Understanding vaccination queues in *NAADSM* 3 and *NAADSM* 4

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Introduction

Vaccination is one of several disease control measures that can be simulated in *NAADSM*. One of the parameters that influences the effectiveness of a vaccination strategy is the capacity to actually carry out vaccination activities. In *NAADSM*, this capacity is represented by the number of units that can be vaccinated on each day. When capacity is inadequate to perform all required vaccination activities on a particular day, units are placed in a prioritized queue, to be vaccinated as resources allow. *NAADSM* users occasionally express the desire to use the number of units in queue to be vaccinated on each day as either a measure of vaccination resources required to control an outbreak, or as an indicator of how vaccination capacity affects simulated outbreak progress.

The way in which units are queued to be vaccinated in *NAADSM* 3 differs from the which queuing is handled in *NAADSM* 4. This difference between versions is subtle, but can influence model outcomes.

The purpose of this technical note is two-fold. First, it describes and compares the approaches used by *NAADSM* 3 (including all releases of *NAADSM* 3.0, 3.1, and 3.2) and the upcoming *NAADSM* 4 for queuing units to be vaccinated. Second, it illustrates why output generated by *NAADSM* 3 regarding the number of units in the vaccination queue on each simulation day is not a particularly good measure of the impact of vaccination capacity. By contrast, as a consequence of changes implemented in *NAADSM* 4, the number of units in queue to be vaccinated in *NAADSM* 4 offers a much more direct indicator of the need on any particular simulation day for vaccination resources.

Vaccination queues in *NAADSM* 3

Three examples are presented below to illustrate how units are queued to be vaccinated in *NAADSM* 3. Each of these examples is a variation of the situation illustrated in Figure 1. In this situation, there are 15 units. Two of these units (unit 1 and unit 15) are infected and might be detected. The remaining units might be vaccinated.

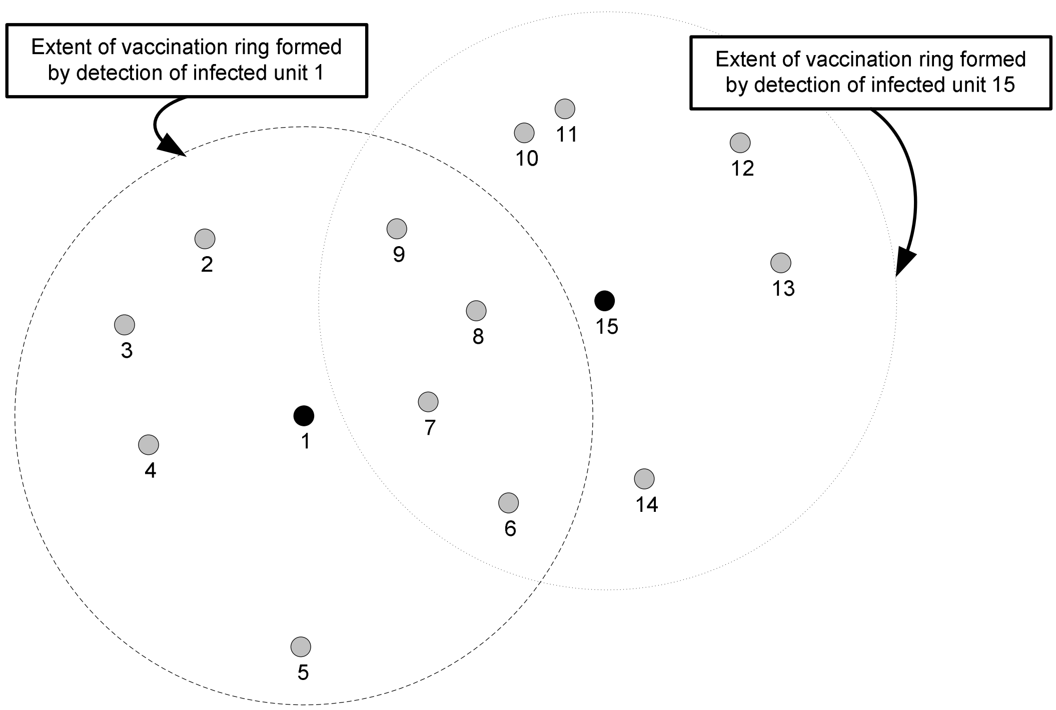

Figure 1. Spatial arrangement of units considered in the examples for *NAADSM 3*. Individual dots represent units. Larger circles represent potential vaccination rings. Units 1 and 15 are infected and might be detected. The remaining units might be vaccinated.

For the purposes of these examples, assume that parameters affecting vaccination have been assigned as follows. (For more information about these parameters, please see the relevant versions of the *User's Guide for NAADSM* and the *Model Description for the North American Animal Disease Spread Model*, both of which are available from *http://www.naadsm.org/documentation*):

- The vaccination campaign will begin upon the first detection of an infected unit
- There is a constant vaccination capacity of exactly one unit per day
- All units have the same production type
- Detected units will not be vaccinated

Example 1. One detected unit

In this example, suppose that unit 1 is detected on day 1, and that unit 15, although infected, is never detected. Events associated with vaccination will occur as shown in Table 1. The situation in this example is straight-forward, and the vaccination queue behaves exactly as might be expected. In this simple case, the number of units in queue to be vaccinated (queue length) is a reliable indicator of the number of units that ultimately will be vaccinated.

Table 1. Sequence of vaccination-related events for the example described in Example 1

Day	*Events*	*Units in the vaccination queue*[1]	*Queue length*[1]
1	Unit 1 is detected, and triggers a vaccination ring. Units 2 – 9 are queued to be vaccinated[2].	2, 3, 4, 5, 6, 7, 8, 9	8
2	Unit 2 is vaccinated. Daily capacity for vaccination is spent, and no further vaccinations can occur until the next day.	3, 4, 5, 6, 7, 8, 9	7
3	Unit 3 is vaccinated.	4, 5, 6, 7, 8, 9	6
etc.			
9	Unit 9 is vaccinated.	(No units remain in queue)	0

Example 2. Two detected units with overlapping vaccination rings

It is rare that only a single vaccination ring (or set of non-overlapping vaccination rings) will be formed in a *NAADSM* scenario. Much more often, situations arise where two or more vaccination rings overlap. When units occur in the intersection of two or more vaccination rings, the way in which the vaccination queue is implemented needs to be considered.

For this example, the following assumptions are made:

- Infected unit 1 is detected on day 1.
- Infected unit 15 is detected on day 4.
- The minimum time that must pass before a unit can be revaccinated is 3 days.

Note in Figure 1 above that several units are in the vaccination rings triggered by the detection of unit 1 as well as by the detection of unit 15. **In *NAADSM* 3, a unit will be placed in the vaccination queue every time a vaccination ring is created that includes that unit, and units may occupy several places in the vaccination queue simultaneously**. This is shown below in Table 2: units 6 – 9 are

[1] These values represent the state of the queue at the "end" of the simulation day when all activities for that day are complete. Equivalently, these values represent the situation at the "start" of the following simulation day, before any activities have begun.

[2] In actual operation, assuming that all other factors that influence vaccination priority are equal for all units, the order in which units would be queued for vaccination would be random. The fact that they appear in consecutive order here is strictly for purposes of the example.

queued for vaccination as a result of the detection of unit 1 on day 1, and are queued again for vaccination as a result of the detection of unit 15 on day 4.

The parameter that determines the minimum number of days that must elapse before a unit can be revaccinated (described in the *Model Description for the North American Animal Disease Spread Model*) is important: a unit will not necessarily be vaccinated each time that it occurs in the vaccination queue. Compare the outcomes shown here and in the third example below.

Table 2. Sequence of vaccination-related events for the example described in Example 2

Day	*Events*	*Units in the vaccination queue*[1]	*Queue length*[1]
1	Unit 1 is detected, and triggers a vaccination ring. Units 2 – 9 are queued to be vaccinated.[2]	2, 3, 4, 5, 6, 7, 8, 9	8
2	Unit 2 is vaccinated. Daily capacity for vaccination is spent, and no further vaccinations can occur until the next day.	3, 4, 5, 6, 7, 8, 9	7
3	Unit 3 is vaccinated.	4, 5, 6, 7, 8, 9	6
4	Unit 4 is vaccinated. Unit 15 is detected, and triggers a vaccination ring. Units 6 – 14 are queued to be vaccinated.[2]	5, 6, 7, 8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	14
5	Unit 5 is vaccinated.	6, 7, 8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	13
6	Unit 6 is vaccinated.	7, 8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	12
7	Unit 7 is vaccinated.	8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	11
8	Unit 8 is vaccinated.	9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	10
9	Unit 9 is vaccinated.	**6, 7, 8, 9,** 10, 11, 12, 13, 14	9
10	Unit 6 comes to the head of the vaccination queue. It has been 4 days since unit 6 was last vaccinated (more than the minimum of three days required before revaccination can occur), so it will be vaccinated again.	**7, 8, 9,** 10, 11, 12, 13, 14	8
11	Unit 7 comes to the head of the vaccination queue. It has been 4 days since unit 7 was last vaccinated, so it will be vaccinated again.	**8, 9,** 10, 11, 12, 13, 14	7
12	Unit 8 comes to the head of the vaccination queue. It has been 4 days since unit 8 was last vaccinated, so it will be vaccinated again.	**9,** 10, 11, 12, 13, 14	6
13	Unit 9 comes to the head of the vaccination queue. It has been 4 days since unit 9 was last vaccinated, so it will be vaccinated again.	10, 11, 12, 13, 14	5
etc.			
19	Unit 14 is vaccinated.	(No units remain in queue)	0

Example 3. Longer minimum time between vaccinations

In examples 1 and 2, the daily length of the vaccination queue provides an accurate measure of how much work remains to be done in order to carry out a vaccination strategy. The fact that, in example 2, some units occupy several places in the vaccination queue does not affect this, as all of those units will actually be vaccinated multiple times. This outcome, though, is coincidental: **in *NAADSM* 3, not every unit in the vaccination queue will necessarily be vaccinated**.

Example 3 illustrates how the length of the vaccination queue can be misleading. In this example, the following change was made from Example 2:

- The minimum time that must pass before a unit can be revaccinated is 6 days.

Table 3. Sequence of vaccination-related events for the example described in Example 3

Day	*Events*	*Units in the vaccination queue*[1]	*Queue length*[1]
1	Unit 1 is detected, and triggers a vaccination ring. Units 2 – 9 are queued to be vaccinated.[2]	2, 3, 4, 5, 6, 7, 8, 9	8
2	Unit 2 is vaccinated. Daily capacity for vaccination is spent, and no further vaccinations can occur until the next day.	3, 4, 5, 6, 7, 8, 9	7
3	Unit 3 is vaccinated.	4, 5, 6, 7, 8, 9	6
4	Unit 4 is vaccinated. Unit 15 is detected, and triggers a vaccination ring. Units 6 – 14 are queued to be vaccinated.[2]	5, 6, 7, 8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	14
5	Unit 5 is vaccinated.	6, 7, 8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	13
6	Unit 6 is vaccinated.	7, 8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	12
7	Unit 7 is vaccinated.	8, 9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	11
8	Unit 8 is vaccinated.	9, **6, 7, 8, 9,** 10, 11, 12, 13, 14	10
9	Unit 9 is vaccinated.	**6, 7, 8, 9,** 10, 11, 12, 13, 14	9
10	Unit 6 comes to the head of the vaccination queue. It has been 4 days since unit 6 was last vaccinated (less than the minimum of 6 days required before revaccination can occur), so it is removed from the vaccination queue without being vaccinated again. No capacity for vaccination has been used. Unit 7 comes to the head of the vaccination queue. It has been 3 days since unit 7 was last vaccinated (less than the minimum of 6 days required before revaccination can occur), so it is removed from the vaccination queue without being vaccinated again. No capacity for vaccination has been used. Unit 8 is similarly removed from the queue without being vaccinated again. Unit 9 is similarly removed from the queue without being vaccinated again. Unit 10 is vaccinated. Daily capacity for vaccination is spent, and no further vaccinations can occur until the next day.	11, 12, 13, 14	4
11	Unit 11 is vaccinated.	12, 13, 14	3
12	Unit 12 is vaccinated.	13, 14	2
13	Unit 13 is vaccinated.	14	1
14	Unit 14 is vaccinated.	(No units remain in queue)	0

Note what happened on days 9 and 10 in this example. At the end of day 9, there were 9 units in the vaccination queue. On day 10, 4 of these units are removed from the vaccination queue without being vaccinated. This is a consequence partly of the parameter that establishes the minimum number of days that must pass before a unit can be revaccinated, and partly of the way in which units are queued for vaccination in *NAADSM* 3.

The queue length on day 9 is not a reliable indicator of how much work remains to be done, since many of the units in that queue will not actually consume vaccination capacity. The vaccination queue in *NAADSM* 3 is used primarily for "housekeeping" purposes by the model as it runs, and can include many units that will not be vaccinated. **In general, in *NAADSM* 3, the number of units in the vaccination queue should not be treated as an indicator either of the work required to carry out a vaccination strategy, or of the day-to-day need for vaccination resources.**

The longer the minimum time between vaccinations is, the worse this problem becomes: many more units will be queued for vaccination, only to be removed from the queue later. As a result, the number of units in the vaccination queue in *NAADSM* 3 can be artificially quite high.

Vaccination queues in *NAADSM* 4

Two major changes to the handling of vaccination queues were made for *NAADSM* 4. These changes are described in RFC-20091016ARa (part of the model specification for *NAADSM* 4, available via *http://www.naadsm.org/documentation/specification*):

- **In *NAADSM* 4, a unit can occur in the vaccination queue only once. If a unit is already in the vaccination queue when another vaccination ring that includes it is formed, it is not added to the queue again.**
- **In *NAADSM* 4, a previously vaccinated unit can be queued for another vaccination only after a specified minimum number of days that must elapse have passed.**

These changes were made by the *NAADSM* Development Team to reflect what is believed to be a more realistic implementation of vaccination strategies. The effects of the first change are illustrated in Example 4. Those of the second modification are shown in Example 5.

Example 4. Two detected units with overlapping vaccination rings and queuing rules for *NAADSM* 4

This example is analogous to example 2 shown above. The assumptions are the same:

- Infected unit 1 is detected on day 1.
- Infected unit 15 is detected on day 4.
- The minimum time that must pass before a unit can be re-queued for vaccination is 3 days.

Table 4 lists the sequence of events that will occur in this situation in *NAADSM* 4. Compare the outcome to example 2.

Table 4. Sequence of vaccination-related events for the example described in Example 4

Day	*Events*	*Units in the vaccination queue*[1]	*Queue length*[1]
1	Unit 1 is detected, and triggers a vaccination ring. Units 2 – 9 are queued to be vaccinated.[2]	2, 3, 4, 5, 6, 7, 8, 9	8
2	Unit 2 is vaccinated. Daily capacity for vaccination is spent, and no further vaccinations can occur until the next day.	3, 4, 5, 6, 7, 8, 9	7
3	Unit 3 is vaccinated.	4, 5, 6, 7, 8, 9	6
4	Unit 4 is vaccinated. Unit 15 is detected, and triggers a vaccination ring that includes units 6 – 14. Units 6 – 9, however, are already in the vaccination queue, and will not be queued again. Units 10 – 14 are queued to be vaccinated.[2]	5, 6, 7, 8, 9, 10, 11, 12, 13, 14	10
5	Unit 5 is vaccinated.	6, 7, 8, 9, 10, 11, 12, 13, 14	9
6	Unit 6 is vaccinated.	7, 8, 9, 10, 11, 12, 13, 14	8
etc.			
14	Unit 14 is vaccinated.	(No units remain in queue)	0

Note that, as a consequence of the changes to queuing rules in *NAADSM* 4, the time required to complete all vaccinations is shorter than it had been in *NAADSM* 3. Also, the total number of vaccinated units is lower. In Example 2 (which represents rules used in *NAADSM* 3), 17 units were vaccinated: units 6 – 9 were each vaccinated twice, and thus count twice toward the total number of units vaccinated. The same situation in *NAADSM* 4, however, would result in the vaccination of only 13 units, as shown in Example 4.

Example 5. Three overlapping vaccination rings and queuing rules for *NAADSM* 4

As mentioned above, *NAADSM* 3 includes a parameter that defines the number of days that must pass before a previously vaccinated unit can be revaccinated. In *NAADSM* 4, there is a similar parameter that has a slightly different interpretation: **In *NAADSM* 4, this parameter represents the number of days that must pass between the time that a unit was vaccinated to the time that it can be placed again in the vaccination queue.** The impact of this change is illustrated in an example that introduces a third detected unit and corresponding vaccination ring, as shown in Figure 2.

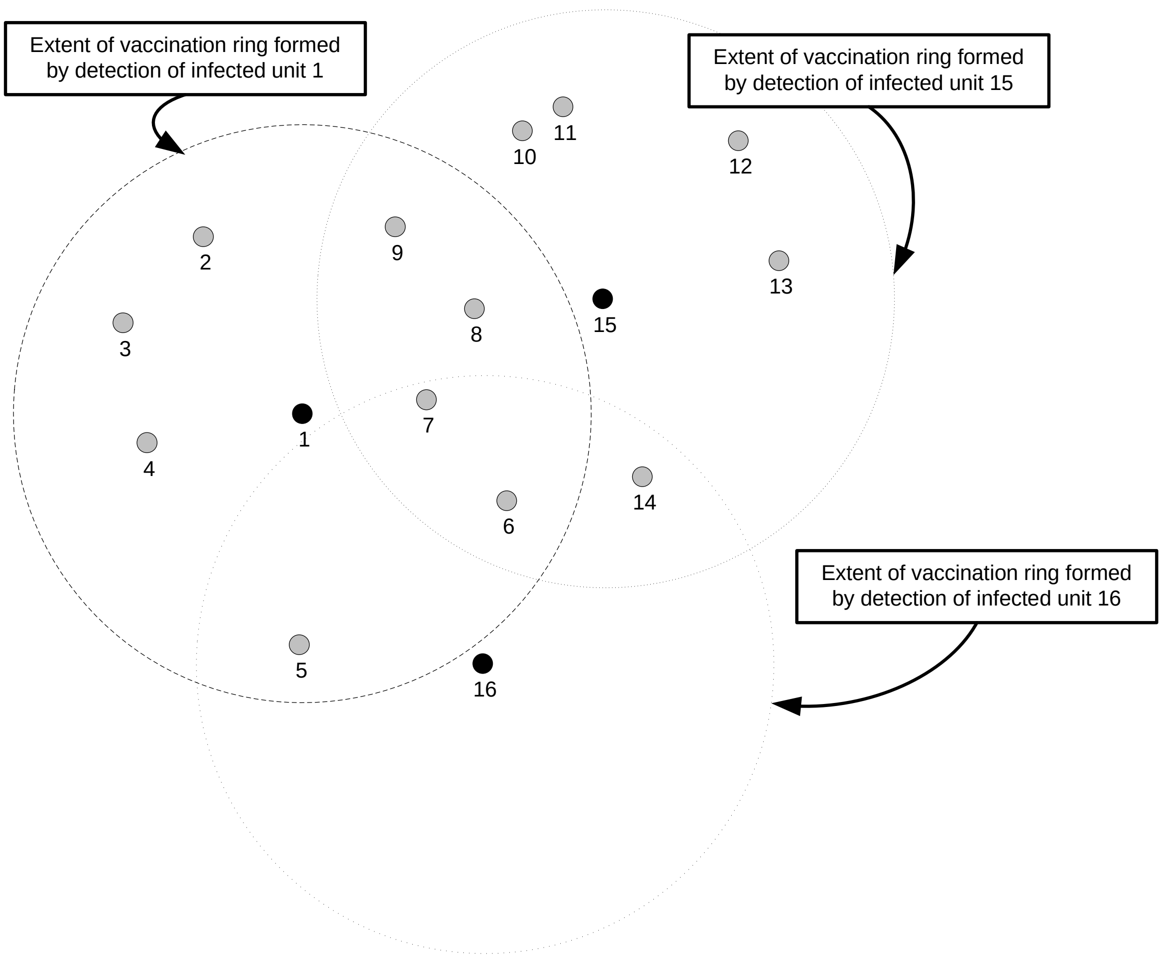

Figure 2. Spatial arrangement of units considered in Example 5. Individual dots represent units. Larger circles represent potential vaccination rings. Units 1, 15, and 16 are infected and might be detected. The remaining units might be vaccinated.

The assumptions used in this example are as follows:

- Infected unit 1 is detected on day 1.
- Infected unit 15 is detected on day 7.
- Infected unit 16 id detected on day 9.
- The minimum time that must pass before a unit can be re-queued for vaccination is 3 days.

The outcome of this scenario is shown in Table 5. A total number of 16 units are vaccinated in this scenario.

Table 5. Sequence of vaccination-related events for the example described in Example 5

Day	*Events*	*Units in the vaccination queue*[1]	*Queue length*[1]
1	Unit 1 is detected, and triggers a vaccination ring. Units 2 – 9 are queued to be vaccinated.[2]	2, 3, 4, 5, 6, 7, 8, 9	8
2	Unit 2 is vaccinated. Daily capacity for vaccination is spent, and no further vaccinations can occur until the next day.	3, 4, 5, 6, 7, 8, 9	7
3	Unit 3 is vaccinated.	4, 5, 6, 7, 8, 9	6
4	Unit 4 is vaccinated.	5, 6, 7, 8, 9	5
5	Unit 5 is vaccinated.	6, 7, 8, 9	4
6	Unit 6 is vaccinated.	7, 8, 9	3
7	Unit 7 is vaccinated. Unit 15 is detected and triggers a vaccination ring that includes units 6 – 14. Units 6 – 9, however, are already in the vaccination queue, and will not be queued again. Units10 – 14 are queued to be vaccinated.[2]	8, 9, 10, 11, 12, 13, 14	7
8	Unit 8 is vaccinated.	9, 10, 11, 12, 13, 14	6
9	Unit 9 is vaccinated. Infected unit 16 is detected and triggers a vaccination ring that includes units 5, 6, 7 and 14. Unit 5 is not currently in the vaccination queue, and was last vaccinated 4 days ago (more than the minimum of three days required before re-queuing can occur), so it will be placed in the vaccination queue again. Unit 6 is not currently in the queue, and was last vaccinated 3 days ago (equal to the minimum time required for re-queuing), so it will be placed in the queue again. Unit 7 is not currently in the queue, but was last vaccinated only 2 days ago, less than the minimum time required before re-queuing can occur. It will not be placed in the queue again. Unit 14 is already in the queue, and will not be queued again.	10, 11, 12, 13, 14, 5, 6	7
10	Unit 10 is vaccinated.	11, 12, 13, 14, 5, 6	6
11	Unit 11 is vaccinated.	12, 13, 14, 5, 6	5
etc.			
17	Unit 6 is vaccinated for the second time.	(No units remain in queue)	0

Examples 4 and 5 illustrate the net effect of the changes introduced in *NAADSM* 4: **in *NAADSM* 4, a unit is never placed in the vaccination queue without the explicit intent to actually carry out vaccination[3]. As a result, the number of units in queue to be vaccinated in *NAADSM* 4 is a reliable indicator of the amount of work remaining to be done to carry out a vaccination strategy, and outputs related to vaccination queue length can be more readily interpreted.** Contrast the situation in *NAADSM* 3, in which units are placed in the vaccination queue with the intent to make the decision at a future time whether to actually vaccinate them.

Summary

All models, regardless of their form, are based on a set of assumptions. It is critical that users and interpreters of models understand those assumptions to properly assess model outcomes.

The simplistic examples shown above illustrate the consequences of assumptions made in *NAADSM* 3 and *NAADSM* 4 regarding the implementation of vaccination strategies. As a result of modifications made to *NAADSM* 4, it is hoped that the approach used to simulate vaccination is a better reflection of reality, and that clear information can be obtained from the model regarding the effects of different levels of resources available to carry out a vaccination strategy.

[3] It is possible, in both *NAADSM* 3 and *NAADSM* 4, for a unit to be in queue to be vaccinated, as well as in queue to be destroyed. If a unit is destroyed before it is vaccinated, it will be removed from the vaccination queue. This does not, however, change the interpretation of the vaccination queue. Other events may intercede, but at the time a unit is placed in the queue in *NAADSM* 4, the intent is to carry out vaccination.