Discontinuities in command decision-making: minimising expected loss results in a catastrophe.

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Abstract

This paper briefly describes the mathematics of a discontinuous Bayesian command decision model. The model uses the principle of minimisation of expected loss and is based on two basic elements: the uncertainty in the decision-makers' belief in outcome; and, his perception of loss (or penalty) associated with all possible actual outcomes (measured with respect to the desired or planned outcome). The belief function is combined with the perceived loss function to give an expected loss function. Minimisation of the expected loss function results in a cusp catastrophe. The two control parameters of the cusp cubic equation are defined by the width of the belief in outcome function (i.e. uncertainty) and the shape of the perceived loss function (i.e. criticality of decided action). In summary, the paper proposes that two main factors drive military decision-making and offers qualitative appreciation of their impact, which is useful, in particular, for Information Operations and C2W. The paper then illustrates the theory with military examples at both tactical and operational levels.

Introduction

The military command process is a multi-faceted and dynamic decision process that deals with control, co-ordination and communication. This paper and the associated theory relate principally to the aspect of control and in particular to the military decision-making process as part of a complex and demanding environment. The paper briefly describes the mathematical principles of a discontinuous Bayesian command decision model [Smith] and then illustrates the theory with some military examples.

Our previous work on catastrophe theory and command decision making discussed the catastrophe fold in qualitative terms only, and we failed to gain a clear understanding of the mathematics of the discontinuities and the nature of the control variables. This top-down approach made it difficult to identify and quantify the two major axes of the cusp catastrophe decision surface. However, some mathematical research carried out in 1970's now allows us to derive explicitly the cusp catastrophe equation; so, the control variables

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are traceable directly from the two lower-level equations that describe belief in outcome and perception of loss (or penalty due to failure to achieve objective).

Whatever the command context, there appears to be a small set of basic elements driving the decision-making. For simplicity, assume that all negative elements are combined into one basic element, referred to as *loss*. Generally, the greater the mismatch between the desired and actual states of our world, the greater is our perception of loss. In a military context, the definition of loss is usually much broader than just casualty figures and includes more global "costs" such as effects of loss of cohesion and other secondary (more global) knock-on effects. The diverse nature of the loss (or negative gain) metric means that it is strictly multi-dimensional and needs to be explored further.

The theory makes three assumptions about the military C2 decision process:

- there is uncertainty in belief about future outcomes;
- losses may result from any decision (or lack of decision);
- the overall desire is to minimise expected loss (or maximise potential gain).

Belief in outcome can be represented by any probability distribution function (e.g log-Normal) and the uncertainty measure is the width (coefficient of variation) of that belief function. The perceived loss is generally a U-shaped function of actual outcome, whose minimum is at the point of desired (or planned) outcome. It is assumed that the shape of this function changes as the degree of responsibility or importance placed on the decision-making HQ to "get-it-right" changes. The two functions combine to give an expected loss function and when this is minimised a cusp catastrophe decision surface emerges. Because the parameters of the belief and perceived loss functions were clearly defined, quantification and definition of the control axes of the cusp catastrophe is straightforward.

Standard Bayesian decision theory makes the assumption that the level of loss increases almost linearly with the (desired-actual) mismatch. For most problems, and indeed certainly for military ones, this assumption of a convex or linear loss function is unrealistic. It is much more likely that as the actual outcome moves further away from that which is desired, the sense of loss becomes rapidly greater, especially when second-order knock-on effects augment the sense of loss or failure.

Another major factor in the decision-making process is uncertainty; in particular, how uncertainty affects the belief about future outcome given a decision to take action (or not). Bayesian decision theory assumes that the distribution function describing the belief in future outcome does not depend on the magnitude of the decision. Again, this assumption is unrealistic; especially in a context of military conflict.

When the two Bayesian assumptions are combined the resulting decision surface is smooth over the changing uncertainty and over the losses felt due to (desired-actual) mismatch. However, several studies of decision-making show that small changes in uncertainty when a decisive action is of critical importance can cause abrupt changes in decision outcome. Smith's theory extends the Bayesian assumptions and shows that a discontinuous cusp catastrophe surface results from the natural extensions of the loss and belief functions.

Catastrophe Theory

Catastrophe theory categorises surfaces of minima of continuous functions with a small number of variables. It was first developed in the 1960's by René Thom then it was developed and applied by Zeeman [1] and grew in popularity during the 1970's [2].

Klein's work on Recognition-Primed Decision making [3] shows that experience and training helps the decision-maker to map the recognised situation to the most appropriate course of action (CoA). The process used to map a continuous decision onto a discrete CoA has been previously investigated and this pattern matching process is fully explained in chapter 5 of reference [4], volume 2. We need, however, to be able to represent both the local and superior commanders' intents and perceptions of the situation.

In a previous report [5], we looked at the emergence of cusp catastrophes from loss functions which were the combination of an 'end point' and 'en route' loss or cost. The focus, here, is on the loss associated with the end point only and neglects any en-route costs. The loss function reflects the potential penalties as perceived by the unit commander due to failure to meet his objective.

The reasoning behind using Catastrophe Theory has been discussed and documented in an earlier report [6]. The outcome of the catastrophe theory model in this previous report indicated whether the local commander should deviate from his current CoA or not. Here, the theory is extended slightly in that the catastrophe theory model, given appropriate input parameters and functions, can also be used to give the CoA the local commander should take.

Catastrophe Theory is able to give fully quantitative solutions to the military decision problem. However, the output decision values are only meaningful if the functions chosen to represent the situation assessment correctly reflect the commanders' perceptions; so, care must be taken in choosing these functions and in their parameterisation.

J. Q. Smith published three key papers, [7,8,9] which we use as the basis of our study into military decision making. The chosen statistical functions represent plausible models of the commander's perceptions and are relatively simple to implement as algorithms in an Operational Analysis combat model. These functions are chosen to reflect a commander's uncertainty in his beliefs of his current state and his potential losses [10].

Previous work on the cusp catastrophe model [11] simply presented the cusp catastrophe model as a useful way of describing the command decision process but because the cusp model had been imposed without any derivation from first principles it was difficult to be explicit about the control axes. Smith's extension of Bayesian decision theory uses well-defined parameterised functions whose combination results in a cusp catastrophe surface. Quantification and definition of the control axes are now straightforward and the following stylised military example shows how the theory can be applied so that, hopefully, decision discontinuities can be better understood.

A simple Battle Group decision

Assume that a Battle Group HQ has been given orders to advance to an objective as part of a Corps plan of attack. En-route to their objective, the BG HQ receives Intelligence to suggest that an enemy unit may be about to intercept the BG's column of march. The BG HQ must decide how much force to assign to flank protection. The information about the enemy unit has medium confidence attached to it and the location and mobility of the enemy unit is uncertain.

The following analysis forms a part of the BG HQ decision process:

- If we decide to by-pass and assign no forces to flank protection, we risk the potential losses associated with a flank attack from an enemy unit that has potentially significant strength.
- If we decide to engage and assign a large proportion of the force to flank protection, we may fail to achieve our objective and suffer the global losses associated with this failure.

The two options above represent extremes of the decision space. The decision space covers the whole range of values that could be assigned to the (proportional) size of force committed to flank protection; that is, from zero (total by-pass) to the entire BG (total engagement). There is an obvious continuum between the two extremes; for example, one of the Companies on the flank may be ordered to engage the enemy unit while the remainder continues to the objective.

The BG HQ makes a decision to assign a proportion of their force (denoted by (1-*c*)) to flank protection. The remainder (c) is then committed to continue advancing. The Brigade plan was that all the BG should continue to the main objective (denoted by *m*=1).

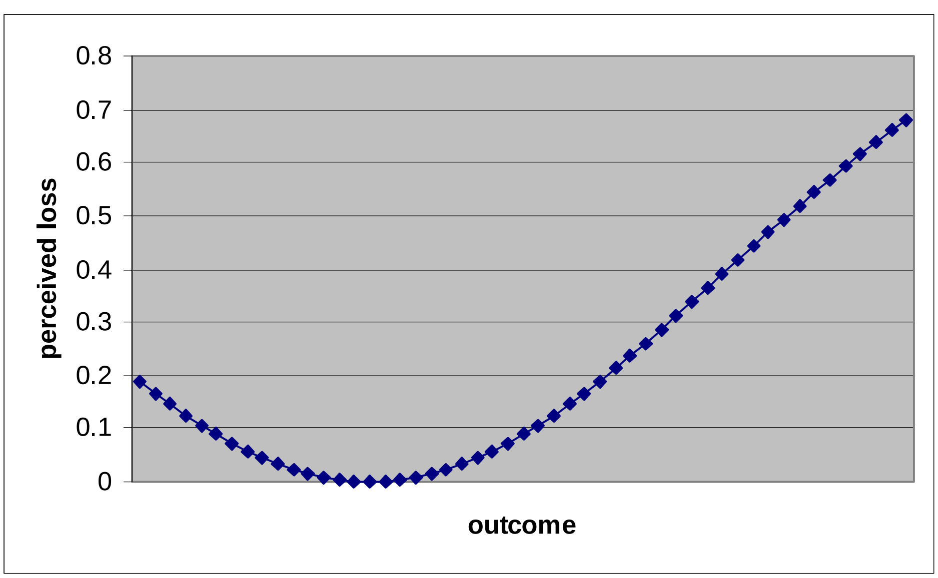
The difference between the planned action and the local action (m-c) combined with the "responsibility/blame" assumed by the command culture determines the overall perceived loss. This loss is then weighted by the probability of that loss occurring (from the projected belief in outcome given the decision) to give an expected loss against all possible decisions.

The definition of loss, used in this analysis, is much broader than just casualty figures and it should include more global "costs" such as effects of loss of cohesion and other knock-on effects which result from not achieving the BG's objective.

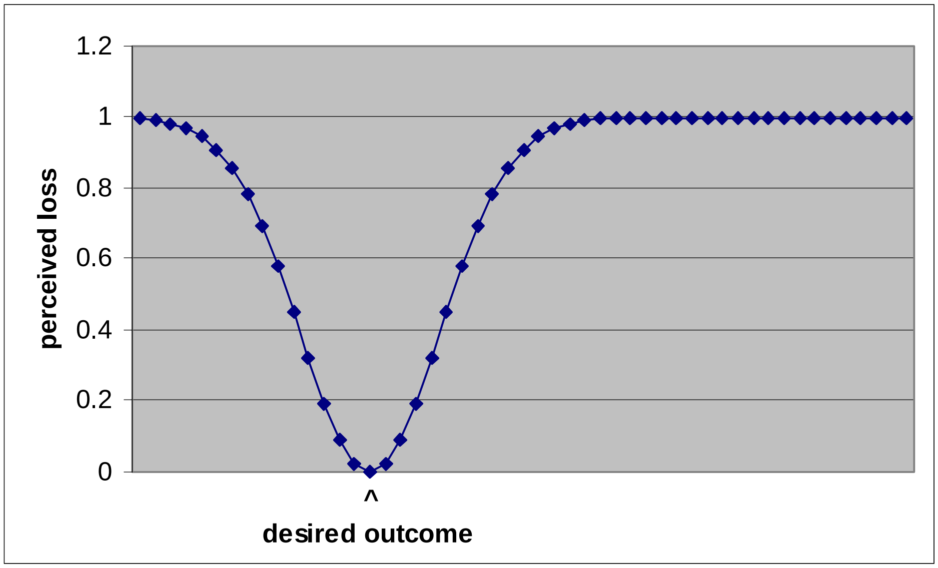
We assume that adhering to the plan (decision=m=1) would have had an expected minimum overall loss, equivalent to an expected outcome of no-change in perceived combat power ratio (PCPR=enemy strength/own strength) for the BG. So if outcome is represented by a multiplicative factor applied to combat power ratio, then the expected outcome = 1 (i.e. PCPR remains unchanged). For example, an outcome factor of 1.5 represents a 50% increase in PCPR (perhaps due to higher than expected enemy force and loss of BG strength).

To illustrate the relationship between perceived loss and the (desired-actual) outcome mismatch the value of *c* has been set to 0.7. So the proportion of the BG assigned to flank protection is 1-*c* (i.e. 30%). Assume that the uncertainty in the belief in outcome given the decision is *v*=0.01.

The responsibility (i.e. criticality or blame) factor (r) determines the shape of the perceived loss function (see the graph below). When r=1 the loss function is wide and represents low blame for outcomes that are different from the desired outcome.

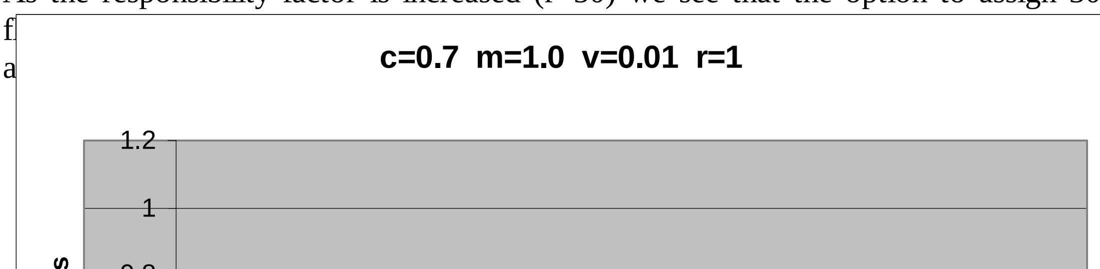


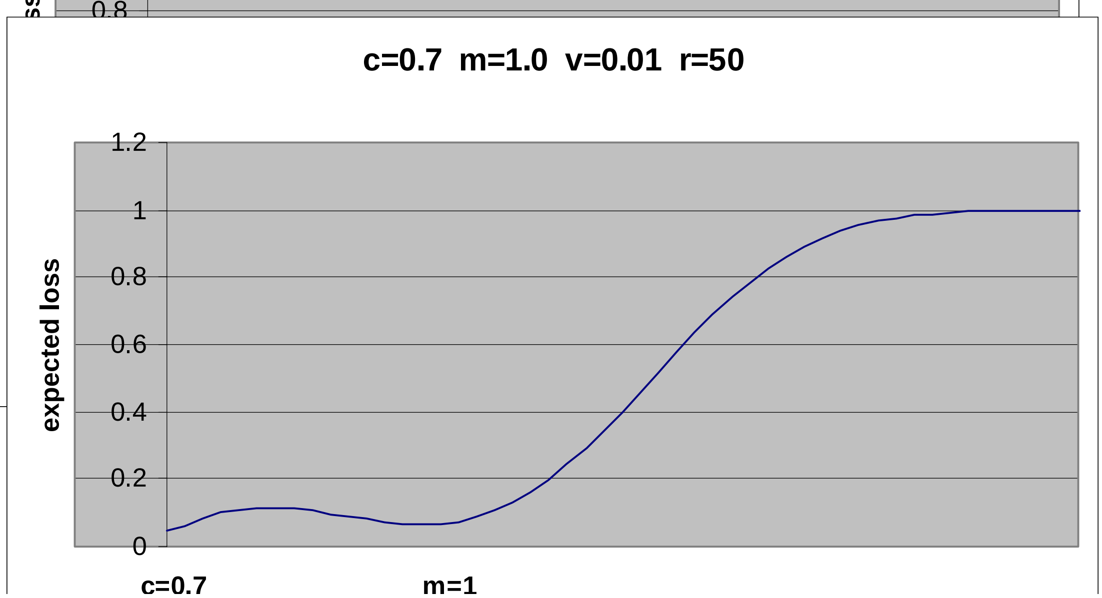
A responsibility factor (r=50) has the effect of narrowing of the loss function. Outcomes that are slightly different from the desired (or planned) outcome now have a high perceived loss associated with them.



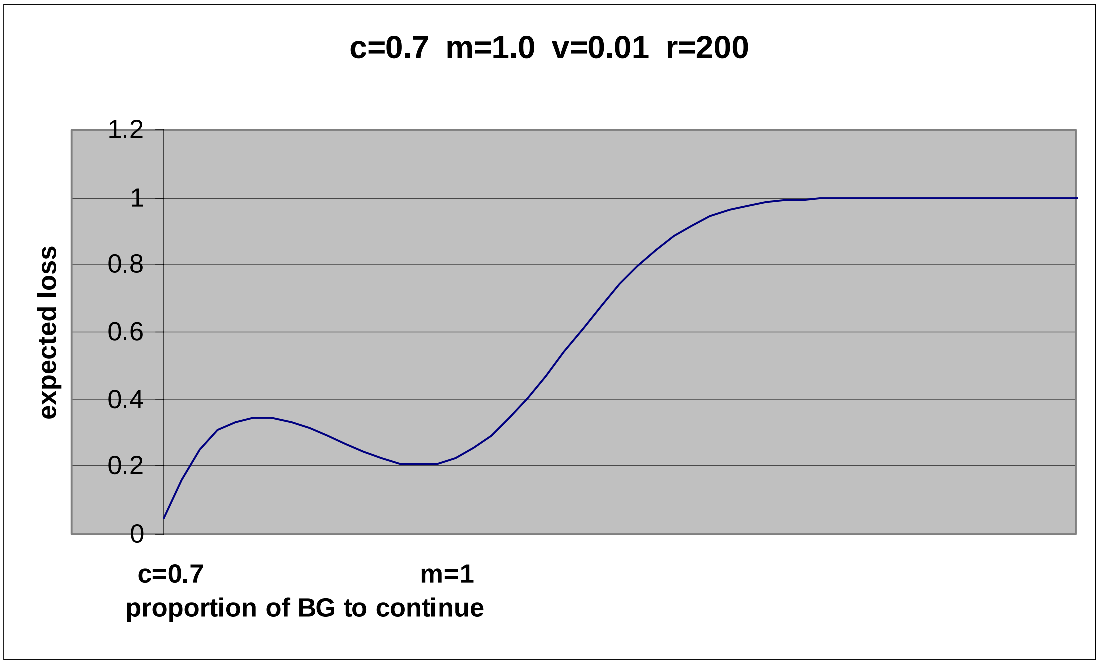
When this loss function is combined with a Normally-distributed belief in outcome we get the expected loss associated with all possible decisions.When r=1 there is little responsibility placed on the BG HQ. The expected loss associated with the local option (i.e. where the graph crosses the vertical axis) is greater than the expected loss from the total by-pass planned option (at the point of desired outcome); but the difference is small and so the decision is perceived to be non-critical.

As the responsibility factor is increased (r=50) we see that the option to assign 30% to f … Q has a …

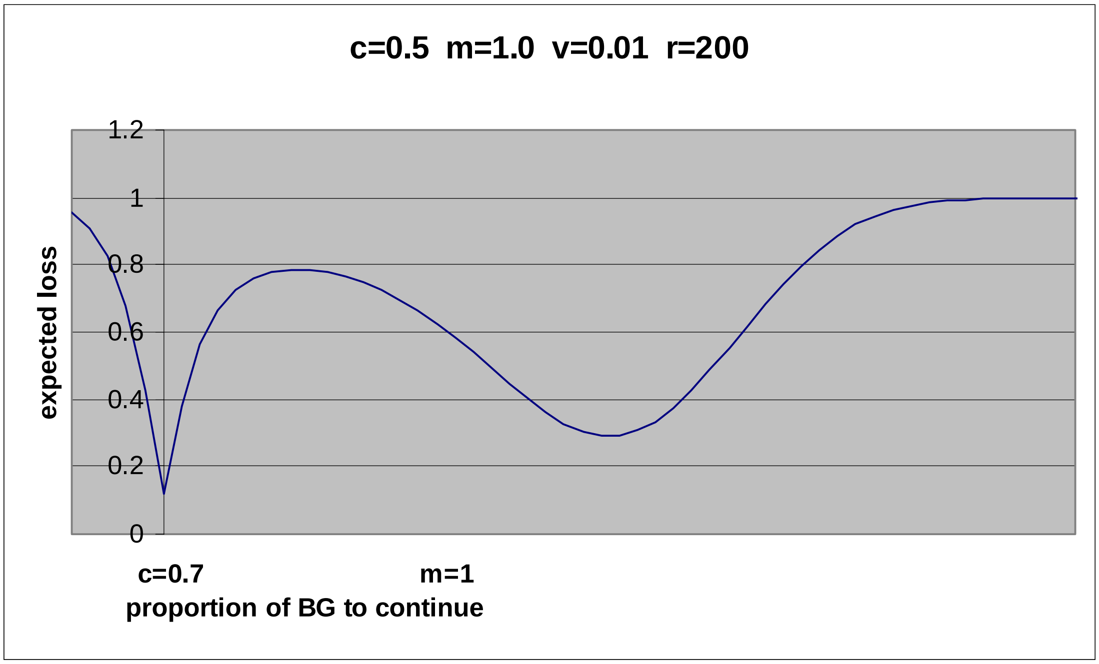




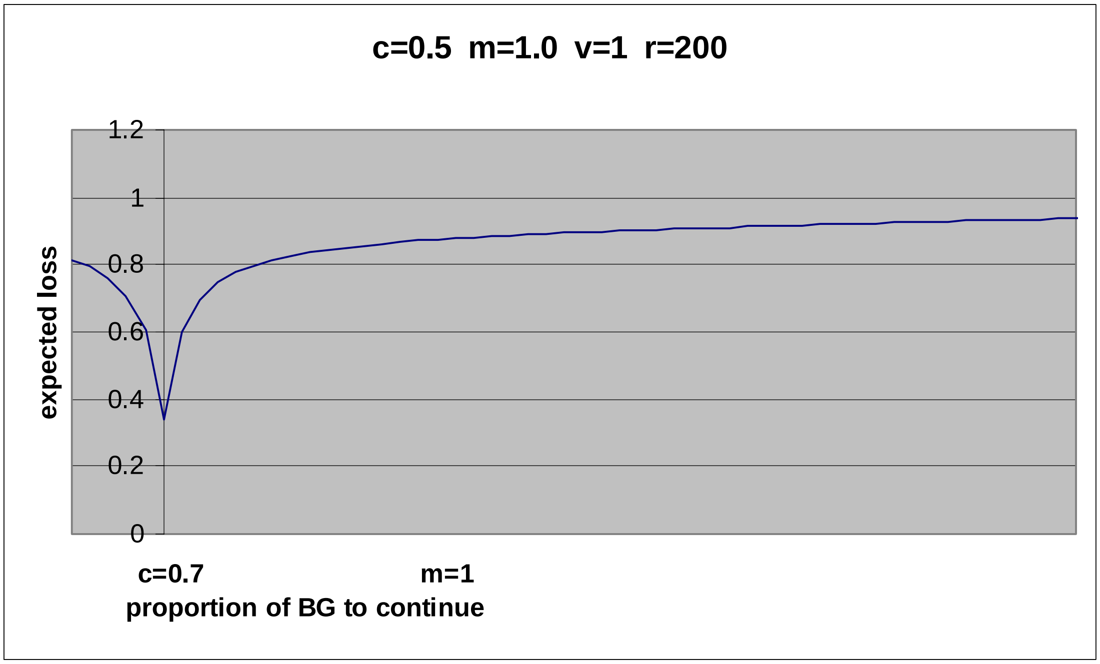
As the responsibility factor is increased still further (r=200), the minimum point of the expected loss function falls firmly and sharply on the local BG decision point. It is considered too costly (in terms of the perception of unreasonably high blame if they don't act) to adopt the by-pass option. Also the losses associated with choices between the two (local and global) minima are expected to be relatively high.



If the assessment of the potential threat causes the BG HQ to consider committing half the force to the engagement whilst the other half continues to the objective (c=0.5), then the expected loss overall is generally higher. So, the BG will tend to fixate on their local decision (which is perceived to be the point of global minimal loss).



Increasing uncertainty (v=1) increases the expectation of perceived loss and removes the planned by-pass option altogether from the decision process.



The graphs of expected loss, specifically the minimum points, give us the link to the familiar folded cusp catastrophe surface. The cusp catastrophe surface is the family of minima across the continuous range of expected loss curves. Changes in the responsibility factor *r* and the coefficient in variation *v* give different values for the minimum points of the expected loss curve. If all these minimum points are plotted out on surface for all the possible values of *r* and *v* then we get the folded cusp catastrophe surface.

This simple example has provided a qualitative introduction to the theory. Two further qualitative examples show how the theory could be used to describe the decision space versus expected losses at operational levels of command and also in a peace support context. We have also applied it to a recent tactical Information Operation in Sierra Leone.

Israeli decision-making in the Sinai Campaign of 1973

Background

Israel had captured the Sinai peninsula during the Six-Day War of 1967. Between 1967 and 1973 Israel constructed a line of fortified observation posts along the East Bank of the Suez Canal. They also prepared plans to defeat the Egyptian Army, in the event of a crossing, using armoured divisions to be mobilised from the Israeli hinterland. The Egyptian Army conducted a surprise crossing of the Canal on 6 October 1973. The fortified outposts were largely neutralised. By 10 October the Egyptians had completed their initial deployment, despite Israeli counterattacks, of a total of 5 infantry divisions, five armoured brigades and an independent amphibious brigade. This force totalled about 80,000 men and 700 tanks. The Egyptians occupied a broad sector of the East Bank but, critically, did not occupy its whole length. Previously, they had established air defences to cover their forces operating out to a distance of several kilometers on the East Bank. Over the period 12-13 October, the Egyptians moved forward one armoured division, plus elements of 2 mechanised divisions; in total, about 250 tanks. This left one armoured and five mechanised brigades on the West Bank, and the GHQ reserve of an armoured division further West. This movement of armour to the East Bank was the trigger for the Israeli decision to counterattack. The Egyptians also moved some air defence systems forward.
The battle on the East Bank continued throughout the War, until 22 October, with major attacks and counterattacks by both sides. These actions are not discussed in any further detail.

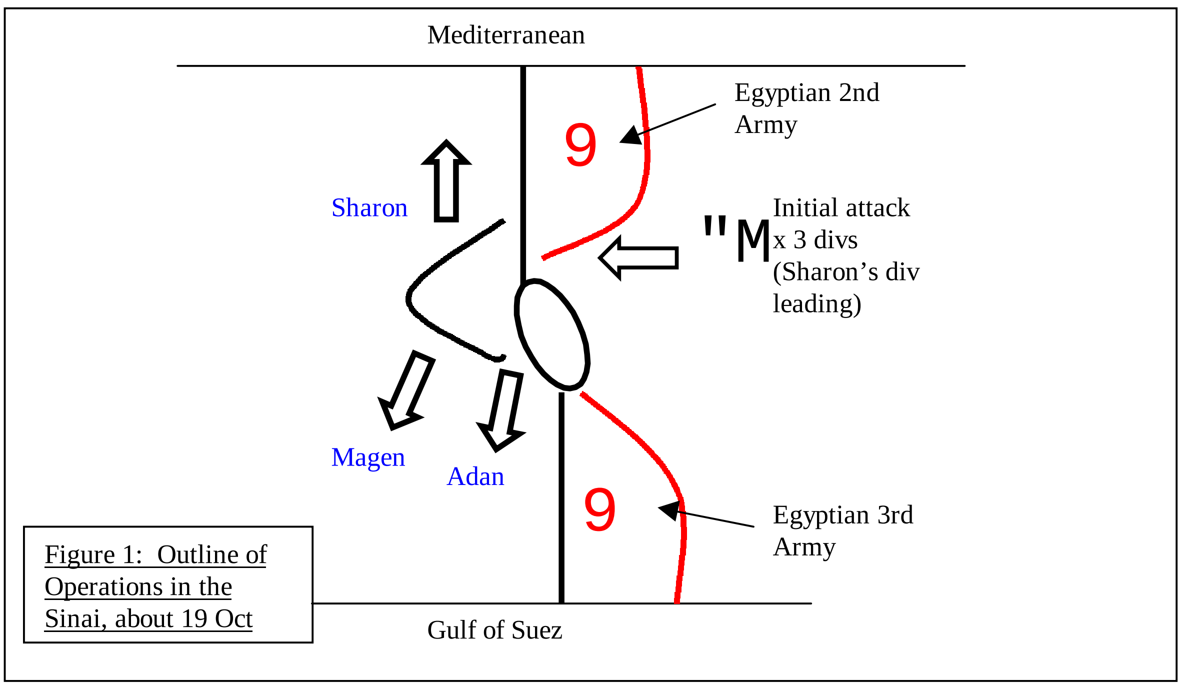


Figure 1: Outline of Operations in the Sinai, about 19 Oct

The Counterattack.

On the afternoon of 15 October, General Sharon's Israeli (armoured) division conducted a feint attack with one brigade, whilst covertly passing a second armoured brigade and a parachute brigade around the southern flank of the Egyptian 2nd Army. The parachute brigade crossed the Suez Canal that night and ferried a total of about 20 tanks and 7 APCs across. The Egyptians became aware of Israeli forces operating on the West Bank during 16 October, but entirely mis-appreciated their significance. The true impact of the Israeli crossing only became apparent to them on 19 October. During 16 October the Israeli armoured force on the West bank raided SAM sites, creating a local gap in the Air Defence coverage. That night the rest of the first armoured brigade, and a second brigade (of Sharon's division), crossed the canal. These forces conducted local attacks to enlarge the bridgehead, and further raids, during 17 October.

On the night of 17-18 October, General Adan's division (less one brigade) crossed to the West Bank. It attacked Southwest to expand the bridgehead from 0545 hours on the 18 October. This force destroyed 2 further SAM sites that day, and the Egyptians withdrew some others. This allowed Israeli CAS to support Sharon's division. During the morning of 18 October, Sharon's 3rd brigade crossed, and captured an Egyptian position overlooking the West Bank from behind. This enabled the brigade to fire across to the East Bank, which in turn assisted the passage of the 3rd brigade of Adan's division and the first brigade of Brigadier Magen's division to cross. Thus by the end of 18 October, the Israelis had two full divisions and elements of a third, plus a parachute brigade, on the West Bank. The Egyptians began to withdraw armoured formations from the East Bank on the 19 October; indeed, two brigades were withdrawn that day. The Israelis captured an airfield during their advance on the West Bank on the 19 October. This enabled them to re-supply their forces by air. A further Israeli parachute brigade crossed on the 19 October.

On 20 October, the Israelis on the East Bank had long-range artillery within range of Egyptian crossing sites. It became difficult for Egyptian forces to withdraw across the Canal. On 21 October the Egyptians began to withdraw SAMs in order to avoid their loss to Israeli ground troops. This widened existing gaps in the SAM coverage, which allowed Israeli CAP and CAS to operate more effectively. During the 21st:

- The Egyptian airforce conducted a 20-aircraft raid on the Israeli crossing sites, but the raid was interrupted by Israeli CAP.
- Egyptian Artillery began shelling the crossings consistently, but Israeli CAS could now attack the guns.
- The Israeli air force could also give more effective support to the divisions exploiting south and Southwest on the West Bank.

On the 22 October the Israelis on the West Bank had so much space, and hence freedom to manoeuvre, that Adan's division could attack with 3 brigades up *and* avoid (or manoeuvre around) enemy positions in order to encircle them. In addition, Magen's Division was attacking southwards, further to the West. Until the morning of 19th October, the Egyptians believed that only 'a few amphibious tanks' were operating on the West Bank. On the previous day, they had detected a second bridge crossing, and a mechanised brigade was thrown in to defeat (what was perceived as) 'a small Israeli armoured force'. (An

Egyptian mechanised brigade was quite small, with perhaps 20-30 tanks and 60-80 APCs). The attack was beaten off.

The Egyptians reported 100-110 enemy tanks on the West Bank. The true figure was probably about 400. The Soviet Premier Kosygin showed Sadat satellite photos of about 270 Israeli tanks and AFVs on the West Bank. Israeli sources state that ‘a note of desperation set in’ amongst the Egyptians on 19 October. Two Egyptian Armoured Brigades were withdrawn from the East Bank on that day. There are few, if any, direct references to Israeli EW but it appears that this quote about desperation came from COMINT sources.

Sadat had ordered his CGS, General Shazli, forward to visit the front on the 19 October. That night, at a high command meeting with the CGS, the War Minister and Sadat, Shazli was reported to be in ‘a state of exhaustion’. He was relieved of his appointment, and Sadat immediately contacted Kosygin to arrange a cease-fire.

Observations

The Suez crossing operation benefited from several synergetic effects:

- Raiding SAM sites enabled Israeli use of CAS and CAP, which in turn increased the effectiveness of the ground forces.
- Enlarging the bridgehead enabled more forces to cross, which could in turn enlarge the bridgehead further. In the case of Sharon’s 3rd brigade, it could also materially support the passage of further brigades.
- Capturing the airfield eased logistic support to the forces on the West Bank.

It is important, however, not to over-emphasise the synergistic effects of the crossing operation. Israeli airforce effectiveness was enhanced by airborne EW equipment hastily supplied by the USA. The Israeli Air force destroyed more SAM sites than the army, by a factor of about 2:1 (but, importantly, the sites in the region of the crossing were destroyed by ground troops). Interdiction of Egyptian bridges was carried out by Israeli long-range artillery from the East Bank. It would be more accurate to stress the overall synergy arising between all elements of the force.

The Egyptians appear largely to have overlooked the crossing until faced with incontrovertible evidence (which, ironically, *underestimated* the size of the Israeli force). Their eventual response bordered on panic, balanced strongly by Sadat’s determination that the Egyptian Army would not be seen to be routed a second time in a decade (it had run away wholesale in the Sinai Campaign of 1967). There is thus some suggestion of a catastrophic switch in Egyptian *behaviour*, which is worthy of further study from the Egyptian perspective.

The Operational decision

The Israelis had developed contingency plans before the 1973 War. They envisaged that an Egyptian force would cross the Canal, and hence presupposed some initial (Israeli) loss. From this perspective the key question could be seen as how to maximise the potential gain (i.e. how to minimise the net loss accruing from an Egyptian attack). The response can be considered as in Figure 2.

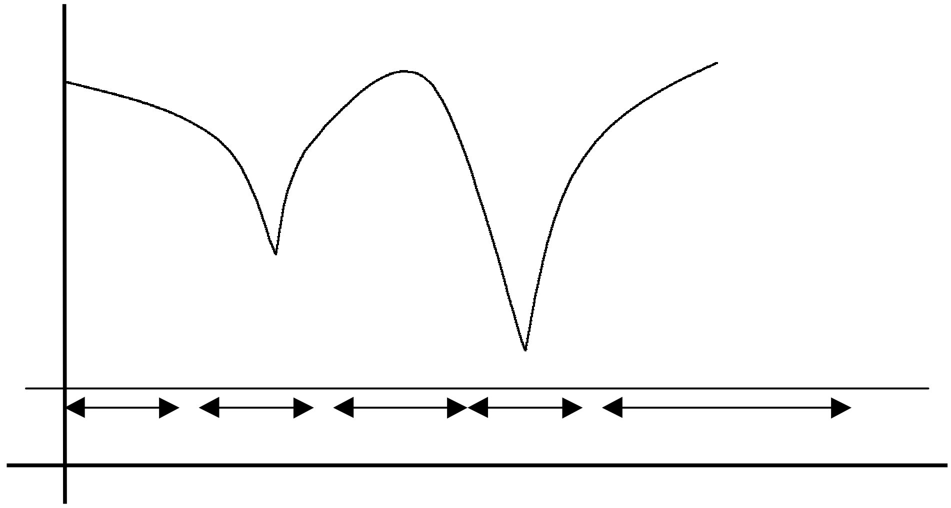


Figure 2: expected loss against Operational decision to push West

Moving from left to right along the curve, Section 1 represents the presupposition of Israeli loss using a small force locally.

Section 2 represents an option (or options) for counterattack solely on the East Bank. This could quite conceivably bring about a significant gain (given the experience of the 1956 and 1967 Sinai Campaigns). However, such a restricted move would be unlikely to defeat the Egyptian Army as they would have the option to withdraw back across the Canal. Thus the potential gain was constrained.

Section 4 represents an attack in sufficient strength and reach to cross the Canal in force and to pin a part of the Egyptian Army with its back to the canal. This might conceivably bring about significant military gain. However, even if it did not, it was likely to force the Egyptians to negotiate from a disadvantageous position. The potential gains from this approach could therefore be seen to be materially greater than an East Bank option.

Section 3 represents options that applied more effort than that required to achieve victory on the East but insufficient to defeat the Egyptians using a West Bank approach. This middle ground option would have larger expected losses (both military and political) for the Israelis. For example, failure to achieve a crossing, or, if a crossing was attempted, it would leave a force in the East that is too weak.

Section 5 represents greater force than is necessary to achieve a material advantage on the West Bank. It includes options such as marching on Cairo once established on the West Bank. This might conceivably have succeeded in retrospect since there was relatively little of the Egyptian Army in a position to resist it. However, such a move was likely to incur Superpower involvement, whilst not necessarily demonstrating a clear-cut advantage as in Section 4. Thus less material gain (taken more globally) was likely to result.

A Peace Support example: early days in Northern Ireland (1968 +)

As with Israeli decision making in 1973, British planning in the early days of the "Troubles" took place in the context of some initial loss. Law and order had broken down to some extent. The initial decision (to commit troops) reflected a failure of the RUC to deal with the situation. The decision response regarding the level of military presence can be considered as per Figure 3:

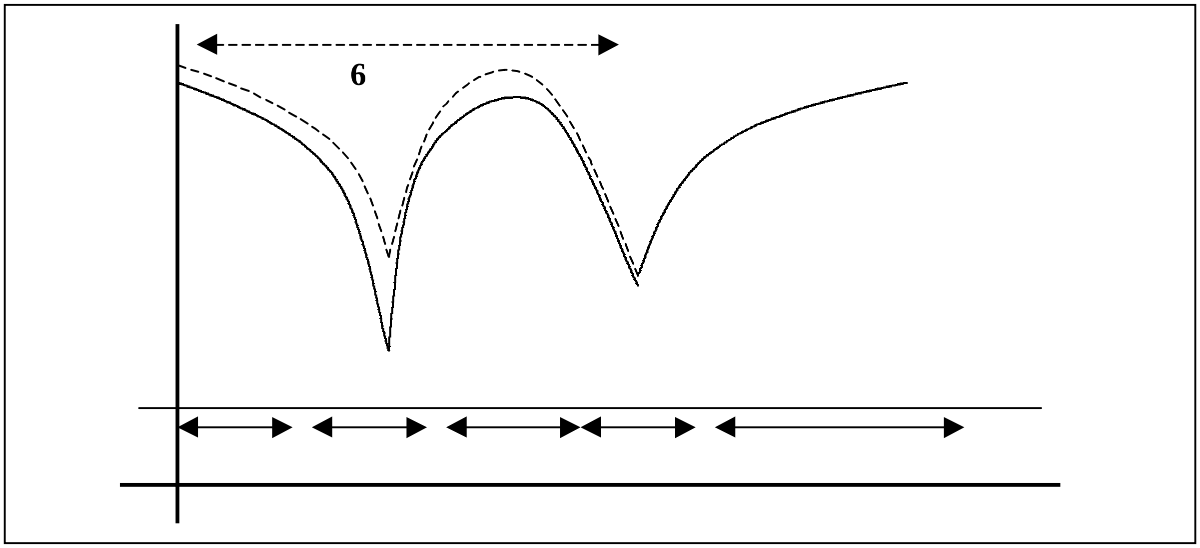


Figure 3: expected loss against level of "military presence"

Moving from left to right along the numbered sections of the curve, section 1 represents the expected loss for a small initial security force presence that seems to have caused an escalation in violence to a level beyond the capability of the units deployed.

As the level of military presence is increased the losses (due to incited violence being contained) are expected to decrease. Section 2 suggests the early effect of deploying sufficient troops. Violence was reduced effectively. The Catholic community largely welcomed the military presence and support for Republican terrorists was limited.

Section 3 represents the effect of increasing force levels by the Government. On the one hand it represents more robust use of troops, including the Balkan Street Search of 3-5 July 1970 (the 'Rape of the Falls'), in which over 3,000 troops searched several (catholic-inhabited) city blocks, killing 5 civilians and wounding 12 more in the process. On the other hand the Six County Parliament enacted the Criminal Justice (Temporary Provisions) Act, which imposed a mandatory 6 month's jail sentence if arrested at the scene of a riot. In practice this discriminated against Catholics, who were more likely to protest at perceived injustice, and thus more likely to be jailed for attending a riot. The effect of these two measures was to alienate much of the Catholic community and increase support for Republican terrorists. Internment was another factor. (The loss function metric must not only reflect casualties but also political failures and "lost ground" in negotiations.) The government's losses increased in many ways, not least the number of terrorist incidents, and the number of soldiers killed and wounded. Internment was another factor.

Section 4 represents the projected effects of increasing force levels and other measures (such as Diplock Courts) to the point where Republican terrorism could to some extent be contained, albeit at a fairly high level of violence (including occasional incidents on the Mainland and the Continent). This situation continued until the early 1990s.

Section 5 suggest what might have happened with even more robust measures on the part of the Government. More terrorists might have been apprehended, and the levels of violence reduced, but the repercussions would probably have been high; for example, in terms of allegations of human rights abuses. The response to Diplock Courts, and 'shoot on sight' allegations, suggest that such strong measures would be seen as oppressive.

The dotted portion, Section 6, is intended to suggest the effect of negotiating towards a long- term settlement. Force levels have now been reduced considerably, and the community seems largely content, but the political cost is high. Some residual force is required: there is currently every indication that removing *all* troops and disarming the police (i.e. operating towards the left of the horizontal axis) would lead back to higher levels of violence than at present.

Discussion

The expected loss curve allows us to explore, relatively, the range of the decision space. In many cases the force capability may be constrained so that parts of the decision space are infeasible and inaccessible. For example, more extreme operational options may only be attainable with allied support. In such cases, the expected loss curve may exhibit a global minimum in a region of the decision space that is beyond current policy boundaries or beyond own force capability. Thus the expected loss curve helps the decision-maker to see and understand the effects of policy boundaries on his decision-making.

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