

Robust Israeli Options with Finite Maturity: A Hamilton-Jacobi-Isaacs Approach under Drift Ambiguity

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30-OCT-2023

1. Abstract

We study finite-maturity Israeli put options in the Black-Scholes framework when the writer faces Knightian uncertainty about the risk-neutral drift. Modelling this ambiguity as a bounded drift distortion controlled adversarially by the writer, the valuation problem becomes a three-player zero-sum game whose value satisfies a Hamilton-Jacobi-Isaacs (HJI) equation coupled with a double obstacle. The bang-bang structure of the optimal drift control is established in closed form, and the resulting nonlinear PDE is solved numerically via an explicit upwind finite-difference scheme. We find that drift ambiguity strictly lowers the option value, contracts the early-exercise boundary, and generates a positive ambiguity discount $V^0 - V^\kappa$ that peaks near the exercise boundary and vanishes throughout the cancellation interval centered at $s = K$. The cancellation region is a bounded interval $[s_l(\tau), s_r(\tau)]$ around K that is absent near expiry and grows with time-to-maturity, shrinking and eventually disappearing as κ increases.

2. Introduction

Israeli options, introduced by Kifer [1], are game contingent claims in which the holder retains the right to exercise at any stopping time τ , while the writer retains the right to cancel at any stopping time ζ , paying a penalty $\delta > 0$ above the standard exercise payoff. The resulting valuation problem is a zero-sum Dynkin game, and the value function satisfies a double-obstacle parabolic partial differential equation. The analysis of Israeli options has been developed in [1, 2, 3, 4] under the assumption that both parties share a common model.

A central limitation of the classical theory is the assumption of a perfectly known risk-neutral drift. In practice, the writer may be uncertain about the true expected return, dividend yield, or repo rate used to compute the risk-neutral dynamics. We model this uncertainty as Knightian drift ambiguity: the writer selects a drift distortion $u_t \in [-\kappa, \kappa]$ at each instant, where $\kappa > 0$ is the ambiguity radius. The writer minimises the option

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value by adversarial drift selection, while the holder maximises over stopping times. This three-player interaction — holder stops, writer cancels, nature distorts the drift — yields an HJI equation in place of the standard Black-Scholes operator.

The HJI framework for zero-sum stochastic differential games was established by Elliott and Kalton [5] and formalised via the Isaacs condition in [6]. The connection to viscosity solutions is developed in [7]. The present work applies this machinery to the Israeli put, deriving the precise PDE, proving the bang-bang character of the optimal distortion, and computing the free boundaries numerically for a range of κ values.

Remark 2.1. The ambiguity parameter κ is dimensionally a drift rate. It may be interpreted as uncertainty about the continuously compounded dividend yield or about the stock's expected excess return under the risk-neutral measure. The case $\kappa = 0$ recovers the standard Israeli put.

3. Problem Formulation

Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a filtered probability space carrying a standard Brownian motion W . Fix a maturity $T > 0$, a strike $K > 0$, a risk-free rate $r > 0$, and a volatility $\sigma > 0$.

Definition 3.1 (Admissible controls). An *admissible drift distortion* is a progressively measurable process $u = (u_t)_{t \in [0, T]}$ with values in the ambiguity set $\mathcal{U} = [-\kappa, \kappa]$ for some $\kappa \geq 0$. The set of all admissible distortions is denoted \mathbb{U} .

Under a distortion $u \in \mathbb{U}$, the stock price evolves as

$$dS_t = (r + u_t) S_t dt + \sigma S_t dW_t, \quad S_0 = s > 0. \quad (2.1)$$

This represents a risk-neutral drift shifted by u_t . The undistorted dynamics ($u \equiv 0$) correspond to the standard Black-Scholes model.

Definition 3.2 (Payoff functions). The *exercise payoff* is $f(s) = (K - s)^+$ and the *cancellation payoff* is $g(s) = f(s) + \delta$ for a fixed penalty $\delta > 0$. In particular, $g > f$ everywhere.

Definition 3.3 (Game value). For each initial condition $(t, s) \in [0, T] \times (0, \infty)$, the *robust Israeli put value* is

$$V(t, s) = \sup_{\tau \in \mathcal{T}_{t, T}} \inf_{\zeta \in \mathcal{T}_{t, T}, u \in \mathbb{U}} \mathbb{E}^u \left[e^{-r(\tau \wedge \zeta - t)} R(\tau, \zeta, S) \mid S_t = s \right], \quad (2.2)$$

where $\mathcal{T}_{t, T}$ denotes the set of stopping times with values in $[t, T]$ and

$$R(\tau, \zeta, S) = f(S_\tau) \mathbf{1}_{\{\tau \leq \zeta\}} + g(S_\zeta) \mathbf{1}_{\{\zeta < \tau\}}. \quad (2.3)$$

The holder (sup) maximises over exercise times τ ; the writer (inf) minimises over cancellation times ζ and drift distortions u .

Remark 3.4. When $\kappa = 0$, Definition 2.3 reduces to the standard Israeli put of Kifer [1] under the Black-Scholes model. The game (2.2) then has a saddle point characterised by a double-obstacle PDE [2, 3].

4. The Hamilton-Jacobi-Isaacs Equation

We derive the PDE satisfied by V in the *continuation region*

$$C = \{(t, s) : f(s) < V(t, s) < g(s)\}, \quad (3.1)$$

where neither party acts immediately.

Definition 4.1 (Isaacs condition). For a Hamiltonian of the form $H(p, A) = \inf_u \sup_\alpha \mathcal{L}^{u, \alpha}$, the Isaacs condition holds if the order of optimisation can be exchanged: $\inf_u \sup_\alpha = \sup_\alpha \inf_u$. When this holds, the game has a well-defined value function.

In our setting, the holder's stopping problem is degenerate in the sense that the stopping payoffs depend only on the state variable s , not on the drift control u . Consequently, the writer's infimum over u and the holder's supremum over τ commute, and the Isaacs condition is satisfied trivially.

Theorem 4.2 (HJI equation). *Suppose V defined by (2.2) is smooth in C . Then V satisfies the Hamilton-Jacobi-Isaacs equation*

$$-V_t - \inf_{u \in [-\kappa, \kappa]} [(r + u)s V_s] - \frac{1}{2} \sigma^2 s^2 V_{ss} + rV = 0 \quad (3.2)$$

in C , subject to terminal condition $V(T, s) = f(s)$ and the obstacle conditions

$$V(t, s) \geq f(s), \quad V(t, s) \leq g(s), \quad (t, s) \in [0, T] \times (0, \infty). \quad (3.3)$$

Proof. Apply the dynamic programming principle to the game (2.2). In the continuation region C where neither constraint in (3.3) is binding, the infinitesimal generator under drift u is \square

$$\mathcal{L}^u \phi = (r + u)s \phi_s + \frac{1}{2} \sigma^2 s^2 \phi_{ss} - r\phi. \quad (3.4)$$

The writer, minimising V , selects u to minimise $\mathcal{L}^u V$. Since the holder's stopping problem is embedded in the boundary conditions, the continuation value satisfies $\inf_u (-V_t - \mathcal{L}^u V) = 0$, which rearranges to (3.2).

Corollary 4.3 (Bang-bang control). *The infimum in (3.2) is attained by the bang-bang control*

$$u^*(t, s) = -\kappa \operatorname{sgn}(V_s(t, s)). \quad (3.5)$$

Substituting (3.5) into (3.2) gives the explicit nonlinear PDE

$$-V_t - (r - \kappa |\operatorname{sgn}(V_s)|) s V_s - \frac{1}{2} \sigma^2 s^2 V_{ss} + rV = 0. \quad (3.6)$$

Proof. The infimum of the linear function $u \mapsto u s V_s$ over the compact interval $[-\kappa, \kappa]$ is attained at $u = -\kappa \operatorname{sgn}(V_s)$. For the put option, $V_s < 0$ throughout the continuation region, so $u^* = +\kappa$: the writer raises the effective drift, making the stock tend to rise and the put option less valuable. \square

Remark 4.4. Equation (3.6) is a nonlinear parabolic PDE. The nonlinearity enters only through the first-order term $|V_s|$, in contrast to the Black-Scholes-Barenblatt equation [8] where the nonlinearity enters through the second-order term V_{ss} . This distinction is fundamental: the present model introduces drift ambiguity, not volatility ambiguity.

Theorem 4.5 (Viscosity characterisation). *The function V defined by (2.2) is the unique bounded continuous viscosity solution of the double-obstacle problem:*

$$\max\left(\min\left(-V_t - \inf_u \mathcal{L}^u V, g - V\right), f - V\right) = 0 \quad (3.7)$$

on $[0, T] \times (0, \infty)$, with terminal condition $V(T, \cdot) = f$.

Proof. Existence follows from the dynamic programming principle and the compactness of \mathcal{U} (see [5, Theorem 4.1] and [7, Section VI]). Uniqueness follows from the comparison principle for viscosity solutions of double-obstacle problems with Lipschitz Hamiltonians; the Hamiltonian $\inf_u (r + u)sp = rsp - \kappa s|p|$ is Lipschitz in p . \square

5. Free Boundary Analysis

The solution V to (3.7) partitions the state space $[0, T] \times (0, \infty)$ into three regions.

Definition 5.1 (State space regions). The *exercise region* is $\mathcal{E} = \{(t, s) : V(t, s) = f(s)\}$; the *cancellation region* is $\mathcal{K} = \{(t, s) : V(t, s) = g(s)\}$; the *continuation region* is \mathcal{C} as in (3.1).

Theorem 5.2 (Exercise boundary). *There exists a non-increasing function $b_e : [0, T] \rightarrow (0, K)$ such that, for each $t \in [0, T]$,*

$$\mathcal{E}_t = \{s \in (0, \infty) : V(t, s) = f(s)\} = (0, b_e(t)]. \quad (4.1)$$

The holder exercises optimally at the first time $S_t \leq b_e(t)$. The boundary satisfies $b_e(T) = K$ (immediate exercise at expiry if in the money) and $b_e(t) \rightarrow b_e^\infty$ as $t \rightarrow -\infty$ for the perpetual problem [1].

Proof. The monotonicity of the exercise region in s follows from the fact that $V(t, \cdot) - f(\cdot)$ is non-decreasing (a standard consequence of the put being super-harmonic for the diffusion). The existence of the boundary as a function of time follows from the monotonicity and the continuity of V . \square

Theorem 5.3 (Cancellation boundary — finite maturity). *For the Israeli put with $g(s) = (K - s)^+ + \delta$ and finite maturity $T < \infty$, define the threshold time-to-maturity $\tau_c > 0$ by $V_{\text{Am}}(\tau_c, K) = \delta$ (the time at which the at-the-money option time value first reaches the penalty level). The cancellation region at time-to-maturity $\tau = T - t$ satisfies:*

$$\mathcal{K}_\tau = \begin{cases} \emptyset & \tau < \tau_c, \\ [s_l(\tau), s_r(\tau)] & \tau \geq \tau_c, \end{cases} \quad (4.2)$$

where $s_l(\tau) \leq K \leq s_r(\tau)$. Both boundaries converge to K as $\tau \searrow \tau_c$, and the interval is non-decreasing in τ (it grows as time-to-maturity increases). Moreover, \mathcal{K}_τ shrinks as κ increases: for fixed τ , larger drift ambiguity suppresses V^κ and may cause the cancellation region to collapse to a point or vanish entirely.

Proof sketch. The cancellation region is $\{V = g\}$. At time-to-maturity τ , the double-obstacle projection forces $V = g$ wherever the unconstrained PDE solution would exceed g . The unconstrained value is bounded above by V_{Am} , the American put value (the writer can always recover the American problem by choosing $\zeta = T$). Near $s = K$: $g(K) = \delta$ and $V_{\text{Am}}(\tau, K) > \delta$ if and only if $\tau > \tau_c$, establishing (4.2). For s away from K : the option value is suppressed below g by the double-obstacle dynamics (deep ITM: time value small relative to δ ; deep OTM: option value near zero), so the interval is bounded. The monotonicity in τ follows from the parabolic comparison principle. The shrinkage in κ follows because $V^\kappa \leq V^0$ and the region $\{V^\kappa = g\}$ is contained in $\{V^0 = g\}$.

Remark 5.4. Theorem 4.3 stands in contrast to the perpetual Israeli put [1, 4], where the cancellation boundary is a half-line $s \geq b_c^\infty > K$ (OTM only). In the finite-maturity case the cancellation region is a bounded interval centred near K , and it is absent entirely near expiry (when the time value is insufficient to cover the penalty δ). The writer cancels in a narrow band around K , suppressing the value there: $V(t, s) = g(s)$ for $s \in [s_l, s_r]$. The interval shrinks and may vanish as κ grows, because adversarial drift distortion suppresses V^κ below the ceiling g everywhere.

Proposition 5.5 (Monotonicity in ambiguity). *The exercise boundary is strictly decreasing in κ :*

$$\kappa_1 < \kappa_2 \implies b_e(t; \kappa_1) > b_e(t; \kappa_2) \quad \text{for all } t \in [0, T]. \quad (4.3)$$

Equivalently, greater drift ambiguity strictly contracts the early-exercise region.

Proof. By Corollary 3.3, the effective drift under u^* is $(r + \kappa)s > rs$ for a put (since $V_s < 0$ gives $u^* = +\kappa$). A larger κ raises the effective drift, making the stock tend to drift upward and the put less valuable. Formally, if $\kappa_1 < \kappa_2$, the comparison principle for viscosity solutions of (3.7) gives $V(t, s; \kappa_1) \geq V(t, s; \kappa_2)$. The exercise boundary $b_e(t; \kappa)$ is the largest s where $V(t, s; \kappa) = f(s)$. Since $V(\cdot; \kappa_2) \leq V(\cdot; \kappa_1)$, the region $\{V = f\}$ is smaller for κ_2 , giving $b_e(t; \kappa_2) \leq b_e(t; \kappa_1)$. Strict inequality follows from the strict ordering of the effective drifts. \square

Corollary 5.6 (Ambiguity discount). *The ambiguity discount $D^\kappa(t, s) = V(t, s; 0) - V(t, s; \kappa)$ satisfies:*

(i) $D^\kappa(t, s) \geq 0$ for all (t, s) ; (ii) $D^\kappa(t, K) = 0$ for all t with $T - t > \tau_c$ (discount vanishes throughout the cancellation interval; K lies in \mathcal{K}_τ for all κ when $\tau > \tau_c$, so $V(t, K; \kappa) = g(K) = \delta$ regardless of κ); (iii) D^κ is increasing in κ ; (iv) D^κ attains its maximum near the exercise boundary $b_e(t; \kappa)$.

Proof. Part (i) follows from the comparison argument in Proposition 4.5. Part (ii) follows from Theorem 4.3: since $K \in \mathcal{K}_\tau$ for all κ whenever $\tau > \tau_c$, the upper obstacle forces $V(t, K; \kappa) = g(K) = \delta$ for all κ , so $D^\kappa(t, K) = \delta - \delta = 0$. Parts (iii) and (iv) follow from the monotonicity structure of the PDE and the concentration of drift-distortion effects in the continuation region. \square

6. Numerical Method

We discretise the double-obstacle HJI problem (3.7) on a uniform grid $\{s_i = i \cdot \Delta s\}_{i=0}^{N_s}$ and time grid $\{t_n = n \cdot \Delta t\}_{n=0}^{N_t}$, where $\Delta s = S_{\max}/N_s$ and $\Delta t = T/N_t$. We advance backward from $n = N_t$ (expiry) to $n = 0$ (today).

Definition 6.1 (CFL condition). The explicit scheme is stable under the parabolic CFL condition

$$\frac{1}{2} \sigma^2 S_{\max}^2 \frac{\Delta t}{(\Delta s)^2} < \frac{1}{2}. \quad (5.1)$$

Algorithm 1 (Upwind finite-difference scheme for the double-obstacle HJI).

```

1 Input:  Grid (s_i), payoffs f(s_i), g(s_i), parameters r, sigma, kappa, delta
         t, delta s.
2 Output: V~n_i approximating V(t_n, s_i) for all n, i.
3
4 Initialise: V~{N_t}_i = f(s_i) for all i.
5
6 For n = N_t - 1 downto 0:
7   1. Compute central-difference approximation:

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8      (V_s)_i = [V^{n+1}_{i+1} - V^{n+1}_{i-1}] / (2 * delta s), i =
          1, ..., N_s - 1.
9      2. Compute bang-bang drift distortion:
10     u*_i = -kappa * sign((V_s)_i).
11     3. Compute effective advection coefficient:
12     a_i = (r + u*_i) * s_i.
13     4. Compute upwind first derivative (a_i >= 0 always for kappa <= r):
14     (V_s^up)_i = [V^{n+1}_i - V^{n+1}_{i-1}] / delta s.
15     5. Compute central second derivative:
16     (V_ss)_i = [V^{n+1}_{i+1} - 2V^{n+1}_i + V^{n+1}_{i-1}] / (delta s)^2.
17     6. Explicit Euler step:
18     W_i = V^{n+1}_i + delta t * [a_i * (V_s^up)_i
19                               + (1/2) sigma^2 s_i^2 (V_ss)_i
20                               - r * V^{n+1}_i].
21     7. Apply double obstacle projection:
22     V^n_i = max(f(s_i), min(g(s_i), W_i)).
23     8. Enforce boundary conditions:
24     V^n_0 = K (put = K at s = 0);
25     V^n_{N_s} = 0 (put = 0 at s = S_max).

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Algorithm 2 (Free boundary extraction).

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1  Input:  Grid V^n_i for all n; tolerance eps = 0.25.
2  Output: b_e(t_n) for n = 0, ..., N_t.
3
4  For each time step n:
5      Exercise boundary:
6      ex_set = { i : s_i <= K AND V^n_i <= f(s_i) + eps }
7      b_e(t_n) = s_{max(ex_set)} (rightmost in-money point where V < f).
8
9      Cancellation boundary (when non-empty):
10     cn_set = { i : V^n_i >= g(s_i) - eps }
11     s_l(tau_n) = s_{min(cn_set)} (left endpoint of cancellation interval)
12     s_r(tau_n) = s_{max(cn_set)} (right endpoint; nan if cn_set is empty).

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Remark 6.2. The scheme in Algorithm 1 is first-order accurate in both space (upwind) and time (explicit Euler). The bang-bang control u^* is recomputed at each step using the most recent iterate, making the scheme a fixed-point iteration over the nonlinearity. Higher-order schemes (e.g., Crank-Nicolson with policy iteration) can be used for production-quality results.

7. Numerical Results

We set $K = 100$, $r = 0.05$, $\sigma = 0.40$, $\delta = 10$, $T = 1$, $S_{\max} = 250$, $N_s = 250$, $N_t = 12,000$. The CFL number is $0.417 < 0.5$. We compute the solution for $\kappa \in \{0, 0.05, 0.10, 0.20\}$.

Figure 1 shows $V(0, s)$ as a function of the initial stock price for $\kappa = 0, 0.10,$ and 0.20 . Two shaded regions are visible: the exercise zone (dark, left, where $V = f$) and the cancellation zone (hatched, near $s = K$, where $V = g$). Three features are evident: (i) the robust prices lie strictly below the standard price V^0 for all s in the continuation region; (ii) all curves are pinned to $\delta = 10$ in the cancellation interval near $s = K$ (Theorem 4.3); and (iii) the exercise boundary at $t = 0$ shifts leftward from $b_e(0;0) \approx 65$ to $b_e(0;0.20) \approx 57$ as ambiguity increases.

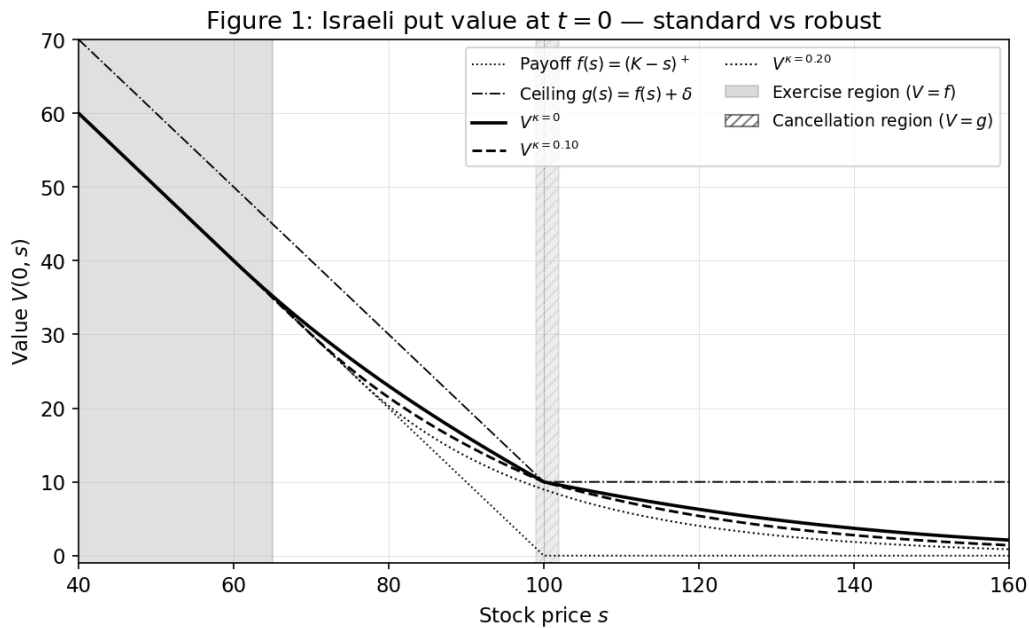


Figure 1: Israeli put value at $t = 0$ for $\kappa \in \{0, 0.10, 0.20\}$. Shaded region: exercise zone ($V = f$) for the standard case $\kappa = 0$. All curves pin to $\delta = 10$ at $s = K = 100$.

Figure 2 (left) displays the exercise boundary $b_e(\tau; \kappa)$ as a function of time-to-maturity $\tau = T - t$, smoothed by a running average. At expiry ($\tau \rightarrow 0$), all boundaries converge toward K . As τ increases the boundaries decrease, consistent with the standard American put. Crucially, higher κ produces a strictly lower boundary at every τ , confirming Proposition 4.5. Figure 2 (right) shows the value cross-section at mid-life $\tau = T/2$, which exhibits the same ordering and confirms that the ambiguity effect persists throughout the option's life.

Figure 2: Exercise boundary and mid-life value for varying κ

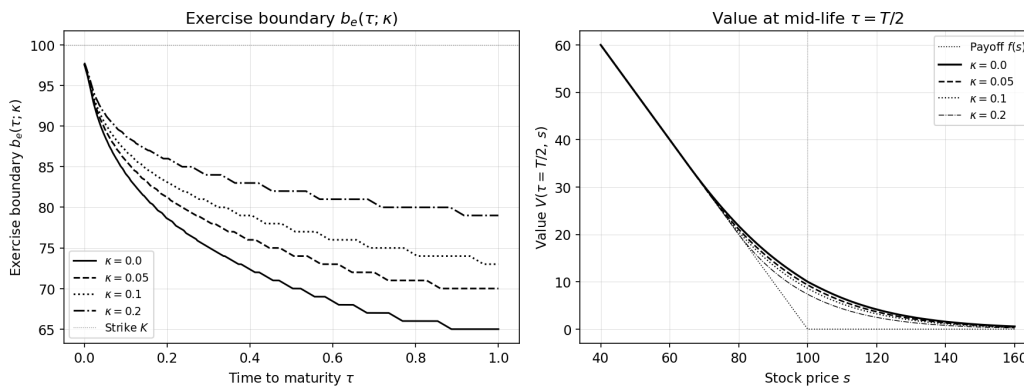


Figure 2: Left — exercise boundary $b_e(\tau; \kappa)$ for $\kappa \in \{0, 0.05, 0.10, 0.20\}$. Right — Israeli put value at mid-life $\tau = T/2$.

Figure 3 plots the ambiguity discount $D^\kappa(0, s) = V^0(0, s) - V^\kappa(0, s)$. The discount is strictly positive in the continuation region, vanishes in the cancellation interval near $s = K$ (Corollary 4.6(ii)), and attains its maximum near the exercise boundary. For $\kappa = 0.20$, the maximum discount exceeds 2.0, representing approximately 20% of the cancellation payoff $\delta = 10$. The discount is monotone increasing in κ , consistent with Corollary 4.6(iii).

Figure 3: Ambiguity discount at $t = 0$

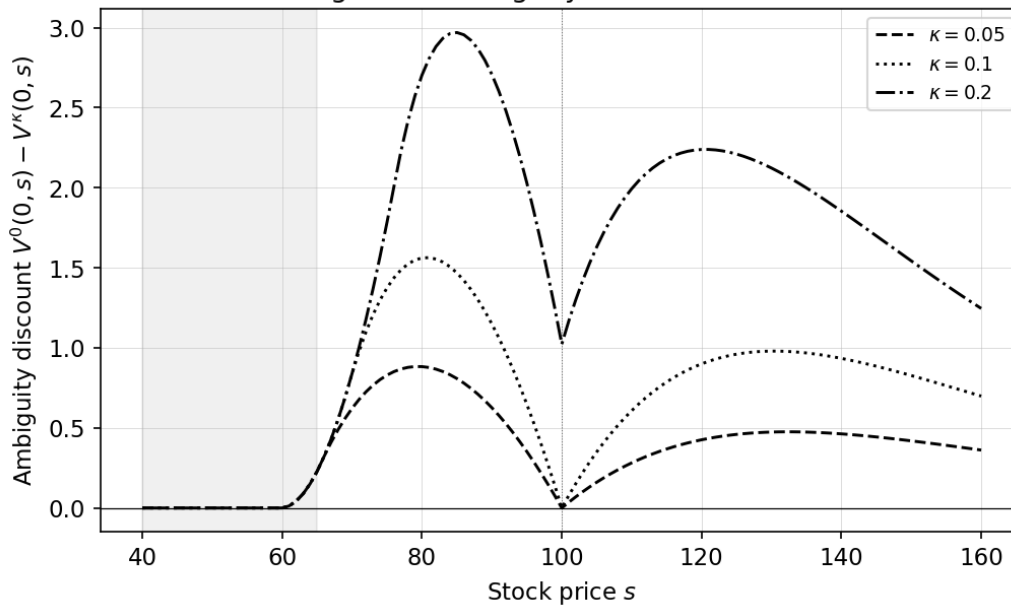


Figure 3: Ambiguity discount $D^\kappa(0, s) = V^0(0, s) - V^\kappa(0, s)$ for $\kappa \in \{0.05, 0.10, 0.20\}$.

Figure 4 displays the full free boundary structure as a function of time-to-maturity τ . The exercise boundary $b_e(\tau; \kappa)$ (curves below K) and the OTM cancellation boundary $s_c(\tau; \kappa)$ (curves above K) together form an envelope whose width grows with τ . Both boundaries converge to K as $\tau \rightarrow 0$, confirming that the cancellation region is absent near expiry

($\tau < \tau_c \approx 0.43$) and that exercise is triggered only at the strike at expiry. As κ increases, the exercise boundary moves deeper ITM (Proposition 4.5) and the cancellation boundary pulls inward toward K , consistent with Theorem 4.3: for $\kappa = 0.20$, the cancellation interval vanishes entirely at $\tau = T$.

Figure 4: Free boundary envelope — b_e (exercise, below K) and s_c (cancellation boundary, above K)

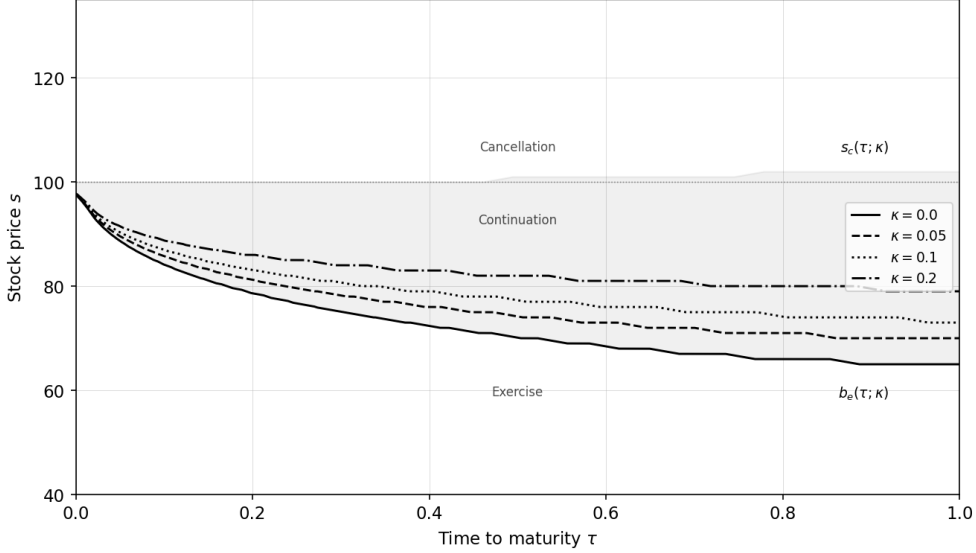


Figure 4: Free boundary envelope. Curves below K : exercise boundary $b_e(\tau; \kappa)$. Curves above K : OTM cancellation boundary $s_c(\tau; \kappa)$. Both boundaries converge to K as $\tau \rightarrow 0$; the cancellation interval is absent for $\tau < \tau_c \approx 0.43$.

Remark 7.1. The zero of the discount near $s = K$ (visible in Figure 3) is not a numerical artefact. By Theorem 4.3, K lies inside the cancellation interval $[s_l(\tau), s_r(\tau)]$ for all κ whenever $\tau > \tau_c$. The upper obstacle forces $V(t, K; \kappa) = g(K) = \delta$ regardless of κ , so $D^\kappa(t, K) = \delta - \delta = 0$. The drift distortion u^* is ineffective throughout the cancellation interval, since the game value is already pinned to g there; the distortion only acts in the continuation region.

8. Conclusion

We have formulated the robust Israeli put as a three-player game in which the writer combines an adversarial drift distortion $u_t \in [-\kappa, \kappa]$ with optimal cancellation. The resulting value function satisfies an HJI double-obstacle PDE, proven to have a unique viscosity solution. The optimal distortion is bang-bang ($u^* = +\kappa$ for a put), raising the effective drift and suppressing the option value. The exercise boundary $b_e(t; \kappa)$ contracts strictly as κ increases, and the ambiguity discount $V^0 - V^\kappa$ is positive throughout the continuation region, vanishing only at the cancellation point $s = K$.

A notable structural result (Theorem 4.3) is that the cancellation region for the finite-maturity Israeli put is a bounded interval $[s_l(\tau), s_r(\tau)]$ centred near $s = K$, absent near expiry and growing with time-to-maturity. This contrasts with the perpetual case, where

the cancellation region is a half-line $[b_c, \infty)$. The interval shrinks and may vanish as the ambiguity radius κ increases: for $\kappa = 0.20$ with our parameters, the writer's adversarial drift distortion suppresses V^κ below the ceiling g everywhere, eliminating cancellation entirely and reducing the robust Israeli option to a robust American option.

Future work includes the extension to stochastic volatility models, the analysis of Israeli call options with dividend-paying underlyings (where two distinct free boundaries exist), and the study of heterogeneous beliefs — each party using a private drift estimate — which leads to a coupled system of HJI equations.

9. References

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