Conditional Risk-Averse Constrained Reinforcement Learning

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Abstract

In Risk-averse Constrained Reinforcement Learning (RaCRL), the optimal tolerance for risk often depends on a preference over the trade-off between reward and safety. This trade-off is influenced by environmental uncertainty, which is generally difficult to quantify, in turn making its effect on an agent's performance difficult to predict at the outset of training. Conventional RaCRL approaches typically train agents under a fixed risk level, set at the beginning of training, leading to an agent with a fixed, often conservative, reward-safety trade-off at deployment time. In this paper, we introduce Conditional Risk-averse Actor Critic (CRAC), a novel algorithm for RaCRL that conditions the agent on risk levels sampled during both exploration and learning. Through exploring and learning from diverse experiences across varied risk levels, CRAC generalises effectively across a spectrum of risk preferences, enabling the deployment of a single agent at risk levels chosen by a user. We evaluate CRAC across a set of environments with increasing difficulty, demonstrating empirically that it generalises effectively across a risk spectrum. CRAC often achieves higher reward than fixed-risk agents, whilst satisfying cost constraints. In cases where CRAC's reward performance is marginally lower than a fixed-risk agent, CRAC retains the advantage of a single risk-conditioned policy that generalises to a risk spectrum, reducing training overhead and providing more control over the reward-cost trade-off.

1 Introduction

Constrained Reinforcement Learning (CRL) extends standard Reinforcement Learning (RL) by introducing safety constraints through a dual objective framework; rewards guide task performance whilst costs guide safety objectives (Altman, 1999; Achiam et al., 2017). Policies are trained to maximise rewards whilst ensuring expected accumulated costs remain below predefined safety thresholds. Risk-averse CRL (RaCRL) extends CRL by addressing variability in cost returns arising from environmental uncertainty by controlling for worst-case outcomes using coherent risk measures such as Conditional Value at Risk (CVaR) (Rockafellar & Uryasev, 2000; Yang et al., 2021). However, the likelihood and magnitude of constraint violations caused by uncertainty is generally hard to quantify, leading to difficulty in specifying an appropriate risk level for training an agent at the outset of training.

Current RaCRL approaches adopt a *fixed* level of risk aversion, training policies to satisfy safety constraints at a single, predefined risk level (Yang et al., 2023; Kim et al., 2023; 2024; Yang et al., 2024), effectively committing to a single reward-cost trade-off thoughout training and deployment. This prevents the adoption of current RaCRL in problem settings that necessitate flexibility over the reward-safety trade-off. For instance, in autonomous building energy management (Vázquez-Canteli et al., 2019), a user may prefer a highly risk-averse agent under uncertain weather conditions, to mitigate the effect of potential power-outages. Conversely, during favourable weather conditions, the same user may prefer a more risk-neutral agent, that maximises energy savings, through efficient energy use. Fixed risk-averse agents are ill-suited to adapt to these changing preferences, requiring retraining in order to switch between different risk-aversions, limiting their flexibility.

To address this limitation, we propose Conditional Risk-Averse Actor Critic (CRAC), an off-policy algorithm for RaCRL that learns a single risk-conditioned policy that satisfies risk-based constraints across a spectrum of risk levels. Building on SAC-based RaCRL algorithms, such as Worst-Case Soft Actor-Critic (Yang et al., 2023), CRAC conditions the actor, reward and cost critic's networks directly on a given risk level. CRAC enables exploration and learning across a spectrum of risk, allowing the policy network to represent a diverse set of behaviours that balance task and safety objectives in different ways. CRAC's *implicit* exploration is beneficial as fixed-risk policies may insufficiently explore the environment, converging to suboptimal or low reward policies (Greenberg et al., 2022; Yang et al., 2024; McCarthy et al., 2025).

We evaluate CRAC in the SafetyGymnasium suite of environments (Ji et al., 2023), specifically the Goal1 and Button1 tasks and the Point and Car variants, and in CityLearn (Vázquez-Canteli et al., 2019), a complex building energy management simulation environment. We compare CRAC against two fixed risk baselines, Worst-Case Soft Actor-Critic (WCSAC) (Yang et al., 2023) and Spectral Risk Constrained Policy Optimisation (SRCPO) (Kim et al., 2024), and a risk-neutral baseline, a SAC-based algorithm Conservative Augmented Lagrangian (CAL) (Wu et al., 2024). Our results demonstrate that CRAC learns constraint satisfying policies across a spectrum of risk levels, often outperforming its fixed risk counterpart, WCSAC, in terms of reward performance. This demonstrates that risk-conditioning not only provides adaptability to changing risk preferences but can also lead to more favourable trade-off's between safety and task performance. We further demonstrate generalisation to unseen risk-levels, and investigate the effect of different risk level sampling during training.

In summary, our main contributions are as follows:

1. We propose CRAC, an off-policy algorithm for RaCRL that learns a single, risk-conditioned policy that adapts to a spectrum of risk-preferences.
2. We empirically demonstrate that CRAC generalises across risk levels and is competitive with or outperforms fixed-risk baselines in terms of the reward-cost trade-off.

2 Related Work

Constrained Reinforcement Learning Specification of safety in RL is a persistently challenging problem (García & Fernández, 2015; Dulac-Arnold et al., 2021). Constrained Reinforcement Learning (CRL) formulates safety as auxillary cost functions with corresponding thresholds, separating task objectives from safety objectives (Achiam et al., 2017; Ray et al., 2019; Tessler et al., 2019; Liu et al., 2022; Zhang et al., 2022). These methods typically enforce constraints in expectation through primal-dual optimisation. Off-policy CRL methods, however, suffer from underestimation of cost returns that lead to constraint violations (Zhang et al., 2024; Wu et al., 2024; Gao et al., 2025). To address this, Wu et al. (2024) propose Conservative Augmented Lagrangian (CAL), which over-estimates cost returns to promote conservative behaviour and improved stability in constraint satisfaction. Similarly, stability is improved through PID-based methods (Stooke et al., 2020; Zhang et al., 2024) and the Modified Differential Method of Multipliers (Platt & Barr, 1987; Kumar et al., 2021; Yang et al., 2023). Despite these advances, expectation-based constraints do not explicitly control for rare but catastrophic outcomes.

Risk Averse Constrained RL To mitigate this limitation, risk-averse constrained RL (RaCRL) incorporates risk measures into the constraint. Yang et al. (2021) introduce Worst Case Soft Actor-Critic (WCSAC), approximating worst-case returns of the policy through distributional critics. The authors later extend WCSAC in (Yang et al., 2023) by incorporating Implicit Quantile Networks (Dabney et al., 2018a), enabling more expressive representations of the cost return distribution. Alternate methods include trust-region approaches with mean-variance style constraints (Kim et al., 2023), on-policy approach using backward value functions for non-stationary policies (Yang et al., 2024), and linearised spectral risk constrained policy optimisation (Kim et al., 2024). Zhang et al. (2025) reformulate the CVaR-constrained problem in an augmented state space and solving the constrained problem through Lagrangian optimisation, deriving near-closed form of the optimal policy. A characteristic shared by these approaches is that a risk level is specified *a priori*, remaining fixed throughout training and deployment.

Risk- and Constraint-Conditioned RL In the reward only setting, Choi et al. (2021) and Yoo et al. (2024) propose conditioning agents on a risk parameter, demonstrating improved reward performance over fixed risk agents, which the authors hypothesise arises from the improved exploration and diversity of experience. In the CRL setting, Yao et al. (2023) propose Constraint-Conditioned Policy Optimisation (CCPO) that trains a CRL policy across various constraint thresholds and adapts to unseen thresholds. In the offline CRL setting Guo et al. (2025) propose Constraint-Conditioned Actor-Critic (CCAC) that conditions the agents networks on the constraint, regularising cost underestimation in out of distribution (OOD) data through an OOD classifier.

Existing RaCRL approaches assume a fixed risk level, and do not learn a single policy capable of generalising across a risk spectrum. Our work addresses this limitation by training a conditional risk-averse policy that jointly optimises reward and risk-based cost constraints across a spectrum of risk levels.

3 Background

3.1 Risk Constrained RL

A *Constrained Markov Decision Process* (Altman, 1999), is defined by a tuple (S, A, P, R, C, d), where S and A are the state and action spaces respectively, $P : S \times A \times S \to [0, 1]$ is the transition probability function, $R : S \times A \times S \to \mathbb{R}$ is the reward function mapping state-action-next state transitions to a real valued scalar, $C : S \times A \times S \to \mathbb{R}^+$ is the cost function mapping state-action-next state transitions to a non-negative real valued scalar, d is the cost function's corresponding threshold. At each time step t, the agent chooses action $a \in A$ given state $s_t \in S$ and policy $\pi(\cdot|s_t)$. The environment responds with a reward $r_t = R(s_t, a_t)$, a cost $c = C(s_t, a_t)$ and next state $s_{t+1} \sim P(\cdot|s_t, a_t)$. We let the random variables $Z^\pi_R(s, a) = \sum_{t=0}^{\infty} \gamma^t r_t$ and $Z^\pi_C(s, a) = \sum_{t=0}^{\infty} \gamma^t c_t$ denote the sum of discounted rewards and costs, respectively, collected along one trajectory of states following π, beginning in state s and taking action a. The risk-averse optimal policy in the CMDP is given by:

$$\max_\pi \mathbb{E}_{s\sim\rho_\pi, a\sim\pi(\cdot|s)}[Z^\pi_R(s, a)] \;\; \textbf{s.t.} \;\; \mathcal{R}^\sigma_{s\sim\rho_\pi, a\sim\pi(\cdot|s)}[Z^\pi_C(s, a)] \leq d \tag{1}$$

where ρ_π denotes the steady state distribution of π and $\mathcal{R}^\sigma$ is spectral risk measure (Acerbi, 2002; Kim et al., 2024). Throughout this paper we use Conditional Value at Risk (CVaR) (Rockafellar & Uryasev, 2000), as our spectral risk measure, quantifying the expected cost returns of the worst α percentile of cost returns under π:

$$\mathrm{CVaR}_\alpha[Z^\pi_C] = \mathrm{E}[z_c | Z^\pi_C \geq F^{-1}_{Z^\pi_C}(1 - \alpha)] \tag{2}$$

where $F^{-1}_{Z^\pi_C}$ is the quantile function of the random variable Z^π_C, and $\alpha \in [0, 1]$ is our desired risk-level. Yang et al. (2023) propose Worst-Case Soft Actor-Critic that aims to solve this risk-averse CMDP problem through the following primal-dual optimisation objective:

$$\min_{\lambda\geq 0} \max_\pi \mathbb{E}_{s\sim\rho_\pi, a\sim\pi(\cdot|s)}[Q^\pi_R(s, a) - \lambda(Q^\pi_{C,\alpha}(s, a) - d)] \tag{3}$$

where $Q^\pi_R(s, a)$ is the reward value function approximation of $\mathbb{E}[Z^\pi_R(s, a)]$, and $Q^\pi_{C,\alpha}(s, a)$ is the cost value function approximation of the $\mathrm{CVaR}_\alpha[Z^\pi_C(s, a)]$. Next, we discuss learning a paramterised distributional critic to approximate $Q^\pi_{C,\alpha}(s, a)$

3.2 Distributional RL

The full quantile function of the state-action return distribution, can be approximated through Distributional RL and quantile regression (Dabney et al., 2018b). Letting $F^{-1}_{Z^\pi_C}$ denote the quantile function of the random variable Z^π_C we learn a parametrised quantile function $Z^\pi(s, a|\theta_C)$, mapping the quantile fraction $\tau \in [0, 1]$ to the quantile value $F^{-1}_{Z^\pi}(\tau)$. The parametrised quantile function $Z^\pi(s, a|\theta_C)$ is trained by minimising the quantile regression loss (Dabney et al., 2018b; Yang et al., 2023; Yoo & Woo, 2025):

$$\mathcal{L}(\theta^c) = \frac{1}{NN'} \sum_{i=0}^{N} \sum_{j=0}^{N'} |\tau_i - 1(\delta_{ij} < 0)| \cdot |\delta_{ij}| \tag{4}$$

where δ_{ij} is the pairwise temporal difference error between target distribution $\bar{Z}(s, a|\tau_j)$ and current distribution $Z(s, a|\tau_i)$ defined:

$$\delta_{ij} = c_t + \gamma \bar{Z}_C^{\pi}(s_{t+1}, a_{t+1}|\tau_j, \bar{\theta}_C) - Z_C^{\pi}(s_t, a_t|\tau_i, \theta_C) \tag{5}$$

where τ_i, τ_j denote N, N' total independent random quantiles drawn from a uniform distribution $U[0, 1]$. Then using this parametrised quantile distribution we can approximate $\text{CVaR}_\alpha(Z_C^{\pi})$:

$$Q_{C,\alpha}^{\pi}(s, a) = \frac{1}{\alpha} \int_{1-\alpha}^{1} Z_C^{\pi}(s, a|\theta_C)(\tau) d\tau \tag{6}$$

4 Conditional Risk-Averse Actor Critic

In this section, we present our problem definition and outline the proposed algorithm.

4.1 Problem Specification

Our aim is to learn a risk-conditioned policy $\pi(a|s; \alpha)$ that maps states $s \in S$ and risk-levels $\alpha \in \mathcal{A} \subseteq (0, 1]$, to a distribution over actions $a \in A$, such that the resulting policy satisfies the risk measure placed on the cost function C for all risk levels in $\mathcal{A}$. Formally, our objective is:

$$\max_{\pi_\alpha} \mathbb{E}_{s\sim\rho_{\pi_\alpha}, a\sim\pi(\cdot|s,\alpha)}[Z_R^{\pi_\alpha}(s, a)] \;\; \textbf{s.t.}\; \mathcal{R}^{\sigma_\alpha}_{s\sim\rho_{\pi_\alpha}, a\sim\pi(\cdot|s,\alpha)}[Z_C^{\pi_\alpha}(s, a)] \leq d; \; \forall \alpha \in \mathcal{A} \tag{7}$$

where $\mathbb{E}[Z_R^{\pi_\alpha}(s, a)]$ is the expected reward return collected following the risk conditioned policy π_α, $\mathcal{R}_{\sigma_\alpha}$ is a spectral risk-measure (e.g. CVaR) at a given risk level α calculated over $Z_C^{\pi_\alpha}(s, a)$ the distribution of cost returns collected following the risk conditioned policy π_α, and d is the cost constraint, fixed across all risk-levels.

4.2 Algorithm

To learn a policy that satisfies our objective in Eq. 7, we propose Conditional Risk-Averse Actor-Critic (CRAC), an off-policy algorithm for RaCRL, extending Worst-Case Soft Actor-Critic (WCSAC) a fixed-risk, SAC style algorithm (Yang et al., 2023), to a *continuous spectrum* of risk levels. Specifically, we condition the actor, the reward and cost critic networks on a given risk parameter α, and train a risk conditioned Lagrangian multiplier, allowing a single set of networks to represent policies across a spectrum of risk levels. Algorithm 1 summarises the full procedure, and below we discuss in more detail the key extensions made to the fixed-risk algorithm.

During exploration, CRAC samples a risk level α_e at the beginning of each episode, and fixes it for the entire episode (lines 3-9). During learning, CRAC samples minibatches of replay experience, (s, a, s', r, c), from the replay buffer, sampling a new risk level α_{tr} from a uniform distribution $\alpha_{tr} \sim U[\alpha_{\min}, \alpha_{\max}]$, where $\alpha_{\min}, \alpha_{\max}$ define the range of the spectrum, with smaller values of α indicating more risk-averse policies (line 12). This experience is then used to update the conditional actor, reward and cost critics and the conditional Lagrangian multiplier.

Conditional Reward Critic We extend the reward critic to approximate the return of the risk-conditioned policy π_α by conditioning on the reward critic on α:

$$Q_R^{\pi_\alpha}(s, a|\alpha) = \mathbb{E}[Z_R^{\pi_\alpha}(s, a)] \tag{8}$$

We train this reward critic by minimising the mean squared TD-error:

$$L(\theta_R) = \mathbb{E}_{(s,a,r,s',\alpha)}\left[\left(Q_R^{\pi_\alpha}(s, a|\alpha) - y_R\right)^2\right] \tag{9}$$

where y_R is the SAC Bellman target:

$$y_R = r_t + \gamma \mathbb{E}_{s_{t+1}\sim B, a_{t+1}\sim\pi(\cdot|s_{t+1},\alpha)}\left[\bar{Q}_R(s_{t+1}, a_{t+1}|\alpha) - \beta \log \pi(a_{t+1}|s_{t+1}, \alpha)\right] \tag{10}$$

Algorithm 1 Conditional Risk-Averse Actor-Critic (CRAC)

Initialize: Policy $\pi_\phi(a|s;\alpha)$, reward-critics $Q_{\theta_R}(s,a;\alpha)$, distributional cost-critics $Z_{\theta_C}(s,a;\alpha)$, target critics $\{\bar{Q}_{\theta_R}, \bar{Z}_{\theta_C}\}$, Lagrange multiplier network $\lambda(\alpha)$, risk cut-offs $[\alpha_{\min}, \alpha_{\max}]$, replay buffer $\mathcal{B}$
for each training episode **do**
  Sample exploration risk level $\alpha_e \sim \mathrm{U}[\alpha_{\min}, \alpha_{\max}]$ ▷ Sample α_e at beginning of episode
  for each environment step **do**
    Select action $a_t \sim \pi_\phi(\cdot|s_t;\alpha_e)$ ▷ Condition actor on α_e
    Execute a_t, obtain s_{t+1}, r_t, c_t
    Store $(s_t, a_t, r_t, c_t, s_{t+1})$ in $\mathcal{B}$
  end for
end for
for each gradient step **do**
  Sample N transitions $\{(s,a,r,c,s')\} \sim \mathcal{B}$
  Sample training risk levels $\alpha_{\text{tr}} \sim \mathrm{U}[\alpha_{\min}, \alpha_{\max}]$
  Update Conditional Reward Critic ▷ Eq. 9
  Update Conditional Cost Critic ▷ Eq. 4
  Update Conditional Actor ▷ Eq. 13
  Update Conditional Lagrangian Multiplier ▷ Alg. 2
end for

Conditional Cost Critic To estimate the CVaR cost returns of policy π_α we approximate the full cost return distribution through the quantile critic $Z_C^{\pi_\alpha}(s,a|\tau,\alpha)$ that approximates the quantile function $F^{-1}_{Z^{\pi_\alpha}}(\tau)$ for policy π_α. The Bellman target distribution is then:

$$Z_C = c_t + \gamma \bar{Z}_C^{\pi_\alpha}(s_{t+1}, a_{t+1}|\tau_j, \alpha) \tag{11}$$

where $a \sim \pi(\cdot|s_{t+1},\alpha)$ and $\tau_j \sim U[0,1]$. We update the cost critic parameters following the quantile regression loss, replacing the pairwise temporal difference error in Eq. 5 with the risk conditioned value estimates:

$$\delta_{ij} = Z_C - Z^{\pi_\alpha}(s_t, a_t|\tau_i, \alpha) \tag{12}$$

where $\tau_i \sim U[0,1]$, sampled separately from τ_j. CVaR cost returns of policy π_α are approximated through:

$$Q^{\pi_\alpha}_{C,\alpha}(s,a|\alpha) = \frac{1}{\alpha}\int_{1-\alpha}^{1} Z_C^{\pi_\alpha}(s,a|\alpha)(\tau)d\tau \tag{13}$$

where in practice we approximate this by averaging over a distorted quantile sampling distribution $\tau_k \sim U[(1-\alpha),1]$, similarly to Dabney et al. (2018a); Yang et al. (2023).

Conditional Actor The risk-conditioned actor is trained to maximise the risk-conditioned objective:

$$J(\pi) = \mathrm{E}_{s\sim\mathcal{B}, a\sim\pi(\cdot|s,\alpha), \alpha\sim\rho}\Big[Q_R^{\pi_\alpha}(s,a|\alpha) - \lambda(\alpha)\big(Q^{\pi_\alpha}_{C,\alpha}(s,a|\alpha) - d\big) - \beta\log\pi(s,a|\alpha)\Big] \tag{14}$$

Where $Q_R(s,a|\alpha)$ is the state-action reward value of the policy π_α , $Q_{c,\alpha}(s,a|\alpha)$ is the risk-based state-action cost value at the risk-level α of the policy π_α, $\lambda(\alpha)$ is the Lagrangian multiplier conditioned at risk-level α, and β is a tunable parameter that controls the actors entropy (Haarnoja et al., 2019). To represent the Lagrangian multiplier across the continuous spectrum of risk levels, we make use of a neural network based representation of a PID Lagrangian Controller (Stooke et al., 2020), which we discuss in detail next.

Conditional Lagrangian Multiplier We parametrise the Lagrangian variable as a neural network $\lambda(\alpha) \geq 0$, projecting its output to ensure non-negative values. Previous work has found PID control (Stooke et al., 2020) to improve the stability of Lagrangian based CRL solutions, reducing overshoot and oscillations (Ray et al., 2019; Ji et al., 2023; Zhang et al., 2024). To this end we extend the PID Lagrangian approach of (Stooke et al., 2020) to a conditional Lagrangian multiplier, taking as input a risk level value α, outputting

Algorithm 2 Risk-Conditioned PID Lagrange Multiplier

1: **Initialise:** Networks $f_I(\alpha)$ (integral) and $f_{prev}(\alpha)$ (previous-cost), Gains $K_P, K_I, K_D \geq 0$, cost limit d
2: **repeat** at each iteration:
3: Receive risk level α and cost estimate $J_C(\alpha)$
4: Predict states: $I(\alpha) \leftarrow f_I(\alpha), \quad J_{C,\text{prev}}(\alpha) \leftarrow f_{\text{prev}}(\alpha)$
5: Constraint error: $\Delta(\alpha) \leftarrow \big(J_C(\alpha) - d\big)$
6: Derivative proxy: $\partial(\alpha) \leftarrow \big(J_C(\alpha) - J_{C,\text{prev}}(\alpha)\big)_+$
7: Integral update: $I(\alpha) \leftarrow \big(I(\alpha) + \Delta(\alpha)\big)_+$
8: Update networks:
9: $I^{\text{tgt}}(\alpha) \leftarrow I(\alpha)$
10: $J^{\text{tgt}}_{C,\text{prev}}(\alpha) \leftarrow J_C(\alpha)$
11: Update f_I, f_{prev} by minimising $\mathcal{L}_{PID} = \text{MSE}(I, I^{\text{tgt}}) + \text{MSE}(J_{C,\text{prev}}, J^{\text{tgt}}_{C,\text{prev}})$
12: **return** Multiplier: $\lambda(\alpha) \leftarrow \big(K_P\Delta(\alpha) + K_I I(\alpha) + K_D\partial(\alpha)\big)_+$

the PID Lagrangian multiplier value, summarised in Algorithm 2. We use an MLP to approximate a risk-conditioned Integral term (line 4), which on its own represents a traditional Lagrangian multiplier network. We then add the Proportional term that immediately responds to constraint violations, and a Derivative term using a second separate MLP to learn risk-conditioned error term. Each MLP approximates a running estimate of the corresponding PID state by minimising mean squared error loss between predicted values and target values (line 9-11).

In this section we introduced CRAC, an extension of fixed-risk off-policy RaCRL algorithms to a continuous spectrum of risk levels. CRAC conditions the actor, reward critic, cost critic and Lagrangian multiplier on a risk level α, enabling a single set of networks to represent policies across a range of risk levels. During training collected experience is relabelled with risk levels sampled from a uniform distribution, allowing CRAC to learn from a diverse set of experience across different risk levels. This risk conditioning enables CRAC to learn different constraint satisfying behaviour at different risk levels, providing more control over the reward-cost trade-off compared to fixed-risk methods, post training.

5 Experiments and Results

In this section, we present our three fold evaluation of CRAC. First, we evaluate CRAC against two fixed risk-averse baseline algorithms, and a risk-neutral baseline, presenting this comparison in Section 5.2.1. Second, in Section 5.2.2, we investigate the generalisation of CRAC to unseen risk-levels, by limiting the spectrum of risk levels it is trained on and evaluating it outside of this spectrum. Finally, we present an ablation study of key ingredients of CRAC in Section 5.3, namely we evaluate its performance under three distinct risk level sampling schemes and compare its performance using a traditional conditional Lagrangian multiplier vs a PID style Lagrangian multiplier.

5.1 Experimental Setup

5.1.1 Environments

The Safety-Gymnasium environments, presented by Ji et al. (2023), act as the standard baseline environments for constrained RL. Reward performance generally decreases with added risk-aversion as agents become increasingly conservative in exploring the environment. In Goal1, the objective is to reach a goal position whilst avoiding static obstacles. In Button1, the objective is to press one of a set of randomly positioned buttons, whilst avoiding both static and moving obstacles, making it the more challenging environment variant. We carry out experiments in both the Point and Car variants of the Goal1 and Button1 environments, with the Car variant being the more challenging of the two as the agent controls a larger Car object, making navigation more challenging. Each environment randomly generates a layout of obstacles at the beginning of each episode and the goal changes position randomly each time the agent reaches it during

an episode. The observation spaces consist of a large number of features representing lidar readings of the agent, describing the distance to obstacles and the goal or button. The reward function is a dense function measuring the absolute distance towards the goal and a constant for reaching the goal location or pushing the correct button. Unsafe behaviour of colliding with an obstacle, entering a static obstacle zone or pushing the wrong button returns a cost of 1, whilst safe behaviour returns a cost of 0. We set the cost constraint to 10 for each episode and truncate the episodes to a max length of 400 steps, adapting changes described in (Liu et al., 2022; Wu et al., 2024) to speed up training of the agents, by increasing the simulation timesteps of the environment by 2.5-3x, but otherwise the environments remain the same. Specifically, we retain the random sampling of the environment initialisations.

CityLearn (Vázquez-Canteli et al., 2019), a real-world simulation environment, presents a challenging environment where the agent is tasked with minimising the electricity demand the building places on the grid, whilst maintaining the thermal comfort of a building, by ensuring temperature of the building be within 1 degree of the desired set-point temperature. Power-outages occur in the environment randomly and infrequently, cutting the supply of electricity from the grid to each building, and can last for a number of hours. During regular operations the agent uses energy supplied from the grid to control the temperature of the building but during outages it must rely on either solar energy or energy stored in its electrical battery. A risk-averse policy should learn to prepare for power-outages by storing electricity in the battery. We set the cost constraint to 720 and each episode has a length of 720 timesteps.

5.1.2 Algorithms

Our aim is to compare the reward-cost trade-off of fixed risk-aversion vs conditional risk-aversion, across a spectrum of risk-aversion levels. Firstly, we establish the risk-neutral reward performance in each environment using the Conservative Augmented Lagrangian (CAL) algorithm Wu et al. (2024), a risk-neutral state-of-the-art off-policy Soft Actor-Critic method. We then use two fixed risk-averse baselines, an off-policy algorithm Worst-Case Soft Actor Critic (WCSAC) (Yang et al., 2023), and an on-policy state-of-the-art baseline Spectral Risk Constrained Policy Optimisation (SRCPO) (Kim et al., 2024). We compare each of these algorithms against our proposed algorithm CRAC, measuring in particular the constraint satisfaction and their reward-cost trade-off against CAL, with increasing risk-aversion. We train each algorithm across 5 seeds, for 5 million timesteps in SafetyGymnasium and 3 million timesteps in CityLearn. We train each fixed risk-averse algorithm under the following risk levels [0.1, 0.25, 0.5, 0.75, 1.0], with 0.1 being the most risk-averse and 1.0 being risk-neutral. We train CRAC across a continuous spectrum of risk levels $\alpha \in [0.05, 1]$.

5.1.3 Implementation Details

We describe two implementation choices applied to both CRAC and its fixed-risk counterpart WCSAC. These are not core contributions of this work but affect stability and performance of CRAC and WCSAC [1].

Cost Augmented State Risk-constrained RL problems are non-Markovian and necessitate a history conditioned policy (Kim et al., 2024; Zhang et al., 2025). Work by Bastani et al. (2022) demonstrate that an optimal history conditioned policy can be defined in an augmented state space, which incorporates the discounted sum of costs. As such, we augment the state space with the discounted sum of costs as follows [2]:

$$\bar{s}_t = (s_t, e_t, b_t), \text{ where } e_0 = 0,\ e_{t+1} = (e_t + C(s_t, a_t, s_{t+1}))/\gamma,\ b_t = \gamma^t \tag{15}$$

For consistency of evaluation, we apply this to each algorithm.

Truncated Quantile Critics CRAC extends fixed-risk SAC based algorithms to a continuous spectrum of risk levels. As such, it inherits known challenges of off-policy CRL, namely cost underestimation due to bootstrapping bias in cost critics (Wu et al., 2024; Zhang et al., 2024). To address this we apply truncation to the distributional cost critic following Truncated Quantile Critics (Kuznetsov et al., 2020). Given N cost

[1] We include ablations of each algorithms performance with and without these components in the supplemental material.

[2] In practice, e_t can grow to extremely large values when $\gamma < 1$, especially in long horizon problems, and destabilise the learning of function approximators, we therefore use $\log(e_t + 1)$. We include ablations of each algorithms performance with and without this augmented state in the supplemental material.

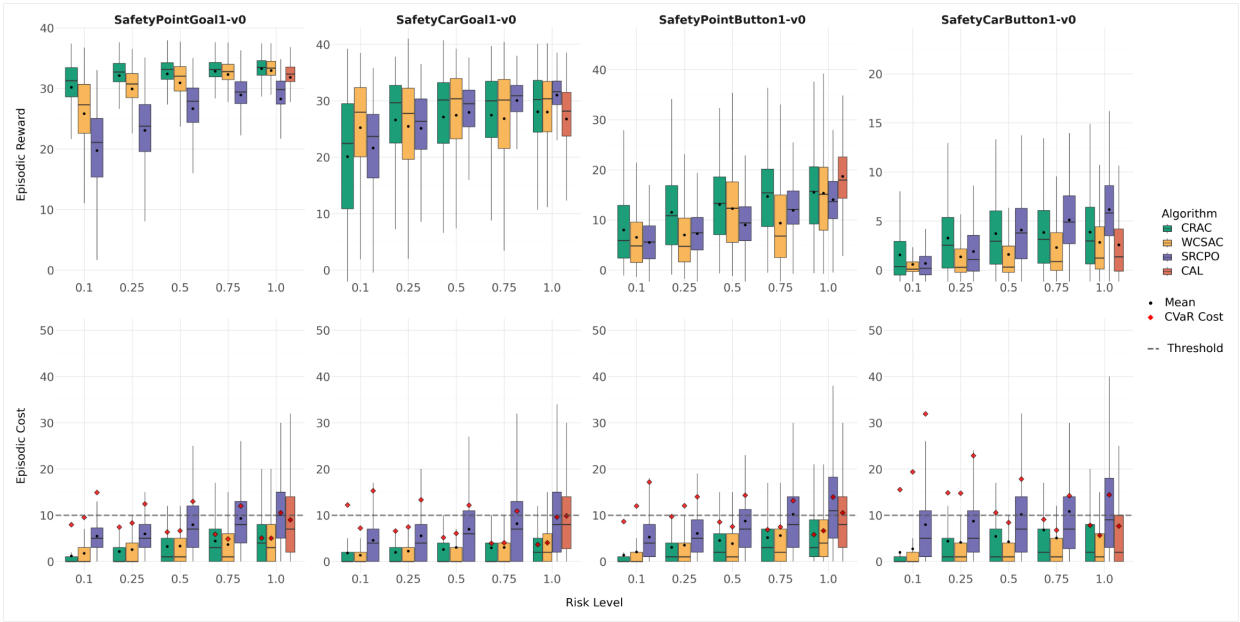

Figure 1: **SafetyGym Reward-Cost Distributions** Box plots of evaluation results for fixed vs conditional risk comparison. Each algorithm is trained with 5 random seeds and evaluated for 100 episodes. Each fixed risk-averse algorithm is trained separately at the fixed risk level intervals shown. For clarity, outliers are removed, with red diamonds indicating CVaR Cost for each algorithm.

critics each predicting M quantiles of the policy's cost return distribution $Z_C^{\pi_\alpha}(s, a|\alpha)$, TQC formulates the target in the TD-learning step as a sorted mixture of $N \times M$ quantiles. In the original form of TQC, K quantiles are truncated from the upper tail of the distribution to mitigate over-estimation of reward, however, as we are concerned with the upper tails of the cost distribution in RaCRL, we truncate K quantiles from the lower tail. For our WCSAC and CRAC we use Implicit Quantile Networks (Dabney et al., 2018a) for the cost critics, applying truncation in SafetyGym only, due to the sparsity in cost.

5.2 Results

5.2.1 Conditional Risk vs Fixed Risk

Safety Gymnasium In Figure 1 we present the results of our comparative experiments in the Safety Gymnasium environments, where each fixed-risk algorithm is trained at a number of risk levels. We observe that CRAC shows more favourable reward performance when compared against the fixed risk-averse algorithms, except in the CarGoal1 environment. In the Point environments, CRAC achieves the best results by satisfying the CVaR based constraints whilst achieving the highest reward. In CarGoal1 we observe that CRAC violates the CVaR based constraints at the most risk-averse level $\alpha = 0.1$, whilst WCSAC satisfies it and achieves higher reward. At other risk levels it is competitive in reward with WCSAC, sometimes outperforming it, whilst satisfying the CVaR constraints. In CarButton1, we note that all algorithms fail to satisfy the CVaR based constraints at the lower risk-levels $\alpha \in [0.1, 0.25]$, whilst exhibiting a low distribution of costs. This indicates a common challenge in the Safety Gymnasium environments of rare but high cost episodes (Ji et al., 2023). We note in particular that SRCPO fails to converge to solutions that satisfy the CVaR based constraints in all environments [3].

In summary, our results demonstrate that CRAC improves the reward-cost trade-off of fixed-risk agents, in particular improving the trade-off over WCSAC, its fixed-risk variant. This indicates that the implicit

[3]In their original work, Kim et al. (2024) trained SRCPO under an CVaR alpha of 0.25 and presented the expected cost-rate, that satisfies the cost thresholds, rather than presenting the CVaR cost rates.

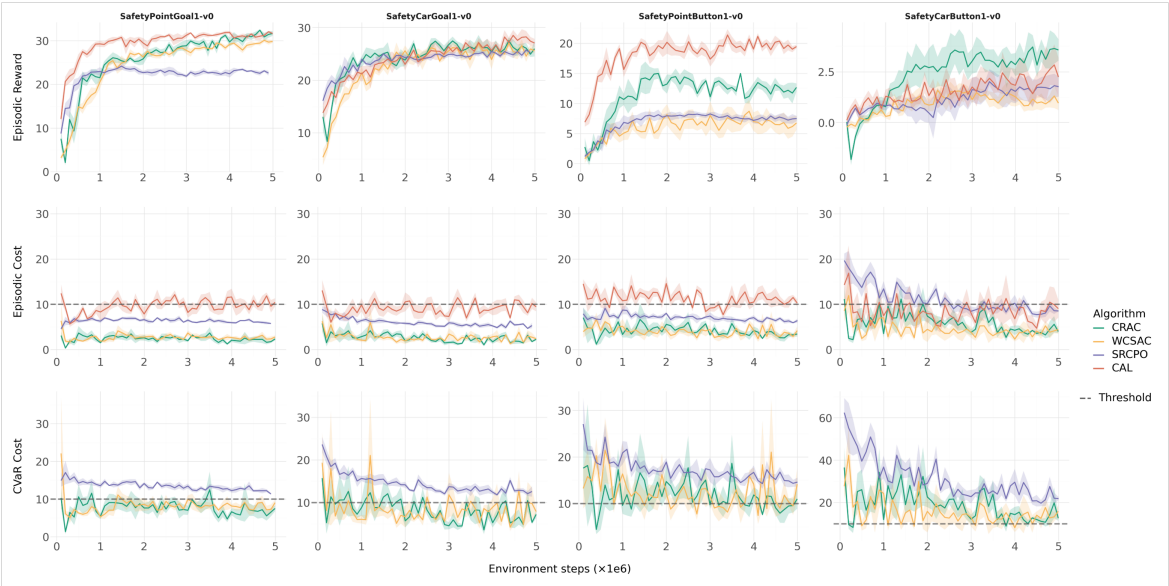

Figure 2: **SafetyGym training curves.** WCSAC and SCRPO are trained at risk level $\alpha = 0.25$; CRAC is trained on a full risk spectrum $[0.05, 1]$ and evaluated at $\alpha = 0.25$; CAL is trained to satisfy expected constraints. Solid lines show the mean; shaded regions show the standard deviation across 5 seeds (scaled by 0.2). For clarity we exclude CAL from "CVaR Cost" plot as it is trained to satisfy expected cost constraints

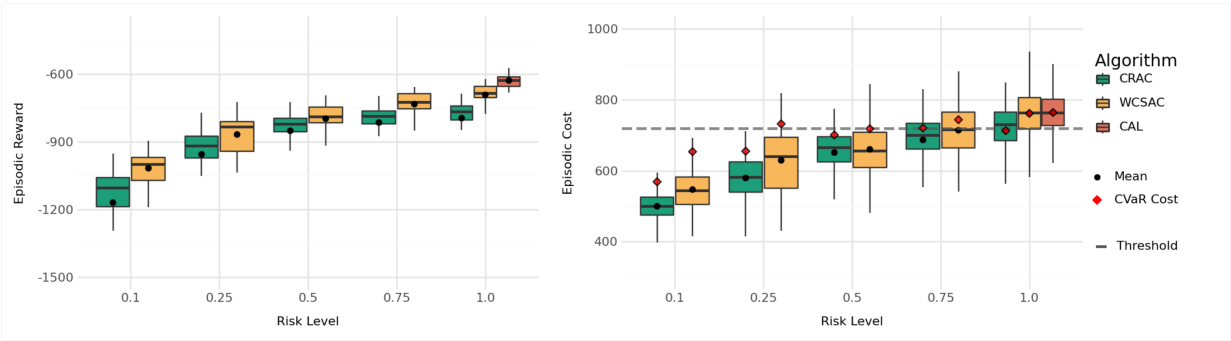

Figure 3: **CityLearn Reward-Cost Distributions**: Box plots of evaluation results for fixed vs conditional risk comparison. Each algorithm is trained with 5 random seeds and evaluated for 100 episodes. Each fixed risk-averse algorithm is trained separately at the fixed risk level intervals show. For clarity, outliers are removed, with red diamonds indicating CVaR Cost for each algorithm.

exploration of CRAC under various risk levels improves the reward performance across the spectrum of risk levels, particularly at lower risk-levels where the conservative nature of risk-averse exploration hampers its exploration and learning (McCarthy et al., 2025). This is further demonstrated in Figure 2, showing that CRAC achieves higher reward throughout training when compared against both WCSAC and SRCPO, reducing the loss in reward performance against the risk-neutral baselines CAL.

CityLearn We conduct comparative experiments in the CityLearn environment (Vázquez-Canteli et al., 2019). Results are presented in Figure 3. We observe that the fixed-risk baseline, WCSAC, achieves marginally better reward-cost trade-off for constraint-satisfying solutions at risk levels $\alpha \in [0.1, 0.25, 0.5]$ compared to CRAC [4].

[4]We were unable to train a SRCPO policy to converge to a meaningful solution, so have therefore excluded it

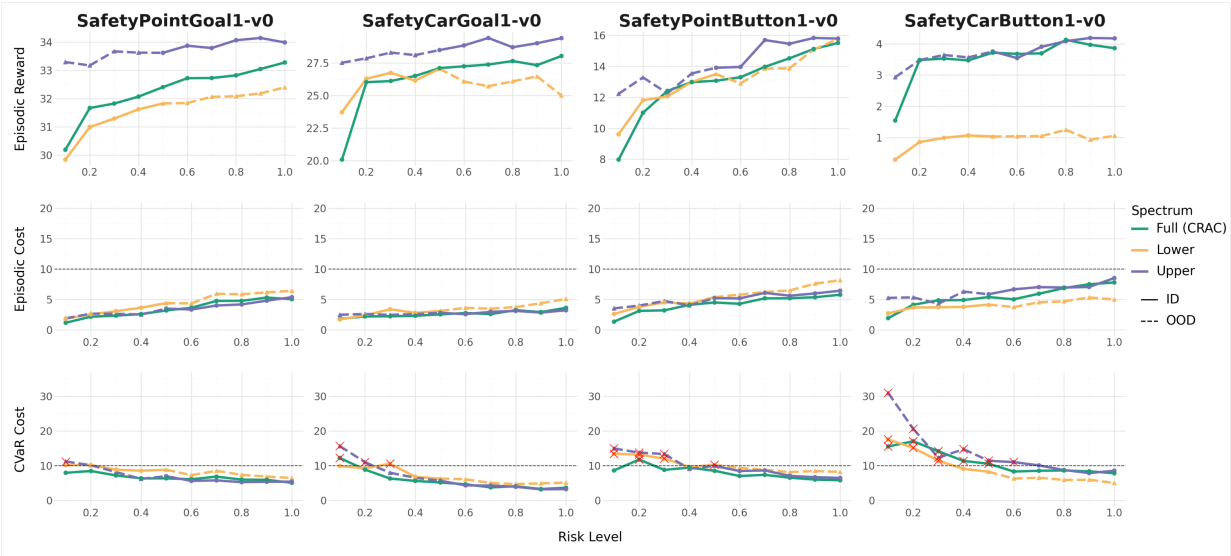

Figure 4: **SafetyGym Generalisation to unseen risk levels.** (i): *Lower* - Risk spectrum biased towards risk-averse behaviour $\alpha \in [0.05, 0.5]$, (ii): *Upper* - Risk spectrum biased towards risk-neutral behaviour $\alpha \in [0.5, 1.0]$. (iii): *Full* - complete risk spectrum $\alpha \in [0.05, 1.0]$. *ID* indicates evaluation at risk levels agent was trained on, *OOD* indicates evaluation at risk levels outside of agents training spectrum.

This comparison, however, highlights a key advantage of the conditional risk-aversion achieved by CRAC, over fixed risk-aversion. A single CRAC agent is trained to satisfy the constraint across the full spectrum of risk-levels, whilst achieving competitive reward performance relative to its fixed-risk counterpart. In contrast, WCSAC requires training separate agents for each risk level. This highlights the primary practical benefit of CRAC, it provides a single, risk-conditioned policy capable of representing the full reward-cost trade-off across a spectrum of risk levels. As such, CRAC is practically valuable to end users who require tuneable risk-aversion or may wish to explore how risk-aversion impacts the reward-cost trade-off, without incurring the computational overhead of training multiple risk-averse agents.

5.2.2 Generalisation to Unseen Risk Levels

To evaluate CRAC's ability to generalise to risk levels beyond its training distribution, we train two sets of CRAC agents under truncated risk level spectrums: (i) a risk-neutral biased spectrum, $\alpha \in [0.5, 1]$, and (ii) a risk-averse biased spectrum, $\alpha \in [0.05, 0.5]$. Each agent is then evaluated on risk levels outside of their respective training risk spectrums, with results shown in Figure 4.

When trained on the risk-neutral biased spectrum, CRAC achieves higher levels of reward than the full spectrum agent. However, its cost performance degrades as evaluation shifts towards more risk-averse levels. In particular, it fails to satisfy CVaR-based constraints at the risk-averse levels furthest from its training data. For the risk-averse biased spectrum, $\alpha \in [0.05, 0.5]$, we observe two trends. Firstly in the Goal environments, the policy converges to a constraint satisfying policy, but achieves lower reward than the full-spectrum CRAC in the PointGoal environment and slightly better reward in CarGoal. In PointButton, the risk-averse biased policy converges to a higher reward policy at more strongly risk-averse levels $\alpha \in [0.1, 0.3]$, when compared to the full-spectram CRAC. It fails, however, to satisfy the CVaR based constraints at these levels, whilst the full spectrum CRAC satisfies them. In the CarButton1 environment, the risk-averse biased agent achieves the lowest reward but generally the lowest cost.

Together, these results highlight an important aspect of CRAC's generalisation across risk levels. Training under more risk-neutral risk levels leads to less conservative exploration of the environment, yielding higher reward, however, without explicit exposure to more risk-averse levels, constraint satisfaction does not reliably transfer further from its training data. Conversely, training on more risk-averse levels, leads to lower reward

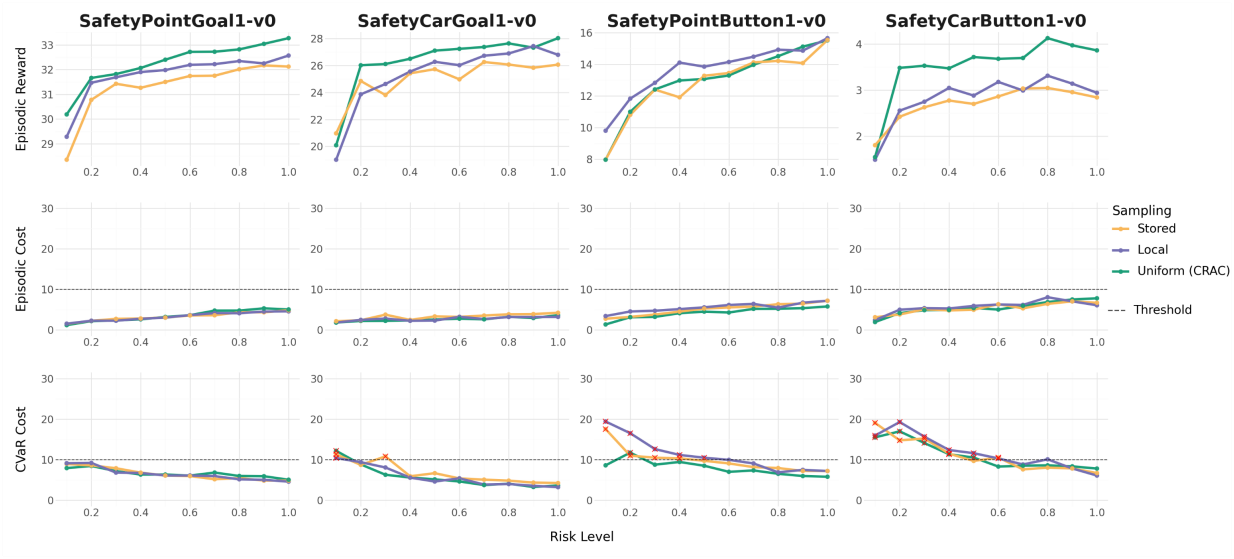

Figure 5: **Ablation of three risk level resampling variants.** (i): *Stored* - No resampling, (ii): *Local* - Local uniform resampling centred on stored risk level, (iii): *Uniform* - Full uniform sampling agnostic to stored risk level

polices and constraint satisfaction outside of its training data. Lastly, training across the full spectrum shows signs of a regularising effect, in all environments bar the CarButton environment, by leading to lower cost than the risk-averse biased agent.

5.3 Ablations

In this section, we report the results of an ablation study of the two key components of CRAC: (i) Risk level sampling during learning and (ii) the formulation of the conditional Lagrangian multiplier.

5.3.1 Risk Level Sampling

In Figure 5 we present comparative results of three risk level sampling approaches in the Safety Gymnasium environments: (i) *Stored* represents CRAC trained using the risk level sampled during the exploration step only, (ii) *Local* represents CRAC trained by resampling the stored risk level from a uniform distribution centred at the stored level, where at boundaries we ensure a minimum sampling width of 0.1 around the stored level, and (iii) *Uniform* represents full uniform risk level resampling, agnostic to the stored risk level.

We observe a clear improvement in CRAC's reward in all environments under both the *Local* and the *Uniform* sampling approaches, except in PointButton1 where each approach achieves similar reward. This indicates that relabelling transition samples significantly improves CRAC's ability to learn higher reward behaviour, by improving the diversity of replay experience available to CRAC through implicit exploration.

We further observe that in all environments, *Uniform* sampling largely improves the cost satisfaction of CRAC over the other two sampling approaches. In particular, at more risk-averse risk levels, learning under *Stored* and *Local* sampling approaches leads to cost violations, indicating that *Uniform* sampling leads to more conservative behaviour, whilst having little to no impact on reward performance. We hypothesise that for more risk-averse risk levels, *Uniform* sampling has similar policy regularisation effects to cost value overestimation techniques such as that of CAL (Wu et al., 2024), by evaluating the cost values at states collected by more risky policies. States may have higher cost values when collected under a risk-neutral biased policy and used to train a more risk-averse biased policy, leading to naturally higher estimated cost returns from the policy.

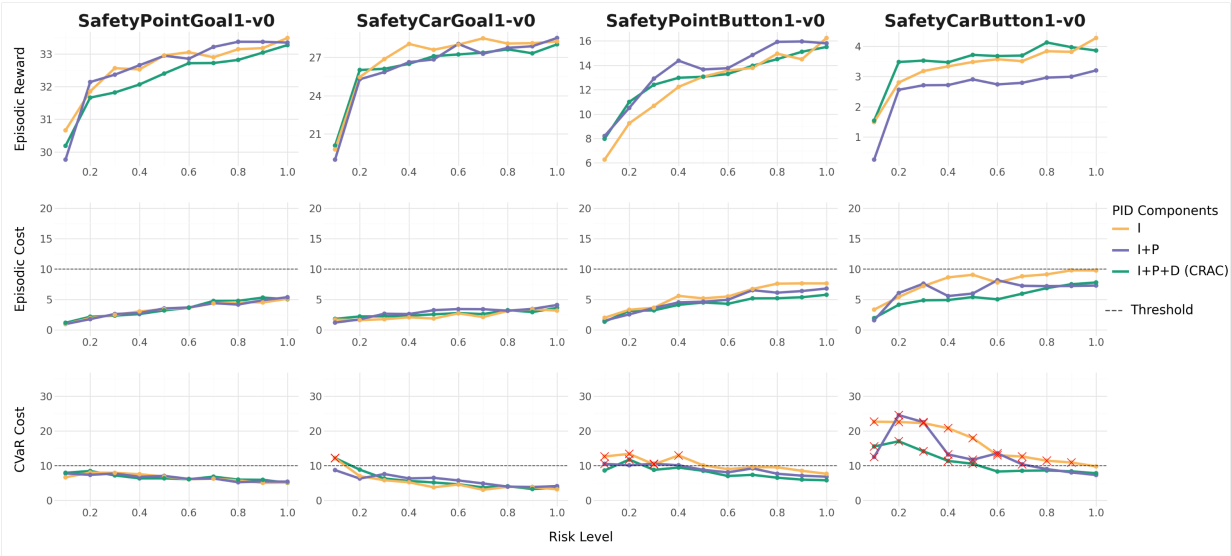

Figure 6: **Ablation of PID components.** (i): I - Integral only term responding to steady-state violations (closest to standard Lagrangian), (ii): $I + P$ - Integral and Proportional Term that responds each samples cost violations, (iii): $I + P + D$ - Integral, Proportional and Derivative terms combined in full PID approach. Derivative term responds to changes in cost

5.3.2 Conditional Lagrangian Multiplier

We analyse the contribution of each PID component to the final performance of CRAC by training three variants of the conditional Lagrangian multiplier: (i) Integral only (I) – represents a simple conditional Lagrangian multiplier most similar to standard approaches, responding to state-state constraint violations, (ii) Integral and Proportional (I+P) – we add the proportional term that responds immediately to constraint violations, and (iii) Integral, Proportional and Derivative (I+P+D) – we use the complete PID formulation with the derivative term to respond to changes in pervious errors. For these experiments, and all experiments, we set the value of PID hyperparameters to I=0.0005, P=0.1 and D=0.0005.

In Figure 6 observe that CRAC is quite robust to the combination of PID components used in the Goal1 environments, satisfying cost constraints and showing similar reward scores. However, in the Button1 environments, we observe a clear performance improvement in cost when the full PID setup is used, with the largest improvement in CarButton1.

6 Conclusion

In this work we presented CRAC, a conditional risk-averse actor critic algorithm for constrained RL that trains a single risk-conditioned policy across a continuous spectrum of risk. Unlike fixed-risk algorithms that require separate training for a single risk level, CRAC trains one policy that generalises across a continuous risk spectrum. CRAC enables tunable deployment of risk based constrained RL agents based on a balance between reward-cost trade-off and risk preferences. Across multiple environments we showed that CRAC achieves competitive performance against fixed-risk baselines, often outperforming them, indicating the implicit exploration and learning across multiple risk levels reduce the impact of conservativism introduced by introducing risk-aversion. Whilst we focused on static risk level sampling schemes, future work may look at how risk level sampling can improve the sample efficiency of CRAC by dynamically responding to the performance of CRAC at specific risk levels.

References

Carlo Acerbi. Spectral measures of risk: A coherent representation of subjective risk aversion. *Journal of Banking & Finance*, 26(7):1505–1518, July 2002. ISSN 03784266. doi: 10.1016/S0378-4266(02)00281-9. URL https://linkinghub.elsevier.com/retrieve/pii/S0378426602002819.

Joshua Achiam, David Held, Aviv Tamar, and Pieter Abbeel. Constrained Policy Optimization. In *Proceedings of the 34th International Conference on Machine Learning*, pp. 22–31. PMLR, July 2017. URL https://proceedings.mlr.press/v70/achiam17a.html.

Eitan Altman. *Constrained Markov Decision Processes: Stochastic Modeling*. Routledge, Boca Raton, 1 edition, 1999. ISBN 978-1-315-14022-3. doi: 10.1201/9781315140223. URL https://www.taylorfrancis.com/books/9781315140223.

O. Bastani, Y. J. Ma, E. Shen, and W. Xu. Regret Bounds for Risk-Sensitive Reinforcement Learning, October 2022. URL http://arxiv.org/abs/2210.05650. arXiv:2210.05650 [cs].

Jinyoung Choi, Christopher R. Dance, Jung-eun Kim, Seulbin Hwang, and Kyung-sik Park. Risk-Conditioned Distributional Soft Actor-Critic for Risk-Sensitive Navigation, April 2021. URL http://arxiv.org/abs/2104.03111. arXiv:2104.03111 [cs].

Will Dabney, Georg Ostrovski, David Silver, and Remi Munos. Implicit Quantile Networks for Distributional Reinforcement Learning. In *Proceedings of the 35th International Conference on Machine Learning*, pp. 1096–1105. PMLR, July 2018a. URL https://proceedings.mlr.press/v80/dabney18a.html.

Will Dabney, Mark Rowland, Marc Bellemare, and Rémi Munos. Distributional Reinforcement Learning With Quantile Regression. *Proceedings of the AAAI Conference on Artificial Intelligence*, 32(1), April 2018b. ISSN 2374-3468, 2159-5399. doi: 10.1609/aaai.v32i1.11791. URL https://ojs.aaai.org/index.php/AAAI/article/view/11791.

Gabriel Dulac-Arnold, Nir Levine, Daniel J. Mankowitz, Jerry Li, Cosmin Paduraru, Sven Gowal, and Todd Hester. Challenges of real-world reinforcement learning: definitions, benchmarks and analysis. *Machine Learning*, 110(9):2419–2468, September 2021. ISSN 0885-6125, 1573-0565. doi: 10.1007/s10994-021-05961-4. URL https://link.springer.com/10.1007/s10994-021-05961-4.

Shiqing Gao, Jiaxin Ding, Luoyi Fu, and Xinbing Wang. Controlling underestimation bias in constrained reinforcement learning for safe exploration. In *Forty-second international conference on machine learning*, 2025. URL https://openreview.net/forum?id=nq5bt0mRTC.

Javier García and Fernando Fernández. A Comprehensive Survey on Safe Reinforcement Learning. *Journal of Machine Learning Research*, 16(42):1437–1480, 2015. ISSN 1533-7928. URL http://jmlr.org/papers/v16/garcia15a.html.

Ido Greenberg, Yinlam Chow, Mohammad Ghavamzadeh, and Shie Mannor. Efficient risk-averse reinforcement learning. *Advances in Neural Information Processing Systems*, 35:32639–32652, 2022.

Zijian Guo, Weichao Zhou, Shengao Wang, and Wenchao Li. Constraint-conditioned actor-critic for offline safe reinforcement learning. In Y. Yue, A. Garg, N. Peng, F. Sha, and R. Yu (eds.), *International conference on learning representations*, volume 2025, pp. 41581–41602, 2025. URL https://proceedings.iclr.cc/paper_files/paper/2025/file/67089958e98b243d5cc1881ad60418b8-Paper-Conference.pdf.

Tuomas Haarnoja, Aurick Zhou, Kristian Hartikainen, George Tucker, Sehoon Ha, Jie Tan, Vikash Kumar, Henry Zhu, Abhishek Gupta, Pieter Abbeel, and Sergey Levine. Soft Actor-Critic Algorithms and Applications, January 2019. URL http://arxiv.org/abs/1812.05905. arXiv:1812.05905 [cs, stat].

Jiaming Ji, Borong Zhang, Jiayi Zhou, Xuehai Pan, Weidong Huang, Ruiyang Sun, Yiran Geng, Yifan Zhong, Josef Dai, and Yaodong Yang. Safety gymnasium: a unified safe reinforcement learning benchmark. In *Thirty-seventh conference on neural information processing systems datasets and benchmarks track*, 2023. URL https://openreview.net/forum?id=WZmlxIuIGR.

Dohyeong Kim, Kyungjae Lee, and Songhwai Oh. Trust Region-Based Safe Distributional Reinforcement Learning for Multiple Constraints. *Advances in Neural Information Processing Systems*, 36: 19908–19939, December 2023. URL https://proceedings.neurips.cc/paper_files/paper/2023/hash/3f20f2b0315c72201e23512fdbd1ee91-Abstract-Conference.html.

Dohyeong Kim, Taehyun Cho, Seungyub Han, Hojun Chung, Kyungjae Lee, and Songhwai Oh. Spectral-risk safe reinforcement learning with convergence guarantees. In A. Globerson, L. Mackey, D. Belgrave, A. Fan, U. Paquet, J. Tomczak, and C. Zhang (eds.), *Advances in neural information processing systems*, volume 37, pp. 92465–92498. Curran Associates, Inc., 2024. doi: 10.52202/079017-2936. URL https://proceedings.neurips.cc/paper_files/paper/2024/file/a7fbf054c80d26e5b4ed67588ea384f0-Paper-Conference.pdf.

Sachin Kumar, Eric Malmi, Aliaksei Severyn, and Yulia Tsvetkov. Controlled Text Generation as Continuous Optimization with Multiple Constraints. In *Advances in Neural Information Processing Systems*, volume 34, pp. 14542–14554. Curran Associates, Inc., 2021. URL https://proceedings.neurips.cc/paper/2021/hash/79ec2a4246feb2126ecf43c4a4418002-Abstract.html.

Arsenii Kuznetsov, Pavel Shvechikov, Alexander Grishin, and Dmitry Vetrov. Controlling Overestimation Bias with Truncated Mixture of Continuous Distributional Quantile Critics. In *Proceedings of the 37th International Conference on Machine Learning*, pp. 5556–5566. PMLR, November 2020. URL https://proceedings.mlr.press/v119/kuznetsov20a.html.

Zuxin Liu, Zhepeng Cen, Vladislav Isenbaev, Wei Liu, Steven Wu, Bo Li, and Ding Zhao. Constrained Variational Policy Optimization for Safe Reinforcement Learning. In *Proceedings of the 39th International Conference on Machine Learning*, pp. 13644–13668. PMLR, June 2022. URL https://proceedings.mlr.press/v162/liu22b.html.

James McCarthy, Radu Marinescu, Elizabeth Daly, and Ivana Dusparic. Optimistic Exploration for Risk-Averse Constrained Reinforcement Learning, July 2025. URL http://arxiv.org/abs/2507.08793. arXiv:2507.08793 [cs].

John Platt and Alan Barr. Constrained differential optimization. In *Neural information processing systems*, 1987.

Alex Ray, Joshua Achiam, and Dario Amodei. Benchmarking Safe Exploration in Deep Reinforcement Learning. pp. 25, 2019.

R. Tyrrell Rockafellar and Stanislav Uryasev. Optimization of conditional value-at-risk. *The Journal of Risk*, 2(3):21–41, 2000. ISSN 14651211. doi: 10.21314/JOR.2000.038. URL http://www.risk.net/journal-of-risk/technical-paper/2161159/optimization-conditional-value-risk.

Adam Stooke, Joshua Achiam, and Pieter Abbeel. Responsive Safety in Reinforcement Learning by PID Lagrangian Methods. In *Proceedings of the 37th International Conference on Machine Learning*, pp. 9133–9143. PMLR, November 2020. URL https://proceedings.mlr.press/v119/stooke20a.html.

Chen Tessler, Daniel J. Mankowitz, and Shie Mannor. Reward constrained policy optimization. In *International conference on learning representations*, 2019. URL https://openreview.net/forum?id=SkfrvsA9FX.

José R. Vázquez-Canteli, Jérôme Kämpf, Gregor Henze, and Zoltan Nagy. CityLearn v1.0: An OpenAI gym environment for demand response with deep reinforcement learning. In *Proceedings of the 6th ACM international conference on systems for energy-efficient buildings, cities, and transportation*, BuildSys '19, pp. 356–357, New York, NY, USA, 2019. Association for Computing Machinery. ISBN 978-1-4503-7005-9. doi: 10.1145/3360322.3360998. URL https://doi.org/10.1145/3360322.3360998. Number of pages: 2 Place: New York, NY, USA.

Zifan Wu, Bo Tang, Qian Lin, Chao Yu, Shangqin Mao, Qianlong Xie, Xingxing Wang, and Dong Wang. Off-policy primal-dual safe reinforcement learning. In *The twelfth international conference on learning representations*, 2024. URL https://openreview.net/forum?id=vy42bYs1Wo.

Qisong Yang, Thiago D. Simão, Simon H. Tindemans, and Matthijs TJ Spaan. WCSAC: Worst-case soft actor critic for safety-constrained reinforcement learning. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 35, pp. 10639–10646, 2021.

Qisong Yang, Thiago D. Simão, Simon H. Tindemans, and Matthijs T. J. Spaan. Safety-constrained reinforcement learning with a distributional safety critic. *Machine Learning*, 112(3):859–887, March 2023. ISSN 0885-6125, 1573-0565. doi: 10.1007/s10994-022-06187-8. URL https://link.springer.com/10.1007/s10994-022-06187-8.

Zhaoxing Yang, Haiming Jin, Yao Tang, and Guiyun Fan. Risk-aware constrained reinforcement learning with non-stationary policies. In *Proceedings of the 23rd international conference on autonomous agents and multiagent systems*, Aamas '24, pp. 2029–2037, Richland, SC, 2024. International Foundation for Autonomous Agents and Multiagent Systems. ISBN 979-8-4007-0486-4. Number of pages: 9 Place: Auckland, New Zealand.

Yihang Yao, ZUXIN LIU, Zhepeng Cen, Jiacheng Zhu, Wenhao Yu, Tingnan Zhang, and DING ZHAO. Constraint-conditioned policy optimization for versatile safe reinforcement learning. In A. Oh, T. Naumann, A. Globerson, K. Saenko, M. Hardt, and S. Levine (eds.), *Advances in neural information processing systems*, volume 36, pp. 12555–12568. Curran Associates, Inc., 2023. URL https://proceedings.neurips.cc/paper_files/paper/2023/file/29906cbd165b78991da2c4dbabc2a04b-Paper-Conference.pdf.

Gwangpyo Yoo and Honguk Woo. Model risk-sensitive offline reinforcement learning. In *The thirteenth international conference on learning representations*, 2025. URL https://openreview.net/forum?id=h6k4809xVV.

Gwangpyo Yoo, Jinwoo Park, and Honguk Woo. Risk-Conditioned Reinforcement Learning: A Generalized Approach for Adapting to Varying Risk Measures. *Proceedings of the AAAI Conference on Artificial Intelligence*, 38(15):16513–16521, March 2024. ISSN 2374-3468, 2159-5399. doi: 10.1609/aaai.v38i15.29589. URL https://ojs.aaai.org/index.php/AAAI/article/view/29589.

Hengrui Zhang, Youfang Lin, Shuo Shen, Sheng Han, and Kai Lv. Enhancing Off-Policy Constrained Reinforcement Learning through Adaptive Ensemble C Estimation. *Proceedings of the AAAI Conference on Artificial Intelligence*, 38(19):21770–21778, March 2024. ISSN 2374-3468, 2159-5399. doi: 10.1609/aaai.v38i19.30177. URL https://ojs.aaai.org/index.php/AAAI/article/view/30177.

Linrui Zhang, Li Shen, Long Yang, Shixiang Chen, Xueqian Wang, Bo Yuan, and Dacheng Tao. Penalized Proximal Policy Optimization for Safe Reinforcement Learning. In *Proceedings of the Thirty-First International Joint Conference on Artificial Intelligence*, pp. 3744–3750, Vienna, Austria, July 2022. International Joint Conferences on Artificial Intelligence Organization. ISBN 978-1-956792-00-3. doi: 10.24963/ijcai.2022/520. URL https://www.ijcai.org/proceedings/2022/520.

Qiyuan Zhang, Shu Leng, Xiaoteng Ma, Qihan Liu, Xueqian Wang, Bin Liang, Yu Liu, and Jun Yang. CVaR-Constrained Policy Optimization for Safe Reinforcement Learning. *IEEE Transactions on Neural Networks and Learning Systems*, 36(1):830–841, January 2025. ISSN 2162-2388. doi: 10.1109/TNNLS.2023.3331304. URL https://ieeexplore.ieee.org/document/10444044/.

A Hyper-Parameters

In this section we outline the hyper-parameters selected for each algorithm. We reimplement CAL, making use of the official hyper-parameters used for CAL (https://github.com/ZifanWu/CAL) and we use the official code repositiory for SRCPO (https://github.com/rllab-snu/Spectral-Risk-Constrained-RL). The only change made to CAL is to use a 1-1 update-to-data ratio, to isolate its performance under the same amount of collected experience. For both WCSAC and CRAC we use the same hyper-parameters for both Safety Gymnasium and CityLearn.

Table 1: Common Hyper-Paramters

Common Hyper-parameters	Value
Reward Gamma	0.99
Cost Gamma	0.99
Policy Lr	3×10^{-4}
Reward Critic Lr	3×10^{-4}
Cost Critic Lr	5×10^{-4}
Agent Entropy AutoTune	True
Agent Entropy Lr	5×10^{-4}
Tau	0.005
Critic Net Update Frequency	5
Actor Net Update Frequency	10
Lagrangian/PID Update Frequency	10
Target Net Update Frequency	10
Buffer Size	10^6
Batch Size	256
Policy Hidden Sizes	[256, 256]
Critic Hidden Sizes	[256, 256]
Quantile Hidden Sizes	[512, 512]
Agent Embedding Dim	32
Number of Quantiles (Critic)	32
Number of Quantiles (Policy)	32
Number of Cost Critics	2
Learning Starts	5000
TQC	1
CRAC Specific Hyper-parameters	Value
Lagrangian MLP Network Size	[64, 64]
PID KI	0.0005
PID KP	0.1
PID KD	0.0005

Apart from conditioning, the only significant difference between CRAC and WCSAC is that WCSAC uses a dampening factor in the actor update following the Modified Differential Method of Multipliers (Platt & Barr, 1987; Kumar et al., 2021; Yang et al., 2023), in the following form:

$$\bar{\lambda} = \lambda - c(d - Q_C^{\pi}(s, a)) \tag{16}$$

where λ is the Lagrangian multiplier value, c is a dampening parameter, we use a value of 10 for all experiments, d is the cost threshold, and $Q_C^{\pi}(s, a|\tau)$ is the CVaR cost value estimate. This leads to the actor loss function:

$$J(\pi) = \mathrm{E}_{s\sim\mathcal{B}, a\sim\pi(\cdot|s)}\Big[Q_R^{\pi}(s, a) - \bar{\lambda}\big(Q_{C,\alpha}^{\pi}(s, a) - d\big) - \beta \log \pi(s, a)\Big] \tag{17}$$

where $Q_R^{\pi}(s, a)$ is the reward value estimate and β is the entropy parameter.

B Truncated Quantile Critics and Cost Augmented State Ablations

In this section we aim to isolate the effects on WCSAC and CRAC of Truncated Quantile Critics (TQC) and the cost-augmented state (CA), and the effect on SRCPO and CAL of the cost-augmented state.

B.1 CRAC

Ablation results in Figure 7 show that both TQC and CA improve the safety performance of CRAC. TQC reduces cost underestimation, leading to lower episodic costs and improved CVaR constraint satisfaction across risk levels, while CA further stabilises its CVaR cost satisfaction by providing the policy with necessary information about accumulated cost. Whilst both mechanisms introduce mild conservatism, which leads to reduced reward, together they act as important components in improving the cost performance of CRAC.

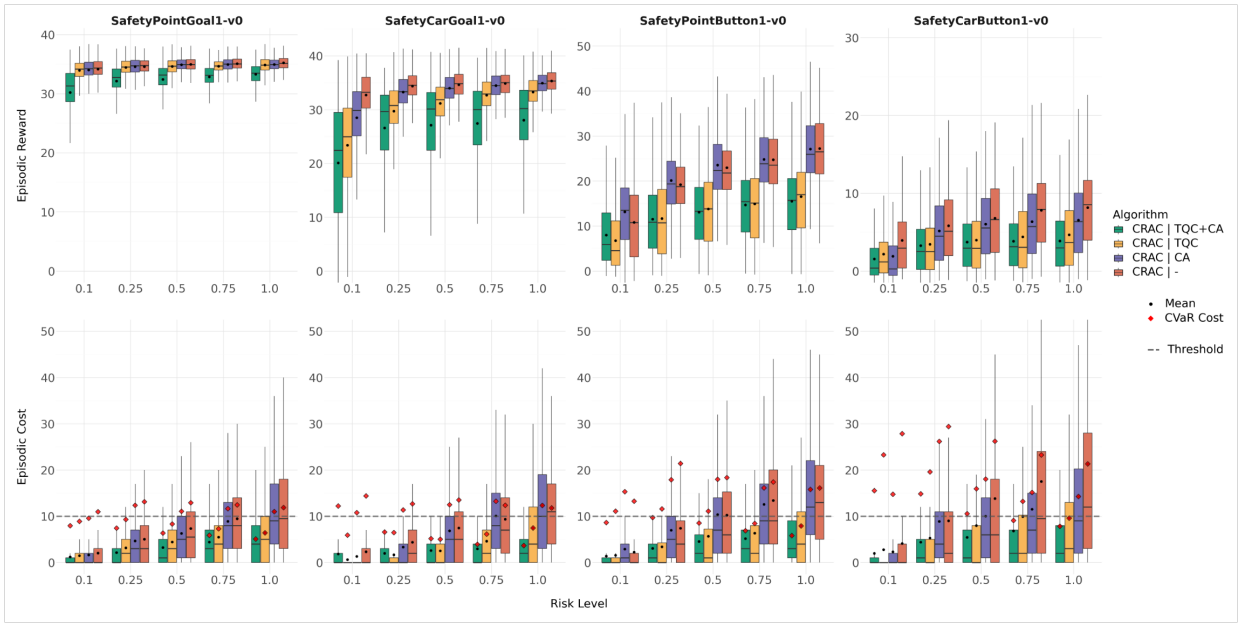

Figure 7: **CRAC** Ablation of TQC and Cost-augmented State: *TQC + CA* - indicates TQC and Cost Augmentation, *TQC* indicates only TQC, *CA* indicates only Cost Augmentation, - indicates neither component is used

B.2 WCSAC

Ablation results in Figure 8 show similar trends to the ablations for CRAC. TQC improves the safety performance of WCSAC by reducing cost underestimation, leading to lower episodic costs and improved CVaR constraint satisfaction across risk levels. Whilst CA further stabilises the CVaR cost satisfaction of WCSAC by providing the policy with necessary information about accumulated cost.

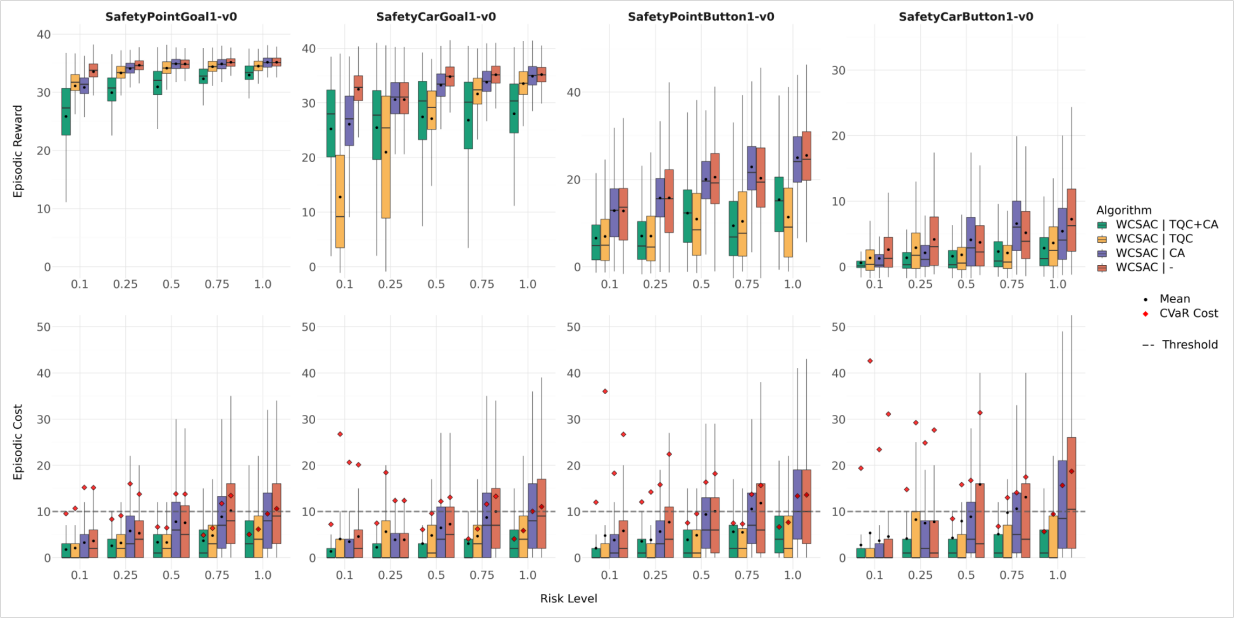

Figure 8: **WCSAC** Ablation of TQC and Cost-augmented State: *TQC + CA* - indicates TQC and Cost Augmentation, *TQC* indicates only TQC, *CA* indicates only Cost Augmentation, - indicates neither component is used

B.3 SRCPO

Ablation results in Figure 9 show that Cost-augmentation has relatively modest affects on the performance of SRCPO. Reward performance is largely similar, with slight improvement in the button tasks. Overall, the impact is less significant to SRCPO than it is to WCSAC and CRAC.

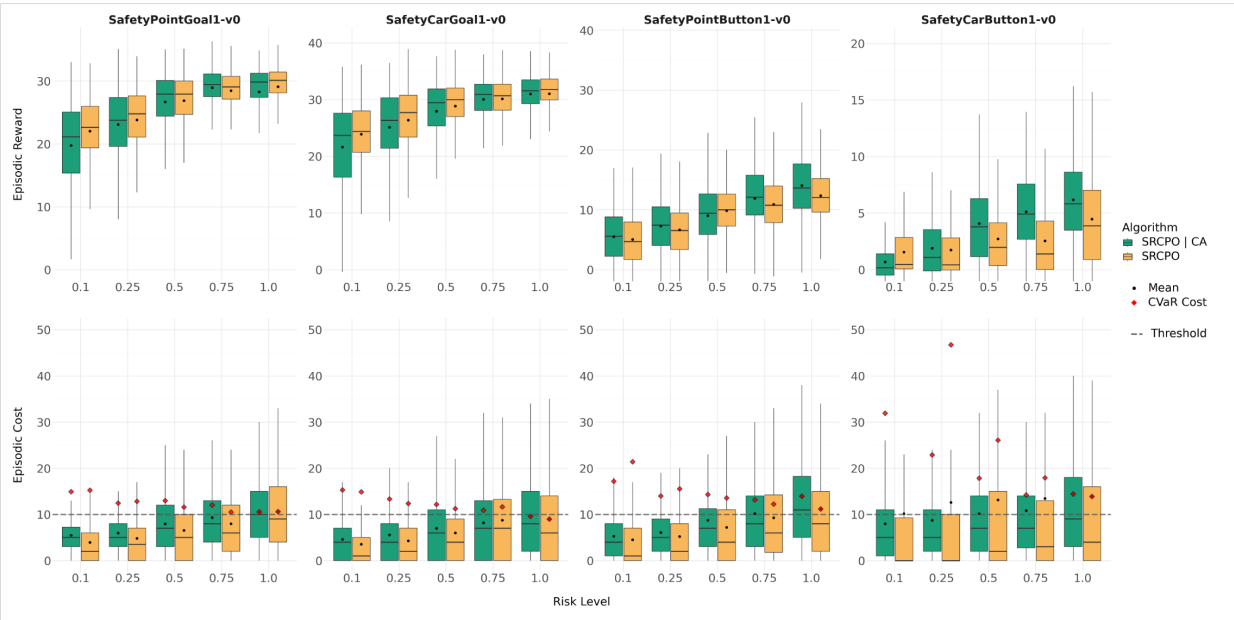

Figure 9: **SRCPO** Ablation of Cost-augmented State

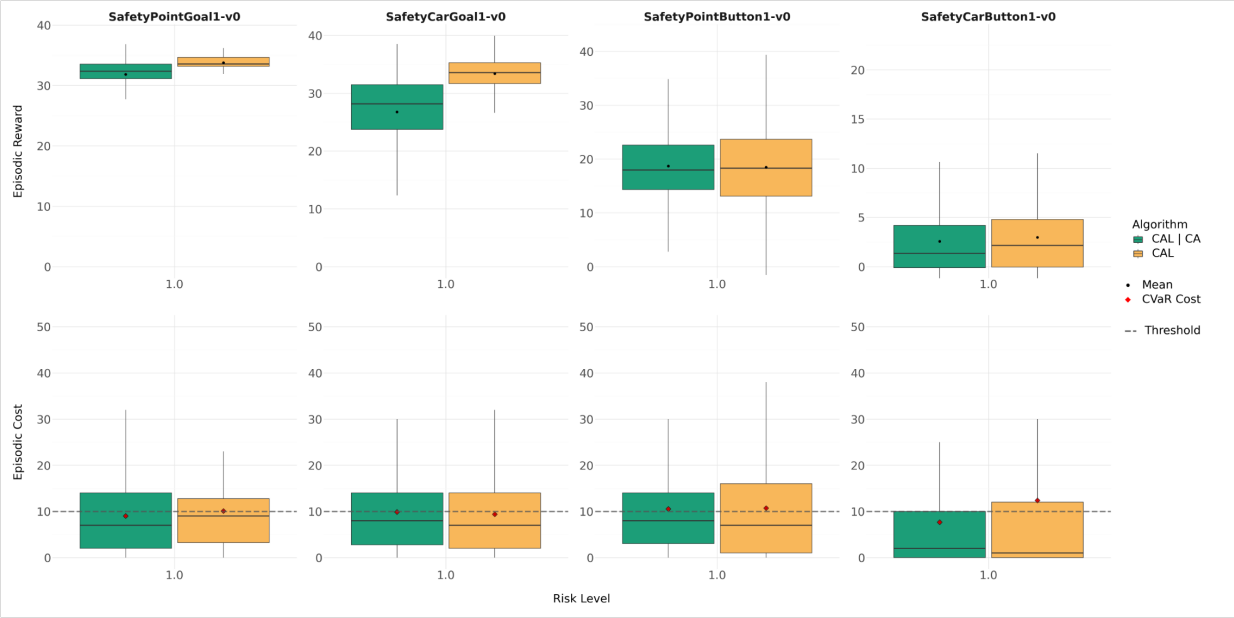

Figure 10: **CAL** Ablation of Cost-augmented State

B.4 CAL

Ablation results for CAL in Figure 10 show that cost-augmentation slightly reduces the reward performance across the environments, with modest improvements to the cost. Its evident that it induces conservatism that may not be necessary for CAL, providing little benefit to its overall performance. To maintain consistency across the algorithms in our main evaluation, we stick with CAL with state-augmentation, but provide the results for comparison here.