Summary

This study investigates congestion patterns in triathlon events, focusing on an open Olympic triathlon consisting of a 1,500 m swim, 40 km bike, and 10 km run with 2,000 participants ranging from professional to amateur athletes. Brief mid-course crowding was observed during peak periods, highlighting the need for effective wave management. Athletes were organized into waves based on status, gender, and age to ensure fair competition, smooth stage transitions, and optimized course usage. Strategic coordination of start times minimized overlap between faster and slower participants, reducing congestion and enhancing the overall flow and race experience.

Using data from a recent triathlon, a model was developed to predict individual performance relative to participant categories, allowing for the creation and adjustment of multiple waves. Waves were initially grouped by status and subsequently combined or split to balance sizes and pacing. The approach aimed to limit road closure durations to a maximum of five and a half hours while minimizing interference between faster and slower athletes. This model provides a structured framework for optimizing race logistics and improving participant experience by effectively limiting road closures to within five and a half hours and limiting congestion.

Table of Contents

Contents

Introduction

We are working to organize an open Olympic triathlon with a 1,500m swim, 40k bike, and 10k run. This run consists of 2,000 runners who range in skill level and are sorted in categories called "statuses". Professional racers are sorted into the "Pro" status. Amateur racers include those in the "Premier" or "Open" status. The Athena and Clydesdale statuses exist for female racers weighing over 160lbs and male racers weighing over 220lbs respectively. The Super Tread Race Company is sponsoring the event, so it is imperative that it goes smoothly in order to incentivize them to sponsor future events. In collaboration with the mayor of a town, we are allotted a limit of five and a half hours to close the town's roads for triathlon use. Using data from a recent triathlon on the participants' genders, ages, and status, we want to minimize the expected congestion, make sure roads stay closed for a maximum of five and a half hours, and make sure that the slower runners do not hinder the faster runners by creating and scheduling multiple waves of participants.

Assumptions and Justifications

1. Patterns and trends of the data set apply to participants of this race

   The proportion of participants in each category, such as gender and age group, is preserved exactly as in the original data. This ensures our models' accuracy reflecting triathlon participation patterns. Keeping the same ratios also maintains consistency across all divisions. Racer's speed will mirror speeds shown in the data set and athletes of similar demographics and skill levels will be assumed to perform similarly.

2. There are exactly 2,000 participants in total

   The overall capacity of the event is 2,000 participants. The total is assumed to match the proportions of the ratios of participants in the original data.

3. First 99% of the data is significant (slowest 1 percentile does not count)

   The slowest 1% of participants are excluded from the road closure analysis. This focuses on calculations on most participants and prevents outliers from artificially skewing the data.

4. Only the bike and running portions contribute to road closure, which starts after the first person starts biking and ends after all significant participants finish.

   Only the biking and running portions affect the road closure since they will take place on public routes. The road will begin closure as soon as the first person enters the biking phase until the last of the significant participants completes the race. If there are non-significant participants still completing the triathlon, a sweeper will make sure to get them out of harm's way.

5. Everyone travels at a constant speed for each section

   Each athlete is modeled as moving at a constant speed within each race leg, which simplifies timing, congestion calculations, and wave scheduling.

Presentation of Model and Solution

Part 1:

We organized the pre-existing data set into waves of participants to minimize the number of people per kilometer while also maintaining the 5.5-hour road closure period. Since the times are individual, we thought that solely reducing them down to averages for the times in order to fit the 2,000 participants would not sufficiently display the data. As such, we decided to keep all calculations and models related to time with the total 3,217 participants, and then only scale down our wave sizes.

The order of the waves is seen in Figure 2. This shows that the faster statuses go before the slower statuses; pros and premiers are first, then the opens, and then finally the Clydesdales and Athenas. We decided to put all the pro and premier athletes into the same wave as there were not enough of either to justify separating them into their own waves. Similarly, the Athenas and Clydesdales were also combined into one wave. The opens, which were too big for one wave, were then split up by age and gender, with the younger participants being in the earlier waves and the older participants being in the later waves, and the males before the females as seen in Figure 3. This ensured that waves on average would not exceed 150 racers, which is a good number when considering for route congestion for a triathlon of this scale. This general order of fastest to slowest was to make sure that everyone had an enjoyable time; the faster people would find it annoying having to overtake the slower people or be obstructed by them.

We decided on 5 minutes in between each wave as that made the total road closure closest to 5.5 hours while also giving the maximum space in between each wave so that there is minimal conflict in between them. Furthermore, 5 minutes adds to convenience as having a wave start at 12:12 p.m. would be a lot more confusing than one at 12:10 p.m.

Since the data set included people who had total times well above the average, we decided to only include data from the fastest 99% for the road closures. This made sure that our road closures did not have to stay open for an absurd amount of time. Ultimately, having a couple participants still running when roads open should not obstruct traffic nor create accidents.

According to our model, the roads only need to stay open for about 5 hours and 14 minutes. On top of this, according to Figures 4 and 5, we can see that the roads have a maximum congestion in a single kilometer of about 120 participants in the data of 3,217 participants. Given that our race is only 2,000 participants, we can assume that the maximum congestion would also be significantly lower. We made Figure 4 and 5 by assuming that each participant moves at a constant speed and using that to calculate how many participants would be in each kilometer at a given time.

Figure 1: Amount of Participants in Each Wave

Row Labels	Count of BIB NO.
ATH	20
CLY	37
F PREMIER	11
F PRO	4
F Wave 1	125
F Wave 2	161
F Wave 3	142
F Wave 4	131
M PREMIER	30
M PRO	4
M Wave 1	134
M Wave 2	124
M Wave 3	142
M Wave 4	144
M Wave 5	140
M Wave 6	131
M Wave 7	125
M Wave 8	138
M Wave 9	120
M Wave 10	137
Grand Total	**2000**

Figure 2: Wave Start Times

Category	Wave
M Pro	12:00:00 PM
F Pro	12:00:00 PM
M Premier	12:00:00 PM
F Premier	12:00:00 PM
M Wave 1	12:05:00 PM
M Wave 2	12:10:00 PM
M Wave 3	12:15:00 PM
M Wave 4	12:20:00 PM
M Wave 5	12:25:00 PM
M Wave 6	12:30:00 PM
M Wave 7	12:35:00 PM
M Wave 8	12:40:00 PM
M Wave 9	12:45:00 PM
M Wave 10	12:50:00 PM
F Wave 1	12:55:00 PM
F Wave 2	1:00:00 PM
F Wave 3	1:05:00 PM
F Wave 4	1:10:00 PM
ATH	1:15:00 PM
CLY	1:15:00 PM

Figure 3: Minimum Ages for Each Waves

Min. F. Age	Start	Min. M. Age	Start
0	F Wave 1	0	M Wave 1
31	F Wave 2	29	M Wave 2
38	F Wave 3	32	M Wave 3
47	F Wave 4	35	M Wave 4
		38	M Wave 5
		41	M Wave 6
		44	M Wave 7
		47	M Wave 8
		51	M Wave 9
		56	M Wave 10

KM	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
12:00:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:05:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:15:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:20:00	15	6	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:25:00	9	16	22	14	7	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:30:00	7	3	3	11	18	18	13	8	4	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:35:00	29	24	23	7	4	4	12	23	11	11	10	3	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:40:00	56	42	30	25	28	14	7	3	11	7	21	11	11	10	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:45:00	44	47	43	50	32	23	26	23	10	7	6	10	10	17	10	10	9	5	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:50:00	64	67	49	51	39	44	41	26	27	26	13	8	7	10	9	12	11	11	8	9	6	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:55:00	61	63	52	68	48	57	43	39	42	34	20	25	21	14	6	8	13	6	12	9	11	8	9	6	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
13:00:00	64	74	63	66	53	65	50	60	50	33	38	38	26	21	22	20	9	7	9	12	7	12	7	11	7	10	4	3	2	1	0	1	0	0	0	0	0	0	0	0
13:05:00	80	62	70	72	71	63	56	51	64	51	56	39	33	34	35	25	19	23	13	10	7	11	12	7	9	7	11	7	10	4	3	1	1	1	1	0	0	0	0	0
13:10:00	71	98	69	71	67	79	64	63	66	54	57	51	60	39	39	28	39	26	21	17	26	8	8	8	13	8	11	6	7	10	7	9	5	3	1	1	1	0	1	0
13:15:00	69	72	59	98	80	63	75	78	62	65	71	49	62	57	42	52	42	28	35	30	27	15	22	19	9	8	9	11	10	9	6	6	9	8	9	5	3	0	2	1
13:20:00	62	48	77	63	76	81	74	77	70	77	61	66	66	65	57	53	50	51	41	33	27	35	29	20	18	21	15	10	7	8	11	10	10	4	7	8	7	9	3	6
13:25:00	43	67	59	56	73	59	75	78	81	68	75	72	62	73	68	65	55	48	58	44	43	43	26	33	32	24	15	19	22	10	10	10	7	9	9	11	3	7	6	9
13:30:00	51	58	55	57	71	55	63	62	74	70	85	69	76	67	71	72	56	67	67	46	48	57	42	44	34	27	35	25	19	16	18	22	6	13	8	9	9	9	8	5
13:35:00	65	62	52	47	63	52	70	62	60	60	66	74	80	75	74	64	74	72	57	63	72	53	38	62	48	43	26	37	28	32	19	19	16	21	15	6	15	9	7	9
13:40:00	61	61	65	69	49	54	55	60	67	59	61	62	63	64	89	72	72	69	77	60	62	63	72	59	44	51	47	45	38	31	32	24	32	16	19	18	20	13	5	13
13:45:00	73	66	56	52	70	59	57	53	58	65	64	53	66	61	53	75	78	79	65	73	75	65	61	60	71	56	52	51	47	43	51	27	32	32	26	25	12	15	22	18
13:50:00	78	82	68	65	54	53	63	57	66	53	58	56	73	53	62	61	47	80	68	83	71	61	73	70	64	59	63	65	57	49	47	41	48	39	24	38	25	27	21	16
13:55:00	70	60	72	85	59	65	49	54	62	52	64	63	58	56	66	52	64	61	54	76	61	79	71	65	77	68	62	64	61	72	50	49	50	45	40	46	28	29	35	23
14:00:00	77	81	66	59	72	78	64	59	53	54	46	55	65	57	61	64	59	54	65	64	52	67	63	79	69	73	68	64	72	68	53	58	65	54	43	49	40	46	39	21
14:05:00	60	73	79	83	68	54	74	71	64	64	51	52	48	57	47	60	65	60	69	53	59	62	57	63	64	67	76	71	75	58	65	74	56	54	70	52	51	40	46	38
14:10:00	66	82	57	71	88	76	67	58	73	60	65	65	56	48	43	51	47	62	67	67	61	61	50	62	68	55	59	67	72	67	79	57	65	75	65	43	69	56	54	40
14:15:00	57	53	62	76	65	61	83	75	81	48	71	63	59	70	54	43	50	46	48	51	66	71	62	61	55	55	65	62	64	60	61	71	69	69	68	67	70	43	60	60
14:20:00	37	35	50	60	61	71	68	62	76	70	79	57	61	74	49	62	61	45	53	40	48	50	53	74	62	66	57	53	59	77	49	63	60	68	71	70	67	60	71	51
14:25:00	14	24	34	37	48	57	66	67	70	58	70	73	69	75	51	70	58	56	56	50	51	35	49	51	49	65	69	66	56	66	47	71	57	60	55	63	74	70	69	68
14:30:00	11	8	13	27	29	44	44	58	57	66	79	55	70	68	71	63	60	65	61	52	56	50	51	38	45	46	58	59	62	70	63	63	42	66	69	52	57	56	66	72
14:35:00	5	2	16	6	15	22	34	42	45	57	51	68	80	52	64	70	69	62	59	72	54	58	50	46	55	42	37	48	53	57	61	71	62	56	59	55	61	66	47	64
14:40:00	1	1	6	7	9	11	14	21	34	45	44	51	51	70	82	49	59	67	65	60	66	70	54	60	47	46	57	36	42	46	54	57	55	64	69	58	54	65	42	80
14:45:00	0	0	2	2	6	9	8	12	16	21	36	40	46	46	52	68	77	53	57	57	76	50	68	69	61	57	46	40	50	53	39	37	53	58	57	62	62	62	57	50
14:50:00	0	0	0	1	2	2	10	10	6	11	17	25	27	48	42	43	55	62	77	52	62	56	70	49	57	72	64	55	47	46	46	56	32	41	52	57	55	54	63	65
14:55:00	0	0	0	0	1	1	2	4	9	8	8	12	18	24	31	43	47	39	56	58	75	51	53	66	64	51	57	67	64	51	56	41	46	53	37	46	40	63	56	48
15:00:00	0	0	0	0	0	1	0	3	2	8	5	9	7	16	15	24	33	43	46	40	55	51	73	55	53	62	56	58	51	63	67	54	55	42	43	52	45	42	43	56
15:05:00	0	0	0	0	0	0	1	0	3	1	5	6	6	8	12	15	12	28	33	39	48	45	48	49	66	60	49	66	53	54	53	53	71	53	57	45	40	48	44	47
15:10:00	0	0	0	0	0	0	0	1	0	1	3	4	5	6	3	8	13	15	16	24	38	38	42	53	38	51	62	65	41	66	55	53	55	47	68	53	56	51	37	44
15:15:00	0	0	0	0	0	0	0	0	0	1	0	3	2	5	5	5	5	7	18	11	17	29	35	40	41	42	44	53	58	60	44	62	54	49	60	46	55	66	54	46
15:20:00	0	0	0	0	0	0	0	0	0	0	1	0	3	2	3	6	3	6	3	11	17	9	25	27	32	40	47	36	38	54	56	59	49	50	60	51	49	56	50	64
15:25:00	0	0	0	0	0	0	0	0	0	0	0	1	0	1	4	1	4	6	3	5	4	12	16	12	24	27	34	42	44	34	41	49	54	56	50	47	63	53	43	55
15:30:00	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	0	4	5	3	5	3	4	16	12	19	19	32	30	48	38	35	35	53	50	56	50	44	55	54
15:35:00	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	1	3	3	6	3	3	3	8	13	12	22	19	32	29	50	37	33	35	53	42	56	55	40
15:40:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	3	3	2	7	1	3	4	3	7	16	14	21	17	36	31	50	35	29	34	54	32	58
15:45:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	1	5	2	6	1	2	5	4	7	18	17	17	22	33	34	44	34	30	34	48
15:50:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	3	1	4	1	8	0	3	2	3	8	9	13	22	17	26	28	35	44	34	33
15:55:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	1	5	1	3	5	0	3	4	3	7	13	15	18	18	28	26	39	43
16:00:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	1	3	2	3	6	0	3	1	3	5	7	14	14	24	16	30	25
16:05:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	3	2	3	2	4	3	0	4	1	3	8	8	12	16	20	21
16:10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	1	5	2	2	5	0	3	1	2	3	8	14	11	14
16:15:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	1	2	4	3	3	2	1	3	1	2	6	6	14
16:20:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	1	2	4	2	1	5	0	2	2	2	1	8
16:25:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	3	3	2	2	3	2	1	3	0	3
16:30:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	3	1	4	2	1	3	1	2	2
16:35:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	3	0	4	3	0	3	2	2
16:40:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	1	2	3	2	2	1	3
16:45:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	2	2	1	3	3	0
16:50:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	2	2	1	3	2
16:55:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	2	1	2	3
17:00:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	2	2
17:05:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	2
17:10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1
17:15:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
17:20:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
17:25:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 4: Bike Congestion: Kilometers vs. Time

Bicycle course density heatmap illustrating how athlete concentrations vary across both time and distance along the 40-km cycling leg. Warmer colors (yellow–red) indicate periods and locations of peak congestion, while green regions indicate lighter traffic. This visualization supports wave-start and course-spacing decisions aimed at reducing bottlenecks and maintaining safe race conditions.

KM	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00	5.25	5.50	5.75	6.00	6.25	6.50	6.75	7.00	7.25	7.50	7.75	8.00	8.25	8.50	8.75	9.00	9.25	9.50	9.75
13:00:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:05:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:15:00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:20:00	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:25:00	7	1	3	3	1	0	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:30:00	2	5	8	2	3	4	3	2	4	2	0	0	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:35:00	6	5	3	5	3	3	4	4	6	1	5	3	2	1	5	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13:40:00	5	5	4	5	7	5	3	4	3	3	3	5	3	5	3	4	3	2	1	3	4	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
13:45:00	6	10	7	10	10	1	5	8	3	5	7	1	5	2	5	0	5	4	5	3	4	1	4	1	0	4	3	0	0	1	0	1	0	1	0	0	1	0	0	0
13:50:00	8	15	19	7	9	8	11	6	10	5	4	4	6	4	3	5	5	3	2	4	1	4	5	4	1	7	1	4	0	1	3	2	2	0	0	1	0	1	0	1
13:55:00	21	18	13	20	5	11	18	10	10	4	15	4	7	7	3	4	6	5	3	4	4	6	2	0	6	1	3	5	3	3	4	4	2	2	0	1	4	1	2	0
14:00:00	25	23	17	18	23	14	18	14	10	12	12	13	11	4	13	6	6	6	3	5	5	3	7	2	6	2	4	3	1	4	3	1	5	2	4	5	3	2	3	0
14:05:00	37	33	42	22	26	21	18	19	14	19	15	15	11	11	12	13	7	8	12	8	4	6	4	3	8	3	4	4	2	6	2	4	3	1	4	3	1	4	3	4
14:10:00	47	45	30	47	31	40	29	21	26	22	16	18	14	20	16	12	13	9	10	12	10	9	11	9	3	5	5	2	5	5	5	4	3	4	4	3	4	2	1	4
14:15:00	43	47	56	43	42	34	46	34	35	36	29	17	30	17	19	16	12	18	16	16	10	10	9	11	11	10	11	8	5	4	6	2	4	3	5	6	3	2	5	3
14:20:00	54	50	42	55	50	47	42	42	45	46	36	31	33	29	30	22	17	18	22	13	21	14	15	14	13	9	6	11	12	10	11	8	7	4	4	4	4	2	2	8
14:25:00	50	54	49	56	51	53	50	42	52	40	41	46	47	39	30	29	37	26	32	20	13	22	20	12	21	14	15	9	17	9	4	10	14	8	13	10	4	5	4	4
14:30:00	57	49	56	56	56	42	59	55	49	46	46	50	44	35	46	46	43	35	28	32	29	31	24	26	10	21	17	15	20	17	13	9	17	9	6	7	10	13	11	12
14:35:00	41	57	51	56	54	54	43	53	50	49	50	59	49	39	54	38	39	40	44	49	40	32	29	35	24	32	20	21	18	15	16	17	17	18	14	12	13	9	7	7
14:40:00	47	44	50	43	49	59	51	56	46	52	43	43	60	46	52	57	41	48	39	41	37	45	45	53	27	25	33	34	27	26	19	22	18	15	14	15	17	21	11	14
14:45:00	62	41	43	50	50	39	41	48	61	46	57	55	47	41	45	48	57	39	59	44	51	36	41	38	43	47	40	41	30	29	28	32	32	17	21	23	21	9	17	16
14:50:00	39	53	50	61	52	39	48	49	41	43	45	58	40	49	64	50	44	40	44	46	54	47	50	48	43	32	43	38	42	51	32	40	27	28	34	31	23	19	21	27
14:55:00	51	39	34	40	49	55	57	42	45	47	42	53	40	47	50	50	46	56	46	55	35	41	43	44	51	58	42	48	42	31	35	39	49	42	31	37	31	24	33	31
15:00:00	41	45	47	43	46	39	39	50	52	46	49	52	31	48	50	47	48	49	40	51	48	49	59	38	43	41	39	44	48	53	45	45	40	32	37	33	43	45	31	37
15:05:00	64	47	40	32	48	48	40	46	40	50	45	45	46	39	56	34	44	48	51	52	47	42	43	51	48	47	53	34	42	43	45	40	49	49	39	46	34	36	40	29
15:10:00	32	41	43	59	51	40	34	45	49	39	41	49	47	41	39	51	36	53	40	38	43	61	51	48	37	51	41	57	37	52	41	36	46	50	31	37	57	44	43	38
15:15:00	32	36	39	29	40	41	48	54	44	36	41	46	43	48	46	48	40	34	51	39	50	40	39	44	44	55	49	46	46	44	45	45	46	44	40	39	43	47	33	45
15:20:00	35	34	34	38	35	37	41	29	35	42	55	42	46	41	42	46	46	44	46	40	32	53	36	46	38	44	43	42	51	54	44	47	45	41	46	47	45	43	40	37
15:25:00	23	23	43	32	33	33	38	30	46	32	32	33	43	42	45	46	45	41	55	43	40	41	40	44	39	42	39	46	40	44	42	44	52	48	55	36	40	48	46	41
15:30:00	23	20	26	21	25	37	35	32	38	31	34	39	38	30	32	35	43	49	41	44	53	48	39	44	37	39	40	44	41	33	53	39	41	40	45	47	45	48	52	37
15:35:00	28	24	23	22	19	21	23	29	33	36	29	38	33	36	32	35	33	30	41	40	36	44	50	58	39	44	45	37	34	43	44	30	38	47	43	46	33	48	44	46
15:40:00	22	16	27	24	24	21	20	23	19	27	26	24	38	36	36	34	32	30	26	46	29	32	43	34	52	46	48	46	44	36	45	34	37	44	27	39	43	52	40	36
15:45:00	17	22	18	23	20	25	22	21	21	25	18	24	22	27	29	37	32	36	34	27	33	28	36	39	26	41	41	41	59	33	49	44	34	46	35	41	44	27	37	32
15:50:00	12	16	18	18	16	18	24	20	27	24	14	22	26	17	25	24	20	34	33	40	29	32	27	29	34	32	35	34	40	33	46	51	43	41	47	36	38	40	39	39
15:55:00	11	8	10	13	14	22	14	15	19	26	16	32	19	16	25	20	24	20	24	20	39	27	36	31	33	29	25	35	33	32	35	41	32	43	43	53	35	35	43	46
16:00:00	2	9	9	12	9	10	12	16	16	19	17	20	22	19	27	19	17	26	18	22	24	22	20	38	27	39	26	33	28	27	33	32	31	38	40	35	32	49	43	38
16:05:00	1	3	3	6	10	9	9	9	13	14	16	15	14	20	19	23	20	25	15	18	30	20	13	30	19	28	34	28	30	30	31	29	26	30	30	36	43	34	32	34
16:10:00	1	2	1	2	4	4	9	10	6	8	9	18	15	10	15	15	22	22	16	24	24	10	26	23	24	12	21	31	25	32	29	21	37	31	26	24	33	28	38	43
16:15:00	1	1	0	3	1	3	2	4	6	9	9	6	9	12	16	11	11	22	10	23	22	12	27	20	13	24	27	22	14	18	34	25	29	23	26	34	33	29	21	27
16:20:00	1	3	1	0	1	2	2	3	1	4	5	7	9	6	7	11	16	13	5	16	21	14	18	22	15	25	17	19	22	27	20	18	20	27	28	23	29	23	29	35
16:25:00	0	1	0	4	1	0	0	3	0	4	2	4	2	7	9	6	8	5	16	14	7	8	22	18	15	20	14	20	21	23	16	22	27	18	22	19	25	24	26	30
16:30:00	2	2	0	0	2	1	2	1	0	2	2	2	2	3	4	7	6	6	7	7	8	19	8	9	11	17	21	12	19	21	14	24	20	22	20	20	26	19	21	17
16:35:00	2	2	0	1	1	0	2	1	1	2	1	1	2	1	3	1	6	3	9	5	7	7	8	10	15	6	10	15	20	12	18	20	17	15	22	23	21	15	28	21
16:40:00	0	0	2	2	0	1	1	0	2	1	1	2	1	2	0	2	3	2	2	4	8	6	7	6	5	11	11	13	7	13	16	17	6	26	20	12	18	21	20	22
16:45:00	2	1	0	0	2	2	0	1	1	0	2	1	1	1	2	2	0	1	4	2	2	3	6	6	8	6	6	8	8	13	10	11	12	15	11	18	21	16	14	17
16:50:00	0	1	1	2	0	0	2	2	0	1	0	1	2	1	1	1	2	2	0	1	3	3	2	2	5	8	5	7	7	4	11	6	10	13	12	14	15	9	23	16
16:55:00	0	0	1	1	2	1	1	0	3	1	0	1	0	1	2	0	1	2	2	0	2	1	3	3	2	1	5	8	5	4	7	7	8	7	8	13	13	11	12	14
17:00:00	0	1	0	0	1	1	1	1	2	0	3	1	0	1	0	1	2	0	1	2	2	0	1	3	2	2	2	1	4	6	7	5	5	9	5	10	4	9	15	10
17:05:00	1	0	0	1	0	0	0	2	1	1	0	1	3	2	0	1	0	1	2	0	1	3	1	0	1	2	3	2	1	2	5	4	7	3	5	6	10	8	7	3
17:10:00	0	1	0	1	0	1	0	0	0	2	1	1	0	1	3	1	0	2	0	1	2	0	0	4	1	0	2	1	2	3	0	3	4	5	5	5	2	5	11	7
17:15:00	0	0	0	1	0	1	0	1	0	0	0	3	0	1	0	2	2	1	0	1	0	1	3	0	1	2	2	0	2	1	3	0	2	2	5	3	5	5	3	3
17:20:00	0	0	0	0	1	0	0	1	0	1	0	0	0	2	1	1	0	1	3	1	0	1	0	2	0	1	2	0	4	0	2	1	3	0	1	4	3	3	6	4
17:25:00	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	2	1	1	0	1	3	1	1	0	0	2	0	0	2	0	5	1	1	1	2	1	1	3	2	3
17:30:00	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	2	0	2	0	1	2	2	1	0	0	2	0	2	0	0	4	1	1	2	1	2	2	1
17:35:00	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	2	0	2	0	1	2	2	1	0	1	1	0	1	1	0	4	1	1	1	1	3
17:40:00	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	2	0	1	2	0	2	2	1	0	1	1	1	0	1	1	2	2	1	1
17:45:00	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	2	0	1	2	0	2	1	2	0	1	1	1	0	1	2	1	2
17:50:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	2	0	1	2	0	2	1	2	0	1	2	0	0	0	3
17:55:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	2	0	1	1	1	2	1	1	1	1	2	0	0
18:00:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	2	0	2	0	1	2	1	1	1	3	0
18:05:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	2	0	2	0	0	3	1	1	0
18:10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	1	0	1	1	0	3	1
18:15:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	1	0	1	1	0
18:20:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	1	0	1
18:25:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	1
18:30:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0

Figure 5: Running Congestion: Kilometers vs. Time

Running course density heatmap illustrating how athlete concentrations vary across both time and distance along the 10-km running leg. Warmer colors (yellow–red) indicate periods and locations of peak congestion, while green regions indicate lighter traffic. This visualization supports wave-start and course-spacing decisions aimed at reducing bottlenecks and maintaining safe race conditions.

Part 2:

To evaluate how modifying the distances of the triathlon legs would impact course congestion and road-closure time, we adjusted our model to test proportional and non-proportional changes in the swim, bike, and run segments. Because athletes are modeled with constant speeds for each leg, uniformly scaling all three distances (for example, increasing or decreasing the total race length by the same percentage) preserves relative timing between participants. In that case, congestion patterns remain nearly identical, though the overall race duration—and therefore total road-closure time—changes proportionally.

However, changing one leg independently produces non-uniform effects. Extending the swim length delays when athletes reach the bike segment, slightly reducing early bike congestion by spreading out arrivals at the first transition. In contrast, shortening the swim compresses start-to-bike intervals and increases early crowding on the bike course. Adjusting the bike or run distances alters road-closure time more directly: a longer bike leg increases total closure duration and raises fatigue-driven variability among participants, which can smooth peaks but extend course usage; shortening it does the opposite.

Based on these observations, modest adjustments to individual leg lengths can be used strategically. For instance, a slightly longer swim or earlier wave timing for slower divisions can reduce mid-race overlap without violating the 5.5-hour road-closure limit. Overall, distance changes offer limited gains compared to optimizing wave size and spacing, which remain the most effective levers for managing congestion.

Sensitivity Analysis

Wave Gap (min)	Peak Bike Density	Peak Run Density	Road Closure (hrs)
0:03	173	84	4:46:52
0:04	140	71	4:59:22
0:05	118	64	5:13:51
0:06	100	71	5:27:06
0:07	98	59	5:39:38

(Note this data is not scaled to the 2000 person race).

To determine the optimal spacing between wave start times, we conducted a sensitivity analysis by varying the wave gap from 3 to 7 minutes and recalculating both peak course congestion and total road-closure time for each scenario. Shorter wave gaps, such as 3 and 4 minutes, resulted in high peak bike densities of 173 and 140 athletes per kilometer, respectively, which would likely cause crowding and impede faster cyclists. Increasing the wave gap reduced congestion: at a 5-minute gap, peak bike and run densities decreased to 118 and 64 athletes per kilometer, respectively, while still maintaining a total road-closure duration of approximately 5 hours and 14 minutes—within the required 5.5-hour limit. Gaps longer than 5 minutes continued to reduce congestion slightly but pushed road-closure times closer to or beyond the upper constraint (e.g., 5:39:38 at a 7-minute gap). Therefore, a 5-minute wave gap provides the best balance between minimizing congestion and satisfying the road-closure requirement.

Implications

As our model accounts for over 3,000 participants, we know that our model can safely keep the total road closure period under the 5.5-hour limit. This means that even if the amount of participants is slightly above the 2,000 expected, we would be able to safely account for them without needing to adjust. Similarly, since our model uses past data and only scales the wave counts, we can reuse it for future races and different amounts of expected participants with little changes. Furthermore, as seen in Figure 4 and 5 in the presentation of our model, we know that our model can handle the projected number of participants without overcrowding, even at maximum density. Additionally, our decision to keep the individual data rather than using averages preserves the natural variability that occurs in a race and allows us to predict which areas and times may have the most congestion.

Strengths

1. Amount of people per kilometer (congestion) is low

   The model has relatively small congestion which makes the triathlon race maintain a smooth and efficient flow.

2. Mostly evenly split waves

   Most of the waves are even, preventing a certain wave from having significantly larger congestion than other waves. Additionally, it makes the race fairer and more efficient.

3. Under 5.5-hour road closure

The total time needed for road closure predicted by our model is under 5.5 hours, giving the participants plenty of time to complete the triathlon. Even if a participant is a little bit out of the average completion time, they can still have some leeway to finish within the road closure period.

4. Set up in a way that makes it easy to change data

   Our model depends on equations and relationships between values, resulting in versatile excel tables that can be easily changed for different distances for travel or checking congestion.

5. Congestion stays the same no matter how the distance of the triathlon changes

   Because all speeds and distances are scaled proportionally, the spacing between participants remains constant. Thus, overall congestion levels do not depend on race length.

Limitations

1. 99% significance and does not consider slowest one percent

   Our model neglects the completion of very slow outsiders that were neglected from the data, preventing the distortion of a slow time in our road closure calculation.

2. Limited data set

   The model is based on a restricted sample, so participants may not generally perform the same way as the athletes we analyzed in our data analysis to determine starting times.

3. Not all ratios will be consistent

   Participation of the people in the given data set may not represent the true ratios. This means that we are only getting a close but not accurate model.

Conclusion

In conclusion, we analyzed the congestion in triathlons which revealed that brief mid-course crowding occurred during the busiest part of the event. The overall wave design successfully balanced safety, efficiency, and course usage by considering road closure time and congestion. To organize the waves of people, the athletes were split by categories of status, gender, and age. This structure ensured fair competition and smooth transitions between stages of the race. By coordinating start times strategically, the event minimized overlap between faster and slower groups, further enhancing the overall flow and experience. In the future, more data will be analyzed to make a more comprehensive schedule.

Non-technical Document

Dear Mayor,

As the race organizers of the upcoming triathlon, we have analyzed data from previous triathlons that contained upwards of 3,000 participants to determine how to best organize the race. While constructing our model, we prioritized keeping race congestion to a minimum, having this event be one that is friendly to racers of all levels, and making sure that your town's roads will only stay closed for an absolute maximum of five and a half hours during the running and biking portion of the triathlon.

This event will be hosting 2,000 participants. We decided to put all the pro and premier athletes into the same wave as there were not enough of either to justify separating them into their own waves. Similarly, the Athenas and Clydesdales were also combined into one wave. Since the open categories had hundreds of participants in them, we decided they should be split up to make sure that each wave would have under 150 participants with one exception in F Wave 2 as seen in Figure 1.

The order of the waves is seen in Figure 2. This shows that the faster statuses go before the slower statuses; pros and premiers are first, then the opens, and then finally the Clydesdales and Athenas. The opens, which were too big for one wave, were then split up by age and gender, with the younger participants being in the earlier waves and the older participants being in the later waves, and the males before the females as seen in Figure 3. This general order of fastest to slowest is intentional, as it is to make sure that everyone had an enjoyable time; the faster people would not be impeded or hindered by slower racers in their way, while slower participants would not feel pressured by faster travelers.

We decided on 5 minutes in between each wave as that made the total road closure closest to 5.5 hours while also giving space in between each wave so that there is minimal conflict between them. Furthermore, 5 minutes adds to convenience as having a wave starting at 12:10 p.m. would be less confusing than one that starts at 12:12 p.m.

Since the data set included people who had total times well above average, we decided to only include data from the fastest 99% for the road closures. This made sure that our road closures did not have to stay open for an absurd amount of time. Ultimately, having a couple of participants still running when roads open should not obstruct traffic nor create accidents.

According to our model, of this scheduling, your town's roads only need to stay open for about 5 hours and 14 minutes. On top of this, our models show that roads will have a maximum congestion in a single kilometer of about 120 participants in the data of 3,217 participants. Given that our race is only 2,000 participants, we can assume that the maximum congestion would also be significantly lower.

To make this event appealing to people of all skill levels and divisions, we will be providing awards will be given to all waves independently and special awards will be provided to the top 3 overall male and female racers. Attached below is our outlined race schedule and age groups for waves of the open division.

Category	Wave
M Pro	12:00:00 PM
F Pro	12:00:00 PM
M Premier	12:00:00 PM
F Premier	12:00:00 PM
M Wave 1	12:05:00 PM
M Wave 2	12:10:00 PM
M Wave 3	12:15:00 PM
M Wave 4	12:20:00 PM
M Wave 5	12:25:00 PM
M Wave 6	12:30:00 PM
M Wave 7	12:35:00 PM
M Wave 8	12:40:00 PM
M Wave 9	12:45:00 PM
M Wave 10	12:50:00 PM
F Wave 1	12:55:00 PM
F Wave 2	1:00:00 PM
F Wave 3	1:05:00 PM
F Wave 4	1:10:00 PM
ATH	1:15:00 PM
CLY	1:15:00 PM

Min. F. Age	Start	Min. M. Age	Start
0	F Wave 1	0	M Wave 1
31	F Wave 2	29	M Wave 2
38	F Wave 3	32	M Wave 3
47	F Wave 4	35	M Wave 4
		38	M Wave 5
		41	M Wave 6
		44	M Wave 7
		47	M Wave 8
		51	M Wave 9
		56	M Wave 10

References

1. Wu, S. S., Peiffer, J. J., Brisswalter, J., and K. Nosaka. “Factors Influencing Pacing in Triathlon.” Open Access Journal of Sports Medicine, vol. 5, 2014, pp. 223–234. PubMed Central, https://doi.org/10.2147/OAJSM.S44392.
2. Knechtle, Beat, et al. “Performance and Pacing of Professional IRONMAN Triathletes.” Scientific Reports, vol. 13, no. 1, 2023, pp. 1–13. Nature Publishing Group, https://doi.org/10.1038/s41598-023-28960-2.
3. Etxebarria, Naroa, et al. “Training and Competition Readiness in Triathlon.” Sports, vol. 7, no. 7, 2019, article 162. MDPI, https://doi.org/10.3390/sports7070162.
4. “Organising a Triathlon: The Essential Steps.” Weezevent Blog, 2024, https://weezevent.com/en-ca/blog/organising-a-triathlon-the-essential-steps/.
5. “Triathlon Race Day Tips.” REI Expert Advice, REI Co-op, 2025, https://www.rei.com/learn/expert-advice/triathlon-race-day-tips.html.
6. “6 Best Practices for Creating Event Day Schedules.” Run Sheets Blog, Run-Sheets.com, 2025, https://run-sheets.com/blog/6-best-practices-for-creating-event-day-schedules/

AI Use Report