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Comparative Analysis of Free and Smart-Gated Cow Traffic Designs in Brazilian Automated Milking System Dairy Farms

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Abstract

Automatic milking systems (AMSs) are increasingly adopted in dairy farms, and barn design, particularly regarding cow traffic design (CowTD), plays a key role in system performance. This study evaluated the association between different CowTDs and operational and production indicators of AMS Brazilian dairy farms. The data were obtained from 149 commercial dairy farms equipped with AMS (average of 1.6 AMS per farm) encompassing approximately 14,642 lactating cows recorded between June and December 2025. Cow traffic designs were classified as free or smart-gated systems, including milk-first (MF) and feed-first (FF) configurations. Mixed models were used to evaluate the effects of regions, housing system, and CowTD on the number of lactating cows per AMS (NCowsAMS), milking frequency (MFreq), milk yield per milking (MYMilking), daily milk yield per cow (MYcow), daily milkings per AMS (MilkingsAMS), and daily milk yield per AMS (MYAMS). On average, farms milked 58 cows per AMS with a mean MFreq of 2.69 milkings/cow per day and produced 2227 kg of milk per AMS per day. Smart-gated CowTD supported a greater number of cows per AMS than free CowTD systems (FF = 57 and MF = 58 vs. Free = 53 cows/AMS). Although free CowTD increased MFreq to approximately three milkings/cow/day, this advantage did not translate into greater or equivalent MYAMS, despite MF and free CowTD exhibiting similar MYcow (37.0 and 37.2 kg/day, respectively). Even though free CowTD achieved the highest MilkingsAMS (Free = 156 vs. MF = 151 and FF = 143 milkings/day), it milked fewer cows per robot, resulting in lower MYAMS. Consequently, FF and MF systems produced 86 and 180 kg/day more MYAMS, respectively, than free CowTD. These results suggest that AMS performance is primarily driven by the NCowsAMS rather than MFreq alone. Under Brazilian commercial conditions, smart-gated CowTD systems appear to be more efficient, as evidenced by higher MYAMS, while allowing higher stocking densities, potentially without increasing labor requirements.

Keywords: dairy cattle; feed-first cow traffic design; milk-first cow traffic design; milking efficiency; smart selection gates

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1. Introduction

In recent years, the adoption of automatic milking systems (AMSs) on dairy farms has increased due to several factors. Dairy farmers commonly cite the scarcity of skilled labor and the pursuit of improved quality of life as key motivating factors for adopting this technology [1–3]. One important aspect when designing barns for an AMS is the cow

traffic flow within the barn. Cow traffic design (CowTD) refers to how cows can access different areas within the barn, including the bedding or resting area, feeding area, waiting area, and the AMS unit or feeding stations [4].

Currently, several CowTD variations exist for AMS barns, but they generally follow two main concepts: free or guided CowTD. The term "guided CowTD" may be misleading because it could imply the need for human intervention to direct cows to the gates, which is not the case. For this reason, "smart-gated CowTD" has been preferred, as both terms describe the same system and the updated terminology better reflects the use of automated smart selection gates. Additionally, smart-gated CowTD has two main general possible configurations: milk-first (MF) and feed-first (FF) [4]. Each one of the CowTDs has different characteristics, advantages, and disadvantages [4]. The free CowTD remains the most prevalent worldwide [5]; however, in recent years, smart-gated CowTDs have gained prominence due to their ability to reduce labor and the necessity to fetch cows [1,6–9].

Data comparing the differences among CowTDs are limited and, when available, typically represent only a small number of herds or provide inadequate comparisons, leading to potentially biased findings. For example, Munksgaard et al. [10] utilized a limited number of cows per CowTD groups (n = 35 cows per group), with a notable predominance of primiparous cows, reporting no differences for milking frequency (MFreq) and daily mean milk yield per cow (MYcow) between free and MF smart-gated CowTDs. Tremblay et al. [11] conducted a study involving 635 AMS herds, of which 93% operated under free CowTD. Their dataset was derived exclusively from farms using Lely AMS, which may limit the generalizability of the findings to systems from other manufacturers, as Lely installations are predominantly associated with free CowTD. Although approximately 7% of the herds in their dataset were classified as guided CowTDs, the design characteristics of these systems were not described in sufficient detail. Consequently, it is difficult to determine whether they would be classified as smart-gated or forced CowTDs according to current definitions. In general, their findings suggested a relationship between free CowTD usage and an increase in MYcow and per AMS/day (MYAMS) [11].

In contrast to Europe and North America, the economic conditions for AMS adoption in Brazil differ substantially. In those regions, acquiring AMSs is less expensive compared to the Brazilian scenario. Currently, the Brazilian currency (Real—R$) has been devalued on the international market, leaving imported products vulnerable to fluctuations of the Dollar and Euro, for example. Thus, Brazilian dairy farmers need to produce more milk per AMS to ensure the economic viability of the technology. This can be achieved by maximizing the number of milkings per AMS per day (MilkingsAMS), either by increasing MFreq or increasing the number of cows milked.

Although AMSs can milk between 60 and 70 cows, countries such as Denmark, Netherlands, and Canada generally do not operate at maximum system capacity, averaging fewer than 55 cows per AMS [12–15]. In Brazil, dairy farmers likely need to exploit this technology with maximum efficiency and higher stocking densities, aiming to perform as many milkings per day as possible per AMS. In this context, several studies suggest that increasing voluntary milkings in AMSs is more effectively achieved with smart-gated than with free CowTDs [1,7–9]. So, minimizing the need to fetch cows is closely associated with enhanced efficiency of the AMS [8,16]. In this context, the use of smart-gated CowTDs (MF and FF) has the potential to reduce the need to fetch cows and enhance AMS efficiency [8,17].

Considering the above, the objective of this research is to compare variables related to AMS efficiency across these distinct CowTDs (free and smart-gated ones). Considered variables were the number of cows milked daily per AMS (NCowsAMS), MFreq, milk yield per milking (MYMilking), MYcow, MilkingsAMS, and MYAMS. In addition, regional and housing system effects (compost barn versus free stall) were also included in the modeling

as secondary explanatory variables. We hypothesized that smart-gated CowTD systems enable AMS units to operate with a greater NCowsAMS, likely because these systems reduce the need to fetch cows. Consequently, smart-gated systems were expected to have higher NCowsAMS, leading to more daily MilkingsAMS and greater MYAMS. Conversely, free CowTD systems were expected to operate with fewer NCowsAMS but potentially higher MFreq.

2. Materials and Methods

2.1. Study Design and Dataset

This research was designed as a longitudinal retrospective study and we followed the recommendations of the STROBE statement for reporting observational studies [18]. The data were provided by DeLaval Brazil personnel. The dataset comprised all farms using DeLaval AMS (DeLaval International A.B., Tumba, Sweden), managed under confinement conditions and adopting a single CowTD. Data collection started on 23 June 2025 and ended on 9 December 2025, totaling a period of 169 days (~5.5 months). Data were provided approximately every 7 to 10 days, resulting in approximately 20 to 22 data records per farm. The dataset comprised 149 dairy farms, with a mean of 1.64 ± 1.27 AMS/farm and a mean of 98 lactating cows per farm, totaling approximately 14,642 lactating dairy cows milked during that period. The data included the following information: date, farm identification, cows' breed, Brazilian state, number of AMS per farm, housing system, CowTD, NCowsAMS, MFreq, MYMilking, MYcow, MilkingsAMS, and MYAMS.

Excel spreadsheets (n = 22) were provided containing the above-mentioned daily farm information. Those spreadsheets were merged and comprised a total of 3478 test-day records. Next, some dataset edits were required to ensure data reliability. Data inconsistencies (e.g., recording errors or data from initial AMS implementation phases) were identified based on percentiles and histograms for each variable. Test-day records presenting values below the following thresholds were excluded: NCowsAMS < 40; MFreq < 2; MYMilking < 8; MYcow < 20; MilkingsAMS < 80; and MYAMS < 1000. After the data editions, 2850 test-day records from those 149 dairy farms remained for final analyses. All herds were predominantly composed of Holstein cows.

2.2. General Descriptions of Cow Traffic Designs

2.2.1. Free Cow Traffic Design System

In the free CowTD system, cows can move freely between the feeding area and resting area and access AMS unit at any time. Access to the AMS unit is voluntary, and cows are usually motivated to visit it through the concentrate feed offered during milking. A figure representing a free CowTD can be found in Busanello ([11], pg. 42, Figure 1).

2.2.2. Smart-Gated Milk-First Cow Traffic Design System

In the smart-gated MF CowTD system, cows pass through a smart selection gate that directs them either to the feeding area if they do not have permission for milking or to the waiting area if they have milking permission. Once in the waiting area, they will enter the AMS unit to be milked. The smart selection gate is the only access to the feeding area, and when cows decide to lie down, they can enter the resting area through one-way gates. Access to the AMS unit is voluntary, and cows are usually motivated to visit it by the concentrate feed offered during milking and by their motivation to reach the feeding area. A figure representing a MF CowTD can be found in Busanello ([11], pg. 43, Figure 2).

2.2.3. Smart-Gated Feed-First Cow Traffic Design System

In the smart-gated FF CowTD system, cows can access the feeding area through one-way gates, and when they decide to return to the resting area or access the AMS unit, they pass through a smart selection gate that directs them to the waiting area if they have permission for milking or to the resting area if they do not have milking permission. Cows in the waiting area will enter the AMS unit to be milked and are then directed to the resting area after milking. In some cases, after milking, cows may be directed again to the feeding area needing to pass through the smart selection gate once more before accessing the resting area, allowing additional time for teat sphincter closure. Access to the AMS unit is voluntary, and cows are usually motivated to visit it by the concentrate feed offered during milking and by their motivation to rest or lie down. A figure representing these FF CowTDs can be found in Busanello ([11], pg. 45, Figure 3).

2.3. Statistical Analysis

All statistical analyses were performed using SAS OnDemand (version 9.4; SAS Institute Inc., Cary, NC, USA) [19], adopting a 5% significance level. Descriptive analyses were performed using SAS PROC MEANS for numerical and SAS PROC FREQ for categorical data. A multiple correspondence analysis (SAS PROC CORRESP) was performed to visualize the relationships among regions, CowTDs, and housing systems, with results presented in a biplot graph.

Following this, general linear mixed models (SAS PROC GLIMMIX) were fitted to the data for the response variables: NCowsAMS, MFreq, MYMilking, MYcow, MilkingsAMS, and MYAMS. Brazilian state, CowTD, housing system, data recording date, farm effect, and interaction effect terms Brazilian state × CowTD and housing system × CowTD were included in the models as predictor variables. Farm effect was considered a random effect with repeated measures. Several variance–covariance matrices were tested for each model, and that with the lowest corrected Akaike Information Criterion was selected for the final analysis. The general model is described below:

$$Y_{ijklmn} = \mu + State_i + CowTD_j + Housing_k + Date_l + State \times CowTD_{(ij)} + Housing \times CowTD_{(ik)} + Farm_m + e_{ijklmn}$$

where

Y_{ijklmn} = is the observed value of the response variable;
μ = intercept;
$State_i$ = fixed effect of Brazilian state, with i = 4;
$CowTD_j$ = fixed effect of cow traffic design, with j = 3;
$Housing_k$ = fixed effect of the housing system, with k = 2;
$State \times CowTD_{(ij)}$ = interaction term effect of the state and CowTD;
$Housing \times CowTD_{(ik)}$ = interaction term effect of the state and housing system;
$Date_l$ = fixed effect of the data recording date, with l = 20;
$Farm_m$ = random repeated measures effect of dairy farm with, m = 149;
e_{ijklmn} = random error associated with the observation Y_{ijklmn}.

Model residuals were assessed for normality using histogram inspection and quantile–quantile plots (SAS PROC UNIVARIATE), and for homogeneity of variances using box plots and graphical analysis of standardized residuals versus adjusted predicted values (SAS PROC SGPLOT). Denominator degrees of freedom were estimated using the Satterthwaite approximation. Least squares means were compared using the Tukey–Kramer adjustment with row-specific degrees of freedom and a stepdown adjustment for multiple

comparisons. These approaches were used to improve inference reliability in mixed models with repeated measures and unbalanced data, while controlling type I error.

3. Results

3.1. Descriptive Results

The geographical distribution indicated that approximately 93% of the evaluated dairy farms were located in Southern Brazil (Table 1). From that, 54% of the farms were located in Rio Grande do Sul. The proportion of free stall (52%) and comport barn (48%) housing systems was quite similar (Table 1). On the other hand, the MF CowTD was the predominant one present in 66% of the farms (n = 99 dairy farms), followed by free (24%, n = 35 dairy farms) and FF CowTD (10%, n = 15 dairy farms) (Table 1).

Table 1. Distribution of dairy farms according to Brazilian states, housing systems, and cow traffic designs.

Brazilian States	**Number of Farms** [1]	**%**
Rio Grande do Sul	81	54.4
Paraná	28	18.8
Santa Catarina	29	19.5
Others [2]	11	7.4
Total	149	100.0
Housing System	Number of Farms	%
Free stall	78	52.3
Compost barn	71	47.7
Total	149	100.0
AMS Cow Traffic Design	Number of Farms	%
Milk-first	99	66.4
Free	35	23.5
Feed-first	15	10.1
Total	149	100.0

[1] Data refer to the period from June to December 2025; [2] states in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo.

A multivariate correspondence analysis indicated that free CowTD was associated with free stall housing and with Rio Grande do Sul, where both were more prevalent (Figure 1). In contrast, FF CowTD was more common in Paraná, and compost barn housing was relatively more frequent outside Rio Grande do Sul, particularly in Paraná and other states (Figure 1). In addition, FF and MF CowTD showed a more balanced distribution between compost barn and free stall systems (Figure 1).

Overall, the 149 Brazilian AMS dairy farms milked a median of 58 cows per AMS (range: 40–86), with cows being milked 2.69 times per day (range: 2.13–3.51) (Table 2). This resulted in a median milk yield of 38.7 kg/cow/day (range: 21.7–52.2) and 14.6 kg/milking (range: 9.2–18.7). At the AMS level, farms performed a median of 156 milkings per AMS per day (range: 104–201), producing 2227 kg/day of milk per AMS (range: 1077–3505) (Table 2).

Table 2. Summary statistics of milk yield and operational performance indicators of automatic milking systems on Brazilian dairy farms.

Variables [1]	N	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
N of cows per AMS (cows)	149	40	53	58	62	86
Cows MFreq (milkings/cow/day)	149	2.13	2.53	2.69	2.84	3.51
MY per milking (kg/milking)	149	9.2	12.8	14.6	15.8	18.7
Daily cows MY (kg/day)	149	21.7	35.0	38.7	41.4	52.2
Daily milkings per AMS (milkings/day)	149	104	140	156	165	201
Daily MY per AMS (kg/day)	149	1077	1890	2227	2565	3505

[1] MY—milk yield, N—number, AMS—automatic milking system, MFreq—milking frequency.

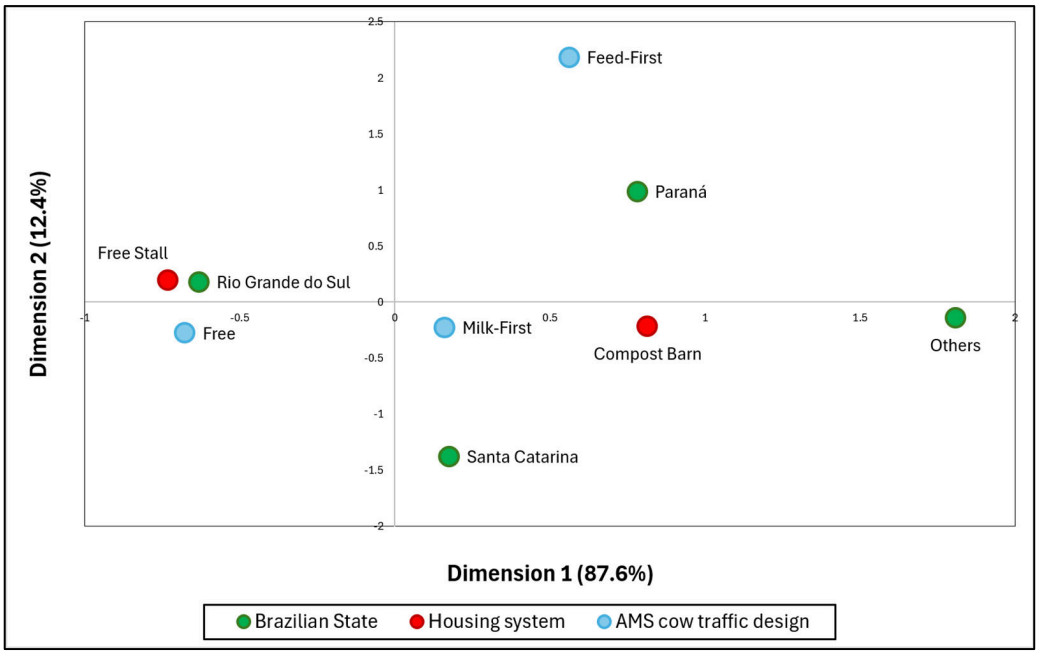


Figure 1. Multiple correspondence analysis biplot showing the relationships among states, housing systems, and cow traffic designs on Brazilian dairy farms with automatic milking systems. States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo.

3.2. Differences Between Regions, Cow Traffic Design, and Housing System

3.2.1. Number of Cows Milked per AMS

Adjusted means of NCowsAMSs differed according to Brazilian states ($p < 0.0001$) and CowTD ($p < 0.0001$), but not housing systems ($p = 0.4319$; Figure 2). AMS units in Santa Catarina and Rio Grande do Sul operated with a greater number of cows per robot (59 and 58 cows, respectively) followed by Paraná (57 cows) and other states (50 cows) (Figure 2). MF and FF milked more NCowsAMS (58 and 57 cows, respectively) than free CowTD (53 cows), whereas compost barn and free stall housing exhibited no differences (56 cows) (Figure 2).

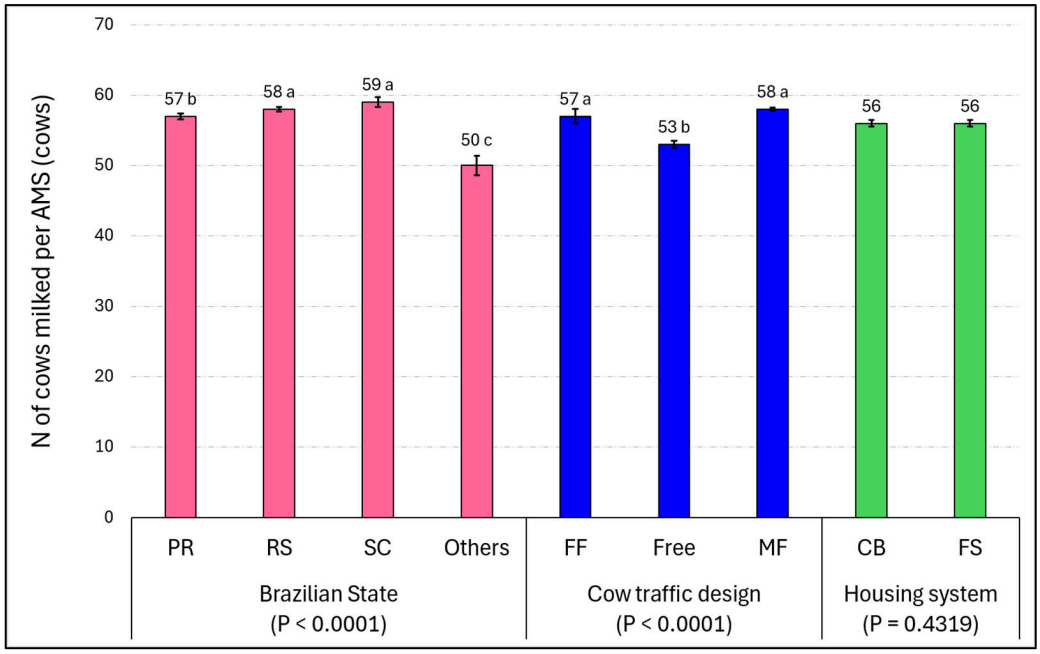


Figure 2. Adjusted means of number of cows milked per automatic milking system according to state, cow traffic design, and housing system on Brazilian dairy farms. (Footnote: Adjusted means were estimated from the statistical model and error bars represent the standard error of the mean. Different letters indicate significant differences among categories within each explanatory variable ($p < 0.05$). States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo. Interaction effects: State × CowTD ($p < 0.0001$) and Housing × CowTD ($p = 0.8292$)).

3.2.2. Milking Frequency per Cow

Adjusted means of MFreq differed according to Brazilian states ($p < 0.0001$), CowTD ($p < 0.0001$) and housing system ($p < 0.0001$; Figure 3). Santa Catarina and Paraná showed higher MFreq (2.81 and 2.73 milkings/cow/day, respectively) than Rio Grande do Sul (2.68 milkings/cow/day) and other states (2.59 milkings/cow/day) (Figure 3). Regarding CowTD, free traffic presented greater MFreq (2.98 milkings/cow/day) compared with MF (2.63 milkings/cow/day), and it was followed by FF (2.50 milkings/cow/day). Considering housing systems, free stall showed greater MFreq (2.74 milkings/cow/day) than compost barn (2.67 milkings/cow/day) (Figure 3).

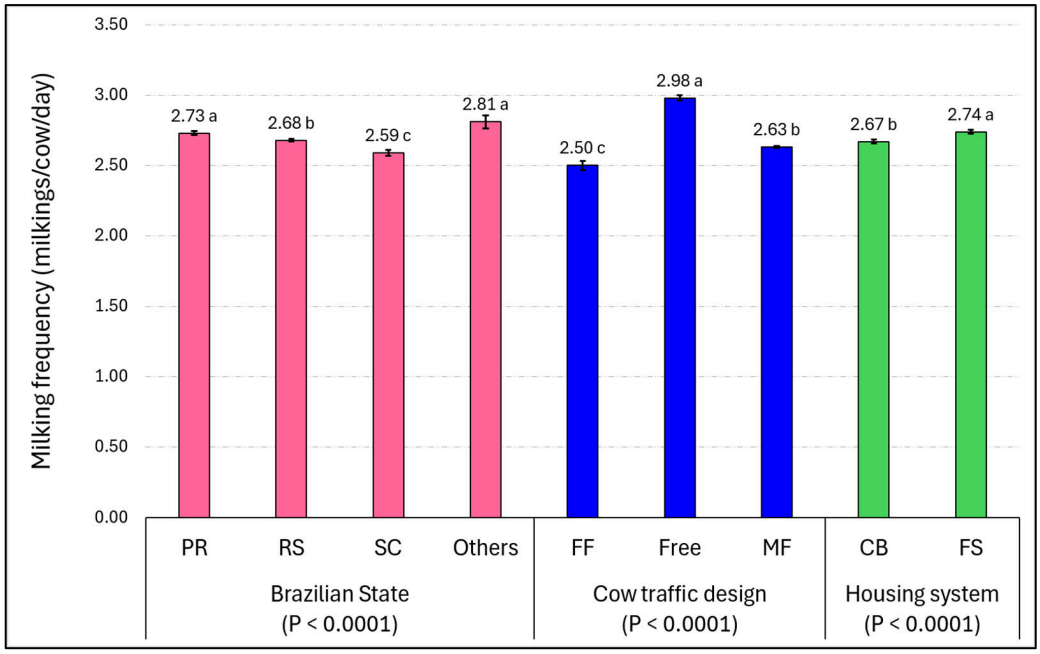


Figure 3. Adjusted means of daily mean milking frequency per cow according to state, cow traffic design, and housing system on Brazilian dairy farms. (Footnote: Adjusted means were estimated from the statistical model and error bars represent the standard error of the mean. Different letters indicate significant differences among categories within each explanatory variable ($p < 0.05$). States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo. Interaction effects: State × CowTD ($p < 0.0001$) and Housing × CowTD ($p < 0.0001$)).

3.2.3. Milk Yield per Milking

Adjusted means of MYMilking differed according to Brazilian states ($p < 0.0001$) and CowTD ($p < 0.0001$), but not according to housing system ($p = 0.1814$; Figure 4). Rio Grande do Sul showed greater MYMilking (14.7 kg/milking), followed by Santa Catarina and Paraná (14.5 and 14.3 kg/milking, respectively), whereas other states (11.0 kg/milking) presented lower values (Figure 4). Regarding CowTD, FF and MF showed greater MYMilking (14.1 kg/milking for both) compared with free CowTD (12.6 kg/milking) (Figure 4). Considering housing systems, no differences were found for MYMilking between compost barn (13.7 kg/milking) and free stall (13.5 kg/milking) (Figure 4).

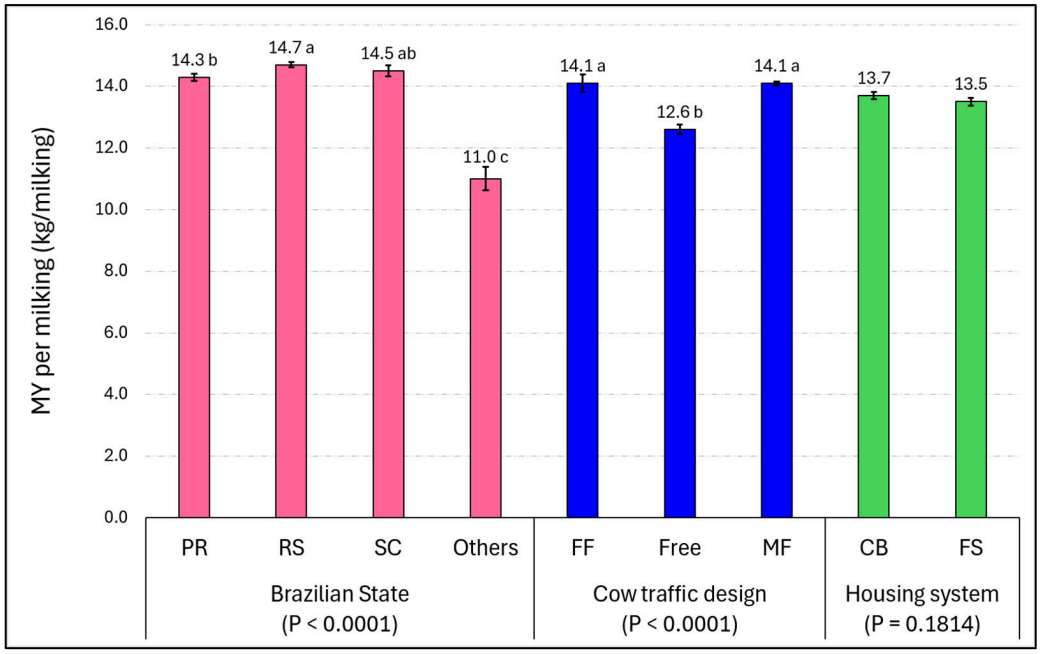


Figure 4. Adjusted means of milk yield per milking according to state, cow traffic design, and housing system on Brazilian dairy farms. (Footnote: Adjusted means were estimated from the statistical model and error bars represent the standard error of the mean. Different letters indicate significant differences among categories within each explanatory variable ($p < 0.05$). States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo. Interaction effects: State × CowTD ($p < 0.0001$) and Housing × CowTD ($p = 0.0002$)).

3.2.4. Daily Cows' Milk Yield

Adjusted means of MYcow differed according to Brazilian states ($p < 0.0001$) and CowTD ($p = 0.0336$), but not according to housing system ($p = 0.2378$; Figure 5). Rio Grande do Sul and Paraná showed higher MYcow (39.1 and 38.8 kg/cow/day, respectively), followed by Santa Catarina (37.2 kg/cow/day) and other states (30.4 kg/cow/day; Figure 5). Regarding CowTD, free and MF showed greater MYcow (37.2 and 37.0 kg/cow/day, respectively) than FF (35.2 kg/cow/day) (Figure 5). Considering housing systems, no differences were found for MYcow between free stall (36.6 kg/cow/day) and compost barn (36.3 kg/cow/day) (Figure 5).

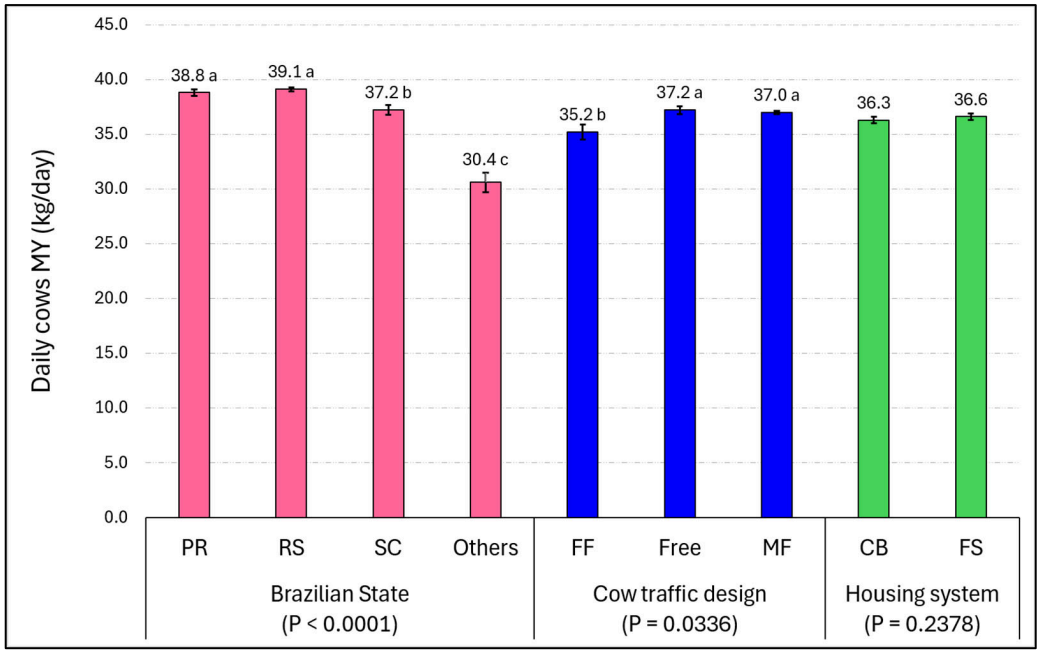


Figure 5. Adjusted means of daily milk yield per cow according to state, cow traffic design, and housing system on Brazilian dairy farms. (Footnote: Adjusted means were estimated from the statistical model and error bars represent the standard error of the mean. Different letters indicate significant differences among categories within each explanatory variable ($p < 0.05$). States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo. Interaction effects: State × CowTD ($p < 0.0001$) and Housing × CowTD ($p < 0.0001$)).

3.2.5. Daily Milkings per AMS

Adjusted means of MilkingsAMS differed according to Brazilian states ($p < 0.0001$), CowTD ($p < 0.0001$), and housing system ($p = 0.0014$; Figure 6). Rio Grande do Sul (155 milkings/day), Paraná (154 milkings/day), and Santa Catarina (151 milkings/day) showed greater MilkingsAMS than other states (142 milkings/day) (Figure 6). Regarding CowTD, free traffic showed greater MilkingsAMS (156 milkings/day), followed by MF (152 milkings/day), whereas FF presented lower values (143 milkings/day) (Figure 6). Considering housing systems, free stall showed greater MilkingsAMS (152 milkings/day) than compost barn (149 milkings/day) (Figure 6).

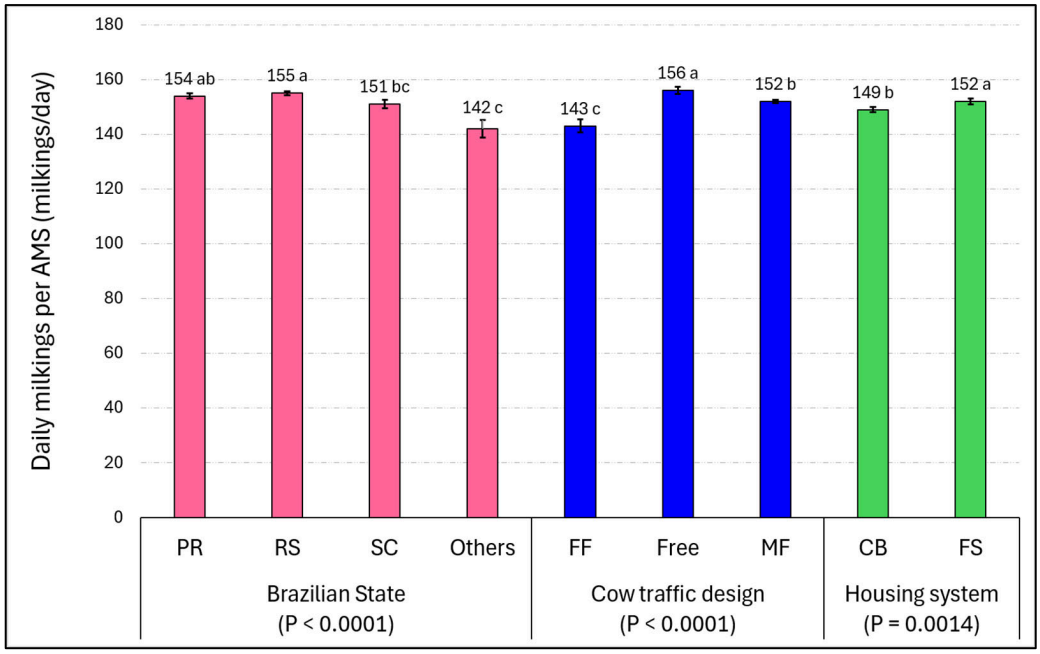


Figure 6. Adjusted means of daily milkings per automatic milking system according to state, cow traffic design, and housing system on Brazilian dairy farms. (Footnote: Adjusted means were estimated from the statistical model and error bars represent the standard error of the mean. Different letters indicate significant differences among categories within each explanatory variable ($p < 0.05$). States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo. Interaction effects: State × CowTD ($p < 0.0001$) and Housing × CowTD ($p < 0.0001$)).

3.2.6. Daily Milk Yield per AMS

Adjusted means of MYAMS differed according to Brazilian states ($p < 0.0001$) and CowTD ($p < 0.0001$), but not according to housing system ($p = 0.2380$; Figure 7). Rio Grande do Sul and Santa Catarina showed greater MYAMS (2275 and 2203 L/day, respectively), followed by Paraná (2194 L/day, without a difference compared to Santa Catarina), whereas other states (1554 L/day) presented lower values (Figure 7). Regarding CowTD, MF showed the greatest MYAMS (2148 L/day) and differed from free CowTD, which presented the lowest value (1968 L/day). FF was intermediate (2054 L/day) and did not differ from either MF or free CowTD (Figure 7). Considering housing systems, free stall (2071 L/day) and compost barn (2042 L/day) presented similar values (Figure 7).

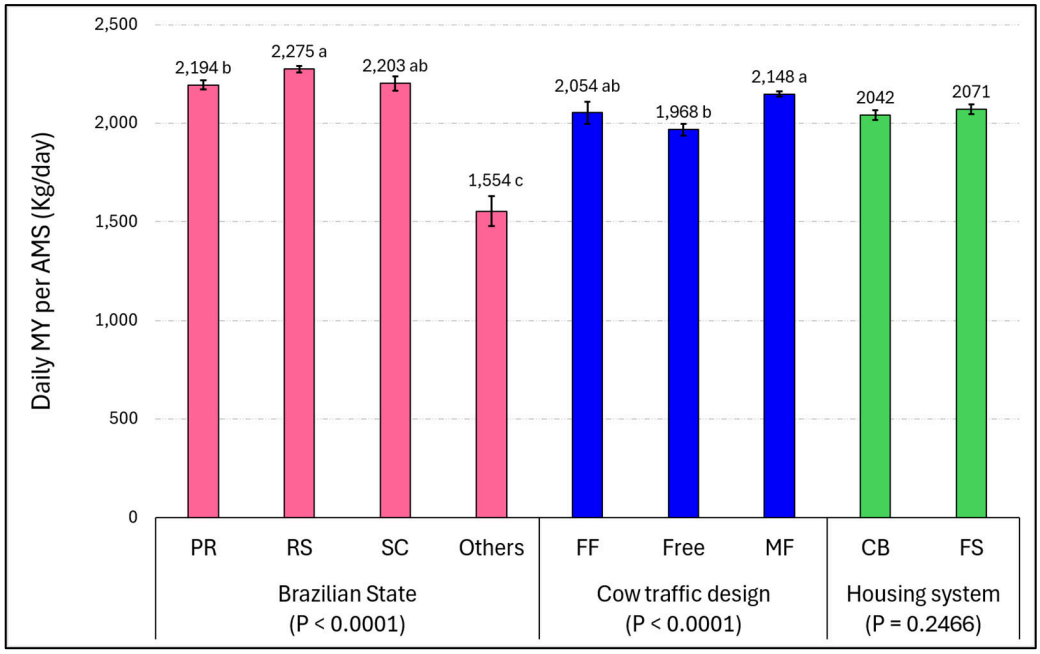


Figure 7. Adjusted means of daily milk yield per automatic milking system according to state, cow traffic design, and housing system on Brazilian dairy farms. (Footnote: Adjusted means were estimated from the statistical model and error bars represent the standard error of the mean. Different letters indicate significant differences among categories within each explanatory variable ($p < 0.05$). States in "others" include Bahia, Goiás, Minas Gerais, Mato Grosso do Sul, and São Paulo. Interaction effects: State × CowTD ($p < 0.0001$) and Housing × CowTD ($p = 0.0008$)).

4. Discussion

Our initial hypothesis was partially confirmed, indicating that smart-gated CowTD systems were associated with increased MYAMS primarily due to the higher number of lactating cows per AMS, as both FF and MF systems operated with four to five additional cows per AMS unit compared with free CowTDs. Contrary to our expectations, free CowTD resulted in a greater number of MilkingsAMS, likely due to milking permission settings that promoted a higher MFreq, an expected outcome for this CowTD. However, despite the higher milking activity, the lower stocking density prevented free CowTD from achieving the MYAMS observed in smart-gated systems. It is important to mention that, because this study was based on observational data collected from commercial dairy farms, the reported associations should not be interpreted as evidence of a direct causal effect of CowTD on AMS performance. Although the statistical models accounted for region, housing system, farm, and repeated measurements over time, other herd-level factors may also have contributed to the observed differences among CowTD systems.

Overall, the differences in MYAMS were +86 and +180 L/day for FF and MF smart-gated CowTD, respectively, relative to free CowTD. On an annual basis, this could represent approximately 31,000 to 65,000 additional kg of milk compared with the free system. This challenges the argument that free CowTD should be preferred because it has lower implementation costs and equivalent or superior MYAMS [10,16], as smart-gated systems can result in considerably greater annual milk production, especially by supporting a higher stocking density of cows without additional human labor.

In addition, our findings contrast with those reported by Tremblay et al. [11], who observed a significant increase of +67 kg of milk per AMS per day in free CowTD systems compared with "smart-gated", "guided", or "forced" CowTD systems on U.S. dairy farms. However, this difference may be explained by the lower NCowsAMS (50 vs. 58 cows/AMS) and MYcow (~32 vs. ~39 L/cow per day) reported in their study compared with ours,

resulting in a lower MYAMS (approximately 1627 vs. 2227 L/day) despite a higher MFreq (2.9 vs. 2.7 milkings/cow per day). Additionally, the comparison may have been influenced by the highly unbalanced distribution of observations between free CowTD (93%) and the other CowTD systems (7%) in the study of Tremblay et al. [11]. A similar limitation may also have affected our findings for FF CowTD, given its relatively small representation in the dataset. Furthermore, because our study was based exclusively on DeLaval AMS dairy farms, the findings are most directly applicable to similar production systems. Differences in AMS design, software algorithms, feeding strategies, and CowTD management among manufacturers may influence system performance; therefore, caution is warranted when comparing and generalizing these results to other AMS brands.

Our findings suggest that higher MYAMS, and thus greater AMS efficiency, is primarily achieved by increasing NcowsAMS rather than solely increasing MFreq, as previously indicated by Tremblay et al. [11] and Bach and Cabrera [16]. In this context, smart-gated CowTD systems appear to have a considerable advantage, as our findings indicate that they enable milking a greater number of cows, possibly without increasing the need for cow fetching [8] or additional labor input [20]. Given that labor reduction is a primary motivation for AMS adoption [1–3], minimizing cow fetching and promoting voluntary visits to the AMS are essential for maximizing system efficiency [21].

Higher MFreq increases MYcow, with gains of about 10–15% when moving from two to three milkings per day [22,23] and an additional increase of about 7–12% when moving from three to four milkings per day [24,25]. An increase in MFreq has also been associated with a protective effect against intramammary infections [26]. Thus, to clarify, we are not suggesting that increased MFreq in AMS is secondary; rather, it should be strategically targeted to the cows that most need greater milking permission, particularly fresh and high-producing cows [16,27], which can be easily configured within the system settings [28]. This contrasts with the common recommendation for free CowTD systems to target a MFreq of around three milkings per cow per day and more than one refusal per cow per day (cows entering the AMS without milking permission) [9,29]. For example, Munksgaard et al. [10] reported that cows visited the AMS up to 13 times per day without being milked, whereas Mangalis et al. [30] reported up to four times more visits without milking in free CowTD systems. Such visits increase box time without milk harvest and may reduce overall AMS efficiency. Moreover, this management strategy is generally achieved only with lower NcowsAMS in the system [9].

In practice, as the number of cows per AMS increases, refusals tend to decrease because access to the AMS becomes more competitive, which may enhance AMS efficiency [9]. In addition, smart-gated CowTD reduces refusals, thereby limiting unnecessary robot visits [30]. Therefore, additional milkings should be directed primarily to cows that truly require them; otherwise, box time increases to harvest the same amount of milk, while also raising costs related to teat preparation (pre- and post-dipping, cleaning, and stimulation) and water use. It is plausible that a free CowTD can accommodate more cows, as an AMS may milk around 60 to 70 [16] or even more cows per day, as evidenced by the maximum NCowsAMS observed in our data (n = 84). However, this requires considerable additional labor, and the argument of improved cow welfare in free CowTD systems becomes questionable under such conditions due to the recurrent need to fetch cows [6–8,30], disturbing their natural eating and resting time. In fact, some studies still describe the use of a fenced waiting area with a one-way gate in free CowTD systems to reduce the need to manually direct cows to the AMS [12,31,32], which contradicts the own principle advocated for these systems.

In general, FF smart-gated CowTD showed an intermediate response compared with MF and free systems. As a more recently developed design, it is still gaining adopters [5]. It appears promising, as the feed area may function as a “secondary” waiting area, potentially

reducing the need for human intervention throughout the day. However, both in Brazil and worldwide, few farms have adopted this CowTD, and definitive conclusions cannot yet be drawn. Data from Estonia with the FF CowTD indicated higher milk yield per AMS, longer milking time, and a greater number of cows per system, with 65 cows/AMS compared with 55 cows/AMS in the free CowTD system [17]. In the Brazilian context, where implementation and rearing costs are increasingly high, maximizing MYAMS is crucial to make this technology economically viable. Therefore, smart-gated CowTD systems may be a better option than free systems in our country, although a detailed cost–benefit analysis is still needed.

Regional aspects were a secondary focus of our study. Rio Grande do Sul is the leading state in AMS adoption in Brazil. Recent data indicate that, around 2023, the state had 116 dairy farms using AMS and 160 AMS units regardless of the AMS brand used; however, this represented only 0.35% of the approximately 33,000 formal dairy farms in the state [33]. In recent years (2015 to 2023), 61% of dairy farms in Rio Grande do Sul have ceased operations due to high production costs and a shortage of specialized labor [33]. The lack of family farm succession in southern Brazil is also an important factor to consider [34]. It is likely that some farms invested in AMS as a strategy to sustain their operations. This situation also reflects broader structural challenges faced by the Brazilian dairy sector. Regarding housing systems, no substantial differences were identified. Free stall and compost barn systems housed similar numbers of cows and showed comparable MYAMS overall and seems to be similar in efficiency.

Our study has some limitations. The data represent only one brand of AMS units, although at least three other brands are currently commercializing AMS in Brazil: BouMatic, GEA, and Lely. Each of these brands has its own particularities. DeLaval is currently the main manufacturer promoting smart-gated CowTD systems, which was one of the main reasons for focusing on a single AMS brand, thereby reducing potential confounding effects associated with differences among manufacturers. For example, Lely systems are predominantly implemented with free CowTD, and nutritional management in these systems, particularly the amount of concentrate feed allocated through the AMS, is generally more intensive than in FF and MF systems [35–37]. Consequently, the findings of the present study are most directly applicable to DeLaval AMS farms operating under similar conditions, and caution is warranted when extrapolating these results to other AMS brands as earlier mentioned. Moreover, potential variation in barn design and facility layout among farms could not be fully accounted for, including differences between pre-existing barns adapted for AMS installation and barns originally designed for AMSs. Other herd-level characteristics were also unavailable, including parity distribution, mean days in milk, nutritional management, grouping strategies, milking permission settings, labor practices, cow fetching routines, and other management factors that may influence MFreq, MYAMS, and overall, AMS efficiency. Furthermore, because the data is observational, residual confounding cannot be excluded. Although the statistical models accounted for several important factors, unmeasured herd-level characteristics may also have contributed to the observed differences among CowTD systems. Therefore, the reported relationships should be interpreted as associations rather than direct causal effects. Although the statistical models accounted for region, housing system, farm, and repeated measurements over time, unmeasured herd-level factors may also have contributed to the observed differences among CowTD systems. Nevertheless, the dataset provides valuable insights into the relationships between CowTD and AMS performance under commercial farming conditions.

5. Conclusions

Smart-gated cow traffic designs are associated with higher AMS efficiency, as reflected by greater daily milk yield per AMS. This improvement is mainly driven by a higher number of cows milked per day within these CowTD systems. In contrast, free CowTD is associated with increase in MFreq and higher number of milkings per AMS/day; however, less milk is harvested per milking, which does not result in daily milk yield per AMS comparable to that observed in smart-gated systems. In the Brazilian context, where AMS acquisition costs are high, smart-gated cow traffic could offer greater system efficiency and return on investment. Nevertheless, because this study was observational and based exclusively on DeLaval AMS farms, these findings should be interpreted as associations and validated in other AMS populations and management conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

AMS	Automatic milking system
CowTD	Cow traffic design
FF	Feed-first cow traffic design
MF	Milk-first cow traffic design
MFreq	Milking frequency
MilkingsAMS	Daily milkings per AMS
MYAMS	Daily milk yield per AMS
MYcow	Daily milk yield per cow
MYMilking	Milk yield per milking
NCowsAMS	Number of lactating cows per AMS

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