Market Valuations of Dairy Bull Characteristics and the Role of Selection Indices

Running Title: Market Valuation of Bull Characteristics

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Abstract

I estimate a hedonic model using the characteristics of over 24,000 dairy bulls sold between 2000 and 2009 to understand how selection indices that estimate the profitability of traits for producers compare to market valuations for those traits. I find that physical traits are valued much higher in the market: physical traits comprise 50% of an equivalent "hedonic index" versus 14% in the USDA's index and 21% in an index produced by Holstein USA, a breed association. Changes in the USDA's index are not completely reflected in bull prices, suggesting that changing these indices may have a limited impact on producer choices.

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Short Description: In the market for dairy bulls, physical traits are valued much higher in the market by the USDA from 2000 to 2009. Changes in the USDA's index are not completely reflected in bull prices, suggesting that changing these indices may have a limited impact on producer choices.

1. Introduction

Selection of high-quality bulls is a significant determinant of productivity growth in the dairy industry (Atsbeha, Kristofersson and Rickertsen 2012; Hutchins, Gong and Du 2024). Since 1937, the US Department of Agriculture (USDA) has played a significant role in helping producers select quality dairy bulls by publishing estimates of the genetic traits of dairy bulls for sale (Hutchins and Hueth 2023). To help farmers understand the impact of these traits on profit, the USDA began releasing an index of the traits in 1971, called a "selection index," which weighted each trait by an estimate of its profitability (VanRaden 2004). The US Holstein breed association, Holstein USA, followed suit in 1976 and began publishing its own weighted index of the USDA's traits called the Type and Production Index (TPI) (VanRaden 2002). Rather than choosing bulls using individual traits, the goal of these indices is to allow farmers to rank bulls on multiple traits using one index number.

Some have suggested that selection indices can be used as a policy lever to guide the breeding decisions of dairy producers. Currently, selection indices are used to deliver information about the profitability of different genetic traits by revising the weights of the index using the latest research (VanRaden 2000). Animal scientists now suggest that changing selection indices to incentivize farmers to breed for less methane emissions, more feed efficiency, or better cow health to address externalities or improve the resilience of the sector (González-Recio et al. 2020; Amer et al. 2018; Richardson et al. 2022; Chesnais et al. 2016; Cole and VanRaden 2018).

Whether this is an effective policy depends on the answer to a key question: how do market valuations compare with what these selection indices tell farmers is profitable? To understand the relationships between selection indices and dairy producers' valuations, I leverage a hedonic model of dairy bull prices to understand which traits producers view as profitable. Ladd and Martin (1976) shows that in the case of inputs, the relationship between the price and the input's characteristics can tell us about the expected profit of those traits from the firm's perspective. While selection indices reflect the judgment of these institutions, hedonic regression coefficients reflect what producers perceive as profitable.

Using data from 24,000 dairy bulls sold between 2000 and 2009, I find evidence that producers value genetic traits very differently from the USDA profitability index, Net Merit (NM), and that of Holstein USA, the Total Performance Index (TPI). During this period, the USDA shifted 17% of its index away from production and towards new health traits that were released. Holstein USA's TPI shifted a smaller percentage away from production, only 5%. By constructing an equivalent index from the hedonic model, I find that the market diverted 10% away from production towards health.

I also find that US dairy producers value physical traits, called type traits, much more than the USDA or Holstein USA. Type traits for Holstein cattle are traits related to physical appearance and are used to assess whether a cow meets the Holstein breed standard. In the Net Merit index, type traits are represented by three composites representing the shape of the udders, the strength of the feet and legs, and the size of the body. In the TPI, these physical attributes are represented by a single trait, called "Type," which measures the score the animal would receive if it were appraised by Holstein USA. A key area where Net Merit and TPI differ is that Net Merit assigns a negative weight to the body size composite, thus judging it to be negatively related to profits.

Type traits make up less than 14% of Net Merit and 21% of the TPI but are nearly 50% of the index made from the hedonic model. In particular, dairy bull prices imply that body size is positively correlated to profits while the Net Merit index assumes the opposite. However, the positive treatment of body size agrees with the TPI which weights body size as positive. Looking at correlations, the market's index had a higher correlation with TPI than NM, suggesting the market ranked bulls more similarly to Holstein USA than the USDA.

After 2009, there were important changes to the dairy genetics industry, including the introduction of sexed semen and genomic testing. While limited data on pricing is available after 2009, it is important to understand how relevant these results are after this sample period. I conduct some descriptive analysis of bull evaluations after 2009 and find that, while type traits continued to grow after 2009, they grew at a slower rate than they did from 2000 to 2009. In a robustness check, I use the little pricing data available after 2009 to check the model's conclusions and find that the primary conclusions are unchanged, namely that type traits, including body size, positively correlate to price.

The policy implications of these results are that there is an important divergence between the market valuations and these popular selection indices in this period. However, there is also reasons to believe that, after the advent of genomic testing, type traits may have become less important to dairy producers. Evidence from some post-2009 genetic evaluations suggests that, while production traits have almost doubled their rate of growth, the growth in type traits has been positive but slower than before. Nonetheless, the divergence in the market valuations from 2000 to 2009 suggests that simply incorporating new traits into popular selection indices may not be an effective strategy for changing how dairy farmers choose genetics. If producers still weight some traits like body size positively, it may be especially challenging to encourage US dairy producers to breed for smaller cattle to control emissions and increase feed efficiency.

This paper contributes to the literature using hedonic analysis to analyze input markets, especially beef cattle, and to a smaller literature examining the specific case of dairy bull markets. The first application of the hedonic model to agricultural input markets was the "input characteristics model" (ICM) from Ladd and Martin (1976). A substantial literature has used the ICM to analyze the relationship between beef cattle prices and their characteristics (Dhuyvetter et al. 1996; Williams et al. 2012; Tang et al. 2023; Melton, Colette and Willham 1994; Pinto et al. 2023). While the prices of feeder cattle are determined by how slaughterhouses and feed lots value the traits of cattle, the prices of breeding bulls are determined by what farmers view as desirable genetic traits. The vast majority of studies of these valuations estimate hedonic models using cross-sections of cattle auction data to determine which traits farmers view as the most profitable (Worley, Dorfman and Russell 2021; Jones et al. 2008; Thompson et al. 2022; Walburger 2002). Some of these studies have used panels of data to analyze how valuations for these traits may have changed over time (Tang et al. 2020; Walburger 2002).

Far fewer studies have analyzed how dairy farmers value genetic traits in the market for dairy bulls. The market for dairy bulls differs from the market for beef bulls in some important ways. First, nearly all dairy bulls are sold in the form of semen for artificial insemination and not alive at an auction. Second, all the valued traits of dairy bulls are estimated from data on their female offspring since all of the traits important to dairy farmers are female traits (e.g. milk production). Third, the use of selection indices for bull selection is more common in dairy than in beef. Richards and Jeffrey (1996) and Schroeder, Espinosa and Goodwin (1992) both use cross-sections of dairy bull prices from Canada and the US to estimate hedonic models using the genetic traits of dairy bulls. Richards and Jeffrey (1996) use their hedonic model to calculate their own selection index and find that it predicts prices better than Canada's most popular selection index, the Lifetime Profit Index.

My approach builds on this literature in three important ways. First, this is one of the few hedonic analyses in this literature that use panel data instead of cross-section. Apart from Tang et al. (2020) and Walburger (2002), nearly all hedonic analyses of cattle markets use one cross-section because of a lack of data. Multiple periods are especially important for this analysis since we would like to see whether changes in index weights influence how producers value genetic traits.

In addition to having more years of data, this study uses a dataset of dairy bulls that is far more comprehensive geographically than previous studies. While many analyses of cattle prices look at a limited number of auction sites (Walburger 2002; Tang et al. 2020) or just a few companies (Richards and Jeffrey 1996; Schroeder, Espinosa and Goodwin 1992), my data are sourced from the National Association of Animal Breeders (NAAB) “active sire” list, which contains bull prices and characteristics from all the major dairy breeders in the US. The members of the NAAB sell the vast majority of dairy semen in the country and my data contain bulls from more than 390 dairy breeders and 90 companies marketing semen.

Finally, the results here, that physical traits were important to dairy farmers during this period, are similar to those in the literature on salience and bounded rationality in decision-making (Bordalo, Gennaioli and Shleifer 2022, 2013; Gabaix et al. 2006). In particular, I find that traits that can be visually appraised by looking at the cattle are significant in the decision even when their impacts are supposedly captured by other attributes. This agrees with existing literature on consumer choice showing that attributes that are visually apparent can be overemphasized in choices (Milosavljevic et al. 2012). A major contribution of this work is providing evidence that there may be similar salience of visual traits in the market for livestock, an insight that is almost never considered when studying livestock pricing.

2. Theoretical Framework

This theory model is based on the Input Characteristics Model of Ladd and Martin (1976), an adaptation of Lancaster (1966) and Gorman (1980) to the case of inputs for a firm. The linear characteristics model for an input market assumes that there is a firm that needs k inputs and has a stock of each input z_k. To increase the stock of each input, the firm can only buy bundles of characteristics in the form of B_i. The “linear” in “linear characteristics model” derives from an assumption about how each bundle B_i increases the input stock z_k. The assumption says that z_k is equal to a linear function of the B_i that the firm has purchased:

(1) $$z_k = \sum_{i=1}^{N} x_{ik} B_i$$

where x_{ik} is the amount of characteristic k that B_i delivers. The amount of z_k that the firm has depends on which bundles the firm buys (B_i) and how much of each k the bundle gives (x_{ik}).

Dairy farms buy bundles of genetic traits by breeding with bulls (B_i) that will produce offspring. That offspring will produce milk and impact profits for the duration of its lifetime, so firms choose each bull to maximize the profits of that offspring's lifetime. The objective of the dairy farmers can then be written as maximizing profits of their herd by buying bundles B_i, each having a price p_i:

(2) $$max_B \quad \pi(z_1, \ldots, z_k) - \sum_{i=1}^{N} p_i B_i \quad \text{s.t.} \quad z_k = \sum_{i=1}^{N} x_{ik} B_i \quad \forall \quad k.$$

Schroeder, Espinosa and Goodwin (1992) and Richards and Jeffrey (1996) both point out that, in the case of a dairy farm, π is not only the current period's profits but actually the net present value of the future profits of the offspring. Regardless of the interpretation of π, the first-order conditions for this model are:

(3) $$p_i = \sum_{k=1}^{K} w_k x_{ik} \quad \forall \quad i.$$
$$\text{s.t.} \quad w_k = \frac{\partial \pi}{\partial z_k}$$

Because of the linear form of equation (1), each bundle's price p_i is a linear function of the amount of each input it delivers (x_{ik}) weighted by w_k, its marginal contribution to the firm's profits ($\frac{\partial \pi}{\partial z_k}$). This model tells us that a bull's price can be described as a linear function of its genetic traits, where each weight is that trait's contribution to the lifetime profit of each offspring.

Both the USDA and Holstein USA produce weightings of genetic traits that represent their own beliefs about the profitability of each trait. Calling these weights ω_k, we can represent a selection index like Net Merit (NM) or Total Performance Index (TPI) in a very similar way:

$$NM_i = \sum_{k=1}^{K} \omega_k^{NM} x_{ik} \tag{4}$$

$$TPI_i = \sum_{k=1}^{K} \omega_k^{TPI} x_{ik}. \tag{5}$$

Both w_k and $\omega_k^{NM}/\omega_k^{TPI}$ represent the lifetime profit of increasing that trait. Using equation (3) as a regression model, we can use the prices of dairy bulls on the market and their genetic traits to estimate w_k. The hypothesis we would like to test is essentially the relationship between w_k and ω_k, or whether dairy producers value genetics the same way a given selection index does. Since both NM and TPI are updated over time, we also have variation in ω_k over time to compare to how w_k changes over time.

The difficulty with comparing ω_k and w_k is that the units may not precisely be the same. One way to compare the two parameters is thus to calculate the relative emphasis of each trait in the index, or $\tilde{w}_k = \frac{w_k}{\sum_{k=1}^{K} |w_k|}$. To ease the comparison between traits of different units, we can also standardize the x_{ik} to have mean zero and standard deviation one: $\tilde{x}_{ik} = \frac{x_{ik} - \bar{x}_k}{\sigma_k}$. Using the relative weights, we can construct an alternative index using estimates of $\tilde{w}_k$ which represents how the market views the valuation of genetic traits, call it "Hedonic Net Merit" (HNM):

(6) $$HNM_i = \sum_{k=1}^{K} \tilde{w}_k \tilde{x}_{ik}.$$

Using this index, we can compare the market's version of profitability to what the NM and TPI say about profitability in two ways. First, we can compare the relative weights calculated from the bull prices p_i to what the selection indices use as weights in different periods of time. Second, we can examine the correlation between the constructed index HNM and the other selection indices over time. In animal science, a weak correlation between selection indices is evidence that they will rank bulls differently for producers (Bryant et al. 2007; Gonzalez-Recio et al. 2014).

3. Context and Data

The National Association of Animal Breeders (NAAB), a trade organization representing all of the major livestock genetics companies selling dairy bulls in the United States, publishes the posted price and genetic traits of all bulls being sold by their members. Traits and prices are posted three times a year at the same time that each bull's predicted genetic traits are calculated and posted publicly by the Council on Dairy Cattle Breeding (formerly the USDA) (Hutchins and Hueth 2023). My data is from the NAAB's published lists from August 2000 to August 2009 and represents over 24,000 dairy bulls, both foreign and domestic, sold by NAAB members during this period. The NAAB represents a substantial portion of the livestock genetics companies and cooperatives in the US and Canada, making these data broadly representative of what is sold to US dairy farmers.

Dairy bull genetic traits have been publicly available to dairy producers as "sire summaries" as early as 1937. The traits themselves have almost exclusively been published by the USDA which, before 1976, were only milk and fat yield (Hutchins and Hueth 2023). Starting in 1971, dairy scientists began creating selection indices published by the USDA that weighted the milk and fat yield into one index by multiplying them by the estimate of their prices, called "predicted difference dollars." Protein yield from milk was entered into a new index called Milk-Fat-Protein Dollars (MFP$) in 1976 (VanRaden 2004).

For Holstein cattle, the breed association Holstein USA publishes its own index, first called the Type and Production Index and later renamed the Total Performance Index (TPI) in 2007 (USA 2007). The TPI was first published in 1976 and had the name Type and Production Index because it was a weighted average of milk production ability and Type, a scoring variable measuring how much the bull's physical characteristics match the ideal of the breed association (VanRaden 2002). Type is calculated by scoring purely physical traits including the udder, feet, legs, and the size and shape of the body. Holstein USA also publishes composite indices called udder composite, feet and legs composite, and body size composite which combine the physical traits used in type scoring into these three categories (VanRaden 2000). In 1994, the USDA published the first Net Merit index, a profitability index that added lifespan, called "productive life," and somatic cell score, a measure of bacteria that correlates to disease, with their own economic weights that translate each trait to units of "lifetime profit." In the 2000 revision, Net Merit added the Holstein USA composite indices for udders, feet, and body size.

However, the USDA gave the body size score a negative weight in their index. According to the 2000 revision, "Research studies … funded by Holstein Association USA at the Universities of Wisconsin and Minnesota concluded that cow size should have negative value in an index because milk income already was accounted for but feed costs were not" (VanRaden 2000). Since the production traits in Net Merit already capture the milk-producing ability of larger cattle, the body composite score is considered to be negatively related to profit. Though bigger animals produce more milk, an animal with a higher body size composite and the same milk-producing ability would cost more feed for the same amount of milk. In contrast, both the udder composite and the feet and legs composite correspond to healthier, more resilient cattle and have always been considered profitable traits by the USDA. While the TPI does not have body size in their index, body size is positively correlated to Type in this period and so receives an implicit positive weight in the index.

[FIGURE 1 about here.]

Genetics companies produce promotional material to help market their bulls, usually a directory or catalog of bulls from which they can sell semen. Figure 1 shows four example "proofs" of dairy bulls sold in the US by four genetics companies: Genex, Select Sires, Semex, and ABS. In all four of these examples, the farmers are shown the genetic traits of the bull, the selection index values for TPI and Net Merit, the ancestry information, the name of the breeder, and photographs of either the bull itself or one of its daughters. In addition to showing the composites of the type traits, all of these proofs have charts that show how the bull's daughters score on each of the individual type traits that make up the composites (e.g. body depth, teat length).

[TABLE 1 about here.]

During the period of study, the Net Merit index was updated in August of three different years: 2000, 2003, and 2006. Table 1 shows how the relative weights of each category of traits changed in the three updates. The traits in Net Merit can be broadly categorized as production (traits having to do with milk production), health (traits having to do with longevity, sickness, and fertility), and type (traits having to do with the appearance of the udders, the feet and legs, and the body). At the beginning of this sample, Net Merit put about 60% of its emphasis on production traits versus about 23% on health traits. After the 2006 revision, production and health were nearly equal at 46% and 41%. The decline in production is mainly explained by a decline in the weight on protein, which was given instead to new health traits such as daughter pregnancy rate and calving difficulty.

The TPI was updated in 2002 and 2007, though the precise weights in those years are not publicly available. However, according to Miglior, Muir and Van Doormaal (2005), the

TPI weighted type traits higher in the index than Net Merit (14% in Net Merit versus 21% in TPI) but weighted production traits similarly (about 55%). Thus, health traits such as longevity and somatic cell score received comparatively less weight in TPI. In the 2007 update, the TPI reduced its emphasis on production to 45%, similar to the Net Merit index update in 2006, to introduce fertility and birthing ability traits into the index (USA 2007).

The increase in health emphasis in Net Merit is explained by a greater emphasis on productive life (lifespan) and the inclusion of traits measuring fertility and birthing ability in 2003. In the 2006 revision, Net Merit included stillbirth rate for calves born either by the sires themselves or the daughters of the sires (male and female stillbirth rate). This was incorporated along with calving difficulty into one index called "calving ability" which was given 5% emphasis in 2006. Type traits were slightly reduced in the index from 15% to 13%.

[TABLE 2 about here.]

Genetic traits in dairy are by default "base-adjusted," meaning that every three years, the average value is subtracted from every bull's trait value. If a trait is above zero, this means it has more of the trait than that period's average (+50 fat pounds means 50 more pounds than the average bull). If a trait is negative, this means it has less of the trait than the average bull. In order to see genetic improvement in the data, I have undone the base adjustments from 2000 to 2010 so that every trait is relative to the average bull in 2000.

Where did breeders focus their efforts during this period? Table 2 shows the average trait values during the three Net Merit revision periods. From 2000 to 2009, all production traits increased between 15 and 25%. Productive life increased 61% and somatic cell score and conception difficulty on the female side all decreased (meaning health improved). All three of the type traits increased over this period, with the udder composite having one of the highest growth rates of all the traits: 75%. Despite having a negative weight in Net Merit, the body size index grew 20% from 2000 to 2009 after dipping between 2003 and 2006.

[FIGURE 2 about here.]

Figure 2 shows the average bull price in each evaluation period from August 2008 to December 2009. These prices are posted by the cooperative or company selling the bull and are usually used in advertisements.[1] Reflecting the increase in traits, bull prices increased from \$16.5 to about \$19 (a 15% increase). From the first period in the data until the 2003 revision, the average price climbed from \$16.5 to about \$17. After the 2003 revision, the price increased another dollar but then stayed around \$18 for the remainder of the period.

4. Methodology

The first order condition of the linear characteristics model, equation (3), implies that we can use data on prices p_{it} and genetic traits x_{ikt} of each bull i in time t to estimate w_k. The primary regression model takes the form:

$$p_{it} = \sum_{k=1}^{K} w_k x_{ikt} + \beta Z_{it} + \epsilon_{it}. \tag{7}$$

To compare the weights from this model to those of Net Merit, the set of K genetic traits is identical to those used in Net Merit. Comparing hedonic weights w_k to Net Merit weights ω_k is easier if the weights are relative weights that are independent of the units of each trait (interpreted as percentage of emphasis on each trait). Net Merit "relative weights" are calculated by dividing each weight by the standard deviation of the trait (making it in units of standard deviation), taking the absolute value of each trait, and dividing each trait by the sum of those absolute values.[2] To convert w_k weights into relative weights, each trait x_{ikt} is standardized by subtracting the sample mean and dividing by the sample standard

[1]Anecdotally, some dairy farms in practice bargain the price lower than the posted price if they have a large enough herd size. While these are not actually transacted prices, they broadly represent the pricing behavior of these companies much in the way that posted home or car prices do. See Appendix C for a robustness check which simulates discounts

[2]See VanRaden (2000) for more details on this calculation.

deviation. The resulting weights w_k can then be compared even when each trait has a different unit. To get the relative weights, each w_k is divided by the sum of the absolute value of the traits.

While the original NM and TPI index weights are interpreted as dollars of profit, it is important to point out that the relative weights do not have the same interpretation. Instead, they indicate how much of the variance of the index or price is explained by variation in the traits. Applying this normalization is helpful for understanding how the emphasis of the indices have changed over time from a profitability perspective. However, unlike the original weights of NM and TPI, they do not tell us how much profit each trait is estimated to change profits.

In the case that there are omitted variables that correlate to both x_{ikt} and p_{it}, I include a vector of control variables Z_{it} within this regression model. One potential source of endogeneity is the bull's popularity or fame, a possible driver of both price and characteristics. To control for these impacts, I include a fixed effect for the stud code (the company that collects the semen from the bull), the controller (the company that markets and sells the bull, which may be the same as the stud) and a fixed effect for the name of the farm that the bull comes from.[3] As a bull ages, the supply of its semen also goes down which can increase its price (Richards and Jeffrey 1996). To control for this impact, I also include the bull's age, the number of herds in its evaluation (which reflects the total units purchased), and a fixed effect for the bull's birth year. To control for factors common to all bulls across time, I also include fixed effects for each period.[4]

During our sample, some companies choose not to report a posted price for one of their bulls in the NAAB list. Approximately 13% of the bulls in this sample are missing prices. To correct for the missing prices, I implement the Heckman two-step correction by first predicting missingness with a probit model and then using it to estimate the inverse-mills

[3]For more details on the difference between the stud code, the controller number, and the farm, see Appendix **??**.

[4]For robustness checks using different levels of fixed effects, see Appendix C.

ratio which is used as a covariate (Heckman 1979). Specifically, the probit model takes the form:

$$P(Missing_i = 1|X, Z) = \Phi(\sum_{k=1}^{K} w_k x_{ikt} + \beta Z_{it}) \tag{8}$$

and the inverse mills ratio (IMR) is calculated as:

$$\lambda(X, Z) = \frac{\phi(X, Z)}{\Phi(X, Z)}$$

where X and Z are the vectors of genetic traits and control variables and Φ and ϕ are the cumulative distribution and probability density functions of the normal distribution. While there is no excluded variable in the selection equation which is not in the main model, identification of the sample selection model is still possible if the sample selection model is correctly specified, meaning the first stage has sufficient predictive power (Honoré and Hu 2020). Since I am including a generated regressor, all of the standard errors for the model coefficients are estimated with a clustered bootstrap at the level of the stud code.

5. Results

I first present the coefficients of the hedonic model (equation (7)), which uses the logarithm of price as an outcome to lessen the influence of any outliers. Like Tang et al. (2020) and Walburger (2002), I estimate the model using three different time periods based on the three Net Merit revisions: 2000-2003, 2003-2006, and 2006-2009. I then compare the relative weights to both TPI and Net Merit before calculating the correlation of the Hedonic Net Merit index to both Net Merit and TPI. Information on the impacts of control variables and fixed effects on the coefficients is available in Appendix **??**. The results of the first stage probit for the missing prices are available in Appendix **??**.

[Table 3 about here.]

Table 3 shows the results of the hedonic model using the logarithm of price as the outcome. Milk production independent of fat and protein, the first variable, is positively related to price from 2000 to 2003, when the NM weight on the trait was positive. In subsequent periods when the NM weight is zero, the trait becomes statistically insignificant from zero. Fat and protein are positively related to price and statistically significant in every period, since this is the metric that many farmers are paid on. Yet, both fat and protein dip after 2003, becoming less strongly predictive of price. The protein coefficient declines from 0.132 in 2000 to 0.08 in 2006 which mirrors Net Merit).

In terms of health traits, somatic cell score becomes more negative over time though not statistically significant unless the data are pooled. Daughter pregnancy rate and the calving traits were not significant in the first period they were introduced but do become significant in 2006. Productive life, the longevity trait, is positively related to price in every period.

All three type traits, udder, feet, and body size, positively impact price. Out of all the Net Merit traits, udder composite has the largest coefficient in every period (at least 0.17). Most striking, body size composite is positively related to price despite that trait receiving a negative weight in the Net Merit index for this whole period.

Since TPI weights are not publicly available, the relative weights for Net Merit and TPI here are calculated using a simple linear regression where either the Net Merit or TPI index is the dependent variable and the traits from each period are the independent variables. As such, the index weights calculated here are best, linear approximations within the set of traits for each period rather than the official weights.[5] Like in the main regression model, the traits used in the regression model are standardized to be mean zero and standard deviation one to have comparable units. Relative weights are then calculated from the

[5] In the event of the official weights being different than what is estimated here, there may be inaccuracies in what is estimated if there are not enough bulls in all parts of the trait space. Nevertheless, without the official weights available for TPI, this is a second-best solution that is a good approximation with enough bulls at every trait level. While the Net Merit weights are available, I calculate the Net Merit and TPI relative weights the same way to ensure comparability.

estimated coefficients using this formula: $\tilde{w}_k = \frac{w_k}{\sum_{k=1}^{K} |w_k|}$.

To calculate standard errors for each of the relative weights from the hedonic model, I bootstrap the model 1,000 times using a cluster bootstrap and calculate the relative weights each time. The standard errors are calculated as the standard deviation of the 1,000 replications of each relative weight. Asterisks indicate whether 0 is outside the 95th percentiles of the replications.

[Table 4 about here.]

[FIGURE 3 about here.]

Table 4 shows the relative weights of the Hedonic Net Merit (HNM), Net Merit, and TPI in each time period. In 2000, fat and protein were 14 and 17% of HNM, 18 and 31% of Net Merit, and 16 and 30% of TPI. HNM put about 12% emphasis on milk yield independent of fat and protein compared to about 5% in Net Merit and 0% in TPI By 2006, fat was still 12% in HNM while protein went down to 12%. This mirrors protein's shift in the Net Merit and TPI, indicating that changes in these indices may have had an influence on market valuations. While health traits are significant determinants of price, they have a much smaller weight in HNM than in Net Merit: productive life is about 8% of HNM and more than 12% in Net Merit and TPI. Likewise, HNM seldom put significant emphasis on somatic cell score, daughter pregnancy rate, or any calving traits.

As in the main model, type traits receive the highest weight in HNM. The udder index is at least 24% of HNM but only about 9% of Net Merit and 17% of TPI. Similarly, the feet and legs index is between 10% and 13% of the HNM but only between 3-4% in Net Merit and around 6% in TPI. Body size receives a positive weight in HNM and is between around 8-10% of the index, which even exceeds TPI's weight (about 5%).

Figure 3 shows the percentage emphasis of nine traits across time. Due to large confidence intervals, it is difficult to determine whether relative emphasis on these traits really changed over time. However, some notable examples of changes in trend are the somatic cell score becoming more negative and the daughter pregnancy rate becoming more positive, both indicators of more emphasis on health. There is a slight downward trend in emphasis on protein yield, which complements the increased emphasis on health. In terms of type traits, the udder and feet composites stay constant while there is a slight increase in emphasis for body size composite.

[FIGURE 4 about here.]

Figure 4 shows the changes in the indices over time aggregated into health, type, and production traits. As seen in Table 1, Net Merit diverted 17% of the index away from production towards health and left type unchanged. The TPI did not change very much from 2000 to 2009 and diverted only about 5% of the index from production to health.

Compared to these indices, the market consistently put more emphasis on type traits while diverting a little over 10% of its emphasis away from production towards health. In the market-calculated HNM, the type traits receive 50% emphasis, versus 30% in TPI and about 17% in Net Merit. As in the other indices, the total weight towards type traits changed only slightly: an increase of 2% emphasis. As Net Merit emphasized health over production, the HNM also placed more emphasis on health and away from production. In health, the HNM increased emphasis from 6% in 2000-2003 to about 17% in 2006-2009. In production, the HNM decreased emphasis from about 44% in 2000-2003 to about 31% in 2006-2009. Thus, while Net Merit and TPI diverted 17% and 5% away from production towards health, the market diverted about 12-13%.

[FIGURE 5 about here.]

Analyses of correlations further emphasize how these indices diverged over time. To compare the indices, I create new indices using the relative weights in Table 4 for HNM, Net Merit, and TPI across all three time periods. The new index is created by multiplying the relative weights by each of the standardized variables and summing them together: New HNM/NM/TPI = $\sum_{k=1}^{K} \tilde{w}_k \tilde{x}_{ik}$.

Figure 5 shows a scatter plot comparing indices created from the relative weights in 2000-2003 for every bull in the sample. This figure uses the weights from 2000-2003 since only the traits in 2000-2003 are available in every year. Dots that are the furthest from the dotted line are bulls that experienced the largest potential changes in their ranking. Based on the spread from the 45 degree line, we can see that the TPI aligns closer to the market index than NM does in general.

The figure also notes with circles and the color red two clusters of bulls (made up of 8 and 12 total bulls). The first cluster was reranked higher by the market and the second cluster was reranked lower. In the first cluster, the bulls were below average on production and health traits but had high values of body size composite (average of 2.18) and feet and legs composite (average of 2.44). In the standardized units, this means that these bulls had two standard deviations higher than average on these type traits. In the second cluster, the bulls were less than one standard deviation below average on production and health but 1-2 standard deviations below average on udder composite (-3.45), feet and legs composite (-2.33), and body size composite (-2.22). These two clusters demonstrate that type traits are a major reason bulls are ranked so differently by the market.

Below Figure 5, I calculate the correlations between the HNM and the other indices in each time period. As a point of comparison, other reranking studies find the lowest correlation between a new and an old index to be typically 0.9 (Bryant et al. 2007; Schmitt, VanRaden and De Vries 2019). In 2000-2003, the market ranked bulls most similarly to TPI, with a correlation of 0.933, while showing weaker similarity to Net Merit, with a correlation of 0.766. Over time, the market's rankings diverged from both indices. The correlation between Net Merit and the HNM is especially weak after 2003: about 0.58-0.63 versus about a 0.85 correlation with TPI.

Overall, the market valued type traits far higher than either index in this period. Yet, the market valuations also followed the other indices by diverting a little over 10% emphasis away from production into health as more health traits were introduced. The rate at which the market changed appears to be between the 17% the NM diverted and the 5% the TPI diverted. In other ways, the market values traits similarly to the TPI. Along with a larger emphasis on type traits, the market, like the TPI, considers body size to be positively correlated to profitability, despite the USDA claiming otherwise.

In Appendix **??**, I conduct a few robustness checks on the results. In Table **??**, I explore more flexible fixed effect specifications by adding stud by time, farm by time, or controller by time fixed effects into the regression model. In Table **??**, I run the model on subsamples of the data made up of stud and controllers with less than 5% of their bulls missing or at least 10 bulls in every period on average. In Table **??**, I test the robustness of the results by simulating price discounts based on the average prices at the stud level. Finally, in Table **??** and **??**, I estimate a version of the model with post-revision indicators to see whether there were statistically significant changes in the coefficients. While there are some fluctuations in the coefficients, the results of these robustness check support the conclusions from the main analysis.

6. External Validity After 2009

[FIGURE 6 about here.]

Due to data limitations, this analysis does not extend past 2009. However, there have been significant changes in the dairy genetics industry that may make the findings here less valid from 2010 to 2020. In this section, I discuss what these changes are and how they might impact the conclusions determined from these data.

The first — and arguably most important — change in the industry was the adoption of genomic testing. Under genomic testing, bulls can be genetically tested to estimate their predicted benefits to their offspring without the use of daughter records. This allows breeders to select bulls with more precision and faster, since they do not need to wait until daughters are born to the bull to market it.

[TABLE 5 about here.]

As a result, the rate of increase in some genetic traits has almost doubled. Table 5 shows the genetics traits present in the 2006 Net Merit revision from 2010 to 2019. It then compares the rate of growth in those nine years compared to another nine year period: 2000 to 2009. Production and health traits both improved greatly in this period and at a faster rate than they did from 2000 to 2009. Notably, while body size and udder composites grew from 2010 to 2019, feet and legs did not. Plus, the rate of growth on the type traits is much lower than it was in the first decade. This would appear to suggest that progress in type traits has slowed because dairy breeders have focused on them less and less.

Promotional materials from 2025 also give suggestive evidence about what role physical traits now play in marketing. Figure 6 shows bull proofs from the same companies in Figure 1 but from the year 2025. The most notable difference is that the pictures of the bulls are much smaller or non-existent in the proof. This might be evidence that breeders have indeed since leaned less on visual characteristics when marketing genetics.

The main sample used in this paper does not extend beyond 2009, unfortunately, due to a lack of price reporting in the lists from 2010 onward. Nevertheless, I present an analysis of these data in Appendix **??** to gauge whether they support the conclusions from the data before 2009. All three type traits appear to be strongly predictive of price after 2009, though depending on the sample their effect on price is either weaker or stronger than it was from 2006 to 2009. Due to the selectivity issues of these post-2009 data, future analysis would need to use more reliable pricing data than what are available in this paper to judge whether the trends identified here continued into the genomics era.

7. Conclusion

The objective of this study was to determine how producer valuations of genetic traits in dairy cattle compare to selection indices used heavily in the industry. During this period of study, more health traits were introduced to the market which caused both Net Merit and TPI to emphasize bulls with higher health traits. Using a hedonic model, I tested whether these changes were reflected in bull prices to see how market valuations responded.

I find that dairy farmers appear to value type traits, that is physical traits, much higher than either index does. Despite the fact that body size composite receives a negative weight in the USDA's index, it receives a positive weight in the market. This agrees more with the breed association Holstein USA's judgement of the trait's importance, and I find evidence that the market's valuations of traits are more highly correlated to the association's index, TPI, than the USDA's index, Net Merit. Yet, I also find that the market shifted about 10% emphasis towards health traits in this period, which is higher than the 5% shift in the TPI but lower than the 17% in the NM.

Why would type traits be so highly valued by farmers independent of production? One potential explanation is that farmers trust type traits as stronger indicators of production and health than production and health traits alone. Udder traits are significantly correlated to health outcomes in dairy cattle, as are feet traits. Dairy producers may believe that these traits predict health outcomes better than traits like somatic cell score and productive life. Body size is associated with higher milk production, and producers may believe that body size is a better predictor of milk production than the genetic traits for fat and protein yield.

Alternatively, these results could be interpreted in light of work on bounded rationality and salience. When dairy farmers choose bulls, there are several characteristics to choose from and it might make sense that dairy farmers will limit their attention to a subset of characteristics that are salient. Judging by the use of photos in promotional material in this period, it may be that physical attributes of cattle continue to be salient in their decisions, even if economically related traits (e.g. milk production) are already measured directly. Compared to other genetic traits, physical traits have also been in use by the industry for far longer. Future work on cattle pricing could explore whether salience of these traits or bounded rationality could explain some of these preferences for breeding bulls.

Above all, the results suggest that recalculating weights or adding traits to indices to shift which bulls dairy farmers use may have a limited impact. At a baseline, dairy farmers in this period have preferences that do not necessarily agree with what the USDA believes dairy farmers should choose. In particular, a preference for larger cows would work against both feed efficiency and methane emissions since these are correlated to body size (González-Recio et al. 2020; Gonzalez-Recio et al. 2014). Still, a limitation of this study is that these data only cover 2000 to 2009. As the industry has changed, the market may no longer value type traits as highly as it did in this period. To understand whether these preferences exist today, more work is needed with more recent data.

Many studies have been done in beef cattle markets about the market valuations of new beef cattle traits (Zimmerman et al. 2012; Williams et al. 2014; Thompson et al. 2022). However, we have far less understanding about how dairy farmers value traits and innovations in bull genetics and this significantly limits how much we can understand about demand for dairy genetics. More revealed or stated preference studies of farmer-adoption of dairy genetics would be an important step in understanding what producer preferences are and how they might work against the goals of scientists to nudge farmers into adopting more efficient dairy cows.

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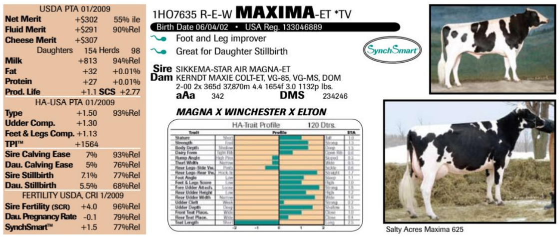
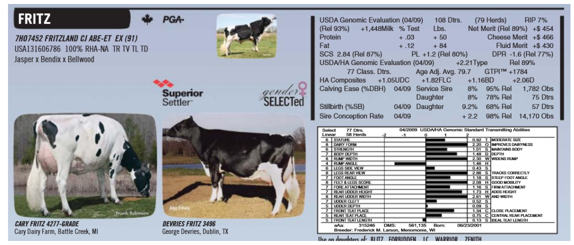
FIGURE 1. Bull Proofs from Four Genetics Companies

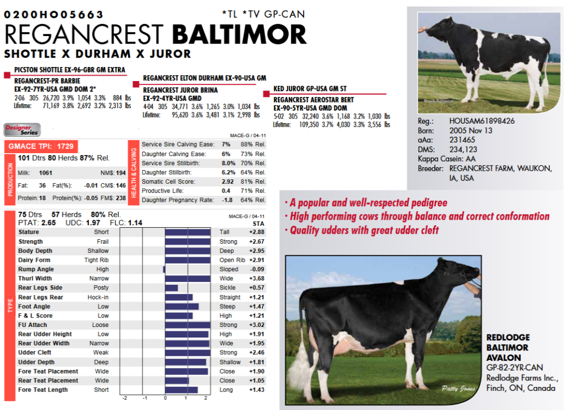
Genex, 2009



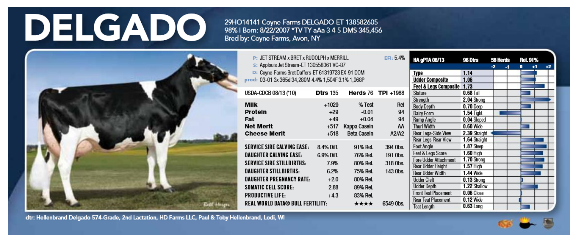
Select Sires, 2009



Semex, 2011

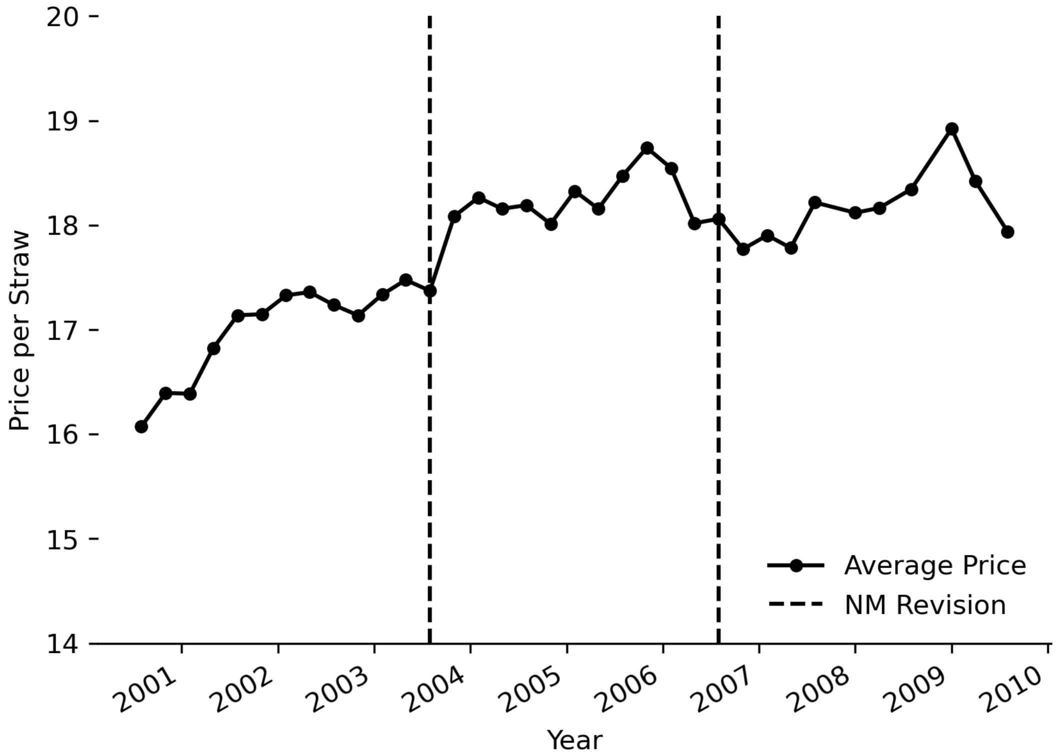


ABS, 2013



Source: Genex (2009), Sires (2009), Semex (2011), ABS (2013).

FIGURE 2. Average Bull Price over Time



Note: adjusted to 2000 CPI index.

FIGURE 3. Percentage Emphasis of Traits Over Time

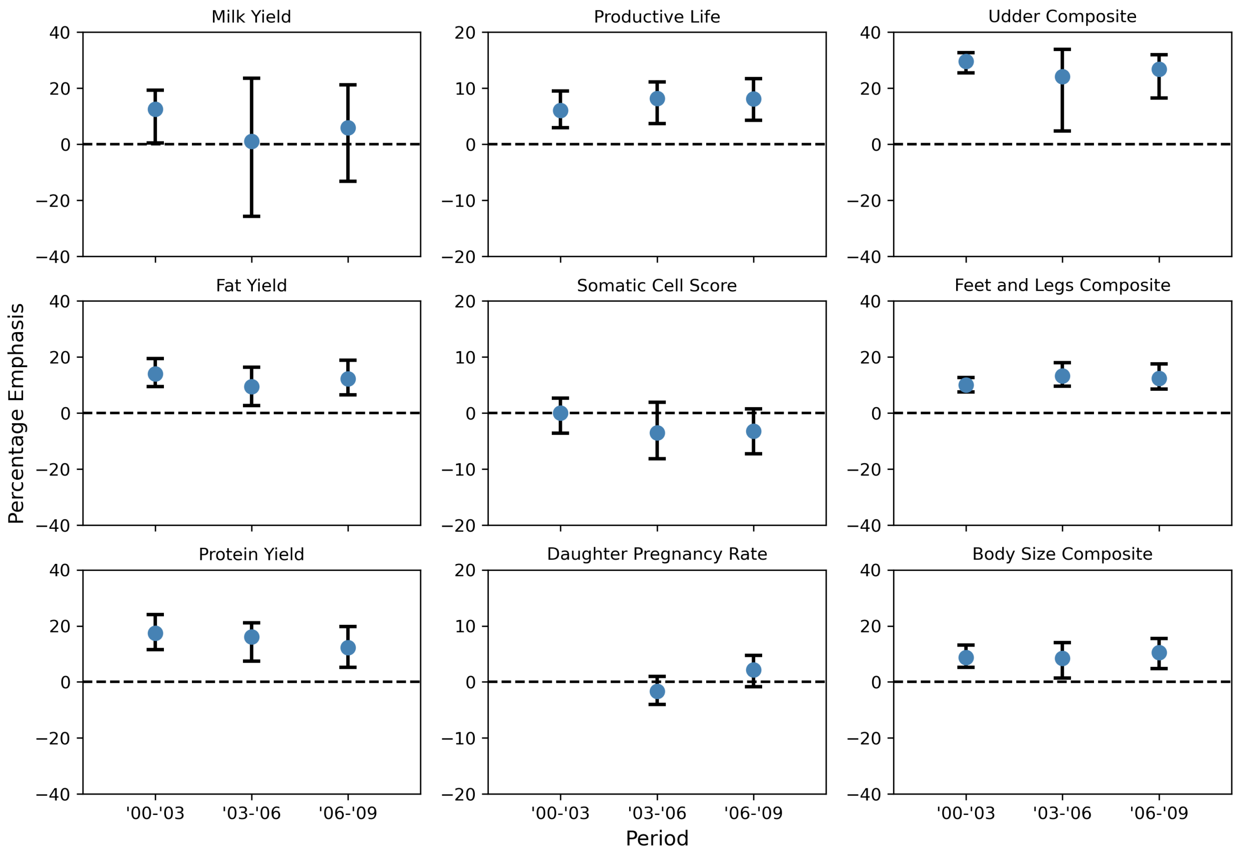


FIGURE 4. Trait Emphasis by Period

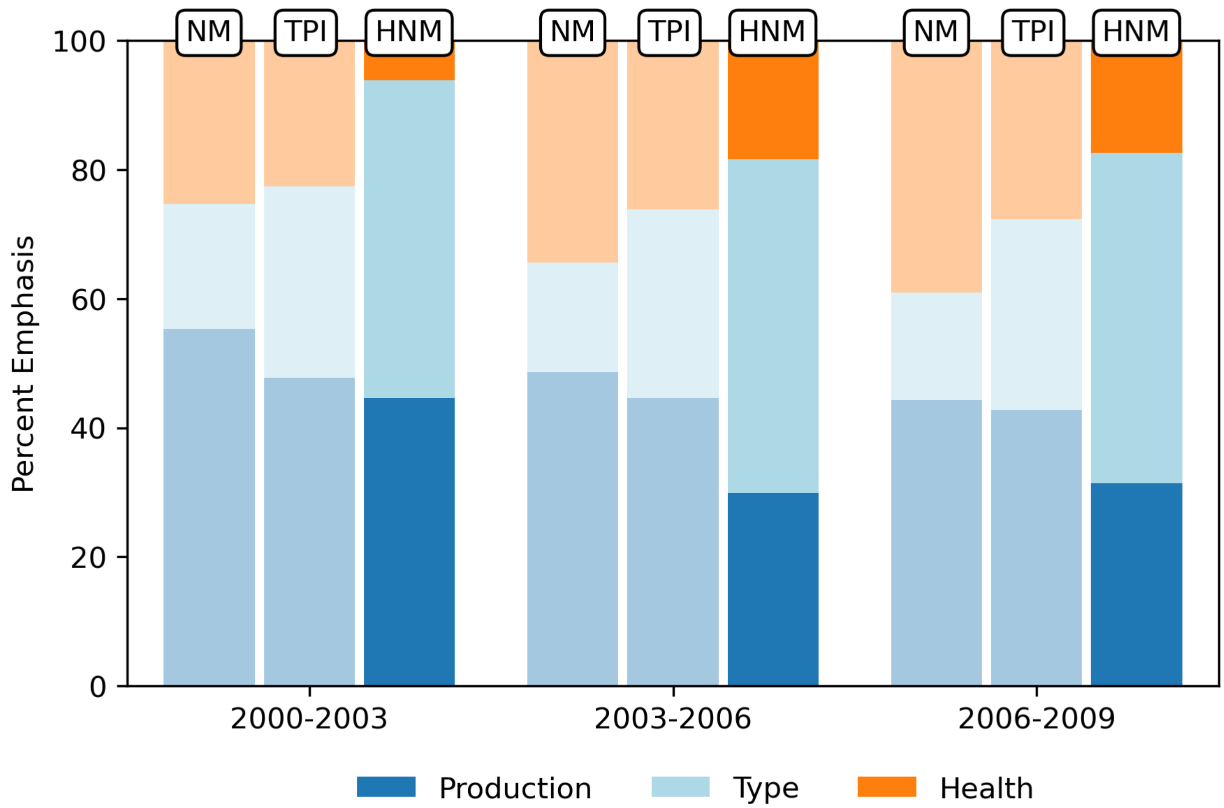
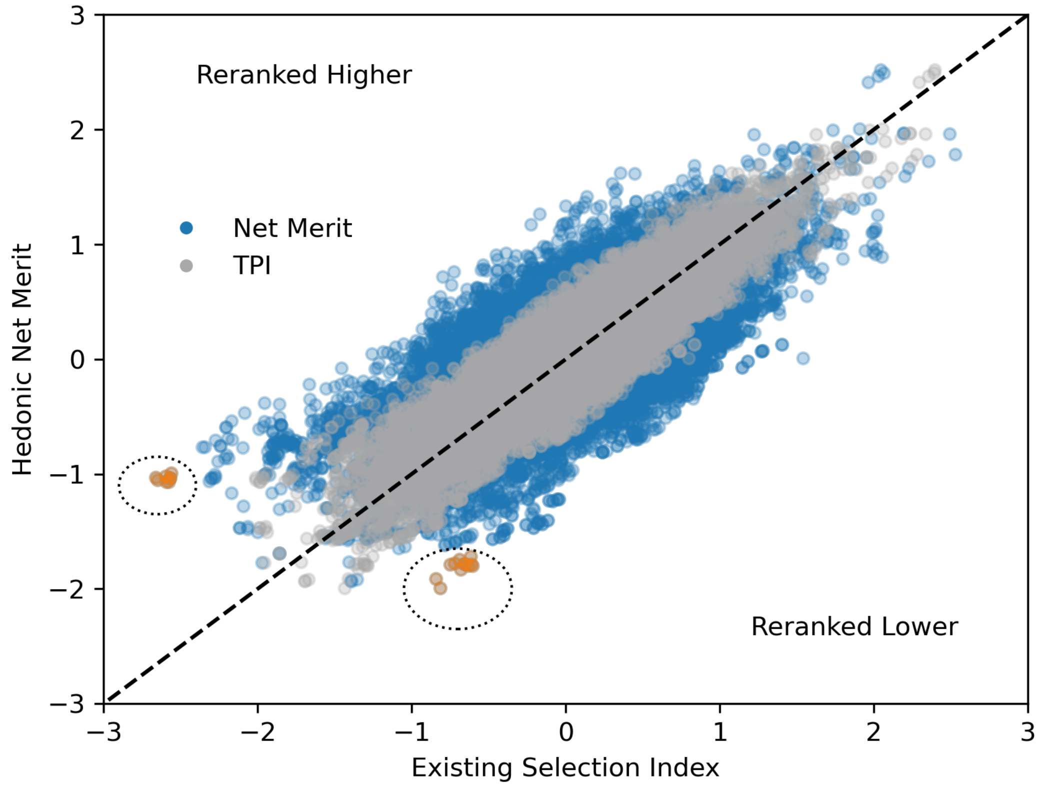


FIGURE 5. Correlations Between Hedonic Net Merit and Estimated Selection Indices

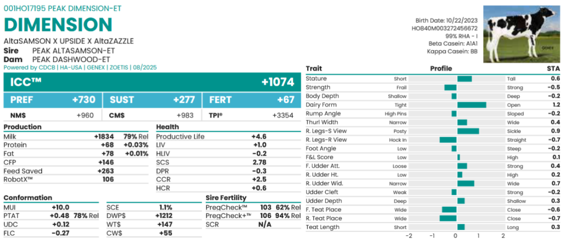


Note: notable clusters of outliers indicated in red.

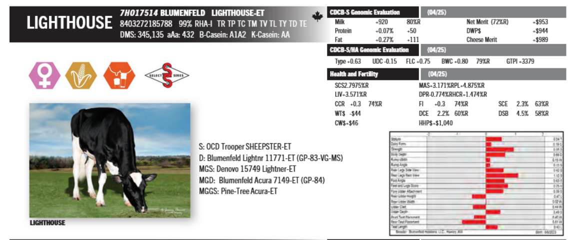
	Correlation to Hedonic Net Merit		
	2000-2003	2003-2006	2006-2009
Net Merit	0.750	0.633	0.585
TPI	0.917	0.845	0.862

FIGURE 6. Bull Proofs from Four Genetics Companies in 2025

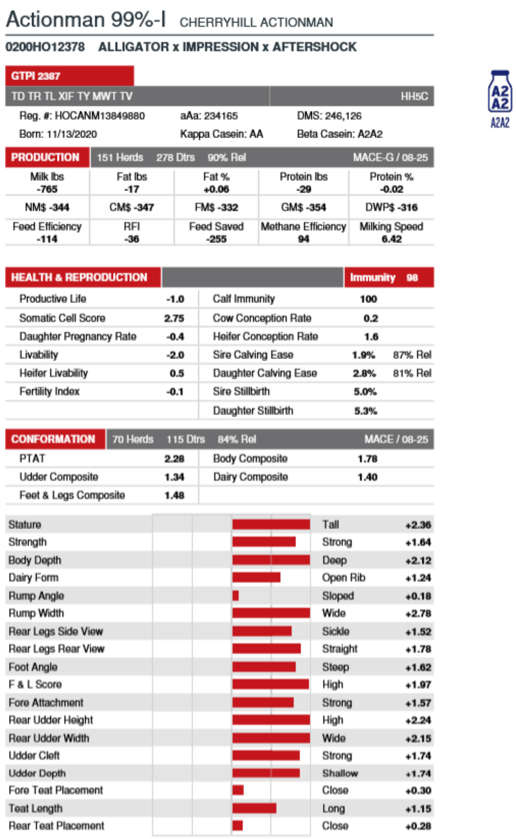
Genex



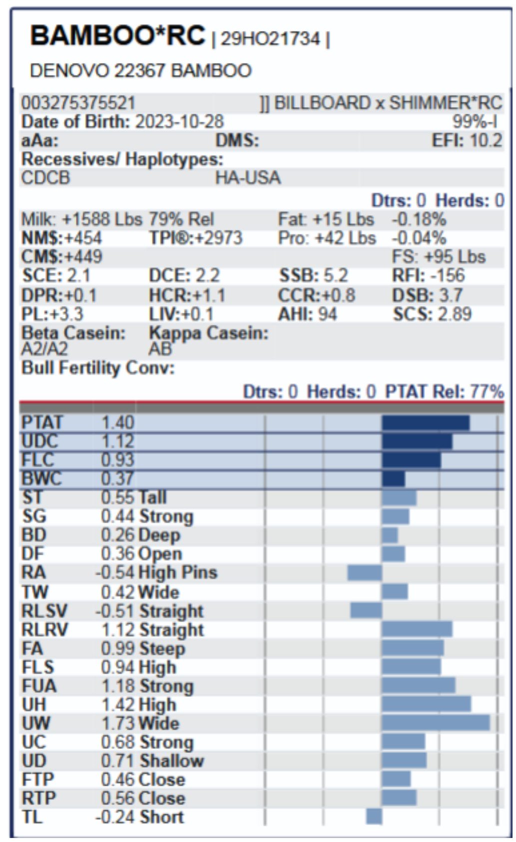
Select Sires



Semex



ABS



Source: ABS (2025), Semex (2025), Sires (2025), Genex (2025)

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TABLE 1. Net Merit Index Relative Weights (%)

Category	Net Merit Revisions		
Trait	2000	2003	2006
Production	**61.91**	**55.48**	**46.00**
Milk (lbs)	4.58	0.00	0.00
Fat (lbs)	20.94	22.38	23.42
Protein (lbs)	36.39	33.10	22.58
Health	**23.12**	**30.70**	**40.57**
Productive Life (months)	13.70	10.74	17.61
Somatic Cell Score	-9.42	-9.14	-8.67
Daughter Pregnancy Rate	-	6.55	8.50
Calving Difficulty (male)	-	-2.34	-
Calving Difficulty (female)	-	-1.93	-
Calving Ability*	-	-	5.78
Type (Physical)	**14.98**	**13.83**	**13.43**
Udder Composite	6.92	7.09	6.32
Feet and Legs Composite	4.04	3.63	3.31
Body Size Composite	-4.02	-3.11	-3.81

*The Calving Ability index is calculated as:
$CA = -4(SCD - 8) - 3(DCD - 8) - 4(SSB - 8) - 8(DSB - 8)$
where SCD and DCD are male and female calving difficulty and SSB and DSB are male and female stillbirth rate.

TABLE 2. Net Merit Traits Over Time

Category Trait	Average, 2000-2003	Average, 2003-2006	Average, 2006-2009	% Change, 2000 to 2009
Production				
Milk (lbs)	1,792.72	1,963.03	2,109.09	17.65
Fat (lbs)	57.44	64.97	72.43	26.09
Protein (lbs)	57.54	63.53	67.24	16.85
Health				
Productive Life (months)	1.24	1.37	1.99	61.21
Somatic Cell Score	3.21	3.19	3.15	-1.65
Daughter Pregnancy Rate		0.02	-0.04	-
Calving Difficulty (male)	-	8.89	9.01	-
Calving Difficulty (female)	-	6.56	5.45	-
Calving Ability	-	-	6.04	-
Type (Production)				
Udder Composite	0.91	1.18	1.60	75.54
Feet and Legs Composite	0.89	0.87	1.15	29.92
Body Size Composite	0.74	0.65	0.88	19.51

Note: all trait values are relative to the 2000 average.

TABLE 3. Hedonic Model Results

	log(Price)			
	Pooled	2000-2003	2003-2006	2006-2011
Production				
Milk (lbs)	0.046	0.109**	−0.011	0.063
	(0.041)	(0.045)	(0.173)	(0.068)
Fat (lbs)	0.089***	0.105***	0.080*	0.086***
	(0.010)	(0.015)	(0.042)	(0.017)
Protein (lbs)	0.106***	0.132***	0.126***	0.079***
	(0.021)	(0.025)	(0.048)	(0.025)
Health				
Productive Life (months)	0.069***	0.050***	0.067***	0.059***
	(0.011)	(0.012)	(0.020)	(0.014)
Somatic Cell Score	−0.016*	0.002	−0.031	−0.020
	(0.009)	(0.012)	(0.030)	(0.014)
Daughter Pregnancy Rate			−0.016	0.018*
			(0.015)	(0.010)
Calving Ability				0.025*
				(0.013)
Calving Difficulty (male)			0.006	
			(0.010)	
Calving Difficulty (female)			−0.010	
			(0.012)	
Type				
Udder Composite	0.189***	0.233***	0.171*	0.201***
	(0.028)	(0.030)	(0.098)	(0.044)
Feet and Legs Composite	0.086***	0.081***	0.096***	0.083***
	(0.009)	(0.012)	(0.009)	(0.012)
Body Size Composite	0.069***	0.070***	0.066***	0.077***
	(0.014)	(0.014)	(0.022)	(0.021)
Other Covariates				
Inv Mills Ratio	−0.004	−0.069	0.202	−0.109
	(0.124)	(0.135)	(0.515)	(0.214)
Herds in Estimate	0.00002***	0.00002***	0.00002***	0.00004***
	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Observations	24,052	7,723	7,569	7,140
Adjusted R^2	0.620	0.673	0.631	0.650

Fixed effects: age of bull, company (stud and controller), evaluation period, birth year, farm name.
Note: *p<0.1; **p<0.05; ***p<0.01.
Standard errors are boostrapped with 1,000 reps and clustered at the stud level.

Table 4. Relative Weights of Selection Indices, 2000-2009

	2000-2003			2003-2006			2006-2009		
	NM	TPI	Hedonic	NM	TPI	Hedonic	NM	TPI	Hedonic
Production									
Milk (lbs)	4.607	-0.656	12.446*	-0.045	0.273	1.009	-0.125	1.076	5.930
			(5.094)			(12.869)			(8.593)
Fat (lbs)	18.766	16.531	14.079*	19.743	17.146	9.382*	21.957	17.229	12.276*
			(2.636)			(3.503)			(3.152)
Protein (lbs)	31.947	30.608	17.487*	28.879	27.242	16.103*	22.235	24.475	12.223*
			(3.061)			(3.683)			(3.658)
Health									
Productive Life (months)	15.748	17.927	6.018*	14.532	12.580	8.167*	15.247	10.825	8.114*
			(1.721)			(1.955)			(1.929)
Somatic Cell Score	-9.522	-4.716	-0.016	-9.004	-5.717	-3.529	-8.487	-5.977	-3.244
			(1.633)			(2.647)			(2.110)
Daughter Pregnancy Rate				6.035	5.937	-1.691	8.453	8.486	2.172
						(1.297)			(1.417)
Calving Difficulty (male)				-3.989	-0.464	1.497			
						(2.977)			
Calving Difficulty (female)				-0.828	-1.493	-1.438			
						(1.378)			
Calving Ability							6.849	2.355	3.318
									(2.013)
Physical									
Udder Composite	9.510	17.555	29.628*	9.117	17.637	24.147*	8.401	18.190	26.747*
			(1.910)			(7.807)			(3.945)
Feet and Legs Composite	4.821	6.650	10.070*	4.119	6.952	13.245*	3.652	6.652	12.322*
			(1.269)			(2.066)			(2.252)
Body Size Composite	-5.078	5.358	8.805*	-3.711	4.558	8.430*	-4.594	4.735	10.531*
			(1.946)			(3.140)			(2.768)

Standard errors are calculated as the standard deviation of 1,000 bootstrap replications.
* indicates that 95th percentiles of the bootstrap distribution are outside 0.

TABLE 5. Summary Statistics, Post-2009

	2010	2019	Percent Change 2010-2019	Percent Change 2000-2009
Milk (lbs)	2255.72	3269.95	44.96	30.59
Fat (lbs)	82.25	136.45	65.89	40.36
Protein (lbs)	74.37	114.44	53.88	27.83
Productive Life (months)	3.22	7.17	122.90	89.97
Somatic Cell Score	3.08	2.92	-5.17	-2.33
Daughter Pregnancy Rate	-0.00	1.08	*	-
Calving Difficulty (male)	8.21	7.49	-8.79	-
Calving Difficulty (female)	6.61	3.48	-47.35	-
Calving Ability	10.92	50.35	361.26	-
Udder Composite	2.43	3.99	64.25	161.22
Feet and Legs Composite	1.19	0.95	-20.57	81.40
Body Size Composite	1.52	1.96	29.10	75.76

* Rate of increase difficult to define when going from negative to positive

Appendix A. Control Variables

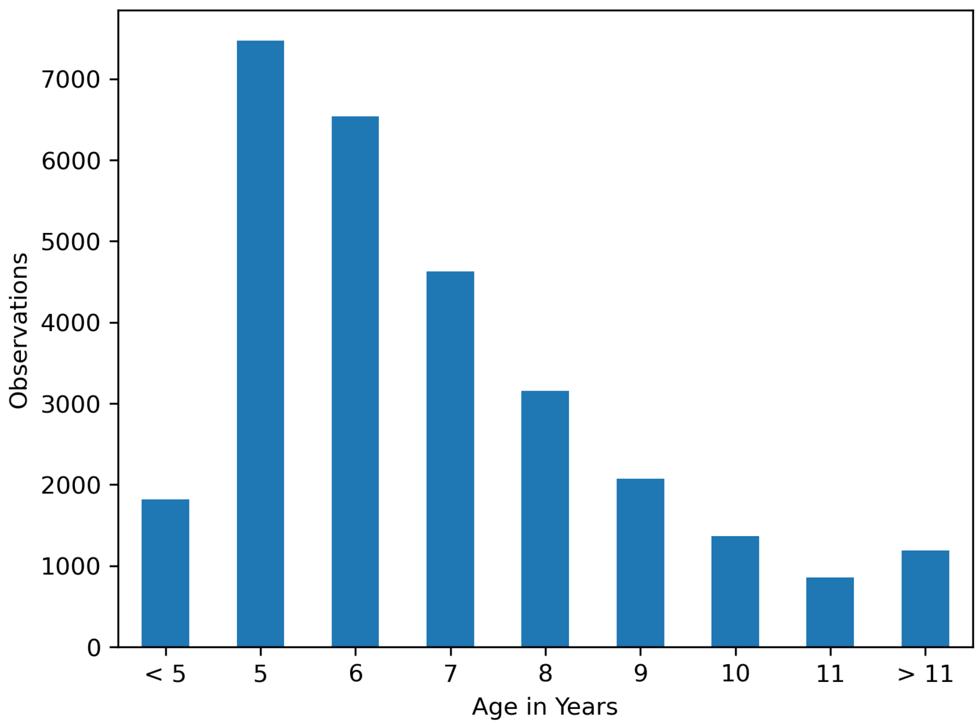
In this analysis, I include fixed effects for both the company selling the bull (the stud) and the farm that bred the bull, or what I refer to throughout as the breeder. In the dairy industry, the breeders are responsible for making crosses of different genetic lines to produce bulls whose semen can be sold on the market. The stud farm's name is almost always contained in the first part of the bull's name. For example, the bull "Braedale Goldwyn" is from Braedale farms and goes by the short name "Goldwyn." Using each bull's full name, we extracted the name of the farm to use a control since some farms may be famous enough to command a price premium. In our data, there are 353 unique farms that have more than five bulls associated with the farm in the data.

Once a breeder produces a bull, they may sell the rights of distribution to a company that is a member of the NAAB (e.g. ABS, Select Sires, Genex). The company that collected the bull's semen is represented by the stud code. The company that owns and markets the bull is represented by the controller number, which may or may not be the same as the stud code. In our data, there are 90 unique stud codes and 76 unique controller numbers, some of which belong to different subsidiaries of the same company (e.g. multiple cooperatives that are associated with one company).

The age of the bull is calculated using the bull's birth date, the distribution of which is shown in Figure A.1. Most bulls are released onto the market in this period at about 5 years old since it takes about that amount of time to gather enough data to calculate genetic evaluations. The average age of a bull in the data is 7.34 years old, with very few bulls being less than five years old.

Table A.1 shows the hedonic model estimates on the whole sample with the subset of traits available in every period and differing levels of controls. Looking at R-squared, the significant increases in prediction power come from including company, breeder, and time fixed effects. The others increase prediction power by only a small amount. In terms

FIGURE A.1. Age Distribution of Bulls in Sample



of the coefficients, there are some small changes to magnitude and standard errors but no changes in the direction. That is, including any of the controls does not have an impact on whether the trait negatively or positively correlates to price.

TABLE A.1. Pooled Sample Estimates with Varying Levels of Controls

	Log(Price)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Milk (lbs)	0.003	0.009	0.027*	0.029**	0.029**	0.034***	0.046
	(0.017)	(0.015)	(0.014)	(0.013)	(0.013)	(0.013)	(0.028)
Fat (lbs)	0.077***	0.079***	0.080***	0.076***	0.076***	0.088***	0.089***
	(0.008)	(0.007)	(0.005)	(0.006)	(0.006)	(0.007)	(0.008)
Protein (lbs)	0.083***	0.080***	0.081***	0.096***	0.096***	0.109***	0.106***
	(0.016)	(0.017)	(0.019)	(0.018)	(0.018)	(0.018)	(0.019)
Productive Life (months)	0.057***	0.054***	0.057***	0.061***	0.061***	0.073***	0.069***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.010)	(0.009)
Somatic Cell Score	−0.010*	−0.013**	−0.015***	−0.015***	−0.015***	−0.015***	−0.016**
	(0.005)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.006)
Udder Composite	0.154***	0.153***	0.156***	0.155***	0.156***	0.181***	0.189***
	(0.013)	(0.012)	(0.011)	(0.012)	(0.012)	(0.012)	(0.019)
Feet and Legs Composite	0.068***	0.071***	0.066***	0.070***	0.071***	0.083***	0.086***
	(0.010)	(0.009)	(0.008)	(0.007)	(0.007)	(0.008)	(0.008)
Body Size Composite	0.058***	0.058***	0.058***	0.056***	0.056***	0.069***	0.069***
	(0.009)	(0.009)	(0.009)	(0.011)	(0.011)	(0.012)	(0.011)
Covariates							
IMR and Herds in Eval		X	X	X	X	X	X
Stud and Controller FE			X	X	X	X	X
Breeder FE				X	X	X	X
Age of Bull					X	X	X
Period FE						X	X
Birth Year FE							X
Observations	24,057	24,052	24,052	24,052	24,052	24,052	24,052
Adjusted R^2	0.407	0.429	0.541	0.587	0.588	0.616	0.620

Note: *p<0.1; **p<0.05; ***p<0.01

Appendix B. Sample Selection Correction

In this sample, an average of 13% of prices are missing for bulls. Figure B.1 shows how this percentage changes over time, ranging from as high as 20% around 2001 to nearer to 10% around 2007. Since bulls with missing prices cannot be included in the analysis, missing prices can create a sample selection bias if only certain kinds of bulls have missing prices.

Table B.1 shows the results of the probit model which works as the first step to the Heckman (1979) approach. From this model, I create the inverse mills ratio which is used as a covariate in the main regression model. While there are no excluded variables predicting the missingness (e.g. an instrumental variable), Honoré and Hu (2020) finds that excluded variables are not necessary if the first stage has sufficient predictive power.

According to the first stage, the main traits that predict missingness are milk yield, fat yield, body size composite, and udder composite. In other words, bulls that have less milk production and less desirable type traits are more likely to have missing prices. It is also more likely that bulls have missing prices when they are younger than 7, which may suggest that bulls without prices are those lower quality bulls that are new entries to the market. Using the pseudo R-squared, a rough measure of the probit model's predictive power, we see that the model also predicts well, and excluded variables are probably unnecessary.

It also bears mentioning that the statistical significance of the inverse mills ratio in the regression tells us whether the correction was necessary (Heckman 1979). Referring to Table 3, we can see that the inverse mills ratio is only 90% statistically significant in the whole sample and insignificant in the subsamples.

Appendix C. Robustness Checks

C.1. Alternative Fixed Effects

To test the robustness of the results, here I present results where I have added fixed effects which are stud, farm, or controller fixed effects interacted with time fixed effects. This is to test whether there are pricing policies at this level that are driving the results. Table C.1.1 shows these results in columns 2-4. In terms of predictive power, adding stud or controller by time fixed effects does increase R^2 while farm by time reduces it. In terms of point estimates, some production traits become a little stronger and some type traits like udder

Figure B.1. Percentage of Bulls Missing a Price: 2000-2009

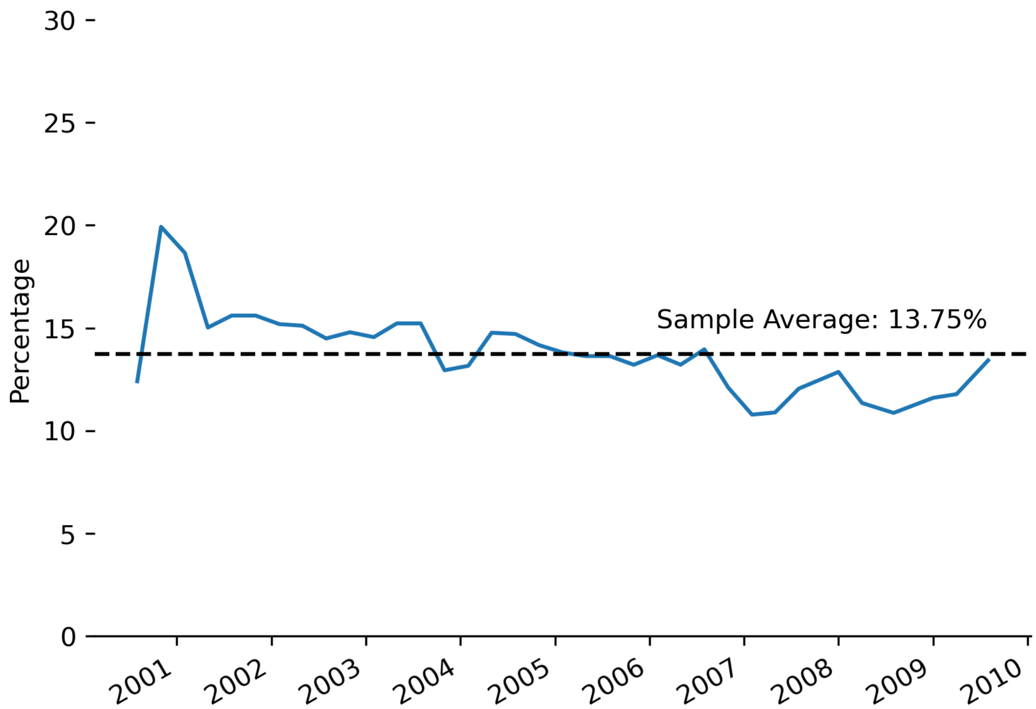


TABLE B.1. First Stage Probit Predicting a Missing Price

	Missing Price
Milk (lbs)	−0.0005***
	(0.0001)
Fat (lbs)	0.002
	(0.002)
Protein (lbs)	0.001
	(0.003)
Productive Life (months)	0.002
	(0.021)
Somatic Cell Score	−0.371**
	(0.172)
Body Size Composite	−0.045
	(0.036)
Udder Composite	−0.235***
	(0.041)
Feet and Legs Composite	−0.012
	(0.034)
Age = 6	−0.057
	(0.150)
Age = 7	−0.238
	(0.171)
Age = 8	−0.473**
	(0.206)
Age = 9	−0.418*
	(0.247)
Age = 10	−0.404
	(0.293)
Age = 11	−0.226
	(0.338)
Age = 12	0.129
	(0.391)
Age > 12	0.585
	(0.479)
Pseudo R-Squared	0.855
Observations	27,656

Fixed effects: company, period, birth year, farm name.
Note: *p<0.1; **p<0.05; ***p<0.01

TABLE C.1.1. Alternative Fixed Effects

	Log(Price)			
	Base Model	Stud by Time	Farm by Time	Controller by Time
Milk (lbs)	0.046	−0.037	0.052**	−0.044
	(0.028)	(0.032)	(0.024)	(0.028)
Fat (lbs)	0.089***	0.103***	0.086***	0.104***
	(0.008)	(0.010)	(0.009)	(0.009)
Protein (lbs)	0.106***	0.115***	0.105***	0.116***
	(0.019)	(0.019)	(0.019)	(0.019)
Productive Life (months)	0.069***	0.073***	0.072***	0.072***
	(0.009)	(0.009)	(0.009)	(0.009)
Somatic Cell Score	−0.016**	−0.034***	−0.013***	−0.034***
	(0.006)	(0.008)	(0.005)	(0.007)
Udder Composite	0.189***	0.139***	0.196***	0.135***
	(0.019)	(0.022)	(0.016)	(0.018)
Feet and Legs Composite	0.086***	0.084***	0.083***	0.083***
	(0.008)	(0.008)	(0.008)	(0.008)
Body Size Composite	0.069***	0.059***	0.075***	0.059***
	(0.011)	(0.012)	(0.013)	(0.012)
Observations	24,052	24,052	24,052	24,052
Adjusted R^2	0.620	0.645	0.610	0.647

Note: *p<0.1; **p<0.05; ***p<0.01

composite and body size composite get a little weaker. Still, the general magnitude of these coefficients do not change substantially and may be statistically indistinguishable between those in the base model. Overall, the conclusions are not substantially impacted by adding these fixed effects though some of them increase the predictive power of the model.

C.2. Alternative Subsamples

About 13% of the prices on average are missing in the sample. In Table C.2.1, I test the model on three subsamples that have less missing prices and more data points for each

TABLE C.2.1. Alternative Samples

	Log(Price)			
	Base Model	< 5% Missing	Top Stud Codes	Top Controllers
Milk (lbs)	0.046	0.054	0.068**	0.056*
	(0.028)	(0.080)	(0.030)	(0.030)
Fat (lbs)	0.089***	0.095***	0.090***	0.091***
	(0.008)	(0.012)	(0.009)	(0.008)
Protein (lbs)	0.106***	0.111***	0.109***	0.109***
	(0.019)	(0.021)	(0.020)	(0.019)
Productive Life (months)	0.069***	0.073***	0.073***	0.072***
	(0.009)	(0.010)	(0.010)	(0.010)
Somatic Cell Score	−0.016**	−0.017	−0.014**	−0.016**
	(0.006)	(0.015)	(0.007)	(0.006)
Udder Composite	0.189***	0.207***	0.211***	0.202***
	(0.019)	(0.048)	(0.021)	(0.019)
Feet and Legs Composite	0.086***	0.093***	0.090***	0.088***
	(0.008)	(0.007)	(0.008)	(0.008)
Body Size Composite	0.069***	0.070***	0.069***	0.073***
	(0.011)	(0.009)	(0.012)	(0.011)
Observations	24,052	20,971	20,702	22,577
Adjusted R^2	0.620	0.620	0.607	0.606

Note: *p<0.1; **p<0.05; ***p<0.01

company. The second column shows the results for a subsample where studs must have less than 5% of their bulls missing prices missing on average in the sample. The third and fourth columns show the results on a subsample made up of studs or controllers who have at least 10 bulls on average in every period. Running the model on these samples, the results are more or less unchanged in their direction and magnitude.

C.3. Simulated Price Discounts

The prices used in the analysis are posted prices, meaning those used to advertise the bulls. Anecdotally, we know that dairy farmers may receive prices that are lower than what is posted if they are buying at a high volume or have an existing relationship with the supplier. To test how a discount might affect the results, I simulate a discount based on the average price posted by each company. I first calculate the average price posted by each company in the entire period and then draw from a normal distribution using the average price as the mean and the standard deviation of the price in the sample as the scale parameter. I then multiplied this draw by .05, .10, or .15 and subtracted it from the posted price to simulate a stud-specific discount:

$$p_{dicount} = p_{it} - (\mu_j + \epsilon_j) * \text{discount}, \quad \epsilon_j \sim N(0, \sigma^p)$$

Table C.3.1 shows the results using the simulated discounts. The larger the discount, the larger the coefficients appear to be. The only other noticeable difference is that the R^2 is lower the larger the discount since extra variance is being added to the data.

C.4. Event Study

To understand whether there were statistically significant shifts in the pricing of traits, here I run two specifications which interact the traits with post-revision indicators. The two specifications are:

$$p_{it} = \sum_{k=1}^{\text{'00 Traits}} w_k x_{ikt} + \mathbf{1}(2003 < t < 2006) \times w_k^{03} x_{ikt} + \mathbf{1}(t > 2006) \times w_k^{06} x_{ikt} + \beta Z_{it} + \epsilon_{it}.$$

$$p_{it} = \sum_{k=1}^{\text{'03 Traits}} w_k x_{ikt} + \mathbf{1}(t > 2006) \times w_k^{06} x_{ikt} + \beta Z_{it} + \epsilon_{it}.$$

TABLE C.3.1. Simulated Price Discounts

	Log(Price)			
	Base Model	5% Discount	10% Discount	15% Discount
Milk (lbs)	0.046	0.075**	0.075*	0.072*
	(0.028)	(0.032)	(0.036)	(0.037)
Fat (lbs)	0.089***	0.094***	0.101***	0.110***
	(0.008)	(0.009)	(0.010)	(0.010)
Protein (lbs)	0.106***	0.115***	0.122***	0.133***
	(0.019)	(0.021)	(0.022)	(0.024)
Productive Life (months)	0.069***	0.077***	0.081***	0.086***
	(0.009)	(0.010)	(0.011)	(0.011)
Somatic Cell Score	−0.016**	−0.014*	−0.015*	−0.016*
	(0.006)	(0.007)	(0.008)	(0.008)
Udder Composite	0.189***	0.226***	0.238***	0.251***
	(0.019)	(0.022)	(0.025)	(0.026)
Feet and Legs Composite	0.086***	0.096***	0.103***	0.109***
	(0.008)	(0.008)	(0.009)	(0.010)
Body Size Composite	0.069***	0.073***	0.075***	0.081***
	(0.011)	(0.013)	(0.014)	(0.015)
Observations	24,052	20,702	20,700	20,690
Adjusted R^2	0.620	0.568	0.544	0.513

Note: *p<0.1; **p<0.05; ***p<0.01

The set of coefficients w_k^{03} and w_k^{06} test the hypothesis that the coefficients are statistically different after 2003 and 2006. The first specification tests this for the 2000 traits and the second tests this for the 2003 traits.

Tables C.4.1 and C.4.2 show the results from these specifications. Using 2000 traits, we see that there were decreases in the coefficient for milk yield, fat, protein, somatic cell score, and udder composite over time. A decreasing coefficient for somatic cell score indicates that better health was being more valued over time. Yet, there is no discernible increase in the other health trait, productive life, in this specification. Looking at data after 2003 with the 2003 traits, there appears to be an increase in daughter pregnancy rate but a reduction in productive life. We know from the main results that there was a drop in emphasis on production and an increase in health emphasis. Unfortunately, none of these trends are consistently shown in these specifications.

C.5. Post-2009 Results

Given the main sample is from 2000 to 2009, we might ask whether the results here have any bearing on the dairy industry as it is today. Figure C.5.1 shows that the percentage of bulls that are missing prices has gone from 13% on average before 2009 to more than 60% by 2019. The reasons companies stopped reporting their posted prices in the data are unknown, though it is likely influenced by some genetics companies deciding to almost entirely opt out of posting their bull prices. The result is that the data after 2009 are almost certainly less representative of the industry before 2009 and inferences cannot be reliably drawn from these data past 2009. Nevertheless, I present an analysis of these data here to provide evidence on whether or not the pricing relationship from 2000 to 2009 persisted in future periods.

In this analysis, I use a subset of the post-2009 data of companies for whom the missing percentage was less than 10% between 2010 and 2019 (26 total). Assuming we can do reliable inference on these companies, we can have results that might be internally valid for the

TABLE C.4.1. Period Interactions with 2000 Traits, 2000-2009

	Log(Price)		
	Base Coef	Post-03 Coef	Post-06 Coef
Milk (lbs)	0.088***	−0.044**	−0.055**
	(0.027)	(0.021)	(0.023)
Fat (lbs)	0.109***	−0.034***	−0.021*
	(0.010)	(0.010)	(0.012)
Protein (lbs)	0.129***	−0.006	−0.052**
	(0.021)	(0.021)	(0.021)
Productive Life (months)	0.059***	−0.001	0.012
	(0.011)	(0.019)	(0.015)
Somatic Cell Score	−0.005	−0.016	−0.017**
	(0.009)	(0.011)	(0.007)
Udder Composite	0.214***	−0.020*	−0.039***
	(0.019)	(0.011)	(0.012)
Feet and Legs Composite	0.081***	0.017	0.006
	(0.008)	(0.013)	(0.014)
Body Size Composite	0.071***	−0.0002	−0.003
	(0.012)	(0.010)	(0.010)
Observations	24,052		
Adjusted R^2	0.630		
Note:			*p<0.1; **p<0.05; ***p<0.01

TABLE C.4.2. Period Interactions with 2003 Traits, 2003-2009

	Log(Price)	
	Base Coef	Post-06 Coef
Milk (lbs)	−0.004	−0.016
	(0.046)	(0.016)
Fat (lbs)	0.079***	0.026***
	(0.013)	(0.009)
Protein (lbs)	0.122***	−0.047**
	(0.025)	(0.020)
Productive Life (months)	0.070***	−0.014**
	(0.012)	(0.007)
Somatic Cell Score	−0.031***	−0.003
	(0.011)	(0.007)
Daughter Pregnancy Rate	−0.013	0.035***
	(0.012)	(0.010)
Calving Difficulty (male)	0.012	−0.024
	(0.020)	(0.015)
Calving Difficulty (female)	−0.015	0.003
	(0.011)	(0.011)
Udder Composite	0.163***	−0.018**
	(0.026)	(0.009)
Feet and Legs Composite	0.099***	−0.010
	(0.012)	(0.010)
Body Size Composite	0.059***	0.003
	(0.016)	(0.009)
Observations	14,486	
Adjusted R^2	0.604	
Note:	*p<0.1; **p<0.05; ***p<0.01	

FIGURE C.5.1. Missing Price Rates, Post-2009

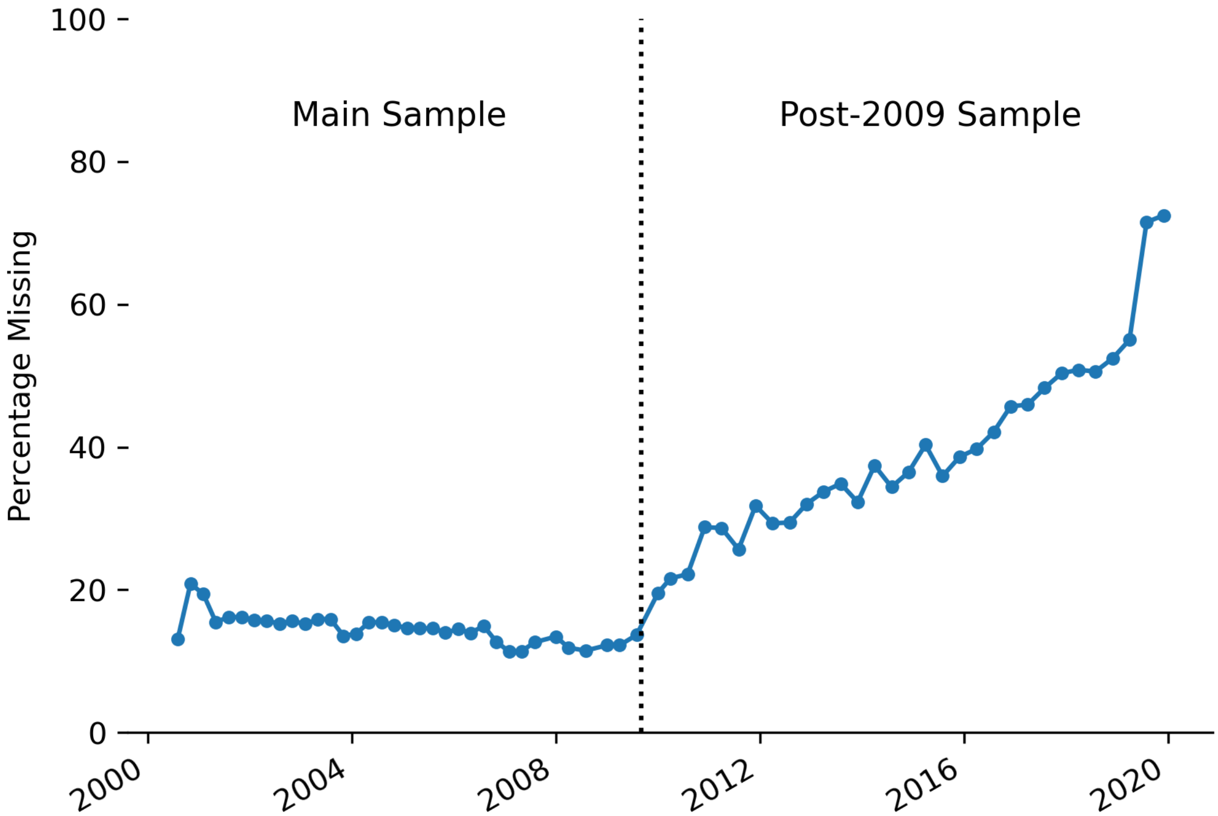


Table C.5.1. Summary Statistics, Post-2009 (Only Non-Missing Studs)

	2010	2019	Percent Change 2010-2019	Percent Change 2000-2009
Milk (lbs)	2335.83	3433.33	46.99	24.76
Fat (lbs)	85.89	142.79	66.25	38.60
Protein (lbs)	76.49	119.20	55.85	23.73
Productive Life (months)	3.92	7.86	100.68	91.25
Somatic Cell Score	3.05	2.91	-4.39	-2.74
Daughter Pregnancy Rate	0.27	1.28	379.58	-
Calving Difficulty (male)	7.86	7.39	-5.99	-
Calving Difficulty (female)	6.32	3.14	-50.37	-
Calving Ability	14.92	55.31	270.76	-
Udder Composite	2.54	4.11	61.58	132.52
Feet and Legs Composite	1.32	0.97	-26.31	55.90
Body Size Composite	1.50	1.86	24.37	72.80

sample but not externally valid for the industry. Table C.5.1 shows trends in the 2006 Net Merit traits only for the 26 companies without missing prices. In the analysis that follows, we are especially interested in whether the relationship to type traits stays the same.

Table C.5.2 shows the results of the price model, using the 2006 NM traits, on different post-2009 subsamples: after 2009 and after 2014. For each subsample, I also report their coefficients on the sample of companies that report the price of at least 90% of their bulls on average. Compared to the 2006-2009 pricing relationship, coefficients are either higher or lower depending on the sample being used. Overall, type traits are still strongly related to price and may be larger or smaller than the relationship from 2006 to 2009. For example, the udder composite index could be even more strongly related to price than in 2006-2009 if we are using the non-missing companies.

To summarize, there is not consistent evidence that type traits have become less important to bull pricing after 2009. Notably, body size composite continues to be positive and statistically significant in these regressions, against the opinion of the USDA. Verifying whether these results are actually applicable to the entire industry requires better pricing data than is available in this paper.

Table C.5.2. Price Model with 2006 NM Covariates, 2009-2019

	Log(Price)				
	2006-2009 All Obs	Post 2009, All Obs	Post 2009, Non-Missing	Post 2014, All Obs	Post 2014, Non-Missing
Milk (lbs)	0.029	−0.014	0.006	−0.031	−0.020
	(0.030)	(0.024)	(0.029)	(0.029)	(0.033)
Fat (lbs)	0.135***	0.133***	0.139***	0.112***	0.157***
	(0.016)	(0.019)	(0.017)	(0.015)	(0.021)
Protein (lbs)	0.119***	0.186***	0.186***	0.181***	0.172***
	(0.031)	(0.026)	(0.023)	(0.050)	(0.035)
Productive Life (months)	0.119***	0.118***	0.145***	0.096**	0.131***
	(0.024)	(0.023)	(0.016)	(0.045)	(0.037)
Somatic Cell Score	−0.026***	−0.003	−0.009	0.006	0.009
	(0.008)	(0.009)	(0.010)	(0.019)	(0.013)
Daughter Pregnancy Rate	0.023	0.025***	0.035**	0.020	0.022
	(0.014)	(0.009)	(0.013)	(0.012)	(0.018)
Calving Ability	0.017	0.035***	0.087***	0.040*	0.091***
	(0.026)	(0.012)	(0.029)	(0.021)	(0.029)
Udder Composite	0.234***	0.209***	0.389***	0.166***	0.310***
	(0.056)	(0.034)	(0.085)	(0.046)	(0.077)
Feet and Legs Composite	0.073***	0.047***	0.056***	0.044***	0.057**
	(0.010)	(0.012)	(0.015)	(0.012)	(0.020)
Body Size Composite	0.083***	0.086***	0.063***	0.088**	0.057***
	(0.018)	(0.020)	(0.015)	(0.040)	(0.016)
Observations	7,109	19,859	10,996	8,704	4,684
Adjusted R^2	0.651	0.490	0.542	0.494	0.572

Note: *p<0.1; **p<0.05; ***p<0.01