This chapter presents selected results from the current version of the PEM model. First we show some comparisons of PEM with the high-resolution simulation. While the two models appear to be consistent, there are too few high-resolution results available for comparison to determine for sure over what parameter ranges PEM agrees with the high-resolution simulation.

Second, we explore the behavior of PEM over a wide range of parameter values. Through this exploratory analysis, we can develop a clear idea of which factors most strongly influence how well BAT performs. The ability to perform an exploratory analysis requiring hundreds or thousands of model runs was one of the major reasons for building an aggregate model such as PEM.

COMPARISONS OF PEM WITH HIGH-RESOLUTION SIMULATION

We select two results from the high-resolution simulation to compare with PEM. They are (1) the number of AFVs in the effective footprint of a salvo, and (2) the number of AFVs killed per salvo. Of course, we will not compare results for any particular salvo. Rather, we will compare the distribution of each of these quantities over salvos.

Figures 6.1 and 6.2 show the results from the high-resolution simulations performed for the DSB ’98 summer study. In these figures we have taken the footprint to have a radius of 4 km. The most notable feature in each figure is the high probability of a “zero” result. There
Figure 6.1—Distribution over Salvos of AFVs in Footprint

Average = 2.17 AFVs in a salvo's footprint

Figure 6.2—Distribution over Salvos of AFVs Killed per Salvo

Average = 0.65 AFVs killed per salvo
were zero AFVs in the footprints of almost half the salvos and more than three-fourths of the salvos killed zero AFVs.

To compare PEM with these results, we must first decide which input values correspond to the DSB '98 simulations. It is evident from the discussion in Chapter Five that PEM will need different inputs to match different salvos from the DSB '98 cases. We ran PEM for packet spacings of 1, 2.5, and 4 km, AFV separations within a packet of 200, 350, and 500 meters, and AFVs per packet of 4, 7, and 10.

In the DSB '98 simulations, it was difficult even to establish criteria for determining what were the open areas. Measuring open stretches of road on a relatively low-resolution map indicated that the average open area was about 5 km long, though many salvos were aimed at shorter areas. But from Figure 5.2 we see that a high-resolution map might show these areas to consist of multiple smaller open stretches. We ran PEM for modal lengths of open areas of 1, 3, and 5 km.1

The other inputs were held constant for these runs. With the maximum open area only 7 kilometers long (see footnote), it was not necessary to consider a range of missile footprint sizes, so we set the footprint at a diameter of 8 km (radius of 4 km). We set the speed of AFV packets at a constant 75 km/hr. Since results for this type of terrain are not very sensitive to the “time since last update” parameter, unless it is made very short (a few minutes), we set it at 15 minutes.

Figures 6.3 and 6.4 show the comparisons. The bars in each figure are repeated from Figures 6.1 and 6.2; they show the results from the high-resolution simulations. Plotted over them are three distributions from PEM, one for each of the values listed above for the length of an open area. Each is formed as a weighted average of 27 PEM cases, in which packet spacing, AFV separation within a packet, and number of AFVs per packet are each varied over the three values listed earlier. We singled out the length of the open area to plot as the x axis because (1) it was the most problematic of the four parameters we varied, and (2) it seemed to make the most difference

1In the current version of PEM, the length of open areas is a random variable with a triangular distribution. The user inputs the mode W. The minimum length is always zero and the maximum is W+2.
in the distribution of both AFVs in the footprint and AFVs killed per salvo.

Clearly, PEM shares with the high-resolution simulation the characteristic that a substantial fraction of salvos have zero AFVs in their footprints, and an even larger fraction of salvos kill zero AFVs. Moreover, the PEM results could be made to agree fairly closely with the high-resolution results by forming an average of the three curves in each of Figures 6.3 and 6.4 with the appropriate weights. Thus, we conclude that so far as these two quantities are concerned, PEM behaves quite similarly to the high-resolution simulation.

However, we should not expect PEM to match these results too closely. In the DSB '98 cases, there were 13 Red vehicle types in three

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2In Chapter Seven we will approximate the distribution of vehicles in the footprint by a geometric distribution, whose single parameter is selected to produce a desired mean number of vehicles in the footprint. Figure 6.3 shows that this approximation introduces no great distortion.
types of packets. Because in most cases the man-in-the-loop could not distinguish AFVs from other types of vehicles, some salvos were aimed at other kinds of packets. This would inflate the proportion of salvos that had zero AFVs in their footprints, which in turn would increase the proportion of salvos that killed zero AFVs (they may have killed other vehicles, however).

EXPLORATORY ANALYSIS WITH PEM

A major advantage of PEM is that one can use it to conduct exploratory analysis. Both PEM and the high-resolution simulation model it approximates are weakly predictive, at best. By this we mean that while the outcomes predicted by the model are plausible, nobody should believe the actual numerical outputs from a single case or a small number of cases to be a reliable prediction of what would happen in detail in a real-life conflict. Any defensible use of these models requires one to generalize and abstract from the actual numerical results they produce to find principles (or at least rules of
thumb) that remain true for broad ranges of scenarios and assumptions—including different assumptions about scale factors. One approach that often succeeds in discovering such principles is exploratory analysis. The analyst runs hundreds or even thousands of cases in which the inputs are varied widely, and systematically searches the dataset generated from them. In other words, the model generates the data, which must then be analyzed. This is in stark contrast with the view that the model does the analysis. But it requires a model that is, like PEM, small, fast, and analytically agile.

Figure 6.5 shows an Analytica “results” display. In the top panel of the figure are boxes containing values for a variety of parameters. In the bottom panel are curves showing, in this instance, the influence of the time since last update on the number of AFVs killed by a Blue missile salvo. Separate curves appear for the first and second missiles in the salvo. As the user changes the parameter values by clicking the arrows next to the boxes, the curves will change to reflect the new parameter values. The user can also select any of the parameters to replace “Time of Update List” on the X-axis, or to replace “Missile” as the “key.” The user can generate such a “results” display with any calculated quantity on the vertical axis.

Analytica’s results display is good for a first look at a broad range of cases, but it does not allow one to bring to bear statistical methods and other data analysis techniques. For that we create an experimental design followed by a long sequence of runs covering the cases of interest and use Analytica’s ability to export the results as a plain ASCII file. We can import the ASCII file into another software package (we chose Excel®) for further analysis. To illustrate, we ran cases for all 720 combinations of the parameter values shown in Table 6.1.

The parameter values in Table 6.1 reflect the Red vehicle configurations noted in the high-resolution simulations (see Chapter Five). But those runs considered much more dispersed Red formations than most military officers believe are likely.3 Thus, we also

3Some officers have asserted that it is impractical to maintain command and control over a column of vehicles if the vehicles are separated by more than about 50 meters. They expect that if a column moves in a dispersed formation, vehicles will get lost along the way and will dribble in to the destination over an extended period of time. Once they begin arriving an enormous amount of time and effort will be required to re-form the unit.
The baseline for our exploratory analysis is an attack against a very long column of closely and uniformly spaced (50-meter separation)

However, if dispersing his forces proves to be an effective enough countermeasure to long-range precision fires, Red might work out ways to do it. In part, then, one can consider the high-resolution cases as a test of whether Red has the incentive to explore this option.
Table 6.1
Parameter Values for Exploratory Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal width of open areas (km)</td>
<td>1 3 5 100</td>
</tr>
<tr>
<td>Time since last update (min)</td>
<td>0 5 10 15 20</td>
</tr>
<tr>
<td>AFVs per packet</td>
<td>4 7 10</td>
</tr>
<tr>
<td>AFV spacing within packet (m)</td>
<td>200 350 500</td>
</tr>
<tr>
<td>Packet separation (km)</td>
<td>1 2.5 4 100</td>
</tr>
</tbody>
</table>

Table 6.2
Parameter Values for High-Density Red Formations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal width of open areas (km)</td>
<td>1 3 5 100</td>
</tr>
<tr>
<td>Time since last update (min)</td>
<td>0 5 10 15 20</td>
</tr>
<tr>
<td>AFVs per packet</td>
<td>1000</td>
</tr>
<tr>
<td>AFV spacing within packet (m)</td>
<td>50</td>
</tr>
<tr>
<td>Packet separation (km)</td>
<td>0</td>
</tr>
</tbody>
</table>

Red AFVs taking place in open terrain (modal width of open areas = 100 km). We will first examine the influence of terrain on the effectiveness of the attack by reducing the modal width of open areas to 5, then 3, and finally to 1 kilometer. Next, we will return to open terrain and examine the degree to which Red can protect himself by deploying his AFVs in a less dense configuration. Finally, we will consider the influence of Red dispersal tactics in terrain that offers some concealment (smaller modal width of open areas).

**Attacks Against a Dense Red Column in Varying Terrain**

Figure 6.6 shows the effectiveness of BAT against a very long column of closely spaced (50 meters) Red AFVs (see Table 6.2 for parameter values). Each salvo consists of two missiles. Each bar indicates a different type of terrain, which we represent by different modal lengths of open areas (W = 1, 3, 5, and 100 kilometers). The time since last update has no effect on these results because all parts of the Red column look the same. The rightmost bar represents our baseline, namely attacks against a long Red column of AFVs spaced uniformly at 50 meter intervals in terrain that offers no concealment. The
Figure 6.6—Effectiveness of BAT Against an Infinite Column of AFVs
Uniformly Spaced at 50 Meter Intervals

Baseline effectiveness is just under 12 kills per salvo of two TACMS missiles equipped with 13 BAT submunitions each.

We see from Figure 6.6 that modal length of open areas has some influence on kills per salvo, as Red vehicles are not vulnerable unless they are in the open. However, the open areas must be quite small in order to offer Red substantial protection.

Attacks in Open Terrain Against Varying Red Configurations

Red can protect his forces to some extent by dispersing them, even if the terrain offers no concealment. Figure 6.7 shows kills per salvo as a function of time since last update. All points are for a modal length of open areas of 100 kilometers, which means the terrain is entirely open and the Red targets are unobscured by foliage. The top line consists of our baseline, in which the Red vehicles are in a
continuous column, separated by 50 meters. All the remaining points assume various less dense configurations of the Red column, as generated from Table 6.1.

The time since last update has no effect on baseline kills per salvo because whenever the missiles arrive over the target, they will see some part of the Red column (it is very long, remember), and all parts look the same. But when Red configures his column differently, then the time since last update can matter. If Blue’s missiles miss the packet they are aimed at, they may fall on the empty space between packets.

But there is another way of looking at Blue’s effectiveness. As Red disperses his forces by increasing the average separation between vehicles, his column becomes longer. The time interval lengthens between the entry of the first vehicle into Blue’s target area and the exit of the last vehicle. If Blue has limited stocks of ammunition, so
that the number of shots he can fire is independent of Red’s exposure time, then Figure 6.7 gives the right view. If instead Blue is constrained by his maximum firing rate, Red may actually harm himself by dispersing.

Figure 6.8 illustrates what happens if the depth of Blue’s target area is very small compared to the length of Red’s column. For example, 1,000 AFVs separated by 50 meters and traveling at 75 kilometers per hour will take only 40 minutes to pass a given point. But if the same 1,000 AFVs are configured in packets of 4 vehicles each, with vehicles within a packet separated by 500 meters and packets separated by 4 kilometers (the lowest density configuration from Table 6.1), then the column will require 20 hours to pass a given point. If Blue’s firing rate is limited (perhaps by C4ISR considerations), Blue can fire up to 30 times as many shots (if he has the ammunition to do so) and can

Figure 6.8—Relative BAT Kills per Unit Time in Open Terrain Against Various Red Configurations
therefore kill more AFVs overall even though each salvo is much less effective.⁴

The solid line in both Figures 6.7 and 6.8 consists of the cases where the Red vehicles are in a continuous column, separated by 50 meters. The values are scaled so that the lines are at the same level in both figures. All the remaining points assume various different configurations of the Red column, as shown in Table 6.1.

We point out that in our treatment, the Red vehicles are restricted to traveling on roads. This makes the problem one dimensional, so that if Red reduces his density of AFVs, he increases the time his column takes to pass a point by the same factor. If Red vehicles could travel off road, they would have two dimensions in which to disperse, and the time used for maneuver would increase only as the square root of the density-reduction factor. Similarly, if Red can find alternative roads to travel on, he can split his force into multiple axes of advance and reduce the density of vehicles on each axis without increasing the time his force requires to pass through Blue’s target area.

**Attacks Against Various Red Configurations in Mixed Terrain**

If Red is traveling through terrain that offers concealment, dispersal is a much more effective countermeasure than in open terrain. In all cases shown in Figure 6.9 (for mixed terrain), the modal length of an open area is 3 kilometers. The top line shows kills per salvo when Red AFVs are uniformly spaced at 50 meter intervals. All 27 Red configurations listed in Table 6.1 appear as points below the top line. Note that the loss in kills per salvo between the top line (the densest configuration) and the points below (various dispersed formations) is much greater in this terrain than it is in open terrain (Figure 6.7).

If the open areas are this small (W = 3 km) and Red disperses, Blue salvos will kill only one or two AFVs on average. Unless Blue is desperate (and has lots of TACMS missiles with BAT), it may not be

⁴This effect—i.e., this penalty to Red for dispersal—is particularly strong with respect to time vulnerable to Air Force sorties. Since sorties are typically prescheduled, without knowing when targets will be in the open, “firing rate” is limited. See also Ochmanek et al. (unpublished).
worthwhile to fire. Decreasing the time since last update improves the effectiveness, though it still remains low.

As before, we rescale the data to estimate kills per time exposed instead of kills per salvo. The results appear as Figure 6.10. For a sufficiently long time since last update (or equivalently, a sufficiently large error in the impact time of Blue’s missile), some dispersed configurations actually reduce Red’s losses over the entire time the column is exposed, and not just per salvo. This reinforces the value to Red of dispersion coupled with concealment, and the value to Blue of accuracy.

In this instance, the penalty for dispersal is less and the relevance of the alternative view (kills per unit time) is also less. Long-range precision munitions such as TACMS with BAT are expensive, and Blue doctrine may call for firing only when he expects to achieve at least a specified threshold number of kills. According to Figure 6.10, Blue will have few opportunities to kill large numbers of AFVs per salvo in

Figure 6.9—BAT Kills per Salvo in Mixed Terrain Against Various Red Configurations
terrain with small open areas. Fewer firing opportunities translates to a slower rate of kills (kills per time exposed), even as it maintains weapon effectiveness (kills per salvo).

**Afterword**

The foregoing is intended as an illustration of the power of exploratory analysis and of the consequent utility of models small and agile enough to support it. We have constructed PEM, just such a small and agile model, and tested it against a high-resolution simulation model. Gaining confidence that PEM behaves more or less as the high-resolution model would, we have run hundreds of cases to help understand BAT’s strengths and weaknesses.\(^5\) Can it be de-

\(^5\)The data for PEM 1.0 treats a relatively small-footprint precision weapon (sensor-fused weapons) as well as BAT. We choose to present results only for BAT because we have yet to compare results for the small footprint weapon with high-resolution results.
feated by terrain or by Red countermeasures? Does its effectiveness depend on accurate predictions of Red’s future positions?

The analysis presented here is illustrative, not complete. But if we were to extend it, the understanding thus gained could be used to suggest improvements to the weapon or perhaps new weapons that have complementary strengths and weaknesses. PEM might also be used within a larger modeling structure to develop better doctrines for the use of the weapon under a variety of circumstances.