

1 **Making tie-stalls more comfortable: I. Adjusting tie-rail height and forward position to**  
2 **improve dairy cows' ability to rise and lie down**

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**SUPPLEMENTARY MATERIAL**

12    Supplementary Table S1. Summary of the recommended tie-stall dimensions

Dimension	Recommendation <sup>1</sup>
Stall width	2× width of the cow at the hook bone
Bed length	1.2× height of cow at rump
Tie-rail height	0.80× height of cow at rump
Tie-rail (forward) position	35 cm more than stall length, from the back of the stall
Manger wall height	<20 cm
Chain length	Height of tie-rail – Height of the manger wall

13    <sup>1</sup>Adapted from NFACC and DFC (2009), Anderson (2014), and Valacta (2014).

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16 Supplementary Table S2. Repeatability scores for measure variables: injury, lying and rising events, cow and stall  
 17 cleanliness, bedding quantity, lameness, and body condition.

Measured variables	Performed live or using videos	Weeks	Number of observers	Inter-observer (overall average $K_w^{1)}$ )	Intra-observer (overall average $K_w$ )
Injury	live	0, 5, 10	4	0.76	0.83
Lying-down events	video	1, 2, 3, 6, 9, 10	3	0.96	0.99
Rising events	video	1, 2, 3, 6, 9, 10	3	0.93	0.96
Cow cleanliness	live	0, 5, 10	4	0.98	0.97
Stall cleanliness	live	0, 5, 10	4	0.80	0.71
Bedding quantity	live	0, 5, 10	4	0.76	0.88
Lameness	video	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	3	0.79	0.77
Body condition	live	0, 5, 10	4	0.63	0.66

<sup>1</sup>Weighted Kappa

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20 Supplementary Table S3. Percentage of injuries<sup>1</sup> per location per term<sup>2</sup> for CR, CF, NL1, and NL2 treatments<sup>3</sup>.

Injury Location	Term	Treatments (% injured)				Treatments (average injury score)				
		CR	CF	NL1	NL2	CR	CF	NL1	NL2	
Neck										
Proximal Neck	Baseline	0	18	8	8	0.00	0.17	0.08	0.17	
	Short	13	13	14	14	0.11	0.12	0.14	0.22	
	Mid	30	45	33	25	0.42	0.73	0.42	0.25	
	Long	63	70	61	22	0.69	0.85	0.78	0.59	
Medial Neck	Baseline	70	36	58	50	0.67	0.42	0.58	0.50	
	Short	60	32	44	56	0.59	0.42	0.50	0.69	
	Mid	40	36	58	67	0.58	0.36	0.75	0.92	
	Long	63	48	86	89	0.69	0.70	1.06	1.09	
Dorsal Neck	Baseline	0	0	0	0	0.00	0.00	0.00	0.00	
	Short	0	0	0	0	0.00	0.00	0.00	0.00	
	Mid	10	0	0	0	0.25	0.00	0.00	0.00	
	Long	3	0	0	3	0.06	0.00	0.00	0.03	
Side										
Back	Baseline	5	0	13	17	0.08	0.00	0.21	0.29	
	Short	8	8	13	6	0.21	0.13	0.22	0.10	
	Mid	5	0	0	0	0.04	0.00	0.00	0.00	
	long	10	2	6	0	0.23	0.03	0.06	0.03	
Hip Bone	Baseline	10	14	29	4	0.21	0.17	0.50	0.08	
	Short	10	10	19	21	0.28	0.12	0.38	0.38	
	Mid	10	5	13	13	0.29	0.05	0.21	0.17	
	long	10	0	10	1	0.26	0.00	0.11	0.03	
Shoulder	Baseline	0	0	0	0	0.00	0.00	0.00	0.00	
	Short	0	0	6	0	0.00	0.02	0.07	0.00	
	Mid	0	0	0	0	0.00	0.00	0.00	0.00	
	long	0	3	0	1	0.00	0.03	0.00	0.03	
Flank	Baseline	30	9	17	25	0.33	0.13	0.25	0.29	
	Short	23	10	19	13	0.22	0.10	0.40	0.13	
	Mid	15	14	38	13	0.13	0.14	0.50	0.13	
	long	23	14	38	15	0.27	0.14	0.43	0.19	
Sacrum	Baseline	0	9	8	21	0.00	0.08	0.08	0.33	
	Short	0	6	14	8	0.03	0.09	0.18	0.18	
	Mid	0	5	0	4	0.00	0.10	0.00	0.08	
	long	2	5	1	7	0.03	0.06	0.01	0.16	
Pine Bone	Baseline	5	9	13	13	0.08	0.17	0.13	0.25	
	Short	3	3	17	8	0.06	0.04	0.29	0.17	
	Mid	0	0	4	4	0.00	0.00	0.08	0.08	
	long	0	0	8	1	0.00	0.00	0.08	0.01	
Back Legs										
Lateral Tarsal	Baseline	100	100	100	100	2.21	2.00	2.29	2.38	
	Short	98	97	97	97	2.51	2.22	2.44	2.48	
	Mid	100	100	100	96	2.71	2.77	2.83	2.63	
	long	100	98	100	100	2.47	2.59	2.78	2.51	
Medial Tarsal	Baseline	0	0	0	8	0.00	0.00	0.00	0.09	
	Short	2	0	0	0	0.04	0.00	0.00	0.00	
	Mid	0	0	0	4	0.00	0.00	0.00	0.04	
	long	0	3	0	0	0.00	0.03	0.00	0.00	
Lateral Calcanei	Baseline	100	100	92	96	1.71	2.04	1.83	2.04	
	Short	100	100	99	99	1.96	2.04	1.88	2.14	

	Mid	100	100	100	96	2.08	2.36	2.08	2.13
	long	100	98	100	97	2.13	2.09	2.17	2.01
Dorsal	Baseline	55	45	46	46	0.87	0.79	0.79	0.68
Calcanei	Short	52	37	44	33	0.71	0.58	0.75	0.56
	Mid	55	32	42	42	1.08	0.68	0.70	0.79
	long	63	45	65	43	1.21	0.85	1.03	0.63
Medial	Baseline	0	5	4	8	0.13	0.04	0.04	0.13
Calcanei	Short	5	5	6	7	0.21	0.07	0.04	0.15
	Mid	5	5	0	8	0.17	0.09	0.00	0.17
	long	8	9	6	7	0.21	0.29	0.13	0.06
Hind	Baseline	25	32	21	29	0.42	0.54	0.33	0.63
Leg	Short	23	34	33	26	0.36	0.60	0.37	0.60
	Mid	15	23	13	29	0.38	0.54	0.21	0.50
	long	20	29	15	24	0.24	0.58	0.39	0.42
Stifle	Baseline	85	55	96	83	1.88	0.92	1.71	1.25
	Short	92	47	74	64	1.87	0.83	1.61	1.04
	Mid	95	59	92	67	1.79	1.05	1.58	1.08
	long	88	55	89	65	1.86	1.08	1.63	1.25
Front Legs									
Carpal	Baseline	95	86	96	100	1.63	1.43	1.54	1.50
Joint	Short	90	85	96	86	1.76	1.53	1.64	1.35
	Mid	100	100	100	100	1.96	1.73	1.83	1.71
	long	98	98	100	100	2.01	1.64	2.10	1.63

21 <sup>1</sup>Percentage of cows with injury scores > 1 for a specific  
22 location on the body.

23 <sup>2</sup>Short-term represents the average scores of weeks 1-3,  
24 mid-term represents the scores for week 6 and long-term  
25 represents the average scores of weeks 8-10.

26 <sup>3</sup>Treatment abbreviations: CR represents current  
27 recommendation, CF represents common on farm, NL1  
28 represents Neckline1, and NL2 represents Neckline2.

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Supplementary Table S4. Descriptive data for Body Condition Score, Lameness, Cleanliness, and milk production and quality between CR, CF, NL1, and NL2 treatments<sup>1</sup> and over the terms<sup>2</sup> in the study.

Outcome measures	Term	Treatments			
		CR	CF	NL1	NL2
Body Condition score, average score	Baseline	2.6	2.7	2.5	2.5
	Short	2.6	2.5	2.5	2.4
	Mid	2.6	2.6	2.6	2.5
	Long	2.6	2.5	2.6	2.5
Lameness, % cows scored lame	Baseline	10	64	50	42
	Short	40	52	56	33
	Mid	60	18	75	33
	Long	40	45	47	47
Rumination/Feeding, % of time/h	Baseline	- <sup>3</sup>	-	-	-
	Short	56	51	52	55
	Mid	56	52	51	55
	Long	52	50	46	50
Bedding quantity, % bedding $\geq$ 2 cm	Baseline	-	-	-	-
	Short	9	6	11	8
	Mid	33	0	17	8
	Long	21	6	0	0
Bedding cleanliness, % dirty	Baseline	-	-	-	-
	Short	22	16	17	22
	Mid	33	10	8	17
	Long	18	23	17	28
Cleanliness of cows					
Leg, % cows scored dirty	Baseline	0	0	0	0
	Short	3	13	0	0
	Mid	0	0	0	0
	Long	6	7	0	94
Flank, % cows scored dirty	Baseline	0	17	0	0
	Short	3	20	0	3
	Mid	8	0	0	0
	Long	6	7	0	6
Udder, % cows scored dirty	Baseline	0	0	0	0
	Short	8	20	0	0
	Mid	8	8	0	0
	Long	8	16	0	11
Milk production (kg/d)	Baseline	42.2	42.0	42.1	41.4
	Short	41.8	40.5	41.8	41.2
	Mid	40.4	38.3	40.5	39.1
	Long	38.4	37.3	40.0	37.7
% cows with somatic cell count > 200 000 cells/mL	Baseline	16.7	8.3	0	0
	Short	19.4	8.3	0	5.6
	Mid	16.7	8.3	0	8.3
	Long	16.7	8.3	11.1	8.3
Somatic cell score, average 000/ml	Baseline	514.5	141.5	43.8	58.3
	Short	360.5	118.6	33.4	151.9
	Mid	376.6	306.8	54.0	66.7
	Long	408.1	140.7	93.7	64.9

<sup>1</sup>Treatment abbreviations: CR represents current recommendation, CF represents common on farm, NL1 represents Neckline1, and NL2 represents Neckline2.

<sup>2</sup>Short-term represents the average scores of weeks 1-3, mid-term represents the scores for week 6 and long-term represents the average scores of weeks 8-10.

<sup>3</sup>Data not available.

39 Supplementary Table S5. Random effects variances ( $\sigma^2_{row}$ ,  $\sigma^2_{cow}$ ,  $\sigma^2_e$ , CS), covariance parameter estimates,  
 40 phenotypic variance ( $\sigma^2_p$ )<sup>1</sup>, variable means ( $\bar{x}$ )<sup>2</sup>, and coefficient of variation (CV)<sup>3</sup> between the 4 tie-rail positions

Variable	$\sigma^2_{cow}$	AR(1)	CS	$\sigma^2_e$	$\sigma^2_p$	$\bar{x}$	CV (%)
Injuries							
Proximal Neck	0.00	0.73	-	0.33	0.33	0.44	130.99
Medial Neck	-	-	0.21	0.27	0.48	0.73	94.63
Distal Neck	0.01	0.15	-	0.04	0.04	0.02	1015.30
Back	0.06	0.31	-	0.07	0.13	0.09	389.69
Hip Bone	0.08	0.40	-	0.09	0.17	0.18	224.12
Shoulder	0.00	0.26	-	0.02	0.02	0.01	1318.28
Flank	0.08	0.34	-	0.09	0.17	0.25	163.22
Sacrum	-	-	-	-	-	-	-
Pin Bone	-	-	-	-	-	-	-
Lateral Tarsal	0.36	0.39	-	0.17	0.53	2.56	28.57
Dorsal Calcanei	-	-	0.51	0.24	0.75	0.79	109.57
Hind Leg	-	-	0.15	0.09	0.24	0.45	108.11
Stifle	0.07	0.38	-	0.18	0.26	1.36	37.20
Lateral Calcanei	0.06	0.31	-	0.25	0.31	2.07	27.00
Medial Calcanei	-	-	-	-	0.00	0.12	0.00
Lateral Tarsal	0.36	0.39	-	0.17	0.53	2.56	28.57
Medial Tarsal	-	-	0.02	0.03	0.06	0.02	1163.13
Carpal; Joints	0.18	0.51	-	0.28	0.45	1.72	39.04
Rising ability							
Backward movements on knees	-	-	0.01	0.02	0.03	0.08	219.33
Tie-rail contact	0.02	0.43	-	0.05	0.07	0.16	164.25
Rising time	-	-	926.11	1689.18	2615.29	19.11	267.57
Rising attempts	0.39	0.38	-	0.26	0.65	1.34	60.27
Delayed rising	0.02	0.20	-	0.01	0.03	0.07	266.10
Horse rising	-	-	-	-	-	-	-
Overall abnormal rising	0.06	0.37	-	0.06	0.12	0.35	98.51
Lying ability							
Lying intention time	-	-	14.45	36.50	50.95	18.94	37.68
Lying-down time	-	-	1.73	1.54	3.27	6.59	27.45
Contact with stall	-	-	0.03	0.05	0.08	0.63	43.33
Slipping	-	-	0.01	0.03	0.03	0.09	199.06
Attempts of lying	-	-	0.00	0.00	0.00	1.00	6.82
Hind quarter stepping	0.02	0.22	-	0.04	0.07	0.17	156.60
Dog sitting	-	-	-	-	-	-	-
Lying on the right	0.00	0.23	-	0.03	0.03	0.51	34.16
Overall abnormal lying	-	-	0.03	0.06	0.09	0.25	120.52
Resting behavior							
Total lying time	4997.77	0.54	-	6147.69	11145.46	699.02	15.10
No. of lying bouts	6.32	0.48	-	4.62	10.94	13.27	24.92
Lying bout duration	-	-	-	-	-	-	-
Cow cleanliness, bedding cleanliness and bedding quantity							
Bedding quantity	0.00	-0.26	-	0.01	0.01	0.08	112.53
Flank cleanliness	-	-	0.01	0.01	0.02	0.95	13.66
Leg cleanliness	-	-	0.00	0.01	0.01	0.98	10.65
Udder cleanliness	-	-	0.00	0.02	0.02	0.93	15.94
Bedding cleanliness	0.00	0.01	-	0.03	0.03	0.78	22.05
Lameness	-	-	0.05	0.03	0.08	0.02	1156.18
BCS	0.05	0.31	-	0.01	0.06	2.53	9.49
Eating-rumination	0.00	0.92	-	49.72	49.72	51.79	13.62

41 <sup>1</sup> $\sigma^2_p = \sigma^2_{cow} + \sigma^2_e$

42 <sup>2</sup> $\bar{x}$  = the average between the 4 treatment LSMEANS

43 <sup>3</sup>CV = (sqrt ( $\sigma^2_p$ ) /  $\bar{x}$ ) \* 100

44 Supplementary Table S6. Mean  $\pm$  SEM, variance, and coefficient of variation (CV)<sup>1</sup>

Variable	Mean	SEM	variance	CV
Injuries				
Proximal Neck	0.44	0.03	0.48	1.09
Medial Neck	0.73	0.03	0.48	0.66
Distal Neck	0.02	0.01	0.04	2.10
Back	0.09	0.01	0.09	0.96
Hip Bone	0.18	0.02	0.15	0.82
Shoulder	0.01	0.01	0.02	1.60
Flank	0.25	0.02	0.15	0.59
Sacrum	0.08	0.01	0.08	0.94
Pin Bone	0.08	0.01	0.08	0.92
Lateral Tarsal	2.56	0.03	0.36	0.14
Dorsal Calcanei	0.79	0.04	0.66	0.83
Hind Leg	0.45	0.04	0.55	1.22
Stifle	1.36	0.04	0.76	0.56
Lateral Calcanei	2.07	0.03	0.43	0.21
Medial Calcanei	0.12	0.02	0.13	1.16
Lateral Tarsal	2.56	0.03	0.36	0.14
Medial Tarsal	0.02	0.01	0.02	1.20
Carpal; Joints	1.72	0.03	0.50	0.29
Rising ability				
Backward movements on knees	0.08	0.01	0.04	0.48
Tie-rail contact	0.16	0.02	0.06	0.41
Rising time	19.11	3.07	2504.09	131.02
Rising attempts	1.34	0.05	0.73	0.54
Delayed rising	0.07	0.01	0.03	0.41
Horse rising	-	-	-	-
Overall abnormal rising	0.35	0.02	0.13	0.37
Lying ability				
Lying intention time	18.94	0.48	61.97	3.27
Lying-down time	6.59	0.11	3.27	0.50
Contact with stall	0.63	0.02	0.10	0.16
Slipping	0.09	0.01	0.03	0.37
Attempts of lying	1.00	0.00	0.00	0.00
Hind quarter stepping	0.17	0.02	0.06	0.39
Dog sitting	-	-	-	-
Lying on the right	0.51	0.01	0.03	0.06
Overall abnormal lying	0.25	0.02	0.08	0.33
Resting behavior				
Total lying time	699.02	6.17	16946.87	24.24
No. of lying bouts	13.27	0.17	13.32	1.00
Lying bout duration	61.46	2.87	3669.83	59.71
Cow cleanliness, bedding cleanliness and bedding quantity				
Bedding quantity	0.08	0.01	0.02	0.19
Flank cleanliness	0.95	0.01	0.01	0.01
Leg cleanliness	0.98	0.01	0.01	0.01
Udder cleanliness	0.93	0.01	0.02	0.02
Bedding cleanliness	0.78	0.02	0.03	0.04
Lameness	0.02	0.01	0.07	2.86
BCS	2.53	0.01	0.05	0.02
Eating-rumination	51.79	0.60	73.97	1.43

<sup>1</sup>CV =  $\sigma / \bar{x}$



47 Supplementary Table S7. Matrix compiling the variances, co-variances and correlations for the 10 weeks of the  
 48 experimentation on the sacrum injury<sup>1</sup>

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Week 1	0.1553	0.1281	0.1188	0.0806	0.0844	0.0593	0.0806	0.0994	0.0508	0.0672
Week 2	0.8254	0.1551	0.1382	0.0880	0.0917	0.0808	0.0896	0.1113	0.0711	0.0555
Week 3	0.7660	0.8916	0.1549	0.0936	0.1205	0.0833	0.0840	0.1163	0.0681	0.0493
Week 4	0.7122	0.7780	0.8285	0.0825	0.0836	0.0545	0.0784	0.0875	0.0504	0.0423
Week 5	0.5829	0.6336	0.8336	0.7929	0.1349	0.0733	0.0740	0.1063	0.0581	0.0393
Week 6	0.4734	0.6455	0.6655	0.5970	0.6275	0.1011	0.0571	0.1117	0.0859	0.0671
Week 7	0.7234	0.8038	0.7547	0.9656	0.7124	0.6348	0.0800	0.0891	0.0530	0.0434
Week 8	0.6507	0.7290	0.7622	0.7859	0.7465	0.9061	0.8122	0.1503	0.0965	0.0747
Week 9	0.0404	0.5765	0.5520	0.5600	0.5046	0.8620	0.5977	0.7944	0.0981	0.0636
Week 10	0.5062	0.4181	0.3723	0.4377	0.3181	0.6270	0.4556	0.5723	0.6025	0.1134

49 <sup>1</sup>The table represent a matrix with 3 different data, variance down the diagonal, co-variance above the diagonal and  
 50 correlation below diagonal.  
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52 Supplementary Table S8. Matrix compiling the variances, co-variances and correlations for the 10 weeks of the  
53 experimentation on the pin bone injury<sup>1</sup>

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Week 1	0.1370	0.0833	0.0812	0.0921	0.0723	0.0892	0.0944	0.0604	0.0795	0.0928
Week 2	0.6037	0.1388	0.1151	0.0926	0.0899	0.1190	0.0835	0.0861	0.0951	0.0941
Week 3	0.5711	0.8039	0.1477	0.0609	0.0821	0.1110	0.0745	0.0781	0.0881	0.0882
Week 4	0.6974	0.6963	0.4443	0.1273	0.0677	0.0984	0.0827	0.0624	0.0744	0.0857
Week 5	0.5474	0.6762	0.5987	0.5320	0.1273	0.1013	0.1130	0.0958	0.1078	0.1130
Week 6	0.6194	0.8206	0.7420	0.7084	0.7294	0.1515	0.0977	0.1227	0.1276	0.1267
Week 7	0.6270	0.5512	0.4767	0.5699	0.7790	0.6174	0.1653	0.1126	0.1276	0.1562
Week 8	0.3653	0.5175	0.4550	0.3917	0.6011	0.7058	0.6201	0.1995	0.1526	0.1446
Week 9	0.0820	0.6682	0.6001	0.5462	0.7913	0.8586	0.8219	0.8948	0.1458	0.1504
Week 10	0.6030	0.6077	0.5517	0.5776	0.7617	0.7828	0.9239	0.7786	0.9473	0.1729

<sup>1</sup>The table represent a matrix with 3 different data, variance down the diagonal, co-variance above the diagonal and correlation below diagonal

59 Supplementary Table S9. Matrix compiling the variances, co-variances and correlations for the 10 weeks of the  
60 experimentation on the medial calcanei injury<sup>1</sup>

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Week 1	0.1302	0.0892	0.0998	0.0706	0.1217	0.0628	0.0589	0.1242	0.0642	0.0706
Week 2	0.6835	0.1309	0.1062	0.0910	0.1402	0.0685	0.0887	0.1664	0.0745	0.0889
Week 3	0.6670	0.7078	0.1720	0.1151	0.1480	0.1040	0.1168	0.2177	0.1327	0.0887
Week 4	0.4975	0.6393	0.7058	0.1546	0.1170	0.0780	0.1638	0.2818	0.1142	0.0671
Week 5	0.7311	0.8400	0.7736	0.6451	0.2128	0.1054	0.1219	0.2174	0.0965	0.1066
Week 6	0.5788	0.6303	0.8344	0.6603	0.7602	0.0903	0.0802	0.1583	0.0951	0.0512
Week 7	0.3032	0.4550	0.5227	0.7732	0.4904	0.4955	0.2903	0.3409	0.1169	0.0596
Week 8	0.4579	0.6119	0.6983	0.9535	0.6270	0.7007	0.8417	0.5650	0.2144	0.1205
Week 9	0.0761	0.4808	0.7476	0.6786	0.4888	0.7393	0.5069	0.6664	0.1832	0.0620
Week 10	0.5667	0.7120	0.6199	0.4946	0.6696	0.4933	0.3205	0.4645	0.4199	0.1191

<sup>1</sup>The table represent a matrix with 3 different data, variance down the diagonal, co-variance above the diagonal and correlation below diagonal

65 Supplementary Table S10. Matrix compiling the variances, co-variances and correlations for the 10 weeks of the  
66 experimentation on lying bout duration<sup>1</sup>

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Week 1	138.0900	186.0800	125.3900	164.8500	346.4900	-28.7204	106.0900	48.5763	126.1800	105.6500
Week 2	0.4247	1390.1700	119.9000	192.2600	971.7800	-33.7068	125.8100	67.1694	77.0873	72.8195
Week 3	0.7555	0.2277	199.4900	223.1500	641.6800	129.9200	142.8900	26.1721	154.2900	129.3000
Week 4	0.7337	0.2697	0.8263	365.5600	1514.9400	173.7100	261.1800	71.9344	243.6700	226.5900
Week 5	0.1858	0.1643	0.2863	0.4994	25175.0000	138.6600	913.9700	-460.6900	416.6000	609.3300
Week 6	-0.0395	-0.0146	0.1486	0.1468	0.0141	3831.3800	325.5400	-403.2800	187.0100	56.9969
Week 7	0.5289	0.1977	0.5927	0.8003	0.3375	0.3081	291.3200	37.4976	245.3400	212.8100
Week 8	0.0587	0.0256	0.0263	0.0535	-0.0413	-0.0926	0.0312	4951.5100	-25.0644	-34.4369
Week 9	0.6076	0.1170	0.6181	0.7211	0.1486	0.1710	0.8133	-0.0202	312.3300	249.7100
Week 10	0.5515	0.1198	0.5616	0.7270	0.2356	0.0565	0.7649	-0.0300	0.8668	265.7400

67<sup>1</sup>The table represent a matrix with 3 different data, variance down the diagonal, co-variance above the diagonal and  
68correlation below diagonal

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