SUPPLEMENTAL MATERIAL

Optimizing a drone network to deliver automated external defibrillators

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Supplemental Methods

Geocoding Procedure

The location of each OHCA episode was provided as either an address or a latitude/longitude pair. For all entries without latitude/longitude information, geocoding was used to convert the recorded addresses into latitude and longitude coordinates. We used Geocoder.ca, Google Maps API, and manual methods for our conversions. To verify the geocoding accuracy, all OHCAs were geographically plotted by region and manually inspected. Figure S1 summarizes our geocoding procedure. All ambulance, fire, and police stations were provided as addresses and manually converted to a latitude/longitude pair. Finally, all latitudes and longitudes were analytically converted to Universal Transverse Mercator (UTM) coordinates for input to the optimization model. Figure 2 in the main text shows the locations of all geocoded OHCAs, ambulance stations, fire stations, and police stations.

Optimization Model

The mathematical model we use to determine the number and location of drone bases is outlined below.

Overview

To begin our optimization process, the user selects a threshold value for improvement over the historical median 911 response time. In particular, we consider three different threshold values for improvement (one, two, and three minutes). We then use an iterative process to determine values for *f* and *t* that yield a drone network configuration that exceeds the chosen threshold. In each iteration, we solve the model outlined below with fixed *f* and *t* (and therefore fixed R and a_{ij}).

Model parameters

- f is a parameter that indicates the percentage of covered cardiac arrests.
- t is a parameter that indicates the maximum drone flying time.
- The coverage radius is given by $R = (t\text{-}d\text{-}10)*27.8$, for $t\text{-}d > 10$ seconds, where d represents the average dispatch time. Recall that accounting for maximum speed and height, 10 seconds are required for takeoff and landing.
- a_{ij} is a binary data parameter that indicates whether OHCA j can be covered by location i. To determine a_{ij}, we first compute the distance (in meters) between each OHCA and each ambulance, fire, and police station. If the distance is less than or equal to R, then $a_{ij} = 1$, else $a_{ij} = 0$.
- I is the number of ambulance, fire, and police stations (i.e., candidate drone bases).
- J is the number of OHCAs in the training set.

Decision variables

- z_{ij} is a binary variable indicating whether OHCA j is covered by a drone base at location i.
- y_i is a binary variable indicating whether a drone base is stationed at location i.

$$
\begin{aligned}
\text{Minimize} \quad & \textstyle\sum_{i=1}^{I} y_i \\
\text{Subject to} \quad & \textstyle\sum_{i=1}^{I} z_{ij} \le 1, \forall\, j = 1, \dots, J, \\
& \textstyle\sum_{i=1}^{I} \sum_{j=1}^{J} z_{ij} \ge \left(\frac{f}{100}\right) \times J\,, \\
& z_{ij} \le a_{ij} y_i, \forall j = 1, \dots, J, i = 1, \dots, I, \\
& z_{ij} \epsilon \{0,1\}, \forall\, j = 1, \dots, J, i = 1, \dots, I, \\
& y_i \epsilon \{0,1\}, \forall\, i = 1, \dots, I.
\end{aligned}
$$

The objective function minimizes the total number of drone bases. The first constraint ensures that each OHCA is assigned to at most one drone base to avoid double-counting, while the second constraint ensures that *f*% of all OHCAs are reached within a maximum time of *t* minutes. The third constraint ensures that OHCA j can be covered by a drone base i only if a base is opened at location i and that base is able to cover OHCA j (i.e., $a_{ij} = 1$). The fourth and fifth constraints force the decision variables to be binary. The input cardiac arrest data for this model is the training set of OHCAs.

Queuing Model

The mathematical model we use to determine the number of drones stationed at each base is outlined below.

Each selected drone base (i.e., each i such that $y_i = 1$) has a catchment area defined by its radius at the macro level, but more precisely by the cardiac arrests the base is assigned to cover (i.e., those j such that $z_{ij} = 1$).

For each catchment area we assume that a Poisson process with an OHCA arrival rate of λ_i governs the occurrences of OHCAs. To determine λ_i, we first find the number of daytime (8:00AM to 7:59PM) training set OHCAs occurring in catchment area i. Next, we determine the duration, in months, over which these OHCAs occurred. Finally, we multiply the number of daytime training set OHCAs by two and divide by the duration over which they occurred. Table S1 shows the average OHCA arrival rate for each region.

For each region, we assume that the "busy" time is an exponentially distributed random variable with rate parameter μ. The busy time comprises the outbound travel time, on-scene time, inbound travel time, and "reset" time. We compute the mean busy time $1/\mu$ for each region and for each problem instance (i.e, each (t, f) pair).

Given the optimal drone base locations, as determined by the optimization model with user inputs t and f, we first determine the outbound and inbound travel time, which we assume to be equal. For each OHCA in the training set, we determine the straight line distance to the closest drone base and we use the assumed drone flying speed of 27.8m/s (plus 10 seconds for acceleration/deceleration and cruising altitude assumptions) to compute the travel time.

The on-scene time, referring to the interval from drone landing to paramedic arrival at patient side, was computed using historical data. To determine the on-scene time, we first compute the drone response time, defined as the time interval from call arrival to drone landing. Next, we determine the historical 911 time-to-patient side, defined as the time interval from call arrival to arrival at patient side. We then compute the difference to determine the on-scene time. If the difference is negative (i.e., 911 arrives before the drone), the on-scene time is assumed to be zero because the drone would turn around mid-flight. Table S1 shows the average scene time for each region, along with the average flight time, on-scene time, and assumed 30 minute reset time.

To model system congestion, we consider each drone base as a multi-server queue with m servers. Given Poisson arrivals and exponentially distributed busy times, we can represent the queuing system as a continuous-time Markov Chain (CTMC). Let S={0,1,2…} denote the state space, where the state number refers to the number of calls in the system. Let $\rho = \frac{\lambda}{m\mu} < 1$ and let π^k denote the steady-state amount of time spent in state k, which we determined from solving the well-known, steady-state equations (Kleinrock 1975):

$$\pi_0 = \left[\sum_{k=0}^{m-1} \frac{(mp)^k}{k!} + \frac{(mp)^m}{m!} * \frac{1}{1-p}\right]^{-1}$$

$$\pi_k = \begin{cases} \frac{m^k p^k \pi_0}{i!}, k = 1,2, \dots, m-1 \\ \frac{m^m p^k \pi_0}{m!}, k = m, m+1, \dots \end{cases}$$

To determine the number of drones (i.e., *m*), we use an iterative process that increases *m* until the probability that at least one drone is available when an OHCA occurs is greater than 0.99. More specifically, we increase *m* until $\pi_0 + \sum_{k=1}^{m-1} \pi_k \geq 0.99$. We repeat this process for each catchment area.

Experimental Setup

For each region, the OHCA data was split into two disjoint sets: a training set and a testing set. The training set was used as the input into our optimization model to determine the number and location of bases. The training set was also used as input to the queuing model to determine the arrival rate and busy times, which result in the required number of drones per base. The disjoint testing set was used to evaluate the performance of the resulting drone networks. In particular, we use the testing set OHCAs to compute the improvement in time to AED metrics, drone response time distributions, and the proportion of cases where the drone AED arrived prior to 911 responders.

Supplemental Tables

Supplemental Table 1. Summary of drone busy time and its components.

		Drone response time improvement goal	Region								
			Toronto	Durham	Simcoe	Muskoka	Peel	Hamilton	Halton	York	All
Region-specific	Flight time (minutes)	1 min.	7.37	11.17	11.19	12.12	7.61	9.99	8.93	10.36	9.84
		2 min.	5.06	7.59	8.05	10.92	5.96	7.28	7.79	7.85	7.56
		3 min.	3.45	4.63	5.86	8.87	3.99	4.02	4.87	5.91	5.20
	On-scene time (minutes)	1 min.	5.27	4.52	5.27	7.70	5.12	4.71	5.02	5.07	5.33
		2 min.	6.35	5.76	6.56	8.15	5.89	5.90	5.59	5.90	6.26
		3 min.	7.15	6.85	7.60	9.03	6.85	7.48	6.93	6.85	7.34
	Reset time (minutes)	1 min.	30	30	30	30	30	30	30	30	30
		2 min.	30	30	30	30	30	30	30	30	30
		3 min.	30	30	30	30	30	30	30	30	30
	Drone busy time (minutes)	1 min.	42.64	45.68	46.46	49.81	42.72	44.71	43.95	45.43	45.18
		2 min.	41.42	43.34	44.60	49.07	41.86	43.18	43.38	43.75	43.83
		3 min.	40.60	41.48	43.46	47.91	40.84	41.50	41.79	42.77	42.54
Integrated	Flight time (minutes)	1 min.	7.24	11.14	16.33	63.74	7.53	8.19	11.95	9.88	17.00
		2 min.	5.38	7.17	7.21	32.75	6.01	5.81	5.86	6.71	9.61
		3 min.	3.54	7.34	9.15	67.77	4.39	4.11	4.49	5.79	13.32
	On-scene time (minutes)	1 min.	5.85	4.11	4.62	0.39	4.91	5.46	3.93	4.82	4.26
		2 min.	6.76	5.45	7.05	2.62	5.58	6.59	6.29	5.99	5.79
		3 min.	7.67	5.80	6.53	0.32	6.42	7.44	6.97	6.56	5.96
	Reset time (minutes)	1 min.	30	30	30	30	30	30	30	30	30
		2 min.	30	30	30	30	30	30	30	30	30
		3 min.	30	30	30	30	30	30	30	30	30
	Drone busy time (minutes)	1 min.	43.09	45.25	50.95	94.13	42.44	43.65	45.87	44.71	51.26
		2 min.	42.14	42.62	44.25	65.37	41.59	42.40	42.15	42.70	45.40
		3 min.	41.21	43.13	45.68	98.09	40.81	41.54	41.46	42.34	49.28

The “All" column represents all of RescuNet (i.e., all eight regions combined). The flight time comprises both the outbound and inbound times. The drone busy time is the summation of flight time, on-scene time, and reset time.

Supplemental Table 2. The annual number of OHCAs and annual median time intervals for various 911 response time metrics.

	Year	Region								
		Toronto	Durham	Simcoe	Muskoka	Peel	Hamilton	Halton	York	All
Number of OHCAs	2006	2237	500	334	66	124	474	-	-	3735
	2007	2769	516	395	74	704	501	-	-	4959
	2008	2975	561	325	65	847	502	234	-	5509
	2009	2997	536	366	88	920	551	337	-	5795
	2010	3030	569	460	59	936	606	339	608	6607
	2011	2924	588	493	79	970	381	366	600	6401
	2012	3121	591	539	84	989	464	408	640	6836
	2013	3375	624	525	71	1029	226	391	705	6946
	2014	3365	647	526	73	1114	-	412	777	6914
	All	26793	5132	3963	659	7633	3705	2487	3330	53702
Dispatch time (i.e., the interval from call arrival at 911 to asset mobilization)	2006	1:26	0:45	0:58	0:17	1:00	1:00	-	-	1:04
	2007	1:35	0:32	0:45	0:24	1:00	1:00	-	-	1:11
	2008	1:37	0:31	1:00	0:22	1:00	1:00	1:00	-	1:07
	2009	1:39	0:34	1:00	0:24	0:49	1:00	1:00	-	1:05
	2010	1:37	0:35	1:00	0:22	0:47	1:00	1:00	0	1:00
	2011	1:36	1:00	1:00	0:20	0:47	1:00	1:00	1:00	1:00
	2012	1:30	1:00	1:00	0:19	0:42	1:00	0:42	0:33	1:00
	2013	1:31	1:00	1:00	0:12	0:43	1:00	0:39	0:31	1:00
	2014	1:34	1:00	1:00	0:19	0:21	-	0:37	0:31	1:00
	All	1:34	0:39	1:00	0:20	0:45	1:00	0:51	0:32	1:00
Response time (i.e., the interval from call arrival at 911 to arrival at the scene)	2006	5:44	5:18	7:33	9:48	5:50	6:00	-	-	5:55
	2007	5:59	5:11	7:18	7:29	5:46	6:00	-	-	6:00
	2008	6:03	5:30	7:00	7:29	6:00	6:00	6:00	-	6:00
	2009	6:05	5:33	7:00	8:37	5:46	6:00	6:00	-	6:00
	2010	6:27	5:29	7:00	8:09	5:44	5:30	6:00	7:00	6:02
	2011	6:28	6:00	8:00	7:51	5:34	6:00	6:09	7:00	6:04
	2012	6:21	5:34	7:00	9:57	5:41	6:00	6:00	6:35	6:04
	2013	6:17	5:50	7:00	7:23	5:44	6:00	5:49	6:32	6:04
	2014	6:24	6:00	7:00	7:00	5:16	-	6:21	6:35	6:08
	All	6:12	5:33	7:00	8:00	5:41	6:00	6:00	6:44	6:00
Patient time (i.e., the interval from call arrival at 911 to arrival at the patient	2006	10:01	8:40	10:29	14:49	10:09	8:52	-	-	9:49
	2007	9:57	9:07	10:33	10:01	9:22	9:00	-	-	9:44
	2008	9:40	9:13	11:00	9:56	9:24	10:00	10:31	-	9:49
	2009	9:40	8:38	9:40	13:05	8:52	11:00	10:29	-	9:39
	2010	9:53	8:50	10:12	11:59	8:57	9:00	10:11	10:21	9:40
	2011	9:28	9:13	10:47	14:12	8:37	10:00	10:05	9:59	9:28
	2012	9:13	9:06	10:21	13:42	8:30	10:00	9:12	9:35	9:12
	2013	9:03	9:00	10:46	11:20	8:29	10:00	8:53	9:15	9:02
	2014	9:02	8:15	10:20	10:53	8:08	-	8:56	9:09	8:54
	All	9:31	8:59	10:30	11:51	8:48	10:00	9:40	9:35	9:25

Note that for certain time frames and regions response time data was only available in minutes (e.g., Hamilton dispatch time).

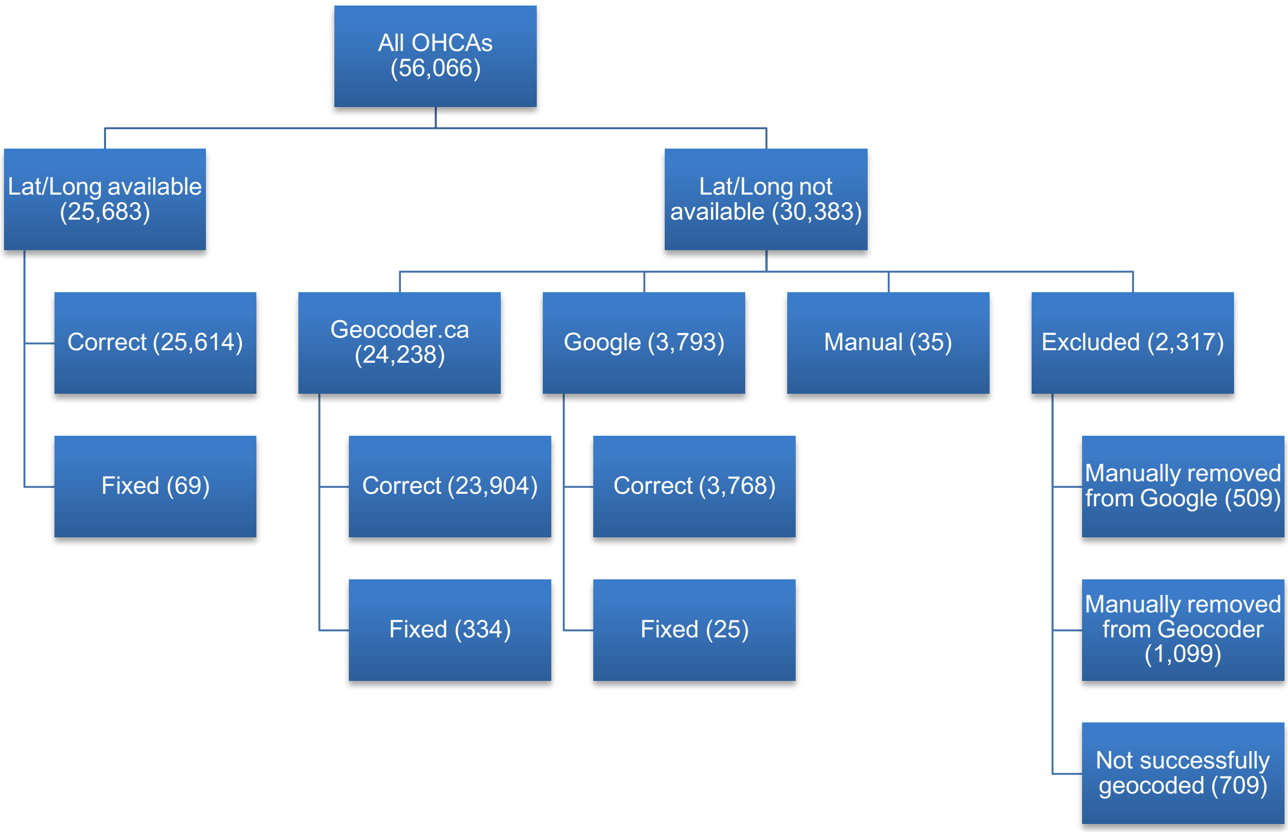
Supplemental Table 3. The number of missing data points for each characteristic and region.

Characteristics (n=53702)		Region								
		Toronto	Durham	Simcoe	Muskoka	Peel	Hamilton*	Halton*	York*	All
Female sex		78	7	6	0	26	15	0	14	146 (0.3%)
Average age		6	5	0	0	4	1	0	0	16 (0.03%)
Dispatch time	Median	191	57	418	5	20	885	67	275	1918 (3.6%)
	90th percentile	191	57	418	5	20	885	67	275	1918 (3.6%)
Response time	Median	393	123	1086	16	78	1165	274	1069	4204 (7.8%)
	90th percentile	393	123	1086	16	78	1165	274	1069	4204 (7.8%)
Access time	Median	13404	2194	2211	284	2747	2223	1295	1968	26326 (49.0%)
	90th percentile	13404	2194	2211	284	2747	2223	1295	1968	26326 (49.0%)
Public location		449	65	55	7	95	1	47	86	805 (1.5%)
Treated		0	0	0	0	0	0	0	0	0 (0%)
Shockable initial heart rhythm		478	69	74	32	98	239	48	83	1121 (2.1%)
Survival to discharge		16	10	34	0	10	37	7	0	114 (0.2%)

*In addition, Hamilton is missing one and a half years of data (2013-2014), Halton is missing 2 full years of data (2006-2007), and York is missing 4 full years of data (2006-2009). This table corresponds to Table 1 in the main body text.

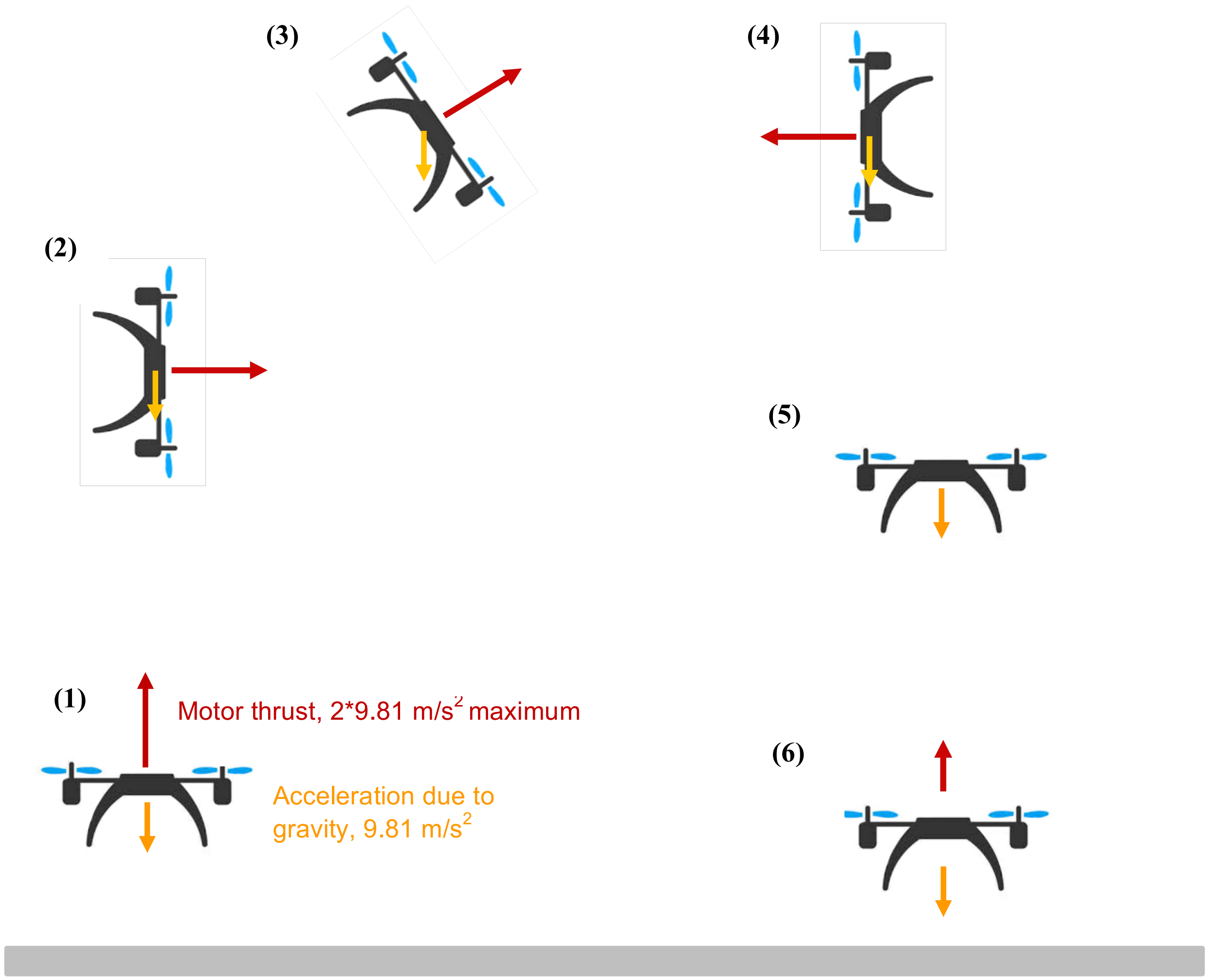
Supplemental Figures

Supplemental Figure 1. Summary of geocoding procedure.

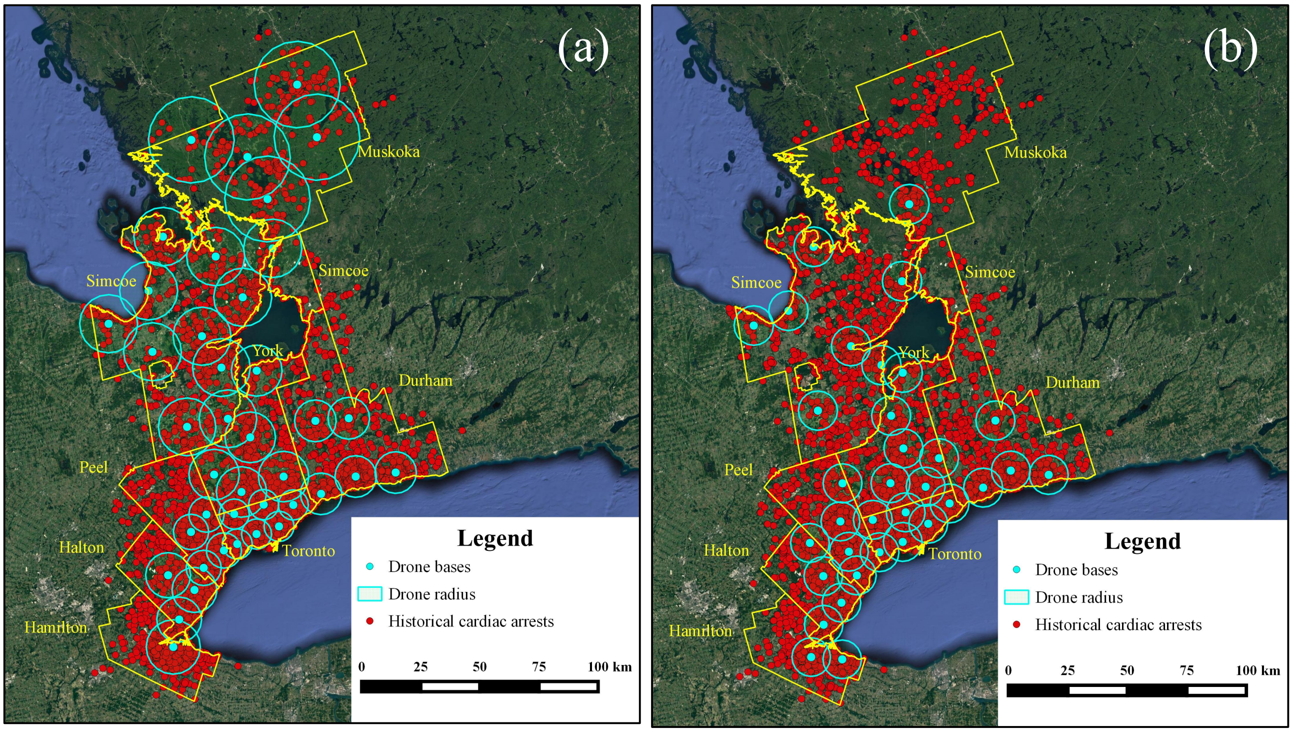


Fixed refers to OHCA locations that were manually checked, found to be incorrect, and changed to the correct location. *Manual* refers to OHCA locations that could not be successfully geocoded by Geocoder.ca or Google API, but whose locations were found manually. OHCA locations were manually removed after geocoding (from Geocoder or Google) if the locations could not be successfully verified or fixed (e.g., geocoded location was in another city or province). OHCA locations were excluded if the locations could not be successfully geocoded (e.g., incomplete or ambiguous address).

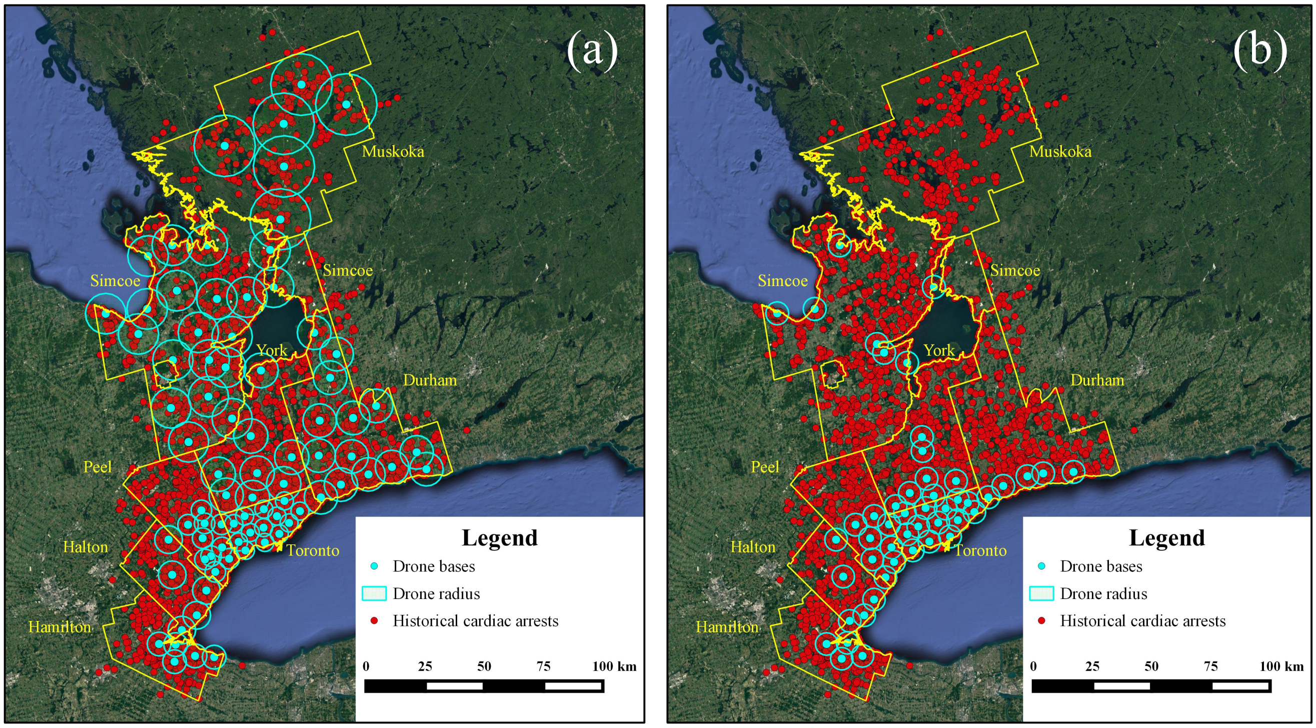
Supplemental Figure 2. A schematic of the drone takeoff and landing phases focusing on acceleration/decelleration. (1) Maximum vertical acceleration. (2) Maximum vertical deceleration and simultaneous maximum horizontal acceleration. (3) Horizontal motion at maximum speed. (4) Maximum horizontal deceleration and simultaneous maximum vertical deceleration. (5) Maximum vertical deceleration. (6) Force balance to safely land.



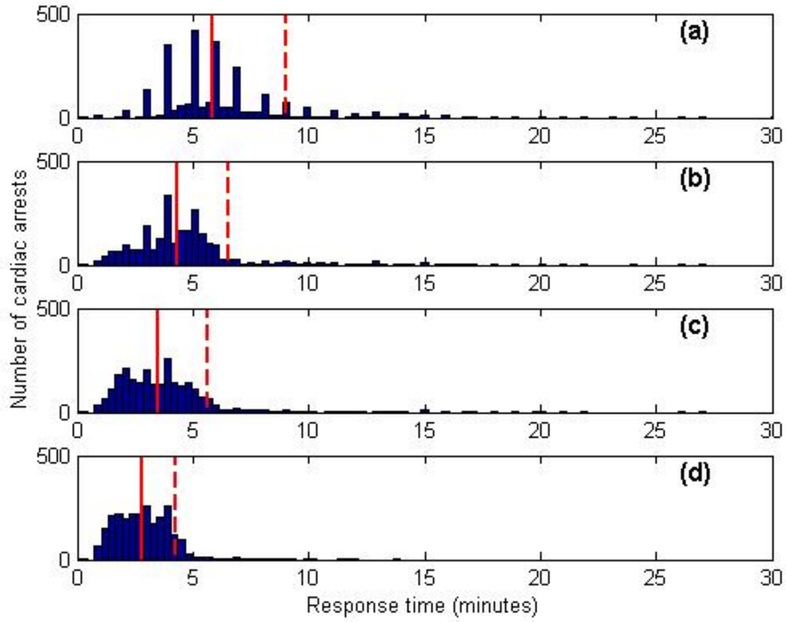
Supplemental Figure 3. Geographic layout of the (a) region-specific and (b) integrated drone networks for the *two-minute response time improvement goal*.



Supplemental Figure 4. Geographic layout of the (a) region-specific and (b) integrated drone networks for the *three-minute response time improvement goal.*

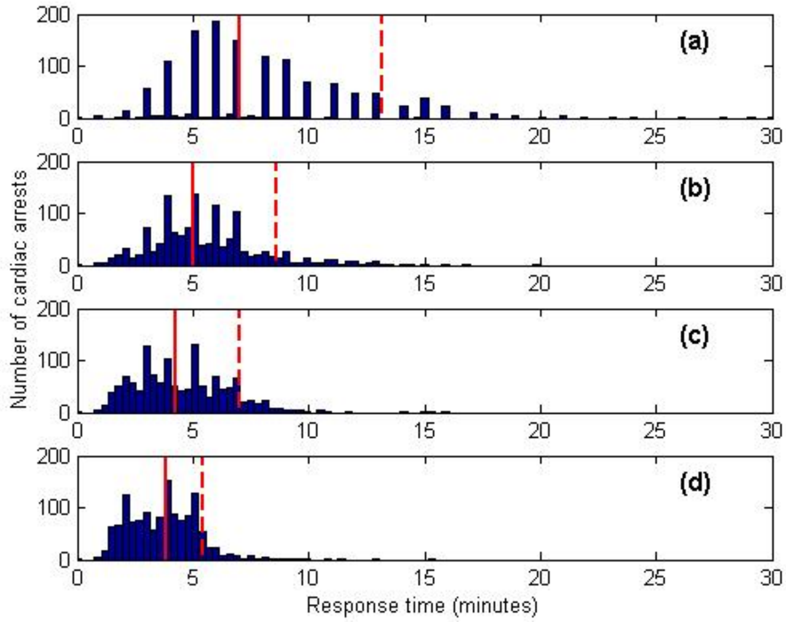


Supplemental Figure 5. Comparison of the historical 911 response time (a) with estimated distribution of response time by combining historical 911 response times with calculated drone response times under the (b) one-minute, (c) two-minute, and (d) three-minute response time improvement goals for Durham.



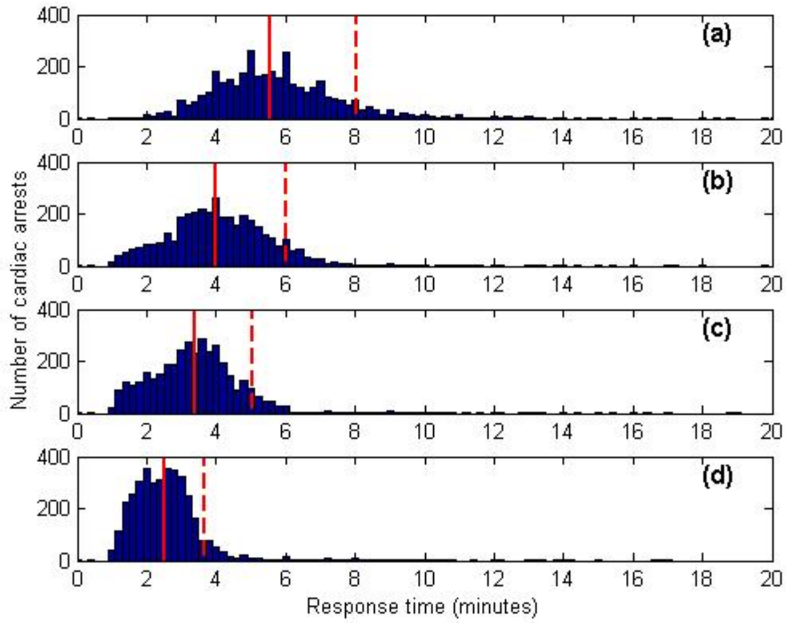
Historical 911 response times in Durham were rounded to the nearest minute up until 2013.

Supplemental Figure 6. Comparison of the historical 911 response time (a) with estimated distribution of response time by combining historical 911 response times with calculated drone response times under the (b) one-minute, (c) two-minute, and (d) three-minute response time improvement goals for Simcoe.

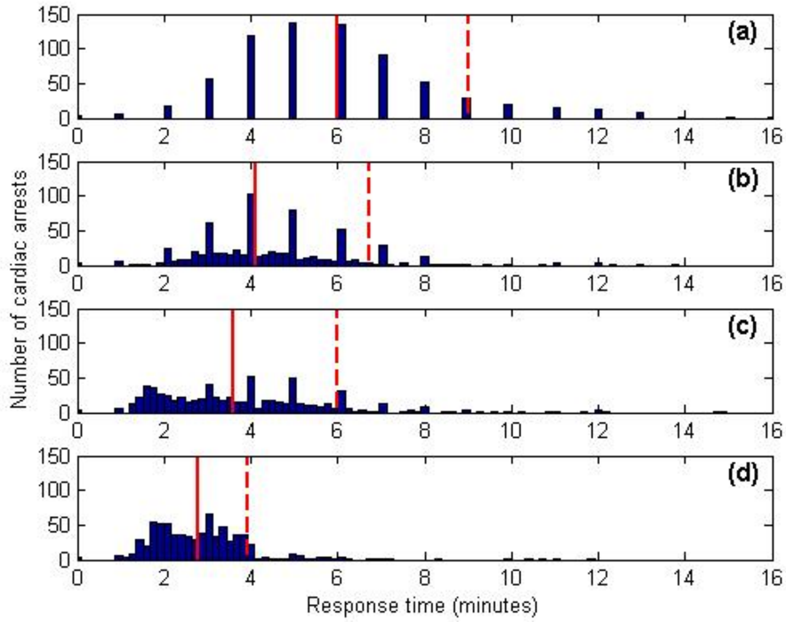


Historical 911 response times in Simcoe were rounded to the nearest minute up until 2013.

Supplemental Figure 7. Comparison of the historical 911 response time (a) with estimated distribution of response time by combining historical 911 response times with calculated drone response times under the (b) one-minute, (c) two-minute, and (d) three-minute response time improvement goals for Peel.

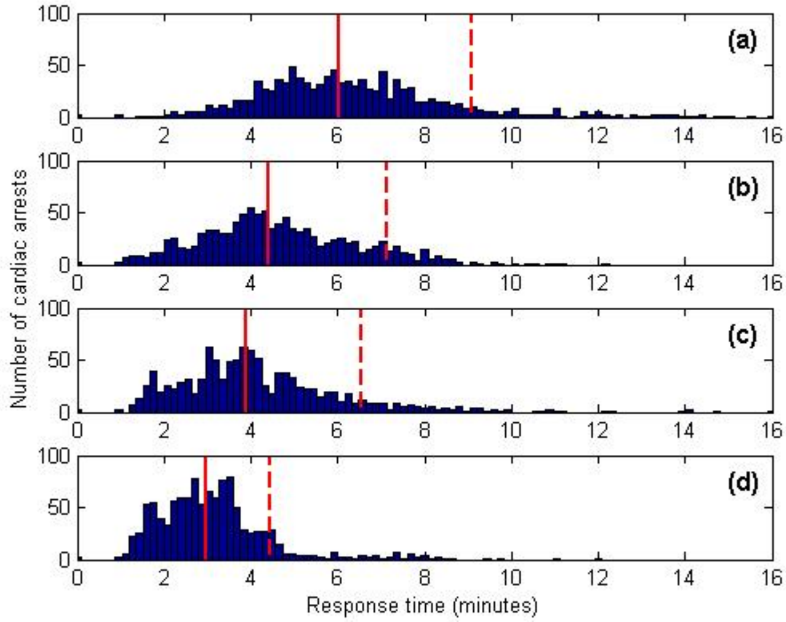


Supplemental Figure 8. Comparison of the historical 911 response time (a) with estimated distribution of response time by combining historical 911 response times with calculated drone response times under the (b) one-minute, (c) two-minute, and (d) three-minute response time improvement goals for Hamilton.



All historical 911 response times in Hamilton were provided to us rounded to the nearest minute.

Supplemental Figure 9. Comparison of the historical 911 response time (a) with estimated distribution of response time by combining historical 911 response times with calculated drone response times under the (b) one-minute, (c) two-minute, and (d) three-minute response time improvement goals for Halton.



Supplemental Figure 10. Comparison of the historical 911 response time (a) with estimated distribution of response time by combining historical 911 response times with calculated drone response times under the (b) one-minute, (c) two-minute, and (d) three-minute response time improvement goals for York.