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# The long-run economics of sustainable orbit use

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## Abstract

La croissance de l'économie spatiale se base sur l'exploitation l'orbite terrestre. Mais à mesure que les améliorations technologiques réduisent les coûts des fusées et des satellites, l'encombrement et la pollution de l'environnement orbital menacent de compromettre l'accès à des services tels que le GPS et la télédétection, limitant d'autant le potentiel de croissance du secteur. Nous proposons un cadre d'analyse graphique représentant la taille et la valeur économique d'une flotte de satellites durable à long terme, en fonction du rythme de lancement des satellites, tenant compte des effets sur l'environnement orbital. Nous montrons comment ce cadre d'analyse permet de décrire les conséquences à long terme de différents modes de gestion et de déterminer des instruments politiques poussant le secteur à maximiser la valeur économique de l'utilisation de l'orbite, ainsi que d'envisager les effets de certaines innovations technologiques une fois prise en compte les adaptations comportementales des agents économiques que celles-ci entraîneront. Nous concluons en abordant diverses questions ouvertes, que nous croyons à la fois pertinentes pour les décideurs politique.

All space-based economic growth requires use of Earth's orbital space. But as rocket and satellite technologies become cheaper, congestion and pollution threaten to reduce terrestrial access to space-based services like GPS and remote sensing and severely limit the potential for space-based growth. We propose a unifying model and a graphical framework to represent the long-term sustainable size of the satellite fleet and its economic value as a function of the launch rate, as well as its effects on the orbital environment. We show how the framework can be used to consider long-term orbital outcomes emerging under different management institutions, derive policy instruments which maximize the economic value of orbit use, and consider the effects of different technological innovations accounting for behavioral responses to the innovations. We conclude with a discussion of open questions in orbit-use management which are both relevant to policymakers around the world and likely to generate insights into environmental management and sustainable growth.



**Keywords:** Space economics, Orbital debris, Sustainability.

**JEL:** L1, L9, Q2.

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# The long-run economics of sustainable orbit use

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# 1 Introduction

Humanity's use of Earth's sphere of influence has created a novel environmental problem: space debris. Human-generated space debris encompasses a wide range of objects, from nuts and bolts to spent rocket stages, all of which increase the risk of collisions in orbit. These collisions, in turn, threaten to reduce the value produced by the growing space sector. The Satellite Industry Association recently estimated the value of the global "space economy"—i.e. the value generated from objects in space and the process of putting them there—to be roughly $371 billion, of which roughly a third is generated by satellite services SIA (2020). How can space debris, particularly in low-Earth orbit (LEO), be managed to support the space sector at the lowest possible cost to society? How should policymakers think about different policy options in relation to each other given likely behavioral responses from orbit users?

In this paper we answer these questions in two ways. First, we survey the existing economic literature on space debris and orbital-use management. We synthesize findings across the literature to determine key issues in and emerging approaches to space debris management. Second, we present a graphical framework which integrates physical and economic models of orbit use and can shed light on the physico-economic mechanisms through which different policy approaches may succeed or fail to achieve their goals. Our framework enables clear comparisons of the effects of different policies and technological innovations and their benefits and costs to society at large.

The essence of the space debris problem is simple: orbiting objects can collide with each other, generating numerous high-velocity debris fragments. These fragments can then collide with other objects, begetting further fragments. A substantial literature has developed in aerospace engineering and related fields to explore the causes and consequences of space debris accumulation. This literature has developed physics-based models to predict the evolution of the debris stock in the coming decades and centuries, e.g. Cordelli et al. (1993); Liou et al. (2004); Drmola and Hubik (2018); Le May, Gehly, and Carter (2018); Somma, Lewis, and Colombo (2019); Lucken and Giolito (2019) and Diserens, Lewis, and Fliege (2020). These debris environment models involve numerically solving a system of differential equations, with higher-fidelity models (e.g. those capable of object-level predictions) being more computationally expensive. They are useful in predicting debris evolution at high spatio-temporal resolutions and in explaining the physical mechanisms driving debris accumulation and collision risk. Achieving these goals has required treating satellite launch and design patterns as exogenous parameters to be estimated from historical data or provided by the user as inputs.

A recent literature in economics has begun to explore the choices driving satellite launch and design patterns and their effects on debris accumulation and collision risk. These studies have combined physical models of satellite lifecycles and debris accumulation with economic models of objective-driven orbit use. Some have been primarily analytical and established general results about long-run orbital use patterns and management policies (Adilov, Alexander, and Cunningham, 2015, 2018; Grzelka and Wagner, 2019; Rouillon, 2020; Béal, Deschamps, and Moulin, 2020; Bongers and Torres, 2021; Guyot and Rouillon, 2021; Bernhard, Deschamps, and Zaccour, 2022; Rao and Rondina, 2022), while others have used empirical and computational models of orbital-use patterns over the coming decades to study specific policy approaches and technology issues (Macauley, 2015; Klima et al., 2018; Rao, Burgess, and Kaffine, 2020; Adilov, Alexander, and Cunningham, 2020; Rao and Letizia, 2021). One common theme is that status quo orbital-use management ("open access") will be insufficient to avoid excessively costly levels of debris accumulation—both directly through collision-related costs and indirectly through the costs of debris mitigation and remediation measures required to maintain satellite operations. Where they study sustainability policies, the studies tend to focus on incentive-based policies (e.g. taxes, tradable permits, deposit-refund schemes) rather than command-and-control policies (e.g. manufacturing and operating norms, launch or orbital-use limits, deorbit requirements). In general they tend to find that incentive-based policies are superior to command-and-control policies or technology deployment alone (Rouillon, 2020; Rao, Burgess, and Kaffine, 2020) or identify potential unintended consequences of command-and-control policies and technology deployment (Rao and Letizia, 2021), though some find cases where command-and-control policies can be superior as well (Adilov, Alexander, and Cunningham, 2020).

This paper distills the key features of orbital-use models from aerospace engineering and economics into a simple analytical framework—a diagram and a few equations—which can be used to assess and predict the long-run effects of management policies and technological innovations. Applying the framework requires only simple algebra and geometry. We demonstrate its utility by applying the framework to study a few representative policies and technological innovations.

In section 2, we present a simple equation predicting the long-run satellite stock resulting from a given constant launch rate and combination of physical and engineering parameters. This equation emerges from a wide class of underlying debris accumulation models. In section 3, we discuss the open access physico-economic equilibrium and the socially-optimal allocation. These concepts provide the foundation for our assessments of policy instruments and technological changes. Integrating the physical equation from Section 2 with the concepts from Section 3 yields the graphical framework described above. In section 4, we explain the effects of incentive-based and command-and-control policies as orbital management tools through our graphical framework. In section 5 we focus on technological innovations and their effects on long-run orbital-use patterns. In section 6 we illustrate several of these concepts with a numerical example calibrated to LEO in recent years. We conclude in section 7 with a discussion of additional theoretical and practical issues in sustainable orbital-use management. Mathematical details on deriving and calibrating the framework are relegated to the Appendix.

## 2 The physics of orbit use

New satellite launches are a primary driver of orbital population growth. Rockets carry satellite payloads into orbit, increasing the stock of operational satellites.[1] The upper stage of the rocket inserts the satellite into orbit and is left in orbit, increasing the stock of inactive objects. At the end of its active lifetime, a satellite which is not deorbited becomes an inactive object.

Objects in orbit can collide, resulting in fragmentation. Collisions between debris and satellites are the main source of new fragments in the long run. The process of separating the rocket from the satellite during orbital insertion also produces some small fragments, e.g. bolts, paint flakes. We ignore collisions between operational satellites and other large objects, by assuming that all operational satellites can perform maneuvers to avoid collisions with other large objects—operational satellites and inactive objects—and are successful in doing so.[2]

While operational satellites expend fuel to maintain their orbits and counter atmospheric drag and Earth's gravitational pull, inactive objects and fragments do not. Consequently, inactive objects and fragments naturally "decay" from orbit as drag and gravity pull them back to Earth. The time it takes inactive objects and fragments to naturally decay is a function of both their cross-sectional area and their orbital altitude. End-of-life deorbit maneuvers and active debris removal can also remove inactive objects from orbit.

Our focus is on long-run sustainable orbit-use management, which we characterize as a "steady state". The steady state describes a situation where space activity-related economic choices (launches, debris removal, and satellite characteristics) and orbital populations (operational satellites, inactive objects, and fragments) are constant over time. The long-run satellite population ($S$) can then be expressed as a function of the long-run constant launch rate ($Q$) and a handful of technical and physical parameters. This "long-run satellite production function", shown in equation 1, is the key physical equation of our

[1] We use the term "orbit" as a synonym for LEO here, recognizing that there are many regions of particular interest within LEO. All of the logic we describe follows when considering smaller regions within LEO.

[2] Recent estimates suggest that fewer than 1500 of 2000 active satellites are maneuverable, and that 86% of collisions occur between uncontrollable objects (Bonnal et al., 2020). We assume that in the long run, technological progress enables very low-cost object detection and avoidance to the point where collisions between active satellites and large uncontrollable objects are negligible.

framework:

$$S = \frac{Q}{A + BQ}, \tag{1}$$

where $A$ reflects the lifetime of a satellite and $B$ reflects the capacity of the orbital region to hold satellites (described in more detail below). Both are positive. Conversely, the "long-run launch requirement" $Q = AS/(1-BS)$ describes the launch rate required to sustain a long-run active satellite fleet of size $S$. We use a simplified physical model of LEO based on Rouillon (2020) (see Appendix 8.1) to obtain equation 1 and derive the forms of parameters $A$ and $B$. That model describes the evolution of the populations of debris fragments, inactive objects (e.g. rocket upper stages, non-operational satellites), and operational satellites using a system of ordinary differential equations. Similar approaches are widely used in the debris modeling literature, e.g. Farinella and Cordelli (1991); Somma, Lewis, and Colombo (2019).

We show the long-run size of the active satellite fleet as a function of the long-run launch rate in Figure 1. The fleet size grows as more satellites are launched annually, but collisions reduce the number of satellites which survive. As a result, the fleet size grows at a decreasing rate as the launch rate increases, approaching a maximum size of $1/B$ as the launch rate goes to infinity. The angle formed by the origin and a line segment to a point on the curve measures the long-run expected operational life of a satellite. It varies between $1/A$ when no satellites are launched to 0 as the launch rate goes to infinity. Intuitively, higher launch rates imply larger fleet sizes. Larger fleets in turn imply more collisions and shorter expected lifetimes.

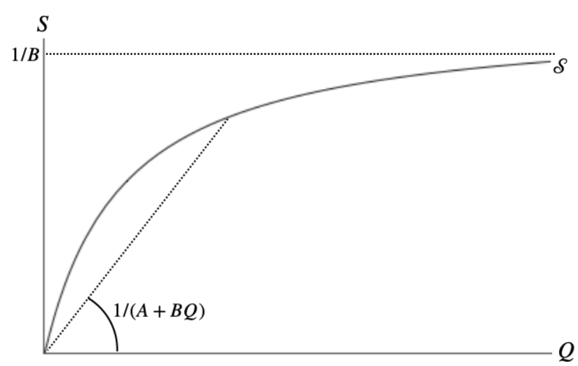


Figure 1: Long-run active satellite stock $S$ as a function of the launch rate $Q$ (i.e. $S = Q/(A + BQ)$. The angle formed by the origin and the line segment joining a point on the curve $S$ measures the expected life of a satellite (i.e. $1/(A + BQ)$).

Using equation 1 we define two physico-economic sustainability indicators: the intrinsic lifetime of a satellite and the carrying capacity of the orbit. The intrinsic lifetime, given by $1/A$, is its operational lifetime in a clean environment with no collisions. The carrying capacity of the orbit, given by $1/B$, is the largest active satellite fleet that can be sustained in the long run given the risk of collisions.[3]

# 3 The economics of orbit use

A key tool in our analysis of sustainable long-run orbit use is the diagram shown in Figure 2. We refer to this as the "long-run orbit-use" diagram. We first describe how to construct it from the long-run satellite production function and estimates of the costs and revenues of orbit use, and then use it to analyze long-run orbit-use patterns under different management institutions.

It is helpful to first define two concepts: "social surplus" and "economic efficiency". "Social surplus" measures the net benefit accruing to society from use of a resource, e.g. orbital space. When the price of a unit of service reflects the benefit to society provided by resource use, and the cost of using the resource reflects the opportunity cost of diverting the necessary inputs from their next-best uses, the social surplus of resource use is the difference between the total revenue generated by resource use and the total cost incurred.[4] Social surplus is also referred to as the "rent" generated by the resource, particularly when discussing cases where a specific entity is able to capture that value (e.g. when a regulator levies a tax which increases social surplus).

"Economic efficiency" refers to the size of the social surplus relative to its maximum possible size. An outcome which brings social surplus closer to its maximum level is said to "increase economic efficiency".[5] More generally, when comparing two outcomes the one with the greater social surplus is said to be "more economically efficient" (or simply "more efficient"). The goal of economic policy analysis is often to identify economically efficient policies, i.e. those which maximize social surplus.

[3]Estimating these parameters for specific orbital regions is a challenging exercise. Part of the challenge is due to uncertainty over the parameter values used for the underlying physical model, which in turn is partly due to the large degrees of freedom satellite operators have in choosing satellite design and operating characteristics. Limited data regarding lethal non-trackable debris (i.e. fragments large enough to damage satellites but too small to be tracked by current systems) poses another challenge. Our framework facilitates developing intuitions about how changes in $A$ and $B$ will affect long-term satellite fleet sizes after accounting for behavioral responses. Given a physical model of orbit use the definition of $B$ (shown in Appendix 8.1 for a particular physical model) also provides a list of parameters which must be estimated, and a recipe for combining them, to obtain an estimate of carrying capacity. A full exploration of the practical challenges in estimating $A$ and $B$ is beyond our scope here.

[4]We discuss these assumptions further in Section 3.4 below.

[5]This comparison involves holding the technologies used and preferences for goods and services constant, e.g. comparing two different launch rates assuming otherwise-identical technologies and uses for satellite services. We discuss how to account for changing technologies in economic efficiency analysis in Section 5.4.

Finally, while our focus is primarily on commercial operators, our use of terms such as “revenue” should not be misconstrued to imply that our model only applies to such operators. The word “revenues” could be replaced, *mutatis mutandis*, with a more general term such as “benefits” to reflect the case of a civil government or military satellite operator. One would then interpret the numerical value of “revenues” (“benefits”) as representing the equivalent flow of funds into the operator’s coffers required to make the operator indifferent between having their satellite in orbit (ignoring launch costs) or not.[6]

## 3.1 Constructing the long-run orbit-use diagram

We begin with the solid curves in quadrants (i), (ii) and (iii). In quadrant (i), curve $\mathcal{S}$ represents the long-run size of the satellite fleet $S$ as a function of the per-period rate of satellite launches $Q$—i.e. the long-run satellite production function shown in equation 1. In quadrant (ii), curve $\mathcal{R}$ represents the total per-period economic revenue from maintaining $S$ active satellites in the long run (i.e. $R = pS$ with $p$ the rental price for satellite services). In quadrant (iii), curve $\mathcal{C}$ represents the total cost of launching $Q$ satellites per period (i.e. $C = cQ$ with $c$ the unit cost of a satellite).[7]

Quadrant (iv) contains a bisector which is used to project points along the production function in quadrant (i), which represents long-run technical and environmental constraints, into the dashed curves in quadrants (ii) and (iii). For example, point $P_{\mathcal{R}}$ in quadrant (ii) is projected into quadrant (iii) as the point $P_{\overline{\mathcal{R}}}$. Projecting curve $\mathcal{R}$ in this way produces curve $\overline{\mathcal{R}}$ in quadrant (iii), which expresses the total per-period revenue from launching $Q$ satellites each period given their effects on the size of the satellite fleet in the long run. Similarly, projecting curve $\mathcal{C}$ produces curve $\overline{\mathcal{C}}$ in quadrant (ii), expressing the total per-period cost of maintaining a satellite fleet of size $S$.

[6]While a civil government or military entity may not have a direct desire for money, those funds can be used to pursue the same objective in different ways—e.g. procuring the same service through a commercial operator—or to achieve a different objective the entity values at that amount. As in economics more broadly, money is used here as a convenient metric to harmonize units and not as a statement of which types of entities are being considered.

[7]The total cost in curve $\mathcal{C}$ includes all costs of launching satellites, e.g. construction and launch costs, non-recurring engineering and design costs.

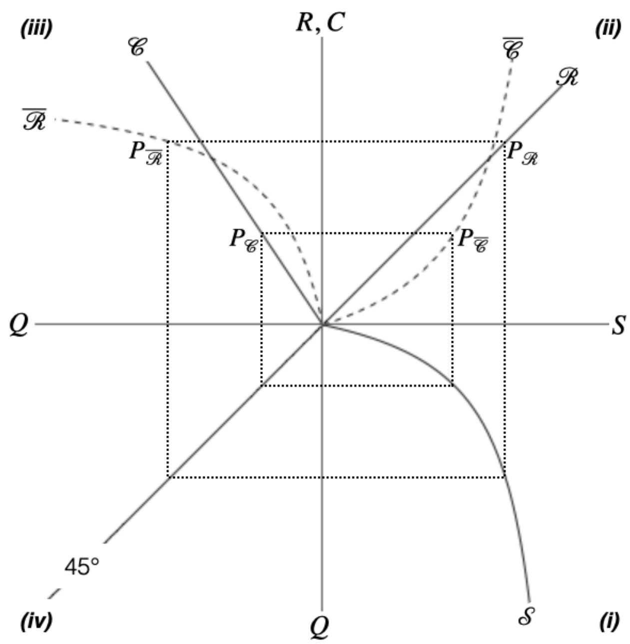


Figure 2: Long-run orbit-use diagram. Quadrant (ii) shows key details in terms of satellite stocks ($S$), while quadrant (iii) shows the same details in terms of launch rates ($Q$).

The economic value of satellites in orbit (i.e. the social surplus) is the distance between the revenue and cost curves within a given quadrant, e.g. between $\mathcal{R}$ and $\overline{\mathcal{C}}$ in quadrant (ii) or between $\overline{\mathcal{R}}$ and $\mathcal{C}$ in quadrant (iii). As shown in Figure 2, launching more satellites produces a larger fleet while also inducing more collisions and requiring more replacements. This is the key long-run trade-off in orbit use. The challenge of sustainable long-run orbit-use management is therefore to find a launch rate which balances the benefits of larger fleets against the costs of maintaining larger fleets.[8]

## 3.2 Long-run orbit use patterns

We use Figure 2 to study two orbital-use management regimes: the "physico-economic equilibrium" and the "social optimum". These regimes are a central focus in the growing economics literature on orbit use, e.g. Adilov, Alexander, and Cunningham (2015); Rao, Burgess, and Kaffine (2020); Rouillon (2020). The physico-economic equilibrium represents orbit-use patterns under existing institutions. The social optimum describes orbit-use patterns coordinated by

[8]Note that the environmental dimension of "sustainability" is embedded in this diagram through the long-run satellite production function (i.e. through the cost function in quadrant (ii) or the revenue function in quadrant (iii)).

institutions which maximize the social surplus from active satellites in orbit.

The physico-economic equilibrium results from the private interests of satellite operators under "open access" to orbit.[9]. Under open access, satellite owners/operators are unable to secure exclusive property rights to orbital paths or recover collision-related costs imposed by others. This leads operators to neglect the "external" costs they impose on other orbit users when designing and launching satellites. As a result, operators will launch satellites until the social surplus from orbit use is dissipated. Points labeled $P^*$ in Figure 3 show the physico-economic equilibrium. The equilibrium lies at the intersection between the total revenue and total cost curves—$\mathcal{R}$ and $\overline{\mathcal{C}}$ in quadrant (ii) or $\overline{\mathcal{R}}$ and $\mathcal{C}$ in quadrant (iii).

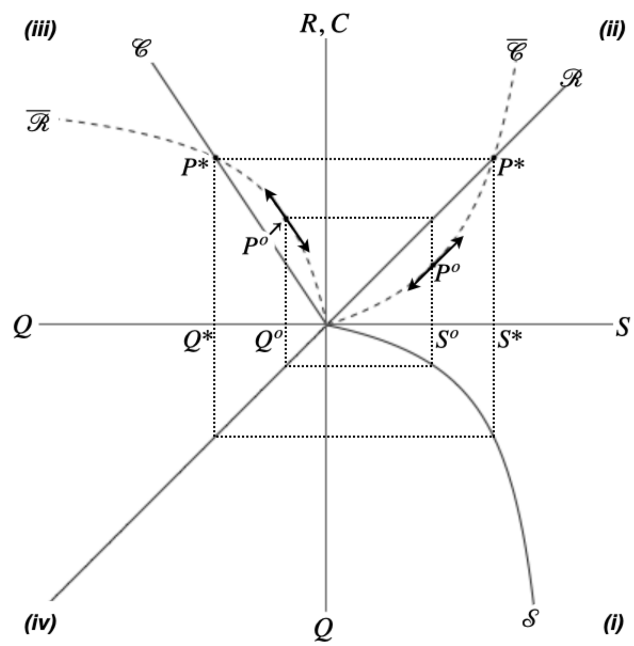


Figure 3: Long-run orbit-use economics diagram. Points labeled $P^*$ mark the physico-economic equilibrium and points labeled $P^o$ mark the social optimum.

At the social optimum, satellite operators coordinate the fleet size to maximize social surplus, i.e. the difference between the total revenue and the total cost curves (either $\mathcal{R}$ and $\overline{\mathcal{C}}$ in quadrant (ii) or $\overline{\mathcal{R}}$ and $\mathcal{C}$ in quadrant (iii)). Points

[9]Open access is a particular institution for managing a "common-pool resource"—a resource where one user's use detracts from another's use, and where one user cannot exclude another. Open access to a common-pool resource is associated with the "tragedy of the commons", though it is worth noting that the "tragedy" arises specifically due to open access as a management institution (Hardin, 1968; Ostrom, 1990).

| | Equilibrium | Optimum | Which is bigger? |
|---|---|---|---|
| **Launch rate** | $\frac{\sigma - A}{B}$ | $\frac{\sqrt{\sigma A} - A}{B}$ | Equilibrium |
| **Fleet size** | $\frac{1}{\sigma}\frac{\sigma - A}{B}$ | $\frac{1}{\sqrt{\sigma A}}\frac{\sqrt{\sigma A} - A}{B}$ | Equilibrium |
| **Expected lifetime** | $\frac{1}{\sigma}$ | $\frac{1}{\sqrt{\sigma A}}$ | Optimum |

Table 1: Formulae for physico-economic equilibrium and social optimum.

labeled $P^o$ in Figure 3 show the social optimum. The social optimum can be found in quadrant (ii) by translating the total revenue curve $\mathcal{R}$ downwards and finding its tangency point with the total cost curve $\overline{\mathcal{C}}$. In quadrant (iii), it can be found by translating the total cost curve $\mathcal{C}$ upwards until it is tangent with the total revenue curve $\overline{\mathcal{R}}$. Indeed, both constructions highlight the points where the distance between the total revenue and the total cost curves is maximum.

The fleet size, launch rate, and satellite lifetime are derived in Appendix 8.2 for both the physico-economic equilibrium and social optimum. We express them in terms of the benefit-cost ratio of a satellite,

$$\sigma = \frac{p}{c}. \tag{2}$$

in Table 1.

Figure 3 reveals several features of these two orbit-use regimes. By definition, the physico-economic equilibrium drives the rents from orbit use to zero while the social optimum maximizes it. Comparing $P^*$ and $P^o$ in quadrant (ii) shows that the physico-economic equilibrium produces a suboptimally-large satellite fleet. Comparing $P^*$ and $P^o$ in quadrant (iii) shows that the physico-economic equilibrium induces suboptimally-high launch rates. Finally, comparing the angle between the origin and $P^*$ with the angle between the origin and $P^o$ in quadrant (i) shows that the physico-economic equilibrium produces suboptimally-low long-run expected satellite lifetimes.[10]

## 3.3 Market competition

Our analysis so far (e.g. Figures 2 and 3) has held the per-period revenue per satellite constant. This simplifying assumption is widely used in theoretical economic models of natural resource use, e.g. Costello, Quérou, and Tomini (2015); Rouillon (2020). The assumption is particularly well-suited to settings where individual operators are "small" relative to the market or where consumers can buy a substitute good whose price constrains the price of the resource-intense good. The constant-price assumption is therefore likely a good representation of satellite telecommunications products (e.g. TV), and perhaps a less-good

[10] This is distinct from the satellite design lifetime, which we hold constant between the two scenarios. The long-run expected lifetime also includes the collision rate.

representation of satellite imaging products (e.g. high-revisit remote sensing).

Relaxing this assumption will make the per-period revenue per satellite a decreasing function of the number of satellites in orbit.[11] In the long run, this will make the total revenue curve a concave function of the per-period launch rate, i.e. increasing at a decreasing (rather than constant) rate. This will make both the equilibrium and socially-optimal satellite fleets smaller. If the curvature is high enough, the equilibrium satellite fleet will be reduced by a greater amount than the socially-optimal satellite fleet. However, the general conclusion from earlier will not be changed by any degree of market competition: the social optimum will feature a smaller and longer-lived satellite fleet than the physico-economic equilibrium.

## 3.4 Public goods

Our analysis so far assumes that the benefits to society from operating a satellite are equal to the revenues received from selling satellite services. In other words, we assume the benefits from satellites are all “private” benefits which can be captured by satellite-operating firms through market prices.[12] While this may be true for some satellite services like satellite TV or commercially-available remote sensing, it is less likely to hold for services like position, navigation, and timing (e.g. GPS, GLONASS) or climate-and weather-related earth observation services (Yang, Gong, and Fu, 2013; Adilov, Alexander, and Cunningham, 2022). These services are either offered for free or provide benefits which are not fully captured by market prices.

Goods and services with such unpriced benefits—what economists call “external benefits”—are often referred to as “public goods”.[13] Just as external costs imply overproduction of a negative externality, external benefits imply underproduction of a positive externality. This situation can be represented in the long-run through a “social benefit” curve which sits above the total revenue curve $\mathcal{R}$. The social benefit curve shows the sum of private and external benefits. Since the external benefits are not captured by satellite operators, the social benefits curve is only relevant in finding the social optimum. The social optimum becomes the point where the difference between the social benefits and total cost curve are maximized, which will generally involve a larger satel-

[11] “Revenue is a decreasing function of satellites” is one way to express the Law of Demand: as prices decrease the quantity demanded increases. While there are cases where quantity demanded may not decrease as the price increases (e.g. Veblen goods), they are unlikely to be relevant to the space sector.

[12] Further, we assume that markets are “competitive”, such that prices reflect the marginal benefit of the good being sold. Like the constant-price assumption, this assumption is standard in theoretical economic models and greatly simplifies the mathematical analysis.

[13] More precisely, a “public good” is one whose consumption is both non-excludable (as in a common-pool resource) and non-rival (i.e. one person’s consumption does not reduce another’s consumption). Non-excludability often makes it challenging to capture the full benefits a good provides through market prices.

lite fleet than in the absence of such benefits. Depending on the magnitude and shape of the external benefits, it is possible for the optimal satellite fleet to be larger and shorter-lived than the equilibrium satellite fleet. Practically, given an estimate of the external benefits per unit of satellite service delivered (call it $eb$), one could adjust the formulae presented in Table 1 by adding this value to the price, i.e. by constructing $\sigma_e = (p + eb)/c$ and using $\sigma_e$ in the formulae for the social optimum. There is as yet no consensus on the magnitude of external benefits produced by satellites, making this an important area for future research.

### 3.5 Constellations

No modern discussion of orbital-use economics would be complete without discussing satellite constellations—coordinated groups of satellites, typically owned by a single entity, used to deliver services like high-revisit rate imaging or global broadband internet access. Telecommunications constellations in particular are growing to such large sizes (e.g. tens of thousands of satellites planned) that they are often referred to as "mega-constellations". While new to orbit use, single entities owning and coordinating multiple units of resource-using capital equipment is not unique to the space industry. Fisheries have long hosted boats belonging to common fleets; in oil and gas extraction it is not uncommon for a single entity to own multiple wells on common or nearby reservoirs (Levhari and Mirman, 1980; Davis and Sims, 2019). The resulting biophysical and market dynamics can be considerably richer than those in models where each entity holds a single unit of capital.

Explicitly modeling the economics of constellations is a challenging exercise. In addition to issues posed by the dynamics of building up the constellation—perhaps avoidable if one is focused on long-run outcomes—there are difficult strategic issues involved in analyzing multiple constellations operating in nearby orbital regions. For example, when will one constellation owner choose to maintain additional satellites in a region to prevent a rival from doing so? Bernhard, Deschamps, and Zaccour (2022) is currently the only extant economic analysis which addresses this issue directly. Using differential game theory, they study a setting where two mega-constellation operators seek to manage their satellites in a common orbital volume and where a tax may be levied to finance active debris removal (ADR) efforts. They find that competition for orbital volume between mega-constellation operators leads to greater collision risk than if the firms coordinated, and that tax policies can effectively finance ADR efforts. These conclusions, particularly the first regarding competition for orbital volume, parallel those from rest of the economic literature on orbit use—competition for orbital volume is generally found to be less environmentally sustainable than coordination.

Research in other settings indicates that coordination between natural resource users can be environmentally beneficial (Adler, 2004). The social optimum is often referred to as the "sole owner" benchmark for this reason, as it reflects the allocation achieved by a coordinated group of users who act as though they are a single user (Gordon, 1954). To retain analytical tractability, the framework presented here does not explicitly address the issue of constellations or mega-constellations.[14] Still, we can draw some insights from the broader literature on coordinated units of natural-resource-using capital in other settings.

First, as constellations grow smaller and more numerous, they approach the case described in this framework. Indeed, this framework can be reinterpreted in terms of identical constellations of satellites—changing the units of $S$ and $Q$ from individual satellites into "standard" constellations. While this may require a different parameter calibration than the interpretation where $S$ and $Q$ are individual satellites, the mechanics of the long-run orbit-use diagram are unchanged.

Second, ownership of multiple satellites is only likely to alter the physico-economic equilibrium if operators internalize the external costs their satellites impose on each other and are able to use their satellite deployment patterns to limit others' access to the region they are using. Intuitively, the ability to deter others from using a particular orbital volume is economically akin to property rights over that region—recall that the key economic feature of property rights is the ability to exclude others from accessing the resource (whether one is currently using it or not). If constellation operators are able to deter smaller operators from using a particular region, they have effectively resolved the open access problem in that region.[15] If the constellation operators also account for the negative externalities their own satellites impose on each other in designing their constellation and choosing their launch rate, they will be able to implement something closer to the social optimum—but only within the region where they are able to deter entrants. "How close" to the social optimum they get, and under precisely what conditions, is an open question for future research. If, however, constellation operators are unable to deter entrants, the physico-economic equilibrium will still result: despite the constellation operators' awareness of the externalities between satellites, they will be unable to prevent entrants from dissipating the orbital rents.[16]

[14] Continued work on the economics of constellations may reveal useful modeling simplifications which enable development of simple graphical and analytical frameworks like the one presented here.

[15] In order to achieve this deterrence the constellation operator must be able to make other operators considering entry to that region perceive no rents from placing their satellites there. Whether such constellation design is possible or not is an open question.

[16] There is a third case, where the constellation operator themselves implement the physico-economic equilibrium. In this case the constellation operator acts as though they do not recognize the externalities their own satellites impose on each other.

# 4 Institutional management of orbit use

Institutional management of orbit use involves controlling the risk of collision and growth of debris through national or international policies. In what follows we focus on coordinated international policies to identify the long-run effects such policies may have if they are implemented uniformly. We also focus on policies which "bind" in the economic sense, i.e. which alter outcomes relative to a no-policy benchmark.[17]

The long-run orbit-use diagram allows us to identify the effects of institutional management policies on space activity. Institutional management policies can be classified into two types: incentive-based policies and command-and-control policies. Incentive-based policies manage orbit use by altering the incentives facing orbit users and allowing them to select behaviors consistent with those incentives. Command-and-control policies manage orbit use by prescribing specific behaviors for orbit users to follow. Incentive-based policies are a central focus of the growing economics literature on orbit-use management, e.g. Adilov, Alexander, and Cunningham (2015); Rao, Burgess, and Kaffine (2020); Rouillon (2020); Béal, Deschamps, and Moulin (2020), in part due to their popularity in economics more broadly (Kling, 1994; Stavins, 1998, 2003; de Vries and Hanley, 2016; Blackman, Li, and Liu, 2018).[18]

## 4.1 Incentive-based policies

An incentive-based policy alters a resource user's incentive to use the resource, usually with direct financial charges or payments. For example, suppose using a resource caused some pollution. An incentive-based policy may make pollution more expensive, inducing resource users to alter their activities in ways which lead to less pollution generation. This may involve using less of the resource, deploying technologies which reduce the amount of pollution generated by using the resource, or some other method chosen by the resource user. In general the resource user is free to determine how they will alter their use, giving flexibility to identify the lowest-cost methods available to them. This leads to environmental improvement being produced at the lowest possible aggregate cost.

While incentive-based policies can take many forms (e.g. user fees, tradable permits, deposit-refund schemes), they can be modeled as taxes to simplify

[17]The economic usage of "binding" is different from the legal usage. In the economic sense, a non-binding policy is typically one which is set at a level which does not affect economic decisions. For example, a "non-binding minimum wage" would be one which is below the prevailing market wage rate, therefore not affecting market outcomes. Whether a policy is economically binding is thus distinct from whether it is *legally* binding.

[18]This popularity, in turn, can be explained by theoretical results establishing that incentive-based policies are more economically efficient than command-and-control policies. While empirical analyses tend to agree with this assessment, studies have also found that command-and-control policies can be better than a no-policy status quo. In some cases, particularly those where incentive-based policies face insurmountable challenges (e.g. political resistance or lack of administrative capacity), command-and-control policies may be the better option.

analysis. Incentive-based policies for orbit use can be classified into two types: launch taxes (which focus on the act of launching a satellite) and satellite taxes (which focus on satellites in orbit). We show these policies and their long-run effects in Figures 4 and 5.[19]

### 4.1.1 Launch taxes

A launch tax $t_Q$ increases the total cost of launching satellites from $C$ to $C+t_Q Q$. Graphically, this rotates the cost curve $\mathcal{C}$ in quadrant (iii) upwards, with larger taxes inducing larger rotations. Using the projector, this shift in the cost curve $\mathcal{C}$ is then reflected in quadrant (ii) by a shift in the cost curve $\overline{\mathcal{C}}$. In Figure 4, the initial cost curves without the launch tax ($\mathcal{C}$ and $\overline{\mathcal{C}}$) are shown as dotted lines, while the final cost curves with the launch tax ($\mathcal{C}'$ and $\overline{\mathcal{C}'}$) are shown as solid lines.

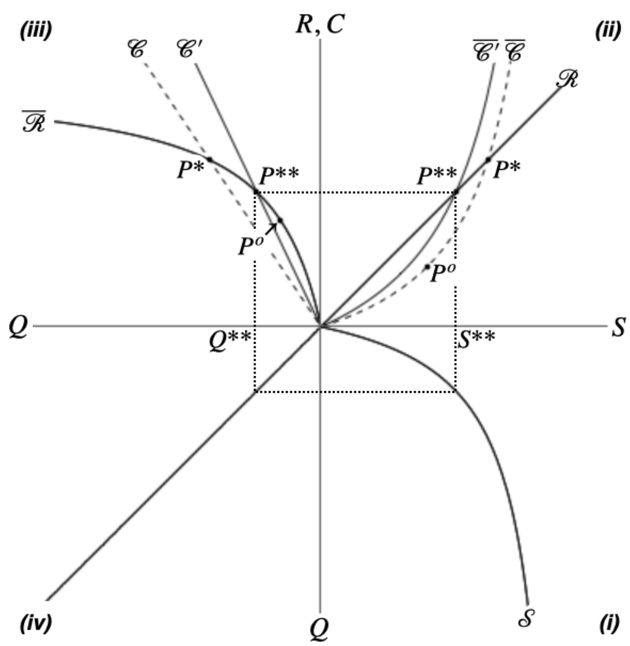


Figure 4: An example of a launch tax rotating the cost curve $\mathcal{C}$ in quadrant (iii) upwards, from $\mathcal{C}$ to $\mathcal{C}'$.

As seen in Figure 4, the launch tax shifts the physico-economic equilibrium towards the social optimum, from $P^*$ to $P^{**}$. This regulated physico-economic equilibrium preserves some rents from orbit use (i.e. increases the social surplus generated), measured by the difference between the revenue curve and the cost

[19]In the short run these policies may have more complicated effects, as described in Rao (2018). We abstract from such issues here.

curve at point $P^{**}$ (either $\mathcal{R}$ and $\overline{\mathcal{C}}$ in quadrant (ii) or $\overline{\mathcal{R}}$ and $\mathcal{C}$ in quadrant (iii)). These rents are revenues for the regulatory agency, collected from the satellite operators.

The rotation of $\mathcal{C}$ induced by the launch tax increases the operational lifetime of satellites (quadrant (i)), decreases the satellite fleet size (quadrant (ii)), and reduces the launch rate (quadrant (iii)). The social optimum can be implemented by choosing a tax rate such that the final cost curve intersects the revenue curve at $P^o$. We derive the launch tax which implements the social optimum in Appendix 8.2.3.

#### 4.1.2 Satellite taxes

A satellite tax $t_S$ reduces the total revenues produced by active satellites from $R$ to $R - t_S S$. Graphically, this rotates the revenue curve $\mathcal{R}$ in quadrant (ii) downwards, with larger taxes inducing larger rotations. Using the projector, this shift in the revenue curve $\mathcal{R}$ is then reflected in the quadrant (iii) by a shift in the revenue curve $\overline{\mathcal{R}}$. In Figure 5, the initial revenue curves without the satellite tax ($\mathcal{R}$ and $\overline{\mathcal{R}}$) are shown as dotted lines, while the final revenue curves with the tax ($\mathcal{R}'$ and $\overline{\mathcal{R}'}$) are shown as solid lines.

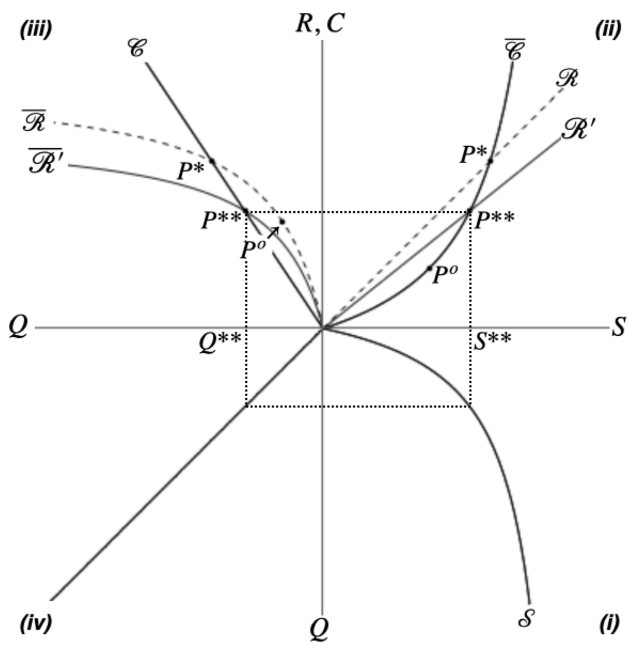


Figure 5: An example of a satellite tax rotating the revenue curve $\bar{\mathcal{R}}$ in quadrant (iii) downwards, from $\bar{\mathcal{R}}$ to $\bar{\mathcal{R}}'$.

As seen in Figure 5, the satellite tax shifts the physico-economic equilibrium towards the social optimum, from $P^*$ to $P^{**}$. As with a launch tax, the regulated physico-economic equilibrium under a satellite tax preserves some rent from orbit use. These rents are revenues for the regulatory agency, collected from the satellite operators.[20]

These rents are precisely the social surplus created by the tax. The tax-created social surplus is measured by the difference between the benefit curve and the cost curve at point $P^{**}$ (either $\mathcal{R}$ and $\overline{\mathcal{C}}$ in quadrant (ii) or $\overline{\mathcal{R}}$ and $\mathcal{C}$ in quadrant (iii)). The long-run effects of a satellite tax are similar to those of a launch tax. The tax causes an increase in the operational lifetime of satellites (quadrant (i)), a decrease in the satellite fleet size (quadrant (ii)) and a reduction in the launch rate (quadrant (iii)). Finally, the social optimum can be implemented by choosing a tax rate such that the final revenue curve intersects the cost curve at $P^o$. We derive the satellite tax which implements the social optimum in Appendix 8.2.3.

## 4.2 Command-and-control policies

A command-and-control instrument directly prescribes modes of behavior for a resource user to adopt, with penalties for noncompliance. Consider again the example where using some resource generated an amount of pollution. A command-and-control instrument could directly instruct resource users to use a specific technology (or set of technologies) to reduce their pollution production, or to instruct all users (or some subset) to reduce their resource use, or some other prescription. What distinguishes this approach from incentive-based policies is that users are given limited flexibility in choosing how they comply with the policy, and users do not pay the regulator anything when they comply. However, the total cost of a given level of environmental improvement will generally be higher under a command-and-control policy than if it were achieved through an incentive-based policy.

Experience in other resource contexts shows that command-and-control policies tend to result in further responses by resource users which may undermine the overall goal of the policy. In fisheries, for example, attempts to preserve fish populations by restricting the number of boats in the fishery led to "capital stuffing", where existing vessels invested heavily in increasing their own capacity

[20] One exception to this statement is when the initial allocation of permits is given to operators for free, e.g. if initial permit allocations are "grandfathered". In this case permits and taxes are not exactly equivalent as the rents from orbit use are traded between firms in exchange for reducing their debris and collision risk production. Such grandfathered permit systems may be used to overcome initial political resistance to regulation by regulated entities. Economic theory (i.e. the "Coase Theorem") predicts that if property rights to pollute are clearly established then equilibrium outcomes in an efficient emissions permit market will be independent of how the emissions permits are initially distributed. Fowlie and Perloff (2013) provide empirical evidence to support this hypothesis.

(Townsend, 1985). Similarly, attempts to preserve fish populations by limiting the total amount which could be harvested led to the "race to fish" phenomenon, where fishers sought to harvest as much as possible before the catch limit was reached (Birkenbach, Kaczan, and Smith, 2017). By contrast, incentive-based policies such as individual tradable quotas directly target the incentive to use the resource and thus avoid such "perverse" effects (Costello, Gaines, and Lynham, 2008).[21] Many types of command-and-control policies can be designed. We briefly describe two types of command-and-control policies: direct limits on the number of satellites launched to a particular region ("keep-out zones"), and binding requirements to deorbit a satellite upon the end of its mission ("deorbit requirements").

#### 4.2.1 Keep-out zones

A "keep-out zone" is a policy which restricts use of a particular orbital region, whether by launching new satellites to the region or moving existing satellites into the region. It may include "grandfathering" clauses allowing existing satellites in the region beyond the limit to stay (or allow already-planned launches to continue). Grandfathering alters the short-run economic incentives to use the region relative to the no-grandfathering benchmark, but not the long-run incentives. Keep-out zones have been proposed for orbital regions currently subject to high potential growth of new debris fragments or containing valuable assets (Schwetje, 1987; Ailor and Peterson, 2004; Anz-Meador, 2020). The long-run effects of a keep-out zone are identical whether it is implemented as a restriction on launches or on satellites.

A binding keep-out zone can be represented in the long-run orbit-use diagram as a constraint on the launch rate or satellite stock, i.e. a vertical line on the $S$ or $Q$ axes before the physico-economic equilibrium point. The constraint will create rents for the satellite operators who have been able to access the region. The value of these rents is measured by the vertical distance between the revenue and cost curves at the vertical line of the constraint. The farther the constraint is from the physico-economic equilibrium point, the more stringent the policy is. The rents are therefore initially increasing in the stringency of the keep-out zone, then decreasing. In the limit where a keep-out zone completely shuts down all use of the orbit—i.e. a constraint at the origin of the diagram—there are no rents created because there are no satellite operators in the region to claim them.

[21] More technically, command-and-control policies can be expressed as an implicit price reflecting forgone profits due to an economically-binding constraint, not a price actually paid to or received by any entity. The policy thus changes the relative prices of using a resource or deploying a particular set of technologies. Incentive-based policies can also be expressed as taxes which change relative prices. However, because command-and-control policies do not directly alter the resource users' objective functions, operators remain interested and able to seek ways to mitigate the effects of the implicit price change. Incentive-based policies do not face this problem because they directly target the users' incentives to produce socially-undesirable outcomes.

When keep-out zones create rents, they incentivize operators with satellites in the zone to increase the amount of revenue derived from their satellites in the zone. Intuitively, the reduction in lifetime collision risk due to the zone increases the profitability of the satellite, allowing for greater financial costs to be incurred per satellite. How this incentive translates to behavior will depend on the details of keep-out zone implementation. Suppose the keep-out zone includes a grandfathering clause allowing all operators with satellites in the region prior to the zone to continue launching a limited number of satellites to the region to replenish their fleets. Then the zone will push those operators to increase the service capacity of their satellites, e.g. by increasing their size, so that the satellites generate more profits over their lifetime. Without a grandfathering clause the incentive will instead tilt towards increasing the lifetime of the satellite, so that each satellite deployed to the keep-out zone can profit from the reduced risk for longer.

#### 4.2.2 Deorbit requirements

A "deorbit requirement" is a policy which ensures satellites are deorbited at some point after the end of their missions. The current 25-year deorbit guideline is a step in this direction, though it is both legally and economically non-binding.[22] There are three ways a satellite can comply with deorbit requirements: through choice of altitude, through use of technologies, and through a mix of both.

The first approach relies on the fact that some regions will be naturally compliant with a given deorbit requirement, i.e. satellites left there will deorbit within the required timeline without any intervention. By choosing a suitable operational altitude, an operator can ensure that their satellite complies with the requirement without any additional end-of-life effort. For example, the region below 550 km altitude is naturally compliant with a 25-year guideline. In general, lower altitudes are naturally compliant with more-stringent requirements.

The second approach relies on technologies which enable a satellite to actively deorbit at the end of its life. With such technologies available, an operator need not place their satellite in a naturally-compliant region. We discuss this approach further in Section 5.

The third approach is to move intact inactive payloads from higher to lower altitudes where they will be naturally compliant with the requirement without

[22] Percy and Landrum (2014) studies the effect of non-binding debris mitigation guidelines in the US on satellite operator behaviors. They find that non-binding guidelines tend to have low compliance relative to those which bind, and consider a suite of options for implementing binding disposal requirements. The "Unilateral Regulation Overhaul" option they describe can encompass both incentive-based and command-and-control policies.

further operator effort. Rao and Letizia (2021) consider the short-run effects of full compliance with the 25-year guideline, focusing on behavioral responses such as substitution across orbits. They find that operators using this approach will increase the expected collision rate at the naturally-compliant altitudes, inducing operators to cluster at nearby higher altitudes. This clustering may create greater collision risks there if collision avoidance maneuvering is imperfect. Thus, a binding deorbit requirement across both naturally compliant and non-compliant regions may have more complicated effects that sustainable policies should fully encompass. Engineering studies have also indicated that the 25-year guideline is insufficient to prevent further growth of debris fragments and collision risk even if compliance were perfect and clustering effects were absent, necessitating a "more stringent" timeline with a shorter post-mission timeline (Virgili, Dolado, and Lewis, 2016; Lewis, 2020). There is as yet no research on the long-run physico-economic effects of either more-stringent timelines or binding deorbit requirements. Extending existing long-run physico-economic models to cases with multiple regions is necessary to conduct such research.

# 5 Technological management of orbit use

The other way to influence the space sector and the orbital environment is to develop and implement technologies which reduce the environmental footprint of orbit use. Such technologies are referred to in other sectors as "clean" technologies, e.g. "clean" energy production technologies are those which reduce emissions per unit of energy generated. Technological approaches to managing orbit use can be classified according to whether they target launch vehicles, satellites, or debris.

All three types of technologies can be represented in the long-run orbit-use diagram through their effects on the parameters $A$ and $B$ in the long-run satellite production function $S = Q/(A - BQ)$ (equation 1). However, a given technology may affect both $A$ and $B$, complicating the overall effect. The diagram reveals both the direct effects of the policy through technical changes (changes in $A$ and $B$) as well as the indirect effects through behavioral responses (changes in the equilibrium and optimal points $P^*$ and $P^o$). Understanding such behavioral responses is critical in assessing the full effects of clean technology deployment (Gillingham, Rapson, and Wagner, 2016).

Our analysis shows that all technological innovations will induce two types of changes in the long-term satellite production function. The first type of change is in the intrinsic lifetime parameter $A$, shown in Figure 6, and the second is a change in the carrying capacity parameter $B$, shown in Figure 7.

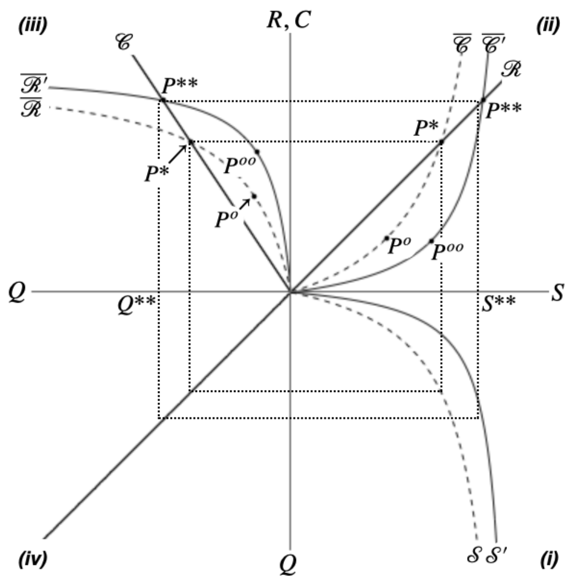


Figure 6: The effects of a decrease in $A$ in equation 1. Curves and points labeled with a $'$ indicate values at a smaller level of $A$, e.g. decreasing $A$ causes $\mathcal{S}$ to shift to $\mathcal{S}'$ in quadrant (i).

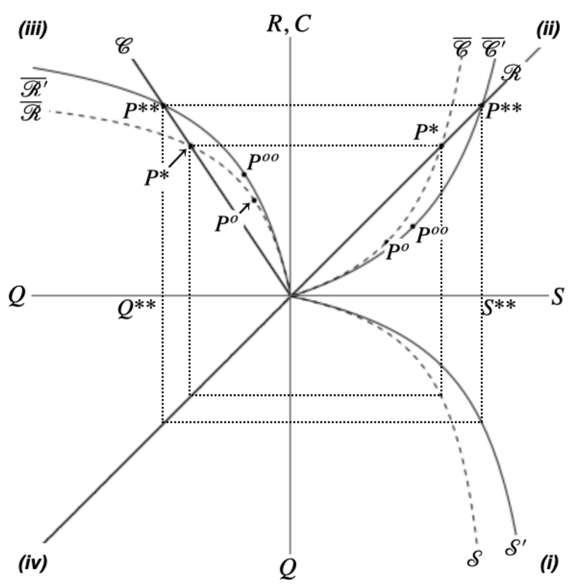


Figure 7: The effects of a decrease in $B$ in equation 1. Curves and points labeled with a $'$ indicate values at a smaller level of $B$, e.g. decreasing $B$ causes $\mathcal{S}$ to shift to $\mathcal{S}'$ in quadrant (i).

In both figures the modification of the long-term satellite production function is shown in quadrant (i), with the curve $\mathcal{S}$ in dashed line representing the situation before the technological change and the curve $\mathcal{S}'$ in solid line representing the situation after the technological change. Following the projection process described earlier, these changes are then reflected in the rest of the graph (quadrants (ii) and (iii)).

Changing $A$ will affect the satellite production function more at intermediate fleet sizes, while changing $B$ will affect the satellite production function more at large fleet sizes. The intuition follows from the parameter interpretations. Since $A$ reflects the intrinsic satellite lifetime, the effects of changes to $A$ will be most pronounced when the environment is neither relatively open nor nearly saturated. Since $B$ reflects the carrying capacity, changes to $B$ will not have much effect on satellite fleets that are relatively small and far from the carrying capacity limit. When the environment is relatively uncluttered, satellites face virtually no debris risk and already experience nearly their full design lifetime. When the environment is nearly saturated, the effect of incremental debris risk reductions on satellite lifetimes is small.

Note that technological changes alter both the physico-economic equilibrium $P^*$ and the social optimum $P^o$. The new physico-economic equilibrium and social optimum after the technological change are represented by points $P^{**}$ and $P^{oo}$. The environmental effects of a technology can be described unambiguously, i.e. it is clear whether a given technology will lead to more or less debris in the long run (holding a specific launch and design scenario constant). However, the economic effects cannot be described unambiguously. In order for a technology to increase economic efficiency it must bring the private allocation closer to the post-technology social allocation. A technology which drives the two further apart—for example, increasing the equilibrium satellite fleet size proportionately more than the optimum satellite fleet size—may be environmentally beneficial while reducing economic efficiency.

We briefly describe the three types of technological management approaches in terms of the long-run orbit-use diagram. We initially abstract from the costs of deploying these technologies, focusing instead on "zero-cost" breakthroughs representing exogenous shifts in or uses of technologies. We then provide simple conditions which can be checked to determine whether deploying a given clean technology will improve overall economic efficiency of orbit use for a given cost of deployment.

## 5.1 Cleaner launch technologies

Clean orbit-use technologies focused on launch vehicles are the simplest to describe. These involve reducing the amount of debris produced by a launch vehicle when delivering a payload to orbit. They can focus on the rocket body (e.g.

boosters to deorbit the upper stage) or on the small debris fragments released (e.g. frangibolts to separate payloads). These in turn reduce the parameter $B$, causing the long-run satellite production function (equation 1) to shift outward.[23] The shift is shown in quadrant (i) of Figure 7. This leads to an outward shift of the long-run cost of operating a satellite in quadrant (ii) (equivalently, of the long-run revenues from launching a satellite in quadrant (iii)). Intuitively, reducing the amount of debris generated by rockets reduces the long-run cost of maintaining any given level of satellites in orbit. This pushes the physico-economic equilibrium point outwards, leading to a larger equilibrium satellite fleet.

## 5.2 Cleaner satellite design technologies

Clean orbit-use technologies focused on satellite design can be classified into three categories: "'reliability" technologies which extend a satellite's operational life; "end-of-life disposal" technologies which enable satellites to be deorbited (or reorbited to a disposal orbit) at the end of their productive life; and "shielding" technologies which improve a satellite's resistance to collisions. Saleh, Hastings, and Newman (2002) discuss various issues driving and limiting spacecraft design lifetime, and develop an economic metric ("cost per operational day") to help guide the necessary design specifications. Davis, Mayberry, and Penn (2019) extend this analysis by considering on-orbit servicing technologies, i.e. satellites which can repair and refuel other satellites. Such technologies would likely affect the average operational lifetime of a satellite. Sánchez-Arriaga, Sanmartín, and Lorenzini (2017) compare several end-of-life disposal technologies, finding that "bare electrodynamic tethers" may dominate other deorbiting technologies in terms of performance and reliability. Wiedemann, Oswald, and Stabroth (2008) model the cost of better satellite shielding to reduce damages from hypervelocity impacts, finding that simple modifications of satellite walls can reduce failure rates by up to 1%—enough to be cost-effective if the shielding is not too expensive. These technologies can affect both $A$ and $B$ in the long-run satellite production function. They will all induce larger equilibrium satellite fleets, though the channels through which the effect operates differ.

Reliability technologies will decrease $A$, causing the satellite production function in quadrant (i) to shift outwards as shown in Figure 6 (the curve $\mathcal{S}$ moves to $\mathcal{S}'$). This causes the cost function in quadrant (ii) to shift outwards as well (the curve $\bar{\mathcal{C}}$ moves to $\bar{\mathcal{C}}'$)—equivalently, the revenue function in quadrant (iii) shifts upwards (the curve $\bar{\mathcal{R}}$ moves to $\bar{\mathcal{R}}'$). Intuitively, greater satellite reliability increases the number of satellites sustained by any given level of launches and increases the long-run revenues accruing to the satellite fleet at any size. The increase in satellite profitability pushes the physico-economic equilibrium point

[23] Recall that $A$ reflects the intrinsic satellite lifetime and $B$ reflects the carrying capacity. Reducing the number of debris objects produced by satellite launches therefore affects $B$ but not $A$.

outwards, leading to a larger equilibrium satellite fleet.

End-of-life disposal technologies will decrease $B$, causing the satellite production function in quadrant (i) to shift outwards ($\mathcal{S}$ moves to $\mathcal{S}'$). As with reliability technologies, this change causes the cost function in quadrant (ii) to shift outwards and the revenue function in quadrant (iii) to shift upwards. Figure 7 shows an example of this type of change. Intuitively, use of disposal technologies at the end of a satellite's productive life reduces the amount of debris created by the satellite over its time in orbit, allowing a larger number of active satellites to be sustained at any given fleet size. The reduction in debris risk to satellites pushes the physico-economic equilibrium point outwards, leading to a larger equilibrium satellite fleet.

Shielding technologies will decrease both $A$ and $B$, again causing the satellite production function in quadrant (i) to shift outwards as shown in Figures 6 and 7. While the exact magnitudes of the changes will depend on implementation details, the effects will be qualitatively similar to those due to better reliability technologies or end-of-life disposal technologies—greater long-run revenues accruing to the satellite fleet at any size, and a larger equilibrium satellite fleet. The intuition differs from those cases, however: rather than directly increasing a satellite's lifetime or reducing the amount of debris in orbit, shielding technologies reduce the consequences to satellites of debris growth.

## 5.3 Debris removal technologies

Active debris removal (ADR) involves technologies which can capture and deorbit debris, whether large intact objects or small fragments. We refer to the former as "intact ADR" and the latter as "fragment ADR". While some technologies such as nets may be effective for both types of objects, different technologies are suited to different object characteristics (Mark and Kamath, 2019). Intact ADR technologies typically involve "rendezvous and proximity operations", where the object to be deorbited is targeted and located in advance. By contrast, "collection/pickup" technologies remove all objects of a given type within a target region, and are better suited to fragment ADR.

Intact ADR will decrease $A$ in equation 1, increasing the long-run satellite stock at all launch rates by rotating curve $\mathcal{S}$ in quadrant (i) away from the $Q$ axis as shown in Figure 6 (the curve $\mathcal{S}$ moves to $\mathcal{S}'$). Intuitively, the removal of large intact objects reduces their contribution to fragment growth, in turn reducing the long-run risk of collisions between fragments and active satellites. This pushes the physico-economic equilibrium point outwards, leading to a larger equilibrium satellite fleet.

Fragment ADR will increase $A$ and decrease $B$ in equation 1. These can have countervailing effects on the equilibrium satellite fleet size: increasing $A$ will tend to decrease the equilibrium fleet size whenever there is a non-zero level of ongoing intact ADR, while decreasing $B$ will tend to increase the equilibrium fleet size. Recall that $A$ is the inverse of the intrinsic lifetime while $B$ is the inverse of the carrying capacity. Reducing the number of fragments increases the carrying capacity as orbital volume occupied by small fragments is made available for larger objects.[24] However, reducing the number of fragments also reduces the effectiveness of intact ADR. This reduces the improvement to intrinsic lifetime delivered by intact ADR, leading to a reduction in the expected lifetime of a satellite proportional to the level of ongoing intact ADR.

While there are a number of companies planning to offer intact ADR services in the near future (Weinzierl, 2018), it is unclear when or how fragment ADR will be offered commercially. Despite the existence of commercial companies to provide intact ADR there remain numerous technological and legal challenges associated with providing ADR services. Mark and Kamath (2019) reviews the technological challenges and concludes that all plausible ADR systems are still in experimental or conceptual stages and require more study before they can be deployed at scale. Weeden (2011) analyzes the legal and policy issues facing ADR deployment and concludes that there are substantial barriers to address before ADR services can be deployed at scale. Muller, Rozanova, and Urdanoz (2017) and Brettle et al. (2019) demonstrate the value of ADR for space actors. In addition, Klima et al. (2018) show that, if ADR decisions are not undertaken under a centralized and neutral scheme, a non-efficient allocation and unfair outcome will result. Finally, Adilov, Alexander, and Cunningham (2020) demonstrate that ADR may be necessary in order to stop the accumulation of debris in orbit.

## 5.4 When can technology deployment be efficiency-improving?

Having described the types of technologies, we can now determine when technology deployment has the potential to increase economic efficiency. The idea behind these calculations is to compare the social surplus at the social optimum before and after the technology is deployed (i.e. $P^o$ and $P^{oo}$). If social surplus at the social optimum increases, then it is at least *possible* for the technology to improve economic efficiency. Whether or not the technology actually improves economic efficiency will depend on the cost of deployment, the change in the physico-economic equilibrium, and the system of regulations in place. We first show that the technologies described above all have the potential to improve economic efficiency, then derive an expression for the maximum technology deployment cost under which such efficiency improvement is possible.

[24]Note that while the volume physically occupied by an object is proportional to its size, the volume it renders unusable by other objects is proportional to its size and the uncertainty over its exact position. Fragments may be small but they are often poorly tracked. The positional uncertainty thus increases their "effective" occupied volume.

**All technology improvements can be efficiency-improving:** Equation 3 shows the social surplus at the social optimum $W^o$, calculated from Table 1 and the definitions of the revenue and cost curves.[25]

$$W^o = R - C = \frac{p}{B}\left(1 - \sqrt{\frac{A}{\sigma}}\right)^2 \tag{3}$$

where $\sigma = p/c$.

Inspection of equation 3 reveals that $W^o$ is decreasing in $A$ and $B$. All of the technologies we described above either decrease $A$ or $B$. Therefore they all have the potential to increase social surplus, provided the deployment cost is not too large.

The only potential exception is fragment ADR, which will both increase $A$ and decrease $B$. When will the increase in $A$ outweigh the decrease in $B$? Since the increase in $A$ is proportional to the level of ongoing intact ADR, at low levels of ongoing intact ADR the decrease in $B$ will dominate. At high levels of ongoing intact ADR the increase in $A$ may dominate. Determining whether the levels of intact ADR where this occurs are likely to be realized is an open question. Answering it will require considerable work to quantify the parameters $A$ and $B$.

**The breakeven technology deployment cost:** How large can the deployment cost be before the technology is too costly to improve social surplus?

The answer to this question depends on the cost of technology deployment, with two extreme possibilities:

1. deployment incurs a fixed cost $k$ and has no effect on the unit cost of a satellite, $c$ (the "fixed cost only" case);
2. deployment increases the unit cost of a satellite, $c$, with no fixed cost $k$ (the "unit cost only" case).

Any technology which both imposes a fixed cost and alters the unit cost of a satellite will be a combination of these two cases.

**1. The "fixed cost only" case.** Consider a technological innovation which changes parameters $A$ and $B$ to $A'$ and $B'$. In this case, there is a one-time cost of $k$ to deploy the technology and no effect on $c$, the unit cost of satellites. Since there is no effect on $c$ the parameter $\sigma$ in equation 3 is unchanged. The resulting change in social surplus, $\Delta W^o$, is shown in equation 4.

$$\Delta W^o = p\left[\frac{1}{B'}\left(1 - \sqrt{\frac{A'}{\sigma}}\right)^2 - \frac{1}{B}\left(1 - \sqrt{\frac{A}{\sigma}}\right)^2\right] - k. \tag{4}$$

[25] See Appendix section 8.2 for more details on these calculations.

The breakeven of the cost of deployment is therefore:

$$p\left[\frac{1}{B'}\left(1-\sqrt{\frac{A'}{\sigma}}\right)^2-\frac{1}{B}\left(1-\sqrt{\frac{A}{\sigma}}\right)^2\right]. \quad (5)$$

If the cost of deploying the technology $k$ exceeds this value, it cannot possibly increase net social surplus. While we attempt to quantify this value in the next section, a detailed analysis of breakeven technology deployment costs is beyond our scope here.

**2. The "unit cost only" case.** Consider a technological innovation which changes parameters $A$ and $B$ to $A'$ and $B'$. In this case, technology deployment changes the unit cost of satellites $c$ to $c'$ without imposing any fixed cost. Since $c$ changes, the parameter $\sigma$ in equation 3 decreases from $\sigma = p/c$ to $\sigma' = p/c'$. The resulting change in social surplus, $\Delta W^o$, is shown in equation 6.

$$\Delta W^o = p\left[\frac{1}{B'}\left(1-\sqrt{\frac{A'}{\sigma'}}\right)^2-\frac{1}{B}\left(1-\sqrt{\frac{A}{\sigma}}\right)^2\right]. \quad (6)$$

The technological change is socially beneficial if:

$$\sigma' > \frac{A'}{\left(1-\sqrt{\frac{B'}{B}}\left(1-\sqrt{\frac{A}{\sigma}}\right)\right)^2}. \quad (7)$$

In the special case where the technological change is such that $A' < A$ and $B' = B$, this simplifies to the simpler condition that:

$$c' < \frac{A}{A'}c. \quad (8)$$

which gives the breakeven of the cost such that the technological change is socially beneficial.

# 6 A numerical example

To illustrate some of the concepts described, we calibrate our physico-economic model to low-Earth orbit and study the effects of cost changes and technology deployment. We study two changes: first an increase in post-mission disposal at zero cost, then a costly increase in post-mission disposal (assuming a unit-cost-only change). Table 2 lists the key parameter values in all of the scenarios along with the resulting equilibrium and optimum outcomes. We assume the unit cost of a satellite is initially \$15.8 million/satellite and the post-mission disposal rate is 25%. We also assume that a satellite generates \$22.1 million/year in revenues throughout.

| Scenario | | 1 (initial) | | 2 (tech. alone) | | 3 (tech. + cost) | |
|---|---|---|---|---|---|---|---|
| **Institution** | | **Eqm** | **Opt** | **Eqm** | **Opt** | **Eqm** | **Opt** |
| **Parameter name** | **Units** | | | | | | |
| **Unit cost** ($c$) | [M$/sat] | 15.80 | 15.80 | 15.80 | 15.80 | 18 | 18 |
| **EOL deorbit rate** | [%] | 25 | 25 | 50 | 50 | 50 | 50 |
| **Launch rate** ($Q$) | [sat/yr] | 636 | 179 | 869 | 245 | 744 | 219 |
| **Fleet size** ($S$) | [sat] | 455 | 327 | 621 | 446 | 606 | 427 |
| **Expected lifetime** ($S/Q$) | [yr] | 0.71 | 1.82 | 0.71 | 1.82 | 0.81 | 1.95 |
| **Total revenues** ($R$) | [M$/yr] | 10045.40 | 7215.93 | 13733.70 | 9865.39 | 13386.30 | 9436.79 |
| **Total costs** ($C$) | [M$/yr] | 10045.40 | 2829.42 | 13733.70 | 3868.30 | 13386.30 | 3949.46 |
| **Rent** ($R - C$) | [M$/yr] | 0 | 4386.50 | 0 | 5997.09 | 0 | 5487.33 |
| **Optimal launch tax rate** | [M$/sat] | | 24.49 | | 24.49 | | 25.01 |

Table 2: Calibrated scenario analysis key inputs and results. Physical values are rounded to integers, while monetary values are rounded to the second decimal place. Monetary values are presented in millions of 2020 US dollars.

The corresponding long-run orbit-use diagram is shown in Figure 8. The equilibrium and optimum outcomes are shown in the columns labeled “1 (initial)” in Table 2.

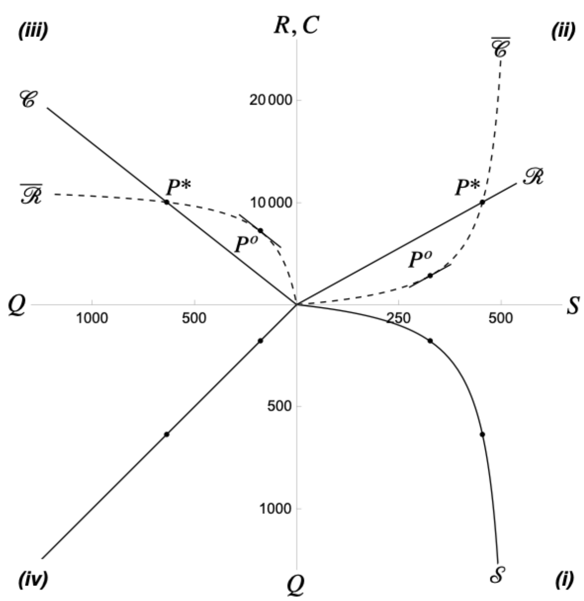


Figure 8: Initial long-run state of low-Earth orbit.

In the second scenario, PMD rates increase to 50% at zero cost. The corresponding 4-quadrant plot is shown in Figure 9. The equilibrium and optimum outcomes are shown in the columns labeled “2 (tech. alone)” in Table 2.

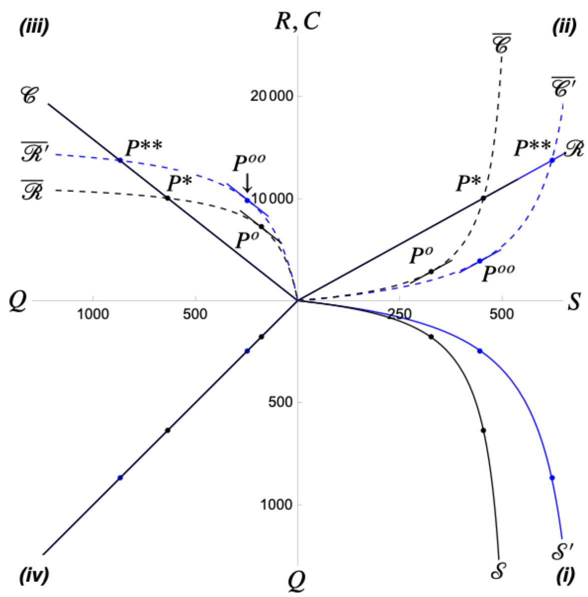


Figure 9: Long-run state of low-Earth orbit with greater PMD. The black curves show the initial state with 25% PMD, while the blue curves show the new state with 50% PMD.

The increase in PMD affects both the physico-economic equilibrium and the social optimum. The equilibrium launch rate increases from $Q^* = 636$ to $Q^{**} = 869$ satellites/year, leading the satellite fleet size to increase from $S^* = 455$ to $S^{**} = 621$ satellites. Total revenues and total costs for the space sector increase equally, leaving no social surplus. The social optimum shows a similar pattern, with the launch rate increasing from $Q^o = 179$ to $Q^{oo} = 245$ satellites/year and the satellite fleet size growing from $S^o = 327$ to $S^{oo} = 446$ satellites. However, the social surplus generated by the space sector grows from \$4836.50 million/year to \$5997.09 million/year—a gain of roughly \$ 1611 million/year. These differing changes in surplus reflect the natures of open access to orbit (in the physico-economic equilibrium) and socially-optimal management. Open access is characterized by actors claiming whatever profits are available, so the additional "environmental capacity" enabled by greater PMD does not translate to greater social surplus (i.e. value generated in excess of the cost required to attain it). Socially-optimal management, on the other hand, is characterized by actors restraining their use of orbital space so as to maximize the social surplus available. Under this institution, a technology change which boosts environmental capacity enables both a larger fleet as well as additional surplus.

In both cases, the expected lifetime of a satellite remains unchanged. As shown in Table 1, the long-run expected lifetime of a satellite reflects the rate of return to orbit use. Greater PMD with no cost changes leaves the rate of return unchanged and so does not affect the expected lifetime. While the socially-optimal expected lifetime also includes physical and engineering parameters through $A$, this parameter is unaffected by PMD (see Appendix 8.1). Similarly, the optimal launch tax remains unchanged at \$24.49 million per satellite. Since the tax will implement the social optimum, under the tax regime a satellite will have an expected operational lifetime of 1.82 years and generate revenues of \$22.1 million/year. The optimal launch tax represents approximately 61% of the revenue generated during the satellite's lifetime. Note that the increase in satellite lifetime between the physico-economic equilibrium and social optimum implies that the tax more than doubles the lifetime revenue of a satellite.

In the third scenario, PMD rates remain at 50% and the unit cost of a satellite rises from \$15.8 million/sat. to \$18 million/sat, reflecting a "unit cost only" PMD technology. The corresponding 4-quadrant plot is shown in Figure 10. The equilibrium and optimum outcomes are shown in the columns labeled "3 (tech. + cost)" in Table 2.

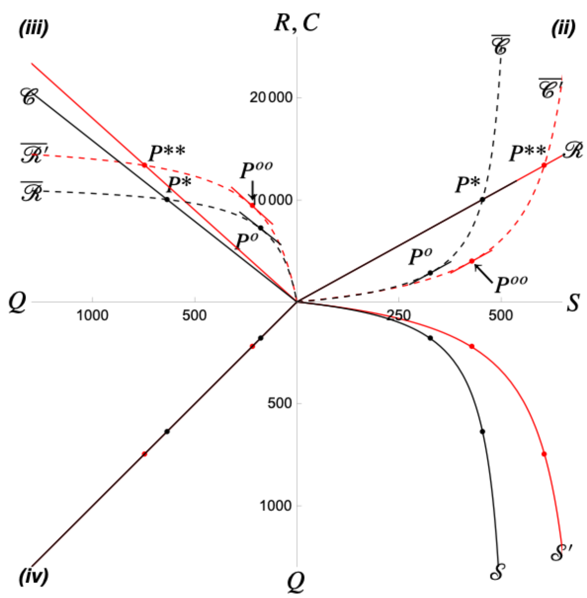


Figure 10: Long-run state of low-Earth orbit with greater PMD and higher satellite unit costs. The black curves show the initial state with 25% PMD, while the red curves show the new state with 50% PMD and higher unit costs.

Like the increase in PMD going from the initial state to the second scenario, the increase in unit costs affects both the physico-economic equilibrium and the social optimum. The combination of greater PMD and higher unit costs mean the equilibrium launch rate only increases from $Q^* = 636$ to $Q^{**} = 744$ sat./year and the satellite fleet only increases from $S^* = 455$ to $S^{**} = 606$ satellites—smaller increases than if the greater environmental capacity due to greater PMD were "provided for free". Total revenues and costs increase, though less than in the technology-only scenario, and again leaving no social surplus. The social optimum shows a similar pattern as before, with corresponding increases in the launch rate from $Q^o = 179$ to $Q^{oo} = 219$ sat./year, fleet size from $S^o = 327$ to $S^{oo} = 427$, and social surplus from \$4386.50 million/year to \$5487.33 million/year—a gain of roughly \$ 1101 million/year. Though the changes in outcomes are smaller than in the technology-only scenario, the intuition for their pattern is similar.

Unlike in the technology-only scenario, the change in satellite unit cost increases the expected long-run lifetime of a satellite in both the physico-economic equilibrium (from 0.71 years initially to 0.81 years) and the social optimum (from 1.82 years initially to 1.95 years). This also changes the optimal launch tax rate, increasing it to \$25.01 million/sat. The optimal launch tax represents approximately 58% of the revenue generated during the satellite's lifetime.

Why does the optimal launch tax increase only when cost of launching increases? Recall that the purpose of the tax is to align the equilibrium launch rate with the optimal launch rate. Figure 10 and Table 2 show that the combination of PMD and a unit cost increase results in larger equilibrium and optimal satellite fleet sizes. Inspection of Table 2 reveals that the relative increases in fleet sizes in the technology-only scenario are nearly identical: both equilibrium and optimal fleets increase by roughly 36% compared to the initial state. In the technology and cost scenario, however, the relative increases differ appreciably: while the equilibrium fleet size increases by roughly 33% compared to the initial state, the optimal fleet size increases only by roughly 30%. Thus, the increase in unit costs leads to a proportionally larger decrease in the size of the optimal fleet compared to the size of the equilibrium fleet. The launch tax must therefore increase to align the equilibrium fleet size with the optimal fleet size.

Finally, in the real world we observe thousands of satellites in orbit, with tens of thousands more planned. Why are the predicted long-run equilibrium and optimum numbers of satellites so much lower? There are two non-exclusive answers to this puzzle within the framework we have articulated: first, the "long run" may not be here yet and the current situation is transitory; second, the model parameters may be incorrect.

The first is easy to address: this framework is concerned with the "long run" state of orbital space, not the near-term state or the dynamics of how the long-term state is approached. The framework predicts the number of satellites to eventually decrease substantially relative to near-term expectations. Put differently, the predictions indicate that if current engineering and economic patterns continue, then the current level of orbit use is unsustainable.

The second is more complicated, containing three further non-exclusive possibilities. First, it is possible that some of the parameter values (listed in Table 4) are simply incorrect, e.g. perhaps the number of fragments per collision ought to be different from what was assumed. Such errors can be resolved in many ways. One approach, popular in econometric analysis, is to estimate the parameter values required to make model predictions fit observed historical data as well as possible. These parameter estimates can then be used to project trends forward, implicitly assuming that aspects of current engineering practice continue. This approach is used in some computational economic studies of orbit use, e.g. Rao, Burgess, and Kaffine (2020); Rao and Letizia (2021); Rao and Rondina (2022). Those studies also tend to find that the current situation is unsustainable and that reductions in the number of satellites in orbit are necessary to preserve the resource for future generations.

It is also possible that the physical model is a poor approximation of reality. There may also be significant heterogeneity in parameter values across different regions of LEO such that the calibrated values do not adequately reflect the orbital state operators are facing. Both issues could be resolved by using a higher-fidelity model or restricting attention to a specific region in LEO, albeit at the cost of some analytical tractability. Such debris environment models exist, and it is an open challenge for researchers to find ways to integrate them with economic models—a call echoed in Adilov, Alexander, and Cunningham (2022).

Finally, the calibrated economic parameters may be inappropriate. The data used to calibrate these parameters (aggregate values from SIA (2020)), while the best available, is fundamentally limited for these purposes. It does not disaggregate revenues and costs by orbital region (i.e. GEO and LEO are lumped together), creating the possibility for error in the share of revenues and costs attributable to LEO use. Historical revenues and costs are also inherently backwards-looking, while investment decisions like launching a satellite are forwards-looking. There is likely a gap between the revenues/costs operators have historically received/incurred and the revenues/costs they expect to receive/incur in the coming decades. Resolving these types of issues would require more detailed data (e.g. survey data from operators regarding their revenue and cost expectations) or a more computationally-intensive process to back out operators' aggregate beliefs over the future trajectories of revenues and costs. Collecting such data and identifying appropriate computational procedures is an important area for future economic research in this area.

# 7 Conclusion

This paper presents a simplified framework which can be used to assess and predict the long-run effects of orbital-use management policies and technological innovations. We have demonstrated how the framework can be applied to several space policy questions of interest, such as understanding the effects of a launch tax or of introducing ADR technologies. The framework can also be calibrated to reflect the physics and economics of a particular region in orbital space, and then used to obtain quantitative predictions regarding the long-run outcomes resulting under different policy and technology scenarios. While the framework is consistent with complex mathematical models found in the aerospace engineering and economics literatures, applying the framework requires only simple algebra and geometry.

While this framework can be useful to policymakers seeking to understand both physical and behavioral responses to policy and technology changes of interest, its limitations must be clearly understood. First, the framework only addresses long-run outcomes. It cannot be used to study short-run processes, e.g. questions like, "what will happen next year if this policy is enacted/technology is deployed." The framework is instead meant to address questions like, "how will enacting this policy/deploying this technology affect orbital sustainability over the coming decades and beyond?" Second, the framework focuses on two polar cases: one where all satellites are coordinated as if they belong to a single actor (the social optimum) and one where all satellites are operated as though each one belongs to a different actor (the physico-economic equilibrium). Between these two polar cases lie infinitely many cases of substantial real-world interest, such as those involving competing mega-constellations. Though the social optimum and physico-economic equilibrium will likely bound the realm of possible outcomes and are thus useful in building intuition for interacting physico-economic effects, further research is needed to develop tractable physico-economic models of constellations. Third, though the framework is agnostic to many of the underlying details of the physical system—recall that equation 1 emerges from many possible physical models—numerical predictions from the framework will be sensitive to the details of the underlying physical system. Even if the qualitative conclusions (e.g. the curve shifts in Figures 6 and 7) are invariant to these details, the magnitudes should be interpreted with caution.

What does all this mean for space policy? We offer a few thoughts based on our analysis and the extant literature. First, the market failure created by space debris and collision risk is unlikely to be resolved on its own without policy action. As Weinzierl (2018) notes, "...a Coasian solution in which affected parties negotiate to internalize externalities will be difficult in the case of space debris because this approach requires clearly delineated property rights, and no such rights exist in space." Articles I and II of the Outer Space Treaty present a fundamental barrier to achieving economically-efficient orbital-use patterns through decentralized bargaining between operators. This does not mean there are no paths toward efficient orbit use. Hanson (2014) offers one path to efficiency through a Pigouvian tax on space debris. Much of the economics literature on space debris comes to similar policy ideas, such as satellite taxes or launch taxes. While there are important distinctions between different orbit-use pricing policies, all of them take aim at the externalities satellite operators impose on each other. Our framework offers a simple way to visualize why such approaches can work to preserve orbital space: reducing the rents that operators perceive from launching satellites by precisely the magnitude of the external costs imposed on others induces those operators to seek the social optimum instead of the physico-economic equilibrium. The resulting rents can then be used for orbit-related purposes such as ADR, as suggested in Bernhard, Deschamps, and Zaccour (2022), or returned to national governments who would implement the scheme to secure political buy-in, as suggested in Rao, Burgess, and Kaffine (2020). Weeden (2011) takes a slightly different approach based on Ostrom (1990), focusing on the nature of the governance system which could ensure long-run orbital sustainability. This analysis reveals the need for better SSA, mechanisms to resolve conflicts between operators, and graduated penalties for noncompliance. We note that these features do not conflict with the economic prescription to use Pigouvian taxes—these approaches may even be mutually reinforcing. Percy and Landrum (2014) suggests that unilateral regulation by a large orbit-user like the United States may be an effective way to begin to institute effective orbital sustainability measures.[26]

Our framework is simple, tractable, and can reveal useful relationships between the physical state of orbital space and behavioral responses. Its limitations point to important directions for future research on orbital sustainability. These include developing tractable physico-economic models of competition between constellations for orbital volume and market share, of short-run processes like constellation buildup and responses to fragmentation events, and methods to incorporate economic behavior into higher-fidelity debris environment models.

Orbital-use management is a complicated problem. Every element, from the legal environment, to the nature of the physical environment, to the economics involved in launching and operating satellites, adds layers of analytical complexity. Our simple framework can help policymakers identify fundamental intuitions, effective policies, and useful technologies to preserve this resource for future generations.

# 8 Mathematical appendix

## 8.1 A physical model

Equation 1 describes the long-run population of active satellites under constant launch rates across many physical models. We use a system of three differential

[26] Analysis in Jain and Rao (2022) supports this argument. They find that even if not all nations impose orbital-use policies like satellite taxes, and even if the nations who do impose them do not harmonize their policies and levy them strategically to maximize national gain from orbit use, unilateral actions can both improve international economic welfare and make implementing an international debris removal treaty more attractive to all spacefaring nations.

equations describing the evolution of object populations: one for debris fragments ($D(t)$), one for inactive objects ($I(t)$), and one for operational satellites ($S(t)$). Large objects such as operational satellites, rocket bodies, and non-operational satellites typically have a cross-section of a few square meters and a mass of hundreds of kilograms. Debris fragments are small objects generated by collisions. They typically have a cross-section of a few centimeters and a mass of a few grams, capable of causing catastrophic breakup when impacting a large object.

This model can represent all human actions capable of impacting the LEO environment while remaining analytically tractable. We focus on catastrophic collisions and ignore those which do not destroy the large bodies involved. The full system of equations is shown below.

$$\dot{D}(t) = \underline{\alpha} Q(t) - (\beta + r(t)) D(t) + \eta\theta D(t) (I(t) + S(t)), \quad D(0) = D_0 \tag{9}$$

$$\dot{I}(t) = \overline{\alpha} Q(t) - R(t) + (1-\rho) \lambda S(t) - \theta D(t) I(t), \quad I(0) = I_0 \tag{10}$$

$$\dot{S}(t) = Q(t) - (\lambda + \theta D(t)) S(t), \quad S(0) = S_0 \tag{11}$$

Equation 9 describes the evolution of the population of debris fragments. The first term, $\underline{\alpha}Q(t)$, refers to the fragments released as a byproduct of satellites launches (i.e. explosion of rocket bodies and space objects). The second term, $(\beta + r(t)) D(t)$, represents decay of the stock of debris fragments. On the one hand, a fraction of the stock of debris fragments falls back to Earth due to the atmospheric drag, with $\beta > 0$ the inverse of their average orbital lifetime. On the other hand, a fraction $r(t)$ of the stock of debris fragments is removed, as a result of active debris removal activities. The last term, $\eta\theta D(t) (I(t) + S(t))$, represents the new debris fragments due to collisions between debris fragments and large objects (inactive large objects and operational satellites), with $\eta > 0$ being the number of fragments per collision and $\theta D(t) \geq 0$ being the rate of collisions with debris per unit of satellite.

Equation 10 describes the evolution of the population of inactive large objects. The first term, $\overline{\alpha}Q(t)$, refers to the number of rocket upper stages released per satellite launched. The second term, $R(t)$ refers to inactive satellites instantly disposed of through debris removal activities. The third term, $\lambda S(t)$, represents the number of operational satellites becoming inactive due to technical failure or natural obsolescence, with $\lambda > 0$ being the inverse of their average operational lifetime. A fraction $\rho$ is deorbited, so only $(1 - \rho)\lambda S(t)$ non-operational satellites will remain in orbit waiting to fall back on Earth naturally. The last term, $\theta D(t)I(t)$, represents the number of intact large objects destroyed in collisions with fragments.

Equation 11 describes the evolution of the population of operational satellites. The first component, $Q(t)$, is the number of new satellites launched at time $t$. The second term, $(\lambda + \theta D(t))\, S(t)$, represents satellites which become non-operational, either for technical reasons (e.g. fuel exhaustion, failures) or environmental reasons (i.e. collisions). We assume intact large objects are monitored and active satellites successfully maneuver in order to avoid collision between them.[27]

To find the steady state, we set the satellite launch rate and debris removals to a constant ($Q(t) = Q$, $r(t) = r$ and $R(t) = R$ for all $t$) and seek constant orbital population stocks ($D(t) = D^*$, $I(t) = I^*$, and $S(t) = S^*$) such that $\dot{D}(t) = \dot{I}(t) = \dot{S}(t) = 0$. System of equations 9-11 can then be solved explicitly to get the steady state levels shown in equations 12, 13, and 14.

$$D^* = \frac{1}{2}\left(\eta\frac{\alpha Q - R}{\beta + r} - \frac{\lambda}{\theta} + \sqrt{\left(\eta\frac{\alpha Q - R}{\beta + r} + \frac{\lambda}{\theta}\right)^2 - 4\rho\eta\frac{Q}{\beta + r}\frac{\lambda}{\theta}}\right), \tag{12}$$

$$I^* + S^* = \frac{\beta + r}{\eta\theta} - \frac{\underline{\alpha} Q}{\eta\theta D^*}, \tag{13}$$

$$S^* = \frac{Q}{\lambda + \theta D^*}. \tag{14}$$

where we let

$$\alpha \equiv \frac{\underline{\alpha}}{\eta} + \overline{\alpha} + 1. \tag{15}$$

For ease of exposition, we use the following linear approximation of debris fragment stock in the main text:

$$D^* = \frac{\eta}{\beta + r}\left((\alpha - \rho)\, Q - R\right). \tag{16}$$

Substituting this in 14, the expression for the long-term operational satellite population will therefore be

$$S^* = \frac{Q}{\lambda + \theta\frac{\eta}{\beta+r}(\alpha - \rho)\, Q - \theta\frac{\eta}{\beta+r}R}. \tag{17}$$

In the main text we use the following "reduced-form" expression:

$$S^* = \frac{Q}{A + BQ}, \tag{1}$$

[27]The effort applied to maneuvering a satellite is a choice, and some operators may exert more effort than others. We assume all operators choose sufficient effort to avoid collisions with tracked objects.

| | $\underline{\alpha}$ | $\bar{\alpha}$ | $\eta$ | $\lambda$ | $\rho$ | $r$ | $R$ |
|---|---|---|---|---|---|---|---|
| $A$ | / | / | + | + | / | + | − |
| $B$ | + | + | + | / | − | − | / |

Table 3: Comparative statics.

where

$$A = \lambda - \theta \frac{\eta}{\beta + r} R \tag{18}$$

and

$$B = \theta \frac{\eta}{\beta + r} \left( \frac{\underline{\alpha}}{\eta} + \overline{\alpha} + 1 - \rho \right). \tag{19}$$

While equation 1 is a valid approximation of the long-run satellite stock size under many plausible physical models of orbit use, the definitions of $A$ and $B$ reflect the specifics of the model used.[28] We use the definitions of $A$ and $B$ to obtain table 3: qualitative descriptions of how these reduced-form parameters respond to changes in the structural parameters in the physical model. A "+" indicates that an increase in the parameter in the column leads to an increase in the parameter in the row, while a "−" indicates that an increase in the column parameter leads to a decrease in the row parameter. A "/" indicates that there is no effect.

## 8.2 An economic model

Following the derivation in Appendix 8.1, we express the long run satellite fleet as presented in equation 1:

$$S = \frac{Q}{A + BQ}, \tag{20}$$

where $A$ and $B$ are positive parameters. $A$ can be interpreted as the inverse of the (intrinsic) operational lifetime of a satellite (units of $[1/time]$) in a pristine orbital environment. $B$ can be interpreted as the inverse of the maximum carrying capacity of the orbit (units of $[satellites]$).

The revenue earned by a fleet of $S$ satellites in a single period is

$$R = pS, \tag{21}$$

where $p$ is the price received for satellite services delivered. The cost of designing and launching $Q$ satellites in a period is

$$C = cQ, \tag{22}$$

where $c$ is the cost of designing and launching a satellite.

[28]The term "reduced-form" is often used in economics to describe an equation whose form is invariant to many reasonable specifications of an underlying model of the process in question, and whose parameters are combinations of the "structural" parameters of the underlying model. Chapter 10 of Kennedy (2008) describes this distinction in more detail and provides a macroeconomic example involving a simultaneous equation system describing aggregate output, consumption, and investment in an economy.

### 8.2.1 The physico-economic equilibrium

By definition, the physico-economic equilibrium is a launch rate $Q$ satisfying a zero-profit condition, shown in equation 23.

$$R - C = 0 \iff p\frac{Q}{A + BQ} = cQ. \tag{23}$$

Assuming an interior solution and solving equation 23 yields the equilibrium launch rate and, with some manipulation, the equilibrium fleet size and lifetimes shown in Table 1. We rewrite these expressions below in terms of the benefit-cost ratio of a satellite, $\sigma = p/c$.

$$Q^* = \frac{\sigma - A}{B} \tag{24}$$

$$S^* = \frac{1}{\sigma}\frac{\sigma - A}{B} = \frac{1 - A/\sigma}{B} \tag{25}$$

$$\frac{S^*}{Q^*} = \frac{1}{\sigma}. \tag{26}$$

Using $\sigma$ here is convenient because, as seen in equation 26, the equilibrium lifetime of a satellite is the inverse of its benefit-cost ratio. Put differently, $1/\sigma$ is the time till the satellite breaks even—the number of years a satellite must operate and generate revenues in order to just cover the cost of designing, building, and launching it.[29] Formally, $p\,(1/\sigma) = c$.

Two properties follow from equations 24-26:

1. Both $Q^*$ and $S^*$ are decreasing in $A$ and $B$, and increasing in $\sigma$.
2. $S^*/Q^*$ is constant for all values of $A$ and $B$, and decreasing in $\sigma$.

The second result is particularly stark: any technical or policy change which improves intrinsic satellite lifetimes or environmental carrying capacity will have no effect on the equilibrium expected lifetime of a satellite *unless* the change also affects the benefit-cost ratio of a satellite. The first result shows that this would occur through additional launches which take advantage of the change.

### 8.2.2 The social optimum

By definition, the social optimum is a launch rate $Q$ which maximizes the net present value of the fleet. That is, the social optimum solves the program in equation 27.

$$\max_Q\{R - C\} = \max_Q\{p\frac{Q}{A + BQ} - cQ\}. \tag{27}$$

[29]Note that $\sigma > A$ is necessary to ensure an "interior" solution, i.e. one where non-zero numbers of satellites are launched. If $\sigma < A$ then operating a satellite would never be profitable because the time required to break even $(1/\sigma)$ would be longer than the asset's intrinsic life $(1/A)$. $\sigma > A$ therefore seems a natural property to assume if satellite operators are not *intending* to lose their satellites before they could be profitable.

The first- and second-order conditions are:

$$\text{(FOC)} \quad Q : p\frac{A}{(A+BQ)^2} = c \tag{28}$$

$$\text{(SOC)} \quad Q : -p\frac{2AB}{(A+BQ)^3} < 0. \tag{29}$$

Assuming again that $\sigma > A$ to ensure an interior solution, we can obtain the optimal launch rate, fleet size, and satellite lifetime shown in Table 1. We rewrite these expressions below in terms of the benefit-cost ratio $\sigma = p/c$.

$$Q^o = \frac{\sqrt{\sigma A} - A}{B} \tag{30}$$

$$S^o = \frac{1}{\sqrt{\sigma A}}\frac{\sqrt{\sigma A} - A}{B} = \frac{1 - \sqrt{A/\sigma}}{B} \tag{31}$$

$$\frac{S^o}{Q^o} = \frac{1}{\sqrt{\sigma A}} \tag{32}$$

Three properties follow from equations 30-32:

1. $Q^o$ is decreasing in $A$ if and only if $\sigma/A < \sqrt{2}$, decreasing in $B$ and increasing in $\sigma$.
2. $S^o$ is decreasing in $A$ and $B$, and increasing in $\sigma$.
3. $S^o/Q^o$ is decreasing in $A$ and $\sigma$ and is constant for all $B$.

The first two properties mirror the first property we described for the physico-economic equilibrium: increases in intrinsic lifetime, carrying capacity, or benefit-cost ratio will increase the optimal launch rate and fleet size. The third property breaks from the pattern of the physico-economic equilibrium: in the social optimum, the lifetime of a satellite is determined by both the benefit-cost ratio as well as the intrinsic lifetime. More precisely, the social optimum ensures that the expected lifetime of a satellite is the geometric mean of the breakeven time and the intrinsic lifetime. As long as satellites are designed to last longer than the time taken to break even (i.e. $\sigma > A$), the expected lifetime at the social optimum will exceed the breakeven time but be less than the intrinsic lifetime.

Finally, we can calculate the social surplus at the optimum (i.e. the maximum surplus attainable for a given set of physical and economic parameters) by substituting $Q^o$ into the fleet profit function:

$$R(Q^o) - C(Q^o) = \frac{p}{B}\left(1 - \sqrt{\frac{A}{\sigma}}\right)^2. \tag{33}$$

Differentiating with respect to $A$, $B$, and $\sigma$ yields the properties described in Section 5.4: the social surplus is decreasing in $A$ and $B$, and increasing in $\sigma$.

### 8.2.3 The optimal taxes

The optimal tax rates are taxes such that the physico-economic equilibrium and the social optimum coincide. In this section we derive optimal launch and satellite taxes.

An optimal *launch tax* $t_L$ must satisfy equation 34:

$$Q^*(t_L) = Q^o \iff \frac{\sigma_L - A}{B} = \frac{\sqrt{\sigma A} - A}{B}. \tag{34}$$

where we define $\sigma_L = p/(c + t_L)$ as the benefit-cost ratio of a satellite accounting for a launch tax. Solving this equation for $t_L$ yields the optimal launch tax:

$$t_L = c\left(\sqrt{\frac{\sigma}{A}} - 1\right). \tag{35}$$

In other words, the optimal launch tax is a fraction $\sqrt{\sigma/A} - 1$ of the unit cost $c$ of a satellite. The ratio $\sigma/A$ measures the number of times a satellite lasting for its full intrinsic lifetime will recover the costs associated with building and launching it. $\sqrt{\sigma/A} - 1$ can be thought of as an "intrinsic incentive" to launch a satellite: large (much greater than 1) values of $\sigma/A$ indicate that a satellite lasting its full intrinsic lifetime will repay its costs more than once, while smaller values indicate fewer payback multiples over the satellite's intrinsic lifetime. The optimal launch tax thus scales with a measure of the intrinsic incentive to launch a satellite. More formally, all else equal $t_L$ is decreasing in $A$ (shorter intrinsic lifetimes produce a weaker incentive to launch), independent of $B$, increasing in $p$ (greater revenues produce a stronger incentive to launch), and decreasing in $c$ if and only if $\sigma/A < \sqrt{2}$.

An optimal *satellite tax* $t_S$ must satisfy equation 36:

$$Q^*(t_S) = Q^o \iff \frac{\sigma_S - A}{B} = \frac{\sqrt{\sigma A} - A}{B} \tag{36}$$

where we define $\sigma_S = (p - t_S)/c$ as the benefit-cost ratio of a satellite accounting for a satellite tax. Solving this equation for $t_S$ yields the optimal satellite tax:

$$t_S = p\left(\sqrt{\sigma A} - 1\right). \tag{37}$$

In other words, the optimal satellite tax is a fraction $\sqrt{\sigma A} - 1$ of revenues $p$ from the satellite services. The quantity $\sqrt{\sigma A}$ measures the inverse of the geometric mean lifetime of a satellite (calculated over the inverse payback period $\sigma$—which is also the expected equilibrium lifetime—and the inverse intrinsic lifetime $A$). $\sqrt{\sigma A} - 1$ measures the "intrinsic incentive" to operate a satellite: large (much greater than 1) values of $\sqrt{\sigma A}$ indicate that a satellite can be expected to repay its costs more than once even if it does not live out its full intrinsic lifetime.[30] The optimal satellite tax thus scales with a measure of the intrinsic incentive to operate a satellite. More formally, all else equal $t_S$ is increasing in $A$, independent of $B$, decreasing in $c$, and increasing in $p$ if and only if $\sigma A > \sqrt{2/3}$.

## 8.3 Calibrated parameter values

The numerical examples in section 6 use the calibration shown in Table 4. We draw these values from the engineering literature on debris modeling.

The values listed in Table 4 are used without modification for the "initial" scenario. In the "tech. alone" scenario we consider a technological innovation which costlessly increases the immediately-deorbited fraction ($\rho$) from 25% to 50%. This leaves the intrinsic lifetime ($1/A$) unchanged, but increases the carrying capacity ($1/B$) from roughly 526 satellites to roughly 714 satellites ($B \approx 0.0019$ to $B \approx 0.0014$). We assume this technological innovation involves a device attached to the satellite which facilitates its disposal (e.g. deployable tethers or drag sails). In the final "tech. + cost" scenario, we relax the assumption that the innovation is costless to operators and allow it to increase the unit cost of a satellite ($c$) from \$15.8 million/satellite to \$18 million/satellite.

A few words on the interpretation of $\sigma$ are in order. Mechanically, $\sigma$ is the benefit-cost ratio of a satellite in one year: the ratio of one year's revenues from the satellite to its costs. Since the revenues are an annual flow while the costs are a one-time payment, $1/\sigma$ is in units of years, reflecting the time taken for a satellite to produce enough revenues to cover its costs. $\sigma$, then, is in units of "times per year": the number of times a satellite will pay back its cost in a one-year period. $\sigma$ can therefore be interpreted as an (inverse) "earnings multiple" for a satellite asset. Similar metrics arise in other settings where investors pay an upfront cost in exchange for a claim on a (possibly risky) stream of revenues over time, e.g. purchasing shares in a company.[31]

[30] Recall that we assume $\sigma > A$ to ensure an interior solution, implying that the payback period is shorter than the intrinsic lifetime (i.e. $1/\sigma < 1/A$).

[31] A stock's "earnings multiple" or "earnings multiplier" is the ratio of the share price (a one-time payment, similar to $c$) to the earnings per share (an annual flow, similar to $p$), and denotes the number of years required for the earnings per share to recover the share price. $\sigma = p/c$ is therefore the inverse of a similar metric for a satellite asset.

| Parameter | Value | Notes | Source |
|---|---|---|---|
| $\alpha$ | 4.43 fragments/sat | Launch-related small fragments | Computed from ESA (2021b) |
| $1/\beta$ | 1000 years | Average orbital lifetime of debris fragments | Consistent with Farinella and Cordelli (1991), Lafleur (2011), and Percy and Landrum (2014) |
| $\overline{\alpha}$ | 0.2 intacts/sat | Launch-related large intact objects | Computed from ESA (2021b) |
| $\eta$ | 5000 fragments/large object | Fragments produced per collision between fragments and large objects (intacts or active satellites) | Consistent with Farinella and Cordelli (1991), Lafleur (2011), and Percy and Landrum (2014) |
| $1/\lambda$ | 4.65 years | Design lifetime of a satellite | Computed from UCS (2021) |
| $\theta$ | $4 \times 10^{-10}$ collisions/fragment-year | Rate of collisions between active satellites and fragments | Consistent with Farinella and Cordelli (1991), Lafleur (2011), and Percy and Landrum (2014) |
| $\rho$ | 0.25 intacts/sat | Fraction of satellites deorbited immediately at end-of-life | ESA (2021a) |
| $1/A$ | 4.65 years | Intrinsic lifetime ($A \approx 0.2150$) | Authors' calculation per equation 18 |
| $1/B$ | 526 satellites | Carrying capacity ($B \approx 0.0019$) | Authors' calculation per equation 19 |
| $p$ | 22.1 M$/sat-year | Annual revenue per satellite | Computed from UCS (2021) and SIA (2020) |
| $c$ | 15.8 M$/sat | Cost per satellite | Computed from UCS (2021) and SIA (2020) |
| $\sigma$ | 1.4 times/year | Benefit-cost ratio | Authors' calculation per equation 2 |

Table 4: Calibrated parameter values used in Section 6. Intact and fragment removal are both set to zero ($r = R = 0$).

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