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An evaluation of parameters which affect dairy herd movement on Irish pasture-based farms

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Abstract

In pasture-based grazing systems, farm roadways are a pivotal link to connect paddocks on the grazing platform to the milking parlour. However, their effectiveness in the efficient movement of the dairy herd between the grazing paddocks and the milking parlour has yet to be fully quantified. A validation experiment was conducted on a research farm to analyse characteristics on farm roadways that may affect cow throughput, which was observed as the number of cows per minute (CPM) passing a specified location. Roadway width (R^2 = 0.96) and surface condition score (SC) (R^2 = 0.78, respectively) were both positively associated with CPM. Public road crossings imposed a 32.7% reduction in CPM in this study. CPM increased from 12.4 CPM on a one-metre-wide roadway with a SC of Index 1 to 107.6 CPM on a five-metre roadway with a SC of Index 5. This exercise allowed for CPM on commercial farms to be predicted. Farm roadways were examined across 55 Irish dairy farms. Greater roadway width, reduced verge width and greater water run-off were each associated with higher SC on commercial farms. Larger herd sizes had a lower CPM relative to herd size in contrast to smaller herd sizes, resulting in a significantly longer total time to move the dairy herd through any specific point on the farm roadway network. The findings from this study have quantified the parameters which affect both CPM on commercial farm roadways and parameters which may be associated with SC on commercial farm roadways.

Introduction

Pasture utilization is a critical factor in the profitability of pasture-based farms, with each additional tonne of herbage utilized worth €173–268 per ha (Ramsbottom *et al*., 2015; Hanrahan *et al*., 2018). To efficiently utilize pasture, a rotational grazing system is commonly used, whereby animals graze the paddocks on the farm in sequence. To access these paddocks from the milking parlour, a high-quality integrated roadway network is required (Roche *et al*., 2017).

One of the main functions of farm roadways is to efficiently move the dairy herd to and from the milking parlour from the paddocks within the grazing platform (Fenton *et al*., 2021). Roadways on commercial dairy farms will range in their frequency of use throughout the grazing season, with some roadways used for over 1200 trips per year (Clarke, 2016), depending on their location in relation to the milking parlour and the grazing platform (Maher *et al*., 2023). The materials used to create roadways on farms can also vary dramatically from compacted soil-based roads to concrete surfaces (Browne *et al*., 2022b). On commercial dairy farms, these roadways provide access for animals and machinery (Clarke, 2016). Both animals and machinery can affect roadway condition, with machinery impacting the presence of potholes or rutting (causing erosion of the surface material) (Browne *et al*., 2022a). This can erode the surface condition of the roadway over time. However, there has yet to be an investigation into any parameters that may be associated with optimal or suboptimal roadway networks for animal movement on commercial dairy farms. This study will aim to identify parameters associated with optimal surface conditions on farm roadways for animal movement.

Browne *et al*. (2022a) and Boyle *et al*., 2017 reported roadways on commercial Irish dairy farms are sub-optimal to the herd size of the farm (DAFM, 2019). It is hypothesized that narrower roadways increase the time required to bring in the herd for milking while also increasing pushing and overcrowding of the herd (Browne *et al*., 2022b). However, there has yet to be a study assessing the impact of varying roadway width (RW) on herd movement between grazing paddocks and the milking parlour.

There has been very limited investigation into the effect roadway conditions (surface condition, roadway width, congestion points and public crossings) have on the movement of dairy herds. It has previously been reported that increasing the stone content of the roadway surface layer reduced walking speed when compared to that of a smooth optimal surface (Phillips and Morris, 2001). Some previous works have investigated the effect of differing surfaces on the speed of animal movement and stride length (Rushen and de Passillé, 2006; Buijs *et al.*, 2019; Medina-González *et al.*, 2022). However, many of these studies have assessed animals individually as opposed to the impact of herd dynamics on the movement of the herd. An examination of varying surfaces on the speed of movement of the dairy herd is required to quantify the impact surface condition score (SC) has on the cow throughput on farm roadways. It has previously been established that sharp turns can increase lameness on farms (Barker *et al.*, 2010; Browne *et al.*, 2022a). The impact of sharp turns (congestion points) on cow throughput on farm roadways and additional time added to the milking process has yet to be quantified.

The objectives of this study are to (1) create benchmarks that quantify the impact of RW, SC, public crossings and congestion points on the movement of the dairy herd (2) examine the current status of farm roadway condition on commercial farms and identify parameters associated with SC on commercial farms and (3) use these benchmarks to assess the suitability of roadway networks on commercial dairy farms for the movement of the dairy herd across a range of dairy herd sizes.

Materials and methods

The following study is split into two distinct stages. (1) A study was undertaken to validate the parameters which may affect herd movement on commercial farms, and (2), 55 pasture-based commercial farms were selected, and the roadway networks were examined.

Experiment 1: validating parameters which may impact herd movement

A validation trial was established to analyse the effect various parameters may have an impact on the movement of pasture-based dairy herds on farm roadways.

The validation procedure took place on the Dairygold Research farm (Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co.Cork, Ireland). Three herds of 60 mid-lactation ($n = 180$) spring-calving cows, which were balanced for breed, milk yield, parity and calving date, were used to assess cow throughput on a range of roadway types, varying in RW, SC and the presence of congestion points. Each assessment occurred before morning or evening milking. Allowing for an examination of cow throughput where labour requirement is greatest on farm roadways, as cows often return to the pasture in smaller groups as they leave the milking parlour. Results were recorded using a cow throughput metric based on the number of cows per minute (CPM) passing a given point on the roadway. This was deemed the most suitable reporting strategy as it captures both the velocity of the herd and the distribution of the herd across the roadway (i.e., whether cows walked in single file or dispersed across the roadway). Three parameters were assessed within the research farm; the RW, the SC of the roadway and the presence of a congestion point on a roadway. Both RW and SC were assessed as independent parameters impacting CPM before an experiment took place to identify if there was an interaction between RW, SC and congestion points on CPM. The presence of a public road crossing (PRC) was assessed independently of these variables due to the fact the herd must wait at this congestion point until the herds person allows the herd to cross the public road regardless of the SC or RW. The widths of all examination sections were recorded with the use of a measuring tape at the start, mid-point and end of each roadway section. The SC of each examination section was recorded using the scoring system Index 1 to Index 5 established by experts in the area of grassland management and soil structure and drainage at Teagasc Animal and Grassland Research Centre Moorepark (Supplementary material). The SC index was broken into five categories, with Index 1 defined as the poorest surface (large aggregate material, sharp stones present, suboptimal for animal movement), and Index 5 was the most optimal surface for dairy herds walking on farm roadways (a fine aggregate material). Information to guide these SC indexes was also attained from Chesterton *et al.* (1989), Chesterton (2011), Buijs *et al.* (2019) and Browne *et al.* (2022a).

The roadways on the research farm were adjusted in width using electrified fences and cones to suspend the wire. To habituate the cows to the experimental set-up, electrified fences and cones were placed on the roadway two weeks ahead of the first day of the examination. The herd was gathered 20 m before the start of each examination section and held behind an electrified tape. Gathering the herd behind the electrified tape allowed for the last cows within the herd to converge with the cows at the front of the herd. The herd may have become dispersed along the roadway due to a poor SC on the previous sections of the roadway network, where the herd might have selected a specific path on the roadway. This would ultimately affect the CPM of the examination section if the herd were widely distributed in the area prior to the examination section. Once the herd had gathered, the tape was opened to allow the herd to walk through the examination section with a herds person remaining a minimum of five metres behind the last cow.

A stopwatch was started when the first cow passed the entry point of the examination section. The time was recorded when the first cow passed the mid-point of the examination section and when she exited the examination section. The last cow was also recorded along with the time at which the last cow passed the mid-point and exit point of the examination section. This allowed the time for the whole herd to pass through the examination section to be calculated, while also allowing the number of CPM passing a given point to be recorded using Eqn (1):

$$CPM = \left(\frac{n}{t_x - t_y}\right) \quad (1)$$

where n is the number of animals within the herd, t_x is the time at which the last cow of the herd passes a given point on the roadway, and t_y is the time at which the first cow of the herd passes the same point on the roadway.

The CPM metric may be limited by the presence of lame cows within the main dairy herd. Where extremely slow cows are present within the herd the CPM may be skewed. However, on many commercial farms, lame cows which have become extremely slow due to lameness are typically removed from the main herd. In the current study, all cows classified as lame by the research farm manager were also removed from the herd before the trial began. The CPM metric is also limited to herd-level values as each individual cow is not recorded. Therefore, the distribution within the herd is unknown. The monitoring and recording of each individual cow was deemed to be too labour-intensive for this study and it would not be feasible on a commercial farm without the use of sophisticated monitor equipment.

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Once the first herd had exited the examination section, the process was repeated with the second and third herds. This may have resulted in loose stones being revealed following the first and second herd which may impact the CPM of the following herd, however, this is a similar practice that may occur on commercial farms, where the herd may use the same section of roadway four times per day. Any instances where individuals in the herd began to trot on the roadway or stopped to consume herbage on the grass verge present on the roadways were excluded from the study.

Roadway width

The impact of varying RWs on CPM was firstly assessed independently of all SCs, and congestion points. Four RWs were evaluated (1, 2, 3 and 4 m, due to the absence of a 5-m roadway on the research farm), along a 60 m long straight section, with a SC of Index 4. Cows were assembled 20 m before the start of the examination section and allowed to walk through the examination section.

Surface condition score

The impact of SC on CPM was also assessed on surfaces of varying SC index. Due to limitations on the SC of the roadway network on the study farm, only surfaces with an SC Index of 2, 3 and 4 were assessed. Cows were assembled 20 m before the start of the 60 m long straight section and allowed to walk through the examination section. Recordings of the time taken to walk from the entry point to the mid-point and exit point for the first and last cow were recorded.

Public road crossing

To assess the impact of PRC on CPM, animals were allowed to gather 20 m before the examination section. The examination section was 60 m in length prior to the public road with an electrified tape placed across the roadway at the exit point of the examination section, as is practised on commercial farms where the herd must cross a public road. The herds person was instructed to walk 5 m behind the last cow of the herd. Once the herd had gathered at the electrified tape, the herds person proceeded to walk to the front of the herd to open the tape. The stopwatch started when the first cow entered the examination section 60 m prior to the public road. The time at which the first cow stopped at the public road was recorded, the time at which the tape was opened and the time when the last cow of the herd walked past the electrified tape at the public road were also all recorded. This allowed for the total additional time required to move the herd to be calculated.

Interaction of roadway width, surface condition score and congestion points

To assess any potential interaction between RW, SC and congestion points on CPM, roadway examination sections were established. Examination sections were determined based on the SC of the roadway and the presence of a congestion point (a 90° bend, a sweeping bend (150°) and a continual straight section). Three sections of roadway were defined as SC Index 4 (Supplementary material), (the highest SC identified on the research farm) and a further three sections other defined as an Index 2 surface (the lowest SC identified on the research farm). Two examination sections (one SC Index 2, one SC Index 4) had a 90° bend present, two further sections (one SC Index 2, one SC Index 4) had a sweeping bend (150°) and the final two examination sections (one SC Index 2, one SC Index 4) had a continual straight section (180°) of roadway, resulting in six examination sections. Each examination section was evaluated at 2 and 4 m widths. There were two test runs (morning and evening) carried out with each combination, resulting in 72 test runs executed. (2 SC × 2 RW × 3 degrees of congestion × 3 herds × 2 times). Both sections had a gradient and camber of less than 5%. Each section was 60 m long. The herd was gathered 20 m before each examination section and held behind an electrified tape as outlined above. Once the herd had gathered, the tape was opened to allow the herd to walk through the examination section.

Experiment 2: commercial farm study

Farmer selection

Farmers were selected to proportionally represent the number of herds within each herd size category reported in a previous study by Maher *et al.* (2023), which contained 135 farms, while the herd size ranges were <100 cows (H1), 100–149 cows (H2), 150–199 (H3), 200–249 (H4) and ⩾250 cows (H5). These farms were selected based on their use of the Pasturebase Ireland platform (PBI; Hanrahan *et al.*, 2017). A minimum of 25 farm cover measurements must have been undertaken on the farm over the grazing season of 2020 to gather accurate grassland data for each farm in this study; this is critical to account for the frequency of use for each section of roadway that is used to access pasture over the grazing season. A total of 55 of these 135 farms were selected for the current study based on their herd size and geographical location in Ireland. This was 40.7% of the sample population and was deemed an appropriate sample size for this study due to labour and time constraints. All farmers who were contacted, agreed to participate in the study. The on-farm assessment of farm roadways took place from May to July 2021.

The farms were located in the following counties: Carlow (1), Cavan (1), Clare (2), Cork (9), Donegal (2), Galway (3), Kerry (3), Kilkenny (3), Laois (2), Limerick (5), Longford (1), Mayo (1), Meath (1), Monaghan (3), Offaly (3), Roscommon (2), Sligo (2), Tipperary (3), Waterford (2), Westmeath (1), Wexford (4) and Wicklow (1) (Fig. 1).

Farm visits

Roadways on commercial farms were assessed using on-farm visits. At the time of the farm visits, all recording items were brought to the farm (including a measuring tape, spirit level, farm map and recording sheet). To minimize observer bias, data was collected by the first author of the study across all 55 farms. Roadways on each farm were broken into sections based on changes in the SC, RW or congestion points present. This method was selected over a predefined length per section due to the varying widths and surfaces present on farm roadways, which may not be captured where a predefined length of roadway is used. The length (m) of each section examined was recorded using satellite imagery, similar to that reported by Maher *et al.* (2023). The SC of each roadway section was recorded using the scoring system (Supplementary material). Other metrics collected on-farm included the presence or absence of a public roadway crossing (PRC) on the section of the roadway. Congestion points were recorded as minor or major congestion points. Minor congestion points were defined as the presence of a water trough on the roadway, while a major congestion point was recorded where there is a 90° bend with no sweeping arch present.

The verge width was recorded as the width between the edge of the roadway used by the dairy herd and the electrified fence alongside the roadway. The verge width was quantified into a binary outcome i.e. greater than the recommended width of 0.5 m

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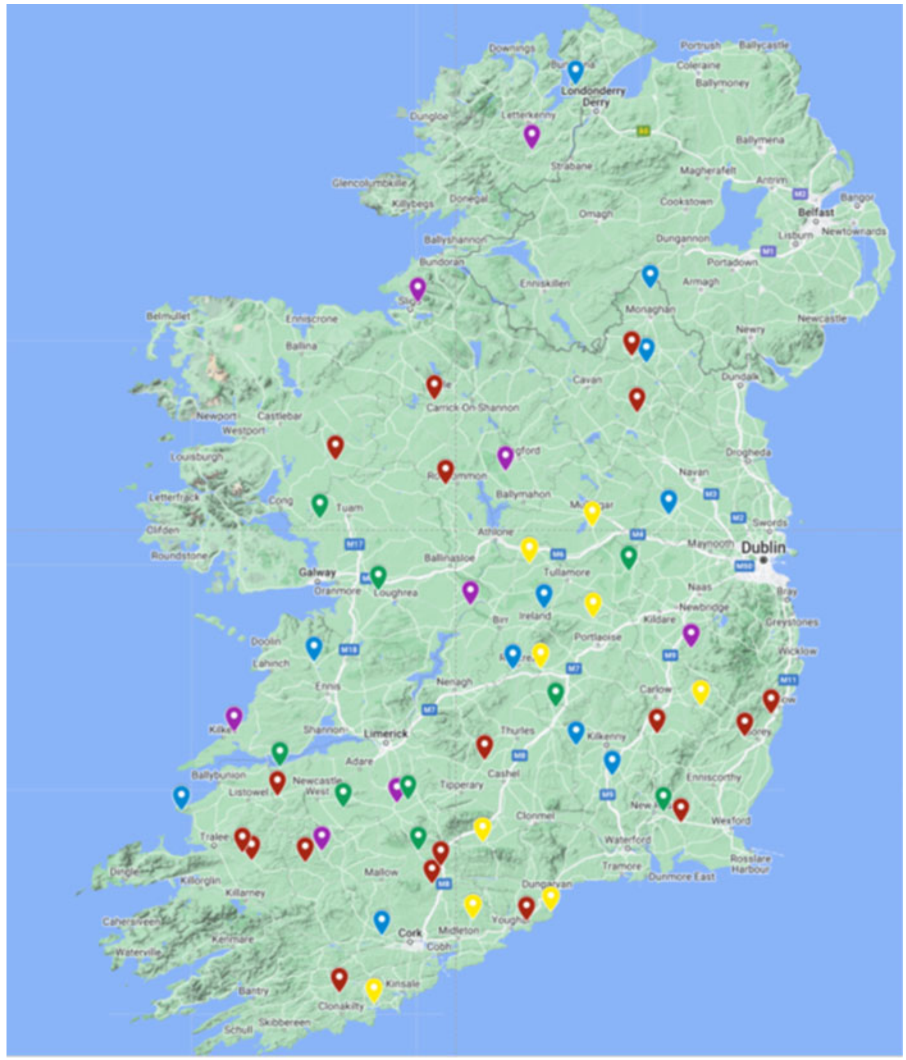

Figure 1. The locations of farms ($n = 55$) selected for the study. Herd sizes are colour coded as follows; Blue: <100 cows, Red: 100–149 cows, Purple: 150–199 cows, Green: 200–249, Yellow: ⩾ 250 cows. Google Maps (2022).

reported by Clarke (2016) or not. The level of surface drainage was also recorded with a subjective score from Index 1 to 5, with Index 1 incapable of draining water, resulting in water ponding on the roadway. Index 5 represented roadways/surfaces with no restrictions on the flow of water into adjoining pastures (Supplementary material). Other parameters which were assessed on commercial farms included the incline (slope of the roadway, recorded in percentage points) and cross-fall (camber, recorded in percentage points) of each farm roadway. Each section of the roadway network was examined to determine whether water run-off from the roadway could enter any adjoining water courses, while any occurrence where the dairy herd walked through a water course to access sections of the grazing platform was also recorded. When all farm visits were complete, all measured parameters were entered into a spreadsheet database for each farm roadway section for each farm.

Data analysis

Experiment 1

Roadway width and SC were firstly assessed to identify if they significantly impacted CPM independently of each other. While secondly assessing if there was an interaction between RW, SC and congestion points on CPM. It was reported that congestion points were not significant in the prediction of CPM, so this variable was removed from the model. The model was used to calculate the predicted CPM on commercial farms (CPM_P), Eqns (3) and (4).

Experiment 2

The CPM_P for each roadway on the 55 commercial farms was assessed using Eqns (3) and (4). Each roadway on the 55 commercial farms was weighted according to their frequency of use from a previous study by Maher *et al.* (2023). Therefore, roadways used more frequently to access the grazing paddocks throughout the grazing season had a greater impact on the overall farm roadway CPM_P. A second metric, absolute time taken (AT) was created to compare CPM_P across a range of herd sizes. This metric encapsulated the total time (minutes) taken for the dairy herd to walk past any given point on a farm roadway.

$$AT = \frac{HS}{CPM_P} \quad (2)$$

where AT is the total time (minutes) it takes a dairy herd to walk past a given point on a farm roadway, HS is the herd size and

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CPM_P is the predicted cows per minute capable of passing a given point on the farm roadway.

All data cleaning, descriptive statistics and statistically significant differences were examined using R software version 4.0.2 (R Core Team, Vienna, Austria). Using a Shapiro-Wilk test, all parameters were initially evaluated for normality. Following this, a one-way ANOVA was employed with homogeneity of variance designated as true or false based on the outcome of a Levene's test to assess the difference between values obtained throughout herd size ranges. When ANOVA test findings were judged significant ($P < 0.05$), a post hoc Tukey test was performed where equal variance was indicated. A Games Howell test was employed when the variance was uneven. A co-efficient of determination was used to determine the strength of the correlation between the variables and herd size, with values of $R^2 > 0.25$ deemed statistically significant.

Results

Experiment 1: validating parameters which impact herd movement

Effect of roadway width on herd movement

There were differences in CPM ($P < 0.05$) between all RW recorded, with the highest CPM observed where RW was 4 m wide at 47.42 ± 1.77 CPM. This reduced to 16.28 ± 0.29 CPM where the RW was 1 m wide ($P < 0.001$). There was a very strong positive correlation between RW and CPM with an $R^2 = 0.96$ ($P < 0.001$) (Fig. 2).

Effect of surface condition score on herd movement

The surface condition affected the CPM across all three treatments, with the Index 4 surface having a cow throughput of 65.8 CPM. This decreased to 51.8 CPM for SC Index 3 and 28.6 CPM for SC Index 2. There was a strong correlation observed between SC and CPM with an $R^2 = 0.78$ ($P < 0.001$). This also allowed for the projection of CPM on SC Index 1, and Index 5 using linear extrapolation.

Effect of public road crossing on animal movement

The public crossing was assessed for the impact it had on the total time to move the herd through the examination section. Where the herd had to wait at a public crossing, there was a greater time taken to move the herd, 203.3 *v.* 136.8 s ($P < 0.001$), a 32.7% reduction in the CPM.

Cows per minute

There was an interaction between RW and SC on CPM ($P < 0.001$), with a strong correlation for the effect on CPM ($R^2 = 0.8702$, $P < 0.05$). The cow throughput (*CT*) on varying SC roadways can be calculated as per Eqn 3.

$$CT = \begin{Bmatrix} 2.0472(RW) + 10.341, & SC = 1 \\ 6.9179(RW) + 4.7725, & SC = 2 \\ 12.535(RW) + 2.7053, & SC = 3 \\ 17.079(RW) - 0.5115, & SC = 4 \\ 21.595(RW) - 0.3459, & SC = 5 \end{Bmatrix} \quad (3)$$

The predicted cows per minute (CPM_P) on farm roadways can be calculated as per Eqn 4.

$$CPM_P = CT[1 - 0.32705(PRC)] \quad (4)$$

where *CT* is the cow throughput, *RW* is the width of the roadway, and *SC* is the surface condition score of the roadway, CPM_P is the predicted number of cows per minute passing a given point on the roadway, *PRC* is the presence or absence of a public roadway crossing, with presence = 1 and absence = 0. The creation of a simple look-up table to represent the CPM relative to varying RW and SC was established upon the outputs of Eqns (3) and (4) (Table 1).

Experiment 2: commercial farm results

Roadway width

In total, 893 roadway sections were assessed on 55 commercial farms. The mean length of each roadway section assessed across all farms was 142 ± 3.3 m. The mean RW across all roadway sections was 3.3 ± 0.09 m. Larger herd sizes tended to have wider roadways in absolute terms (H1 = 2.97 m wide, H5 = 3.89 m wide) ($P < 0.001$). The mean utilizable agricultural area under farm roadways was 0.85 ha or 1.25% (0.47–2.12%) of the grazing platform.

Surface condition score

A total of 14.2% of roadways were determined to be SC of Index 5, a further 20.0% were ranked as Index 4, 23.5% as Index 3, 18.4% as Index 2 and 24.4% as Index 1. There was no correlation between herd size, and SC recorded. However, H5 did record a greater mean average SC of 3.06, compared to that recorded for H1 (2.46) ($P < 0.001$) (Table 2).

Parameters associated with surface condition score on commercial farms

There were several parameters assessed which were associated with SC on commercial farms (Table 3). Greater RW was associated with a higher SC from Index 1 compared to Index 5 ($P = 0.01$). There was a higher proportion of congestion points present on roadways classified Index 1 for SC in contrast to the proportion of congestion points on roadways classified Index 3–5 for SC ($P = 0.001$). The presence of a grass verge of 0.5 m or less was associated with a higher SC for the roadway ($P < 0.001$). The ability of a roadway to drain surface water onto an adjoining pasture as opposed to water remaining static on the roadway or flowing along its surface had a positive association with the SC of the roadway ($P < 0.001$). Neither roadway incline nor camber had a significant association with SC.

The presence of a public crossing

There were 95 incidents recorded across 32 of the study farms where animals had to cross a public roadway without the use of an underpass. In these instances, the herd must wait at the PRC for the herds person to allow the herd across the public road.

There were 119 major congestion points (sharp bends; where the angle was approximately 90°) recorded on farm roadways (an occurrence on 13.3%), while a further 181 were defined as minor congestion points due to short restrictions in width on the roadway (e.g. a narrow bridge crossing) (20.3%).

Assessment of farm roadways and adjoining water courses

Where farm roadways were observed for water run-off into adjoining water courses, it was reported that on 104 sections of farm roadway (11.6%), water runoff was capable of entering water courses. This occurred across 31 farms with a large geographical spread and was not isolated to any particular region. There were six farm roadways on which the dairy herd had to

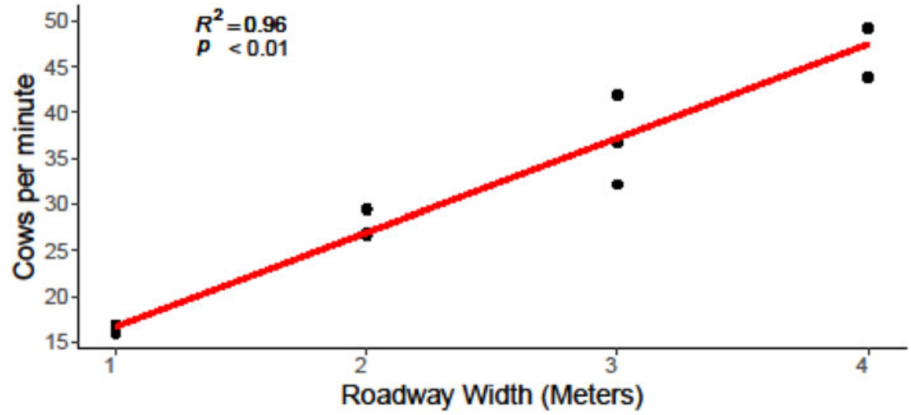

Figure 2. Effect roadway width (m) has on the number of cows per minute passing a specific point on a farm roadway.

walk through a water course on a farm roadway to access a section of the grazing platform across five different farms.

Total farm cows per minute

The CPM_P was calculated for each farm roadway and the mean across all roadways within the farm for each of the 55 commercial farms (which incorporated frequency of use). The predicted average CPM_P across all 893 farm roadways was 42 (±0.77) CPM_P. The predicted average CPM_P on farm level was 49.7 (±2.17) CPM. This was 51% of the recommended CPM_P across the study farms of 98.22 CPM_P. There was a moderately positive correlation between herd size and CPM_P on farm roadways, where larger herd sizes had an increased CPM_P ($R^2 = 0.26$, $P < 0.01$). The highest predicted CPM_P on a farm level was 97.0 CPM_P with a herd size of 500 cows, while the recommended CPM_P for this herd size is 151 CPM_P. The lowest predicted CPM_P on a farm level was 24.3 CPM_P with a herd size of 89 cows, while the recommended CPM_P for this herd size is 78 CPM_P.

There was a strong positive correlation between herd size and the AT for the herd to walk past any given point on the farm roadway ($R^2 = 0.74$, $P < 0.001$) (Fig. 3). The average time it took the whole herd to walk past any given point on the roadway was three minutes and 48 s across the study farms. This was two minutes and six seconds greater than the recommended time if an optimal RW and SC were implemented. However, there was a large range in these results, with the lowest additional time just 10 s above the recommended time, compared to the highest additional time of 10 min 11 s for the farm with the lowest CPM_P relative to the herd size of the farm (Fig. 3).

No farm achieved the CPM_P recommended based on the herd size. The greatest proportion recorded was 81% of the recommended CPM_P, while the poorest performing farm recorded just 28% of the recommended CPM_P relative to the herd size.

Table 1. The predicted number of cows per minute passing a given point on a roadway with a range of roadway widths and surface condition scores

	Surface Condition (Index)				
Width (m)	1	2	3	4	5
1	12.4	13.8	15.2	16.6	21.3
1.5	13.4	15.6	21.5	25.1	32.1
2	14.4	17.4	27.8	33.6	42.9
2.5	15.5	21.2	34.0	42.2	53.6
3	16.5	25.0	40.3	50.7	64.4
3.5	17.5	28.8	46.6	59.3	75.2
4	18.5	32.6	52.8	67.8	86.0
4.5	19.6	36.4	59.1	76.3	96.8
5	20.6	40.2	65.4	84.9	107.6

Note: Visual indicators of the least optimal CPM to the optimal CPM are reported in this study.
Red represents the lowest CPM and green represents the most optimal CPM.

Discussion

Validation of parameters affecting cows per minute

The validation of parameters affecting CPM indicated that both RW and the SC of the roadway impacted the CPM passing a given point on a farm roadway. Interestingly, it was reported in this study that congestion points did not impact CPM. It was reported that the SC had a greater impact than RW on CPM at greater roadway widths. To the best of the authors knowledge, this is the first study to define the impact of RW on the movement of a dairy herd as opposed to individual animals, as reported by Telezhenko and Bergsten (2005) and Buijs *et al.* (2019).

Impact of roadway width, surface condition score, congestion points and public road crossings on cows per minute

Increasing the SC from Index 1 to Index 5, at RW of 5 m, increased CPM from 20.6 to 107.6 CPM (Table 1). Previous studies have reported that reducing the surface quality material resulted in more selective paths being taken by the animals (Telezhenko *et al.*, 2007; Buijs *et al.*, 2019). In this study, it is hypothesized that animals may have followed this similar trend in selecting their paths where poor-quality surfaces were present on the research farm due to the lower CPM observed in the current study, where SC reduced and RW remained static. There may have been a potential increase in the herds walking speed in the present study when more optimum surfaces were used due to

Table 2. Results of parameters assessed on commercial farm roadways, including roadway width, surface condition, number of public road crossings and the predicted cows per minute across a range of herd sizes

	Herd size categories[a]						
Category	H1	H2	H3	H4	H5	S.E.M	*P* value
Number of herds	11	18	8	5	13		
Sample size of roadways (n)	130	260	124	87	292		
Mean length of section examined (m)	87	129	114	157	185	3.3	<0.001
Mean roadway width (m)	2.97	2.94	3.30	3.6	3.89	0.029	<0.001
Range roadway width (m)	1.7–6.0	1.2–5.0	1.8–7.7	2.5–5.3	1.9–10.0		
Relative roadway width (m) to herd size	0.76	0.70	0.69	0.74	0.62	0.005	<0.001
Mean surface condition score	2.46	2.75	2.81	2.64	3.06	0.046	<0.001
Number of public road crossings	10	20	20	4	41	6.3	
Mean total farm CPM_P[b]	36	37	41	44	55	2.0	<0.005
Total farm CPM_P adjusted for frequency of use.	40	45	47	45	67	2.2	<0.001

[a]H1 = <100 cows; H2 = 100 to 149 cows; H3 = 150 to 199 cows; H4 = 200 to 249 cows; H5 ⩾ 250 cows.
[b]CPM_P = Predicted cows per minute.

Table 3. Parameters that were significantly associated with varying surface condition scores on commercial farm roadways

	Surface condition score						
Category	Index 1	Index 2	Index 3	Index 4	Index 5	S.E.M.	*P – value*
Sample size of Roadways	218	164	210	174	127		
Roadway width (m)	3.23	3.35	3.44	3.40	3.55	0.029	0.01
Verge width[a]	0.35	0.46	0.50	0.61	0.71	0.067	<0.001
Water run-off[b]	2.60	2.69	2.99	3.37	3.76	0.036	<0.001
Congestion points[c]	2.25	2.47	2.56	2.62	2.53	0.026	<0.001

[a]Verge width: '0' >0.5 m, '1' ⩽0.5 m.
[b]Water run-off: 1: Water run-off incapable from the roadway onto adjoining pasture, 5: Optimal water run-off, no restrictions of water onto adjoining pasture.
[c]Congestion points: 1: Major congestion point, 2: Minor congestion point, 3: No congestion point.

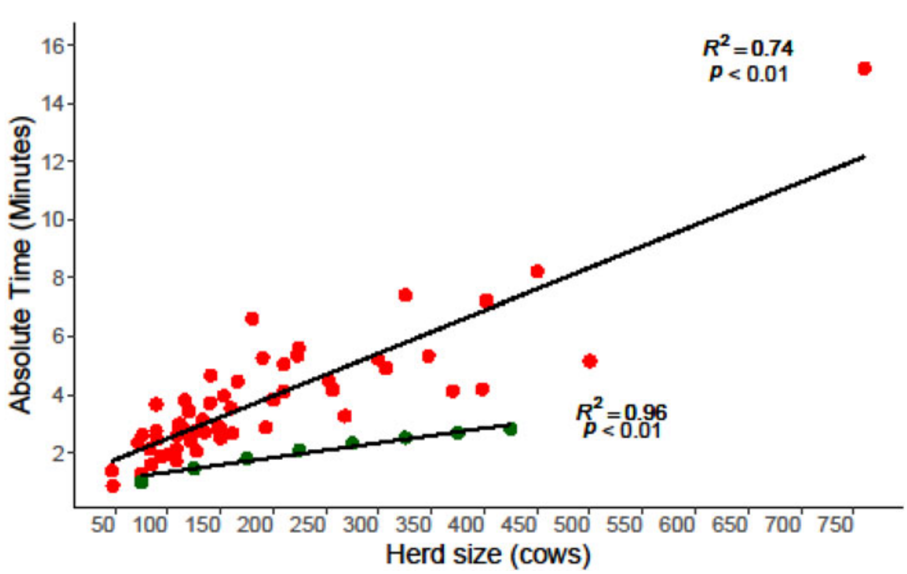

Figure 3. Absolute time reported for the herd to pass a specific point on a farm roadway across the commercial farms assessed (red) and the optimal absolute time it should take the herd (green) to move the herd past a specific point on a farm roadway.

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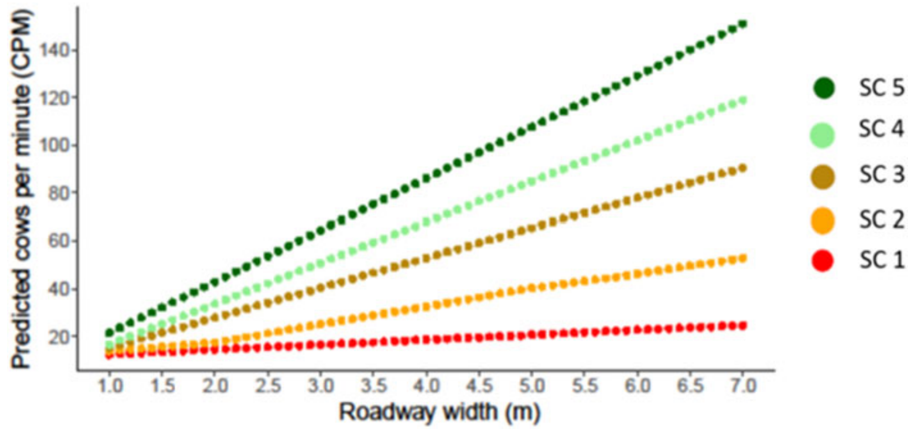

Figure 4. The predicted cows per minute passing a specific point on a farm roadway across various roadway widths and different surface conditions.

the greater CPM reported. This would follow similar studies whereby individual cow velocity increased as the surface examined improved (Rushen and de Passillé, 2006; Telezhenko *et al.*, 2007; Chapinal *et al.*, 2011).

This study indicated there was no impact of congestion points on CPM across varying RW and SC. In previous studies, this was predicted to impact cow throughput with a recommendation to remove 90° bends (Clarke, 2016). Previous studies have reported that congestion points may be a cause of reduced roadway SC and increased lameness (Chesterton, 1989; Browne *et al.*, 2022a). In this study, the presence of congestion points was associated with reduced SCs on commercial farms. Therefore, although this study did not find a direct link between congestion points and CPM, there may be a higher incidence of lameness on commercial farms (due to poorer SCs on roadways and animal management practices [Chesterton *et al.*, 1989]) where congestion points are present, which will ultimately lead to a reduction in CPM.

Cows per minute

Due to the strong correlations with RW, SC and CPM, it was possible to calculate the maximum potential CPM for varying widths and surfaces (Table 1). Commercial farmers may use this table to evaluate their own roadway networks and identify areas of improvement. This is of particular importance where future investments in farm roadways are required as it can aid farmers in optimizing their investment to ensure they increase their CPM on commercial farm roadways for the lowest capital expenditure required. It may also be useful for farm technical advisors to indicate the potential benefits of upgrading the SC on sections of farm roadways. While RW may be a limiting factor for CPM on other sections of the farm roadway network. However, a key metric to the effective use of this metric is the inclusion frequency of use of each roadway section as outlined in the Material and Methods using data generated from PBI grazing data. To the best of the authors' knowledge, this is the first study to quantify the movement of the dairy herd across varying RWs and SCs. Surface condition had a greater impact on CPM than RW. However, the impact of SC was limited at lower RW. This was at least in part due to the restriction on the animals' ability to pass one another at reduced RW (Fig. 4).

Commercial farm results

The data gathered on commercial dairy farms revealed that farm roadways were 69.9% of the recommended width (Clarke, 2016; Tuohy *et al.*, 2017) relative to the mean herd size of the farms assessed (189 ± 17.7 cows), with only 4.0% of farm roadways recorded as the optimal width or greater relative to the herd size across all farms (Fig. 5). There have been other studies which suggested larger farms, in particular have not adapted their grazing infrastructure to meet the requirements of larger herd sizes (Maher *et al.*, 2023). Similar results were observed in the current study, where AT increased with larger herd sizes (Fig. 3). This study also reported that 1.25% of the utilizable agricultural area was covered with farm roadways, this is similar to previous estimates across Irish dairy farms (Ryan, 2009). Larger farms (H5) had a greater SC than H1 and tended towards

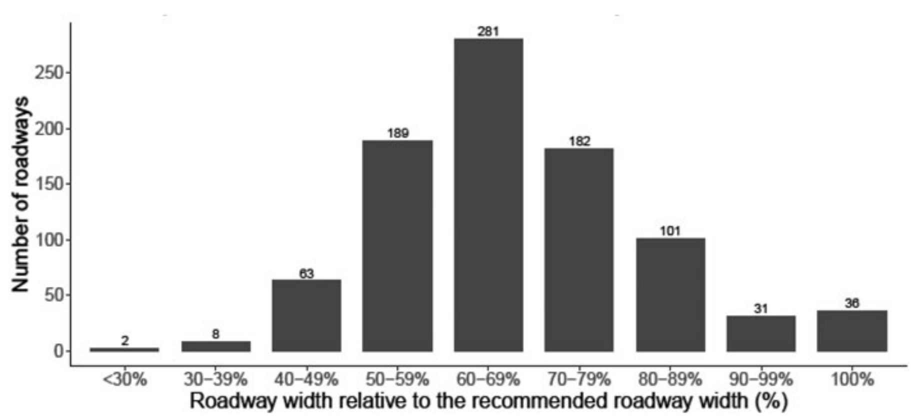

Figure 5. Roadway width (m) as a percentage of recommended roadway width relative to the herd size of the farm.

significant for H2. These larger farms had a greater disposable income (Hanrahan *et al.*, 2018) and may have invested in resurfacing farm roadways, resulting in greater SC observed on larger commercial dairy farms.

There were 95 locations within the 55 farm sample study where herds had to cross a public road without the use of a tunnel. Public roadway crossings did not significantly impact the SC across the commercial farms. Previous research has reported that the number of defecations correlated with the time spent in a particular area (White *et al.*, 2001). This may suggest that farmers are placing a greater emphasis on SC at the PRC, or the herd is retained in the collecting yard until all cows are milked as opposed to gathering at the PRC on their return to the grazing paddock. In the current study, there were 12 tunnels in use across the 55 farms, whereby the herd do not have to be retained post-milking. Retaining the herd post-milking has been reported as a risk factor for suboptimal mobility (O'Connor *et al.*, 2020). So, there may be other benefits for animal health with the installation of tunnels beyond the increased CPM_P as observed in this study.

All parameters recorded on commercial farms were assessed for their association with SC on farm roadways. Wider roadways were associated with increased SC, while reduced congestion points were also associated with increased SC. This would agree with previous work by Chesterton (1989), who reported congestion points and poorly maintained roadways are linked. The presence of a grass verge greater than 0.5 m was negatively associated with SC. This may be due to the propensity of animals to carry loose stones or clay on their hooves onto the farm roadway from wider verges. The ability of a roadway to shed water onto an adjoining pasture was positively associated with the SC. This follows similar recommendations on commercial roads (Skorseth, 2000; Tuohy *et al.*, 2017).

Assessment of farm roadways and adjoining water courses

It has previously been reported by Adams *et al.* (2014) that farm roadways were a critical source of nutrient runoff into water courses. In this study, 11.6% of farm roadways failed to comply with current regulations concerning water run-off from farm roadways (DAFM, 2019), where surface water from farm roadways has the opportunity to flow directly into adjoining water courses. This is similar to the 8.4% of roadways requiring management strategies to prevent runoff into water courses, as reported by Rice *et al.* (2022). Recent recommendations to address this issue include the implementation of a camber on the farm roadway away from the watercourse or implementing buffer zones to capture discharge from farm roadways allowing the roadway to drain naturally (Fenton *et al.*, 2021). There is similar guidance in both the UK (UK, Environment Agency n.d.) and New Zealand (Ministry for the Environment n.d.) with respect to restricting water run-off from farm roadways entering water courses. However, currently, there is limited data within these countries relating to the frequency of water runoff occurrences from farm roadways.

Total farm cows per minute

When assessing the CPM_P achieved across all commercial farms, it became clear that when the usage frequency of each roadway was accounted for, there was an increase in the total farm CPM_P received by each farm. Roadways that were used more frequently, had a greater capacity for more efficient movement of the dairy herd between the milking parlour and the grazing paddocks. This may be due to an increased level of maintenance by the farmer on these particular roadways that are used more frequently, which follows previous recommendations (Clarke, 2016). However, results from this study have indicated the suitability of farm roadways for movement of the dairy herd are sub-optimal across all farms, particularly those with larger herd sizes. No farm across the study population achieved the recommended CPM relative to herd size.

Although larger herd sizes had higher CPM_P on farm roadways, when assessed for AT, they had greater total time taken for the movement of the dairy herd passed a given point on a farm roadway. This is despite the observation that larger herds tended to have increased SC and wider RW, but the width of these roadways were still sub-optimal for the herd sizes on these farms. This supports previous work by Maher *et al.* (2023), which showed farms with larger herds have not adapted their pasture allocation to meet increased herd demands. Previous labour studies have also reported greater total hours per year worked at larger herd sizes (Deming *et al.*, 2018), this study identified similar results where the AT increased as herd size increased.

Further investigation may be required into the effect camber and roadway incline have on CPM. While the economic costs involved in upgrading SC and RW of farm roadways may need to be reported and beneficial effects on reduced lameness in the herd where SC is increased (Chesterton *et al.*, 1989).

Conclusion

This study investigated parameters that affect CPM on farm roadways for the movement of the dairy herd between the milking parlour and the grazing paddocks. There was a strong relationship between both RW and SC on CPM on farm roadways. There was an interaction effect between RW, SC and CPM. Interestingly, congestion points did not impact CPM, which contradicts current literature proposing that they may affect cow flow on farm roadways, this allowed for the prediction of CPM_P on commercial farms. It became clear that all farms had sub-optimal roadway conditions for the movement of the dairy herd to the milking parlour. Although farms with larger herd sizes did have significantly wider roadways and higher SCs, they had a significantly greater AT for the movement of the dairy herd through a given point of the roadway network. Further research is required into the economic return on future investment in roadway infrastructure to improve CPM on commercial farms.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0021859623000497

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Authors' contribution. The primary author, second and fourth authors created the scoring metric, which was implemented on commercial farms. The primary author gathered the data on these farms, the primary second and third author created the validation procedure. While the third author also performed the statistical analysis. All authors helped to write the manuscript.

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Competing interests. None.

Ethical standards. Ethics approval has been obtained for this project through Munster Technological University. The study was a non-invasive study.

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