Analysis of Factors Affecting Daily Milk Yields: An Initial Case Study in an Automatic Thrice-Milking Farm

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Abstract

The methodologies and parameters for estimating daily milk yields in the United States were mainly developed from the 1960s through the 1990s. A recent initiative by the Council on Dairy Cattle Breeding, USDA Animal Genomics and Improvement Laboratory, and the National Dairy Herd Improvement Association aims to update these methods and parameters for estimating daily yields by collecting and analyzing milking data from dairy farms. This study, serving as an initial case study, examined the factors influencing daily milk yield estimation at a dairy farm in New York State and compared the performance of the existing method with a recently proposed one. In total, 63,562 milking data were extracted from approximately 2,200 cows milked thrice daily in this farm. Data cleaning eliminated incomplete or missing records, retaining 47,670 entries from 1,869 cows for subsequent analyses. The average partial yields in kilograms (milking interval time in hours) of the three milkings were 14.6, 16.5, and 13.8 (7.88, 8.79, and 7.25), respectively. Analysis of variance based on an extended version of the Wiggans (1986) model revealed significant effects of milking interval time and months in milk on proportional daily milk yields. The lactation effects on proportional daily yields were significant for the first two milkings but not for the third milking. Nevertheless, the relative importance of milking interval time and lactations was very low. The polynomial-interaction-regression model analysis showed significant effects from partial yields and significant interactions between partial yields and milking interval times on daily yields. The latter model gave more accurate estimates than the Wiggans (1986) model. Regarding the relative predictability of the three milkings, the 2nd milkings, having the longest average milking interval time, gave more accurate estimates than the 1st and 3rd milkings. The calculated multiplicative correction factors in this farm increased slightly for the 1st milkings and remained roughly comparable (or slightly decreased) for the 2nd and 3rd milkings compared to the Wiggans (1986) assessment. These results revealed only minor changes in daily yield correction factors over the past four decades.

Keywords: accuracy, dairy cattle, milking interval time, interactions, lactation, test-day

Introduction

The 1960s witnessed a significant shift in milk testing in the United States. Previously, farms followed a rigorous schedule of twice-daily milk tests conducted under supervision every month. This system then shifted towards more economical sampling methods to reduce the costs associated with supervisory visits by the Dairy Herd Improvement Association (**DHIA**). Test frequencies are often adopted to align with varied herd management practices. On a test day, a cow is usually milked two or more times daily, but not all milkings were recorded. One prevalent technique is the morning and evening (**AM-PM**) method, which alternates between morning and evening milking throughout the lactation period (Porzio, 1953). Then, the total daily milk yield (**DMY**) was estimated by doubling the yield of a single milking, assuming equal length and rate of milk production on both sessions, each lasting precisely 12 hours. In the case of unequal morning and evening milking intervals, the biases are assumed to be offset by complementary unevenness between AM and PM milkings. However, these assumptions do not hold in reality. Morning milking intervals tend to be longer than afternoon milking intervals. Hence, AM milk yields are usually higher than PM milk yields (Putnam and Gilmore, 1970).

Various statistical approaches have been developed to estimate daily milk yields from incomplete milking data (reviewed by Wu et al., 2023a,b). The methodologies and parameters for estimating DMY in the United States were primarily developed from the 1960s through the 1990s. A recent initiative by the Council on Dairy Cattle Breeding, USDA-AGIL, and the National DHIA seeks to update these methods and parameters for estimating DMY by collecting and analyzing milking data from dairy farms. This study represented an initial case study amid ongoing or planned data collection at other locations. We examined the factors influencing DMY estimation at a specific site, Farm 1 in New York State, and compared the performance of the existing method with a recently proposed one for estimating daily DMY.

Materials and Methods

Milking data

We extracted 63,562 milking data from Farm 1, representing thrice-milkings daily for around 2,200 Holstein cows. Milkings were collected and weighed at all three milkings for 18 weeks, starting May 5 and ending September 1, 2023. After that, three-day monthly milking data collections were carried out up to 305 days of milk and beyond. Milking times are 4am-12pm (1st milking), 12pm-8pm (2nd milking), and 8pm-4am (3d milking). Milk yields and timestamps were extracted from BouMatic parlor software (https://boumatic.com/us_en/). Records with incomplete and missing data were removed. Milking records with prolonged lactation beyond 305d for up to one more month were retained. Records with days in milk greater than 335 days, approximately accounted for 0.6% of the milking records, were excluded. After data cleaning, we retained 47,670 milking records representing 1,869 cows. The cleaned data represented up to nine lactations (Figure 1), with 64.0% from the first two lactations and 97.1% from the first five lactations. Milking records from lactation six and beyond, accounting for 2.9%, were pooled. Around 74.1% of the cleaned milking records were collected before 156 days in milk, and around 95.5% were collected before 250 days.

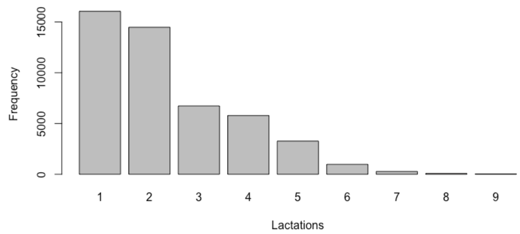

Figure 1. Distribution of milking records by lactation

Statistical methods

Two statistical models are defined. Firstly, for the i-th animal, a proportional DMY ($\frac{x_{ijl}}{y_{ijl}}$) is assumed to be a linear function of milking interval time (t_{ijl}), months in milk (m_j), lactations (γ_l), and a residual term (ε_{ijl}).

$$\frac{x_{ijl}}{y_{ijl}} = \alpha + \beta t_{ijl} + m_j + \gamma_l + \varepsilon_{ijl} \qquad (1)$$

The above model expands the Wiggans (1986) model by additionally including the categorical effects due to lactations and months in milk.

MCF are derived for milking interval classes, each spanning 30 minutes while accounting for the average months in milk and lactation effects:

$$F_k = \frac{1}{\hat{\alpha} + \hat{\beta}\bar{t}^{(k)} + \bar{m} + \bar{\gamma}} \qquad (2)$$

where $\bar{t}^{(k)}$ is the average milking interval time for the k-th milking interval class, and $\bar{m}$ and $\bar{\gamma}$ are weighted averages for estimated months in milk and lactation effects, respectively. Omitting these two effects in (1) reduces the model to the original Wiggans (1986) model, with MCF calculated as follows:

$$F_k = \frac{1}{\hat{\alpha}+\hat{\beta}\bar{t}^{(k)}} \quad (3)$$

Hence, a DMY is estimated as follows:

$$\hat{y}_{ijl(k)} = F_k x_{ijl(k)} \quad (4)$$

The second model accounts for the interactions between partial yields and milking interval time in linear linear and quadratic terms, as follows:

$$\begin{aligned} y_{ijl} &= (b_0 + b_1 t_{ijl} + b_2 t_{ijl}^2) x_{ijl} + m_j + \gamma_l + \epsilon_{ijl} \\ &= b_0 x_{ijl} + b_1 (t_{ijl} x_{ijl}) + b_2 (t_{ijl}^2 x_{ijl}) \\ &\quad + m_j + \gamma_l + \epsilon_{ijl} \quad (5) \end{aligned}$$

This model is referred to as the polynomial-interaction regression (PIR) model. MCF are derived pertaining to a specific milking interval time t,

$$F_t = \hat{b}_0 + \hat{b}_1 t + \hat{b}_2 t^2 \quad (6)$$

In the above, the MCF at time t can be viewed as a baseline MCF, $F_0 = \hat{b}_0$ and adjusted according to the milking interval time, $\Delta_t = \hat{b}_1 t + \hat{b}_2 t^2$.

Then, a DMY is estimated as follows:

$$\hat{y}_{ijl} = F_{t=t_{ijl}} x_{ijl} + \hat{m}_j + \hat{\gamma}_l \quad (7)$$

Here, $F_{t=t_{ijl}}$ stands for a MCF on specific milking interval time t, assigned to all animals satisfying $t_{ijl} = t$.

Accuracy measures

The accuracy of estimated DMY was evaluated based on two criteria: correlation and R^2 accuracy. The former is the correlation between estimated and actual DMY. The R^2 accuracy is the following:

$$R^2 accuracy = \frac{Var(y)}{Var(y)+MSE} \quad (8)$$

where $Var(y)$ is actual phenotypic variance, and MSE stands for mean squared errors.

Analysis of variance (ANOVA) was conducted based on each of the two models separately. The importance of predictor variables was assessed by the Lindeman, Merenda, and Gold (LMG) metric of R squared (Lindeman et al., 1980), which measures the contribution of each predictor to the R-squared value, averaged over all possible orders of entering the predictors into the regression model. The confidence intervals for relative importances were obtained via 1000 bootstrap samples of the LMG R^2.

Results & Discussions

Milking data summary statistics

Overall, the mean (95% Confidence interval) of test-day milk yields was 45.0 (28.6 ~ 62.8) kg. Across lactations, the average test-day milk yield increased from 38.1 kg on the first lactation to 47.2 kg on the second lactation 2, peaked (49.9 kg) on lactation 3, and then began to drop on lactation four and beyond, from 49.7 kg (lactation 4) to 48.8 kg (lactation 6+) (Figure 2; upper).

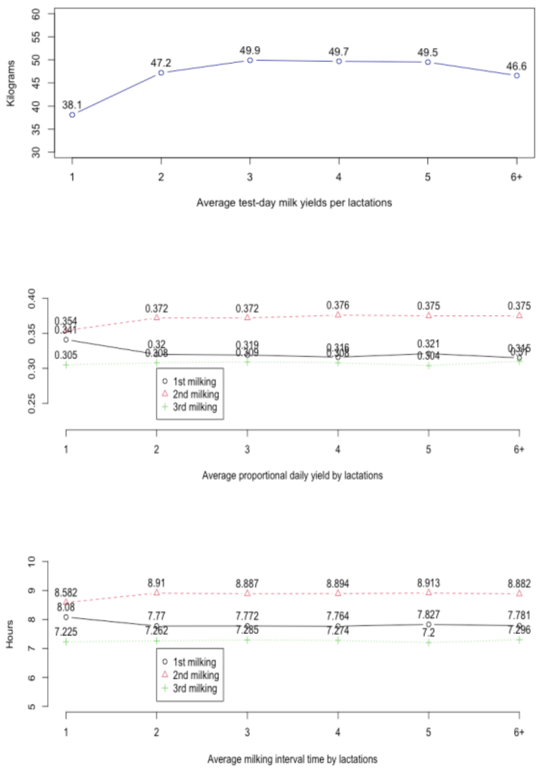

Figure 2. Trends of changes by lactations in average test-day milk yield (upper), average proportional daily yields (middle), and average milking interval time (bottom).

Average proportional daily yields showed slight variations between lactations, except lactation 1 (Figure 2; middle). The pattern agreed with the changes in the average milking interval times for the three milkings across the lactations (Figure 2; bottom). Proportional daily milk yields are primarily determined by the milking interval time. Assuming consistent milking interval time across lactations, common yield correction factors are arguably plausible.

Overall, average proportional daily milk yields varied substantially between the three milkings (Figure 2; middle). The first milkings had the largest average proportional daily milking yield across lactations (0.35 – 0.38), followed by the third milkings (0.32 – 0.34); the second milkings had the least average proportional daily milk yield (0.31). The substantial differences in proportional daily yields were attributed to varied milking interval times for the three milkings (Figure 3; bottom). The average (95% confidence interval) of milking interval time was 8.79 (7.84-9.75) hours, 7.25 (6.39-8.07) hours, and 7.88 (7.06-8.81) hours, respectively, for the three milkings. On average, the first milking interval time was approximately 1 hour longer than the third and 1.5 hours longer than the second. Nevertheless, the average milking interval time varied very slightly between lactations, except for lactation one. Approximately the first milking interval time was 8.6 hours for lactation 1 and 8.9 hours for lactations 2 through 6+; the second milking interval time was 8.1 hours for lactation 1 and 7.8 hours for lactations 2 through 6+; the third milking interval time was 7.3 hours for lactation 1 and 7.3 hours (Figure 3; bottom). In accordance with the lengths of milking interval time, the first milkings had the largest average DMY (16.5 kg), followed by the third milkings (14.6 kg); the third milkings had the lowest average DMY (13.8 kg).

Relative importance of predictor variables

Analysis of variance based on model (1) showed significant effects of milking interval time (Pr <2.20e-16 for all three milkings), months in lactation (Pr = 0.0008 for 1st milkings; Pr = 2.52e-10 for 2nd milkings; Pr = 0.0001 for 3rd milkings), parities (Pr <2.20E-16) on proportional DMY. ANOVA based on the PIR model (5) revealed significant effects from partial milk yields (Pr < 2.20e-16), months in milk (Pr < 2.20e-16), and parities (Pr < 2.20e-16) on DMY. The results also showed significant interactions between partial yields and linear milking interval times (Pr < 2.20e-16) on DMY and significant interaction effects between partial yields and quadratic milking interval time for 1st milkings (Pr = 9.42e-08) and 3rd milkings (Pr = 1.03e-11) but not significant for the 2nd milkings (Pr = 0.1785) on DMY. These significant interaction effects justified using PIR models in the present study.

Table 1 presents the relative importance of predictor variables for two models in estimating daily milk yields across three different milkings (1st, 2nd, and 3rd). The values provided are the means and 95% confidence intervals of the LMG R^2, which measure the proportion of variance explained by each predictor. For the proportional DMY Model (1), milking interval time was the most significant predictor, with relatively high mean importance values across all milkings (0.157, 0.135, 0.159); months in milk had very low importance, indicating it contributes minimally to explaining the variance in DMY (0.002, 0.004, 0.002); Lactations also had a minor contributor, with slightly higher values than months in milk but still low (0.040, 0.032, 0.001). The low importance of months in milk and lactations agrees with the Wiggans (1986) model, which ignores these variables. Nevertheless, the total relative importance sums to around 0.199 for the 1st milking, 0.170 for the 2nd milking, and 0.148 for the 3rd milking, suggesting that the predictors in this model together explain only a low to modest portion of the variance in daily milk yields. There may be other significant variables influencing proportional DMY that have not yet been identified.

For the PIR model, partial yields were the most significant predictor, with consistently high importance across all milkings (0.285, 0.280, 0.274). The interactions between partial yields and linear and quadratic milking interval time also had a major contributor, with substantial mean importance values (0.226, 0.244, 0.225) for the interaction with a linear milking interval time and also notable mean importance values (0.158, 0.199, 0.172) for the interaction with quadratic milking interval time. Months in milk showed higher importance in the PIR Model (5) compared to the proportional DMY Model (1), but still relatively low (0.022, 0.021, 0.020). The relative importance of lactations varies more across milkings, with higher values in the 1st and 3rd milkings compared to the 2nd (0.129, 0.083, 0.101). The total relative importance sums to 0.820 for the 1st milking, 0.830 for the 2nd milking, and 0.790 for the 3rd milking, indicating that the PIR Model predictors together explain a much larger portion of the variance in daily milk yields compared to the proportional DMY model. However, both results are not directly comparable because they modeled different quantities. The dependent variable in the former model was proportional DMY, whereas it was DMY in the latter model.

Table 1. Relative importance (mean and 95% of IMG R^2) of predictor variables in two models [1]

Predictors	1st milking			2nd milking			3rd milking		
	Mean	Q2.5%	Q97.5%	Mean	Q2.5%	Q97.5%	Mean	Q2.5%	Q97.5%
Model 1									
MIT	0.157	0.145	0.171	0.135	0.121	0.149	0.159	0.146	0.172
MIM	0.002	0.001	0.004	0.004	0.003	0.007	0.002	0.002	0.005
LACT	0.040	0.035	0.046	0.032	0.026	0.037	0.001	0.001	0.003
Sum	0.199			0.170				0.148	
Model 2									
PY	0.285	0.280	0.290	0.280	0.276	0.284	0.274	0.269	0.279
TAR1	0.226	0.222	0.230	0.244	0.240	0.247	0.225	0.222	0.229
TAR2	0.158	0.154	0.162	0.199	0.196	0.202	0.172	0.168	0.175
MIM	0.022	0.020	0.025	0.021	0.019	0.024	0.020	0.018	0.023
LACT	0.129	0.124	0.133	0.083	0.080	0.086	0.101	0.096	0.106
SUM	0.82			0.83			0.79		

[1] MIT = milking interval time; MIM = months in milk; LACT = lactations; PY = partial yields (1st, 2nd, or 3rd); TAR1 = interaction between PY and linear MIT; TAR2 = interaction between PY and quadratic MIT.

Accuracy of estimated daily milk yields

Table 2 compares the accuracy of estimated daily milking yields using two models, each under two scenarios. The scenarios differed based on whether the effects of months in milk and lactation were accounted for. GW1 and PIR1 did not include the variables for months in milk and lactations, whereas GW2 and PIR2 accounted for their effects. The accuracy is measured by the correlation between estimated and actual daily milk yields, the R^2 accuracy, and the K value, which is the ratio of the estimated daily milk yields over the variance of actual daily milk yields.

The Wiggans (1986) models, GW1 and GW2, showed roughly similar performance with slight differences in correlations, R^2 accuracies, and K values. Both models tend to overestimate the variance ($K > 1$). The PIR1 and PIR2 models generally had a higher correlation and R^2 accuracies than GW1 and GW2, indicating they provide more accurate estimates of daily milk yields than the current method. Compared to the GW models, PIR1 had around 1-2% increase in R^2 accuracy, and PIR2 had around a 4-6% increase in R^2 accuracy. The PIR models derived continuous yield correction factors, which remedies the biases with discrete yield correction factors, and consider possible interactions. Nevertheless, these two PIR models performed differently on the variance of estimated DMY. PIR1 gave an overestimated variance of estimated DMY, whereas PIR2 led to a smaller variance of DMY than the actual daily milk yield variance. Generally speaking, the estimates from a linear regression tend to have a smaller estimate variance than the actual variance because the residuals are excluded. However, PIR1 was defined without intercept.

When fitting linear regression models, the inclusion or exclusion of an intercept has a significant impact on the variance of the predicted values. The intercept in a regression model captures the average expected value of the dependent variable when all predictor variables are at zero (assuming zero is within the range of normal values for these predictors).

Table 2. Accuracy metrics of estimated daily milking yields using the Wiggans (1986) (GW) and the polynomial-interaction-regression (PIR) models [1,2]

Methods	1st milking			2nd milking			3rd milking		
	Corr	R^2	K	Corr	R^2	K	Corr	R^2	K
Before variance rescaling									
GW1	0.880	0.781	1.237	0.901	0.809	1.253	0.875	0.769	1.285
GW2	0.879	0.791	1.152	0.902	0.801	1.3207	0.875	0.769	1.283
PIR1	0.883	**0.800**	1.205	0.903	**0.815**	1.2277	0.877	**0.777**	1.249
PIR2	0.906	**0.847**	0.821	0.909	**0.852**	0.8278	0.889	**0.827**	0.792
After variance rescaling									
GW1	0.880	0.806	1.000	0.901	0.835	1.000	0.875	0.800	1.000
GW2	0.879	0.806	1.000	0.902	0.836	1.000	0.875	0.800	1.000
PIR1	0.883	**0.811**	1.000	0.903	**0.837**	1.000	0.877	**0.803**	1.000
PIR2	0.906	**0.841**	1.000	0.909	**0.847**	1.000	0.889	**0.819**	1.000

[1] Corr = correlation; R2 = R2 accuracy; K = ratio of estimated versus actual daily milk yield variance.
[2] GW1, PIR1 = Omitting months in milk and lactations; GW2, PIR2 = These models included the effects of months in milk and lactations.

Including an intercept typically reduces the sensitivity of the model to fluctuations in the data by adjusting the baseline level of the response. This often leads to smaller coefficients for the predictors because the intercept absorbs much of the average outcome, reducing the variability that each predictor needs to explain. Hence, the variance of the predicted values generally reflects more closely the natural variability in the data centered around the mean.

For a model without an intercept, each predictor variable must account not only for the variability related to its specific influence on the dependent variable but also for its overall mean. This often requires larger coefficients, as each predictor must scale more significantly to fit the data points. Because the model without an intercept is overly sensitive to changes in the predictor variables and tends to have larger coefficients, the range of predicted values can be significantly wider. This amplifies the variance of the predictions because the model tries to compensate for the lack of a baseline adjustment by stretching the effect of the predictors to cover all data points. Table 3 shows model parameters for the PIR models. Without accounting for the effects of months in milk and lactations (PIR1), the regression coefficients for partial yields were between 5.19 and 8.36. In contrast, the regression coefficients were substantially smaller (2.78 – 5.97) with the PIR2 model when accounting for the effects due to months in milk and lactations.

PIR2 had a higher R2 accuracy than PIR1 because it accounted for the effects of months in milk and lactation. This is often the case when one or more secondary variables are not randomized in the experimental design, such that deviates due to these differences are not zero. Otherwise, PIR and PIR2 would perform similarly. In contrast, GW1 and GW2 performed similarly, which may suggest that simply accounting for secondary variables by their averages in the Wiggans (1986) is inefficient.

It should be noted that, in PIR2, the effects of the months in milk were estimated for each category, which is inherently related to the overall mean. In other words, though the overall mean was not present in the PIR2 model equation, it was presented via the months in milk effects. Therefore, PIR2 gave a smaller estimate variance than the actual variance.

Variance rescaling brought all K values to 1, indicating that the variance of estimated daily milk yields now matches the actual yields perfectly. Thus, variance rescaling effectively adjusted the variance of estimated yields to match the actual yields, improving the overall accuracy of the models except for PIR2. For PIR2, because the estimated daily yield variance was smaller than the actual variance and because the months in milk and lactation effects were adjusted additively, variance rescaling led to a slight decrease in the accuracy.

Table 3. Model parameters for the polynomial-interaction-regression with and without accounting for the effects due to months in milk and lactations in a thrice-milking dairy farm [1]

Model parameters	1st Milking		2nd Milking		3rd Milking	
	Estimate	SE	Estimate	SE	Estimate	SE
M1a: Excluding the effects due to months in milk and locations						
b_0	8.358	0.353	5.185	0.288	7.554	0.535
b_1	-1.003	0.088	-0.326	0.066	-0.832	0.147
b_2	0.042	0.005	0.005	0.004	0.032	0.010
M1b: Including the effects due to months in milk and lactations						
b_0	5.973	0.290	2.781	0.254	5.313	0.457
b_1	-0.754	0.02	-0.014	0.057	-0.605	0.126
b_2	0.034	0.004	-0.008	0.003	0.025	0.009
m_1	10.49	0.172	10.51	0.170	11.75	0.184
…...						
m_{11}	9.650	0.316	7.892	0.314	10.70	0.340
γ_2	3.563	0.083	1.438	0.084	2.559	0.089
…...						
γ_6	3.897	0.188	1.136	0.186	2.476	0.203

[1] M1a: $y_{ijl} = (b_0 + b_1 t_i + b_2 t_{ijl}^2) x_{ijl} + \epsilon_{ijl}$; M1b: $y_{ijl} = (b_0 + b_1 t_i + b_2 t_{ijl}^2) x_{ijl} + m_j + \gamma_l + \epsilon_{ijl}$

Table 4. Comparison of 3X multiplicative correction factors (MCF) obtained for every 30 minutes based on the present milking dataset and the reference (Ref) MCF for trice-milkings[1,2]

Milking interval time, hrs	1st milking			2nd milking			3rd milking		
	Ref.	GW	PIR	Ref.	GW	PIR	Ref.	GW	PIR
5.75	3.76	4.11	3.98	3.89	3.74	3.48	3.92	3.94	3.83
6.25	3.54	3.81	3.73	3.65	3.53	3.34	3.68	3.69	3.60
6.75	3.34	3.55	3.50	3.45	3.33	3.21	3.47	3.46	3.40
7.25	3.17	3.32	3.29	3.26	3.16	3.08	3.28	3.26	3.20
7.75	3.01	3.11	3.11	3.10	3.01	2.96	3.12	3.08	3.03
8.25	2.87	2.94	2.94	2.95	2.87	2.84	2.96	2.92	2.87
8.75	2.74	2.78	2.80	2.81	2.74	2.72	2.83	2.78	2.72
9.25	2.62	2.63	2.67	2.69	2.62	2.60	2.70	2.64	2.60
9.75	2.51	2.51	2.57	2.57	2.51	2.48	2.59	2.53	2.48
10.25	2.41	2.39	2.49	2.47	2.42	2.37	2.48	2.42	2.39

[1] GW = MCF according to Wiggans (1986); PIR = polynomial-interaction-regression; both models did not account for the effects due to months in milk and lactations.

[2] Reference MCF (Wiggans, 1986): $F_{1st} = \frac{1}{0.077+0.0329t}$; $F_{2nd} = \frac{1}{0.068+0.0329t}$; $F_{3rd} = \frac{1}{0.066+0.0329t}$

In Table 4, multiplicative correction factors (MCF) for three milkings were derived from a historical reference (Wiggans, 1986), and compared to the current results derived by two models (GW and PIR) across milking intervals between 5.75 and 10.25 hours. For the 1st Milkings, the GW and PIR models consistently show higher MCF values than the historical reference across all intervals. For the 2nd and 3rd milkings, MCF derived from the GW and PIR models are slightly lower than the reference. These results indicate minor changes in MCF over the past decades. The PIR model shows a trend towards slightly lower MCF values across all milkings compared to the GW model. The average (range) of the reference MCF (Wiggans, 1986) was 3.00 (2.41 – 3.76) for the 1st milking, 3.08 (2.47 – 3.89) for the 2nd milking, and 3.10 (2.48 – 3.92) for the 3rd milking. Based on the recent milking dataset analyzed by the Wiggans (1986) model, the average (range) of MCF was 3.11 (2.39 – 3.98) for the 1st milking, 2.99 (2.42 – 3.74) for the second milking, and 3.07 (2.39 – 3.83) for the 3rd milking.

Conclusions

In conclusion, this initial case study demonstrated that modeling proportional DMY as a linear function of milking interval time is a valid strategy. The present results have shown that milking interval is the primary predictor for proportional DMY, whereas the effects of months in milk and lactations are considered secondary. Still, other major variables that have not yet been discovered can influence proportional DMY. Still, we have also shown that the polynomial-interaction-regression model can provide more accurate yield estimates than the Wiggans (1986) model. A primary reason was that discrete MCF introduces biases. Besides, precisely adjusting secondary variables with the Wiggans (1986) model is not straightforward. Instead, the new model captures linear and quadratic interactions between partial yields and milking interval times and can naturally accommodate secondary predictor variables. In Farm 1, the second milking had the longest interval and offered the most precise estimates. The calculated MCFs showed only minor deviations over the past four decades despite the significant genetic improvement in daily and lactation yields in the past decades. This result suggests that the proportional daily yields, reciprocal to MCF, remain relatively comparable over the past decades. Finally, this study represents an initial case study, and all the conclusions are subject to large-scale validation.

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