0.8–1.2	151	152	148*	0.7–1.1
Final 100 DIM (kg)	126	125	116**	1.0–1.5	125	125	118**	0.8–1.3

[1]MO × VR /HO = Montbéliarde × Viking Red/HO, VR × MO/HO = Viking Red × Montbéliarde/HO.
**P* < 0.05, ** *P* < 0.01 for difference of crossbred from Holstein cows.

Table 10. Difference of the least squares estimates (Legendre polynomial random regression minus Best Prediction) for the lactation curve characteristics presented in Tables 6 to 8 of the 3-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Milk			Fat			Protein		
Item	HO	MO×VR/HO	VR×MO/HO	HO	MO×VR/HO	VR×MO/HO	HO	MO×VR/HO	VR×MO/HO
Primiparous									
305-d production (kg)	470	165**	98**	15.1	13.6*	10.7**	8.2	8.0	6.1**
Peak production (kg/d)	0.9	1.1*	0.4**	0.03	0.01**	0.04*	-0.01	0.00**	-0.01
DIM of peak	-11	-8	-2**	-10	-7	-3**	-11	-1**	-2**
Initial 100 DIM (kg)	16.5	-128.6**	-80.9**	-1.6	-3.6**	-2.8**	-1.4	-2.5 **	-1.7
Middle 102 DIM (kg)	240.5	194.4**	136.6**	8.1	11.4**	9.2**	5.4	7.3**	5.9*
Final 100 DIM (kg)	212.7	98.8**	42.2**	8.6	5.8**	4.3**	4.2	3.2**	1.9**
Multiparous									
305-d production (kg)	215	107**	15**	3.0	5.3**	1.0**	0.6	5.0**	1.7*
Peak production (kg/d)	-1.5	-1.5	-1.4	-0.16	-0.15	-0.14**	-0.07	-0.05**	-0.04**
DIM of peak	7	6	5	-6	3**	-5	6	2	3
Initial 100 DIM (kg)	-43.3	-83.3**	-73.4**	-5.6	-4.6**	-4.6**	-3.8	-1.2**	-2.2**
Middle 102 DIM (kg)	190.4	163.2**	161.0**	4.9	7.2**	7.1**	4.0	5.5**	6.4**
Final 100 DIM (kg)	69.7	24.8**	-71.2**	3.8	2.8**	-1.4**	0.4	0.7	-2.5**

[1]MO × VR/HO = Montbéliarde × Viking Red/HO, VR × MO/HO = Viking Red × Montbéliarde/HO.
**P* < 0.05, ** *P* < 0.01 for difference of crossbred from Holstein cows.

Table 11. Measures of persistency for 3-breed crossbred cows[1] and their Holstein (HO) herdmates.

	Legendre polynomial random regression			Best Prediction		
Item	HO	MO×VR/HO	VR×MO/HO	HO	MO×VR/HO	VR×MO/HO
Primiparous						
n	1,043	479	430	1,043	479	430
Final 100 DIM divided by initial 100 DIM						
Milk	1.045	1.069**	1.013**	0.989	0.997	0.972*
Fat	1.060	1.059	1.014**	0.986	0.989	0.976*
Protein	1.125	1.139*	1.099**	1.071	1.081*	1.062*
Initial 100 DIM minus final 100 DIM						
Milk (kg)	-150.5	-206.1*	-19.7**	45.7	21.3	103.4**
Fat (kg)	-7.5	-7.3	-3.5**	2.6	2.1	3.7
Protein (kg)	-13.3	-14.1	-10.0**	-7.6	-8.5	-6.4*
Multiparous						
n	827	431	399	827	431	399
Final 100 DIM divided by initial 100 DIM						
Milk	0.761	0.762	0.704**	0.741	0.743	0.705**
Fat	0.808	0.807	0.753**	0.766	0.774	0.743**
Protein	0.835	0.825	0.778**	0.811	0.814	0.782**
Initial 100 DIM minus final 100 DIM						
Milk (kg)	1,252.9	1,156.7*	1,435.5**	1,366.7	1,263.4*	1,438.2
Fat (kg)	35.6	34.4	44.2**	45.0	41.8*	47.4
Protein (kg)	25.6	27.5	33.9**	29.8	29.3	33.7**

[1]MO×VR/HO = Montbéliarde × Viking Red/HO, VR×MO/HO = Viking Red × Montbéliarde/HO.
**P* < 0.05, ** *P* < 0.01 for difference of crossbred from Holstein cows.

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