The Effectiveness of Rocket Attacks and Defenses in Israel

Michael J. Armstrong
Associate professor of operations research
Goodman School of Business, Brock University
michael.armstrong@brocku.ca

This is a pre-copyedited, author-produced version of an article accepted for publication in the Journal of Global Security Studies following peer review. The version of record [Michael J. Armstrong; The effectiveness of rocket attacks and defenses in Israel, Journal of Global Security Studies, Volume 3, Issue 2, 11 April 2018, pages 113-132] is available online at [https://doi.org/10.1093/jogss/ogx028].

Abstract

This empirical paper studies rocket attacks and defenses in Israel during operations Protective Edge, Pillar of Defense, and Cast Lead, plus the Second Lebanon War. It analyzes publicly available counts of rockets, fatalities, casualties, and property damage. The estimates suggest that interceptor deployment and civil defense improvements both reduced Israel’s losses slightly during Pillar of Defense and substantially during Protective Edge. They also imply that interceptor performance during Pillar of Defense may have been overstated. Ground offensives were the most expensive way to prevent rocket casualties. Interceptors were at least as cost-effective as military offensives, and improved over time. Without its countermeasures, Israel’s rocket casualties could have been over fifty times higher during Protective Edge. These results imply that Israel’s rocket concerns were more justified than critics admit, but its military operations were less worthwhile than intended.

Keywords: Arab-Israeli conflict; counterterrorism; missile defense; Gaza

Introduction

From 2005 to 2014, militants such as Hamas in the Gaza Strip and Hezbollah in Lebanon fired over 16,510 rockets carrying roughly 260 metric tons of warheads into Israel, causing 2,605 wounded or dead and over $160 million in property damage. In defense, Israel spent billions of dollars (including over $1 billion of American aid) on interceptors, shelters, and sirens. It also ran three military operations against Gaza that cost the Israeli Defense Forces (IDF) about $3.6 billion and 536 casualties, and inflicted substantial collateral damage on civilians there.

There has been much controversy as to whether those operations were justified. Some observers consider the rocket attacks a “strategic threat” (Rubin 2011), while others discount them (Perry 2014). Controversy also surrounds Israel’s Iron Dome interception system. While some call it a “game changer” (Hamilton 2012), others question its effectiveness (Broad 2013), or its effects on peace efforts and defense priorities (Kober 2013; Shapir 2013a; 2013b).

Given these issues, this essay analyzes rocket attacks and defenses in Israel during Operation Protective Edge in 2014, Operation Pillar of Defense in 2012, Operation Cast Lead in
2008-2009, and the Second Lebanon War in 2006. It leaves aside their political, diplomatic, legal, and ethical dimensions, as well as their effects on Gaza’s civilians. It focuses instead on the effectiveness and efficiency of Israeli countermeasures as tools for reducing rocket losses. Are offensives against Gaza worthwhile? Are ground assaults needed, or are airstrikes sufficient? Is rocket effectiveness declining (Hamilton 2012; Rubin 2015)? If so, is that due to interceptor batteries or to civil defenses? If those measures work, are they economical?

The study begins by calculating fatality, casualty, and property damage rates per rocket for each operation. The data available from public sources is limited, and its analysis necessarily employs several approximations. The resulting numbers therefore are only rough estimates; they are calculated to several decimal places simply to prevent rounding errors. Nonetheless, they enable many qualitative comparisons.

The loss rates show that ground assaults reduced rocket fire day-to-day within each Gaza operation, but airstrikes alone did not. They also confirm that per-rocket effectiveness has been decreasing, despite increases in volume, range, consistency, and warhead size.

The study then compares these loss rates to infer whether the decreasing rocket effectiveness should be attributed to interceptor deployment and/or civil defense improvements. The calculations suggest that Iron Dome batteries intercepted less than 32 percent of all hazardous rockets during Pillar of Defense, but between 59 and 75 percent during Protective Edge. Civil defense improvements further reduced casualties by up to 36 percent for the former operation, and between 57 and 75 percent for the latter one. The declining casualty rates highlight the growing relative importance of the conflict’s economic aspects. The calculations also suggest the possibility that during Pillar of Defense the number of rockets hitting populated areas was understated while the number threatening them was overstated, implying that Iron Dome’s effective interception rate may have been significantly lower than reported.

Without these countermeasures, Israel could have suffered some 4,500 rocket casualties during Protective Edge, over 50 times the actual number. This indicates that Israel’s justification for responding militarily to rocket attacks was stronger than it might appear. When judging the country’s actions, observers should consider not only the hundreds of casualties it actually experienced, but also the thousands more it could have suffered.

The research also estimates the costs of Israel’s countermeasures for the stated goal of preventing rocket losses. Preemptively destroying rockets in Gaza via military operations, especially ground assaults, incurred high costs while preventing few casualties. The marginal cost for each rocket casualty prevented was roughly $3.8 million for Cast Lead and $1.6 million for Pillar of Defense, while Protective Edge saw more Israeli casualties than the destroyed rockets would have caused. By comparison, interception grew increasingly cost-competitive over time. Its marginal cost per casualty prevented exceeded $1.7 million during Pillar of Defense, but fell to between $0.4 and $1.1 million during Protective Edge. Finally, civil defenses prevented the most casualties with the lowest marginal costs.

The paper concludes by discussing its implications and limitations. Most of its data and calculation details are provided in an online Excel file appendix.
Rocket Data and Calculations

This section describes the rocket data for each conflict and estimates metrics for comparing them. The data mostly come from the Israeli Security Agency (ISA) online archive of annual (e.g., ISA 2014) and monthly (e.g., ISA 2014 August) reports. Where those reports combined casualties from rockets and mortars, the rocket ones were estimated via pro-rating. (About 6839 mortar shells were fired at Israel during 2005-2014 (ISA 2014).) This paper analyzes casualties (dead plus wounded) as well as fatalities (dead) to more broadly measure the attacks’ human impact (Fazal 2014) and help corroborate the results.

Attacks Outside of Operations, 2005-2014

While the first rockets from Gaza landed in Israeli in 2001, the attacks “transformed from nuisance to strategic threat” (Rubin 2011) after the IDF’s withdrawal in 2005. Table 1 shows the rockets fired and casualties inflicted each year from 2005 to 2014, excluding those during IDF operations (ISA 2006 to 2014). The rockets also damaged property, reduced economic output, and increased psychological stress.

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockets</td>
<td>401</td>
<td>1726</td>
<td>1276</td>
<td>1791</td>
<td>166</td>
<td>150</td>
<td>419</td>
<td>821</td>
<td>63</td>
<td>205</td>
<td>7018</td>
</tr>
<tr>
<td>Casualties</td>
<td>56</td>
<td>165</td>
<td>157</td>
<td>167</td>
<td>18</td>
<td>1</td>
<td>24</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>600</td>
</tr>
</tbody>
</table>

The attacks included a variety of unguided artillery rockets; for specifications see Federation of American Scientists (1999) or Dullum (2009). The locally produced short range Qassams were the most common. They increased in size during this period, with warhead weights growing from 5 to 15 kg, and ranges extending up to 17 km. Medium range rockets like Grads were also common, and carried 18-21 kg warheads up to 45 km. Long range M75 and Fajr-5 rockets were rare. All are relatively inaccurate and best suited to large area targets.

Several analysts have noted declining rocket lethality over this period. Rubin (2011, 21-22) estimated that the average number of rockets fired per fatality climbed from about 100 in 2002 up to 2,100 by 2008. Hamilton (2012) reported a similar trend, from between 50 and 75 rockets per fatality in the early 2000s, up to 500 in 2012, despite larger warheads. Figure 1 shows a corresponding downward trend in casualty rates per rocket. The decade’s overall average was 0.085 casualties per rocket (or about 12 rockets per casualty), but this fell from 0.1049 for 2005-2009 to just 0.0223 for 2010-2014.
Figure 1. Casualties per rocket fired outside of major operations.

Operation Protective Edge, 2014

Israel launched Operation Protective Edge in 2014 to “stop Hamas’ incessant rocket attacks against Israel’s civilians” (IDF 2014b) and “restore sustained calm and security to the Israeli civilian population.” (State of Israel 2015, 22). It began with airstrikes from July 8 to 17, followed by ground combat from July 18 to August 4. Alternating skirmishes and ceasefires ensued from August 5 to 26, including eight days without rocket fire. The IDF claimed to have destroyed 3000 rockets on the ground, plus other targets (Yaakov 2014).

Figure 2. Daily rocket fire during Protective Edge’s air and ground phases.

Each day the IDF (2014a; 2014b; 2014c) announced tentative rocket counts; see Figure 2. The heaviest fire came on July 10, when 192 rockets launched and 185 arrived in Israel. July 26
fire was low due to a brief cease-fire. An IDF summary reported 3356 rockets fired as of August 4: 475 misfired or landed within Gaza, 578 were intercepted, 116 hit “populated areas”, and 2187 landed elsewhere (Yaakov, 2014); it did not define “populated areas”. The ISA (2014) later reported 2968 rockets and 1724 mortar shells launched during the operation. Some 1963 rockets (presumably Qassams) flew under 20 km, 760 (presumably Grads) flew 20 to 50 km, and 255 traveled over 50 km into Israel (ISA 2014 July; 2014 August).

To counter this barrage, Israel deployed seven Iron Dome batteries before the operation and three more during the first week (Lappin 2014), though one remained unstaffed (David 2014). Reports variously said the batteries intercepted 735 of the 799 rockets and shells they engaged (Ginsburg 2015), 89.6 percent of their targets (Harel and Cohen 2015), or 83 percent of all rockets headed into populated areas (Richardson, 2014b).

July (Hartman and Udasin 2014) and August (ISA 2014 August) each saw one rocket death. The ISA (2014) reported 110 civilians wounded by mortar and rocket fire, while the Ministry of Foreign Affairs (2014) reported 126. For August, the ISA (2014 August) reported 30 people wounded by rockets and 10 by mortars; it did not give a breakdown for July. The Israeli Tax Authority received 4600 insurance claims worth $38.9 million (133 million shekels) for property damaged by rockets or mortars (Azulai 2014). The Bank of Israel estimated the economy suffered $1 billion (3.5 billion shekels) of indirect losses (Globes 2015). The government budgeted $225 million of American aid to replenish its supply of Tamir interceptors, nominally priced at $100 thousand each (Dagoni 2014). Estimates for the military operation’s cost ranged from $1.9 to $2.6 billion (6.5 to 9 billion shekels) (Barkat 2014), plus 67 IDF soldiers killed (ISA 2014) and 469 wounded (Hartman 2014).

Table 2. Rocket data summary.

<table>
<thead>
<tr>
<th></th>
<th>Second Lebanon</th>
<th>Cast Lead</th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days of fighting</td>
<td>33</td>
<td>23</td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>Rockets fired</td>
<td>&gt;3970</td>
<td>660</td>
<td>1506</td>
<td>&gt;3356</td>
</tr>
<tr>
<td>Rockets arriving</td>
<td>3970</td>
<td>617</td>
<td>1354</td>
<td>2968</td>
</tr>
<tr>
<td>Rockets hitting</td>
<td>901</td>
<td>?</td>
<td>58</td>
<td>120</td>
</tr>
<tr>
<td>Daily average arriving</td>
<td>120.3</td>
<td>26.8</td>
<td>169.3</td>
<td>70.7</td>
</tr>
<tr>
<td>Percent long range</td>
<td>6.3</td>
<td>0.0</td>
<td>0.7</td>
<td>8.6</td>
</tr>
<tr>
<td>Dead</td>
<td>42</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Wounded</td>
<td>1489</td>
<td>141</td>
<td>240</td>
<td>83</td>
</tr>
<tr>
<td>Damage claims</td>
<td>26,653</td>
<td>1475</td>
<td>3921</td>
<td>3450</td>
</tr>
<tr>
<td>Damage $ millions</td>
<td>108</td>
<td>8.1</td>
<td>14.8</td>
<td>29.2</td>
</tr>
<tr>
<td>Preemptions</td>
<td>300</td>
<td>1200</td>
<td>980</td>
<td>3000</td>
</tr>
<tr>
<td>Interceptions</td>
<td>-</td>
<td>-</td>
<td>421</td>
<td>595</td>
</tr>
<tr>
<td>Resupply $ millions</td>
<td>-</td>
<td>-</td>
<td>200</td>
<td>182</td>
</tr>
<tr>
<td>Iron Dome batteries</td>
<td>-</td>
<td>-</td>
<td>4+1</td>
<td>7+3</td>
</tr>
</tbody>
</table>

The IDF summary indicates 475 / 3356 = 14.15 percent of fired rockets remained in Gaza and 85.85 percent arrived over Israeli. Of those arrivals, 20.06 percent were intercepted, 4.03
percent hit populated areas, and 75.91 percent landed elsewhere. This means that 24.09 percent of the arrivals were “threats” that either hit populated areas or were intercepted; and that batteries claimed interception of 83.29 percent of those threats. Applying the arrival breakdown to the ISA’s 2968 arriving rockets implies 715 threats, 595 interceptions, 120 populated area hits, and 2253 landings elsewhere. The daily average across the 42 days of fighting was 70.7 rockets arriving per day, or 7.86 arrivals daily per active battery. The peak rate per battery was 26.43 arrivals on July 10. Long range rockets (reaching over 50 km) made up 8.6 percent of the arrivals. Table 2 summarizes this data.

The ISA reported that rockets caused $30 / (30+10) = 75$ percent of August’s civilian wounded; assuming July was similar, the civilians wounded by rockets totaled $110 \times 0.75 = 83$. This gives $83 + 2 = 85$ rocket casualties in total, and 41.5 times as many wounded as killed. Applying the 75 percent share to property damage gives 3450 claims worth $29.2$ million and averaging $8457$ each. There were 1725 claims per fatality and 40.59 claims per casualty. For the IDF, the wounded-to-dead ratio was $469 / 67 = 7$. If rockets consumed $595 / 735 = 81$ percent of the expended interceptors, then their share of the resupply cost was $182$ million.

Casualties per arriving rocket averaged $85 / 2968 = 0.0286$, slightly above the 2010-2014 “peacetime” average of 0.0223. The casualty rate can instead be expressed as $85 / 715 = 0.1189$ per threatening rocket or $85 / 120 = 0.7083$ per hitting rocket. Table 3 shows these rates, plus those for fatalities and claims.

For the air phase, linear regression of the daily number of rockets fired against calendar days showed no statistically significant trend, indicating the airstrikes did not change the rate from day to day within the operation (regression $p = 0.836$; see details in Excel appendix). The rate had a mean of 141.9, standard deviation of 23.57, and coefficient of variation of $23.57 / 141.9 = 0.166$. About 95.2 percent of fired rockets arrived over Israel, 21.5 percent of arrivals were threats, and 90.4 percent of threats were intercepted.

### Table 3. Calculated loss rates per rocket.

<table>
<thead>
<tr>
<th></th>
<th>Second Lebanon</th>
<th>Cast Lead</th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatalities per arrival</td>
<td>0.0106</td>
<td>0.0049</td>
<td>0.0037</td>
<td>0.0007</td>
</tr>
<tr>
<td>Fatalities per threat</td>
<td>0.0466</td>
<td>-</td>
<td>0.0104</td>
<td>0.0028</td>
</tr>
<tr>
<td>Fatalities per hit</td>
<td>0.0466</td>
<td>-</td>
<td>0.0862</td>
<td>0.0167</td>
</tr>
<tr>
<td>Casualties per arrival</td>
<td>0.3856</td>
<td>0.2334</td>
<td>0.1809</td>
<td>0.0286</td>
</tr>
<tr>
<td>Casualties per threat</td>
<td>1.6992</td>
<td>-</td>
<td>0.5115</td>
<td>0.1189</td>
</tr>
<tr>
<td>Casualties per hit</td>
<td>1.6992</td>
<td>-</td>
<td>4.2241</td>
<td>0.7083</td>
</tr>
<tr>
<td>Claims per arrival</td>
<td>6.714</td>
<td>2.391</td>
<td>2.896</td>
<td>1.162</td>
</tr>
<tr>
<td>Claims per threat</td>
<td>29.582</td>
<td>-</td>
<td>8.186</td>
<td>4.825</td>
</tr>
<tr>
<td>Claims per hit</td>
<td>29.582</td>
<td>-</td>
<td>67.603</td>
<td>28.750</td>
</tr>
<tr>
<td>Claims per fatality</td>
<td>635</td>
<td>492</td>
<td>784</td>
<td>1725</td>
</tr>
<tr>
<td>Claims per casualty</td>
<td>17.41</td>
<td>10.24</td>
<td>16.00</td>
<td>40.59</td>
</tr>
</tbody>
</table>

For the ground phase, regression again found no trend ($p = 0.348$). The daily rocket fire had a mean of 89.56, standard deviation of 30.41, and coefficient of variation of 0.340. Some
88.2 percent of fired rockets arrived, 18.4 percent of arrivals were threats, and 94.3 percent of threats were intercepted. The air and ground phases had statistically significant differences in their fire means (t-test p = .000), arrival percentages (z-test p = .000) and threat percentages (z-test p = .048). Thus, the quantity and quality of the fire were lower during the land phase than during the air phase.

**Operation Pillar of Defense, 2012**

Operation Pillar of Defense consisted of airstrikes from November 14 to 21, 2012, that claimed 980 rocket launchers. It was “launched in response to incessant rocket attacks .... to cripple terror organizations in the Gaza Strip and defend Israelis living under fire.” (IDF 2012b). The IDF (2012a) counted 1506 rockets fired: 152 stayed in Gaza, 875 landed in open areas, 421 were intercepted, and 58 hit “urban areas”. Figure 3 displays the daily counts. Only 10 long range rockets arrived (ISA 2012b). Israel started with four Iron Dome batteries near Gaza, and later added a fifth farther north (Agence France Press 2012).

**Figure 3.** Daily rocket fire during Pillar of Defense.

The ISA (2013) reported 5 killed and 232 wounded by rockets, while the IDF (2012a) reported 240 wounded. There were 3921 damage claims worth $14.81 million (57.4 million shekels) (Rubin 2015, 2013). The indirect cost to the Israeli economy was $240 million (1 billion shekels). The government spent $285 million (1.2 billion shekels) for the military operation, and another $200 million from the U.S.A. (Lev 2012) to replenish its nearly depleted interceptor supply (Bergman 2014).

The calculations follow the same logic as before. About 10.09 percent of fired rockets stayed in Gaza and 89.91 percent arrived over Israel. Of the 1354 arrivals, 31.09 percent were intercepted, 4.28 percent hit urban areas, and 64.62 percent landed elsewhere. Thus 35.37 percent (479) of arrivals were threats, of which 87.89 percent were intercepted. The daily averages were 188.3 rockets fired and 169.3 arriving. Long range rockets made up 0.74 percent of the arrivals. Property damage claims averaged $3777. There were 48 times more wounded than dead civilians. The average battery in southern Israel faced a mean of 42.03 and a peak of 71.02 arriving rockets per day. The daily fire had a mean of 188.3, a standard deviation of 76.21, a coefficient of variation of 0.405, and no significant trend (regression p = 0.700).
Operation Cast Lead, 2008-2009

Operation Cast Lead began with airstrikes from December 27, 2008 to January 2, 2009, followed by land battles from January 3 to 18 (see, e.g., Farquhar 2009; Rubin 2009). The goal was to “stop Hamas’ almost incessant rocket and mortar attacks upon thousands of Israeli civilians and its other acts of terrorism.” (State of Israel 2009, 1). The IDF destroyed 1200 rockets (Sharnoff 2009). The government’s final report estimated 617 rockets and 178 mortar shells landed in Israel, killing 4 and wounding 182; 6.5 percent of all rockets fired remained within Gaza (Israel 2009, 23). The ISA (2008; 2009) reported 664 rockets and 257 mortar shells launched. Another source (Journal of Palestine Studies 2009, 201-206) said 640 rockets and 162 shells, and gave daily counts; see Figure 4. About 230 were Grads, while the rest were Qassams (Rubin 2015, 25). The number hitting populated areas is unknown. There were 1900 property damage claims worth $10.4 million (40 million shekels) from the combined fire (Sderot 2010; Kana and Avital 2012). IDF cost estimates ranged from $0.9 to $1.3 billion (3.57 to 5 billion shekels) (Lehav 2014; Filut 2009); 10 soldiers died (Reuben 2014).

Given 617 arrivals and 6.5 percent of fired rockets falling short, there were 43 short and 660 fired. This gives daily averages of 28.7 fired and 26.8 arriving; the peak day saw 62 fired. There were 45.5 times as many wounded as dead civilians. Since 77.61 percent of the arriving rounds were rockets, about 141 wounded, 3 dead, and 1475 damage claims worth $8.1 million ($5492 each) can be attributed to them. Assuming the same 7-to-1 IDF wounded-to-dead ratio of Protective Edge, there might have been 70 wounded soldiers.

Figure 4. Daily rocket fire during Cast Lead.

![Figure 4](image-url)

During the air phase, the daily rocket fire showed no trend (regression $p = 0.773$). It had a mean of 45.29, standard deviation of 18.30, and coefficient of variation of 0.404. The fire during the land phase decreased by 0.79 rockets per day (regression $p = 0.030$ and $R^2 = 29.2$ percent). It had a mean of 20.19, standard deviation of 6.93, and coefficient of variation of 0.343. The difference in means was statistically significant ($t$-test $p = .013$). Thus, the rate of fire was not reduced by airstrikes, but decreased after the army advanced.
Second Lebanon War, 2006

The Second Lebanon (or Israeli-Hezbollah) War consisted of airstrikes and ground combat against Hezbollah militants in Lebanon from July 13 to August 14, 2006 (Cordesman 2007; Harel and Issacharoff 2008). The airstrikes claimed over 300 long range rockets (Cordesman 2007, 123), but had little impact on daily fire (Harel and Issacharoff 2008, 96). Police reported 972 rockets hitting “built-up areas”, 3256 in open areas, and 53 deaths. Between 33 and 250 rockets arrived each day. Almost all were Grads, but 250 (perhaps Fajr-5) landed over 50 km inside Israel (Rubin 2006). The IDF reported 901 rockets hitting “population centers” and 3069 in rural areas, leaving 42 dead and 1489 wounded (Cordesman 2007, 103). There were 26,653 property claims worth $108.1 million (479 million shekels) (Rubin 2015, 29). Indirect economic losses totaled $1.6 billion and the operation cost $3 billion (Eis 2012); 120 soldiers died (Cordesman 2007, 17).

The IDF numbers indicate 120.3 rockets arrived daily on average; 22.70 percent hit population centers and 6.3 percent penetrated over 50 km. Civilian casualties totaled 1531, with 35.5 times as many wounded as dead. Damage claims averaged $4056 each.

Rocket Fire Trends

Over 9,492 rockets were fired at Israel during its four operations, causing 2,005 casualties (including 52 fatalities) and 35,499 damage claims worth $160 million. Adding the peacetime counts from Table 1 brings the totals to 16,510 rockets and 2,605 casualties. The preceding calculations indicate two general trends: increasing scale and decreasing effectiveness.

Increasing Scale

Between 2008 and 2014, rocket fire from Gaza grew more comparable to that from Lebanon in 2006. The volume of fire and the proportion of long range rockets both increased, thereby threatening more of Israel’s territory, population, and economy.

The amount of explosives also increased. During Second Lebanon, about 3720 Grads and 250 long range rockets struck Israel. Since Grad warheads weigh about 20 kg and the long range warheads likely weighed 175 kg (Cordesman 2007), the warhead weight totaled about 118.2 metric tons and averaged 29.76 kg per rocket. Cast Lead involved 230 Grads and 387 Qassams. If the Qassam warheads averaged 7.5 kg (Rubin 2011, 21) each, then the barrage totaled 7.5 tons at 12.16 kg per rocket. Protective Edge included 255 long range, 760 medium range (presumably Grads), and 1953 short range rockets (presumably advanced Qassams). Assuming 20 kg warheads for the two former types (Rubin 2015, 13) and 12.5 kg for the Qassams gives 44.7 tons total and 15.07 kg on average. If the Grad-Qassam mix for Pillar of Defense was half-way between Cast Lead and Protective Edge, with 20 kg Grads and 10 kg Qassams, then it totaled 18.4 tons at 13.57 kg per rocket. Similar estimates indicate about 73 tons between operations, putting the decade’s warhead total at 262 tons, or about 8.3 B-52H bomber payloads (USAF 2005). (These estimates are rough; it is unlikely Cast Lead’s mean was exactly 29.76 – 12.16 = 17.60 kg below Second Lebanon’s. However, the true difference was surely closer to that, than to the zero implied by treating all rockets equally.)
Table 4 shows these warhead averages and totals. It also converts the losses per arriving rocket from Table 3 into losses per arriving metric ton of warheads. For example, Cast Lead’s claims rate becomes $2.391 \times 1000 / 12.16 = 196.5$ claims per ton. From this “throw weight” perspective, Protective Edge losses seem much lower than those of earlier operations.

<table>
<thead>
<tr>
<th></th>
<th>Second Lebanon</th>
<th>Cast Lead</th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean warhead kg</td>
<td>29.76</td>
<td>12.16</td>
<td>13.57</td>
<td>15.07</td>
</tr>
<tr>
<td>Total warhead tons</td>
<td>118.2</td>
<td>7.51</td>
<td>18.38</td>
<td>44.72</td>
</tr>
<tr>
<td>Claims per ton</td>
<td>225.6</td>
<td>196.5</td>
<td>213.3</td>
<td>77.16</td>
</tr>
<tr>
<td>Fatalities per ton</td>
<td>0.3555</td>
<td>0.3997</td>
<td>0.2720</td>
<td>0.0447</td>
</tr>
<tr>
<td>Casualties per ton</td>
<td>12.96</td>
<td>19.19</td>
<td>13.33</td>
<td>1.901</td>
</tr>
</tbody>
</table>

In terms of the numbers of rockets, Pillar of Defense saw the heaviest daily rate, largely due to its lack of ground combat. Its average was 139 percent higher than that of Protective Edge overall, but only 19 percent higher than the air phase. The remaining difference may have been due to militants firing from tunnels during Protective Edge to reduce their airstrike exposure (Rubin 2015, 21). This slower fire was also more consistent day-to-day: the coefficient of variation (which measures variability relative to the average) was just 0.166 during the Protective Edge air phase, less than half that of Cast Lead’s air phase (0.404) or of air-only Pillar of Defense (0.405). The militants apparently had improved their ability to operate during airstrikes, perhaps due to their tunnels. Although airstrikes may have helped reduce the average rate of fire from what it could have been, and they destroyed many rockets (i.e., reduced the rocket stockpiles) during each operation, they did not decrease the number fired day to day within any of the operations; the militants apparently were able to protect or replace their launch crews and equipment. The daily rate decreased only after ground units advanced, indicating that control of the ground was needed for control of the air.

**Decreasing Effectiveness**

While the scale of fire increased, Table 3 shows that its effectiveness per rocket decreased. That is, the number of fatalities, casualties, and claims per arriving rocket generally declined over time. This is similar to the decreases in casualty rates shown in Figure 1, and in fatality rates noted by other observers. The largest drops occurred between Second Lebanon and Cast Lead, where, e.g., the claims rate fell 64 percent, from 6.714 to 2.391. Table 3 also shows fatality and casualty rates falling faster than claim rates, making claims relatively more numerous; e.g., the ratio of claims to casualties increased from 10.21 for Cast Lead to 40.59 for Protective Edge. This highlights the increasing economic aspects of the conflicts. The next section explores some potential explanations for the decreasing effectiveness.

**Evaluating Rockets, Interceptors, and Civil Defenses**

**Potential Influences**

Iron Dome’s deployment has received much of the credit for the declining loss rates (Hamilton 2012; Rubin 2015, 27). The first battery arrived in March 2011; two more deployed
by August (Katz 2011), the fourth in March 2012 (Shapir 2013b) and the fifth during Pillar of Defense. Israel added two more batteries before Protective Edge and three during it. The technology reportedly cost over a billion dollars to develop, followed by the costs of battery construction ($50 million each), interceptor resupply, and ongoing upkeep (Reuters 2014).

Civil defenses have also been credited for reducing losses (Postol 2014; Rubin 2011, 22). Israel’s spending on shelters and reinforced buildings totaled $384 million from 2005 to 2012 (State of Israel 2015, 110); by 2014, over 70 percent of homes had shelters (Lappin 2016a). In 44 communities near to Gaza, 10,140 home shelters have been constructed (Kamisher 2016). Israel’s $140 million investment in warning systems (Israel 2015, 110) has yielded increasingly precise alerts. The country was divided into only 25 warning zones in 2006, but 127 in 2012, 200 in 2014, and 248 in 2015 (Isby and Richardson 2014; Lappin 2015); 3000 zones are expected by 2018 (Cohen 2016).

Many other factors could also influence loss rates, such as changes in rocket warheads, attackers’ tactics, and targets’ population densities. This paper estimates the changes that can be attributed to warhead size differences, interceptor deployment, and civil defense improvements, while initially assuming all other factors had negligible influence. The following conceptual equation illustrates how loss rates change as a product of these factors.

\[
\text{Loss per rocket} = (\text{Warheads})(\text{Interceptors})(\text{Civil defenses})(\text{Other factors})
\]

While imperfect, this analysis is much more detailed than previous ones. For example, Hamilton (2012) and Rubin (2013, 2015) attributed decreasing loss rates entirely to interception while ignoring other factors. Conversely, Postol (2014) discounted interception and credited the low rates largely to civil defense.

The analysis first estimates the influence of changing warhead sizes. Next, it uses the following logic to distinguish between interceptor and civil defense influences. Interceptors prevent harm to both people and property, whereas civil defenses primarily prevent harm to people. If only civil defenses improve, there should be little change in claim rates, while fatality and casualty rates should decline. If only interception improves, there should be equal declines in claim, casualty, and fatality rates. If both countermeasures improve, there should be small decreases in claim rates, plus large decreases in casualty and fatality rates.

Table 3 already hints that all three factors matter. The large rate drops between Second Lebanon and Cast Lead correspond to decreased warhead weights. The further decreases for Pillar of Defense and Protective Edge suggest the interceptors’ influence. The fact that casualties and fatalities fell faster than claims suggests that civil defense improvements also helped. The following subsections investigate these influences in more detail.

**Warhead Sizes**

Warhead sizes differed materially between operations, but a warhead that is twice as large does not necessarily cause twice the loss. One way to account for this is to compare their relative blast areas. (A simpler comparison based directly on warhead weights will be mentioned...
Blast pressure at a given distance from an explosion is proportional to explosive mass taken to the one-third power (FEMA 2003), while the affected circular area is proportional to that radius squared. Thus, the lethal blast area of 20 kg of explosives is \((20/10)^{1/3})^2 = 2^{2/3} = 1.587\) times as large as that of 10 kg.

To compare operations, each row of Table 5 shows a warhead mass, that mass taken to the two-thirds power (i.e., to represent the nominal blast area), and the numbers of those warheads per operation; the bottom row shows the weighted average area by operation. For example, Second Lebanon had 250 warheads of 175 kg and 3720 of 20 kg; its weighted average area was \((250 \times 175^{2/3}) + (3720 \times 20^{2/3}) / (250 + 3720) = 8.874\). These nominal averages are used in the next sub-section’s interception calculations.

### Table 5. Relative blast area comparison using warhead weights and rocket counts.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Mass^{2/3}</th>
<th>Second Lebanon</th>
<th>Cast Lead</th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>175 kg</td>
<td>31.287</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 kg</td>
<td>7.368</td>
<td>3720</td>
<td>230</td>
<td>484</td>
<td>1015</td>
</tr>
<tr>
<td>15 kg</td>
<td>6.082</td>
<td>194</td>
<td></td>
<td>870</td>
<td>977</td>
</tr>
<tr>
<td>10 kg</td>
<td>4.642</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 kg</td>
<td>2.924</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean relative area</td>
<td>8.874</td>
<td>5.121</td>
<td>5.616</td>
<td>6.048</td>
<td></td>
</tr>
</tbody>
</table>

### Interceptor Metrics and Controversies

There are several ways to quantify the performance of interceptor systems like Iron Dome, depending on which rockets are considered. The interception rate is the percentage of rockets destroyed before they hit defended areas; it ignores rockets over undefended areas. It provides a tactical measure of a battery’s performance against the rockets it directly faced. Israel reports average interception rates for Iron Dome, but they cannot be confirmed from public data.

The single-shot kill probability provides a more technical measure that is particularly relevant for engineering analysis. It represents the success rate of individual interceptor-versus-rocket engagements, and only considers rockets that were engaged. This is a very useful metric, but cannot be derived from public data.

The data does allow calculation of “aggregate” measures like the percentage of arriving rockets intercepted. These measures consider all rockets, whether headed toward defended areas or elsewhere. They represent how well the batteries protected the country overall, making them suitable for strategy and policy analysis. This paper analyzes such metrics.

Israel claims very high interception rates for Iron Dome. Ginsburg (2015) reported the batteries intercepted 735, or 91.99 percent, of the 799 rockets and mortar shells engaged during Protective Edge. Harel and Cohen (2015) said the batteries intercepted 85 percent of their targets during Pillar of Defense and 89.6 percent during Protective Edge.
However, Pedatzur (2013) and others have challenged these claims. Intercepting a ballistic rocket, as opposed to a more vulnerable cruise missile (Armstrong 2014b), requires breaking apart the warhead. Merely damaging the metal casing is inadequate, as the rocket could continue along its original trajectory, or another equally dangerous one. The controversy arises because public photographs lack enough detail to confirm the warheads’ destruction.

The controversy is also partly due to tendencies for missile defense advocates to overstate systems’ capabilities. For example, during the 1991 Gulf War, American Patriot batteries initially reported intercepting 95 percent of incoming Scud missiles, but later reduced that to 59 percent; some analysts suggest it was below 10 percent (Postol 1991; Sullivan et al 1999). More recently, Israel’s Defense Ministry was accused of exaggerating test results for its Arrow interceptors (Melman 2014; Cohen 2014).

Iron Dome critics have advanced two main arguments. The first notes that the interception claims seem unbelievably good for such a challenging task, and those claims cannot be verified independently. It is consequently possible that the actual performance was worse than claimed, or even that some reportedly intercepted rockets never really existed (Globes 2014). The claims also are often vague or mistaken regarding the rockets they include. (Even Rubin (2015, 11) has complained about this lack of clarity.) For example, one military interview said the IDF managed to “successfully intercept 85 percent of 1500 rockets” during Pillar of Defense and “up to 90 percent out of 4700 rockets” during Protective Edge (Lapidot 2015); but most of those rockets were not even engaged.

A better-substantiated criticism comes from assessments of the Tamir interceptors’ behavior. Theodore Postol and Richard Lloyd separately studied videos and photos of interception attempts. They used the images to estimate kill probabilities, and then inferred the interception rates. Based on the Tamirs’ approach trajectories and design, they argued that most attempts probably did not destroy the rockets. Lloyd (2014) estimated effective interception rates of 30 to 40 percent, while Postol (2014) put them below 5 percent. They also noted that while the IDF reported 58 rocket hits on urban areas during Pillar of Defense, Israeli police reported 109 (Pedatzur 2013). (The IDF and police may count “hits” differently because of their different roles. E.g., if a rocket breaks in half during flight, the IDF might record one rocket launching while police investigate two rocket landings.)

Proponents of Iron Dome have responded with two main rebuttals. The first notes that critics rely on amateur photos and videos of lower quality than those of the IDF. Consequently, the IDF claims should be more credible (Richardson 2014a; Shapir 2013a).

The second counterargument compares loss rates from different conflicts. Rubin (2015) noted that the fatalities and damage claims per rocket fired had decreased between Second Lebanon, Pillar of Defense, and Protective Edge; notably, he omitted Cast Lead and discounted any improvements in civil defenses. He argued that the batteries therefore must have been effective; otherwise, the loss rates would have been much higher. Rubin (2013) similarly compared Second Lebanon and Pillar of Defense, arguing that without Iron Dome the latter would have had 14,400 damage claims instead of 3,165.
Comparing Losses to Arrivals: Interception

This sub-section analyzes losses per arriving rocket to see what they suggest. Since neither Cast Lead nor Second Lebanon had batteries, they can serve as baselines for estimating interceptor effectiveness during the later operations. Cast Lead is the more obvious choice because it occurred in the same part of Israel as Pillar of Defense and Protective Edge. The analysis includes Second Lebanon as a second baseline to give a sense of the estimates’ uncertainty and allow comparisons with earlier studies (e.g., Rubin 2013; 2015).

The first step is to take the loss rates from Table 3 and scale them as proportions of the Second Lebanon rates after adjusting for warheads’ average blast areas. For example, expressing the claims rate for Protective Edge as a proportion of Second Lebanon’s gives (1.162 / 6.714)(8.874 / 6.048) = 0.2540. That is, Protective Edge saw only 25 percent as many claims as Second Lebanon, or 75 percent less, after considering warhead differences. Table 6 displays these loss rate proportions.

<table>
<thead>
<tr>
<th></th>
<th>Second Lebanon</th>
<th>Cast Lead</th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claims</td>
<td>1</td>
<td>0.6171</td>
<td>0.6816</td>
<td>0.2540</td>
</tr>
<tr>
<td>Fatalities</td>
<td>1</td>
<td>0.7965</td>
<td>0.5515</td>
<td>0.0935</td>
</tr>
<tr>
<td>Casualties</td>
<td>1</td>
<td>1.0488</td>
<td>0.7414</td>
<td>0.1090</td>
</tr>
</tbody>
</table>

Table 7 similarly shows the adjusted loss rates as proportions of Cast Lead’s. There, the Protective Edge rate relative to Cast Lead was 0.4117, or 59 percent lower. Thus Tables 5 and 6 suggest that during Protective Edge, Iron Dome intercepted between 59 and 75 percent of all hazardous rockets, whether headed toward defended areas or elsewhere.

<table>
<thead>
<tr>
<th></th>
<th>Cast Lead</th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claims</td>
<td>1</td>
<td>1.1045</td>
<td>0.4117</td>
</tr>
<tr>
<td>Fatalities</td>
<td>1</td>
<td>0.6925</td>
<td>0.1173</td>
</tr>
<tr>
<td>Casualties</td>
<td>1</td>
<td>0.7069</td>
<td>0.1039</td>
</tr>
</tbody>
</table>

For Pillar of Defense, the adjusted claims rate was 32 percent lower than that of Second Lebanon but 10 percent higher than that of Cast Lead, suggesting the batteries intercepted at most 32 percent of the hazardous rockets, and perhaps much less. The fact that one calculation shows increased claims indicates the uncertainty in the estimates, and suggests Iron Dome’s influence may have been small enough to be overshadowed by changes in other factors. Figure 5 illustrates the estimates for each operation versus the two baselines, along with their means. It highlights how interception was far less influential for Pillar of Defense than for Protective Edge.
The interception calculations above, including Tables 5 to 7, try to account for the complexities of rocket hits by assuming that losses are roughly proportional to warhead mass taken to the two-thirds power. A simpler approach could assume instead that losses are proportional to the warhead mass itself; e.g., a 20 kg warhead causes twice the loss of a 10 kg one. The calculations for this alternative are provided in the appendix, using the loss per ton values from Table 4. Those results show that during Protective Edge, claims rates decreased between 61 and 66 percent relative to the two baselines. During Pillar of Defense, the claims rate estimates range from a 5 percent decrease to a 9 percent increase. That is, the interception estimates from this simpler approach are slightly lower and much narrower than the ones calculated previously. But they still indicate substantial benefits during Protective Edge and marginal ones during Pillar of Defense.

More complex calculations might try to account for the physics of fragmentation (Zucker and Kaplan 2014), explosive content of the warheads, kinetic energy of the rocket casings, etc. However, that extra complexity is not worthwhile here, given the limited data.

Comparing Losses to Arrivals: Civil Defense

The next step is to estimate the effects of civil defense improvements by comparing fatality and casualty rates to the corresponding claims rates from Table 3. For example, Protective Edge saw 1725 claims per fatality, whereas Second Lebanon had 635. This means Protective Edge had 1725 / 635 = 2.718 times fewer fatalities per claim, or that fatalities decreased by proportion 1 – (635 / 1725) = 1 – 0.3679 = 0.6319, or 63 percent.

Comparing scaled proportions from Table 6 is another way to reach the same result. The Protective Edge claims rate after warhead adjustments is 0.2540, or 25.4 percent of Second Lebanon’s; interception presumably also reduced casualties to that extent. However, the Protective Edge fatality rate was only 0.0935, or 9.35 percent. The ratio 0.0935 / 0.2540 = 0.3681 indicates fatalities were only 37 percent of the expected rate, so civil defense improvements are credited with 63 percent savings. Table 8 shows the remaining ratios.
Table 8. Ratios of fatality and casualty rates to claim rates for each baseline.

<table>
<thead>
<tr>
<th></th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatalities v. Second Lebanon</td>
<td>0.8092</td>
<td>0.3679</td>
</tr>
<tr>
<td>Fatalities v. Cast Lead</td>
<td>0.6270</td>
<td>0.2850</td>
</tr>
<tr>
<td>Casualties v. Second Lebanon</td>
<td>1.0878</td>
<td>0.4289</td>
</tr>
<tr>
<td>Casualties v. Cast Lead</td>
<td>0.6400</td>
<td>0.2524</td>
</tr>
</tbody>
</table>

These estimates suggest that during Protective Edge, civil defense improvements reduced fatalities by 63 to 72 percent, and casualties by 57 to 75 percent. These savings were in addition to fatalities and casualties prevented by interceptors, or by pre-existing (2008 or earlier) civil defenses. The Pillar of Defense benefits were more modest, with fatalities from 19 to 37 percent lower and casualty estimates from 9 percent higher to 36 percent lower. Figures 6 and 7 illustrate these results. The different estimates from the two baselines again indicates other factors’ influences, such as differences in civil defenses between northern Israel and southern Israel, or in the population densities where individual rockets hit.

**Figure 6.** Fatality rate changes attributed to civil defenses.

**Figure 7.** Casualty rate changes attributed to civil defenses.
One way to review these multiple-step calculations is to combine them and work backwards. For example, Second Lebanon had 0.3856 casualties per arriving rocket. Evaluations of Protective Edge against that baseline estimated that warhead blast areas were 6.048 / 8.874 = 0.6815 times as large; interceptions made all loss rates 0.2540 times as large; and civil defenses made casualties 0.4289 times as large. Multiplication yields $0.6815 \times 0.2540 \times 0.4289 = 0.07424$, indicating 93% lower casualties per rocket from warhead, interceptor, and civil defense influences combined. Multiplying by the Second Lebanon casualty rate gives $0.07424 \times 0.3856 = 0.0286$, the Protective Edge rate.

In summary, these calculations regarding arriving rockets suggest that both interceptor deployment and civil defense improvement reduced Israel’s losses modestly for Pillar of Defense and substantially for Protective Edge. Table 9 summarizes the estimates.

Table 9. Summary of loss reduction percentages.

<table>
<thead>
<tr>
<th></th>
<th>Pillar of Defense</th>
<th>Protective Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss reduction due to interceptors</td>
<td>0 to 32</td>
<td>59 to 75</td>
</tr>
<tr>
<td>Fatality reduction due to civil defenses</td>
<td>19 to 37</td>
<td>63 to 72</td>
</tr>
<tr>
<td>Casualty reduction due to civil defenses</td>
<td>0 to 36</td>
<td>57 to 75</td>
</tr>
</tbody>
</table>

Comparing Losses to Hits

The number of damage claims per rocket hitting “populated” or “urban” areas (the IDF’s terms) provides another way to evaluate interceptor performance. The ratio of claims to hits in Table 3 for Pillar of Defense was more than double those of Protective Edge and Second Lebanon. Perhaps Pillar of Defense rockets were aimed much differently, or had much more luck; but an alternative explanation is that its number of hits was understated.

Plausible estimates can be found via the other operations’ loss rates. For example, Pillar of Defense involved 3921 damage claims. To generate that many claims using the Protective Edge claims-to-hits ratio of 28.75 would require $(3921 / 28.75) \times (6.048 / 5.616) = 147$ hits after adjusting for warheads. The Second Lebanon numbers imply 209 hits.

These comparisons assume that the ratio of losses in populated areas to those in rural areas was similar in all three operations. However, interceptors mostly defended populated areas, so those should have seen fewer losses as batteries were added. This likely means the 147 hits calculated via Protective Edge (which had twice as many batteries) is an underestimate, while the 209 calculated via Second Lebanon (which had no batteries) is an overestimate.

It is difficult to say why these estimates are much higher than the reported 58 (IDF) or 109 (police) hits. Perhaps the definition of “populated area” varied over time. Some reports may have counted only rockets within city boundaries, while others included outlying suburbs. Each report then would be correct on its own, but distorted relative to the other.
Comparing Threats and Interceptions to Arrivals

While the number of hits during Pillar of Defense seems understated, the number of threats seems overstated. The IDF data for that operation indicate 35.38 percent of arrivals either hit urban areas or were intercepted. By contrast, only 24.09 percent hit or were intercepted during Protective Edge, and only 22.70 percent during Second Lebanon. This means the threat percentage was about one-half larger during Pillar of Defense. Similarly, 31.09 percent of arrivals were reportedly intercepted during Pillar of Defense, versus only 20.05 percent during Protective Edge, despite the latter having twice as many batteries.

Pillar of Defense saw 1354 arriving rockets, of which 479 (35.38 percent) were reportedly threats. If the true proportion was 24.09 percent, as in Protective Edge, that would imply 1354 x 0.2409 = 326 threats, rather than 479. If it was 22.70 percent, as in Second Lebanon, then the estimate becomes 307. If the proportion intercepted was 20.06 percent, as in Protective Edge, then the interceptions become 1354 x 0.2005 = 272 instead of 421. The threats would then become 272 + 58 = 330, or 272 + 209 = 481, etc.

It is unknown why these estimates are mostly lower than the reported counts. Perhaps “defended areas” differed significantly from “populated areas” during Pillar of Defense. For example, if the software and/or crews added safety margins around populated sites, then rockets heading into the added area would have “threatened” it without threatening the population. (To give an extreme example, since 2014 the IDF has used one-mile margins around Ben Gurion airport (Oren 2014).) The apparent threats then would have increased due to batteries engaging “extra” rockets. Regarding interceptions, perhaps the IDF counted both “confirmed” and “probable” ones during Pillar of Defense, but only “confirmed” ones for Protective Edge.

Alternatively, perhaps imperfections in the battery hardware or software caused it to misclassify some incoming rockets as threats; “false positives”, in terms of Armstrong (2014a). For example, Patriot batteries in the 1991 Gulf War had software that caused tracking errors after extended operation (GAO 1992). More recently, an Iron Dome battery fired at mortar shells falling outside of Israel (Shoval and Brenner 2016). Operating procedures and operator decisions might also have affected performance, for better or for worse. For example, during Protective Edge, “In about 65 instances, operators decided to utilize the defense system contrary to Iron Dome launching policy” (Harel and Cohen 2015).

Combining the Estimates

The loss-per-arrival analysis suggests that during Protective Edge, Iron Dome intercepted 59 to 75 percent of all hazardous rockets, while civil defense improvements reduced human losses a further 57 to 75 percent. These substantial savings support both civil defense advocates like Postol and interception advocates like Rubin.

Interception was much less influential during Pillar of Defense, with the loss-per-arrival analysis suggesting that batteries intercepted less than 32 percent of hazardous rockets. As to why, the loss-per-hit analysis implies there were more than 58 urban area hits, perhaps between
147 and 209. The threats-per-arrival analysis implies less than 479 threats, perhaps between 307 and 326; and less than 421 interceptions, perhaps just 272.

Consider the implications of combining these estimates. The IDF reported 58 hits and 421 interceptions during the operation, meaning the batteries intercepted 88 percent of 479 threats. Suppose there really were 58 hits, but only 326 threats; this would mean the batteries only intercepted 82 percent of them. If there were 479 threats, but 147 hits, then the batteries intercepted 69 percent. Assuming 147 hits and 272 interceptions, the score becomes 64 percent. Table 10 summarizes these possibilities, along with several others.

Table 10. Percentage intercepted during Pillar of Defense for various combinations of rockets that hit (columns) and threatened (rows).

<table>
<thead>
<tr>
<th>Threats</th>
<th>Hits</th>
<th>58</th>
<th>109</th>
<th>147</th>
<th>209</th>
</tr>
</thead>
<tbody>
<tr>
<td>479</td>
<td></td>
<td>88</td>
<td>77</td>
<td>69</td>
<td>56</td>
</tr>
<tr>
<td>419</td>
<td></td>
<td>86</td>
<td>74</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>326</td>
<td></td>
<td>82</td>
<td>67</td>
<td>55</td>
<td>36</td>
</tr>
<tr>
<td>307</td>
<td></td>
<td>81</td>
<td>64</td>
<td>52</td>
<td>32</td>
</tr>
</tbody>
</table>

Since this analysis aggregates all incoming rockets, whether headed toward defended areas or elsewhere, it is not directly comparable to the tactical interception rate. However, if the percentage of threats intercepted during Pillar of Defense really was lower than the reported 88 percent, then the effective interception rate may also have been lower than the reported 85 percent. This analysis therefore partly supports earlier technical estimates based on imagery analysis. Postol’s (2014) 5 percent interception estimate looks too low, but Lloyd’s (2014) 30 to 40 percent suggestion seems plausible.

By contrast, these results differ from Rubin’s (2013; 2015) for several reasons. First, by comparing rockets one-for-one, Rubin’s work implicitly assumed the warheads were equal. Second, by explicitly assuming civil defenses were constant, it credited any improvements to interception. Third, by using only Second Lebanon and not Cast Lead as the baseline, it calculated the largest possible improvements.

Of course, the indirect analysis herein cannot “prove” that Israel’s interception claims were incorrect, any more than interception proponents can “prove” they were correct. Thus, those proponents might dismiss these calculations as merely circumstantial. Conversely, critics might argue that the calculations rely on Israeli government reports, and so could have been misled. It consequently seems unlikely that “the decades-long debate in Israel between proponents and critics of missile defense has now been laid to rest” (Rubin 2015, 32). However, whereas that debate previously concerned interception’s potential feasibility and desirability, it now focuses on the actual effectiveness and efficiency.

The analysis also cannot reveal why interception performance differed between Pillar of Defense and Protective Edge, though several possibilities are apparent. The number of batteries doubled between operations, allowing them to defend more areas and engage more rockets. The quality of the batteries also improved: Israel was using the fourth version of Iron Dome.
technology in 2014, and continues to upgrade it (Reuters 2014; JPost 2015). In that regard, it is easy to imagine programmers refining Iron Dome’s software between operations. For example, the 1991 Patriot software bug was fixed within two weeks of its discovery (GAO 1992), and more recently the IDF rebuilt its battle management software within three months (Lappin 2016b). Similarly, the IDF could have used its experience from the earlier conflict to improve its procedures before the later one. For example, after facing difficulties during Second Lebanon, IDF ground forces improved their doctrine in time for Cast Lead (Farquhar 2009). Regarding system hardware, Lloyd’s (2014, 1) report had suggested several enhancements, though implementing those could have taken longer.

**Were Israel’s Countermeasures Worthwhile?**

*Countermeasures’ Benefits*

Both Israel’s defensive strengths and the rockets’ inherent weaknesses have prevented higher losses. For example, during Protective Edge, only 24.09 percent of all arriving rockets threatened targets. If all the rockets had been that accurate, casualties could have been $1 / 0.2409 = 4.151$ times as high, or 315 percent higher. The IDF’s preemptive destruction of 3000 rockets in Gaza kept casualties from being $3000 / 2968 = 101$ percent higher, or 2.011 times as high. If batteries intercepted 66.71 percent (the mean estimate) of hazardous rockets, they prevented casualties from being $1 / (1 - 0.6671) = 3.004$ times or 200 percent higher. Zucker and Kaplan (2014) estimated that civil defenses kept rocket casualties from at least tripling during 2000-2010. If improvements prior to Protective Edge further reduced casualties by the mean estimate of 65.94 percent, then that kept them from being another 2.936 times as high, or 194 percent higher. This implies civil defenses overall kept casualties from being $3.000 \times 2.936 = 8.808$ times as high. (Each multiplier assumes the others stay constant; e.g., 315 percent more casualties due to higher rocket accuracy, if the proportion intercepted remains constant.)

For Pillar of Defense, similar calculations imply that preemption prevented 72 percent more casualties. If civil defense improvements reduced casualties by 13.61 percent, then they prevented 16 percent more. If batteries intercepted 10.70 percent of hazardous rockets, then they prevented 12 percent more casualties. If rocket inaccuracy was half-way between that of Second Lebanon and Protective Edge, then it prevented 327 percent more casualties. For Cast Lead, preemption prevented 194 percent more casualties.

Figure 8 displays these percentage casualties avoided. (A fatalities diagram would look similar, while a property damage diagram would delete the civil defense portions.) The figure illustrates the importance of rocket inaccuracy and civil defenses. If attackers ever manage to improve rocket accuracy or negate civil defenses, then Israel’s losses would sharply increase. By contrast, preemptively destroying rockets on the ground reduced casualties surprisingly little, except during Cast Lead. This is because each rocket had little chance of success. For example, during Protective Edge only $0.2409 \times (1 - 0.6671) \approx 8$ percent would have flown accurately and evaded interception; and even those would have harmed relatively few people.
**Figure 8.** Potential casualties avoided, as percentages of actual.

![Bar chart showing potential casualties avoided](chart.png)

**Higher Potential Losses**

These multipliers also reveal how much greater the rocket danger would have been without Israel’s countermeasures. For example, during Protective Edge the country suffered 85 rocket casualties. That number could have been multiplied by 8.808 if Israel had not built civil defenses, by 3.004 if it had not developed Iron Dome, and by 2.011 if it had not destroyed rockets in Gaza. Rocket casualties therefore could have been $8.808 \times 3.004 \times 2.011 = 53.21$ times as high, around 4,523 people, triple those of Second Lebanon. (Mortar casualties would also have risen to a lesser extent.) For perspective, in 2014 terrorist attacks outside of Protective Edge not involving rockets or mortars caused 78 casualties (ISA 2014), while road accidents caused 21,910 casualties (Central Bureau of Statistics 2015).

Critics should keep these multipliers in mind when judging the proportionality of Israel’s actions. While such judgements should consider the relatively low losses that the country actually suffered, they should also consider the much greater ones that could have occurred absent its extensive countermeasures.

**Expensive Military Operations**

The IDF operations publicly aimed to protect Israeli civilians from rocket attacks. Each operation destroyed rockets and related facilities, but at considerable cost. For example, Pillar of Defense destroyed 980 rockets and cost $285 million, or $291 thousand per rocket. That saved Israel from 72 percent higher rocket losses, i.e., 177 casualties and $10.7 million in damage, for a marginal cost of $(285 - 10.7) / 177 = $1.55 million per casualty avoided.

Cast Lead rocket destructions avoided 194 percent higher losses: 280 civilian casualties and $15.8 million in damage. The IDF spent $(910 + 1280) / 2 = $1095 million and suffered 80 military casualties. Prorating of rockets and mortars assigns the rockets 77.6 percent: $850 million and 62 military casualties. The cost to prevent each civilian casualty was $2.98 million plus 0.221 military casualties, or $3.83 million after netting civilian and military casualties.
Protective Edge prevented 101 percent higher losses: 86 casualties and $29.5 million of damage. It cost \((1900 + 2600) / 2 = $2250\) million and 536 military casualties; prorating assigns the rockets 75 percent, or $1688 million and 402 military casualties. Each prevented civilian casualty cost $19.3 million plus 4.67 military casualties, indicating the operation incurred more casualties than it prevented.

These rough calculations include only the operations’ direct marginal costs and benefits, and assume the only goal was to prevent rocket losses. They omit many costs that are not meaningful to allocate per-rocket or per-casualty, such as the IDF’s sunk costs of purchasing weapons and training soldiers, and its fixed costs of maintenance and salaries. They also exclude Israel’s large indirect economic losses. The calculations similarly neglect the operations’ other outcomes, such as damage to militant tunnels and civilian buildings.

The calculations ignore deterrence of Hamas because it seemed negligible in this period. Each operation was followed by another a few years later, with hundreds of rockets fired in between, a routine called “mowing the grass” (Inbar and Shamir 2014). If partial deterrence were applicable, one could add the estimated losses prevented between operations, but also the costs of supporting the IDF deterrent force. (Hamas perhaps has been deterred since 2014 (Ahronheim 2017c), whereas Hezbollah clearly has been deterred since 2006 (Sobelman 2016).)

**Competitively Priced Interceptions**

Israel budgeted $225 million of American aid to replenish its interceptor supply after Protective Edge (Dagoni 2014). Prorating implies $182.1 million for the 595 rocket interceptions, or $306 thousand each. By keeping rocket losses from being 143 to 294 percent higher, interceptions prevented 122 to 250 casualties, and $41.7 to $85.7 million in damage. This puts the marginal cost per prevented casualty between $386 and $1,151 thousand.

The country similarly spent $200 million on resupply after Pillar of Defense (Lev 2012). This equates to $475 thousand for each of the 421 claimed interceptions, or, e.g., $1.18 million each if there were only 326 – 147 = 179 effective interceptions. If interceptions prevented at most 47 percent higher losses, i.e., $6.9 million in damage and 115 casualties, then the net marginal cost exceeded $1.68 million per casualty avoided. If they only prevented 12 percent higher losses, then that cost was $6.84 million.

These estimates assume the funding only replaced previously fired Tamirs. If, contrary to the news reports, it also increased stocks beyond their original levels, then the marginal cost would be lower. Conversely, the estimates exclude the capital costs of developing the technology and building the batteries, as well as their ongoing support costs.

An alternative “bottom-up” costing approach could multiply the cost per interceptor by the number fired, but this would require knowing the number of Tamirs fired, the price paid, and any marginal expenses for delivery, launcher refurbishment, etc. For example, if the 799 engagements during Protective Edge each used 1.5 Tamirs on average, and if each Tamir cost $100 thousand, then the total would have been at least $120 million. (The real cost of Tamirs is
unknown, but unit prices mentioned in public over the past few years have climbed to $100 thousand, rather than dropping to $10 thousand as Hamilton (2012) had hoped.)

**Durable Civil Defenses**

Unlike infantry and interceptors, civil defense usage involves negligible marginal costs, making it a bargain by that measure. Israel’s civil defense improvements prevented up to 138 casualties during Pillar of Defense, plus between 113 and 252 during Protective Edge. Civil defenses also protect against mortars and other attacks.

**Discussion**

**Implications**

One implication of this study is that the controversy over Israel’s military operations is partly misplaced. On the one hand, its justification for responding militarily is better than some critics admit, as the rocket attacks pose substantial potential danger. Its losses have been relatively low only because of its multi-layered defenses. On the other hand, the benefits from the military operations seem not to have been worth their cost (Perry 2014). So perhaps there should be fewer questions about their proportionality, and more about their productivity.

Another implication is that the controversy over Iron Dome has been overly polarized. While the system was perhaps “little more than a bluff” (Globes 2014) originally, it has become a valuable shield (Elis 2012). However, it is not a “game-changer that heralds the end of rockets” (Hamilton 2012); rather, it represents another move within an ongoing arms race (Shapir 2013b). Hamas has rebuilt its rocket stockpile since Protective Edge (JPost 2017), while Hezbollah has amassed over 120 thousand rockets (Ahronheim 2017a), plus some guided missiles and drones. Given sufficient quantities and accuracy, rockets could overwhelm a battery and greatly increase Israeli losses (Armstrong 2014a).

This relates to the increasing importance of the conflict’s economic dimension. Israel’s defenses have greatly reduced its fatalities and casualties, and somewhat reduced its direct property damage, but done little for the billions of dollars in indirect economic losses. (Reducing economic disruption is one reason it is improving its warning system’s precision.) Furthermore, casualties and fatalities are light only because the country has spent billions on defenses. All these costs detract from Israeli prosperity, and complicate defense policies and spending priorities (Kober 2013; Shapir 2013b).

This paper has analyzed the actual performance of rocket countermeasures, but their perceived performance also matters. Despite the effectiveness and efficiency of civil defense, some Israelis may see it as overly passive or even defeatist. By contrast, military operations are assertive responses that might satisfy domestic political pressures or signal determination to foreign enemies, regardless of their actual impacts (Shapir 2013b).

Public perception is similarly complicated for Iron Dome. Even if interception became influential only during Protective Edge, it was perceived that way during Pillar of Defense, and
boosted civilian morale during both operations. Consequently, civilians now demand interceptor protection, even if military facilities sometimes ought to have priority. That perception might reduce political pressure for offensives against Gaza, but also for negotiating peace. It also may have fostered a complacent belief that interception will always work, even against Hezbollah attacks involving 1500 rockets per day (Ahronheim 2017a; Cohen 2016; Limor 2017).

Altogether, Israel seems to have an awkward menu of countermeasures from which to choose. Civil defense seems to provide the greatest actual benefits, by preventing many casualties and fatalities (but not property damage), while being the most cost-effective. However, its passivity may unattractive domestically.

Interception occupies a middle position. Iron Dome now seems able to provide substantial rocket protection at a lower cost than airstrikes. As an active defense, it offers a positive public image at home and abroad, though with several strings attached.

Military operations incurred the highest costs and prevented the fewest losses. (Rubin (2015, 34) notes that IDF activities in Gaza before 2008 likewise had high costs and limited benefits.) Airstrikes were more cost-effective than ground assaults; the latter were inefficient or even counterproductive. However, ground operations carry an assertive image, and were the only option that at least temporarily “stopped” rocket fire.

These rocket challenges exist within an increasingly missile-filled Middle East. Israel faces missile threats from Syria (Siryoti 2017) and especially Iran. Iran’s missiles have increased in size and quantity, though perhaps not in accuracy (Harel 2017); they also threaten Saudi Arabia, which has already suffered missile and drone attacks from Houthi militants in Yemen (Frantzman 2017). Israel therefore has deployed two more interceptor systems: David’s Sling for medium range missiles, and Arrow for long range ones (Ahronheim 2017b).

Other countries are also interested in Israel’s interceptors. The U.S.A. so far has supplied $1.3 billion for Iron Dome and $1.7 billion for Israel’s other missile defense efforts, and has committed to providing $500 million annually for the next decade (White House 2016). It might eventually adapt some of the Israeli technology for its own anti-missile programs. Buyers of Israel’s interceptors will likewise care how well they perform. South Korea and Singapore have been mentioned as potential candidates, though so far only Azerbaijan has bought them (JPost 2017; Armstrong 2017).

**Limitations**

This study relies on the limited data that is publically available. Most comes from Israeli government reports that vary in format and content, and may have been disguised for security reasons. Thus, the word “reportedly” should accompany almost every number.

The study’s indirect approach is another limitation. It treats rocket battles as “black boxes”, analyzing inputs and outputs outside each box to infer the events inside. In effect, the research verifies the data’s internal consistency: do the numbers make sense relative to each other? It is less able to validate the data for accuracy: do the numbers represent reality?
ideal study would physically observe rocket trajectories, interception attempts, and impact sites; but such hard evidence is rarely made public, and even the IDF likely has only a subset. Thus, the word “approximately” should accompany most numerical results, even those calculated to several decimal places.

The paper compensates for these challenges by calculating three loss rates (fatalities, casualties, and property damage) that have different strengths and weaknesses; and by comparing their relationships with rocket fire across several operations in several different ways. Since these differing approaches reveal similar patterns, they help to corroborate the results.

Acknowledgements

Thanks are due to several anonymous reviewers for their helpful suggestions.

References


Rocket Attacks on Israel

Michael J. Armstrong

19 Sep 2017


Richardson, Doug. September 1, 2014b. “Hamas rocket attacks less accurate and less intense than in 2012,” *Jane’s Missiles and Rockets* 18 (9).


