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Net merit as a measure of lifetime profit: 2021 revision

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Overview

The lifetime net merit (NM$) index ranks dairy animals based on their combined genetic merit for economically important traits (Cole et al., 2021). Indexes are updated periodically to include new traits and to reflect prices expected in the next few years. This update of NM$ includes genetic evaluations for the new traits feed saved (FSAV), heifer livability (HLIV), and early first calving (EFC). Selection for these new traits will improve health and growth of calves and feed efficiency of cows.

The new FSAV evaluation includes the economic value of cow body weight composite (BWC) along with actual feed intake data from several thousand Holstein cows in U.S. and Canadian research herds. The trait residual feed intake (RFI) measures the difference of actual and expected feed intake. Relative economic values for BWC and RFI are presented separately because BWC is available for all breeds, whereas FSAV is available only for Holsteins. Now BWC gets more negative emphasis because of larger maintenance costs estimated from actual feed intake data. The −9.4% emphasis on BWC and −3.8% emphasis on RFI combine for +13.2% emphasis on FSAV.

Emphasis on the calving trait subindex (CA$) was reduced in August 2020 when the phenotypic bases and genetic standard deviations (SDs) were reduced for the four calving ease and stillbirth traits that CA$ includes. The CA$ subindex is not published directly. Total costs for six health traits are included in NM$ for Holsteins and Jerseys in the form of a health trait subindex (HTH$) that also is not published separately; the individual economic values within HTH$ have not changed. Emphasis was reduced on udder composite (UDC) because recent gains in udder conformation have reduced the milking labor required and on feet/leg composite (FLC) because the linear traits are not well correlated with hoof health or lameness. Previous indicator traits can be replaced by direct income and expense traits if the indexes include sufficient data for the new traits.

Emphasis on productive life (PL) was increased by accounting for profit from individual lactations instead of assuming constant profit across lactations. Relative emphasis decreased slightly on cow livability (LIV) because death rates and cull cow prices declined. Relative emphasis on most other traits such as daughter pregnancy rate (DPR), cow conception rate (CCR), and heifer conception rate (HCR) decreased because of the inclusion of new traits. Other income or cost variables such as milk prices and feed requirements were updated.

The 2021 and 2018 NM$ (VanRaden et al., 2018) indexes are correlated by 0.992 for young Holstein bulls and 0.981 for recently progeny-tested bulls.

Updated economic values

New economic values for each unit of predicted transmitting ability (PTA) and relative economic emphasis of traits will be implemented in August 2021 for NM$, cheese merit (CM$), fluid merit (FM$), and grazing merit (GM$). Previous versions of NM$ reported relative values using the SD of true transmitting ability (TTA) but now report relative emphasis using the SD of PTA. Relative value shows which traits are most important, whereas relative emphasis shows their contribution given their limited data and prediction reliability (REL) (Zhang and Amer, 2021). Showing relative emphasis helps compare trait contributions to the ranking, whereas relative value better explains each trait's contribution to NM$ REL. This has no effect on the economic values or ranking and little effect on the reported emphasis because most traits have similar RELs, but the relative value of −14% for RFI was equivalent to only −4% relative emphasis because PTA for FSAV and RFI have low SD for young animals due to lower REL. The relative emphasis was calculated for young animals; progeny-tested bulls and cows have differing REL and emphasis. Previously reported relative values are not directly comparable with the new relative emphasis values below.

The traits are now displayed in the historical order that they were included in NM$:

Trait	Units	SD	Value ($/PTA unit)				Relative emphasis (%)			
			NM$	FM$	CM$	GM$	NM$	FM$	CM$	GM$
Milk	Pounds	567	0.002	0.142	−0.015	0.002	0.3	21.9	-2.2	0.3
Fat	Pounds	25	4.18	4.18	4.18	4.41	28.6	28.3	27.2	27.6
Protein	Pounds	15	4.67	0.00	5.23	4.92	19.6	0.0	20.9	18.9
PL	Months	1.7	34	34	34	16	15.9	15.7	15.1	6.9
SCS[1]	Log	0.14	−74	−42	−95	−78	−2.8	−1.6	−3.5	−2.8
BWC	Composite	0.76	−45	−45	−45	−57	−9.4	−9.3	−8.9	−10.9
UDC	Composite	0.65	19	19	19	23	3.4	3.4	3.2	3.8
FLC	Composite	0.53	3	3	3	3	0.4	0.4	0.4	0.4
DPR	Percent	1.4	11	11	11	34	4.1	4.1	3.9	11.7
CA$	Dollars	10.41	1	1	1	1	2.9	2.8	2.7	2.6
HCR	Percent	1.3	1.1	1.1	1.1	2.3	0.4	0.4	0.4	0.7
CCR	Percent	1.6	2.2	2.2	2.2	6.9	1.0	1.0	0.9	2.8
LIV	Percent	1.6	9.8	9.8	9.8	8.0	4.4	4.3	4.2	3.3
HTH$	Dollars	4.54	1.0	1.0	1.0	1.2	1.2	1.2	1.2	1.4
RFI	Pounds	46.2	−0.30	−0.30	−0.30	−0.36	−3.8	−3.8	−3.6	−4.2
EFC	Days	2.05	2.1	2.1	2.1	1.7	1.2	1.2	1.1	0.9
HLIV	Percent	0.4	5.0	5.0	5.0	4.1	0.5	0.5	0.5	0.4

[1]SCS = somatic cell score

The SDs listed above are for PTAs of young bulls, whereas previous versions listed TTAs for a hypothetical unselected population. The SDs of TTAs for NM$, CM$, and FM$ are all estimated to be $234 and larger than the $197 for 2018 indexes (VanRaden, 2018), mainly because of the increased genetic variance from FSAV, decreased marginal feed needed for extra yield, and higher value of PL. The SDs for GM$ would be larger because of longer PL in grazing herds, except that milk yield differences are often reduced in such herds. Economic values in GM$ are rescaled to make the SDs equal to the other indexes.

An economic value is the added profit caused when a given trait changes by 1 unit and all other traits in the index remain constant. For example, an economic value for protein is determined by holding pounds of milk and fat constant and examining the increase in price when milk contains an extra pound of protein. The genetic merit for each trait of economic value ideally should be predicted from both direct and indirect measures. Multitrait methods currently are used within the trait groups of conformation, fertility, and PL with LIV. The economic value of a trait may change when other correlated traits are added to the index. Selection of animals to be parents of the next generation is most accurate when all traits of economic value are included in the index. Selection for some traits measuring efficiency, longevity, or disease resistance may have additional benefits to consumers but only the direct benefits for herd profit are considered in the economic math.

Relative values for each trait expressed as a percentage of total selection emphasis are obtained by multiplying the economic value by the SD for TTA and then dividing each individual value by the sum of the absolute values. The SDs differ slightly among breeds and are set to 0 for traits not evaluated for individual breeds. Economic values are derived using trait averages for Holsteins, and missing traits such as RFI are assumed to be 0 for other breeds. That increases relative values of other traits for those breeds because relative values sum to 100%.

Holsteins are evaluated for all major traits, but feed intake, health, stillbirth, and calving ease are not evaluated in some or all other breeds. Two new genomic predictions introduced in December 2020 for the traits milking speed for Brown Swiss and rear teats (side view) for Jerseys are not evaluated for Holsteins. They are included in NM$ via breed-specific type composites. Relative economic values for NM$ traits within each breed follow using the subset of traits and genetic SDs specific to that breed’s evaluation:

Trait	Ayrshire	Brown Swiss	Guernsey	Holstein	Jersey	Milking Shorthorn
Milk	0.3	0.3	0.3	0.3	0.3	0.3
Fat	25.2	24.0	24.1	21.8	27.0	25.2
Protein	21.5	21.5	20.8	17.0	23.1	21.5
PL	19.6	22.4	20.2	15.1	19.7	19.6
SCS	−3.9	−3.8	−3.9	−2.9	−3.1	−3.9
BWC	−11.4	−7.2	−12.5	−9.4	−5.6	−11.4
UDC	4.7	3.4	2.8	3.1	2.6	4.7
FLC	0.6	0.5	0.6	0.5	0.5	0.6
DPR	6.0	6.4	6.1	5.0	6.9	6.0
CA$	0.0	1.9	0.0	2.8	0.0	0.0
HCR	0.7	0.7	0.6	0.5	0.7	0.7
CCR	1.4	1.5	1.6	1.2	1.6	1.4
LIV	3.5	4.8	5.4	4.3	4.4	3.5
HTH$	0.0	0.0	0.0	1.7	2.1	0.0
RFI	0.0	0.0	0.0	-12.4	0.0	0.0
EFC	1.3	1.4	1.2	1.1	1.4	1.3
HLIV	0.0	0.0	0.0	0.8	1.0	0.0

NM$ calculation

Calculation of NM$ and its REL can be demonstrated using the following example Holstein:

Trait	Example PTA	Example REL (%)
Milk	+2,073	96
Fat	+114	96
Protein	+70	96
PL	+5.1	83
SCS	2.90 (−3.00)	90
BWC	−1.49	95
UDC	+0.76	95
FLC	+0.58	93
DPR	−0.1	79
CA$	+27	93
HCR	+0.7	82
CCR	+1.4	78
LIV	+0.9	74
HTH$	+11	61
RFI	+21	20
EFC	+4.4	72
HLIV	+1.1	55

The PTAs for each trait are multiplied by the corresponding economic value and then summed. For Holsteins, the BWC and RFI are already combined into FSAV using the math and economic value in the feed saved section. For the example bull, FSAV is 205 with 47% REL. A value of 3 must be subtracted from PTA for SCS, which originally was the phenotypic mean of SCS and is still used as the base for all breeds. After that subtraction and combining all traits, the NM$ for this example bull is $1130, FM$ is $1090, CM$ is $1136, and GM$ is $1105.

Calculation of NM$ also can be expressed in matrix form:

$$\textbf{NM\$} = \mathbf{a}'\mathbf{u},$$

where vector **a** contains each trait's economic value and vector **u** contains each trait's PTA. The average of 3.00 for SCS is removed from the corresponding element of **u**.

The REL of NM$ is computed using matrix algebra from REL of each trait and genetic correlations among the traits. The NM$ REL is the variance of predicted NM$ divided by the variance of true NM$:

$$\textbf{REL NM\$} = \mathbf{r}'\mathbf{G}\mathbf{r}/\mathbf{v}'\mathbf{G}\mathbf{v},$$

where **r** contains the relative economic values multiplied by the square root of REL for each PTA trait, **G** contains the genetic correlations among the traits, and **v** contains the relative economic values for the traits. For the example bull, REL is 85%. This is less than the 91% REL reported with the 2018 NM$ formula because FSAV has high value but lower REL than previously selected traits.

Trait parameters

Genetic correlations among all traits and composites were estimated from correlations among PTAs of Holstein bulls with high REL because restricted maximum-likelihood estimates were not available between all traits. Genetic and phenotypic correlations for each of 24 PTA traits and composites are provided in a supplemental table \\10.19.53.11\data-m\PAUL\misc\NMcorrelations.txtfor Holsteins along with SDs of TTAs and heritabilities for each breed.

Expected genetic progress

Correlations of PTAs for each trait with NM$, FM$, CM$, and GM$ were obtained from young Holstein bulls born in 2019. The expected PTA progress was obtained as the correlation of PTA with NM$ multiplied by the PTA SD multiplied by 0.35, which is the expected annual trend in SD of NM$. The PTA SDs generally are lower than the TTA SDs because of selection and because RELs are less than 1. Genetic trend (change in breeding value) equals twice the expected progress for PTA. Thus, multiplication of annual PTA gain by 20 gives expected genetic progress per decade.

Expected progress in actual units and correlations with NM$ based on the 2018 formula (VanRaden et al., 2018) are shown for comparison:

	Correlation of PTA with index					Expected genetic progress from NM$		
PTA trait[1]	2018 NM$	2021 NM$	2021 FM$	2021 CM$	2021 GM$	2018 NM$ PTA change/year	2021 NM$ PTA change/year	2021 NM$ breeding value change/decade
Milk	0.60	0.64	0.71	0.62	0.60	119.04	126.98	2,539.62
Fat	0.91	0.88	0.86	0.88	0.87	7.92	7.66	153.26
Protein	0.82	0.83	0.83	0.83	0.81	4.38	4.44	88.72
PL	0.80	0.82	0.82	0.83	0.82	0.48	0.49	9.76
SCS	−0.38	−0.37	−0.36	−0.38	−0.35	−0.02	−0.02	−0.36
BWC	−0.20	−0.28	−0.31	−0.27	−0.30	−0.05	−0.07	−1.49
UDC	0.41	0.35	0.34	0.36	0.34	0.09	0.08	1.59
FLC	0.22	0.16	0.14	0.16	0.14	0.04	0.03	0.59
DPR	0.05	0.06	0.03	0.06	0.14	0.02	0.03	0.58
CA$	0.63	0.63	0.62	0.63	0.64	2.30	2.30	45.91
HCR	0.34	0.33	0.33	0.34	0.37	0.15	0.15	2.93
CCR	0.25	0.27	0.25	0.28	0.34	0.14	0.15	3.08
LIV	0.41	0.44	0.42	0.44	0.44	0.23	0.25	4.99
GL	−0.32	−0.34	−0.33	−0.34	−0.34	−0.12	−0.13	−2.62

PTA trait[1]	Correlation of PTA with index					Expected genetic progress from NM$		
	2018 NM$	2021 NM$	2021 FM$	2021 CM$	2021 GM$	2018 NM$ PTA change/year	2021 NM$ PTA change/year	2021 NM$ breeding value change/decade
HTH$	0.62	0.61	0.59	0.62	0.61	0.99	0.97	19.39
RFI	−0.05	−0.12	−0.12	−0.12	−0.12	−0.81	−1.94	−38.81
MFEV	0.22	0.21	0.20	0.22	0.21	0.01	0.01	0.13
DA	0.61	0.62	0.62	0.62	0.61	0.06	0.07	1.30
KETO	0.75	0.74	0.72	0.75	0.74	0.15	0.15	2.95
MAST	0.26	0.25	0.23	0.26	0.24	0.11	0.11	2.10
MET	0.47	0.46	0.45	0.46	0.48	0.09	0.09	1.77
RETP	0.02	0.02	0.02	0.02	0.03	0.00	0.00	0.03
EFC	0.43	0.45	0.46	0.45	0.46	0.31	0.32	6.46
HLIV	0.63	0.62	0.62	0.62	0.60	0.08	0.08	1.56

[1]DA = displaced abomasum, KETO = ketosis, MAST = clinical mastitis, METR = metritis, MFEV = milk fever (hypocalcemia), REPL = retained placenta

Derivation of economic values

Prices, math, and assumptions used in deriving economic values are shown below for FSAV, HLIV, EFC, health traits, fertility traits, yield traits, SCS, PL and LIV, and type traits. Economic values for most traits in CM$, FM$, and GM$ are the same as in NM$. Primary differences in economic values for grazing versus confinement herds are 2.5 times higher value of fertility to maintain seasonal calving, 15% less production per lactation but 50% more lactations, 25% less death loss, and 25% less MAST incidence (Gay et al, 2014).

Feed saved

The 2021 NM$ includes actual feed intake data instead of only expected feed intake based on correlated traits. Since 1994, NM$ has subtracted the expected feed costs associated with milk, fat, and protein yields, and since 2000 also expected feed costs associated with BWC. The subtraction to calculate net instead of gross income was the main reason for the word “net” in NM$. Evaluations for RFI (the difference between actual and expected intake) are computed from research herd data (Li et al., 2020) and expressed in pounds of dry matter intake (DMI) per lactation. Cost reductions due to less actual than expected intake and those associated with lower BWC are now combined for Holsteins into FSAV with positive values favorable. The PTAs for BWC contribute more than RFI to FSAV because of higher REL, and correlations with FSAV are −0.83 for BWC and −0.37 for RFI. The PTA and REL for FSAV formulas were revised slightly since December and are calculated as:

$$\text{PTA FSAV} = -1(\text{PTA RFI}) - 151.8(\text{PTA BWC});$$
$$\text{REL FSAV} = 0.633(\text{REL RFI}) + 0.367(\text{REL BWC}).$$

For other breeds, NM$ continues to include the costs for BWC but not RFI or FSAV until feed data become available for those breeds.

Maintenance

Large cows and bulls were favored by dairy cattle breeders for many years, but many research studies concluded that cow size should have negative value in an index because milk income already was accounted for, but feed costs were not. Feed costs are the largest cost of producing milk and currently are assumed to average 32% of the value of extra production plus 15% for cow maintenance for a total of 47% of the income from milk produced. Higher producing cows use a smaller percentage of feed for maintenance and thus are often more profitable.

Incomes and expenses assigned to BWC include the cost of extra feed eaten by heavier cows for body maintenance, marginal cost of growing larger replacements ($0.75/pound), growth cost from replacement to mature weight ($0.50/pound), extra beef income from heavier cull cows ($0.60/pound), income from heavier calf weights (0.06 pounds/pound of cow weight), and increased housing costs for larger cows ($0.04/pound of cow weight/lactation). Maintenance is the main cost because heifer growth cost and cull value largely cancel out.

Maintenance feed intake is being increased by the NRC (National Research Council, 2021) from 0.08 to 0.10 Mcal of net energy of lactation (NE_L) per kilogram of metabolic body weight (MBW) calculated as $(BW)^{0.75}$. Typical NE_L value of diets is around 1.6 Mcal/kg DMI. Maintenance requirement is then 0.10/1.6 = 0.063 kg DMI/$(\text{kg BW})^{0.75}$. Within the normal BW range (550–850 kg), an increase in 1 kg of MBW translates into approximately a change of 6.67 kg in BW. Daily maintenance requirements expressed on a BW basis should be 0.063/6.67 = 0.0094 kg DMI/kg BW. Across an entire lactation and converting kilograms to pounds for both DMI and BW gives 365(0.0094) = 3.4 pounds of DMI/pound BW/lactation according to the NRC.

Maintenance costs were also estimated from 6,345 research cows by regressing DMI kg/day on phenotypic BW, genetic BWC, or sire BWC. Conversion from daily to lactation basis assumed 305 days/lactation analogous to yield traits plus 60-day dry periods. Because cows are sold after their final lactation, the actual number of dry periods is always 1 less than the number of lactations, which is now 2.69. Days of maintenance/lactation could be set to 305 + 60(1.69)/2.69 = 343 but was assumed to be 365 for simplicity.

Phenotypic regression on MBW gave 0.107 kg DMI/day, which converted using the same math as above to 5.9 pounds of DMI/pound BW/lactation and is much higher than the National Research Council estimate of 3.4. Genomic regression on BWC gave 0.238 kg DMI/day; multiplying by 365 and dividing by 15.7 to convert BWC to BW gives 5.5 pounds, which is nearly the same as for phenotypic regression. Sire regression on BWC gave 0.128 kg DMI/day, which was about half the regression on cow estimated breeding value as expected. Multiplying by 2 and 365 and dividing by 15.7 gives 6.0 pounds DMI/lactation, which agrees with estimates from cow's phenotype or genotype.

Estimates of lactation maintenance and their standard errors based on data from the Council on Dairy Cattle Breeding (Bowie, MD) are summarized:

Estimate	Maintenance (pounds DMI/pound BW)	Standard error
NM$ previous value	1.7	...
NRC 2001 value	2.7	...
NRC 2021 value	3.4	...
Phenotypic regression	5.8	±0.2
Genomic regression	5.5	±0.4
Sire genomic regression	5.9	±0.5
NM$ new value from averaging NRC 2021 value and new regressions	4.5	...

The 4.5 pounds DMI/lactation multiplied by 35 pounds BW/unit of BWC convert to 157.5 pounds DMI/1 point BWC. The other lifetime incomes and expenses convert to −5.7 pounds DMI/1 point BWC for a net of 151.8. The economic value in NM$ is then 151.8(2.69 lactations)($0.11/pound DMI) = −$45. The much higher cost of maintenance in NM$ is counteracted somewhat by the reduced estimate of 35 instead of 40 pounds BW/BWC as defined in the type traits section. The direct selection emphasis in NM$ is now 9.4% against BWC, which is included in FSAV for Holsteins.

Feed cost for yield components

Feed intakes associated with each milk component were also examined from U.S. research herd data. Several methods to estimate feed costs for milk components each gave differing costs, especially for fat yield. Feed required for milk, fat, and protein from phenotypic and genetic regressions and the total dollar value of feed eaten to produce an additional 100 pounds of standardized milk with 3.5% fat and 3.0% protein are compared:

Method	Marginal feed cost ($)/ 100 pounds standardized milk	DMI (pounds) required per unit of component output					
		Milk	Milk standard error	Fat	Fat standard error	Protein	Protein standard error
Phenotypic regression	2.92	0.007	±0.08	2.82	±0.13	5.32	±0.31
Genomic regression	7.60	0.076	±0.03	10.82	±0.60	7.88	±1.34
Sire regression × 2	5.13	0.043	±0.05	6.43	±1.14	6.66	±2.35
NM$ 2018	7.25	0.225	...	5.42	...	7.50	...
NM$ 2021	5.23	0.120	...	5.00	...	6.00	...
Theoretical (Dado et al. 1994)	5.63	0.112	...	4.42	...	8.17	...
ECM[1] (National Research Council, 2001)	4.14	0.122	...	4.82	...	2.85	...

[1]Energy-corrected milk

The genomic regressions used 305-day yields in pounds to predict daily DMI kg and were multiplied by 305 and 2.2 to match the units. The sire regressions were further multiplied by 2 because sires contributed only half the genes.

Phenotypically, much more feed was needed to produce protein than to produce fat. Total feed cost from the phenotypic regressions were only $2.92/100 pounds of standardized milk, which seems too low compared with a milk income of $16.50. The low estimate from phenotypic regression of DMI on the cow's own fat yield was probably because the model accounted for change in the cow's BW but not in her body composition during the feeding trial.

Genetically, using the cow's genomic evaluations to predict the cow's phenotypic feed intake gave the opposite result, with more feed required to produce fat than to produce protein and a much higher total feed cost. Those regression coefficients agreed with the fat to protein ratio assumed in ECM, but with much less feed intake estimated for milk (lactose) than in ECM.

Using sire's genomic evaluations gave intermediate values that are close to those assumed for 2018 NM$. Cow's DMI was much higher from regressions on cow's genomic PTA and intermediate from regressions on sire's genomic PTA compared with phenotypic regression. All three estimates of the DMI associated with milk fluid were much less than in NM$ or from the estimate in ECM, indicating that lactose is less expensive to produce than previously assumed, which increases the value of milk in NM$. New estimated costs of components are intermediate between the two genomic estimates and with a higher ratio of DMI required for fat than for protein compared with the previous estimate, which decreases the relative emphasis on fat yield compared with protein yield.

For many years only the theoretical study of Dado et al. (1994) was available, which assumed protein input is more limiting than energy in most U.S. rations because of its higher cost. Nutritionists often calculated intake and output based only on the energy in individual milk components because "feed energy requirements for production of individual milk components have not been defined… It is envisioned that future net energy requirements for milk will be centered more on substrate requirements for production of individual milk components rather than a more general requirement for total milk energy output" (National Research Council, 2001). Thus, nearly all other countries assumed that feed costs for each component were proportional to ECM (Peter Amer, Abacusbio, New Zealand, personal communication, 2020). Now more detailed estimates and estimation methods are available. Small standard errors indicate that the phenotypic and genomic regressions really differ, and biological explanations are needed. Although RFI can be defined as independent of yield and body weight using either phenotypic or genetic regressions, genetic regressions should be used for combining genetic evaluations (Tempelman and Lu, 2020).

Previous NM$ formulas assumed that feed costs for milking cows were about 50% of their milk income. Because the estimated maintenance cost increased from about $300 to $700/lactation, the marginal feed associated with milk production decreased from $7.68 to $5.94 to keep total feed costs nearly constant. If needed, a PTA for total DMI/lactation can be predicted as 0.12(PTA milk) + 6(PTA fat) + 7(PTA protein) – FSAV to combine the feed intakes associated with yield, BWC, and RFI.

In the future, the feed price could be kept proportional to the milk price. In 2018, those were $0.12/pound DMI and $17/100 pounds milk; in the 2021 formula, they are $0.11/pound DMI and a forecast milk price of $16.50/100 pounds milk. Expression of FSAV as pounds instead of dollars makes the PTAs more stable regardless of prices and more similar to yield traits expressed as pounds per lactation. The feed costs associated with milk, fat, and protein are not included in FSAV but are directly subtracted from yield trait economic values to obtain net income as in all previous NM$ formulas.

Heifer livability

Genomic evaluations for HLIV were developed by Neupane et al. (2021) and implemented in December 2020. The HLIV PTAs are expressed in percentage points of additional calves that live, and positive PTAs are favorable. Increasing heifer survival can have great economic benefits because rearing of replacement heifers is a major cost on dairy farms. Mortality also affects selection intensity of the herd, which will ultimately reduce genetic gain.

Heifer calves were assumed to be worth an average of $500 across the ages when calf death losses occur. Most deaths occur in the early months, but raising expenses also may be higher in the early months. Current assumptions are a $200 value for newborn heifers and a $1400 value at freshening with an average cost of heifer loss estimated to be $500, which gives HLIV a value of $5.00 per 1%. Additional value could be justified for correlated calf health costs, for the livability of bull calves, or for heifers that die after the 18-month edit limit, but direct data were not available for those costs.

Because of the low heritability of HLIV, the SD of PTA HLIV is only 0.5% for Holsteins, and the relative emphasis on HLIV thus is also low. The economic contributions of HLIV to NM$ are small for individual animals and usually less than ±$5 but should contribute to additional economic progress of $50,000 per year. The genetic correlation between genomic HLIV PTA and NM$ was strong (0.55) because of favorable correlations with most other traits already included in NM$.

Early first calving

Genomic evaluations for EFC were developed by Hutchison et al. (2017) and implemented in 2019 (Council on Dairy Cattle Breeding, 2019). The trait EFC is measured in days with positive PTAs indicating earlier calving and an SD of 2.5 days. An edit now further excludes records initiated by abortion so that heifers that calve early only get credit if the lactation is normal and usable. The primary benefit of EFC is to reduce the time required to raise replacements with costs valued at $75/month or $2.50/day. Milk production records are standardized for age at calving, but the actual 305-day yield produced in first lactation is reduced by about 5 pounds per day of EFC. This lost milk yield is valued at $0.17/pound but with a reduced feed cost of $0.08/pound, which gives a net economic value of $2.50 – 5($0.17 – $0.08) = $2.05/day for EFC.

Relative emphasis on EFC is 1.2% of NM$. With EFC included in the NM$ index, emphasis on HCR declined to 0.6% because HCR included an indirect benefit for EFC that is now replaced by the direct benefit of HCR. The two traits EFC and HCR have a moderate genetic correlation of 0.32 for Holsteins. Other benefits associated with EFC are longer PL and higher fertility and thus more lifetime milk yield but with additional stillbirths. Those benefits and costs are already accounted for in NM$.

Benefits and costs of EFC are nonlinear especially on the phenotypic scale and may not apply to breeding and calving at very young ages. A good analogy is use of a voluntary waiting period before breeding cows. Selection of cows for high fertility does not require that they be inseminated at the first heat after calving, just as selection for EFC does not require inseminating heifers at the first heat after puberty. Heifers are often bred at a given weight rather than age, and high PTAs for EFC indicate better fertility and heifer growth rate, a trait that is not yet measured directly. Adverse effects on stillbirth and calving difficulty can be managed through careful mate selection (Cole et al., 2007), but farmers and consumers may prefer management and selection strategies that improve EFC without increased stillbirths or calving difficulty.

Inclusion of EFC in NM$ will result in about $150,000 per year economic benefits to U.S. dairy producers. Heifers and cows should be bred only after a reasonable voluntary waiting period that balances the benefits from production, reduced raising costs, and shorter calving intervals with some increased costs such as stillbirth to maximize lifetime profit.

Health traits

Evaluations for six health traits recorded by producers were introduced in 2018 for Holsteins and in 2020 for Jerseys: clinical mastitis (MAST), ketosis (KETO), retained placenta (REPL), metritis (METR), displaced abomasum (DA), and milk fever (MFEV; hypocalcemia). Cows with genes that keep them healthy are more profitable than cows with health conditions that require extra farm labor, veterinary treatment, and medicine.

Economic values of the six new traits were obtained as averages of two recent research studies plus additional yield losses not fully accounted for in published genetic evaluations for yield traits. Direct treatment, labor, and discarded milk costs for health disorders were estimated from veterinary and producer survey responses (Liang et al., 2017) and obtained health treatment costs from eight cooperating herds in Minnesota (Donnelly, 2017; Hazel et al., 2020). Some yield losses associated with health conditions are not fully accounted for when 305-day lactation records include adjusted test days that are coded as sick or abnormal. Economic values, relative values, and SDs of TTAs for the six health traits and LIV follow:

Trait (cases/lactation, %)	TTA SD	Value ($/case) *(direct cost + yield adjustment)*	Relative value (%)	
			HTH$	NM$
MFEV	0.4	34 (38 – 4)	2.3	0.04
DA	0.7	197 (178 + 19)	23.3	0.42
KETO	1.0	28 (28 + 0)	4.7	0.08
MAST	2.6	75 (72 + 3)	32.9	0.59
METR	1.4	112 (105 + 7)	26.5	0.48
RETP	0.9	68 (64 + 4)	10.3	0.19
HTH$	$8.50	…	100	1.7
LIV/lactation	0.8	975	…	4.5

The economic values include direct costs per case plus additional yield losses not accounted for by yield PTAs because those are adjusted for abnormal test days.

Healthy and unhealthy cows were compared with and without the test-day milk, fat, and protein adjustments of Wiggans et al. (2003). Most health traits had only 2-pound differences for fat and 1-pound differences for protein between adjusted and unadjusted lactation yields. The value per lactation was $1.23 for fat and $1.32 for protein, resulting in only about $4 more value to add to direct health costs/case to account for unadjusted yield minus published adjusted yield. Only DA had bigger differences of 6 pounds for fat and 8.5 pounds for protein, but those differences added only $19 to the $178 value of direct costs assumed for DA. Because DA has acute effects requiring surgery, cows with DA may be more likely be coded as sick or detected as abnormal on test day. Thus, adjustments to released evaluations for yield contribute little to total direct health costs. Relative values for each trait again are obtained by multiplying economic value by TTA SD and then dividing each individual value by the sum of the absolute values.

To calculate HTH$, the PTAs for each trait are converted from percentages by multiplying by 0.01. Then they are multiplied by the corresponding economic value ($/case) and converted to lifetime values by multiplying by 2.69, which is the assumed number of lactations in a lifetime. The HTH$ index is the sum of the lifetime values for all traits.

Calculation of HTH$ can be demonstrated using the following example Holstein:

Trait	Example PTA	Example lifetime value ($)
MFEV	−0.2	−0.18
DA	+0.5	2.65
KETO	+1.2	0.90
MAST	+2.0	4.04
METR	+2.1	6.33
RETP	−0.1	−0.18

The lifetime value for MFEV is calculated as the animal's PTA of −0.2 times 0.01 times the economic value of $34/case times 2.69 lactations = −$0.18. After the lifetime values for all traits are summed, this example Holstein's HTH$ is $13.56.

Fertility traits

Measures of fertility in merit indexes include HCR and CCR along with DPR. Separating the benefits from CCR and DPR is not simple because the two traits overlap. Both are major components of PL, but the benefits from more lactations are already included in the PL economic value. Economic values were obtained with the following assumptions.

Numbers of services were assumed to average 1.8 for heifers and 2.9/lactation for cows, which is equivalent to conception rates of 56% and 34%, respectively. Semen price ($15/unit), insemination labor costs ($5/unit), and heat detection labor and supplies ($5 for heifers and $7 for cows) were assumed to be proportional to the number of services. Synchronization costs are higher than simple heat detection and range from $13 to $25 per insemination (Stevenson, 2012), but synchronization can improve conception rates and reduce calving intervals. Pregnancy checks ($10/exam) were assumed to increase by 0.4 times the number of services.

For heifers, each 1% increase in HCR should decrease age at first calving by 1.8(30/100) = 0.54 days, assuming that failed services increase age at first calving by 30 instead of 21 days because of incomplete heat detection and abortion loss. A cost of $2.10/day was assumed for calving after the optimum age. Losses from culling heifers for poor fertility should be included in HCR because PL does not include those losses. If heifers are culled after 5 unsuccessful services, $(1 - 0.56)^5$ = 1.6% of heifers would be culled, with 0.2% more for each 1% lower HCR. Alternatively, natural service might be used for problem breeders, but with potentially higher cost than for artificial insemination. When infertile heifers are culled at about 1,000 pounds live weight, economic loss equals the raising cost of $1,200 minus the beef value of $900. Total value of HCR including age at first calving, insemination costs, heat detection, pregnancy checks, and reproductive culling was $2.10(0.54) + [$15 + $5 + $5 + $10(0.4)]1.8/100 + $300(0.002) = $2.26.

For cows, reduced profit from lactations longer or shorter than optimum was estimated to be $0.75/day open. Poor cow fertility is correlated with other unmeasured health expenses, and $0.20/day open was added to account for these. The economic loss for 1 day open is then converted to DPR by multiplying by −4. Numbers of calves born increase with both DPR and PL. At a constant PTA PL, 1% higher DPR results in about 1% more calves per lifetime with an average value of $150, which then results in an extra $1.50/PTA unit of DPR. Per lactation costs for CCR and days open are converted to lifetime values by multiplying by 2.39, which assumes that cows have 2.69 lactations but that no inseminations are attempted for 30% of the cows during their final lactation because a decision to cull was made previously for other reasons (2.39 = 2.69 − 0.3). Total value of CCR was 2.39[($15 + $5 + $7 + $10(0.4)]2.9/100 = $2.15. Total value of DPR was 2.39(4)($0.75 + $0.20) + $1.50 = $10.58.

Yield traits

A base price of $16.50 was assumed for milk containing 3.5% fat, 3% true protein, and 350,000 somatic cells/ml before deducting hauling charges, which were assumed to be $0.57 based on actual costs (about $0.0057/100 pounds/loaded mile in 2009). The milk price after hauling charges was equal to $15.93. Component prices follow, along with marginal feed costs required for higher yield with the non-yield traits in NM$ held constant; values in the volume column are computed as (milk value) − 3.5(fat value) − 3(protein value) divided by 100:

Index	Milk ($/100 pounds)	Fat ($/pound)	Protein ($/pound)	Volume ($/pound)
NM$ and GM$	15.93	2.10	2.39	0.0197
CM$	15.93	2.10	2.60	0.0078
FM$	15.93	2.10	0.84	0.0606
Feed cost	6.78	0.96	0.84	0.0090

Feed costs are assumed to average about half of the milk price. Total feed costs were divided into separate costs for milk, fat, protein, and maintenance using actual feed intake data from 6,338 lactations in U.S. research herds. Those costs were presented in the feed saved section. Those DMI requirements in pounds were converted to DMI cost by multiplying by $0.11/pound and then by number of lactations for use in lifetime NM$. A cost of $0.002 for bulk tank, equipment, and electricity costs to cool and store each pound of milk also is subtracted along with the feed cost. The milk price did not include costs or benefits from participating in the USDA Margin Protection Program or other direct cash payments.

Correlations of merit indexes based on recent young Holstein bulls were 0.999 for NM$ with CM$, 0.990 for NM$ with FM$, and 0.982 for FM$ with CM$. A small protein premium equal to feed cost plus health cost is included to make FM$ more acceptable as a breeding goal and results in no direct selection for or against protein in the FM$ index. Producers that expect low future protein premiums should select on FM$, and those that expect high protein premiums should select on CM$; breeders targeting the U.S. average price should select on NM$.

The value of milk, fat, and protein is converted from a lactation basis to a net lifetime basis by subtracting feed and hauling costs and then multiplying by the average number of record equivalents in a lifetime. For Holsteins, the average number of record equivalents is 2.69, and the lifetime value of PTA protein in NM$ is (2.39 − 0.66)2.69 = $4.67.

Prices for milk, fat, and protein vary by use of milk and across time. Average prices for milk and individual components in Federal order markets are available from USDA's Agricultural Marketing Service. Actual prices from 2006 until September 2020 for class III milk used in cheese making are:

Year	Milk ($/100 pounds)	Fat ($/pound)	Protein ($/pound)	Volume ($/pound)	SCC ($/1,000 cells)[1]
2020	17.48	1.75	3.21	0.0172	−0.00093
2019	16.96	2.51	2.38	0.0104	−0.00088
2018	14.61	2.53	1.65	0.0080	−0.00077
2017	16.17	2.61	1.87	0.0142	−0.00082
2016	14.87	2.31	2.10	0.0048	−0.00082
2015	15.80	2.30	2.24	0.0103	−0.00083
2014	22.34	2.38	3.79	0.0264	−0.00110
2013	17.99	1.66	3.30	0.0228	−0.00090
2012	17.44	1.72	3.04	0.0230	−0.00085
2011	18.37	2.15	2.97	0.0194	−0.00091
2010	14.41	1.85	2.31	0.0100	−0.00076
2009	11.36	1.20	1.99	0.0119	−0.00062
2008	17.44	1.57	3.89	0.0028	−0.00094
2007	18.04	1.47	3.51	0.0236	−0.00084
2006	11.89	1.33	2.09	0.0097	−0.00063
Forecast					
2021 CM$	16.50	2.10	2.60	0.0135	−0.00085
2018 CM$	17.00	2.10	2.75	0.0140	−0.00090

[1]SCC = somatic cell count; see SCS section for a fuller explanation of quality premiums

Milk prices over the last 4 years averaged $16.30 for class III compared to the forecast price of $17.00 used in 2018 NM$ (VanRaden et al., 2018); the current price as of September 2020 is $16.43. Future contract prices for 2021 average about $16.75 and the USDA World Agricultural Supply and Demand Estimates Report (WASDE) 2021 forecast price for Class III milk is $16.00.

Protein prices over the last 4 years averaged $2.28 and were less than the $2.75 forecast in 2018. Butterfat prices averaged $2.35 and were slightly higher than the $2.10 forecast in 2018, but current component prices as of September 2020 are $3.39 for protein and $1.59 for butterfat. Demand for butterfat increased after trans fats were banned as an ingredient in food (U.S. Food and Drug Administration, 2015), but during 2020 the milk and component prices varied wildly as markets shifted between restaurant and grocery store demands.

Predicted prices used in CM$ are now $2.60 for protein and $2.10 for fat. Fluid milk processors usually pay no premium for extra protein because grocery store milk is not yet labeled or priced by protein content, but a protein premium is included in FM$ to prevent the actual value of protein from becoming negative after feed costs are subtracted. Selection on FM$ is appropriate mainly in southeastern states or in countries that do not yet pay for protein.

The value of protein in NM$ represents an average across milk markets of price formulas paid to U.S. producers. Before 2014, NM$ was a weighted average of prices paid by processors for four usage classes: 1) fluid milk, 2) soft/frozen products, 3) hard cheese, and 4) butter/powdered milk. That approach was used since the milk-fat-protein dollars (MFP$) index was first introduced (Norman et al., 1979) and is still used to charge processors in Federal Orders. However, 8 of the 10 Federal Orders ignore the actual usage of milk when paying producers and instead pay component prices to producers as if all milk is used for cheese. Use of the average prices received by producers instead of average prices charged to processors and protein pricing for 92% of U.S. milk makes the NM$ price closer to CM$ than in the past.

Historical component and milk prices after deducting hauling charge used since 1977 to calculate NM$ and MFP$ follow:

Year	Milk	Fat	True protein	Volume
1977	12.30	1.48	1.24	0.034
1978	12.23	1.51	1.18	0.034
1979	12.25	1.52	1.21	0.033
1980	12.32	1.61	1.26	0.029
1981	12.35	1.63	1.28	0.028
1982	12.24	1.64	1.30	0.026
1983	12.34	1.70	1.33	0.024
1984	12.32	1.75	1.33	0.022
1985	12.26	1.72	1.28	0.024
1986	12.35	1.85	1.29	0.020
1987	12.28	1.74	1.23	0.025
1988	12.26	1.68	1.26	0.026
1989	12.31	1.46	1.50	0.027
1990	12.33	1.13	1.39	0.042
1991	12.23	1.12	1.47	0.039
1992	12.29	0.79	1.54	0.049
1993	12.33	0.70	1.66	0.049
1994	12.24	0.58	1.57	0.055
1995	12.29	0.72	1.69	0.047
1996	12.27	0.89	1.65	0.042
1997–99	12.30	0.80	2.12	0.031

Year	Milk	Fat	True protein	Volume
2000–03	12.68	1.15	2.55	0.010
2003–06	12.70	1.30	2.30	0.013
2006–09	12.70	1.50	1.95	0.016
2010–13	14.36	1.63	1.94	0.029
2014–16	17.43	1.95	2.48	0.032
2017	16.93	2.00	2.32	0.030
2018–20	16.43	2.10	2.17	0.026
2021	15.93	2.10	2.39	0.024

Prior to 1997, component prices were previous-year average prices. Crude protein prices reported prior to 2000 were converted to true protein prices by multiplying by 1.064. Milk prices paid to producers were stable from 1977 through 2010 when much inflation occurred in labor, feed, and many other input prices. Milk prices increased moderately during the last decade but were much less stable, which is why average prices over several years are used in forecasting. Additional history on economic indexes is provided in the NM$ history section.

SCS

Inclusion of MAST in 2018 reduced the value assigned to SCS in the NM$ formula, but SCS still receives some emphasis because lower PTA SCS gives higher milk prices in markets where quality premiums are paid. For the last 4 years, premiums and penalties in Federal orders for class III milk averaged a price increase of $0.00085 for each 1,000 cell/ml decrease in SCC.

Somatic cell premiums were originally converted from SCC scale to SCS scale with an assumed average of 350,000, but the Dairy Herd Information average of 320,000 in 2002 fell rapidly to 199,000 by 2013 (Norman and Walton, 2014). Until 2014, the SCC value per 1,000 cells was converted to the SCS value/double by dividing by 0.0041, which was the difference between log base 2 of 351,000 and log base 2 of 350,000, but now is converted by dividing by 0.0072, which is the difference between log base 2 of 201,000 and log base 2 of 200,000. The value of SCC/100 pounds of milk is now converted to the value of SCS as $0.00085/0.0072 = $0.118. The actual change in SCC from a 1-unit change in PTA SCS (a doubling of SCC) and the actual SCC differences among bull daughters are now much less than when SCC premiums were introduced. Also, the actual value of PTA SCS is higher for herds with more MAST and lower for herds with less MAST because payments are linear with SCC rather than with SCS.

Different premiums for SCS are applied in each index. The full class III premium is applied to SCS in CM$ because manufacturing plants typically provide incentives for improved milk quality. The premium in NM$ uses the assumption that 80% of the milk will be sold in blend markets that are paid the class III premium. Because some producers in fluid markets receive premiums for improved milk quality, 50% of the premium was assigned to SCS in FM$. The actual value of reduced SCS in fluid milk is substantial because of improved shelf life and taste (Ma et al., 2000).

PL and LIV

The trait PL measures how long cows stay in the herd by summing lactation credits from first calving until the cow is sold for beef or dies on the farm. Cows sold for dairy purposes are given partial credit as of the date sold, and their future PL is projected, the same as for cows still alive on the farm. The lactation curve credits give more credit to months of peak lactation, more credit to mature-cow lactations, and no credit to dry periods, with an average credit of 10 months for a 305-day lactation. Cow LIV measures only the on-farm death loss per lactation expressed as the percentage of additional cows that live so that positive numbers are favorable.

The 2021 economic value of PL now better accounts for maturity effects by assuming differing profits for each parity instead of equal profit across lactations and accounts for genetic progress by assuming that the merit of replacement heifers improves in each subsequent year. Faster genetic gain makes young cows more valuable relative to older cows, and NM$ now accounts for the improvement of lifetime NM$ of $60 per year for transmitting ability or $120 for breeding value following methods recommended by Schmitt et al. (2019) and De Vries (2017).

Instead of simply multiplying average profit by number of lactations as in the previous NM$ formula, adjusted profit is now summed across parities with the fraction of cows in each parity calculated as $[1 - 1/(2.69 + PL/10)]^{parity-1}$ except that parities after fifth were summed and treated the same as fifth. Average profit is adjusted for NM$ trend, higher mature yield, higher maintenance cost at mature weights, and higher compound interest charges for later lactations. Those adjustments estimate highest profits in the third and fourth parities and more profit as a function of PL than previously assumed and an increased emphasis on PL. Adjusted profits follow:

Parity	Herd fraction (%)	Average profit ($)	NM$ trend ($)	Mature yield ($)	Mature weight ($)	Compound interest ($)	Adjusted profit ($)[1]
1	37.1	155	75	−436	89	−77	−50
2	23.3	155	31	0	0	−81	249
3	14.7	155	−14	167	−50	−85	317
4	9.2	155	−58	228	−66	−89	314
5+	15.7	155	−103	228	−74	−93	256

[1]Sum of NM$ trend, mature yield, mature weight, and compound interest plus a constant of $299 so that average profit weighted by fraction of cows in each parity equals $155

The SD of PL earlier increased in the 2006 revision by 40% when including the months in milk beyond 7 years of age and beyond 305 days per lactation using credits determined from lactation curves (VanRaden et al, 2006). Those extra credits for higher mature-lactation yield accounted for 6% of the SD increase and were removed by dividing the PL economic value by 1.06 when recalculating economic value based on lactation profit instead of lactation yield.

Cow LIV was included as a new trait in April 2017. Cows that die or are euthanized on the farm generate no beef income and may have more health expenses than cows that are culled. The value of PL was reduced at that time because the loss of beef income is now directly tied to cow LIV rather than indirectly to PL. Cows that die are assumed to generate $975 less income than those sold for beef calculated as 1,500 pounds times $0.60/pound plus $75/death for on-farm labor and cow disposal charges. Because PTA LIV is expressed as the percentage of deaths per lifetime, the economic value is $975(0.01) = $9.75.

Replacement costs now are assumed to include a newborn 100-pound heifer price of $200, a cost of $0.75/pound of growth, and a fixed cost of $400 for a total of $1,425 to raise the heifer to 1,200 pounds. The interest rate also remains at 5%. Relative emphasis increased for PL and decreased for LIV because of these income and cost adjustments.

Type traits

Linear type traits provide additional information about incomes and expenses. Instead of directly using PTAs for all type traits, composites are used in NM$. For Holsteins, UDC, FLC, and BWC are calculated by Holstein Association USA (Holstein Association USA, 2017). For other breeds, published PTAs for linear traits are converted to standardized transmitting abilities by dividing by TTA SD and then are combined into composites that are not released. Estimated genetic SDs follow:

Trait	SD					
	Ayrshire	Brown Swiss	Guernsey	Holstein	Jersey	Milking Shorthorn
Stature	1.7	1.3	2.0	1.0	1.1	1.3
Strength	1.0	0.7	1.2	1.0	0.7	0.8
Body depth	0.9	0.9	1.4	1.0	…	1.0
Dairy form	0.8	0.9	1.5	1.0	0.7	1.1
Rump angle	1.0	0.9	1.4	1.0	0.8	1.1
Thurl width	1.0	0.7	1.3	1.0	0.7	0.8
Rear legs (side view)	0.7	0.7	0.7	1.0	0.6	0.5
Rear legs (rear view)	1.0	0.3	0.6	1.0	1.0	0.7
Foot angle	0.7	0.7	0.7	1.0	0.5	0.7
Feet & legs score or mobility	…	1.0	…	1.0	…	…

Trait	SD					
	Ayrshire	Brown Swiss	Guernsey	Holstein	Jersey	Milking Shorthorn
Fore udder	1.0	1.0	1.3	1.0	0.9	0.7
Rear udder height	1.1	0.9	1.2	1.0	0.9	1.0
Rear udder width	0.9	0.8	1.3	1.0	0.8	0.8
Udder cleft	0.9	0.8	1.0	1.0	0.7	0.6
Udder depth	1.0	0.9	1.4	1.0	1.2	0.9
Teat placement	1.0	1.0	1.2	1.0	0.9	1.0
Teat length	1.2	1.3	1.5	1.0	0.8	1.4
Rear teat placement	…	…	…	1.0	1.5	…
Rear teat placement (side view)	…	…	…	…	0.9	…
Milking speed	…	5.0	…	…	…	…

Relative values of udder and feet/legs traits for Jerseys, Guernseys, and Brown Swiss are obtained from the official Functional Trait Indexes or Functional Udder Indexes of those three breed associations. Jersey values are applied to Ayrshires and Milking Shorthorns. Breed association Functional Trait Index formulas were obtained from correlations with PL, but partial regressions are difficult to estimate in small populations with many traits.

Udder. The formula for Holstein UDC was updated by Holstein USA in August 2017 (Holstein USA, 2017) and applied in merit indexes in December 2017. The Holstein UDC now adjusts for the correlated influence of stature, and intermediate optima are assigned for both teat length and rear teat placement. Current relative weights used for merit index calculations are:

Trait	Relative value (%)			
	Holstein	Brown Swiss	Guernsey	Jersey and other breeds
Stature	−20	…	…	…
Fore udder	16	21	15	7
Rear udder height	23	6	15	33
Rear udder width	19	1	5	19
Udder cleft	8	2	15	1
Udder depth	20	35	33	31
Teat placement	4	11	15	4
Rear teat placement (nonlinear)	5	…	…	…
Teat length	5	−24	−2	4
UDC	…[1]	100	100	100

[1]Holstein values are weights (expressed as percentages) from composite formula calculated by Holstein Association USA (2017) and, therefore, do not sum to 100

Milking speed and mobility are evaluated for Brown Swiss and rear teats (side view) is evaluated for Jerseys, but those traits [not shown in table] are not evaluated for other breeds. They will be included in NM$ via the breed-specific composites.

Feet/legs. The formula for Holstein FLC was updated by Holstein USA in August 2017 (Holstein USA, 2017) and applied in merit indexes in December 2017. The Holstein FLC now adjusts for the correlated influence of stature. Because rear legs (rear view) and feet & legs score are not available for breeds other than Holstein, STAs for foot angle and rear legs (side view) are included in the FLCs for other breeds. Current relative weights used for merit index calculations are:

Trait	Relative value (%)			
	Holstein	Brown Swiss	Guernsey	Jersey and other breeds
Stature	−17	…	…	…
Rear legs (side view)	…	−32	−16	−30
Rear legs (rear view)	18	…	36	…
Foot angle	8	68	48	70
Feet & legs score	58	…	…	…
FLC	…[1]	100	100	100

[1]Holstein values are weights (expressed as percentages) from composite formula calculated by Holstein Association USA (2017) and, therefore, do not sum to 100

Body size/weight. Since April 2017, BWC replaced the previous body size composite formula used in NM$ from 2000 through 2016. Research by Holstein Association USA (2016) used recent weight and linear type data from the research herds that also measured feed intake to predict BW more accurately. In December 2017, a new BWC was introduced for Jerseys based on research by the American Jersey Cattle Association and the University of Wisconsin (American Jersey Cattle Association, 2017). The Jersey BWC was also used for Brown Swiss because neither breed scores body depth. Holstein BWC is used for breeds other than Jersey and Brown Swiss. Current relative weights for combining the linear traits into BWC are:

Trait	Relative value (%)	
	Jersey and Brown Swiss	Holstein and other breeds
Stature	28	23
Strength	28	72
Body depth	…	8
Dairy form	−35	−47
Rump width	9	17
BWC	100	…[1]

[1]Holstein values are weights (expressed as percentages) from composite formula calculated by Holstein Association USA (2017) and, therefore, do not sum to 100

A new regression of BW on BWC EBV was estimated from additional Holstein research cows to be 15.7 kg BW = 35 pounds BW per unit of BWC compared with 40 pounds from Manzanilla-Pech et al. (2016) used previously in NM$.

Derivation of the economic value of BWC is now in the feed saved section.

Calving ability

Calves that die or are born with difficulty reduce dairy farm profit. Because calving ease and stillbirth effects from the service sire and the dam differ, CA$ includes 4 traits: service-sire calving ease (SCE), daughter calving ease (DCE), service-sire stillbirths (SSB), and daughter stillbirths (DSB). Many other countries use the terms direct and maternal or paternal and maternal instead of service sire and daughter. Comparisons of evaluations can be confusing because of terminology, direction of scales, and evaluation of pure maternal effects by several countries with an animal model instead of a sire-maternal grandsire (MGS) model. The NM$ index has included calving ease since 2003 (VanRaden and Seykora, 2003) and stillbirth since 2006 (Cole et al., 2007) The CA$ index combines these traits and is included in NM$ but not released directly.

Economic values for stillbirths of Holsteins were derived as follows. Value of 2-day-old calves was assumed to be $150 for bulls and $450 for heifers. The SSB and DSB evaluations are percentages of calves that die as compared with the bases of 5.6 and 6.6%. Lifetime value of a 1% decrease in DSB is 2.8 lactations multiplied by average calf value: 2.8($150 + $450)/2(100) = $8.40. For SSB, this value must be halved because SSB measures the full effect of the service sire, whereas DSB measures only half of the dam's effect. Other breeds had insufficient data to begin stillbirth evaluations.

The value of DCE includes $70 per difficult birth (score 4 or 5) for farm labor and veterinary charges as well as a 1.5% increased probability of cow death multiplied by $1,800. Those expenses are multiplied by 2 because scores 2 and 3 contribute additional smaller effects that occur more frequently. Difficulty in later parities is 0.3 as great, which results in a lifetime incidence of 1 + 0.3(1.8) = 1.5. Total value of DCE is [$70 + 0.015($1,800)]2(1.5)/100 = $2.91. Calving ease costs are based primarily on research by Dematawewa and Berger (1997).

The value of SCE also includes losses in the bull's mates of \$100 for yield and \$75 for fertility and longevity. Difficult births reduce 305-day milk yield by 700 pounds and delay the bull's mates from becoming pregnant again by 20 days on average. Such losses are not charged to DCE because the bull's daughter evaluations for yield, fertility, and longevity already account for them. The value of SCE must be halved as done for SSB. Total value of SCE is [\$50 + 0.015(\$1,800) + \$100 + \$75]2(1.5)/2(100) = \$3.78. Values were then rounded to \$4 for SCE, \$3 for DCE, \$4 for SSB, and \$8 for DSB. The units of CA\$ are the lifetime dollar value that the calving traits contribute to NM\$. Calculation requires subtracting trait averages, multiplying by economic values, and reversing direction to obtain net benefit instead of net cost:

$$CA\$ = -4(SCE - 2.2) - 3(DCE - 2.7) - 4(SSB - 5.6) - 8(DSB - 6.6).$$

For Brown Swiss, both the SCE and DCE averages are 2.9, and the economic values are −6 for SCE and −8 for DCE because separate stillbirth evaluations are not available and calving ease values include the correlated response in stillbirth:

$$CA\$_{\text{Brown Swiss}} = -6(SCE - 2.9) - 8(DCE - 2.9).$$

For Holsteins, the TTA SDs are 1.7 for SCE, 1.4 for DCE, 1.0 for SSB, and 1.7 for DSB with corresponding relative emphasis of 25, 15, 15, and 45% in CA\$. The CA\$ SD is \$14, and the relative emphasis on calving traits in NM\$ is 2.9%. This emphasis decreased compared with 2018 NM\$ because of scale revision in August 2020 for the reduced phenotypic average and SD of calving traits in recent years.

Cows that are not genotyped do not have PTAs available to compute CA\$ because a sire-MGS model (instead of an animal model) is used for evaluation of CA\$ traits. Therefore, a pedigree index (0.5 sire PTA + 0.25 MGS PTA + 0.125 maternal great-grandsire PTA, etc.) is substituted for PTA for all generations of the maternal line; breed average replaces any unknown ancestors.

Mating programs should assign bulls with low and high PTAs for service-sire effects to heifers and cows, respectively. The economic value used in NM\$ is a weighted average of losses for cows and heifers. Thus, when ranking sires for heifer use, another \$4 should be subtracted from NM\$ for each percentage of SCE, and \$2 for each percentage of SCE should be added back to NM\$ when ranking service sires for cows. These minor adjustments for the differing economic values in heifer versus cow matings can be handled with computerized mating programs.

Lifetime profit

The NM\$ index is defined as expected lifetime profit as compared with the breed base cows born in 2015. Incomes and expenses that repeat for each lactation are multiplied by the cow's expected number of lactations. This multiplication makes the economic function a nonlinear function of the original traits. For official NM\$, a linear approximation of this nonlinear function is used as recommended by Goddard (1983). The linear function is much simpler to use and was correlated with the nonlinear function by 0.999.

Index selection based on computer calculation is efficient, and computer mating programs that account for inbreeding using complete pedigrees also should be used. Selection and mating programs both can have large, nearly additive effects on future profit. Gains from mating programs do not accumulate across generations, whereas gains from selection do. Cows and bulls within each breed are ranked with the same NM\$ even though the timing of gene expression differs by sex.

The NM\$ measures additional lifetime profit that is expected to be transmitted to an average daughter but does not include additional profit that will be expressed in granddaughters and more remote descendants. Gene flow methods and discounting of future profits could provide a more complete summary of the total profit from all descendants. Animal welfare may be a goal of society but is not assigned a monetary value in NM\$. Healthier cows can make dairying a more enjoyable occupation, and traits associated with cow health may deserve more emphasis as labor costs increase. Production of organic milk with fewer treatment options could require cows with more natural ability to resist disease and remain functional.

The profit function approach used in deriving NM\$ lets breeders select for many traits by combining the incomes and expenses for each trait into an accurate measure of overall profit. Averages and SDs of the various traits in the profit function may differ by breed, but official NM\$ is calculated by using Holstein values instead of having a slightly different NM\$ formula for each breed. Producers should use the lifetime merit index (NM\$, CM\$, FM\$, or GM\$) that corresponds to the market pricing that they expect a few years in the future when buying breeding stock and 5 years in the future when buying semen.

History and future of NM$

Current and previous NM$ changes can be quickly summarized as:

Year	Correlation between new and previous NM$	New traits
2021	0.981[1]	FSAV, EFC, HLIV
2018	0.994	MFEV, DA, KETO, MAST, METR, RETP
2017	0.989	LIV
2014	0.965	HCR, CCR
2010	0.990	None
2006	0.975	Stillbirth, revised PL scaling
2003	0.970	DPR, calving ease
2000	0.931	Type composites (UDC, FLC, BWC)
1994	0.888	PL, SCS

[1]Correlation for young bulls = 0.992

The 2021 NM$ index includes the new traits FSAV, EFC, and HLIV along with updated economic values and is correlated with the 2018 NM$ formula (VanRaden et al., 2018) by 0.981. An increase in genetic progress worth $20 million/year is expected on a national basis, assuming that all changes are improvements and that all breeders select on NM$. The 2018 NM$ index included 6 new health traits and was correlated by 0.994 with the 2017 NM$ index (VanRaden, 2017). The 2017 index included the new trait LIV and was correlated by 0.989 with the 2014 NM$ index (VanRaden and Cole, 2014) for recent progeny-tested bulls. The 2014 NM$ index , which included new traits HCR and CCR, was correlated by 0.965 with the 2010 NM$ index (Cole et al., 2009). The 2010 NM$ index was correlated by 0.99 with the 2006 NM$ formula (VanRaden and Multi-State Project S-1008, 2006); the 2010 changes were mostly caused by an increase in the price of feed, decrease in the value of heifer calves, and higher cost of raising replacements, but no new traits. The 2006 NM$ index was correlated by 0.975 with the 2003 NM$ formula (VanRaden and Seykora, 2003) for recent progeny-tested bulls; about half the changes were caused by the PTA PL revision and the rest from addition of stillbirth and updates of trait economic values.

In the 2003 NM$ revision (VanRaden and Seykora, 2003), cow fertility and calving ease were incorporated into NM$. In the 2000 NM$ revision (VanRaden, 2000), type traits were included along with yield and health traits using a lifetime profit function based on research of scientists in the S-284 Health Traits Research Group. Before 2000, breed association indexes had included type traits but not health traits, and NM$ had included health traits but not type traits. In 1994, PL and SCS were combined with yield traits into NM$ using economic values that were obtained as averages of independent literature estimates (VanRaden and Wiggans, 1995).

In the 1980s as part of Project NC-2 of the North Central Regional Association of Agricultural Research Experiment Station Directors, researchers developed a profit function to compare genetic lines in their experimental herds:

$$\text{lifetime profit} = \text{milk value} + \text{salvage value} + \text{value of calves} \\ - \text{rearing cost} - \text{feed energy} - \text{feed protein} - \text{health cost} - \text{breeding cost.}$$

Relative net income also was developed to measure profit from field data with adjustment for opportunity cost to more fairly compare short- and long-term investments (Cassell et al., 1993). The main difference between NM$ and the profit function approaches is that a PTA is calculated for each evaluated trait and then combined instead of combining each cow's phenotypic data directly. The PTA approach is more accurate because heritabilities of traits differ, genetic correlations are not the same as phenotypic correlations, and all phenotypes are not available at the same time.

In 1984 and 1977, economic index formulas based on cheese yield price (CY$) and protein price (MFP$), respectively, were introduced. In 1971, USDA introduced its first genetic-economic index called predicted difference dollars (PD$), which combined only milk and fat yields. The three different milk pricing formulas (Norman, 1986) continued to be released until 1999 when they were replaced by the more complete merit indexes CM$, NM$, and FM$, respectively (see the yield traits section for a history of milk price formulas).

A history of the changes in relative values for traits included in the U.S. indexes follows:

Traits included	PD$ (1971)	MFP$ (1976)	NM$ (1994)	NM$ (2000)	NM$ (2003)	NM$ (2006)	NM$ (2010)	NM$ (2014)	NM$ (2017)	NM$ (2018)	NM$ (2021)
Milk	52	27	6	5	0	0	0	−1	−1	−1	0
Fat	48	46	25	21	22	23	19	22	24	27	22
Protein	…	27	43	36	33	23	16	20	18	17	17
PL	…	…	20	14	11	17	22	19	13	12	15
SCS	…	…	−6	−9	−9	−9	−10	−7	−7	−4	−3
BSC/BWC	…	…	…	−4	−3	−4	−6	−5	−6	−5	−9
UDC	…	…	…	7	7	6	7	8	7	7	3
FLC	…	…	…	4	4	3	4	3	3	3	1
DPR	…	…	…	…	7	9	11	7	7	7	5
CA$	…	…	…	…	…	6	5	5	5	5	3
HCR	…	…	…	…	…	…	…	1	1	1	1
CCR	…	…	…	…	…	…	…	2	2	2	1
LIV	…	…	…	…	…	…	…	…	7	7	4
HTH$	…	…	…	…	…	…	…	…	…	2	2
RFI	…	…	…	…	…	…	…	…	…	…	−12
EFC	…	…	…	…	…	…	…	…	…	…	1
HLIV	…	…	…	…	…	…	…	…	…	…	1

Emphasis on yield traits has declined as other fitness traits were introduced. As protein yield became more important, milk volume became less important because of the high correlation of those two traits. A more complete history and comparisons with selection indexes used by other countries are available (Shook, 2006; VanRaden, 2002; VanRaden, 2004).

Future selection indexes and potential for future genetic progress have also been forecast by Cole and VanRaden (2018).

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Abbreviations

BW = body weight
BWC = body weight composite
CA$ = calving trait subindex
CCR = cow conception rate
CM$ = cheese merit index
CY$ = cheese yield index
DA = displaced abomasum
DCE = daughter calving ease
DMI = dry matter intake
DPR = daughter pregnancy rate
DSB = daughter stillbirth
ECM = energy-corrected milk
EFC = early first calving
FLC = feet/leg composite
FM$ = fluid merit index
FSAV = feed saved
GM$ = grazing merit index,
HCR = heifer conception rate
HLIV = heifer livability
HTH$ = health trait subindex
KETO = ketosis
LIV = cow livability
MAST = clinical mastitis
MBW = metabolic body weight
METR = metritis
MFEV = milk fever (hypocalcemia)
MGS = maternal grandsire
MFP$ = milk-fat-protein index
NE_L = net energy of lactation
NM$ = lifetime net merit index
NRC = National Research Council
PD$ = predicted difference milk-fat index
PL = productive life
PTA = predicted transmitting ability
REL = reliability
RETP = retained placenta
RFI = residual feed intake
SCC = somatic cell count
SCE = service-sire calving ease
SCS = somatic cell score
SD = standard deviation
SSB = service-sire stillbirth
TTA = true transmitting ability
UDC = udder composite

References

American Jersey Cattle Association. 2017. Body Weight Composite to be updated for JPI and net merit in December. Jersey J. 64(12):34.

Cassell, B.G., B.B. Smith, and R.E. Pearson. 1993. Influence of herd-life opportunity and characteristics of cows and herds on different net income functions. J. Dairy Sci. 76:1182–1190.

Cole, J.B., J.W. Dürr, and E.L. Nicolazzi. 2021. *Invited review:* The future of selection decisions and breeding programs: What are we breeding for, and who decides? J. Dairy Sci. 104:5111–5124.

Cole, J.B., and P.M. VanRaden. 2018. *Symposium review:* Possibilities in an age of genomics: The future of selection indices. J. Dairy Sci. 101:3686–3701.

Cole, J.B., P.M. VanRaden, and Multi-State Project S-1040. 2009. Net merit as a measure of lifetime profit: 2010 revision. AIPL Res. Rep. NM$4 (12-09).

Cole, J.B., G.R. Wiggans, and P.M. VanRaden. 2007. Genetic evaluation of stillbirth in United States Holsteins using a sire-maternal grandsire threshold model. J. Dairy Sci. 90:2480–2488.

Council on Dairy Cattle Breeding. 2019. CDCB changes to evaluation system (April 2019). News release, Mar. 12.

Dado, R.G., G.E. Shook, and D.R. Mertens. 1994. Nutrient requirements and feed costs associated with genetic improvement in production of milk components. J. Dairy Sci. 77:598–608.

De Vries A. 2017. Economic trade-offs between genetic improvement and longevity in dairy cattle. J. Dairy Sci. 100:4184–4192

Dematawewa, C.M.B., and P.J. Berger. 1997. Effect of dystocia on yield, fertility, and cow losses and an economic evaluation of dystocia scores for Holsteins. J. Dairy Sci. 80:754–761.

Donnelly, M.R. 2017. Genetic control of health treatment costs for Holsteins in 8 high-performance herds. Ms. Thesis. Univ. of Minnesota, St. Paul.

Gay, K.D., N.J.O. Widmar, T.D. Nennich, A.P. Schinckel, J.B. Cole, and M.M. Schutz. 2014. Development of a Lifetime Merit-based selection index for US dairy grazing systems. J. Dairy Sci. 97:4568–4578.

Goddard, M.E. 1983. Selection indices for non-linear profit functions. Theor. Appl. Genet. 64:339–344.

Hazel, A.R., B.J. Heins, and L.B. Hansen. 2020. Health treatment cost, stillbirth, survival, and conformation of Viking Red-, Montbéliarde-, and Holstein-sired crossbred cows compared with pure Holstein cows during their first 3 lactations. J. Dairy Sci. 103:10917–10939.

Holstein Association USA. 2016. New Body Size Composite, an improved way to estimate body weight. News, Aug. 9.

Holstein Association USA. 2017. Updates to the Total Performance Index (TPI) and type composites. News, Aug. 7.

Hutchison, J.L., P.M. VanRaden, D.J. Null, J.B. Cole, and D.M. Bickhart. 2017. Genomic evaluation of age at first calving. J. Dairy Sci. 100:6853–6861.

Li, B., P.M. VanRaden, E. Guduk, J.R. O'Connell, D.J. Null, E.E. Connor, M.J. VandeHaar, R.J. Tempelman, K.A. Weigel, and J.B. Cole. 2020. Genomic prediction of residual feed intake in US Holstein dairy cattle. J. Dairy Sci. 103:2477–2486.

Liang, D., L.M. Arnold, C.J. Stowe, R.J. Harmon, and J.M. Bewley. 2017. Estimating US dairy clinical disease costs with a stochastic simulation model. J. Dairy Sci. 100:1472–1486.

Ma, Y., C. Ryan, D.M. Barbano, D.M. Galton, M.A. Rudan, and K.J. Boor. 2000. Effects of somatic cell count on quality and shelf-life of pasteurized fluid milk. J. Dairy Sci. 83:264–274.

Manzanilla-Pech, C.I.V., R.F. Veerkamp, R.J. Tempelman, M.L. van Pelt, K.A. Weigel, M. VandeHaar, T.J. Lawlor, D.M. Spurlock, L.E. Armentano, C.R. Staples, M. Hanigan, Y. De Haas. 2016. Genetic parameters between feed-intake-related traits and conformation in 2 separate dairy populations—the Netherlands and United States. J. Dairy Sci. 99:443–457.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle, 7th rev. ed. National Academy Press, Washington, DC.

Neupane, M., J.L. Hutchison, C.P. Van Tassell, and P.M. VanRaden. 2021. Genomic evaluation of dairy heifer livability. J. Dairy Sci. 104:(in press).

Norman, H.D. 1986. Sire evaluation procedures for yield traits. NCDHIP Handbook (J.L. Majeskie, ed.), Fact Sheet H-1. Extension Service, USDA, Washington, DC.

Norman, H.D., B.G. Cassell, F.N. Dickinson, and A.L. Kuck. 1979. USDA-DHIA milk components sire summary. USDA Prod. Res. Rep. 178. Science and Education Administration, USDA, Washington, DC.

Norman, H.D., and L.M. Walton. 2014. Somatic cell counts of milk from Dairy Herd Improvement herds during 2013. CDCB Res. Rep. SCC15 (2-14).

Schmitt, M.R., P.M. VanRaden, and A. De Vries. Ranking sires using genetic selection indices based on financial investment methods versus lifetime net merit. 2019. J. Dairy Sci. 102:9060–9075.

Shook, G.E. 2006. Major advances in determining appropriate selection goals. J. Dairy Sci. 89:1349–1361.

Stevenson, J. 2012. What's the best timed A.I. program? Hoard's Dairyman, Reproduction E-Source, Apr. 12, 2012, 3:16 pm.

Tempelman, R.J., and Y. Lu. 2020. *Symposium review:* Genetic relationships between different measures of feed efficiency and the implications for dairy cattle selection indexes. J. Dairy Sci. 103:5327–5345.

U.S. Food and Drug Administration. 2015. The FDA takes step to remove artificial trans fats in processed foods. U.S. Department of Health and Human Services, U.S. Food and Drug Administration, FDA News Release, June 16.

VanRaden, P.M. 2000. Net merit as a measure of lifetime profit – 2000 version. AIPL Res. Rep. NM$1 (11-00).

VanRaden, P.M. 2002. Selection of dairy cattle for lifetime profit. Proc. 7th World Congr. Genet. Appl. Livest. Prod., Commun. 01-21.

VanRaden, P.M. 2004. *Invited review:* Selection on net merit to improve lifetime profit. J. Dairy Sci. 87:3125–3131.

VanRaden, P.M. 2017. Net merit as a measure of lifetime profit: 2017 revision. AIP Res. Rep. NM$6 (2-17).

VanRaden, P.M., and J.B. Cole. 2014. Net merit as a measure of lifetime profit: 2014. AIP Res. Rep. NM$5 (10-14).

VanRaden, P.M., J.B. Cole, and K.L. Parker Gaddis. 2018. Net merit as a measure of lifetime profit: 2018 revision. AIP Res. Rep. NM$7 (5-18).

VanRaden, P.M., C.M.B. Dematawewa, R.E. Pearson, and M.E. Tooker. 2006. Productive life including all lactations and longer lactations with diminishing credits. J. Dairy Sci. 89:3213–3220.

VanRaden, P.M., and Multi-State Project S-1008. 2006. Net merit as a measure of lifetime profit: 2006 revision. AIPL Res. Rep. NM$3 (7-06).

VanRaden, P.M., and A.J. Seykora. 2003. Net merit as a measure of lifetime profit: 2003 revision. AIPL Res. Rep. NM$2 (7-03).

VanRaden, P.M., and G.R. Wiggans. 1995. Productive life evaluations: Calculation, accuracy, and economic value. J. Dairy Sci. 78:631–638.

Wiggans, G.R., P.M. VanRaden, and J.C. Philpot. 2003. *Technical note:* Detection and adjustment of abnormal test-day yields. J. Dairy Sci. 86:2721–2724.

Zhang, X., and P. Amer. 2021. A new selection index percent emphasis method using subindex weights and genetic evaluation accuracy. J. Dairy Sci. 104:5827–5842.