HEURISTIC AND
EVOLUTIONARY
ALGORITHMS
LABORATORY

UNIVERSITY
OF APPLIED SCIENCES
UPPER AUSTRIA

Identifying Differential Equations to predict Blood Glucose using Sparse Identification of Nonlinear Systems

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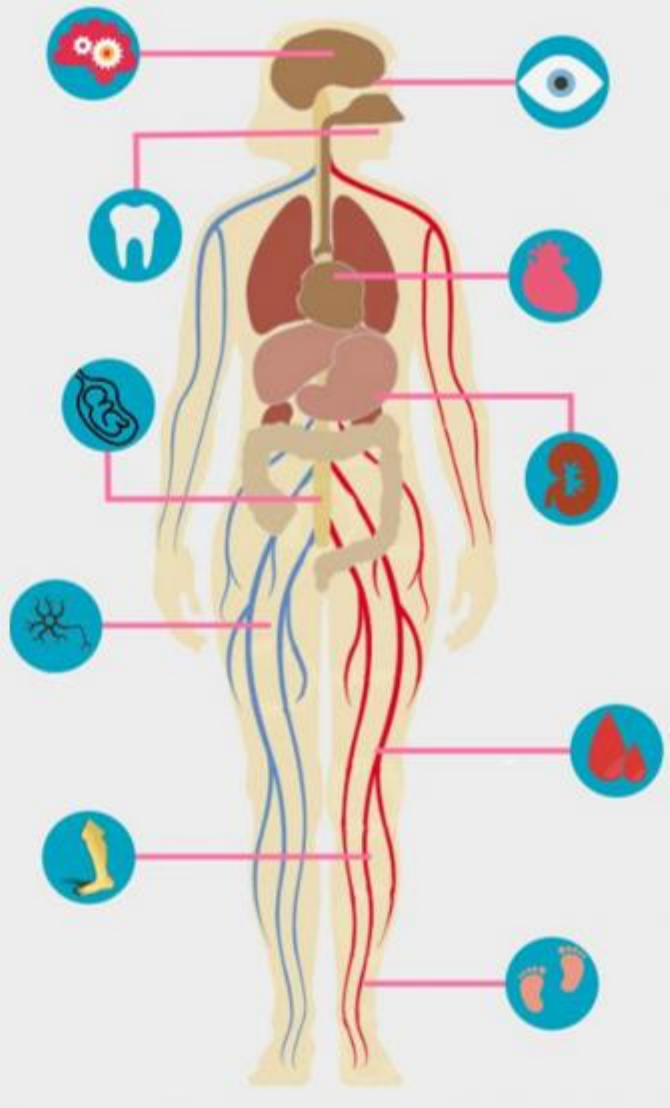
EUROCAST 2022 | Theory and Applications of Metaheuristic Algorithms
23rd of February 2022
Las Palmas | Gran Canaria

Background & Motivation

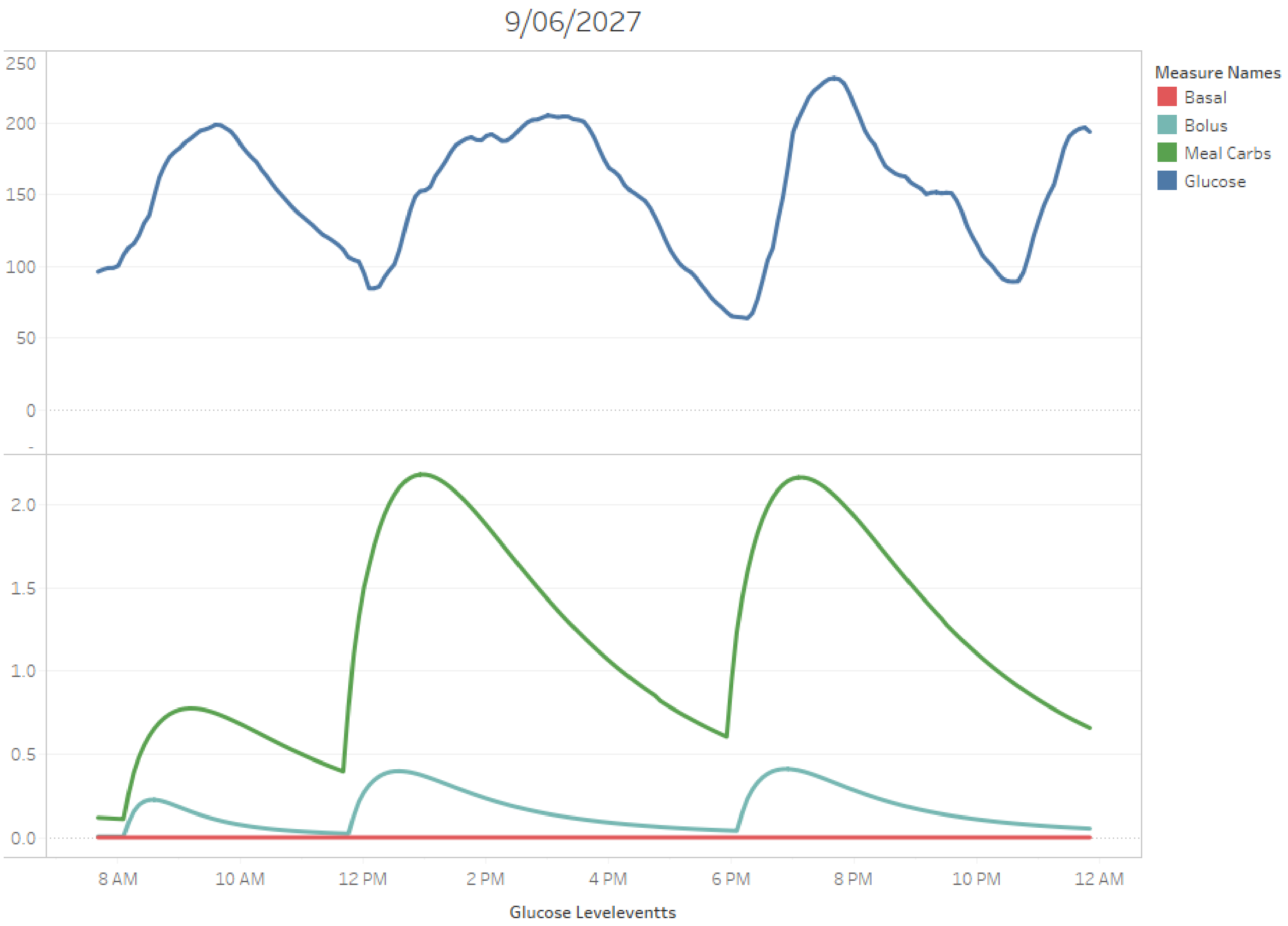
- 463 million people worldwide diagnosed with diabetes
- Diabetes leads to ~4.2 million deaths per year
- Diabetes results from ineffective use of insulin by the body
- Ordinary differential equations are often used to model biological processes over time
- **Goal: Predict blood glucose level using carbs and Insulin with differential equations**



http://smarthealth.cs.ohio.edu/OhioT1DM-dataset

Data

- OhioT1DM Dataset
- 8 weeks of data
- 6 patients (type 1 diabetes)
- Continuous glucose monitoring (every 5 minutes)
- Insulin data and self-reported life-event data



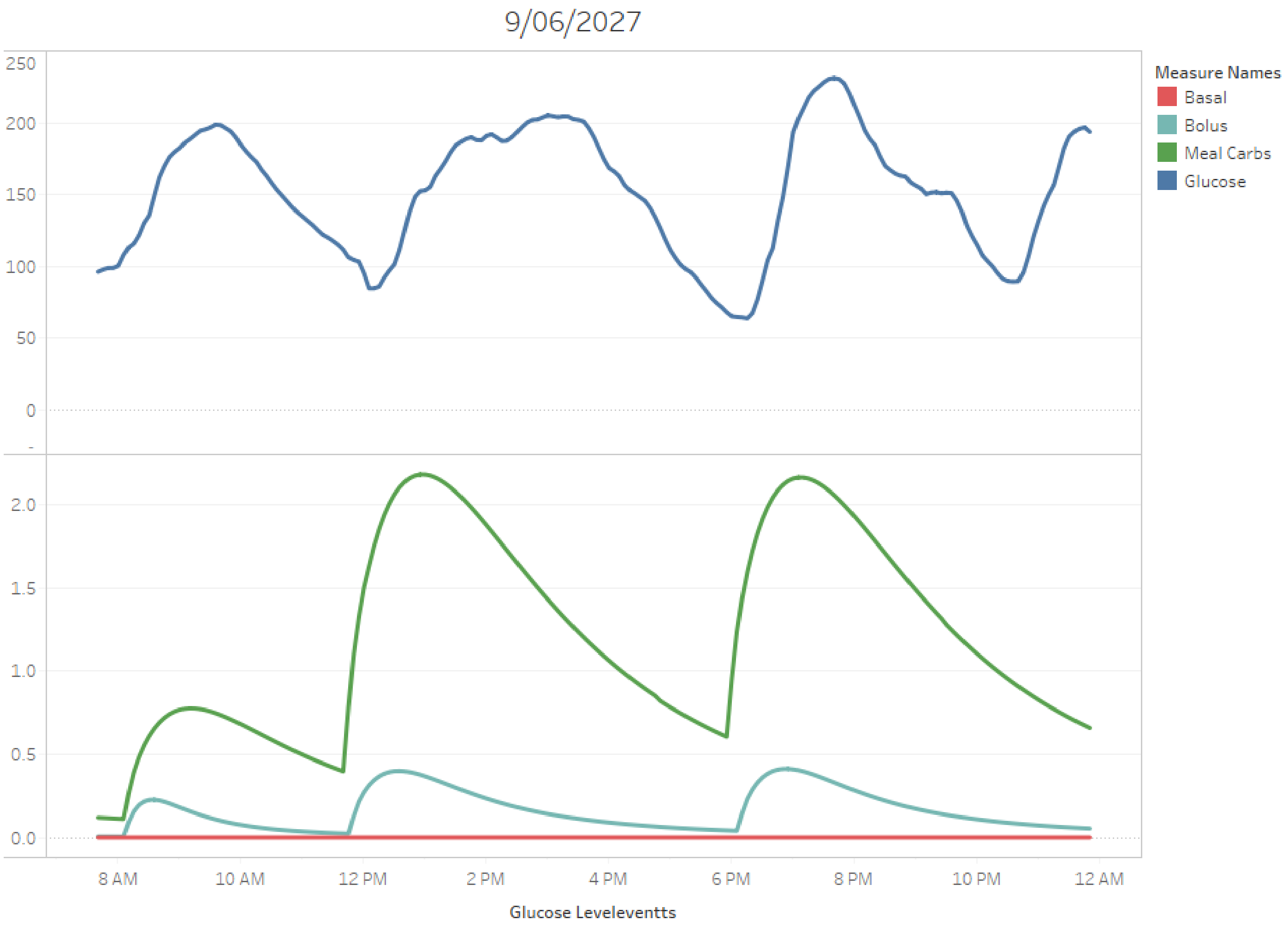
Research Question

Is it possible to simulate the glucose level of an insulin patient over one day with differential equations using only bolus, basal and meal values?

Methodology

Overview

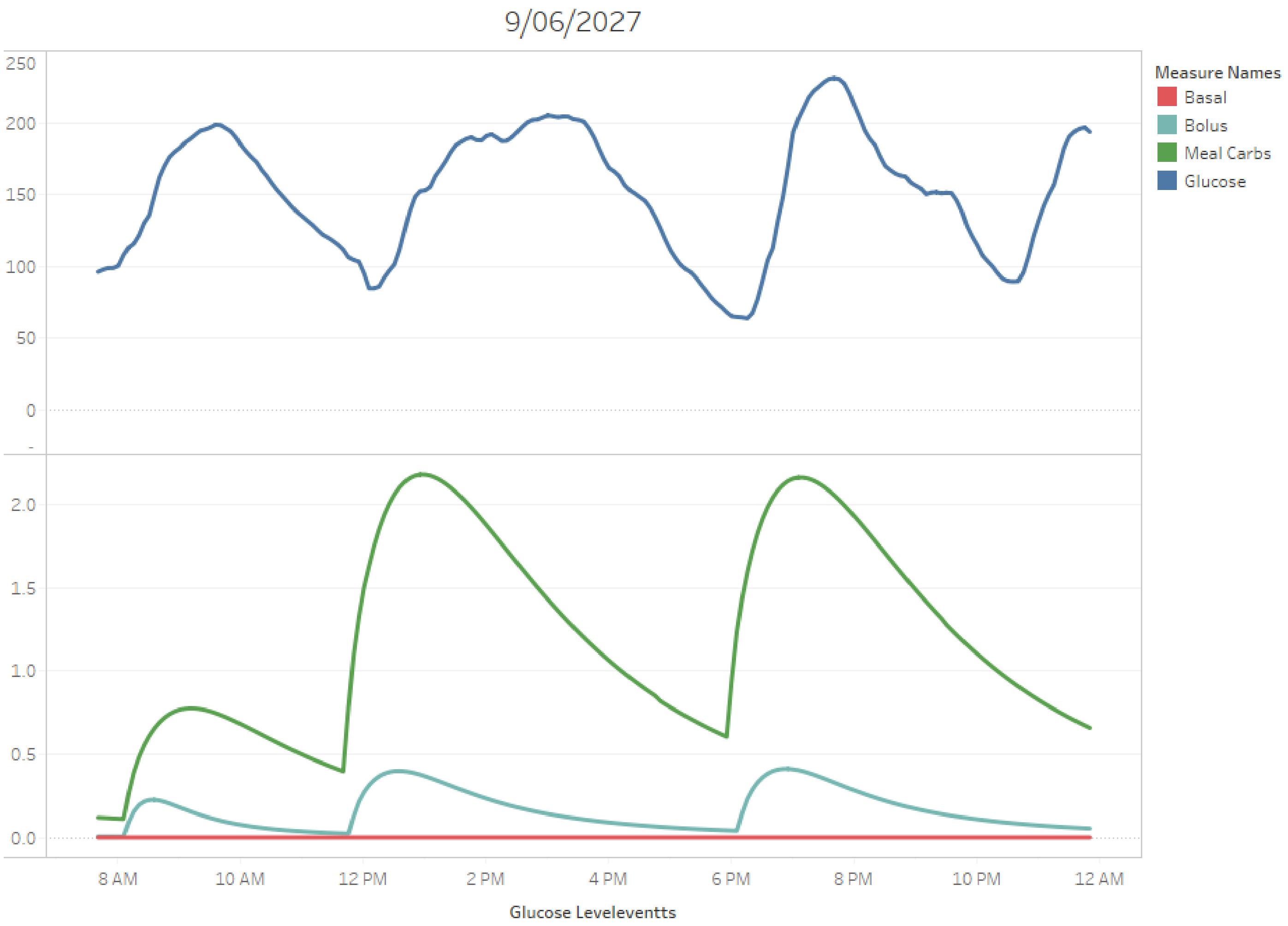
- Time Shifts
- Algorithm
- Grid Search



Methodology

Time Shifts

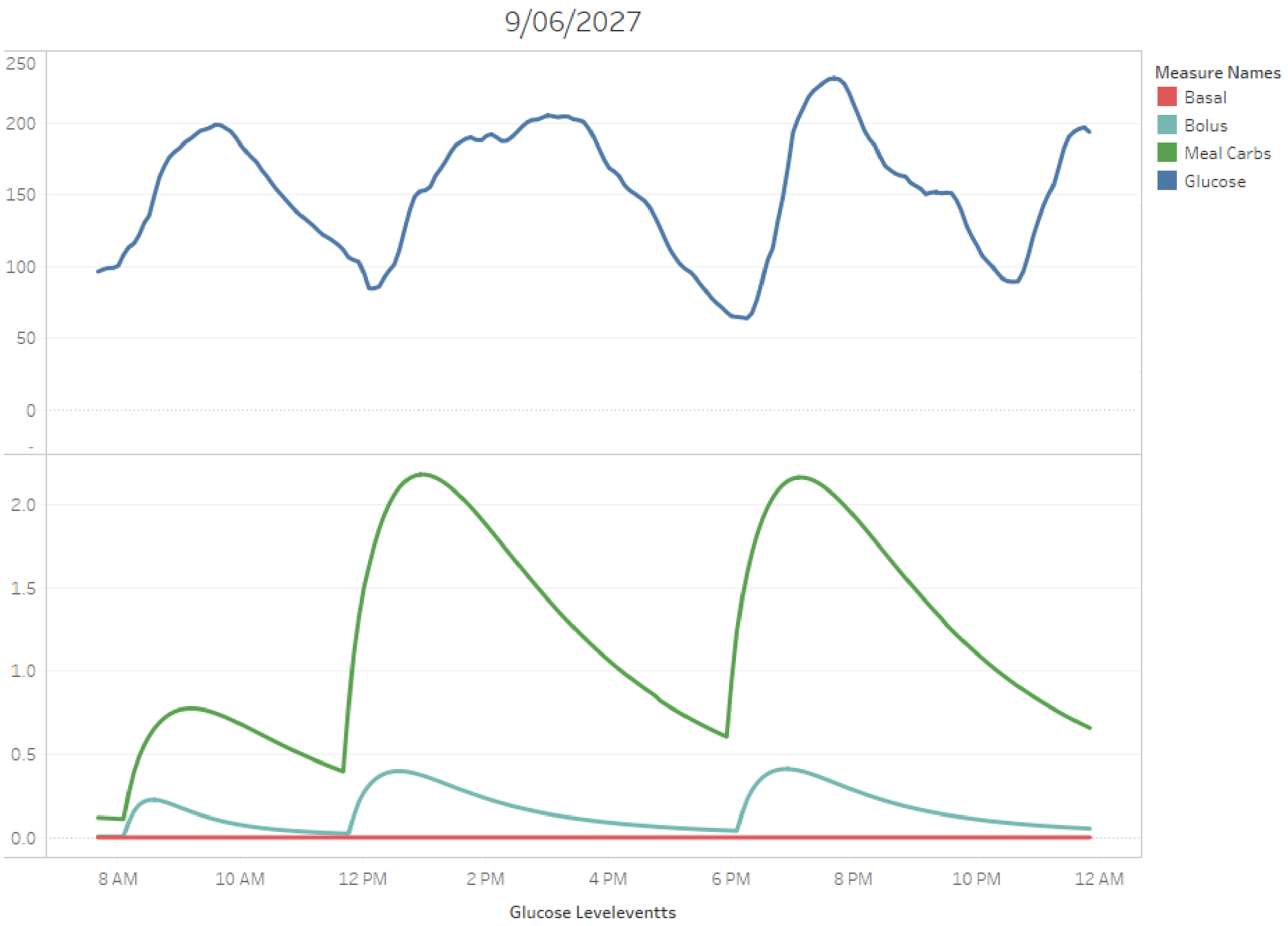
- **Time Shifts**
- Algorithm
- Grid Search



Methodology

Time Shifts

- Time Shifts
  - Influence of distribution in relation to time
  - Time shifts help to damp this influence
  - Find optimal time shift during training
  - Time shift for both meals and carbs



- Algorithm
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Methodology

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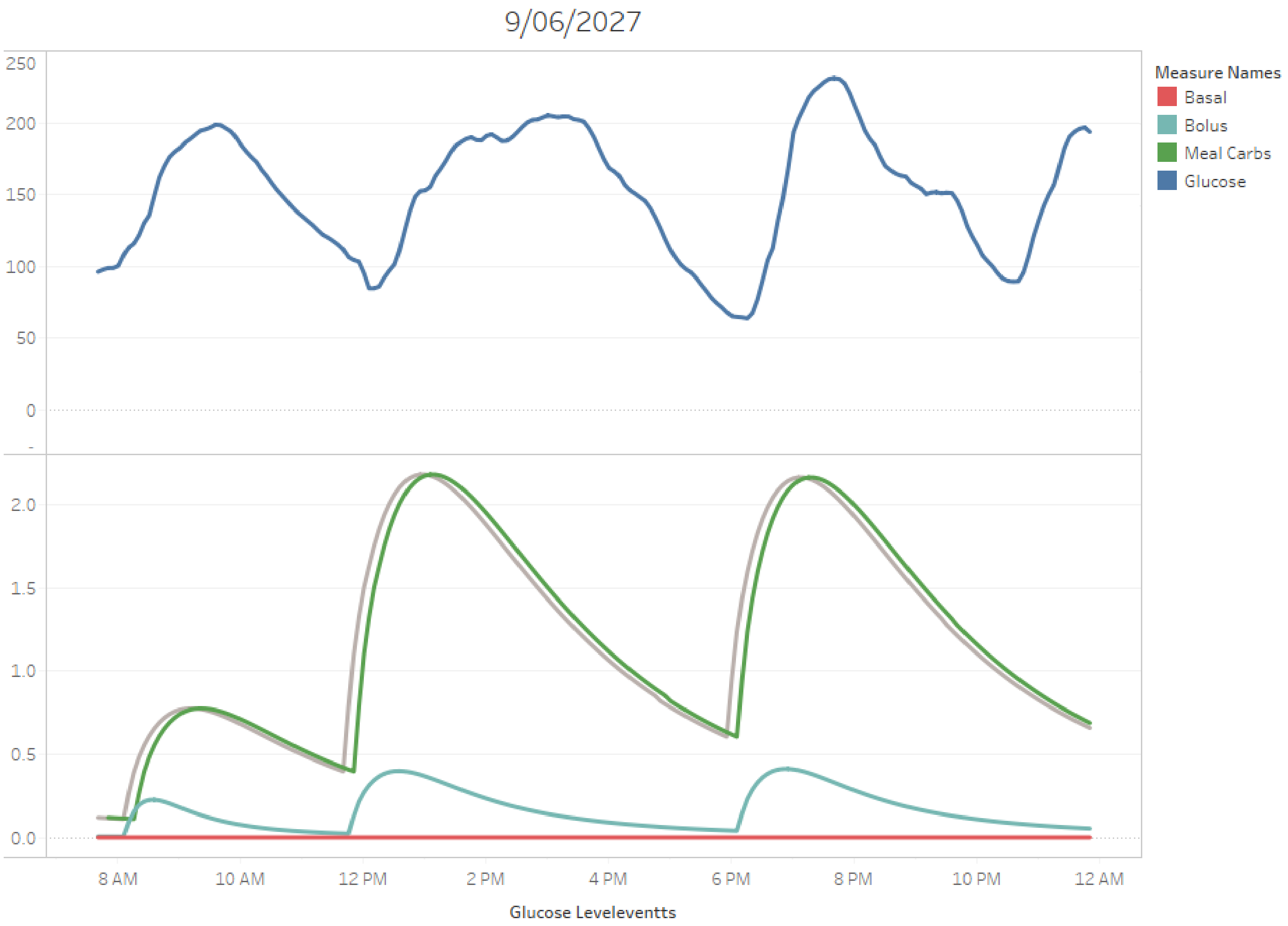

Methodology

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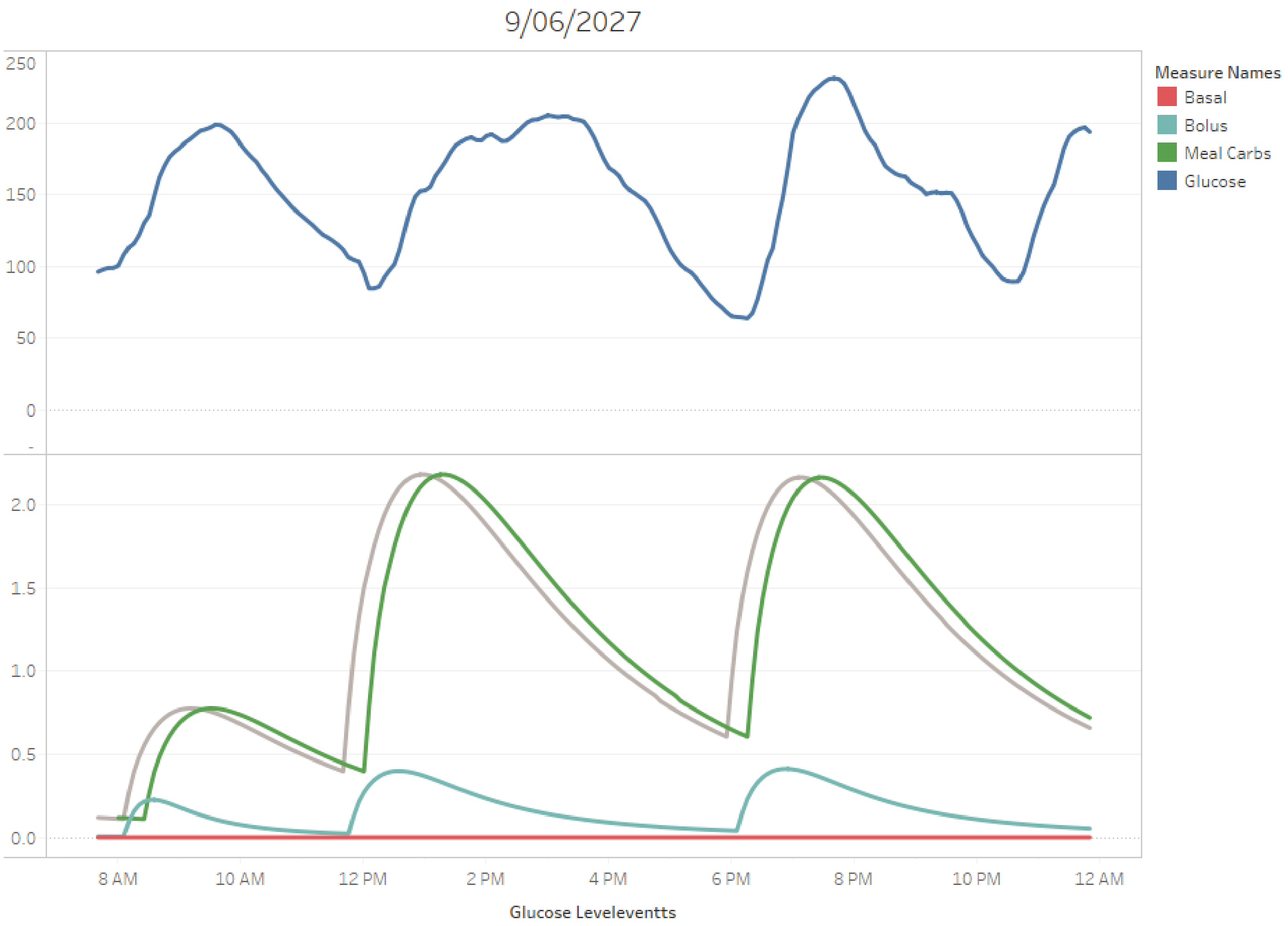

Methodology

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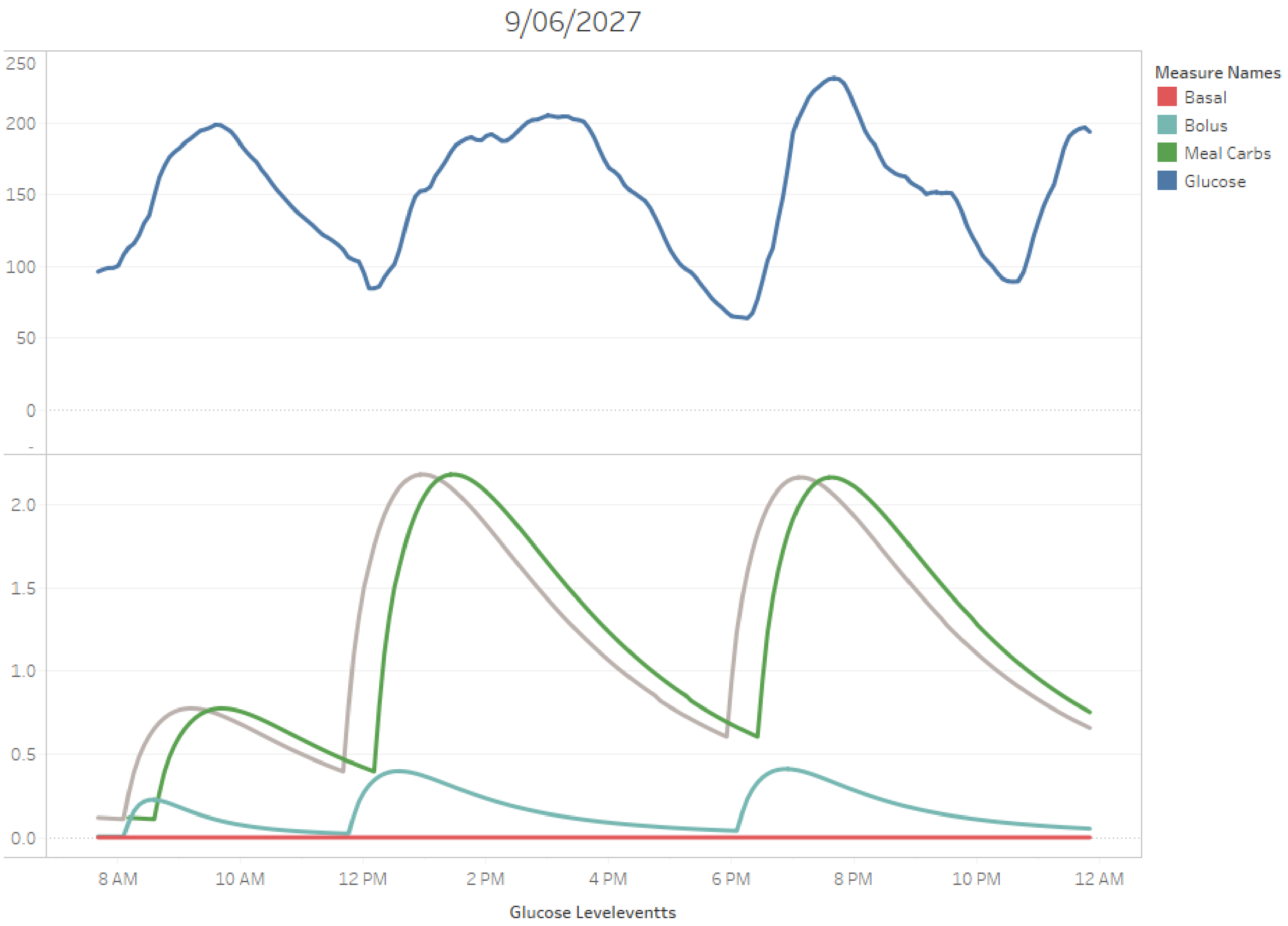

- Algorithm
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Methodology

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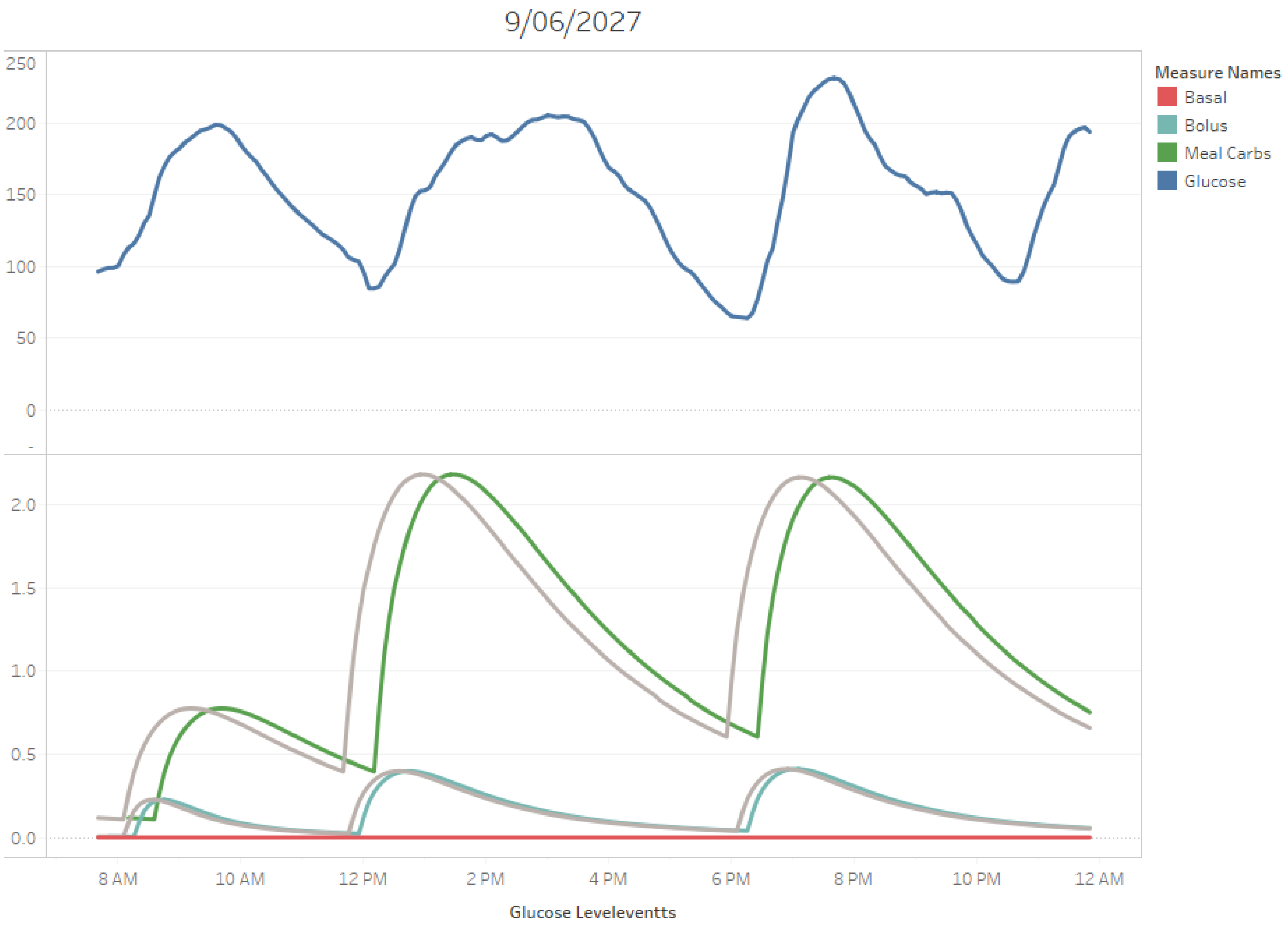

Methodology

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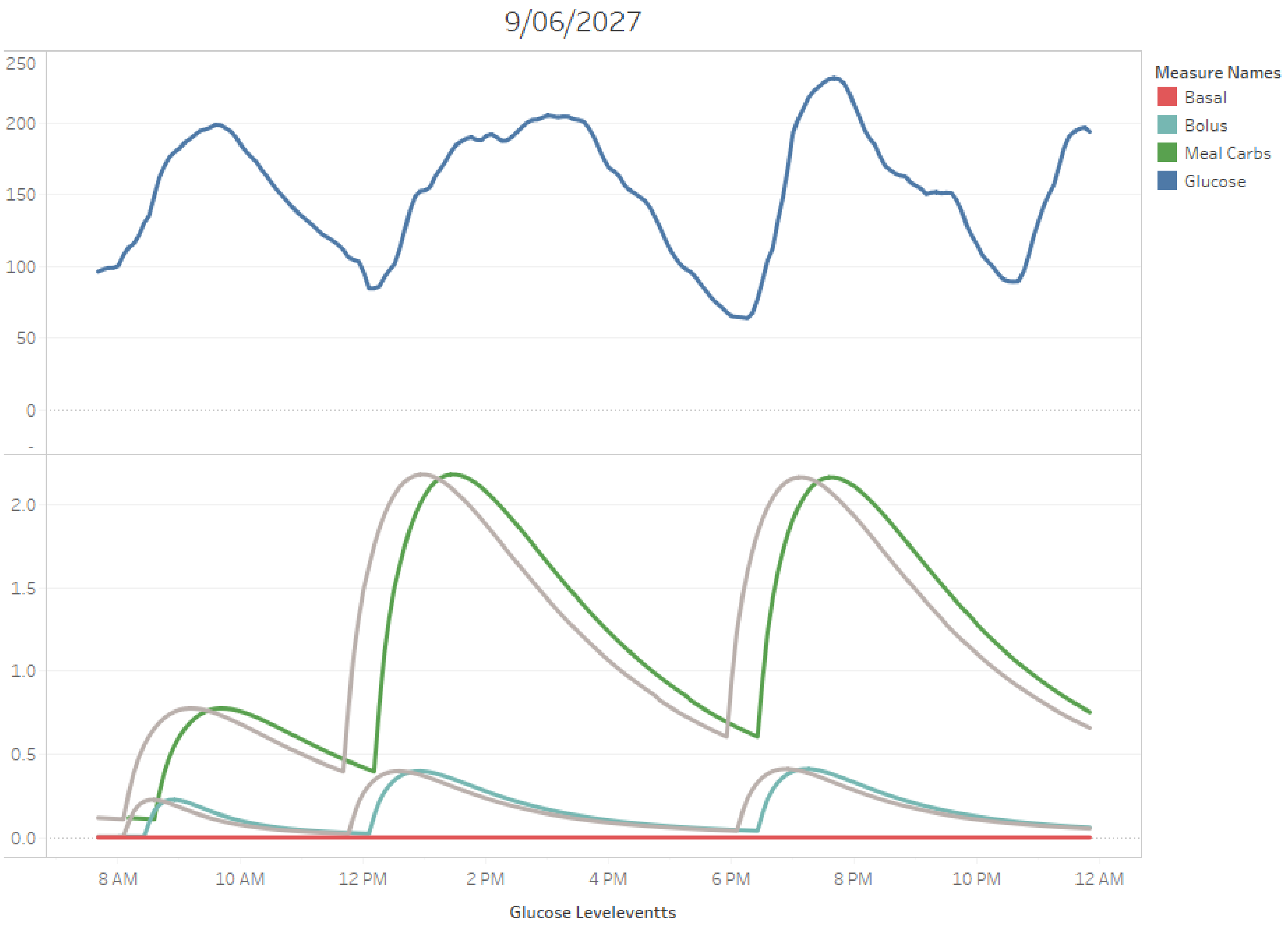

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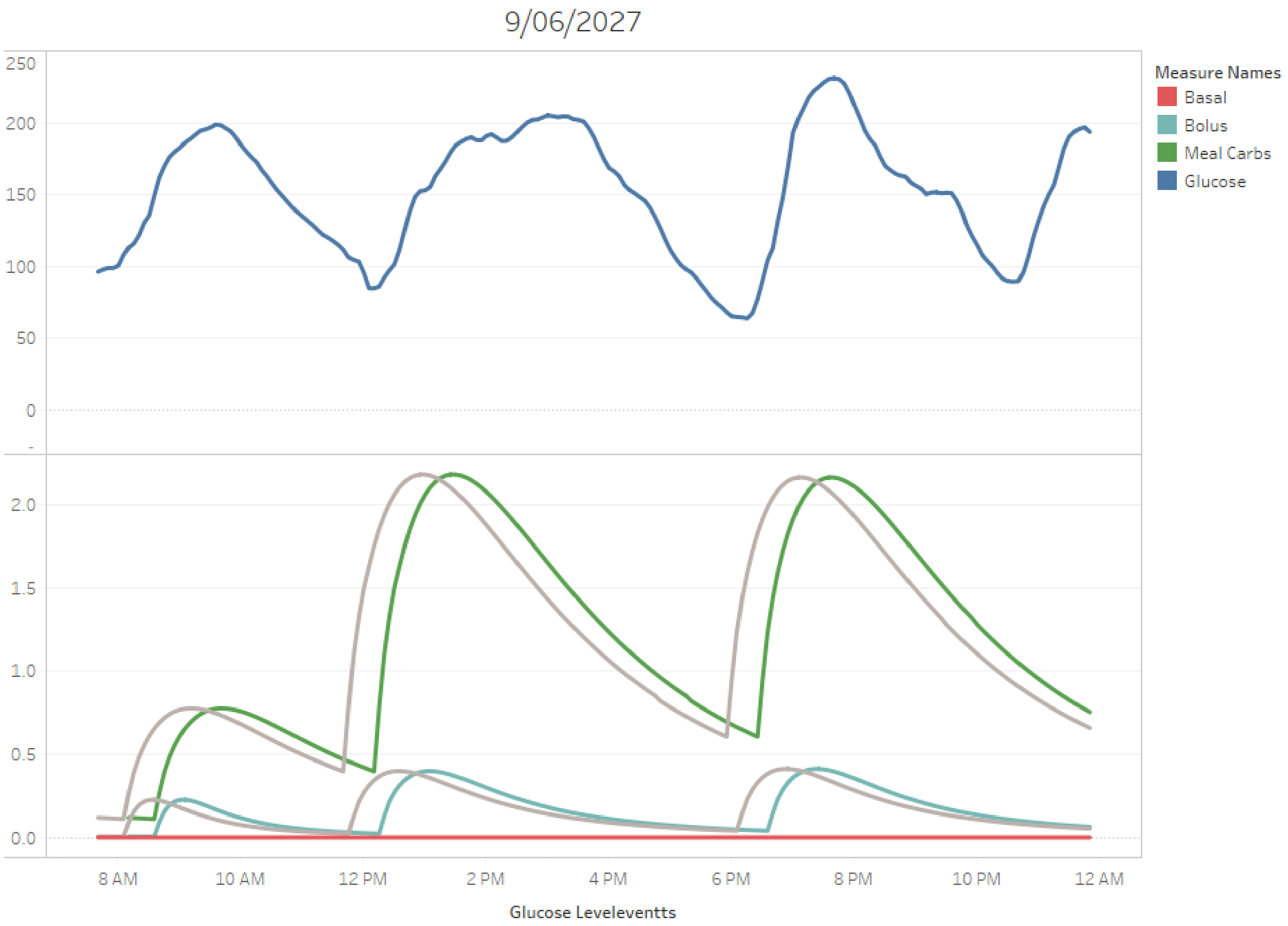

Methodology

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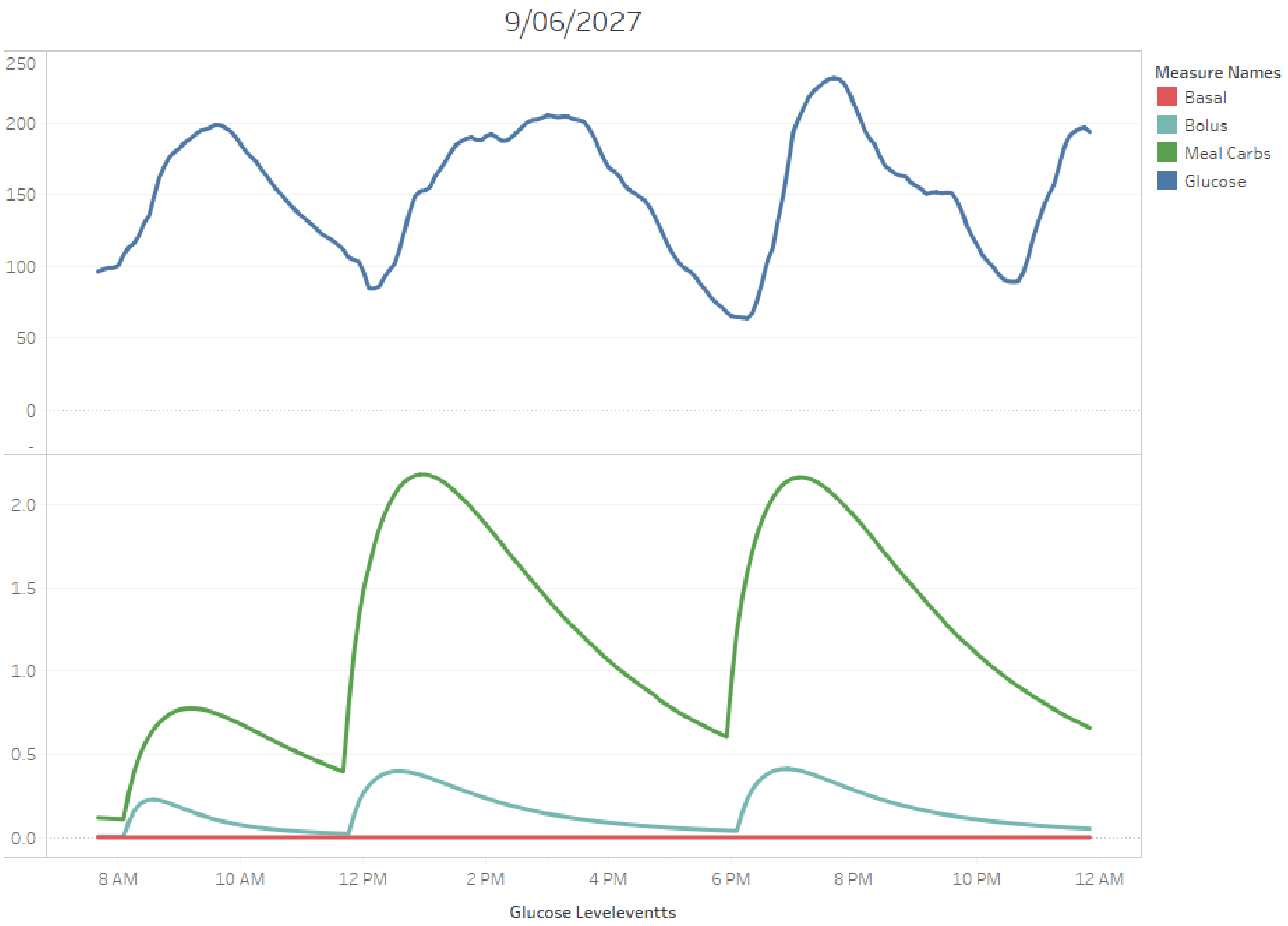

Methodology

Algorithm

- Time Shifts
- **Algorithm**
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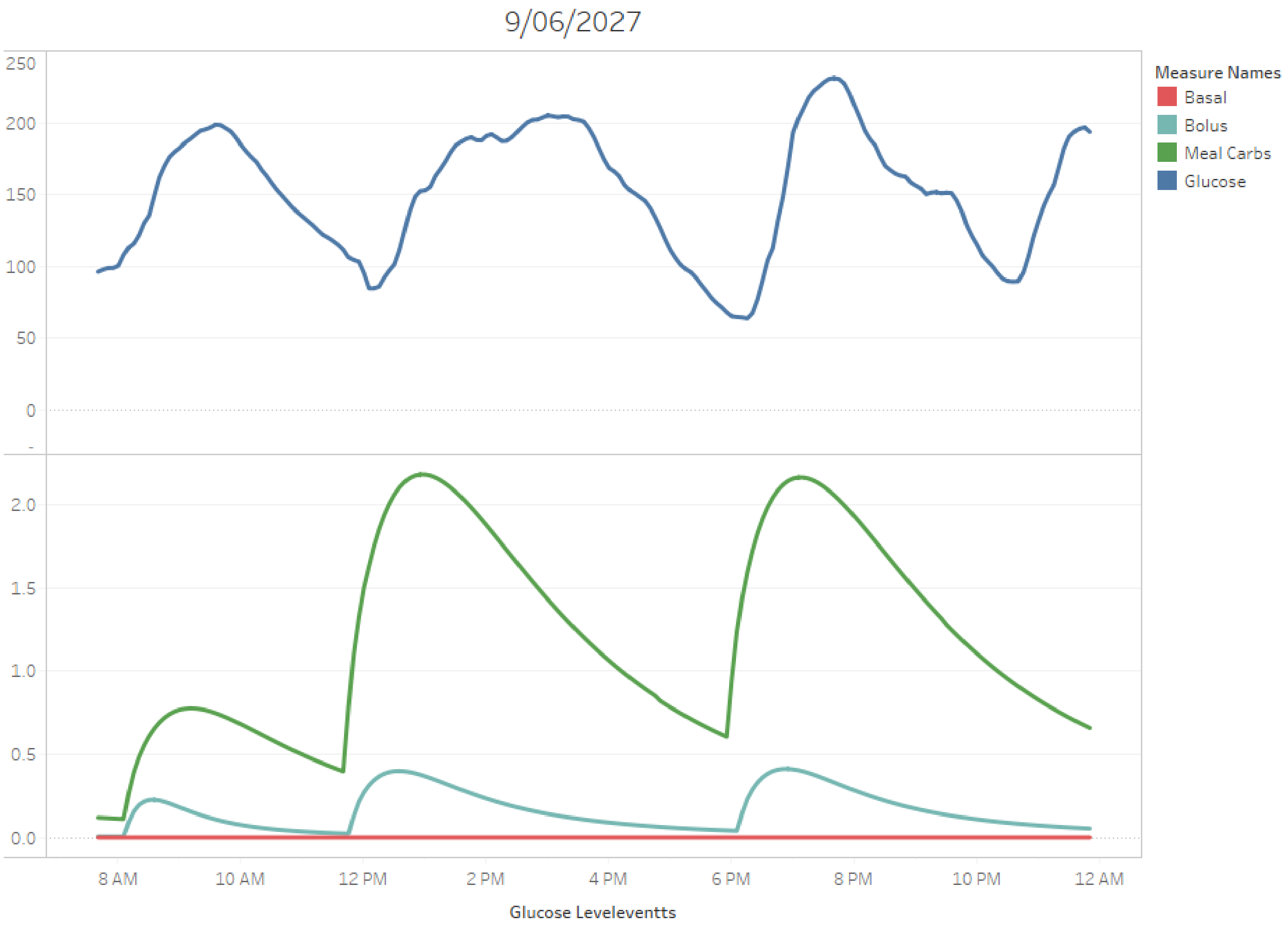
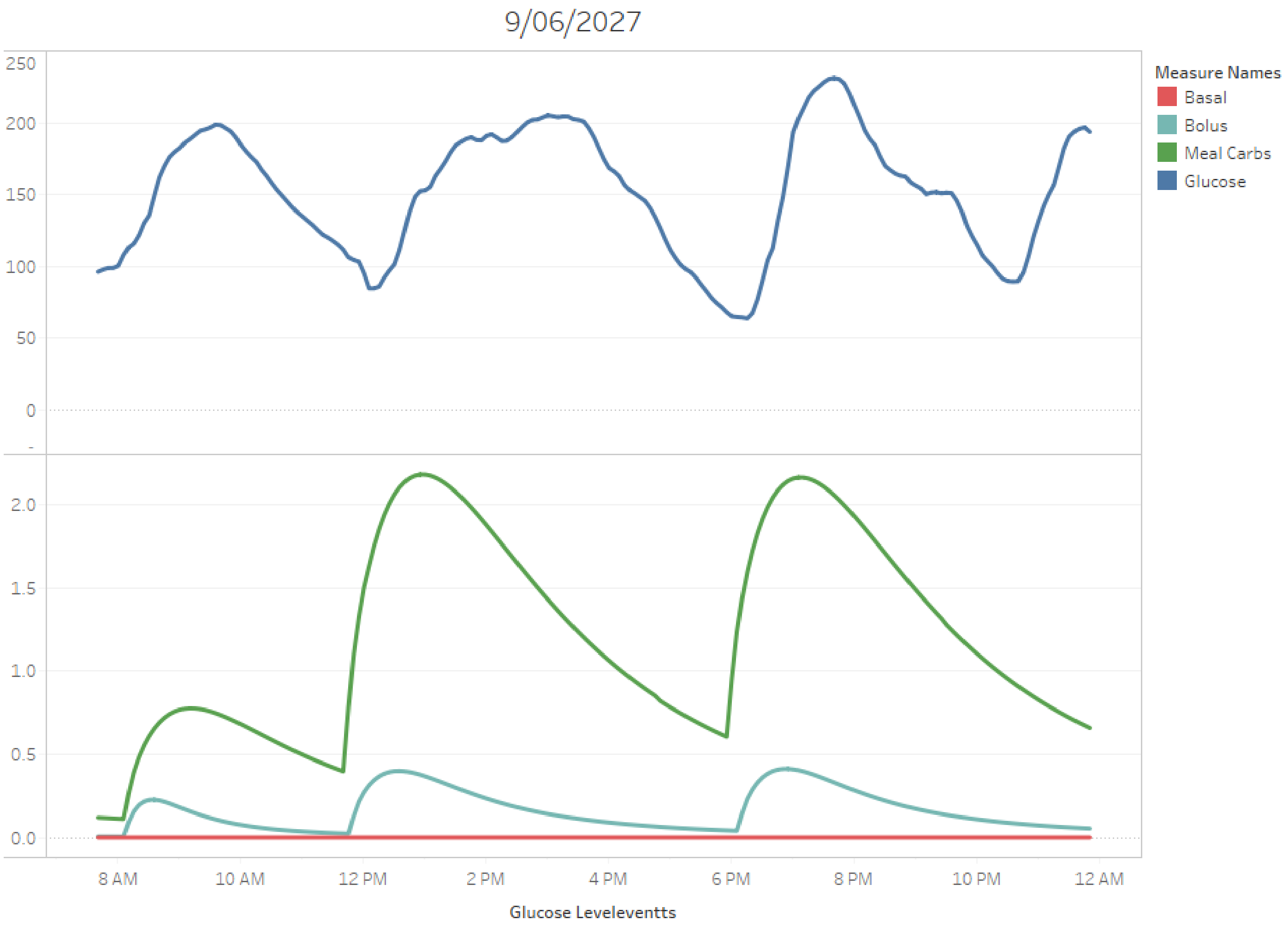


Methodology

Algorithm

https://doi.org/10.1073/pnas.1517384113
https://github.com/dynamicslab/pysindy

- Time Shifts
- Algorithm
  - Sparse Identification of Nonlinear Dynamics



- Grid Search

Methodology

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- Time Shifts
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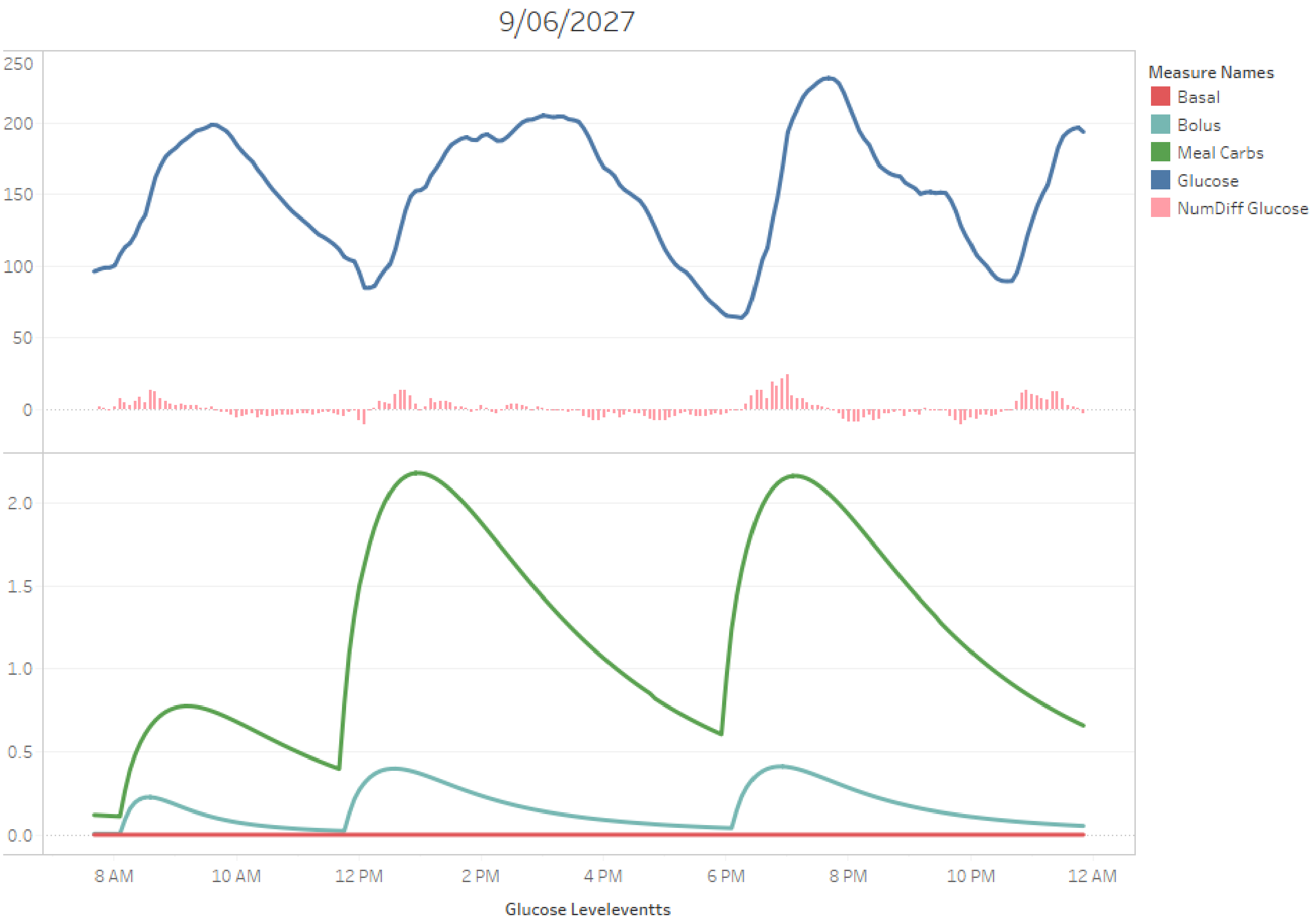
    - Sparse Identification of Nonlinear Dynamics
    - Perform sparse nonlinear regression on numerical differences
- Grid Search



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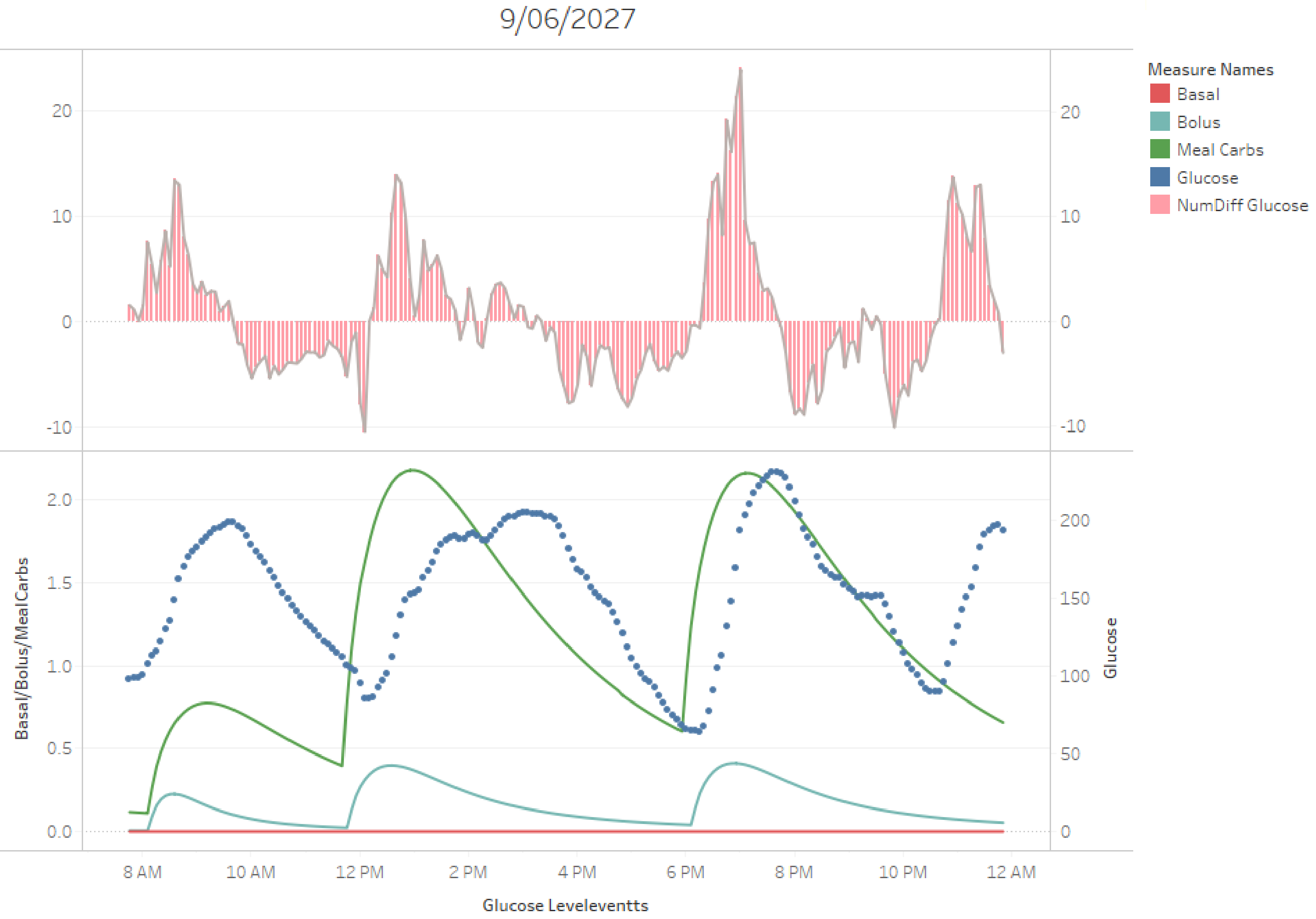

Methodology

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- Time Shifts
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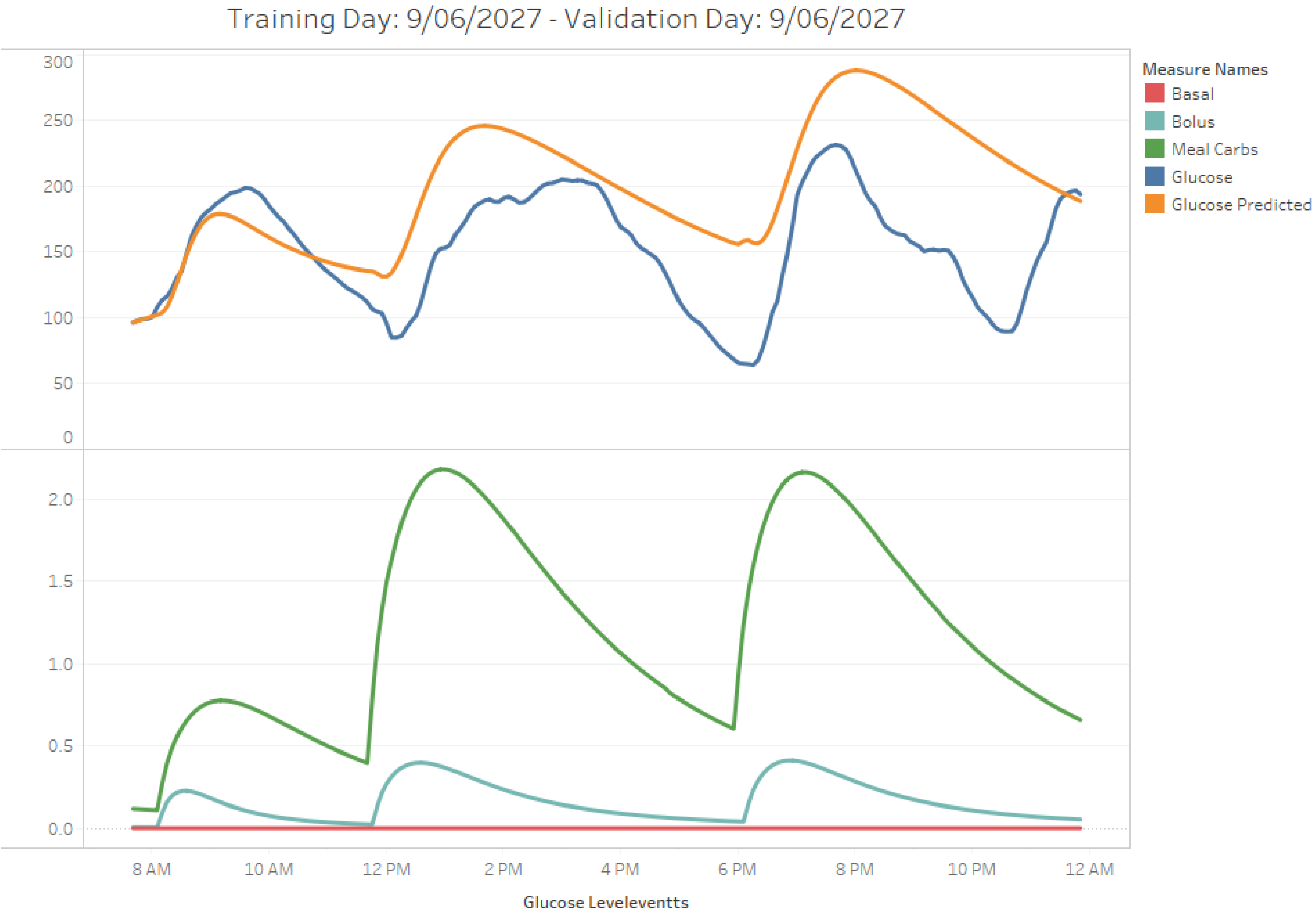
  - Sparse Identification of Nonlinear Dynamics
  - Perform sparse nonlinear regression on numerical differences
  - Integrate forward with model from SINDy



- Grid Search

Methodology

Algorithm

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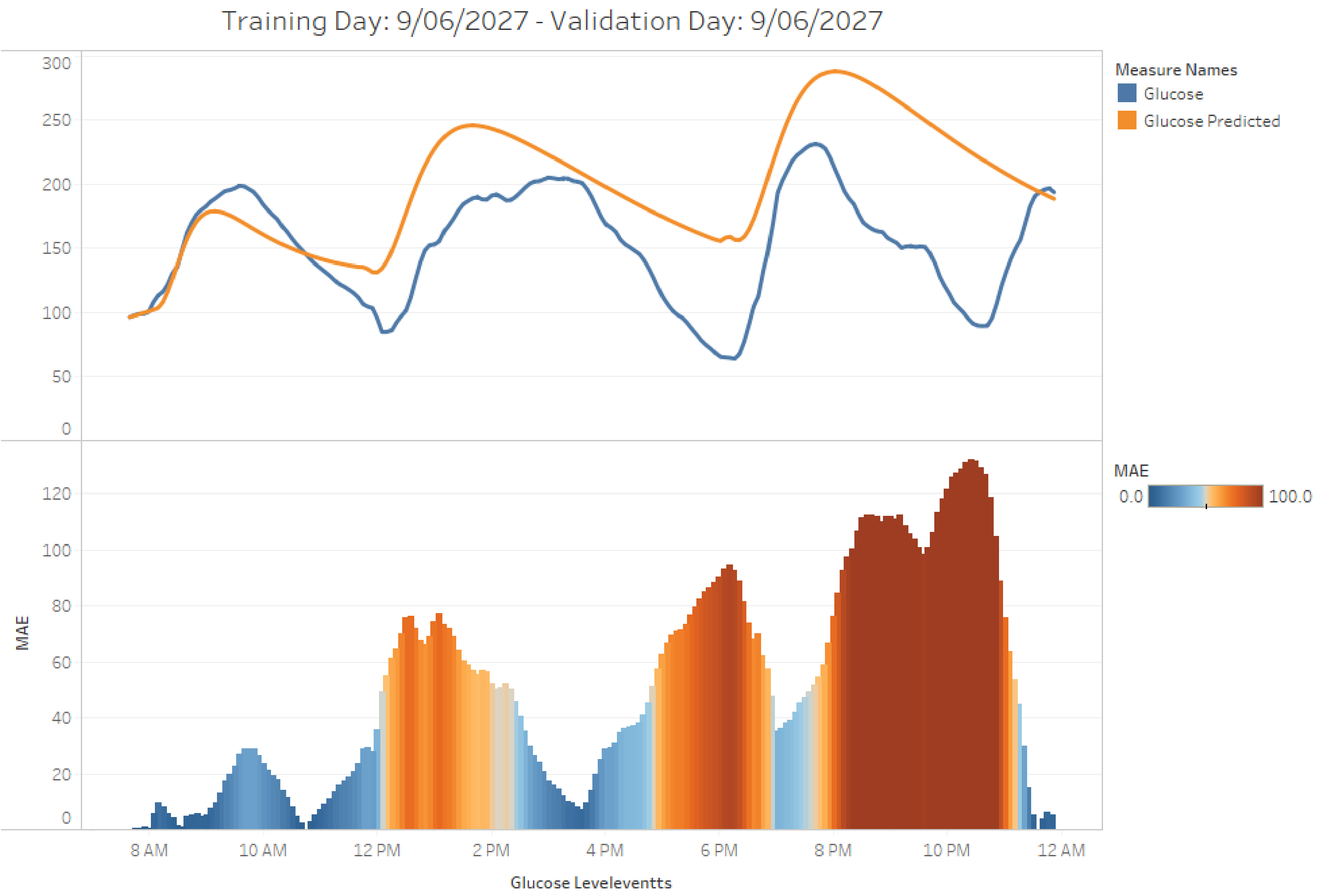
- Time Shifts
- Algorithm
  - Sparse Identification of Nonlinear Dynamics
  - Perform sparse nonlinear regression on numerical differences
  - Integrate forward with model from SINDy
  - Calculate error between training and validation
- Grid Search



Methodology

Algorithm

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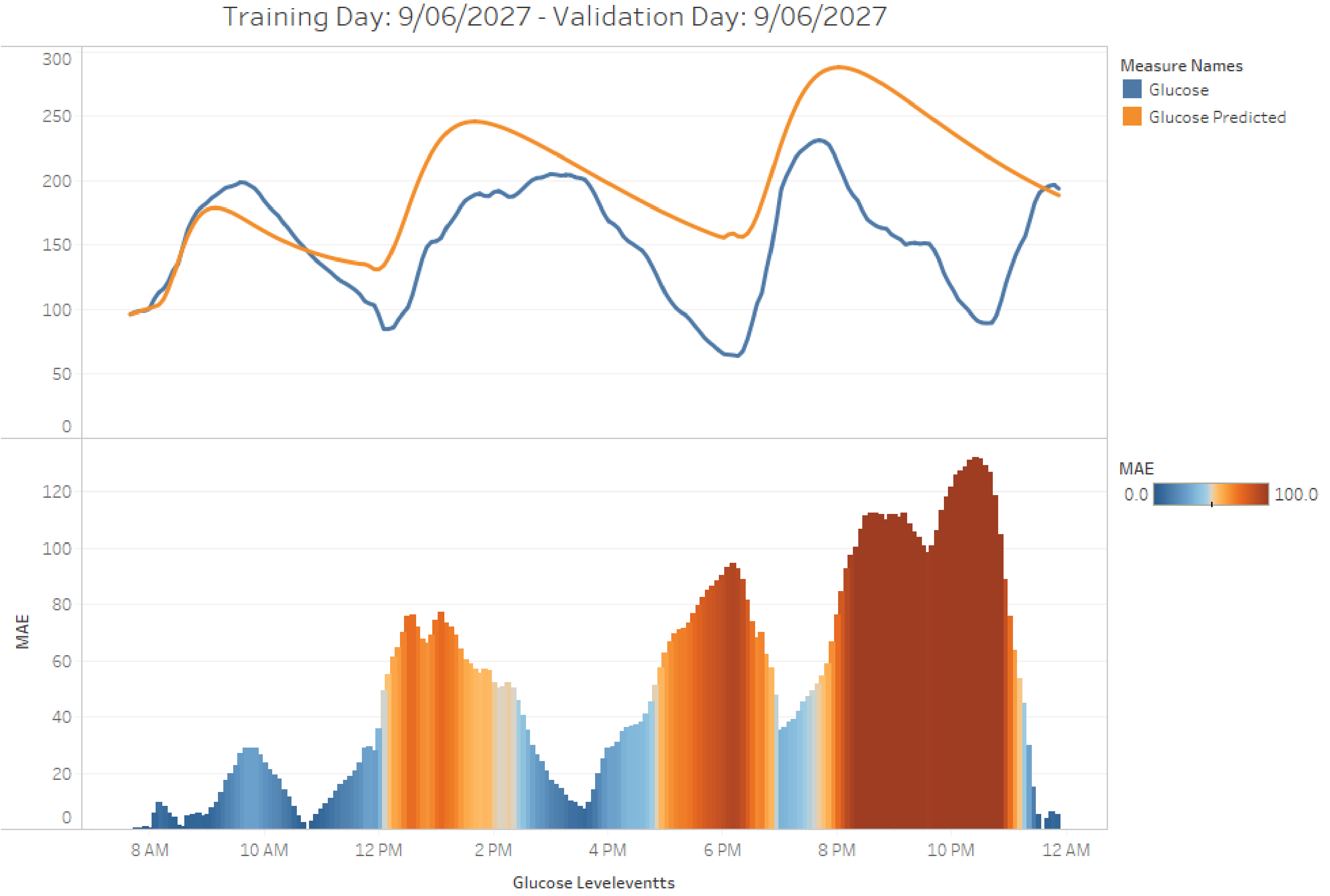
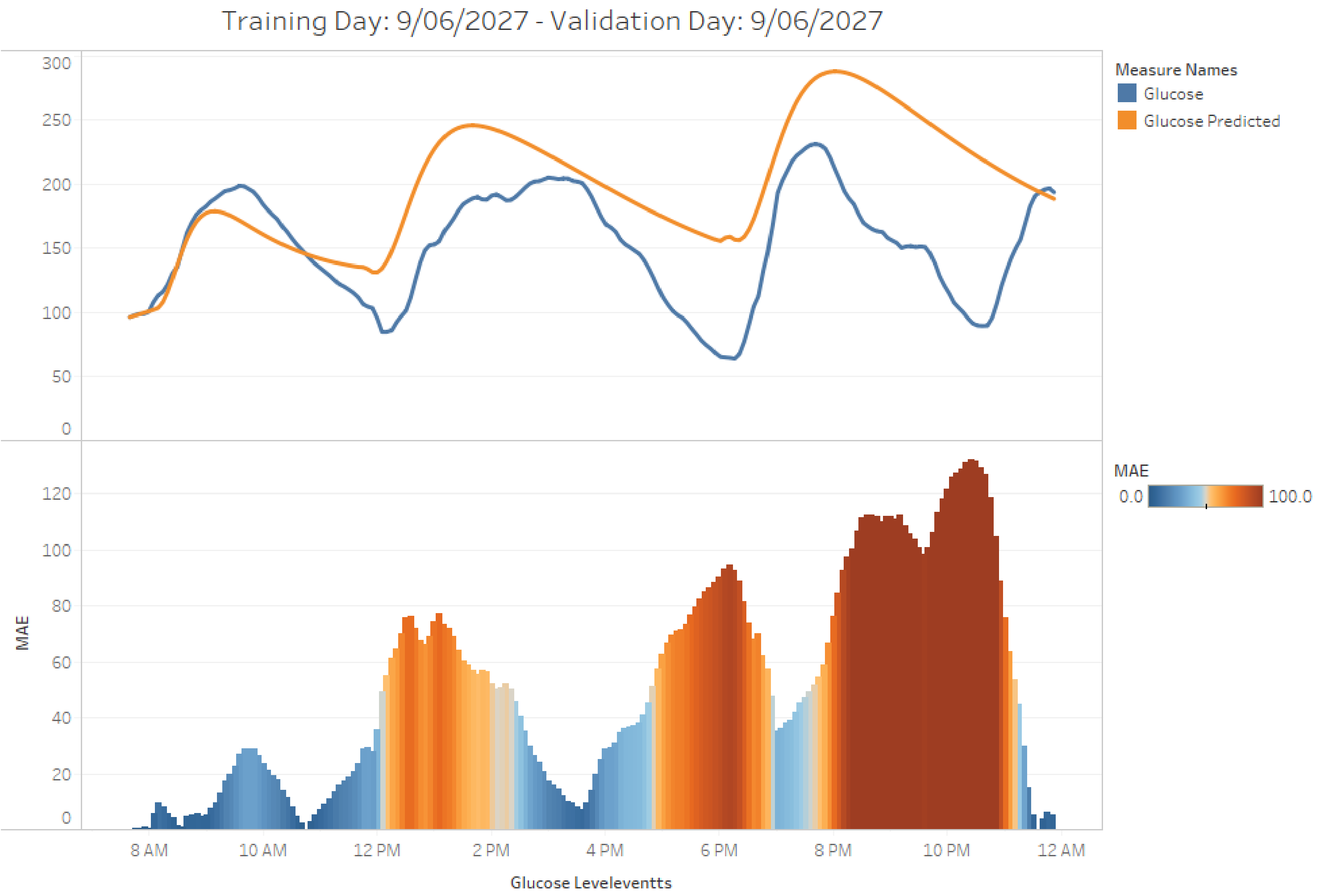
- Time Shifts
- **Algorithm**
- Grid Search



Methodology

Grid Search

- Time Shifts
- Algorithm
- **Grid Search**

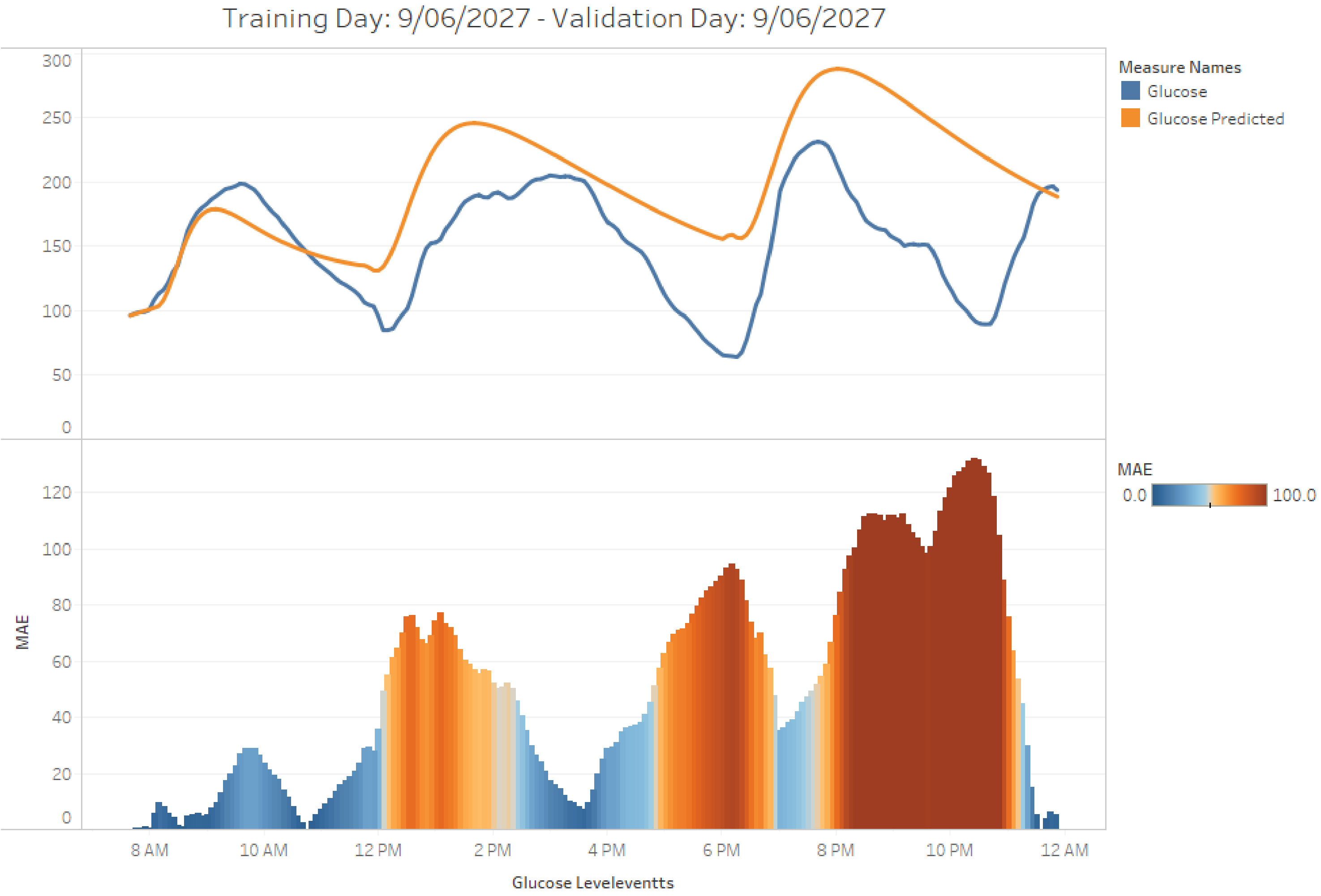


Methodology

Grid Search

Shifts:	Training:		Validation:	
	Bolus:	0	Bolus:	0
	Carbs:	0	Carbs:	0

- Time Shifts
- Algorithm
- Grid Search
    - Perform algorithm for each combination of training day, validation day and both shifts

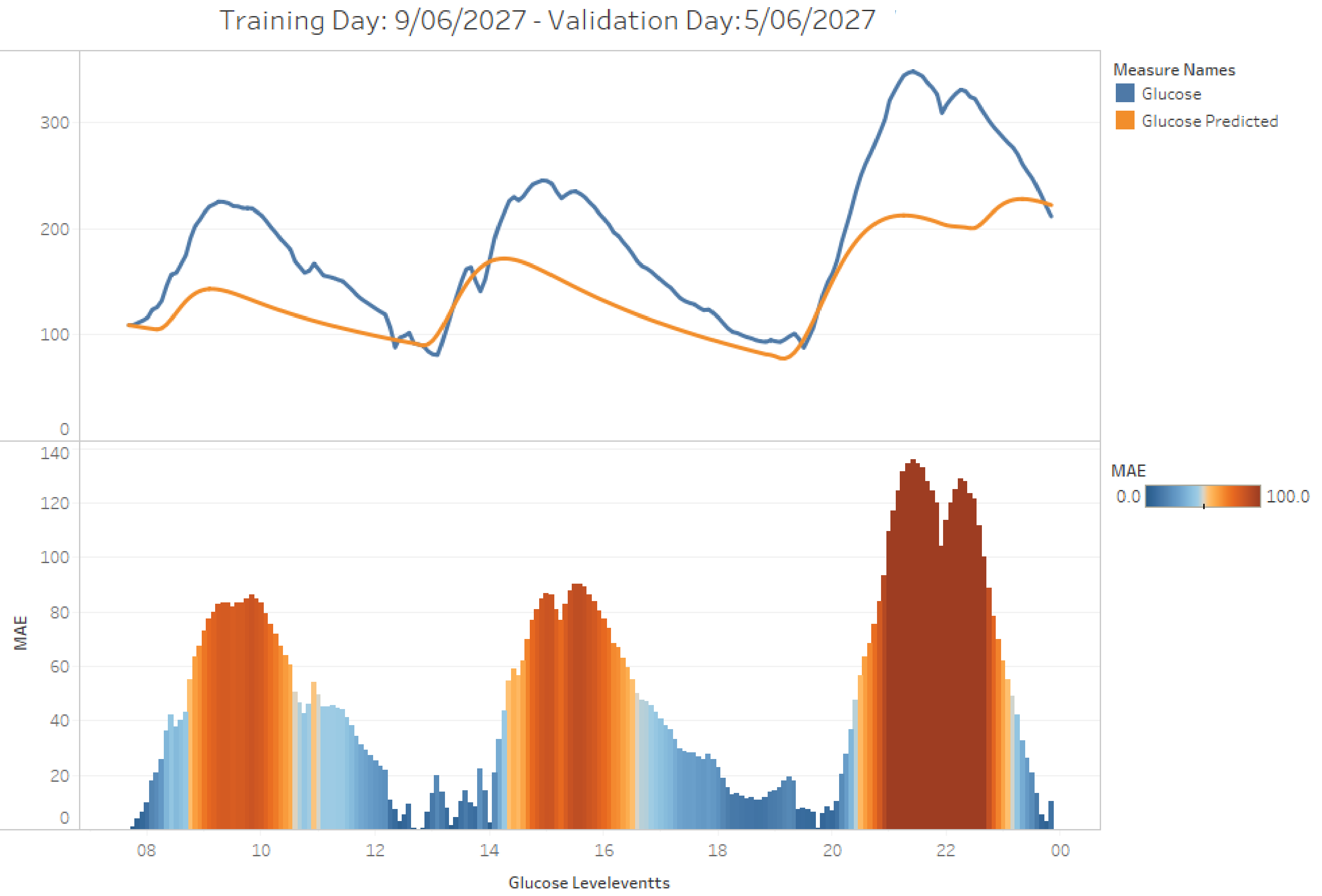

Training Day: 9/06/2027 - Validation Day: 9/06/2027

Methodology

Grid Search

Shifts: Training: Validation:
Bolus: 2 Bolus: 4
Carbs: 5 Carbs: 3

- Time Shifts
- Algorithm
- Grid Search
  - Perform algorithm for each combination of training day, validation day and both shifts



Methodology

Grid Search

- Time Shifts
- Algorithm
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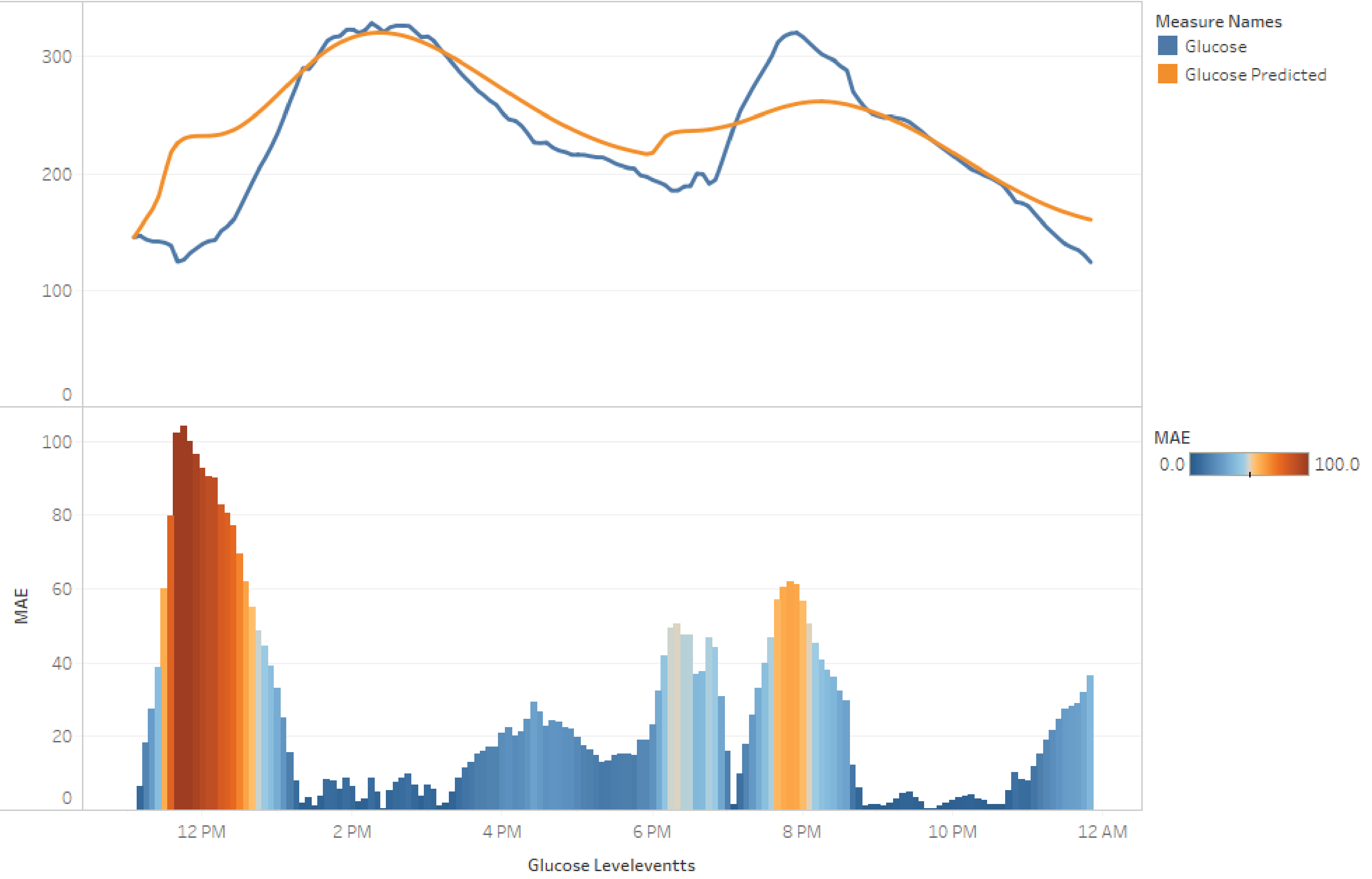
  - Perform algorithm for each combination of training day, validation day and both shifts

<u>Shifts:</u> Training: Validation:

Bolus:	4	Bolus:	0
Carbs:	0	Carbs:	3

Training Day: 9/06/2027 - Validation Day: 15/05/2027



Methodology

Grid Search

Shifts:	Training:		Validation:	
	Bolus:	4	Bolus:	0
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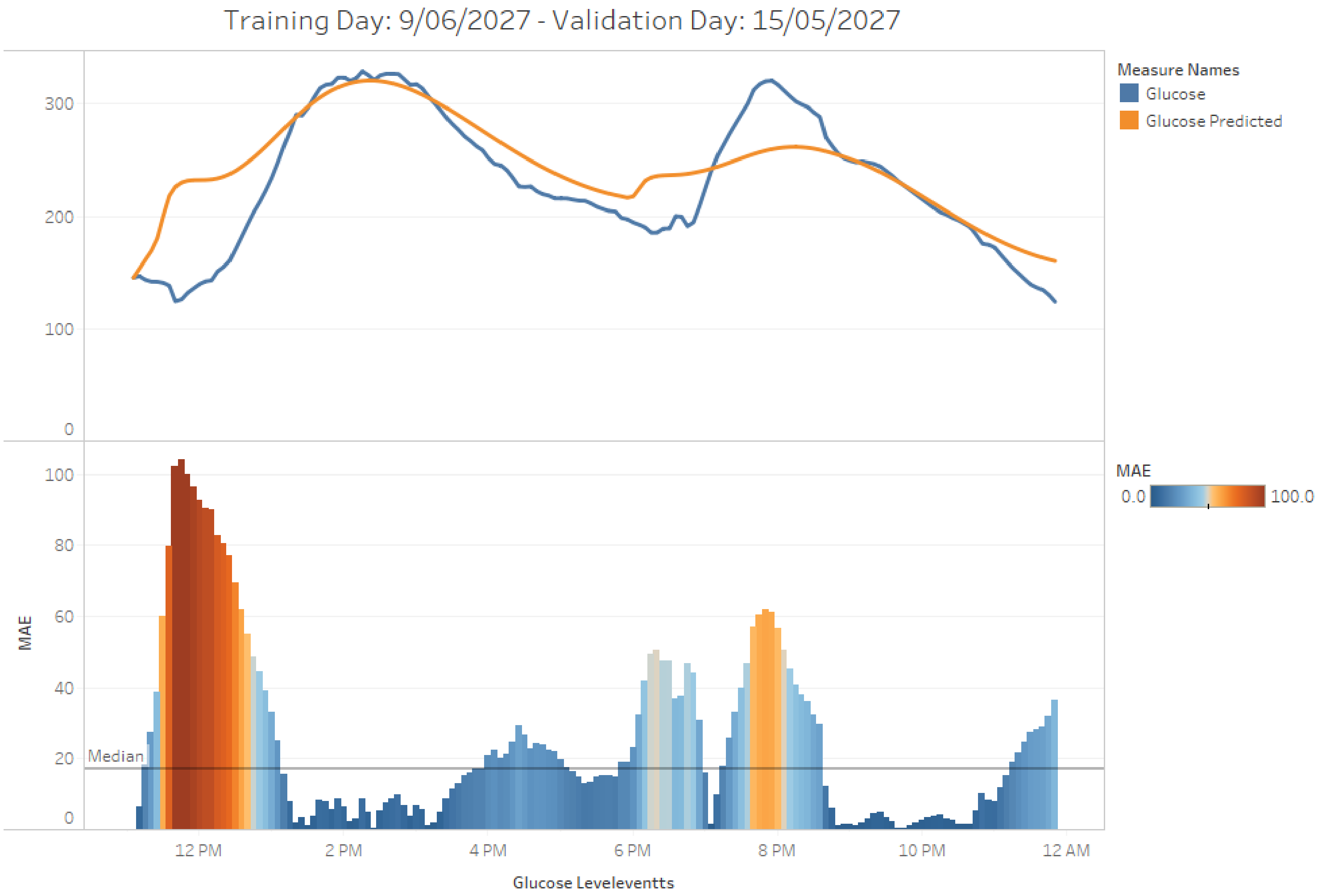
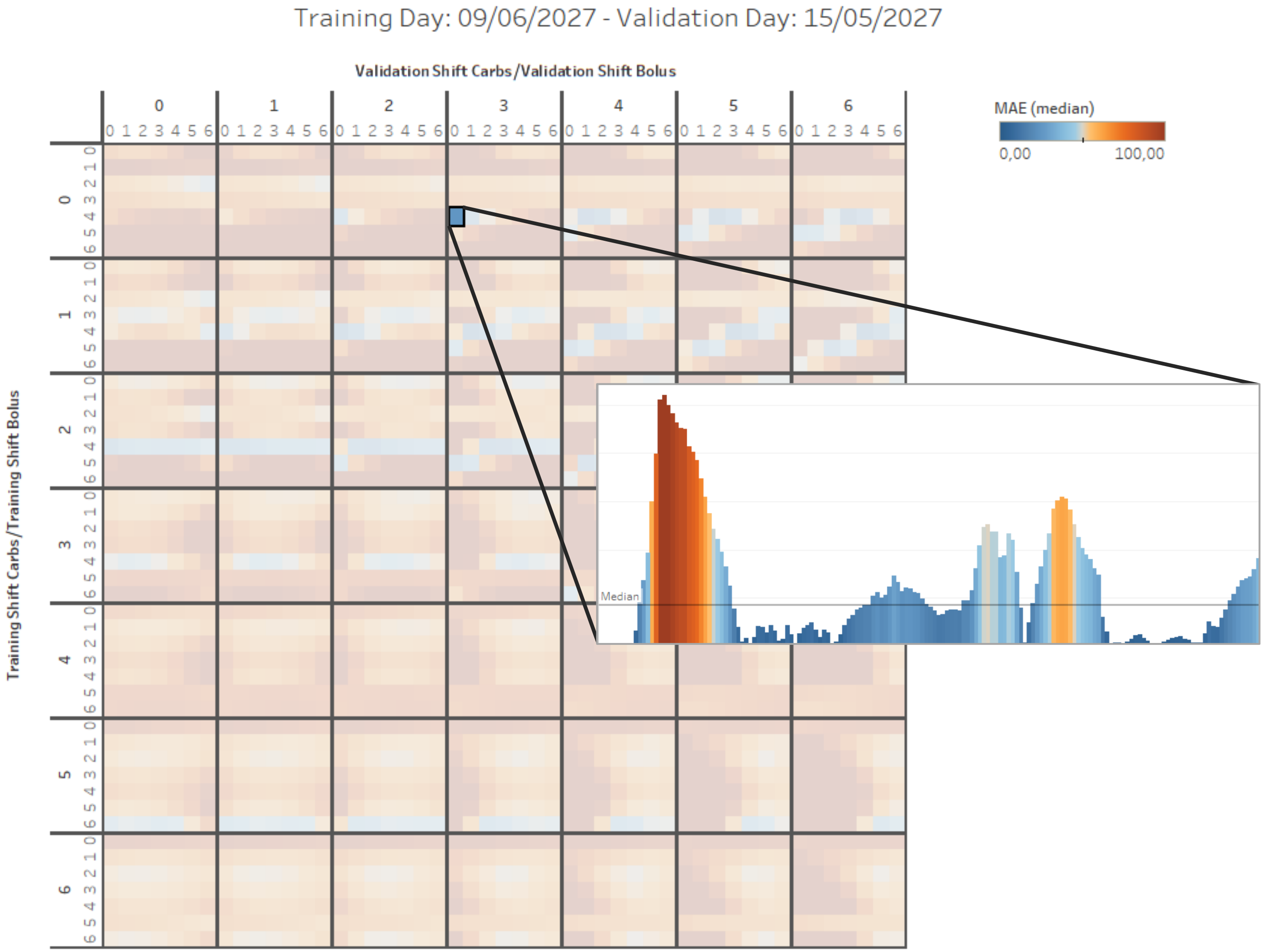


Training Day: 9/06/2027 - Validation Day: 15/05/2027

Methodology

Grid Search

- Time Shifts
- Algorithm
- Grid Search
    - Perform algorithm for each combination of training day, validation day and both shifts
    - Create error grid of shifts for each training/validation combination



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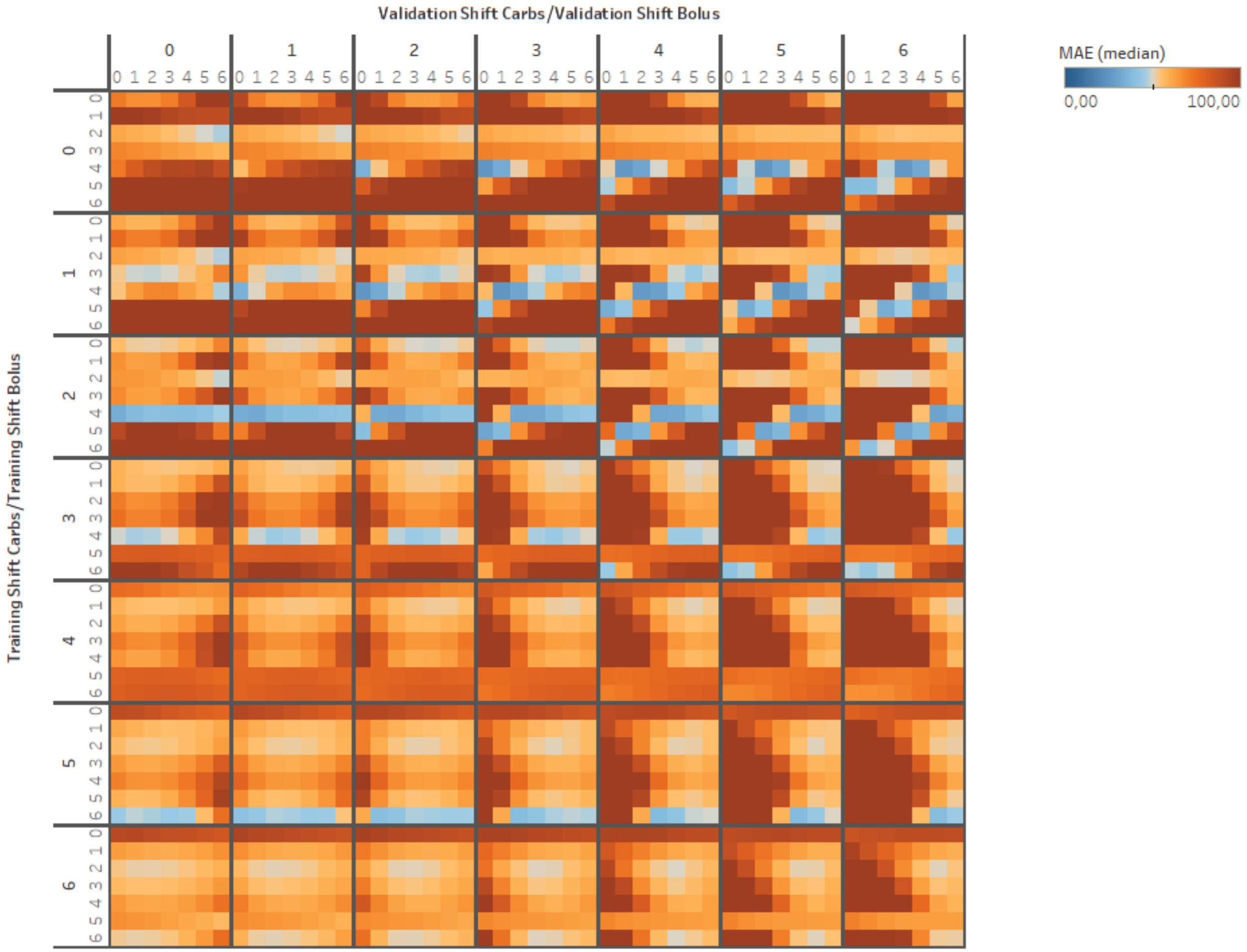
Training Day: 09/06/2027 - Validation Day: 15/05/2027



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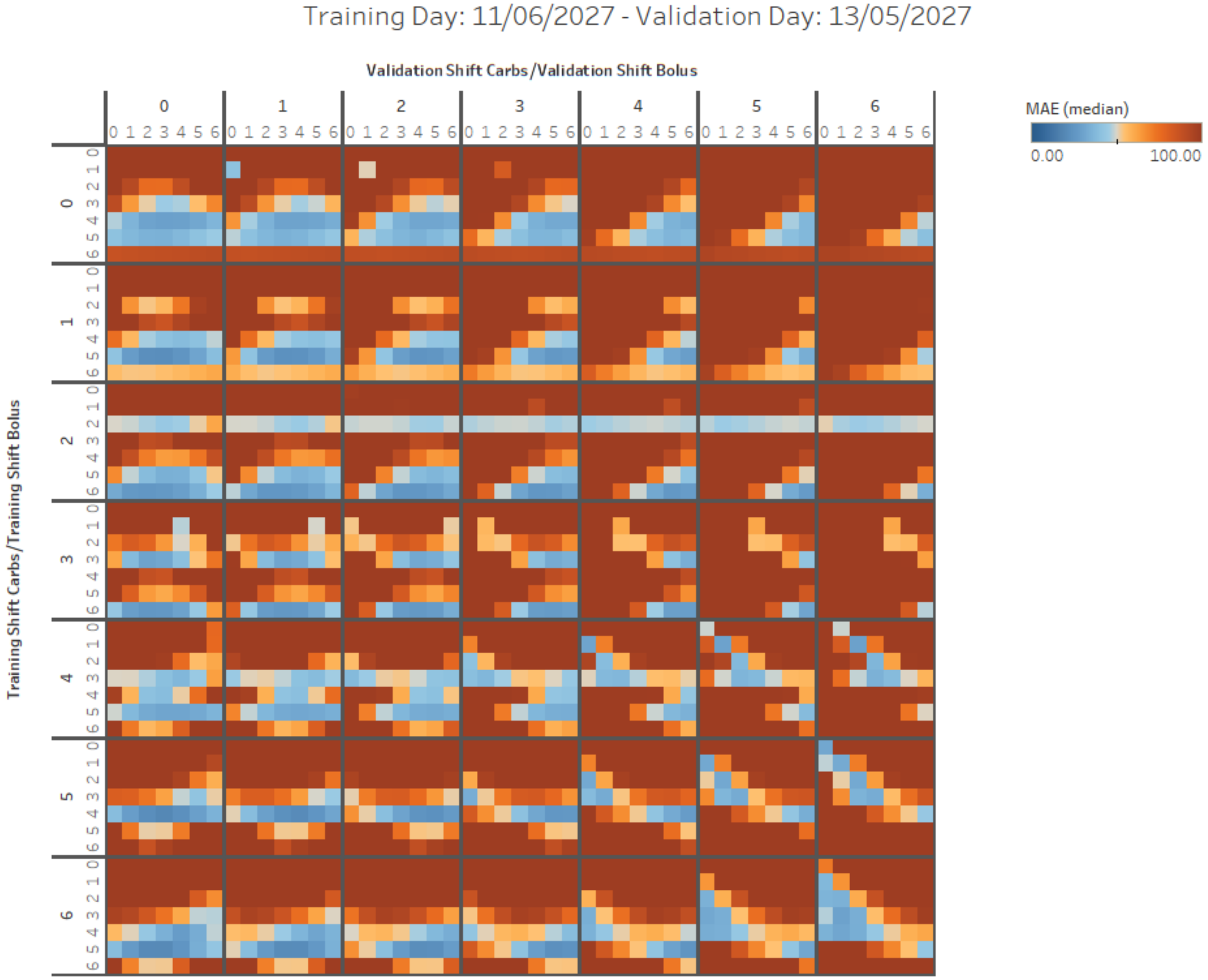

Training Day: 11/06/2027 - Validation Day: 13/05/2027

Methodology

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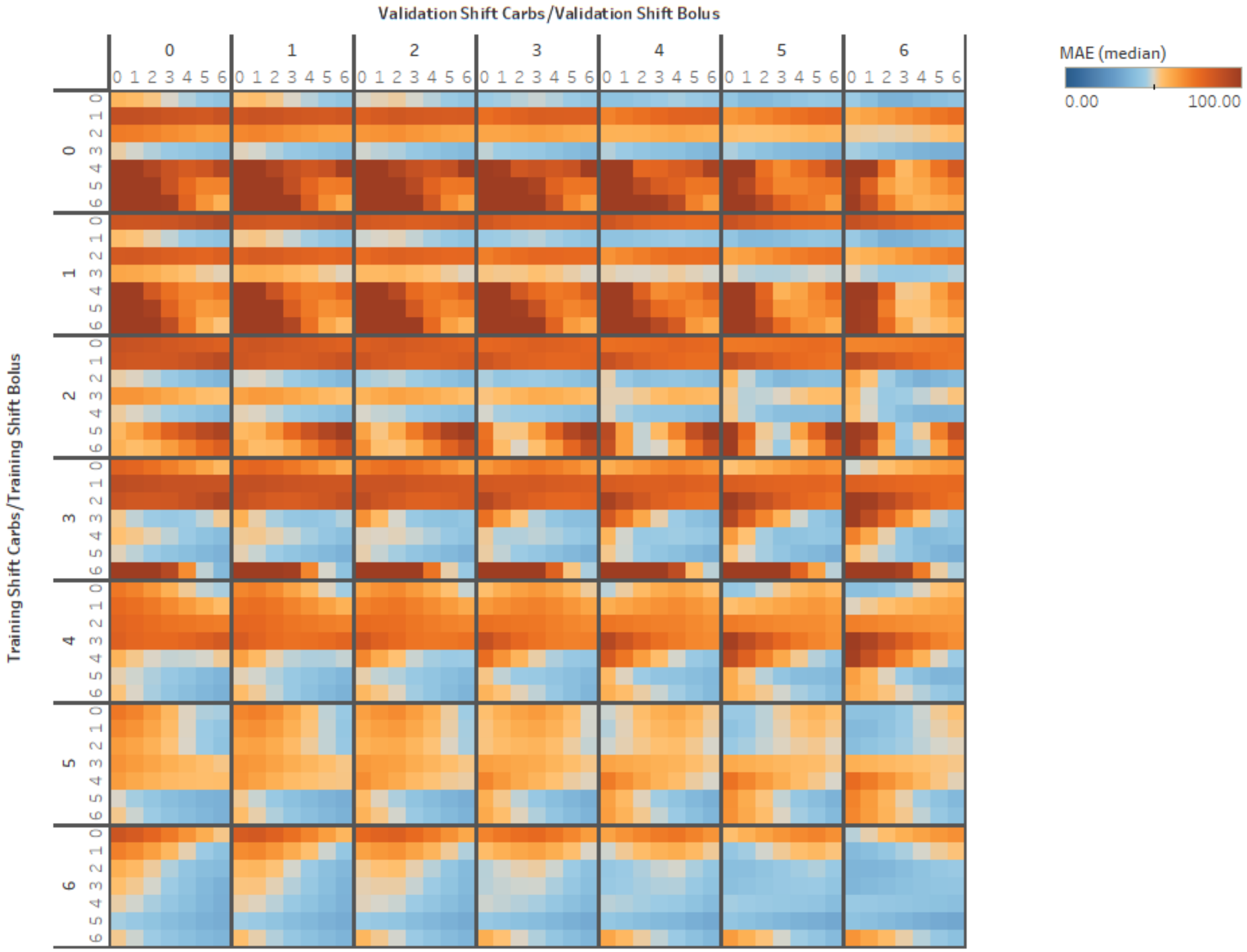
    - Create error grid of shifts for each training/validation combination

Training Day: 05/06/2027 - Validation Day: 03/06/2027

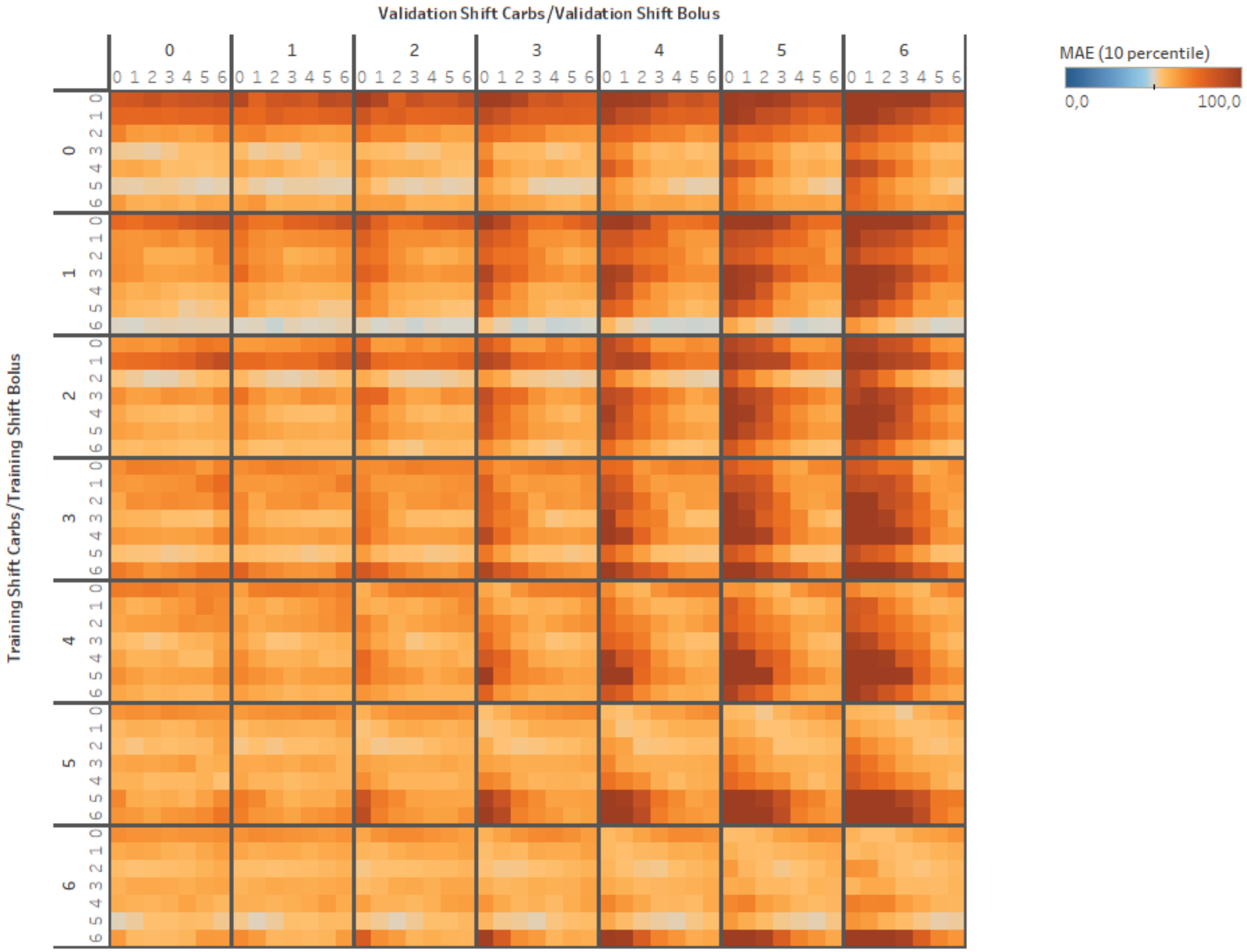


Methodology

Grid Search

- Time Shifts
- Algorithm
- Grid Search
    - Perform algorithm for each combination of training day, validation day and both shifts
    - Create error grid of shifts for each training/validation combination
    - Select best parameter for shifts (10 percentile)

Training Day: All - Validation Day: All



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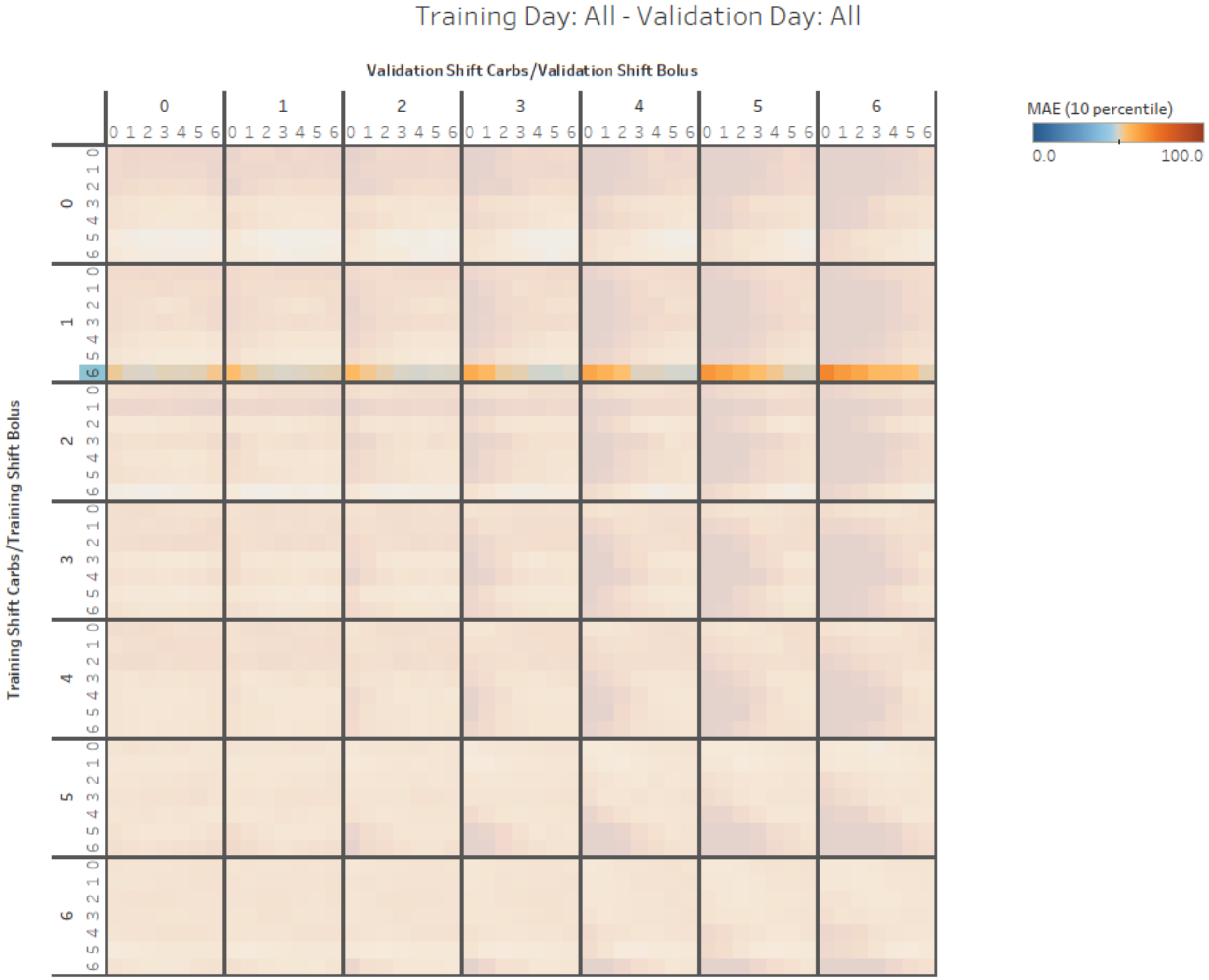

Methodology

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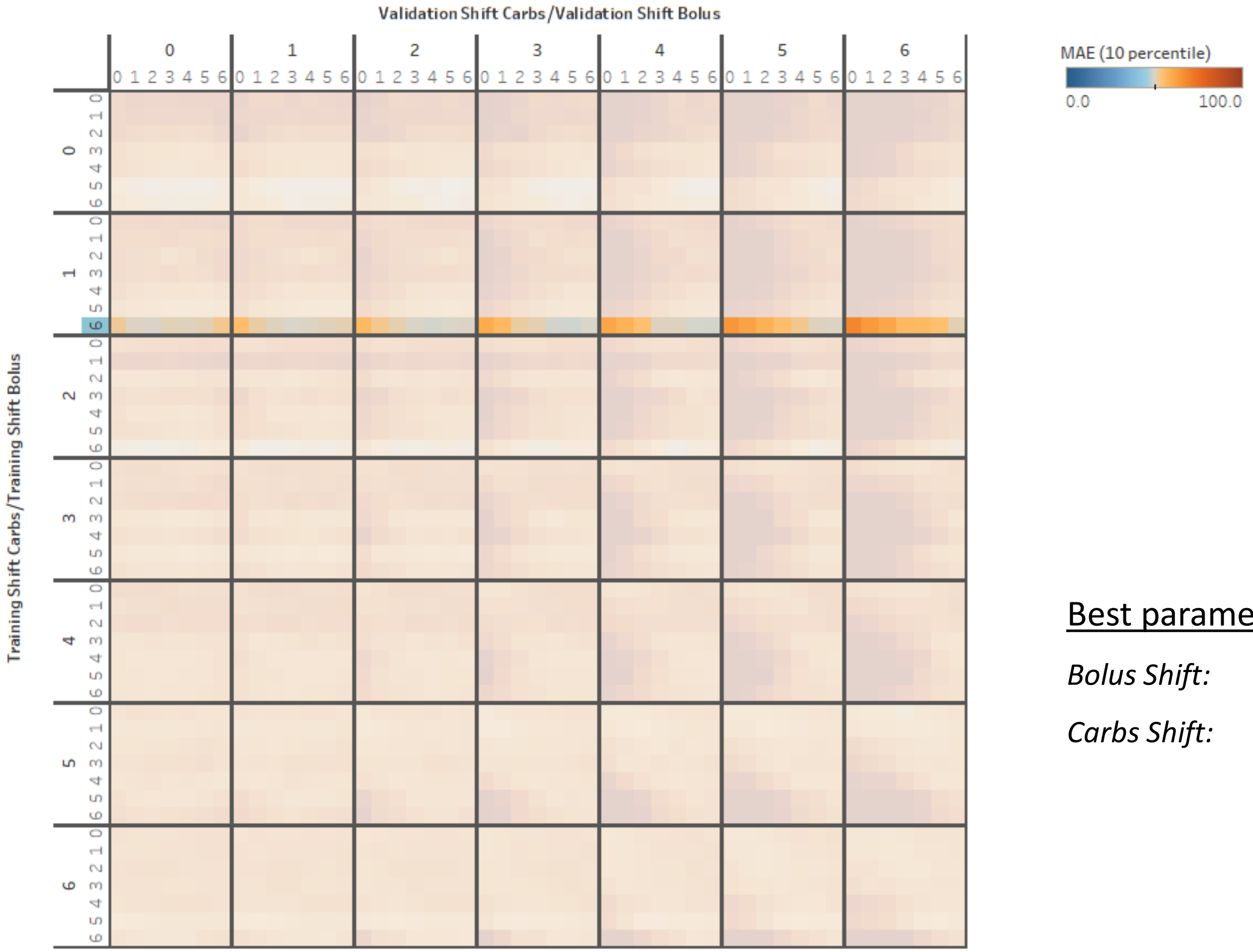
Training Day: All - Validation Day: All



Best parameter:

Bolus Shift: 6

Carbs Shift: 1

Methodology

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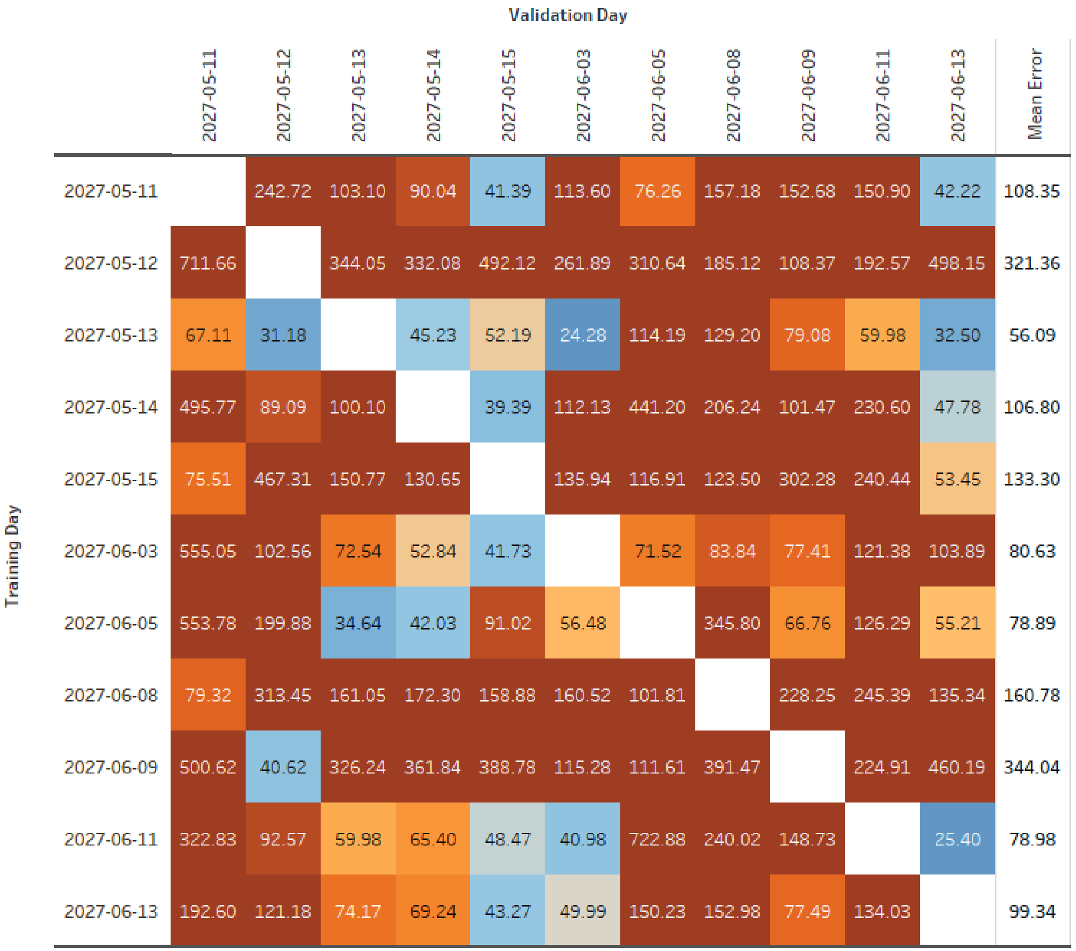

Validation Day

Training Day

	2027-05-11	2027-05-12	2027-05-13	2027-05-14	2027-05-15	2027-06-03	2027-06-05	2027-06-08	2027-06-09	2027-06-11	2027-06-13	Mean Error
2027-05-11		242.72	103.10	90.04	41.39	113.60	76.26	157.18	152.68	150.90	42.22	108.35
2027-05-12	711.66		344.05	332.08	492.12	261.89	310.64	185.12	108.37	192.57	498.15	321.36
2027-05-13	67.11	31.18		45.23	52.19	24.28	114.19	129.20	79.08	59.98	32.50	56.09
2027-05-14	495.77	89.09	100.10		39.39	112.13	441.20	206.24	101.47	230.60	47.78	106.80
2027-05-15	75.51	467.31	150.77	130.65		135.94	116.91	123.50	302.28	240.44	53.45	133.30
2027-06-03	555.05	102.56	72.54	52.84	41.73		71.52	83.84	77.41	121.38	103.89	80.63
2027-06-05	553.78	199.88	34.64	42.03	91.02	56.48		345.80	66.76	126.29	55.21	78.89
2027-06-08	79.32	313.45	161.05	172.30	158.88	160.52	101.81		228.25	245.39	135.34	160.78
2027-06-09	500.62	40.62	326.24	361.84	388.78	115.28	111.61	391.47		224.91	460.19	344.04
2027-06-11	322.83	92.57	59.98	65.40	48.47	40.98	722.88	240.02	148.73		25.40	78.98
2027-06-13	192.60	121.18	74.17	69.24	43.27	49.99	150.23	152.98	77.49	134.03		99.34

MAE (median)

0.00 100.00

Best parameter:

Bolus Shift: 6

Carbs Shift: 1

Methodology

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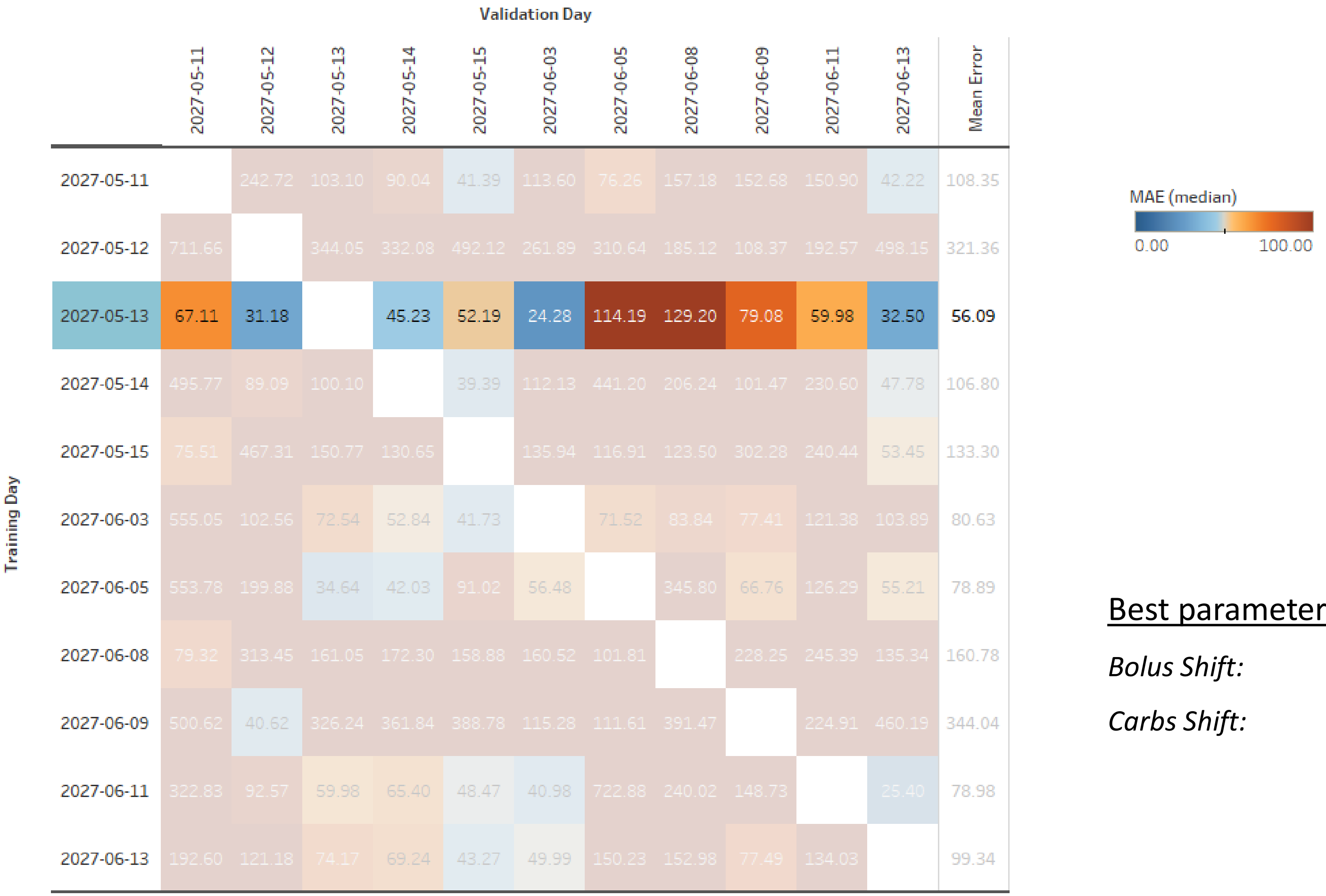
    - Select best model



	2027-05-11	2027-05-12	2027-05-13	2027-05-14	2027-05-15	2027-06-03	2027-06-05	2027-06-08	2027-06-09	2027-06-11	2027-06-13	Mean Error
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<u>Best parameter:</u>

Bolus Shift:	*6*
Carbs Shift:	*1*

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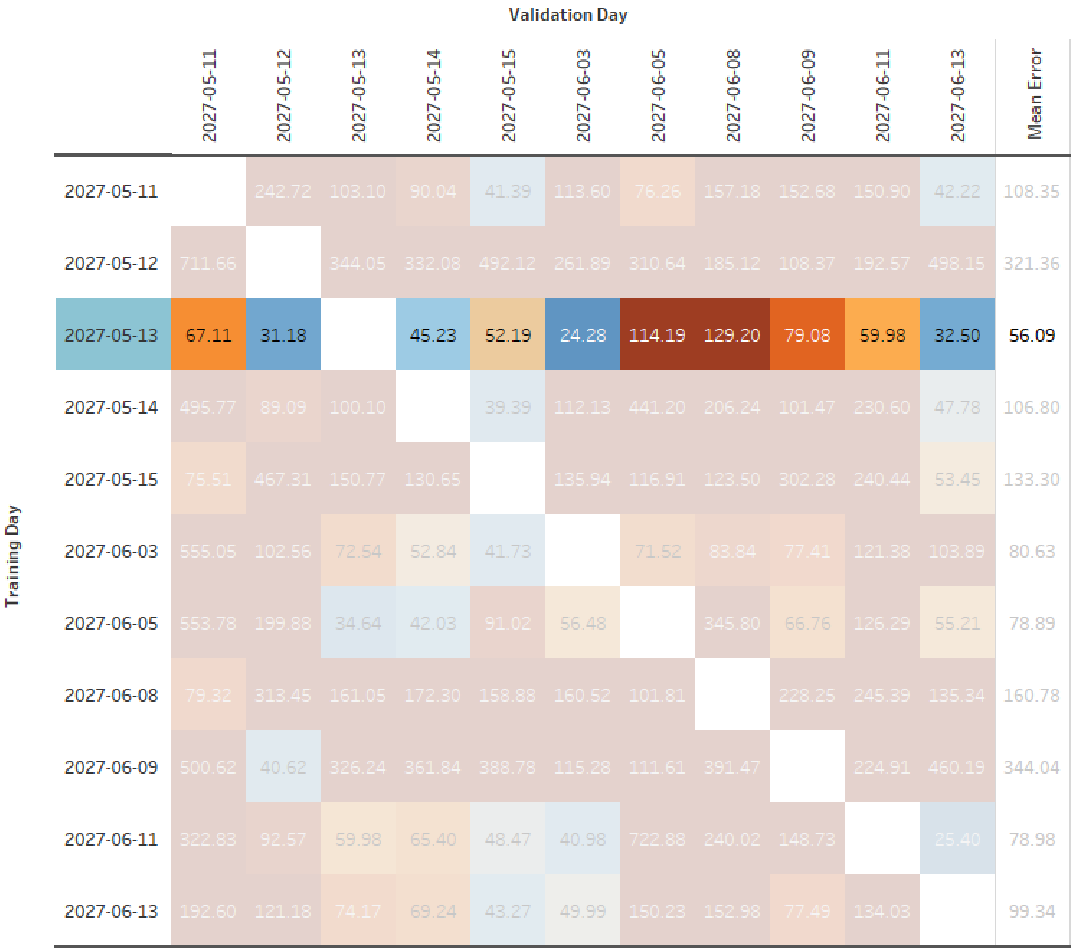

Validation Day

Training Day	2027-05-11	2027-05-12	2027-05-13	2027-05-14	2027-05-15	2027-06-03	2027-06-05	2027-06-08	2027-06-09	2027-06-11	2027-06-13	Mean Error
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2027-06-08	79.32	313.45	161.05	172.30	158.88	160.52	101.81		228.25	245.39	135.34	160.78
2027-06-09	500.62	40.62	326.24	361.84	388.78	115.28	111.61	391.47		224.91	460.19	344.04
2027-06-11	322.83	92.57	59.98	65.40	48.47	40.98	722.88	240.02	148.73		25.40	78.98
2027-06-13	192.60	121.18	74.17	69.24	43.27	49.99	150.23	152.98	77.49	134.03		99.34

Best parameter:

Bolus Shift: 6

Carbs Shift: 1

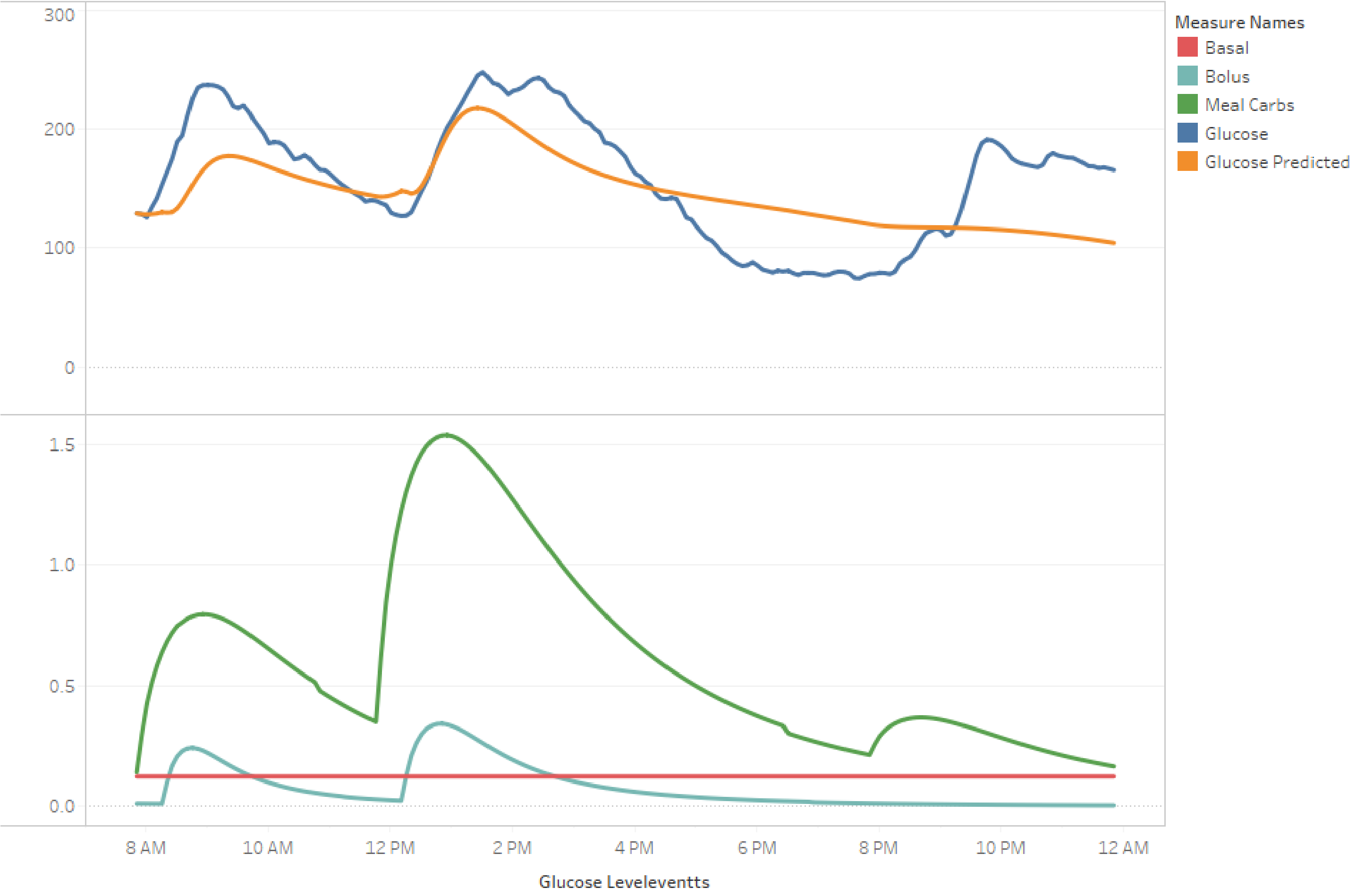
Model: 2027-05-13

Results

Predicted Values

Test MAE: $34.15\,\frac{mg}{dL}$

Test Day: 14/06/2027

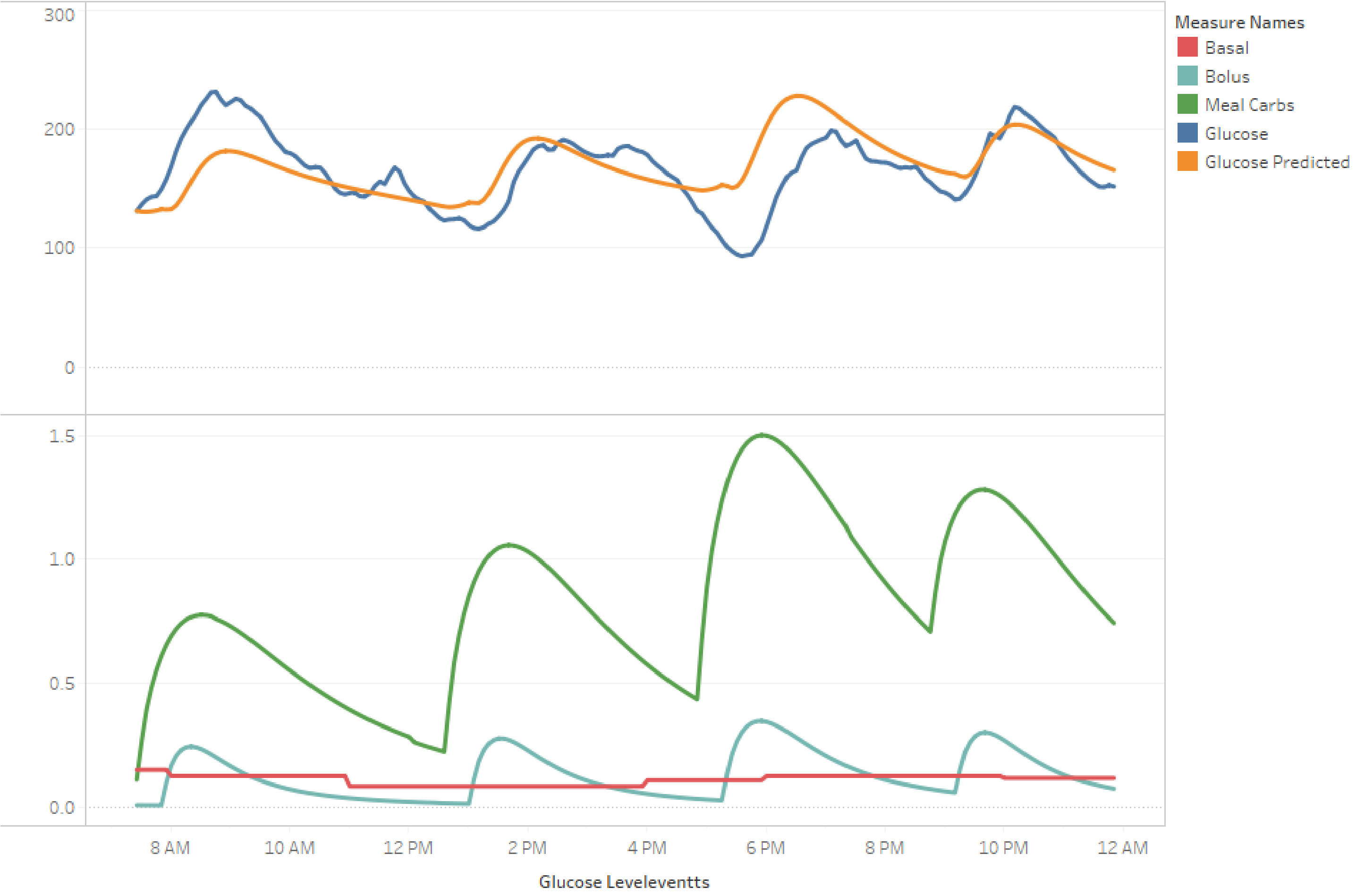


Results

Predicted Values

Test MAE: $20.92 \frac{mg}{dL}$

Test Day: 29/06/2027

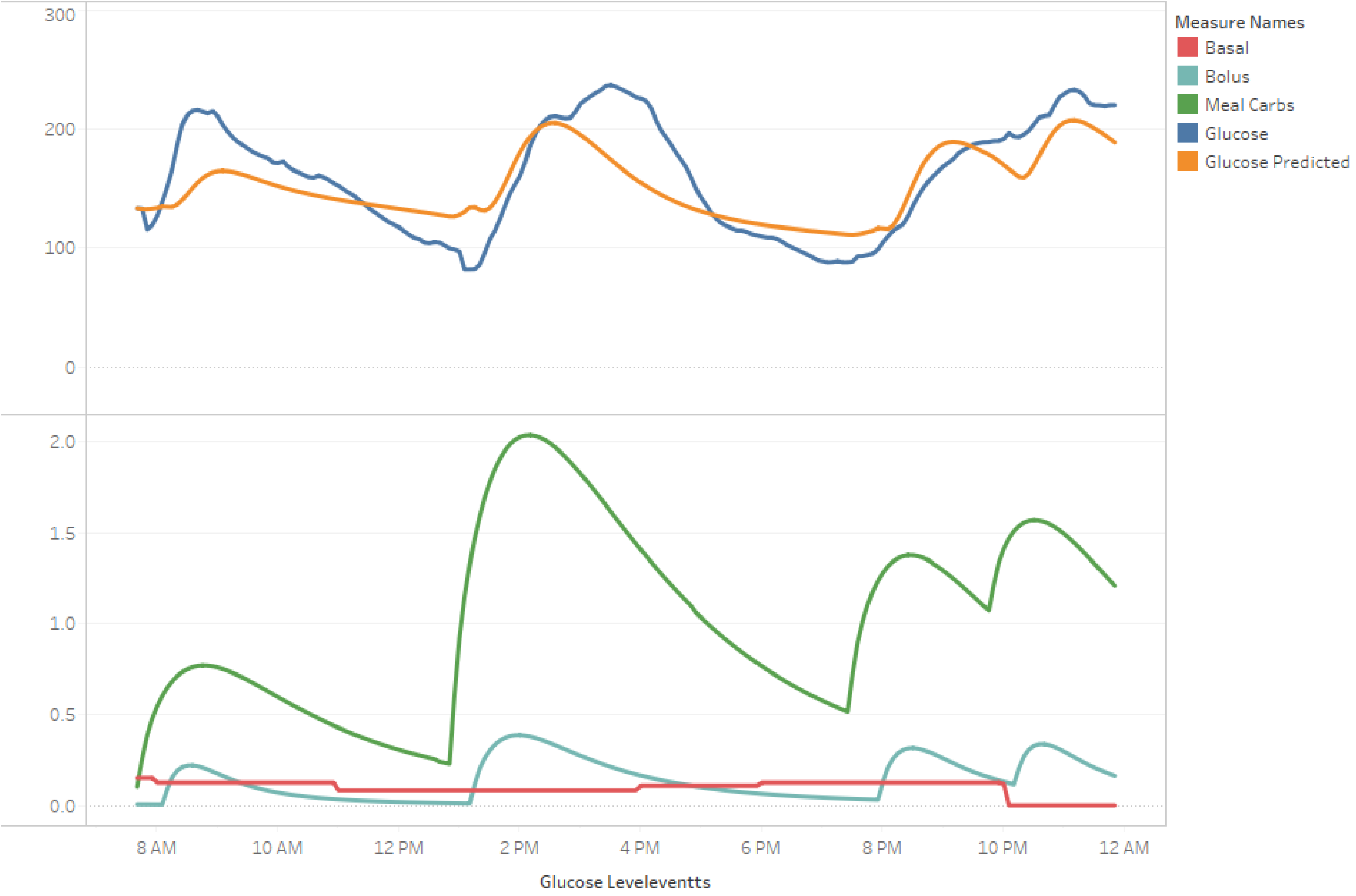


Results

Predicted Values

Test MAE: $23.59\frac{mg}{dL}$

Test Day: 30/06/2027

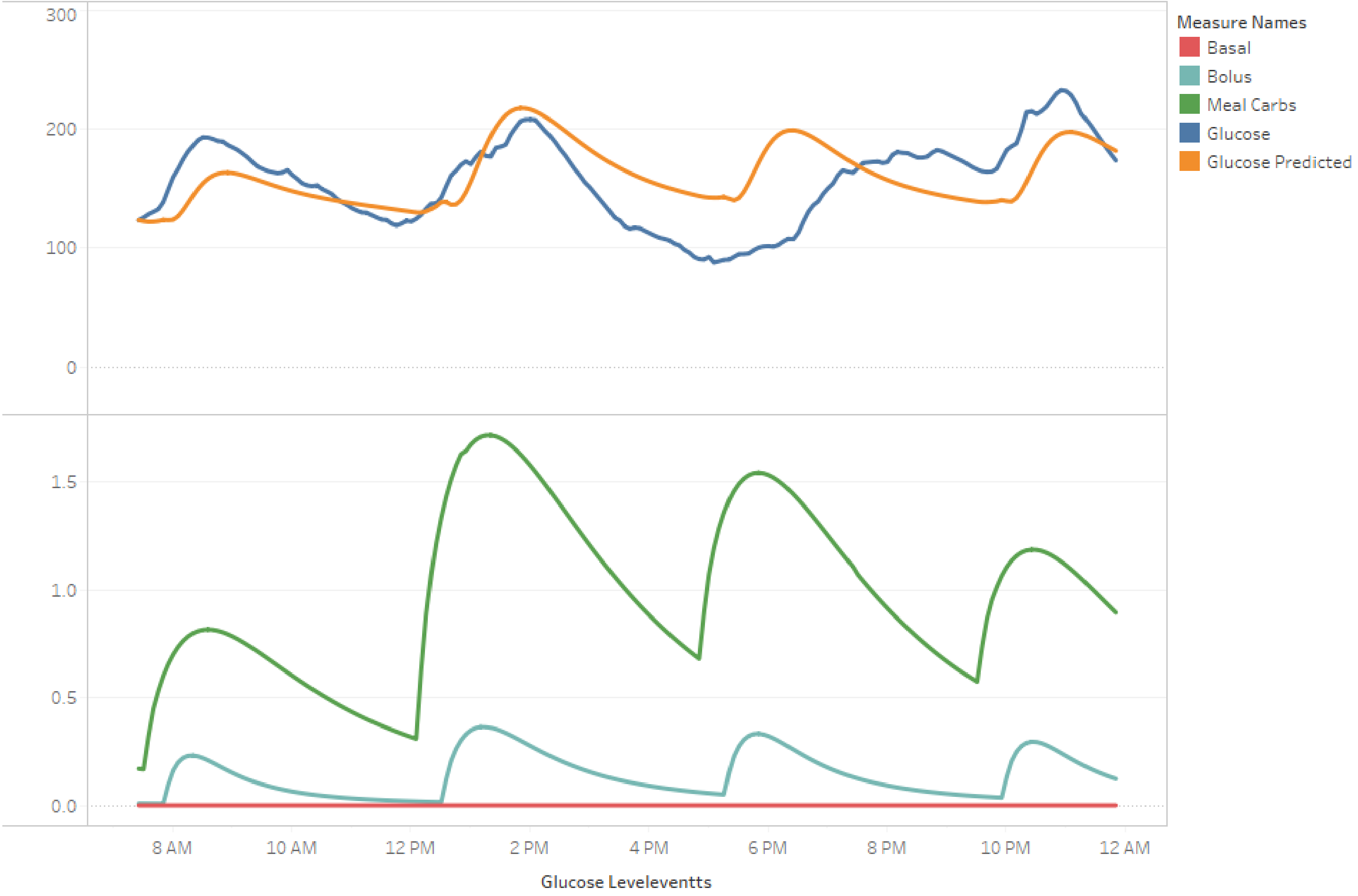


Results

Predicted Values

Test MAE: $28.16\frac{mg}{dL}$

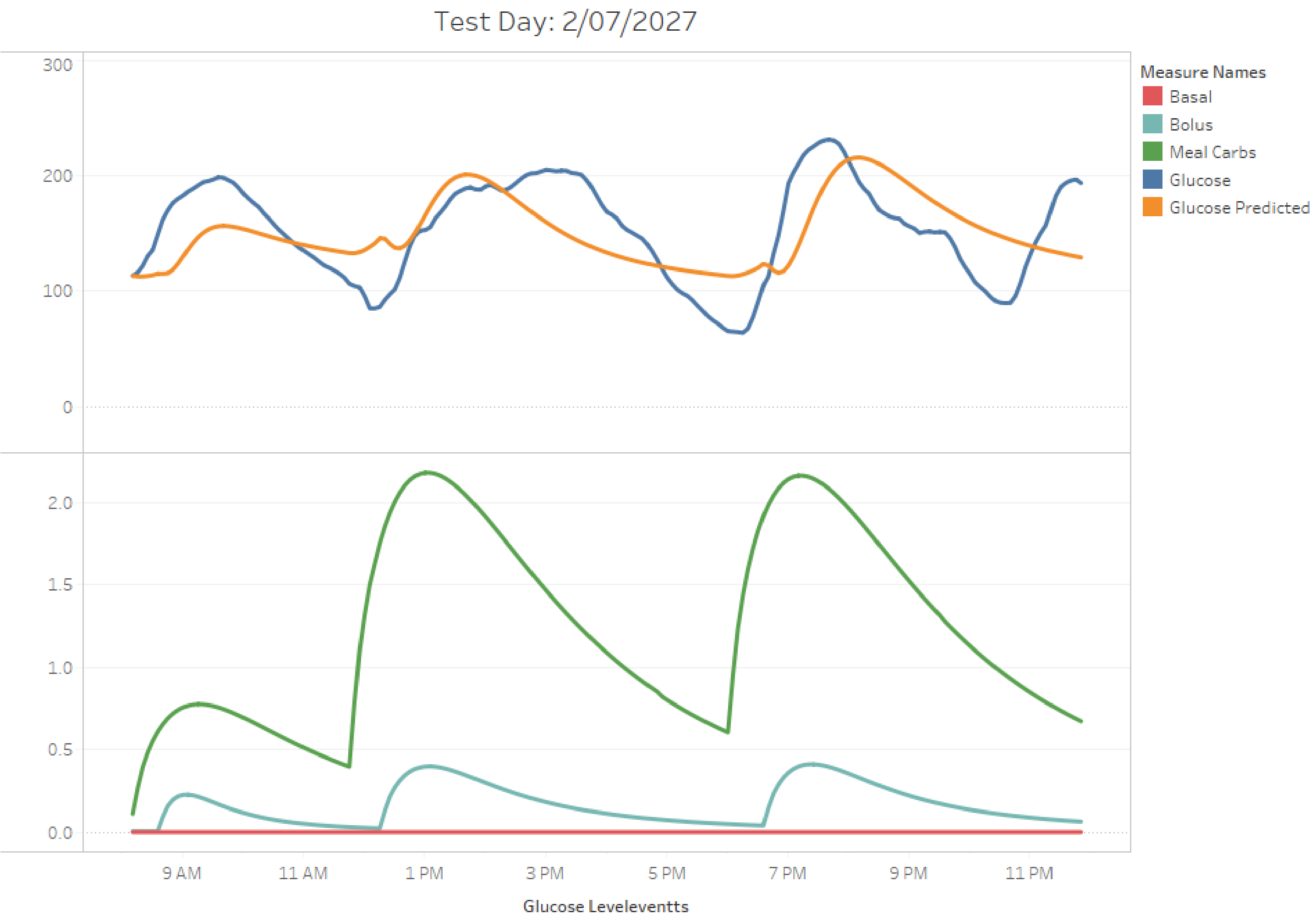
Test Day: 1/07/2027



Results

Predicted Values

Test MAE: $31.40\frac{mg}{dL}$

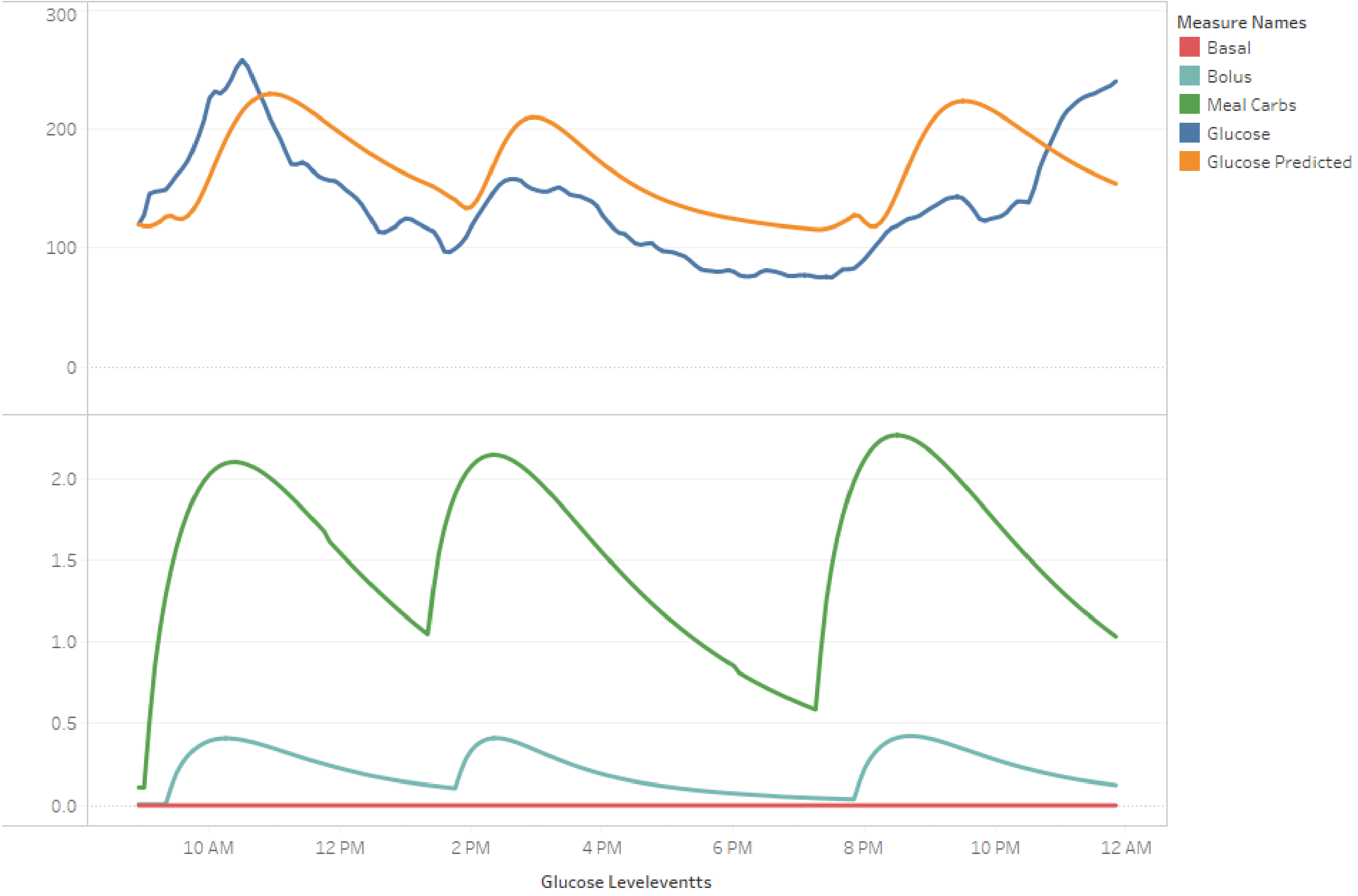


Results

Predicted Values

Test MAE: $45.68 \frac{mg}{dL}$

Test Day: 3/07/2027



Conclusio & Outlook

Is it possible to simulate the glucose level of an insulin patient over one day with differential equations using only bolus, basal and meal values?

Conclusio & Outlook

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Conclusio & Outlook

It is possible to simulate the glucose level of an insulin patient over one day with differential equations using only bolus, basal and meal values.

- Include better cost function (critical glucose values)
- Usage of more influencing variables (activities, sleep, heart rate)
- Handling of extrapolation problematic
- Better usage of SINDy algorithm (grammar, parameter, version)
- Patient independent modelling

Q&A

Backup

Backup

Formula (Model: 2027-05-13, Patient 540)

$$\frac{dG}{dt} = p_1 + p_2 \cdot b + p_3 \cdot C + p_4 \cdot G + p_5 \cdot B \cdot b + p_6 \cdot b^2 + p_7 \cdot b \cdot C + p_8 \cdot b \cdot G + p_9 \cdot C \cdot G + p_{10} \cdot G^2$$

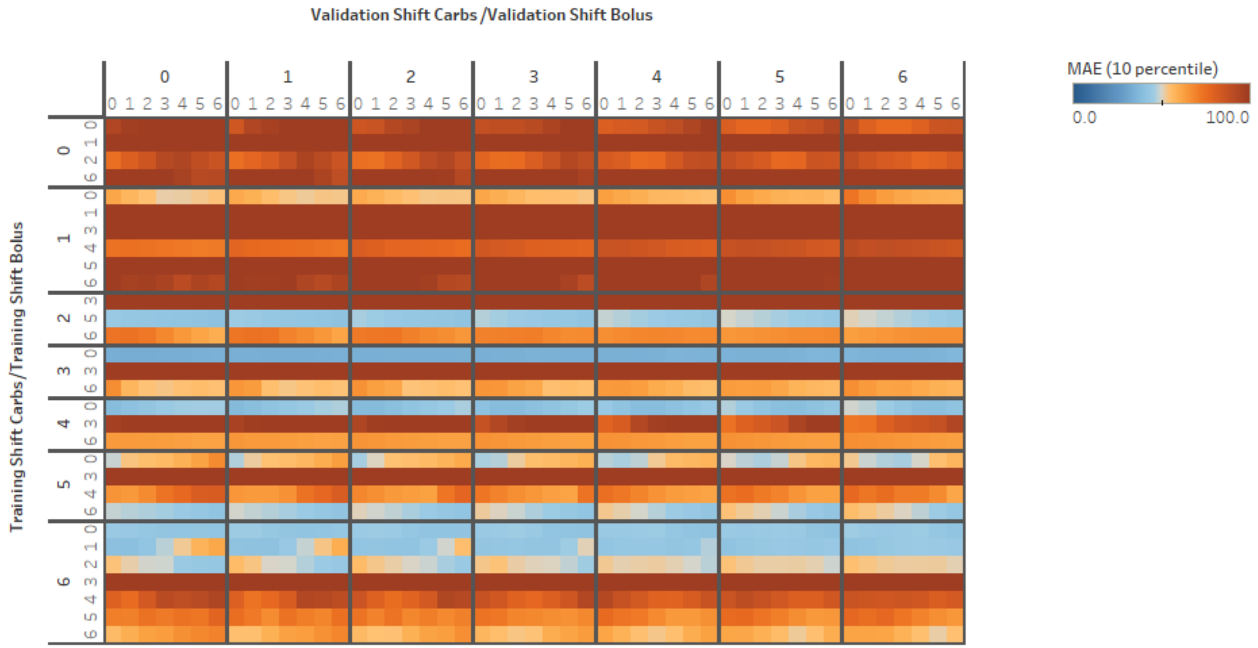
$p_1 = -1.14$
$p_2 = 102.39$
$p_3 = -0.14$
$p_4 = -7.69$
$p_5 = -0.21$
$p_6 = 648.80$
$p_7 = 12.80$
$p_8 = -185.42$
$p_9 = -0.96$
$p_{10} = 11.39$

$G = glucose(t)$
$B = bolus(t)$
$b = basal(t)$
$C = carbs(t)$

Backup

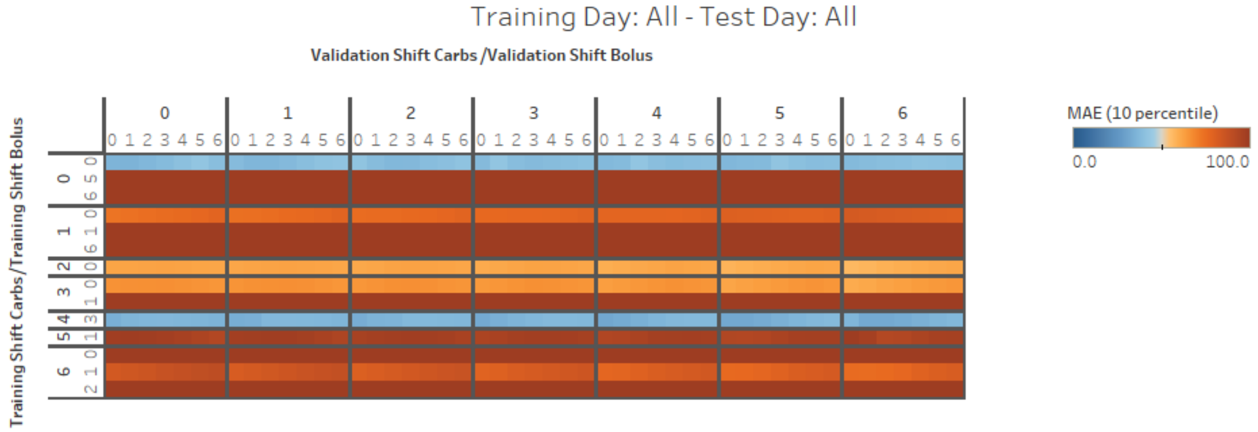
Grid: Patient 540

Training Day: All - Test Day: All



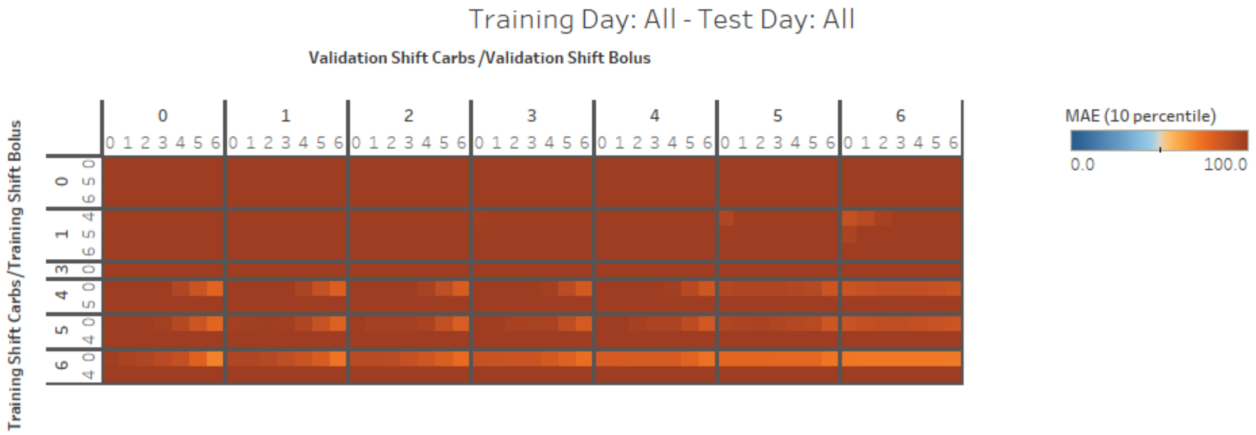
Backup

Grid: Patient 552



Backup

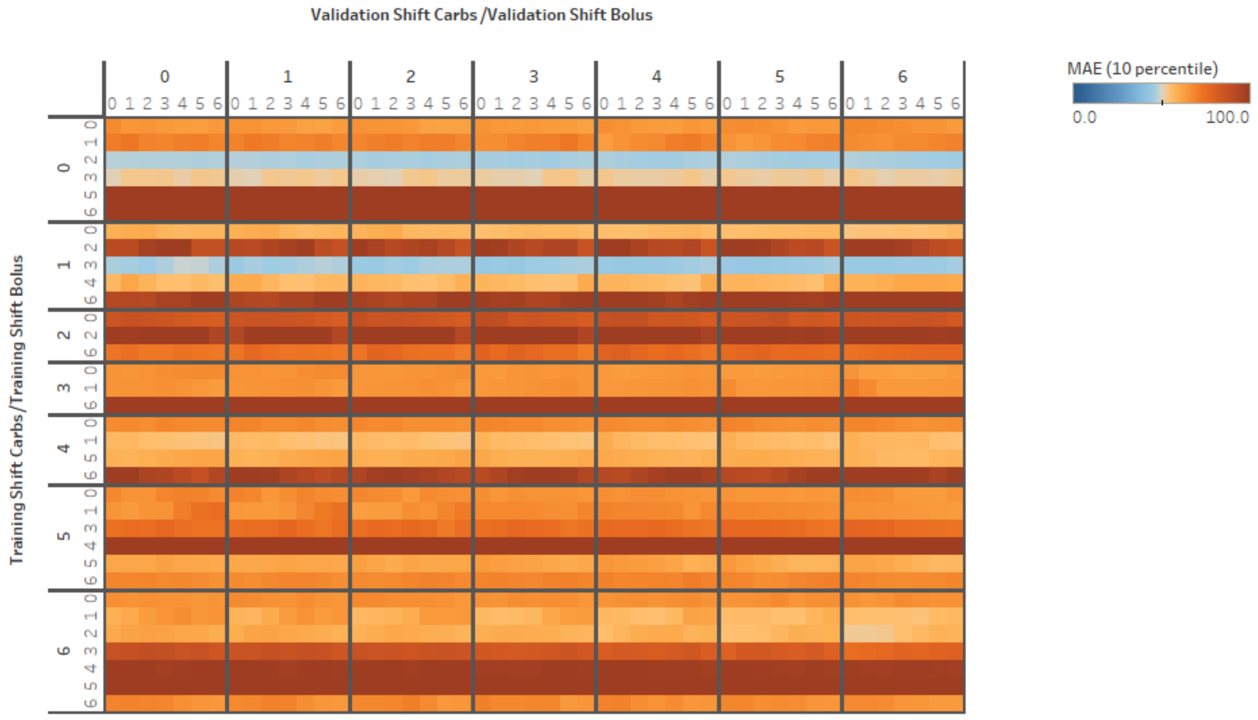
Grid: Patient 567


Training Day: All - Test Day: All

Backup

Grid: Patient 540

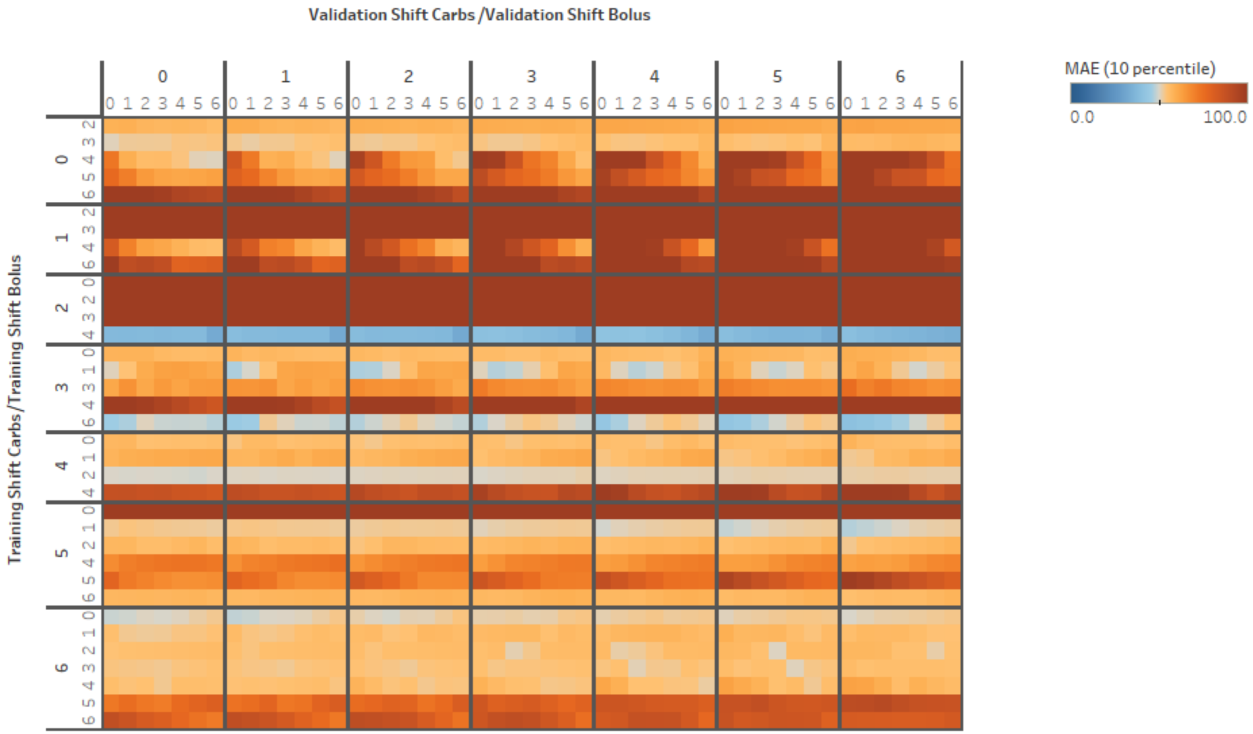
Training Day: All - Test Day: All



Backup

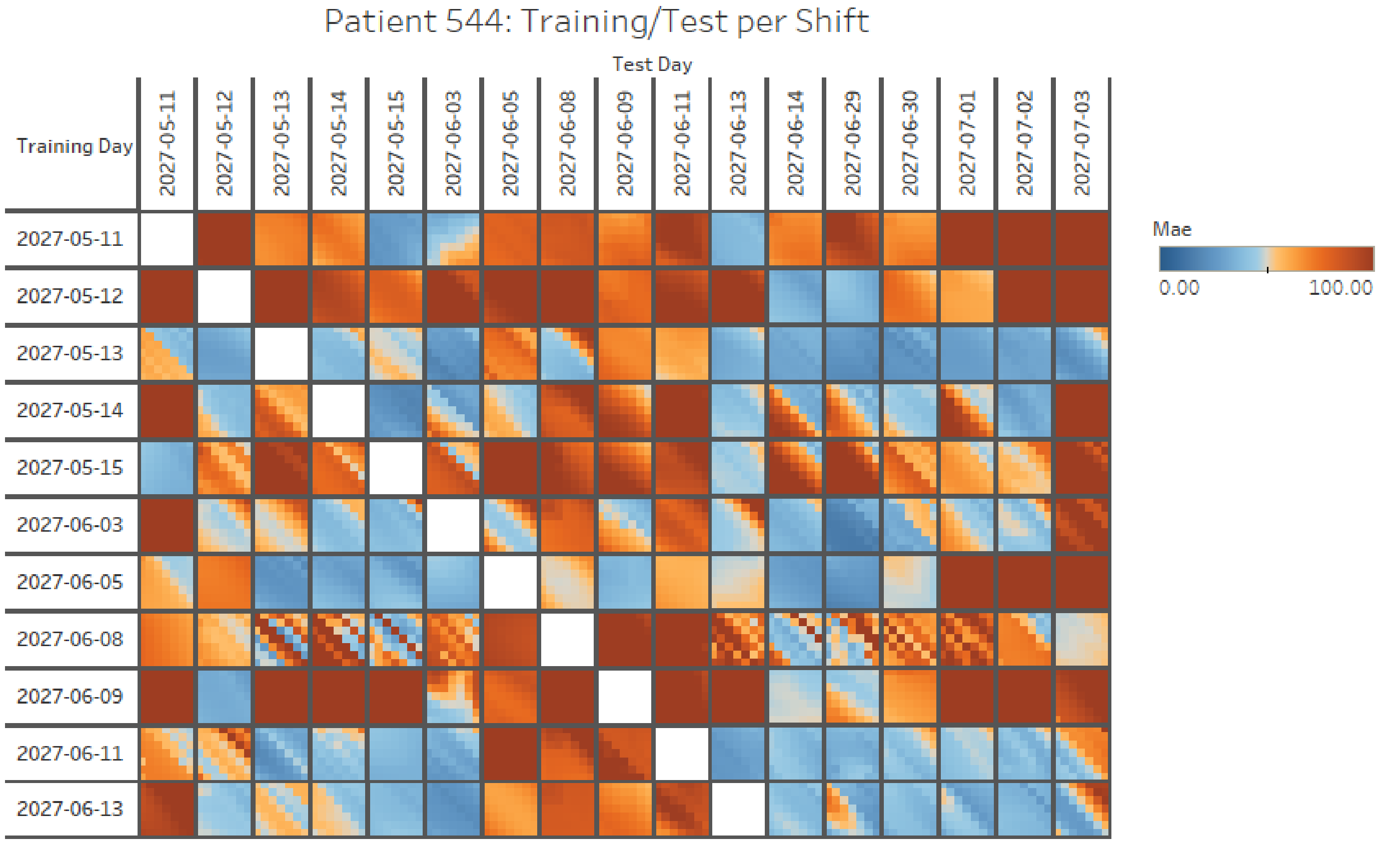
Grid: Patient 540

Training Day: All - Test Day: All



Backup

Detailed Shift View



Backup

MAE Distribution