Commercial Space Expansion under Economic Kessler Syndrome: Evaluating Orbital Sustainability–Utilization Trade-offs under a Launch Tax–ADR Policy

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Background: Earth orbit is a shared global infrastructure supporting navigation, communications, Earth observation, weather services, disaster response, and digital timing, yet its long-run usability is increasingly threatened by persistent debris and traffic congestion. Higher object density raises collision risk, collisions create additional fragments, and those fragments further raise future risk—creating the reinforcing mechanism associated with the *Kessler Syndrome* (Kessler and Cour-Palais, 1978). Economic analyses further show that open-access incentives can make orbital use increasingly self-undermining as congestion worsens—an *Economic Kessler Syndrome* (EKS) (Adilov et al., 2018). Market-based proposals such as orbital-use fees seek to internalize congestion externalities (Rao et al., 2020), while active debris removal (ADR) is moving from concept toward demonstration and procurement.

Research question: This study asks whether commercial launch expansion can remain governable under interacting physical, behavioral, and fiscal pressures. Specifically, it examines whether a launch tax linked to ADR financing can substantially reduce debris while preserving long-run orbital utilization, and whether outcomes depend more on launch-growth pressure or on the governance regime through which that growth is managed. The analysis extends the launch tax–ADR system dynamics framework of Minato and Yamaguchi (2025) from historical what-if analysis to forward-looking policy-experiment simulations through 2075.

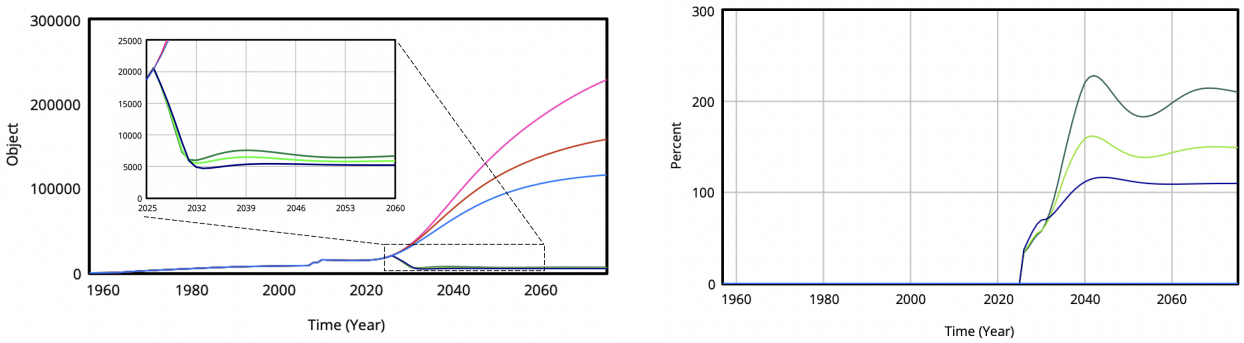
Model design and simulation experiments: The model is a stylized aggregate source–sink representation of orbital environment and policy intervention rather than a high-fidelity debris evolutionary model. It contains stocks of spacecraft and debris, launch- and collision-related inflows, natural deorbiting, and ADR. Historical behavior over 1957–2025 reproduces the broad long-run evolution of spacecraft, debris, and total tracked objects, including major level shifts associated with the 2007 Chinese anti-satellite (ASAT) test and the 2009 Iridium–Cosmos collision.

Four extensions support the future experiments. First, the horizon is extended to 2075. Second, an EKS-related balancing loop is introduced: worsening perceived debris conditions reduce expected launch demand, providing an endogenous brake on orbital expansion. This behavioral response is deliberately reduced-form and uses debris stock as the baseline risk proxy. Third, three future launch-pressure scenarios are examined: constant launches at the 2025 level (S1), an announced-plans case reflecting major constellation programs (S2), and a sustained high-expansion stress case (S3). Fourth, the ADR target is reformulated as a strong stock-reduction benchmark responding to both the existing debris stock and continuing net inflows. It is a stylized remediation experiment, not a literal implementation of ESA's preventive Zero Debris approach.

The simulations compare unmanaged/open-access reference cases with explicit governance through the launch tax–ADR regime. Policy operates through two balancing channels: taxation raises launch cost and moderates demand, while tax revenue finances ADR and directly reduces the debris stock.

Results: Three findings stand out. First, the launch risk response (EKS) loop restrains launch demand but does not by itself reverse long-run debris accumulation. Under S2, debris reaches 158,169 objects in 2075

with EKS but no policy. Second, the launch tax–ADR regime changes the qualitative trajectory: under S2 the policy case declines to 5,872 debris objects by 2075 while sustaining expected launch demand of about 200 launches per year. Across S1–S3, the difference between governance regimes is substantially larger than the difference among growth scenarios in determining long-run debris outcomes.



(a) Number of space debris in orbit

(b) Required launch-tax rate (% of average launch price)

Reference cases include the EKS response but no tax–ADR policy; policy cases include both EKS and the tax–ADR regime.

Third, strong debris reduction does not necessarily imply lower long-run utilization. In S1 and S2, the policy cases sustain more spacecraft in orbit by 2075 than their corresponding unmanaged EKS cases while maintaining far lower debris levels. Under S2, for example, the policy case reaches 53,620 spacecraft compared with 46,365 in the EKS reference case. The mechanism is dynamic: successful remediation weakens the congestion-driven contraction that would otherwise suppress future orbital activity. Under the high-expansion S3 case, this utilization advantage is weaker and delayed, indicating a more pronounced medium-term restraint.

Fiscal and policy implications: The countervailing result is fiscal. Here, the required launch-tax rate is expressed as a percentage of the average launch price; thus, a 100% tax rate means a tax equal to the average launch price itself. Under the stringent stock-reduction target, the peak required tax rate rises from about 116% in S1 to 162% in S2 and 228% in S3. These values are diagnostic indicators of the fiscal effort implied by the modeled objective, not literal tax recommendations. The current architecture omits tax smoothing, stabilization funds, multi-period budgeting, and binding ADR-capacity constraints; consequently, very high rates signal how demanding the target becomes when remediation costs must be financed mechanically from the contemporaneous launch base.

The simulations therefore suggest that orbital sustainability and commercial utilization are not linked by a simple one-dimensional trade-off. Governance can protect the environmental resource on which future utilization depends, but environmental effectiveness alone does not guarantee institutional sustainability. Fiscal burden, implementation capacity, environmental targets, financing rules, and operator response must be designed as an interacting system.

Conclusion: Long-run orbital outcomes are shaped jointly by physical accumulation, endogenous behavioral response, and institutional intervention. In the modeled system, unmanaged congestion eventually constrains utilization through the EKS feedback, whereas tax-financed ADR shifts the system to a much lower-debris trajectory and can, in some scenarios, support higher long-run utilization. The policy challenge is therefore less a choice between ‘‘growth’’ and ‘‘sustainability’’ than the design of governance arrangements capable of sustaining environmental improvement without creating an unmanageable fiscal burden. Because the model is intentionally aggregate and its behavioral and fiscal mechanisms are stylized, the results should be interpreted as dynamic tendencies and institutional diagnostics rather than forecasts or direct policy prescriptions.

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