

# Directed Technical Change in the Space Economy: Growth, Spillovers, and Orbital Fragility

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## Abstract

This paper studies directed innovation in a dynamic space economy where orbital space is a productive but congestible commons. Space services raise aggregate productivity, while orbital debris increases collision risk and weakens the long-run value of space infrastructure. Innovation can be directed toward orbit-intensive technologies or toward orbit-preserving technologies. We solve a finite-horizon policy problem in which a planner chooses the path of preserving research and an orbital-use tax, and we compute the preserving-research subsidy required to decentralize the optimal allocation. The results show that the optimal transition operates mainly through the innovation margin. Redirecting scientists toward orbit-preserving research raises the relative productivity of preserving technologies, reduces collision risk and debris accumulation, and supports higher long-run output. The orbital-use tax is inactive in the benchmark calibration but becomes relevant when the welfare cost of debris is high. The findings suggest that sustainable growth in the space economy requires policies that not only regulate current orbital use, but also redirect technological change toward preserving the orbital environment.

**Keywords:** Space economy; directed technical change; orbital debris; innovation policy; growth; orbital commons.

**JEL Codes:** O31; O33; O44; Q54; Q58; H23.

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# 1 Introduction

Space is becoming a critical infrastructure of modern economies. Satellite systems support communication, navigation, financial transactions, logistics, Earth observation, climate monitoring, disaster management, and defense. Although the space sector remains small relative to aggregate GDP, its services are increasingly embedded in the functioning of the broader economy. The macroeconomic relevance of space activity therefore cannot be assessed only through the direct size of the space industry. Space activity raises new questions for economic growth, innovation, and the measurement of modern productive infrastructure (Corrado et al., 2023; Highfill and MacDonald, 2022; OECD, 2012, 2014). At the same time, orbital space is a finite and congestible environment. Satellites, rocket bodies, mission-related objects, and fragments accumulate in orbit and increase collision risk. Collisions may destroy operational satellites and generate additional fragments, creating a self-reinforcing process of orbital degradation. This mechanism is commonly associated with the possibility of a collision cascade, or Kessler syndrome (Kessler, 1991; Kessler and Cour-Palais, 1978; Liou and Johnson, 2006). The economic cost of this process is not only the loss of individual satellites. A deteriorating orbital environment can reduce the productivity of space services and weaken the infrastructure on which many Earth-based activities rely.

Recent work in space economics has begun to formalize these issues. Macauley (1998, 2015) emphasize the economic value of orbital and spectrum resources and the policy relevance of debris mitigation. Adilov et al. (2015, 2018) analyze orbital debris as an externality affecting launch and satellite decisions. Rao et al. (2020) show that orbital-use fees can increase the value of the space industry by internalizing congestion externalities. Related contributions develop integrated approaches to orbit use, debris propagation, and macroeconomic consequences (Bongers et al., 2025; Nozawa et al., 2023; Rao and Rondina, 2023; Rao et al., 2023). This paper studies the interaction between space-enabled growth, orbital debris, and the direction of innovation. The central idea is that the space economy generates a new form of growth-fragility trade-off. Expanding space activity raises productivity, but it also increases congestion and debris risk. Whether this trade-off becomes severe depends on the direction of technological change. Innovation can be directed toward orbit-intensive technologies, which expand current space-service provision, or toward orbit-preserving technologies, which improve the safety, resilience, and long-run usability of orbital infrastructure.

The paper connects three strands of literature. The first is directed technical change. Acemoglu (2002) develops the theory of directed technical change, while Acemoglu (2007) studies equilibrium bias in technological change. Acemoglu et al. (2012) apply this logic to environmental policy, showing that policy can redirect innovation away from dirty technologies and toward clean alternatives. Related work emphasizes the role of path dependence, induced innovation, and environmental regulation in shaping long-run technological transitions (Acemoglu et al., 2014; Aghion et al., 2016; Jaffe et al., 2003; Newell et al., 1999; Popp, 2002). The second strand is the macroeconomic literature on the space economy. This literature emphasizes that the space economy is difficult to capture through narrow sectoral accounting because space assets provide services used by many downstream activities (Highfill and MacDonald, 2022; OECD, 2012, 2014). Corrado et al. (2023) discuss the new economic questions raised by space exploration, including the interaction between space activity, growth, and resource constraints. The third strand studies orbital debris and integrated space-economy

modeling. Existing contributions analyze launch decisions, congestion externalities, orbital-use fees, and the economic consequences of debris accumulation (Adilov et al., 2015, 2018; Bongers et al., 2025; Rao and Rondina, 2023; Rao et al., 2020, 2023).

Despite these advances, the three strands have not yet been fully integrated. Directed technical change models focus mainly on environmental problems on Earth rather than on the orbital commons. Macroeconomic models of the space economy emphasize productivity spillovers and measurement issues, but often abstract from the endogenous direction of research. Integrated space-economy models provide a rich physical description of debris dynamics, but generally treat mitigation technologies and innovation paths as exogenous or policy-imposed. This paper fills this gap by developing a dynamic model in which the orbital environment is a productive commons, space services raise aggregate productivity, and innovation can be directed between orbit-intensive and orbit-preserving technologies.

The model has three core components. First, space services raise Earth-side productivity. This captures the role of space infrastructure in communication, navigation, monitoring, and information services, and reflects the idea that space activity creates economic value beyond the direct size of the space sector (Corrado et al., 2023; Highfill and MacDonald, 2022; OECD, 2012). Second, the orbital environment is modeled through a physical debris block. Total debris is decomposed into derelict satellites, rocket bodies, and fragments. Debris increases collision risk; collisions destroy operational space capacity; and collisions generate new fragments. Third, a directed-innovation block allows scientists to work either on orbit-intensive or orbit-preserving technologies. The model is solved numerically over a finite horizon. In the main policy experiment, a planner chooses the path of the preserving-research share and the orbital-use tax. The preserving-research subsidy is then computed as the minimum subsidy required to decentralize the chosen research allocation. We compare the optimal transition with *laissez-faire*, a tax-only benchmark, a no-directed-innovation benchmark, and a delayed-intervention case.

The quantitative analysis delivers four main findings. First, *laissez-faire* can generate a technological bias toward orbit-intensive activity when orbit-intensive technologies start with an initial advantage. This bias expands current space services but raises orbital congestion and debris accumulation. Second, the optimal policy redirects research toward orbit-preserving technologies. This raises the relative productivity of preserving technologies, reduces collision risk, stabilizes the orbital environment, and preserves the productivity of space services. Third, the orbital-use tax and the preserving-research subsidy operate on different margins. The tax acts on the current-use margin, while the research subsidy acts on the innovation margin. Fourth, physical mitigation policies and directed innovation are complements. De-orbiting, debris-free launch systems, and collision avoidance reduce specific sources of debris, while research redirection changes the long-run technological path.

The paper contributes to the literature in four ways. First, it extends directed technical change to the orbital commons. The model replaces the standard clean–dirty distinction with an orbit-preserving versus orbit-intensive technological choice. This is not only a relabeling exercise. Orbital debris is a stock externality that damages productive infrastructure through collision risk and asset destruction. Second, the paper contributes to the macroeconomics of the space economy by linking space-enabled productivity gains to orbital sustainability. Existing work shows that space activity raises new questions for growth, innovation, and

measurement (Corrado et al., 2023; Highfill and MacDonald, 2022; OECD, 2012). We show that these gains depend on the long-run preservation of orbital infrastructure. Third, the paper contributes to integrated space-economy models by endogenizing the direction of innovation. Fourth, the paper contributes to policy debates on orbital governance by showing that current-use instruments, research incentives, and physical mitigation operate on different margins and should be viewed as complements.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 describes the calibration and numerical solution. Section 4 presents the optimal-transition results and compares them with *laissez-faire*, tax-only, no-directed-innovation, and delayed-intervention benchmarks. Section 5 concludes.

## 2 Model

This section develops a dynamic model of directed innovation in a congestible orbital commons. The framework combines the directed-technical-change logic of Acemoglu (2002); Acemoglu et al. (2012) with a physical representation of the orbital environment in line with the Dynamic Integrated Space-Economy approach of Bongers et al. (2025). Space services raise aggregate productivity, consistent with the view that space activity operates as an enabling infrastructure for modern economies (Corrado et al., 2023; Highfill and MacDonald, 2022; OECD, 2012).

The model is designed to study a growth-fragility trade-off. Space activity supports productivity and growth, but it also increases orbital congestion and debris accumulation. The resulting collision risk weakens the same orbital infrastructure that generates macroeconomic benefits. Policy can affect this trade-off not only by taxing orbit-intensive activity, but also by redirecting innovation toward technologies that preserve the long-run productive value of orbital space.

Time is discrete and indexed by  $t = 0, \dots, T$ . There are two space technologies. Technology  $I$  is orbit-intensive: it expands current space-service provision but contributes more strongly to congestion and debris accumulation. Technology  $P$  is orbit-preserving: it also produces space services, but it reduces orbital fragility and improves the resilience of space infrastructure. This distinction is the space-economy analogue of the clean-dirty distinction in directed technical change models. The difference is that the externality is not an emissions flow, but a stock externality that degrades a productive orbital commons.

### 2.1 Preferences and Welfare

We begin with preferences. The representative household derives utility from consumption and suffers disutility from orbital degradation. The benchmark specification uses logarithmic utility. This is a standard choice in growth and environmental macroeconomic models because it delivers a tractable welfare criterion and implies unit intertemporal elasticity of substitution. The welfare costs of debris and collision risk are represented by quadratic terms. This reduced-form specification captures convex social damages from orbital degradation, in line with integrated assessment models where the cost of environmental degradation increases more than proportionally with the stock of the externality.

Social welfare is specified as:

$$W_0 = \sum_{t=0}^T \beta^t \left[ \log C_t - \varrho_D D_t^2 - \varrho_\pi \pi_t^2 - \frac{\chi_s}{2} (s_t^P - s_{t-1}^P)^2 \right], \quad (1)$$

where  $C_t$  denotes consumption,  $D_t$  is orbital debris,  $\pi_t$  is collision risk, and  $s_t^P$  is the share of scientists allocated to orbit-preserving research. The parameter  $\beta \in (0, 1)$  is the discount factor. The parameters  $\varrho_D$  and  $\varrho_\pi$  govern the welfare cost of debris and collision risk.

The last term captures a quadratic adjustment cost in the direction of research. This term is introduced because the reallocation of scientists across research lines is unlikely to be instantaneous. It also avoids implausible jumps in the optimal research allocation. This type of smooth adjustment friction is commonly used in quantitative dynamic models when policy affects the composition of investment or innovation.

The research-adjustment cost is:

$$\mathcal{A}_t^s = \frac{\chi_s}{2} (s_t^P - s_{t-1}^P)^2, \quad (2)$$

with  $\chi_s > 0$ . A higher value of  $\chi_s$  makes the redirection of research more gradual.

## 2.2 Final Output

Final output is produced using physical capital and space-enabled productivity. The production function is Cobb–Douglas. This is the standard benchmark in growth models and integrated assessment frameworks. We use this parsimonious specification to isolate the role of space-enabled productivity, orbital degradation, and directed innovation.

Final output is:

$$Y_t = A_t^E K_t^\alpha, \quad (3)$$

where  $K_t$  is physical capital,  $A_t^E$  is Earth-side productivity, and  $\alpha \in (0, 1)$  is the capital share. Labor is normalized to one.

Physical capital evolves according to:

$$K_{t+1} = (1 - \delta_K)K_t + s_K Y_t, \quad (4)$$

where  $\delta_K$  is the depreciation rate of capital and  $s_K$  is the exogenous saving rate. This reduced-form law of motion follows the standard structure of neoclassical growth and integrated assessment models. It allows the analysis to focus on the interaction between space services, orbital fragility, and technological direction.

Consumption is then given by:

$$C_t = (1 - s_K)Y_t. \quad (5)$$

This specification implies that the welfare effects of orbital degradation and directed innovation operate through output and consumption, while keeping the savings margin exogenous.

## 2.3 Space Services

Space services are produced by two technological lines. Orbit-intensive services use orbit-intensive technology and orbit-intensive operational capacity. Orbit-preserving services use orbit-preserving technology and preserving operational capacity. This distinction allows the model to capture the idea that some space technologies expand current service provision, while others improve safety, resilience, and long-run orbital usability.

Orbit-intensive services are:

$$X_t^I = A_t^I N_t^I, \quad (6)$$

where  $A_t^I$  is orbit-intensive technology and  $N_t^I$  is orbit-intensive operational space capacity.

Orbit-preserving services are:

$$X_t^P = A_t^P N_t^P, \quad (7)$$

where  $A_t^P$  is orbit-preserving technology and  $N_t^P$  is orbit-preserving operational space capacity.

The two types of space services are combined through a CES aggregator. This choice follows the directed-technical-change literature, where the elasticity of substitution between competing technologies is central for the cost and feasibility of the transition ([Acemoglu et al., 2012](#)). In our setting, the elasticity of substitution governs how easily orbit-preserving services can substitute for orbit-intensive services in producing aggregate space services.

Aggregate space services are:

$$X_t = \Omega(D_t) \left[ \left( \tilde{X}_t^I \right)^{\rho_X} + \left( X_t^P \right)^{\rho_X} \right]^{1/\rho_X}, \quad (8)$$

where:

$$\rho_X = \frac{\varepsilon_X - 1}{\varepsilon_X}. \quad (9)$$

The parameter  $\varepsilon_X$  is the elasticity of substitution between orbit-intensive and orbit-preserving services.

The term  $\Omega(D_t)$  captures the loss in effective space-service productivity caused by orbital degradation. We use an exponential damage term because it ensures that productivity remains strictly positive while declining with debris. This reduced-form is in line with integrated assessment models, where environmental degradation reduces effective productivity through a smooth damage channel.

The orbital-quality term is:

$$\Omega(D_t) = \exp(-\xi_D D_t), \quad \xi_D > 0. \quad (10)$$

A higher  $D_t$  lowers the effective productivity of the space-service bundle. This captures the idea that debris does not only destroy individual satellites; it also reduces the reliability and productive value of orbital infrastructure.

The orbital-use tax reduces the effective use of orbit-intensive services. This is a reduced-form representation of orbital-use fees, which are designed to internalize the congestion and debris externalities generated by space activity ([Rao et al., 2020](#)).

Effective orbit-intensive services are:

$$\tilde{X}_t^I = (1 - \vartheta_\tau \tau_t) X_t^I, \quad (11)$$

where  $\tau_t$  is the orbital-use tax and  $\vartheta_\tau > 0$  measures how strongly the tax reduces effective orbit-intensive activity. The tax directly affects the current-use margin. It lowers the use of the technology that contributes more strongly to orbital congestion.

Space services raise Earth-side productivity. This channel reflects the role of satellites and space infrastructure in communication, navigation, Earth observation, logistics, financial systems, climate monitoring, and disaster management. We use a concave function to capture decreasing marginal macroeconomic returns to space services.

Earth-side productivity is:

$$A_t^E = \bar{A}(1 + \lambda_X X_t^\nu), \quad \lambda_X > 0, \quad 0 < \nu \leq 1. \quad (12)$$

The parameter  $\lambda_X$  governs the strength of space-enabled productivity spillovers. The curvature parameter  $\nu$  ensures that these spillovers are positive but not explosive.

## 2.4 Orbital Environment

The orbital environment is a productive but congestible commons. Following the physical structure of integrated space-economy models, and in particular [Bongers et al. \(2025\)](#), we decompose total orbital debris into derelict satellites, rocket bodies, and fragments. This decomposition is important because different mitigation policies operate on different physical sources of debris.

Total orbital debris is:

$$D_t = W_t + Z_t + F_t, \quad (13)$$

where  $W_t$  denotes derelict satellites,  $Z_t$  denotes rocket bodies, and  $F_t$  denotes fragments.

The stock of derelict satellites evolves according to:

$$W_{t+1} = (1 - \delta_W - \delta_W^b)W_t - \pi_t W_t + \chi_t \delta_N N_t, \quad (14)$$

where  $N_t = N_t^I + N_t^P$ . The parameter  $\delta_W$  is the natural decay rate,  $\delta_W^b$  is the breakup rate, and  $\chi_t$  is the fraction of end-of-life satellites left in orbit. The term  $\pi_t W_t$  captures losses from collisions involving derelict satellites.

The stock of rocket bodies evolves as:

$$Z_{t+1} = (1 - \delta_Z - \delta_Z^b)Z_t - \pi_t Z_t + \phi_t L_t, \quad (15)$$

where  $L_t$  denotes launches,  $\delta_Z$  is the natural decay rate,  $\delta_Z^b$  is the breakup rate, and  $\phi_t$  is the fraction of launches that leave rocket bodies in orbit.

Fragments evolve according to:

$$\begin{aligned} F_{t+1} = & (1 - \delta_F)F_t + \omega_t L_t + \sigma \delta_W^b W_t + \rho \delta_Z^b Z_t \\ & + \gamma X_t^{coll} + \epsilon \pi_t W_t + \nu_F \pi_t Z_t. \end{aligned} \quad (16)$$

The term  $\omega_t L_t$  captures mission-related debris generated at launch. The terms  $\sigma \delta_W^b W_t$  and  $\rho \delta_Z^b Z_t$  capture fragments generated by breakups. The final terms capture collision-generated fragments. This law of motion reproduces the central physical feature of orbital debris dynamics: debris accumulation can become self-reinforcing when collisions generate additional fragments.

## 2.5 Collision Risk and Operational Space Capacity

Collision risk depends on total debris, the scale of operational space capacity, and the state of orbit-preserving technology. We use an exponential hazard formulation because it guarantees that the collision probability lies between zero and one. This is consistent with the physical interpretation of collision risk as an increasing function of object density and a decreasing function of avoidance and resilience technologies.

The collision probability is:

$$\pi_t = 1 - \exp(-\mathcal{H}_t), \quad (17)$$

where the collision hazard is:

$$\mathcal{H}_t = \theta_D D_t N_t \exp(-\chi_P A_t^P). \quad (18)$$

The hazard increases with debris and operational capacity, and decreases with orbit-preserving technology. Thus:

$$\frac{\partial \pi_t}{\partial D_t} > 0, \quad \frac{\partial \pi_t}{\partial N_t} > 0, \quad \frac{\partial \pi_t}{\partial A_t^P} < 0. \quad (19)$$

The last inequality captures the role of tracking, maneuverability, shielding, de-orbiting capability, and collision avoidance.

Operational capacity evolves according to:

$$N_{t+1}^j = (1 - \delta_N - \pi_t) N_t^j + i_t^j N_t^j, \quad j \in \{I, P\}. \quad (20)$$

This law of motion shows how orbital debris affects the economy through a stock externality. Higher debris raises collision risk, which destroys operational space assets and reduces future productive capacity. This differs from standard climate-economy models, where pollution often enters as a direct damage to aggregate productivity. Here, the damage operates through the degradation of orbital infrastructure.

## 2.6 Directed Innovation

There is a unit mass of scientists. Scientists can work on orbit-intensive or orbit-preserving innovation. This follows the directed-technical-change framework of [Acemoglu \(2002\)](#); [Acemoglu et al. \(2012\)](#), where the direction of research responds to relative profitability across technological lines.

The research resource constraint is:

$$s_t^I + s_t^P = 1. \quad (21)$$

The value of orbit-intensive innovation is:

$$V_t^I = \beta \gamma_I \eta_I A_t^I J_t^I, \quad (22)$$

where  $\gamma_I$  is the innovation step size,  $\eta_I$  is research productivity, and  $J_t^I$  is the return to improving orbit-intensive technology. This formulation follows the quality-ladder logic of directed technical change: the value of research depends on the size of the productivity

improvement, research efficiency, the existing technology stock, and the market return to that technology.

The value of orbit-preserving innovation is:

$$V_t^P = (1 + q_t^R)\beta\gamma_P\eta_P A_t^P J_t^P, \quad (23)$$

where  $q_t^R$  is a preserving-research subsidy. The subsidy raises the private return to orbit-preserving research and therefore affects the direction of innovation.

The return to preserving innovation includes a production component and a preservation component:

$$J_t^P = P_t^P N_t^P + \omega_P B_t^P. \quad (24)$$

The first term captures the market return to improving orbit-preserving services. The second term captures the social value of reducing orbital fragility.

The preservation value is:

$$B_t^P = \phi_D Y_t (D_t + \bar{D}) + \phi_\pi Y_t N_t \left( -\frac{\partial \pi_t}{\partial A_t^P} \right). \quad (25)$$

This term captures two channels. First, preserving innovation is valuable when debris is high because it protects the productive value of the orbital environment. Second, it is valuable because it lowers collision risk. In the decentralized economy, this preservation value is only partially internalized, creating a wedge between private and social research incentives.

Scientists are allocated according to a smooth logit rule. This specification is consistent with the random-utility and discrete-choice tradition (McFadden, 1974; Train, 2009). In our setting, it is used as a tractable reduced form for research allocation under heterogeneous research opportunities or idiosyncratic project-specific returns. The logit rule preserves the main mechanism of directed technical change: higher relative innovation values attract more scientists. It also avoids discontinuous corner solutions.

The share of scientists in orbit-intensive research is:

$$s_t^I = s_{\min} + (1 - 2s_{\min}) \frac{\exp(\rho_s V_t^I)}{\exp(\rho_s V_t^I) + \exp(\rho_s V_t^P)}. \quad (26)$$

The share of scientists in orbit-preserving research is:

$$s_t^P = 1 - s_t^I. \quad (27)$$

The parameter  $\rho_s$  governs the responsiveness of research allocation to relative innovation values. The lower bound  $s_{\min}$  ensures that both research lines remain active.

Technologies evolve according to:

$$A_{t+1}^I = (1 + \gamma_I \eta_I s_t^I) A_t^I, \quad (28)$$

and:

$$A_{t+1}^P = (1 + \gamma_P \eta_P s_t^P) A_t^P. \quad (29)$$

These laws of motion follow the directed-technical-change logic: productivity growth in each line is proportional to the share of scientists working on that line and to the productivity of research. This mechanism generates path dependence. If orbit-intensive technology starts with an advantage, private returns may direct research toward orbit-intensive innovation, reinforcing the initial technological gap. Policy can overturn this path dependence by changing relative research incentives.

## 2.7 Policy Problem

The planner solves a finite-horizon policy problem. In the benchmark policy experiment, the planner chooses the path of the preserving-research share and the orbital-use tax.

The policy controls are:

$$\{s_t^P, \tau_t\}_{t=0}^T. \quad (30)$$

The planner maximizes welfare in (1) subject to the laws of motion for capital, technologies, operational space capacity, collision risk, and orbital debris. This formulation follows the computational logic of directed-technical-change models: the planner chooses the research allocation and the tax path, while the subsidy needed to implement the chosen research allocation is recovered ex post.

The preserving-research subsidy is therefore not directly optimized. After solving for the optimal path of  $s_t^P$ , we compute the minimum subsidy that decentralizes that path. Let  $\tilde{V}_t^P$  denote the value of preserving innovation before the subsidy.

The implied subsidy is:

$$q_t^R = \max \left\{ 0, \frac{V_t^I + \rho_s^{-1} \log \left( \frac{s_t^P}{1-s_t^P} \right)}{\tilde{V}_t^P} - 1 \right\}. \quad (31)$$

This expression should be interpreted as an implementation instrument. It measures the subsidy required to make the decentralized research allocation consistent with the planner's chosen path.

We also consider restricted policy environments. In the tax-only case, the planner chooses only:

$$\{\tau_t\}_{t=0}^T, \quad (32)$$

while scientists are allocated according to private innovation values. In the no-directed-innovation case, the research allocation is fixed and the planner again chooses only the orbital-use tax. These restricted allocations isolate the contribution of endogenous research direction.

## 3 Calibration

The model is calibrated at an annual frequency. The calibration combines standard values from macroeconomic growth models, parameter values from directed-technical-change models, and physical parameters from the space-debris literature. The objective is not to match a single economy, but to construct a disciplined global space-economy environment in which the interaction between innovation, orbital congestion, and macroeconomic spillovers can be evaluated.

The calibration follows four principles. First, the macroeconomic block is disciplined using standard growth-model parameters and integrated-assessment-model conventions. Second, the space-production block is calibrated to capture the idea that space services generate aggregate productivity spillovers, in line with the empirical evidence on space activity and growth in [Corrado et al. \(2023\)](#). Third, the directed-innovation block follows the logic of [Acemoglu \(2002\)](#); [Acemoglu et al. \(2012\)](#): research is allocated between two technological lines and responds to relative innovation values. Fourth, the orbital-environment block is

disciplined by the physical debris structure in [Bongers et al. \(2025\)](#), who distinguish derelict satellites, rocket bodies, and fragments and provide calibrated values for the main debris-generation parameters.

The discount factor is set to  $\beta = 0.99$ . Utility is logarithmic in the baseline, corresponding to a CRRA coefficient equal to one. The capital share is set to  $\alpha = 0.33$ , close to standard values in aggregate macroeconomic models. The saving rate is set to  $s_K = 0.22$ , close to the saving rates used in integrated assessment models and to the value calibrated in [Bongers et al. \(2025\)](#). The depreciation rate of physical capital is set to  $\delta_K = 0.025$  per model period. In the sensitivity analysis we verify that the results are robust to alternative economic calibrations.

The space-services aggregator combines orbit-intensive and orbit-preserving technologies with elasticity of substitution  $\varepsilon_X = 3$ . This value implies that the two technologies are imperfect but relatively substitutable. This is consistent with the role of substitutability in environmental directed-technical-change models, where the ease of substitution between clean and dirty technologies is central for the transition dynamics ([Acemoglu et al., 2012](#)). The strength of space-enabled productivity spillovers is governed by  $\lambda_X = 0.18$  and  $\nu = 0.65$ . These values are normalized to generate a quantitatively relevant but not explosive contribution of space services to aggregate productivity, consistent with the view that space activity generates macroeconomic spillovers beyond the direct size of the sector ([Corrado et al., 2023; ?](#)).

The directed-innovation block uses  $\gamma_I = 0.022$  and  $\gamma_P = 0.026$ , allowing orbit-preserving technologies to have a slightly higher innovation potential. This asymmetry captures the idea that preserving technologies, such as tracking, maneuverability, reusable launch systems, shielding, de-orbiting systems, and collision-avoidance capabilities, may be less mature but potentially more dynamic. The research productivity parameters  $\eta_I$  and  $\eta_P$  are normalized to one. The responsiveness of research allocation to relative innovation values is governed by  $\rho_s = 7$ . The lower bound on research shares is  $s_{\min} = 0.01$ , ensuring that both technological lines remain active.

The orbital-debris block is calibrated using the physical structure of [Bongers et al. \(2025\)](#). In their DISE model, the stock of orbital debris is decomposed into derelict satellites, rocket bodies, and fragments. We adopt the same decomposition. The debris decay rate is set to  $\delta_D = 0.01$ , consistent with their baseline calibration. The fraction of abandoned satellites is set to  $\chi = 0.35$ , the fraction of rocket bodies abandoned per launch to  $\phi = 0.80$ , and the breakup rates of derelict satellites and rocket bodies to  $\delta_W^b = 0.002$  and  $\delta_Z^b = 0.001$ , respectively. The values for fragments generated by breakups and collisions are based on the same physical calibration, but rescaled in the normalized model so that the stocks remain of order one. This rescaling preserves the relative importance of the different sources of debris.

Collision risk is calibrated to increase with total debris and operational space capacity, and to decline with orbit-preserving technology. The baseline value of the collision-risk parameter is chosen to generate a non-negligible but not immediately catastrophic collision probability along the laissez-faire path. This is consistent with the space-debris literature, where collision risk is treated as a central channel through which debris affects the value and sustainability of space activity ([Bongers et al., 2025; Kessler and Cour-Palais, 1978; Rao et al., 2020; ?](#)). The effectiveness of preserving technology in reducing collision risk is governed by  $\chi_P = 0.45$ .

The welfare weights on orbital debris and collision risk are set to  $\varrho_D = 0.02$  and  $\varrho_\pi = 0.50$ . These parameters are not directly observable. They are chosen so that orbital degradation is

**Table 1:** Baseline calibration

Parameter	Value	Description	Source
<i>Preferences and welfare</i>			
$\beta$	0.99	Discount factor	<a href="#">Acemoglu et al. (2012)</a>
$\sigma$	1.00	CRRA coefficient	<a href="#">Acemoglu et al. (2012)</a>
$\varrho_D$	0.02	Welfare weight on orbital debris	Internal calibration
$\varrho_\pi$	0.50	Welfare weight on collision risk	Internal calibration
$\chi_s$	4.00	Research adjustment cost	Internal calibration
<i>Aggregate production</i>			
$\alpha$	0.33	Capital share	<a href="#">Acemoglu et al. (2012)</a>
$\delta_K$	0.025	Physical capital depreciation rate	Standard macro calibration
$s_K$	0.22	Saving rate	<a href="#">Bongers et al. (2025)</a>
$A$	1.00	Earth-side productivity normalization	Normalization
<i>Space services and macroeconomic spillovers</i>			
$\varepsilon_X$	3.00	Elasticity of substitution	<a href="#">Acemoglu et al. (2012)</a>
$\rho_X$	$(\varepsilon_X - 1)/\varepsilon_X$	CES curvature parameter	Implied by $\varepsilon_X$
$\xi_D$	0.030	Productivity loss from orbital degradation	Internal calibration
$\lambda_X$	0.18	Space-enabled productivity spillover	<a href="#">Corrado et al. (2023)</a>
$\nu$	0.65	Curvature of space-service spillovers	Internal calibration
$\vartheta_\tau$	1.50	Tax response of orbit-intensive activity	<a href="#">Rao et al. (2020)</a>
<i>Directed innovation</i>			
$\gamma_I$	0.022	Innovation step size, orbit-intensive	<a href="#">Acemoglu et al. (2012)</a>
$\gamma_P$	0.026	Innovation step size, orbit-preserving	Internal calibration
$\eta_I$	1.00	Research productivity, orbit-intensive	Normalization
$\eta_P$	1.00	Research productivity, orbit-preserving	Normalization
$\rho_s$	7.00	Research-allocation responsiveness	Internal calibration
$s_{\min}$	0.01	Minimum research share	Numerical bound
$s_P^{\max}$	0.95	Maximum preserving-research share	Numerical bound
<i>Operational space capacity</i>			
$\delta_N$	0.040	Operational space-capacity depreciation	<a href="#">Bongers et al. (2025)</a>
$\phi_N$	0.035	Capacity-investment sensitivity	Internal calibration
$\mu_N$	0.060	Capacity-stabilization parameter	Internal calibration
<i>Orbital debris and collision risk</i>			
$\delta_D$	0.010	Natural debris decay rate	<a href="#">Bongers et al. (2025)</a>
$\chi$	0.35	Fraction of abandoned satellites	<a href="#">Bongers et al. (2025)</a>
$\phi$	0.80	Rocket bodies abandoned per launch	<a href="#">Bongers et al. (2025)</a>
$\delta_W^b$	0.002	Derelict-satellite breakup rate	<a href="#">Bongers et al. (2025)</a>
$\delta_Z^b$	0.001	Rocket-body breakup rate	<a href="#">Bongers et al. (2025)</a>
$\omega$	4.00	Mission-related debris per launch	<a href="#">Bongers et al. (2025)</a>
$\sigma$	44.6	Fragments from derelict-satellite breakup	<a href="#">Bongers et al. (2025)</a>
$\rho$	100.2	Fragments from rocket-body breakup	<a href="#">Bongers et al. (2025)</a>
$\gamma$	100	Fragments from operational-satellite collision	<a href="#">Bongers et al. (2025)</a>
$\epsilon$	100	Fragments from derelict-satellite collision	<a href="#">Bongers et al. (2025)</a>
$\nu_F$	100	Fragments from rocket-body collision	<a href="#">Bongers et al. (2025)</a>
$\theta_D$	0.035	Collision-hazard parameter	<a href="#">Farinella and Cordelli (1991)</a>
$\chi_P$	0.45	Collision-risk reduction from preserving technology	Internal calibration

*Notes:* Parameters labeled as “Internal calibration”, “Normalization”, or “Numerical bound” are not directly taken from external estimates and are varied in the sensitivity analysis. Physical debris parameters are reported at the scale used in the space-debris block.

welfare-relevant without dominating consumption. This choice is disciplined by the finding in [Bongers et al. \(2025\)](#) that the long-run economic cost of orbital debris can exceed 0.5 percent of world GDP under laissez-faire. The robustness of the results to alternative welfare weights is examined in the sensitivity analysis.

Finally, the adjustment cost in the direction of research is set to  $\chi_s = 4$ . This parameter prevents the planner from reallocating the entire research sector instantaneously. The value is chosen to produce smooth transitions and is varied in the sensitivity analysis. The upper bound on the preserving-research share is set to  $s_P^{\max} = 0.95$ , ruling out corner allocations in which all scientists are assigned to a single research line.

Table 1 summarizes the baseline calibration.

**Table 2:** Main transition outcomes

Scenario	$W$	$\Delta W$	$\bar{C}$	$\bar{Y}$	$\bar{D}$	$D_T$	$\bar{\pi}$	$A_T^P/A_T^I$
Laissez-faire	51.948	0.000	2.652	3.400	0.683	1.054	4.435	0.530
Full policy	53.270	1.321	2.742	3.516	0.557	0.719	3.285	2.810
Tax only	51.948	0.000	2.652	3.400	0.683	1.054	4.435	0.530
No directed innovation	51.953	0.005	2.652	3.400	0.682	1.051	4.427	0.536
Delayed full policy	52.766	0.817	2.709	3.473	0.595	0.774	3.548	2.257

*Notes:*  $W$  denotes the present value of welfare.  $\Delta W$  is the welfare gain relative to laissez-faire.  $\bar{C}$ ,  $\bar{Y}$ , and  $\bar{D}$  denote average consumption, output, and orbital debris over the transition.  $D_T$  is terminal debris.  $\bar{\pi}$  is the average collision probability, expressed in percentage points.  $A_T^P/A_T^I$  is the terminal ratio between orbit-preserving and orbit-intensive technology.

## 4 Quantitative Results

This section presents the quantitative implications of the model. We organize the analysis in three steps. First, we study the benchmark optimal transition and compare it with laissez-faire and restricted-policy allocations. Second, we assess the robustness of the mechanism to key economic parameters. Third, we vary the welfare weight of orbital debris in the utility function to clarify when the orbital-use tax becomes quantitatively relevant.

The main message is that, under the benchmark calibration, the optimal transition operates primarily through the innovation margin. The planner redirects research toward orbit-preserving technologies, raises the relative productivity of preserving innovation, reduces collision risk, and sustains the productivity of space services. The orbital-use tax is essentially inactive in the benchmark calibration. However, it becomes active when the welfare cost of orbital debris is sufficiently high.

### 4.1 Main Results

We begin by comparing five allocations. The first is laissez-faire, where there is no orbital-use tax and no intervention in the direction of research. The second is the full policy allocation, where the planner chooses the path of the preserving-research share and the orbital-use tax. The third is a tax-only benchmark, where the planner can only choose the orbital-use tax and research remains privately allocated. The fourth is a no-directed-innovation benchmark, where the research allocation is fixed. The fifth is a delayed-policy experiment, where the economy first evolves under laissez-faire and then implements the full policy.

Table 2 summarizes the main transition outcomes.

The full policy allocation delivers a welfare gain of 1.32 relative to laissez-faire. The gain is associated with higher average consumption and output, lower average debris, and a substantial reduction in terminal debris. Terminal debris falls from 1.05 under laissez-faire to 0.72 under the full policy allocation. Average collision risk also declines, from 4.43 to 3.28 percentage points.

The restricted benchmarks clarify the source of these gains. The tax-only allocation coincides with laissez-faire in the benchmark calibration. The orbital-use tax is not used, and the economy remains on the same technological and environmental path. The no-directed-innovation benchmark also produces negligible gains. This indicates that, under the benchmark calibration, the main distortion is not corrected by a contemporaneous tax alone. The welfare gain comes from changing the direction of innovation.

**Table 3:** Policy instruments and research allocation

Scenario	$\bar{\tau}$	$\max \tau$	$\bar{q}^R$	$\max q^R$	$s_0^P$	$s_T^P$
Laissez-faire	0.000	0.000	0.000	0.000	0.496	0.497
Full policy	0.000	0.000	95.264	156.610	0.654	0.950
Tax only	0.000	0.000	0.000	0.000	0.496	0.497
No directed innovation	0.000	0.000	0.000	0.000	0.500	0.500
Delayed full policy	0.000	0.000	85.811	158.420	0.496	0.950

*Notes:*  $\bar{\tau}$  and  $\max \tau$  denote the average and maximum orbital-use tax.  $\bar{q}^R$  and  $\max q^R$  denote the average and maximum implied preserving-research subsidy. The subsidy is not directly chosen by the planner. It is computed as the minimum subsidy required to decentralize the optimal research allocation.  $s_0^P$  and  $s_T^P$  denote the initial and terminal shares of scientists allocated to orbit-preserving research.

Table 3 reports the policy instruments and the research allocation.

The orbital-use tax is zero in the benchmark optimal allocation. This does not imply that taxation is irrelevant in general. Rather, it indicates that, for the baseline welfare weights, the planner finds it more efficient to correct the dynamic innovation externality than to tax orbit-intensive activity directly. The implied preserving-research subsidy is instead large. Under the full policy allocation, the average subsidy is 95.26 and the maximum subsidy is 156.61. This reflects the large wedge between the private and social value of orbit-preserving innovation in the early phase of the transition.

Figure 1 reports the policy paths and selected transition variables.

Panel A shows that the full policy allocation immediately redirects scientists toward orbit-preserving research. The preserving-research share rapidly reaches its upper bound and remains there throughout the transition. The delayed-policy case displays the same qualitative adjustment, but only after the initial laissez-faire phase. By contrast, the tax-only and no-directed-innovation benchmarks remain close to laissez-faire because they do not directly alter the direction of research.

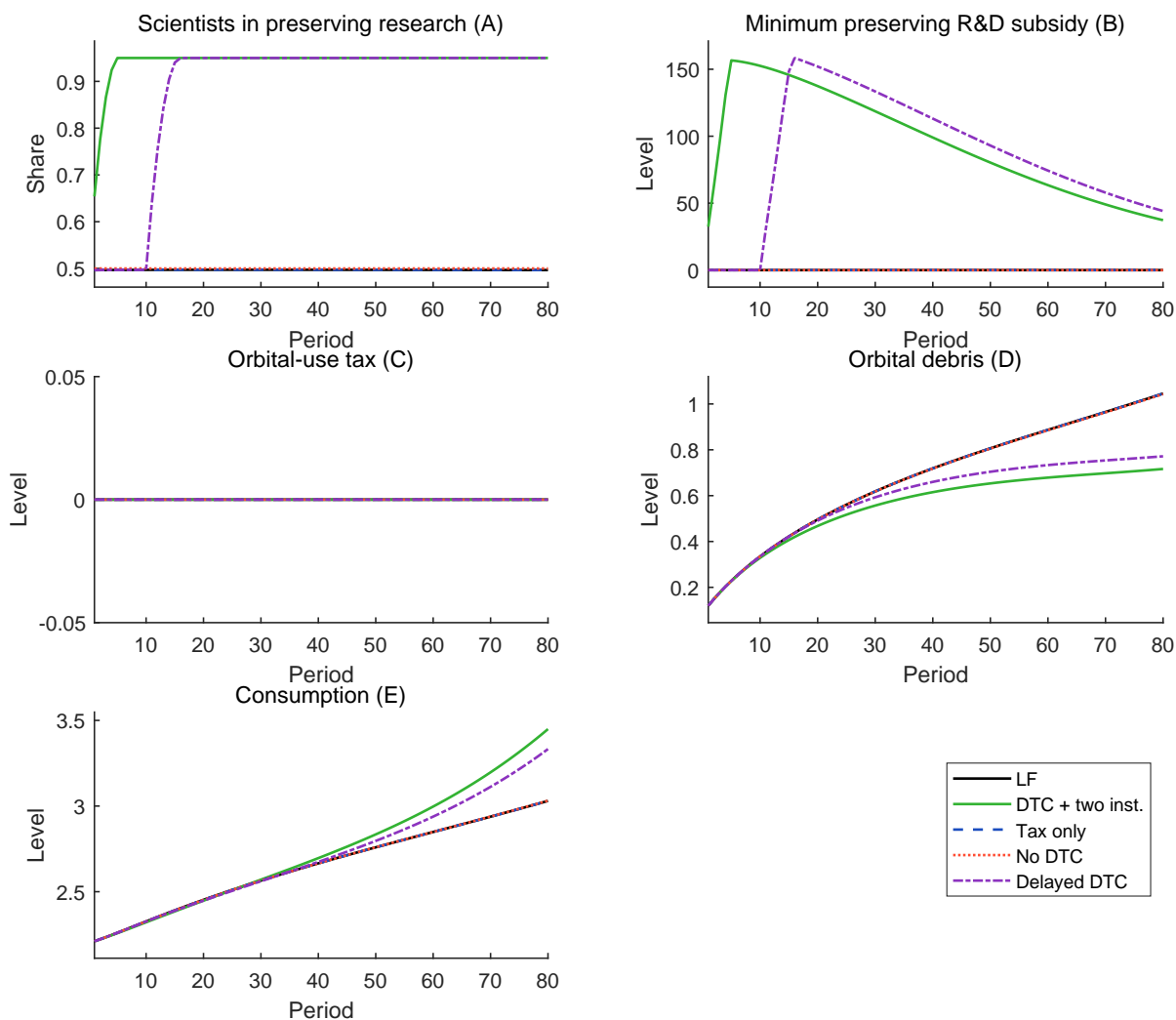
Panel B shows that the implied preserving-research subsidy is high at the beginning of the transition and gradually declines over time. Early in the transition, orbit-preserving technologies are initially less developed and require a large subsidy to attract scientists. As preserving technology accumulates, the subsidy needed to sustain the same research allocation declines.

Panel C confirms that the orbital-use tax is inactive in the benchmark calibration. Panel D shows that laissez-faire, the tax-only benchmark, and the no-directed-innovation benchmark generate almost identical debris paths. The full policy allocation produces a substantially lower debris path, while the delayed-policy case reduces debris only after the initial laissez-faire phase. Panel E shows that the full policy allocation produces a higher consumption path in the medium and long run.

Figure 2 clarifies the mechanism behind these results.

Panel A shows that the full policy allocation generates a strong increase in the preserving-to-intensive technology ratio,  $A_t^P/A_t^I$ . The delayed-policy case eventually follows the same direction, but the technological gap opens later and remains smaller. In contrast, laissez-faire, the tax-only benchmark, and the no-directed-innovation benchmark display almost no change in relative technology.

Panel B shows that the increase in orbit-preserving technology reduces collision probability. This is the central environmental channel of the model. A higher  $A_t^P$  improves the

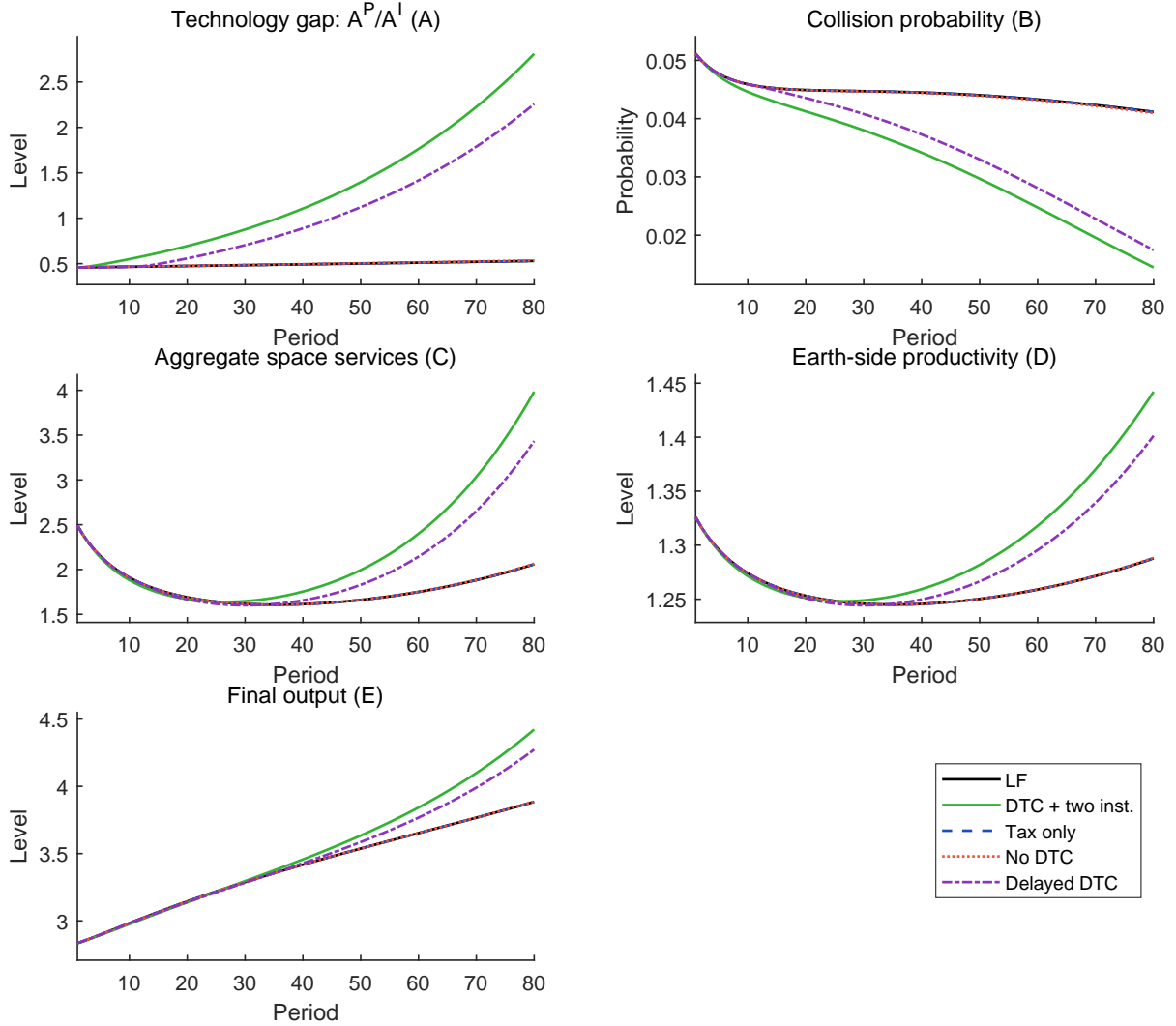


**Figure 1:** Optimal transition and policy paths

*Notes:* The figure reports the transition paths for the main policy variables and selected state variables. The preserving-research subsidy is computed ex post as the minimum subsidy required to decentralize the optimal research allocation.

resilience and safety of the orbital infrastructure, lowering the probability of collisions. Panels C and D show that lower orbital fragility translates into higher aggregate space services and higher Earth-side productivity. Panel E reports final output. The full policy allocation generates the highest output path. The delayed-policy case also improves output relative to laissez-faire, but less than immediate intervention.

Overall, the main results show that the optimal transition operates mainly through the innovation margin. The policy redirects scientists toward orbit-preserving technologies, raises the relative productivity of preserving innovation, lowers collision risk, and sustains the productivity of space services.



**Figure 2:** Directed innovation, orbital risk, and macroeconomic outcomes

*Notes:* The figure reports the main transmission mechanism from research allocation to technology, collision risk, space services, Earth-side productivity, and output.

## 4.2 Economic-Parameter Sensitivity

We next assess the robustness of the mechanism to key economic parameters. We vary the discount factor, the curvature of utility, the elasticity of substitution between orbit-intensive and orbit-preserving services, the capital share, the innovation step size, the relative productivity of preserving research, and the strength of space-enabled productivity spillovers.

Table 4 reports the results.

The full optimal transition delivers positive welfare gains in all cases, while the tax-only benchmark remains inactive. This confirms that, under the benchmark welfare weights, the relevant distortion is primarily dynamic and technological rather than a purely contemporaneous use externality.

The strength of the mechanism depends especially on innovation parameters. When the innovation step size is low, the welfare gain is small and the terminal preserving-to-intensive technology ratio remains close to one. When innovation is faster, the welfare gain rises

**Table 4:** Economic-parameter sensitivity

Sensitivity	Case	Value	$\Delta W^{opt}$	$\bar{q}^R$	$A_T^P/A_T^I$	$D_T$	$Y_T^{opt}$
<i>Discount factor</i>							
	Less patient	0.970	0.195	101.140	2.135	0.710	4.077
	Baseline	0.990	0.760	102.190	2.211	0.701	4.095
	More patient	0.995	1.047	102.250	2.224	0.700	4.098
<i>Intertemporal curvature</i>							
	Low curvature	0.500	1.271	103.060	2.232	0.699	4.100
	Log utility	1.000	0.760	102.190	2.211	0.701	4.095
	High curvature	2.000	0.305	99.758	2.153	0.708	4.081
<i>Elasticity of substitution</i>							
	Low elasticity	1.500	1.507	47.429	2.232	0.694	5.565
	Baseline	3.000	0.760	102.190	2.211	0.701	4.095
	High elasticity	5.000	0.615	118.300	2.206	0.704	3.945
<i>Capital share</i>							
	Low capital share	0.250	0.742	134.130	2.209	0.701	2.928
	Baseline	0.330	0.760	102.190	2.211	0.701	4.095
	High capital share	0.400	0.779	78.223	2.212	0.701	5.802
<i>Innovation step size</i>							
	Low innovation	0.015	0.064	222.990	1.095	0.709	3.627
	Baseline	0.024	0.431	115.560	1.916	0.708	3.987
	High innovation	0.035	1.391	63.162	3.754	0.722	4.777
<i>Relative preserving research productivity</i>							
	Low preserving R&D	0.750	0.087	155.870	1.424	0.714	3.782
	Baseline	1.000	0.760	102.190	2.211	0.701	4.095
	High preserving R&D	1.250	1.658	71.235	3.375	0.698	4.549
<i>Space-enabled productivity spillovers</i>							
	Low spillovers	0.100	0.490	184.520	2.187	0.704	3.450
	Baseline	0.180	0.760	102.190	2.211	0.701	4.095
	High spillovers	0.300	1.089	59.927	2.226	0.699	5.127

Notes:  $\Delta W^{opt}$  denotes the welfare gain of the full optimal transition relative to laissez-faire.  $\bar{q}^R$  is the average implied preserving-research subsidy. The subsidy is not directly chosen by the planner; it is computed ex post as the minimum subsidy required to decentralize the optimal preserving-research path.  $A_T^P/A_T^I$  is the terminal preserving-to-intensive technology ratio.  $D_T$  is terminal orbital debris.  $Y_T^{opt}$  is terminal output under the full optimal transition. The tax-only benchmark is omitted because it delivers zero welfare gains across all economic-parameter sensitivity experiments.

sharply and the economy reaches a much larger preserving-technology advantage. A similar pattern emerges for the relative productivity of preserving research. Higher  $\eta_P$  increases the technology gap, raises output, and reduces the subsidy required to implement the preserving transition.

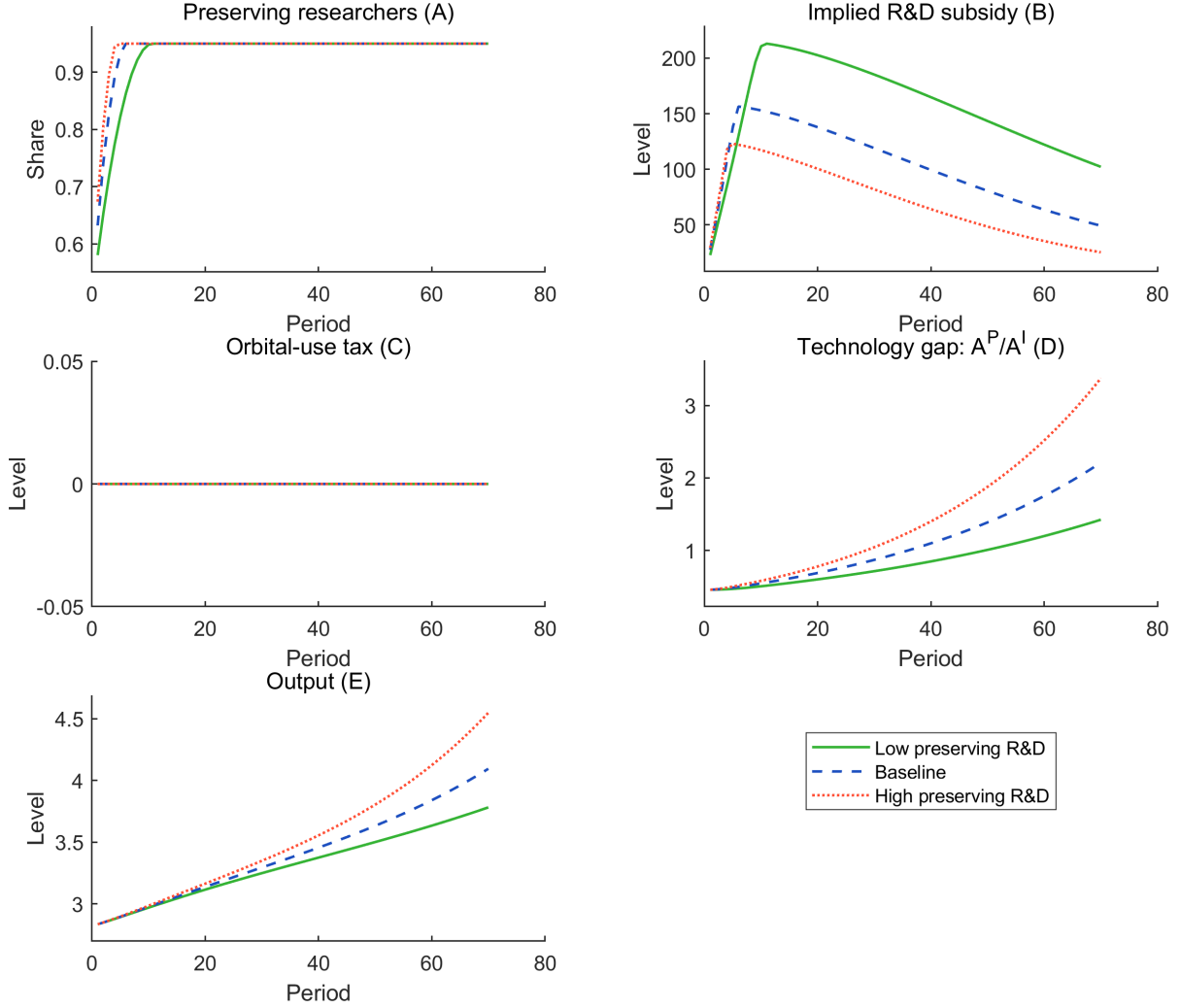
The elasticity of substitution affects mainly the macroeconomic payoff from the transition. When orbit-intensive and orbit-preserving services are more complementary, the output gain is larger and the required subsidy is lower. This suggests that preserving innovation is more valuable when the two types of space services jointly contribute to aggregate space productivity.

Figure 3 reports the sensitivity to the relative productivity of preserving research.

The planner reallocates researchers toward the preserving sector in all cases. However, the consequences of this reallocation differ substantially across calibrations. When preserving research is more productive, the same research allocation generates a larger increase in  $A_t^P/A_t^I$  and a higher output path. The implied subsidy is lower because the policy needs to compensate less for weak preserving-research productivity.

Figure 4 reports the sensitivity to the elasticity of substitution between space technologies.

The output response is sensitive to  $\varepsilon_X$ . In the low-elasticity case, output is higher along



**Figure 3:** Sensitivity to preserving-research productivity

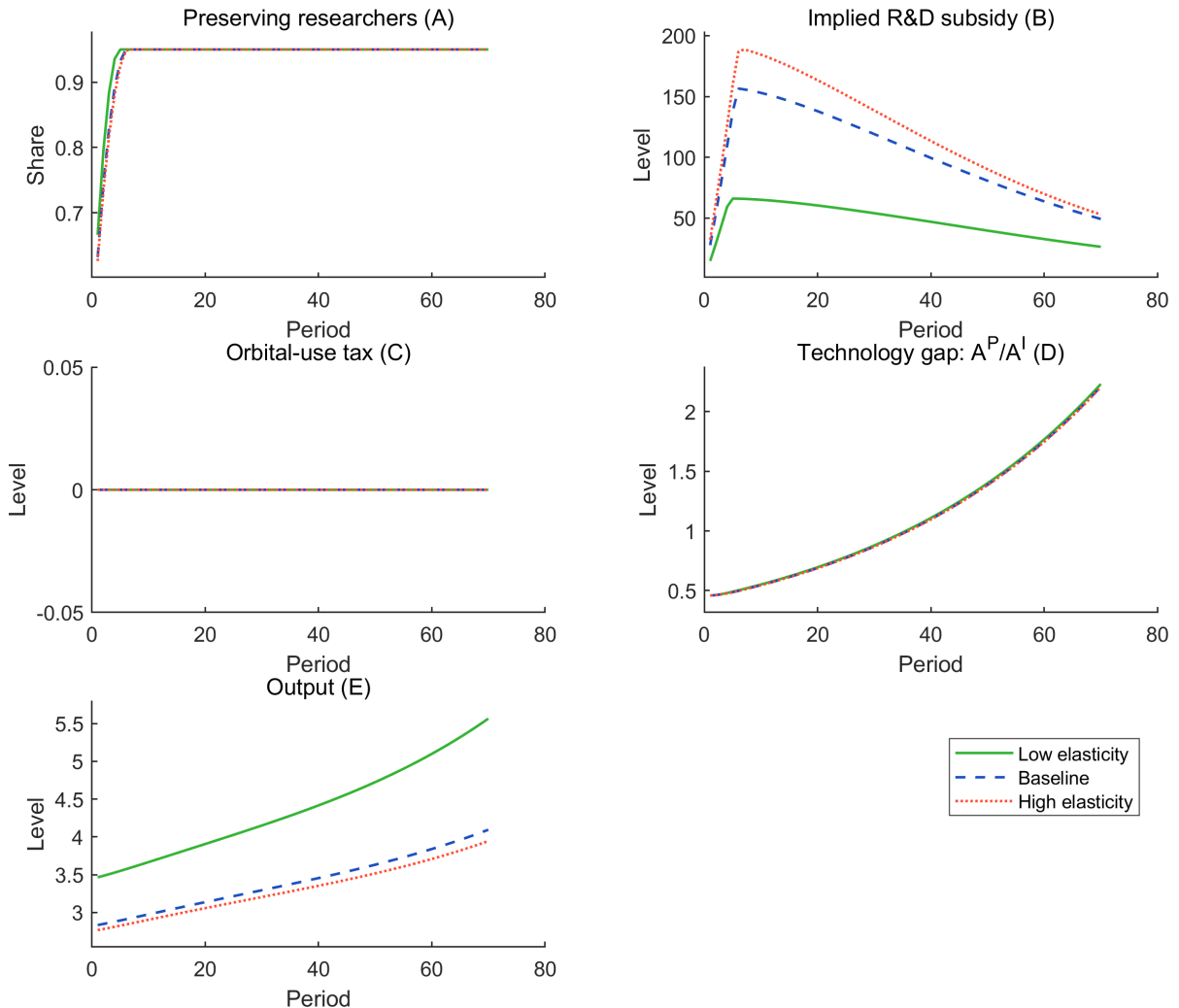
*Notes:* The figure reports the optimal transition for different values of the productivity of orbit-preserving research,  $\eta_P$ . The preserving-research subsidy is computed ex post as the minimum subsidy required to decentralize the optimal path of preserving research.

the transition. This reflects the complementarity between orbit-intensive and orbit-preserving services. When the two inputs are less substitutable, improvements in preserving technology raise the value of the aggregate space-service bundle more strongly. Conversely, when the elasticity is high, the economy can substitute more easily across the two technologies, and the output gain from preserving-technology accumulation is smaller.

### 4.3 Sensitivity to the Welfare Weight of Orbital Debris

The previous results show that, under the benchmark welfare weights, the orbital-use tax is not used. We now vary the welfare weight on orbital debris to study when the tax becomes active. The period utility is

$$U_t = u(C_t) - \varrho_D D_t^2 - \varrho_\pi \pi_t^2 - \frac{\chi_s}{2} (s_t^P - s_{t-1}^P)^2. \quad (33)$$



**Figure 4:** Sensitivity to the elasticity of substitution between space technologies  
*Notes:* The figure reports the optimal transition for different values of the elasticity of substitution between orbit-intensive and orbit-preserving space services,  $\varepsilon_X$ .

The parameter  $\varrho_D$  governs the direct welfare penalty associated with orbital debris.

Table 5 reports the results.

When the welfare cost of debris is low, the optimal transition relies almost entirely on the research-allocation margin. The orbital-use tax remains inactive, and the tax-only benchmark coincides with laissez-faire. As the welfare weight on debris increases, the tax becomes progressively more active. Under the highest debris-cost calibration, the average orbital-use tax rises to 0.08 and terminal debris falls substantially.

The comparison with the tax-only benchmark clarifies the role of the two policy margins. Taxation becomes quantitatively relevant only when debris damages are sufficiently high. However, the full optimal transition dominates the tax-only benchmark in all cases. This indicates that the orbital-use tax corrects the contemporaneous debris externality, while research policy changes the long-run technological composition of the space economy.

Figure 5 shows the transition paths.

The research margin is active across all calibrations. In all cases, the planner rapidly real-

**Table 5:** Sensitivity to the welfare weight of orbital debris

Case	$\varrho_D$	$\Delta W^{opt}$	$\Delta W^{tax}$	$\bar{\tau}$	$\bar{q}^R$	$D_T^{opt}$	$D_T^{tax}$
Zero debris cost	0.000	1.151	0.000	0.000	95.156	0.719	1.054
Baseline	0.020	1.321	0.000	0.000	95.264	0.719	1.054
High debris cost	0.100	2.058	0.119	0.006	93.258	0.689	1.003
Extreme debris cost	0.500	9.396	6.791	0.080	87.163	0.400	0.524

*Notes:*  $\varrho_D$  is the welfare weight on orbital debris.  $\Delta W^{opt}$  is the welfare gain of the full optimal transition relative to laissez-faire.  $\Delta W^{tax}$  is the welfare gain of the tax-only transition relative to laissez-faire.  $\bar{\tau}$  is the average orbital-use tax under the full optimal transition.  $\bar{q}^R$  is the average implied preserving-research subsidy required to decentralize the optimal research allocation.  $D_T^{opt}$  and  $D_T^{tax}$  denote terminal debris under the full optimal transition and tax-only benchmark, respectively.

locates scientists toward orbit-preserving innovation. The orbital-use tax behaves differently. When the welfare cost of debris is zero or close to the baseline value, the tax is inactive. As  $\varrho_D$  increases, the tax becomes active. Under the highest debris-cost calibration, the tax initially reaches its upper bound and is then gradually phased out.

Panel C reports the implied preserving-research subsidy. The subsidy remains large across all calibrations because the planner wants to sustain a high share of scientists in preserving innovation. Its gradual decline over time reflects the accumulation of preserving technology: as  $A_t^P$  rises, a smaller subsidy is required to keep research directed toward the preserving sector.

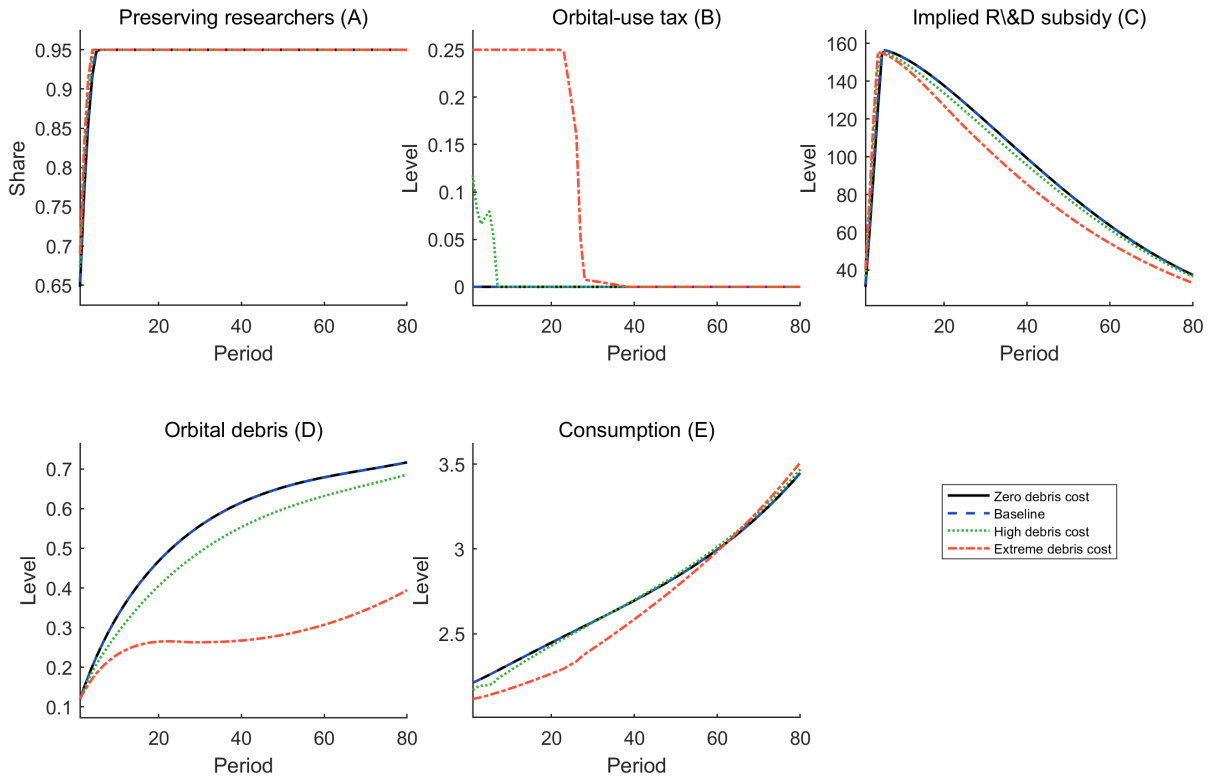
Panels D and E show the trade-off between orbital quality and consumption. A higher debris weight leads to a substantially lower debris path, especially in the high and extreme debris-cost cases. This improvement comes with lower consumption in the early part of the transition because the tax reduces orbit-intensive activity and the economy reallocates resources toward preserving innovation. Over time, however, consumption recovers and eventually exceeds the paths associated with lower debris costs.

Overall, the sensitivity analysis confirms that the two policy margins play distinct roles. The preserving-research subsidy implements the long-run redirection of innovation. The orbital-use tax becomes relevant only when the social cost of orbital debris is sufficiently high. Hence, the optimal policy does not rely on taxation alone. It combines a temporary correction of orbital overuse with a persistent redirection of technological change.

## 5 Conclusion

This paper develops a dynamic model of the space economy in which orbital space is a productive but congestible commons and the direction of innovation is endogenous. The framework combines three elements: space services raise aggregate productivity, orbital debris increases collision risk and weakens the productive value of space infrastructure, and research can be directed either toward orbit-intensive or orbit-preserving technologies. This structure allows us to study whether long-run growth in the space economy can be sustained without degrading the orbital environment on which that growth depends.

The main result is that the optimal transition operates primarily through the innovation margin. Under the benchmark calibration, the planner redirects scientists toward orbit-preserving research. This raises the relative productivity of preserving technologies, lowers collision risk, reduces orbital debris, and supports higher space-enabled productivity. The



**Figure 5:** Sensitivity to the welfare weight of orbital debris

*Notes:* The figure reports the optimal transition for different values of the welfare weight on orbital debris,  $q_D$ . The preserving-research subsidy is computed ex post as the minimum subsidy required to decentralize the optimal path of preserving research.

gains are therefore not driven by a static reduction in current orbital use. They arise from a change in the long-run technological composition of the space economy.

The comparison with restricted-policy benchmarks clarifies this mechanism. The tax-only allocation is essentially identical to laissez-faire in the benchmark calibration. Similarly, the no-directed-innovation benchmark delivers negligible welfare gains. These results show that, when the direct welfare cost of debris is moderate, a contemporaneous orbital-use tax is not sufficient to generate a meaningful transition. What matters is the ability of policy to alter research incentives and redirect technological change toward orbit-preserving innovation.

The delayed-policy experiment highlights the cost of waiting. Delayed intervention improves welfare relative to laissez-faire, but it performs worse than immediate intervention. The reason is dynamic. During the initial laissez-faire phase, the economy accumulates debris and remains on a less favorable technological path. Once policy is introduced, it can still redirect innovation, but it starts from a more degraded orbital environment and a weaker preserving-technology base. This suggests that policy timing is central in environments characterized by technological path dependence and stock externalities.

The sensitivity analysis reinforces the interpretation of the main results. Across a broad range of economic parameters, the full optimal transition delivers positive welfare gains, while the tax-only benchmark remains largely inactive. The strength of the gains depends especially on innovation parameters. When preserving research is more productive, or when innovation proceeds more rapidly, the preserving-technology advantage becomes larger and output

increases more strongly. The elasticity of substitution between orbit-intensive and orbit-preserving services also matters, because it determines how valuable preserving technologies are within the aggregate space-service bundle.

A separate sensitivity exercise varies the welfare weight assigned to orbital debris. This exercise shows when the orbital-use tax becomes quantitatively important. When the welfare cost of debris is low or close to the benchmark value, the tax remains inactive and the transition is driven almost entirely by research redirection. When the welfare cost of debris is high, the tax becomes active and reduces the debris path substantially. Even in that case, however, the full policy allocation dominates the tax-only benchmark. Hence, taxation and research policy operate on different margins: the tax corrects the contemporaneous overuse of the orbital commons, while research policy changes the future technological trajectory.

The paper therefore suggests that orbital sustainability is not only a problem of debris mitigation or launch regulation. It is also a problem of directed innovation. Policies aimed at preserving the orbital environment should not focus exclusively on current use. They should also affect the incentives that determine whether future technologies become more orbit-intensive or more orbit-preserving. In this sense, preserving-research subsidies, support for collision-avoidance technologies, de-orbiting capabilities, tracking systems, shielding, and debris-reduction technologies are central components of a long-run policy architecture for the space economy.

The analysis has some limitations. The model is deliberately stylized and focuses on the interaction between directed innovation, orbital debris, and aggregate productivity. The calibration is normalized and should be interpreted as a disciplined quantitative exercise rather than as a full structural estimation. Moreover, the preserving-research subsidy is computed as an implementation instrument rather than optimized directly as an independent policy control. Future work could extend the framework by introducing heterogeneous space operators, strategic international interactions, endogenous physical mitigation choices with explicit costs, and a richer physical description of orbital shells and altitude-specific debris dynamics.

Despite these limitations, the results point to a clear policy lesson. The long-run value of the space economy depends on preserving the orbital infrastructure that makes space services productive. If private innovation incentives favor orbit-intensive technologies, laissez-faire may generate a path in which current space activity expands at the expense of future orbital quality. A policy architecture that combines research incentives with instruments correcting orbital overuse can redirect the economy toward a more sustainable technological trajectory. Sustainable growth in the space economy requires not only using space more efficiently today, but also innovating in ways that preserve its productive value for the future.

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