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Earth Orbit Debris: An Economic Model

Nodir Adilov, Indiana-Purdue University Fort Wayne
Peter J. Alexander, Federal Communications Commission
Brendan M. Cunningham, United States Naval Academy

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Abstract

Space debris, an externality generated by expended launch vehicles and damaged satellites, reduces the expected value of space activities by increasing the probability of damaging existing satellites or other space vehicles. Unlike terrestrial pollution, debris created in the production process interacts with firms' final products, and is, moreover, self-propagating: collisions between debris or extant satellites creates additional debris. We construct an economic model to explore private incentives to launch satellites and to mitigate space debris. The model predicts that, relative to the social optimum, firms launch too many satellites and under-invest in debris mitigation technologies. We discuss remediation strategies and policies, and calculate a socially optimal Pigovian tax.

*Contact author: peter.alexander@gmail.com (Alexander). This is a preliminary draft. The views presented here reflect the views of the authors, and do not reflect the views of the Federal Communications Commission or the United States Naval Academy. No government resources were used in producing this draft, and all data are from publicly available sources. We are indebted to David Sappington, Donald Kessler, Bill Gibson, Michael Ash, Nicholas Johnson, J.C. Liou, Scott Pace, Brian Weedon, Henry Hertzfeld, Heidi Garrett-Peltier, James Boyce, Ceren Soylu, Kevin Crocker, and the seminar participants in the Environmental Working Group, PERI Institute, University of Massachusetts, Amherst, for their useful comments on early drafts.

1 Introduction

Common resources (e.g., fisheries, grazing land, etc.) may be over-consumed relative to the social optimum, because individuals have incentives to over-use common resources as long as private marginal benefits exceed marginal costs.[1] This over-use may come at the expense of other users or even the eventual sustainability of the resource. This view is presumed by Hardin (1968), who observes:

> Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. As a rational being, each herdsman seeks to maximize his gain. The rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another; and another....But this is the conclusion reached by each and every rational herdsman sharing a commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit–in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all.[2]

Hardin suggests private property rights or government ownership as institutional solutions to over-use of common resources. Private property rights as a solution to commons over-use is a mainstay paradigm within economics (see e.g. Demsetz, 1967), although other recent work explores alternatives to a simple property rights approach (see e.g., Fehr et al. 2008).

A nuanced, and complementary, perspective is offered by Ostrom (1999), who implies that private property and government ownership of common resources are extrema on a higher-dimensional spectrum of institutional solutions. According to Ostrom (1990), the evolution of local governance structures of a common resource is typical of many successfully exploited common resources. In short, in these instances, neither private property nor government ownership is required to successfully manage a common resource. Rather, local institutions emerge from the interactions of local users, who successfully negotiate with each other to mitigate over-use that might confer unfair benefits

[1] A very general economic taxonomy of types of goods is straightforward: private goods are rival (in use) and excludable; club goods are non-rival and excludable; public goods are non-rival and non-excludable; and common goods are rival and non-excludable.

[2] Hardin observed over-use of common resources by individuals; in the case of orbital space, overuse is driven by nations.

on individual users or generate a collapse of the resource.[3]

Orbital space, the common resource we explore here, is however, local only in a narrow sense, and structuring workable institutions to effectively govern its use is difficult. Perhaps unsurprisingly, orbital space is the type of global common resource where Ostrom (1999) sees the greatest management urgency and complexity, noting:

> The lessons from local and regional common pool resources are encouraging, yet humanity faces new challenges to establish global institutions to manage biodiversity, climate change, and other ecosystem services. We have only one globe with which to experiment. Historically, people could migrate to other resources if they made an error in managing a local CPR. Today, we have less leeway for mistakes at the local level, while at the global level there is no place to move.

Prior to the launch of Sputnik in 1957, resource rights over orbital space were nonexistent, and earth orbital space was a 'pristine' common.[4] Shortly after Sputnik, orbital rights were largely assumed and administered by the United States and the Soviet Union, via the United Nations.[5] Not much more than fifty years after Sputnik, orbital rights have evolved into a complex blend of international, national, and (implicitly) private, property.

In 2010, worldwide revenue from orbital commercial satellite services was over 100 billion dollars.[6] These services include, among other things, satellite television, radio, and broadband, mobile voice and data services, a variety of business and governmental applications, and GPS (global positioning services).[7] There are approximately 965 active satellites currently in orbit, the majority of which belong to the United States (443),

[3]Unlike many terrestrial common resources, technological progressivity generally out-weighs geography in accessing earth-orbit. A nation's geographic proximity to space is roughly equivalent to any other nation's; technological capability is the essential separating feature, which can only be overcome by developing the required technological knowledge and skills, or by contracting with an entity that has a presence in orbit. Contrast this with access to other common resources such as the earth's oceans: even some technologically-advanced landlocked countries do not have ocean-faring navies or direct access to fisheries. Thus, the rules of access are, in this instance, driven by technology.

[4]In fact, space was, and is, not a pristine common in the generally accepted sense of pristine. Enormous quantities of naturally occuring debris pass through orbital space in the form of meteriods and space dust.

[5]Awareness of the need for an institutional framework for the use of space trace back to the first half of the 20th century. A detailed review of this earlier literature is given in Lyall and Larsen, 2009.

[6]http://www.spacecolorado.org/news/2011-state-of-the-satellite-industry-report-shows-growth.html

[7]http://www.futron.com/upload/wysiwyg/Resources/Reports/SSIR2010.pdf

China (69), and Russia (101).[8] Of the United States' total, 194 are commercial, 121 are military, 118 are government, and 10 are civil. Comparable figures are not available for the Chinese and Russian fleets.

Satellites are typically in one of three possible orbits: LEO, MEO, or GEO. LEO (low-earth orbit) comprises the region between 110-1,240 miles above the surface of the earth; MEO (mid-earth orbit) the region between 1,240-26,200 miles; and GEO (geostationary orbit) anything greater than 26,200 miles.[9] Approximately 49 percent of extant satellites are in LEO; 6 percent are in MEO; and 41 percent are in GEO (the remainder are in elliptical or other orbits).[10]

1.1 Orbital Debris

Orbital debris is space pollution. NASA (National Aeronautics and Space Administration) defines debris as non-functional human-made space objects.[11] Initially, debris is created from the upper stages of expended launch vehicles when a satellite is launched. This is analogous to a standard terrestrial industrial process where pollution is "jointly-produced" with manufactured goods. Additional debris is created by the satellites themselves, both as they reach the end of their productive lives and break up, and as the result of impact with debris or with other satellites, among other things.

Debris can damage or destroy communication, weather, navigational, governmental, and military satellites. On multiple occasions, for example, astronauts from the International Space Station have evacuated to an emergency escape capsule because debris threatened to impact the Space Station.[12] Schwartz (2010) provides additional detail:

> [In 2009] a stray motor chunk hurtled toward the International Space Station. Cruising at an altitude of 220 miles, astronauts aboard the 100 billion dollar laboratory were going about their daily chores at around noon EDT when they received a warning-prepare for possible impact. The crew was directed to scramble into the station's equivalent of a lifeboat, an attached Russian-made Soyuz capsule. It would give them a chance to abandon ship, if necessary. After a few minutes, the motor zipped by, missing the ISS by

[8] http://www.ucsusa.org/nuclearweaponsandglobalsecurity/spaceweapons/technicalissues/ucs-satellite-database.html.

[9] http://earthobservatory.nasa.gov/Features/OrbitsCatalog/

[10] http://www.ucsusa.org/nuclearweaponsandglobalsecurity/spaceweapons/technicalissues/ucs-satellite-database.html

[11] http://www.orbitaldebris.jsc.nasa.gov/library/EducationPackage.pdf

[12] http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv13i2.pdf

> just a few miles - in space terms a close call.
>
> Then on December 1 [2009], with almost no warning, a small chunk from a [defunct] Cosmos satellite hurtled toward the ISS, coming within a mile of a direct hit. Due to its speeding-bullet velocity, even this fragment could have had an impact equal to that of a truck bomb. “A ten-centimeter sphere of aluminum would be like seven kilograms of TNT,” says Jack Bacon, a senior NASA scientist charged with keeping the ISS safe. “It would blow everything to smithereens.”

According to NASA, 42 percent of total extant debris is fragmentation debris (resulting primarily from the break-up of satellites), 22 percent is non-functional spacecraft, 19 percent is mission related debris, and 17 percent is rocket bodies.[13] Currently, there are approximately 21,000 human-generated (radar tracked) pieces of debris measuring over 10 centimeters, 600,000 (untracked) pieces of debris between 1 and 10 centimeters, and over 100,000,000 (untracked) pieces of debris between .1 and 1 centimeter in earth orbit.[14]

Debris greater in size than 10 centimeters can be tracked by earth stations, and satellites can, given sufficient warning, engage in evasive maneuvers to potentially avoid a collision. A collision with a piece of debris greater than 10 centimeters, however, will likely destroy a satellite and generate significant amounts of additional debris. Debris greater in size than 1 centimeter but less than 10 centimeters cannot be earth-tracked, but can destroy a satellite.[15] Thus, these pieces of debris are particularly dangerous (since they are not currently tracked). Debris less than 1 centimeter in size can damage or potentially destroy a satellite, although additional shielding, which increases production costs, can protect the satellite from damage.[16]

Orbital debris has degrees of persistence: a few days if the debris is less than 125 miles above the earth’s surface; a few years if the debris is between 125 and 370 miles; decades if the debris is between 370 and 500 miles; centuries if the debris is greater than 500 miles, and essentially forever if the debris is at greater altitudes, especially as one approaches GEO altitudes. Thus, at very low altitudes (less than 125 miles) space is quickly self-cleansing, however, peak debris density in LEO occurs at 550 miles, which

[13] http://www.orbitaldebris.jsc.nasa.gov/library/EducationPackage.pdf

[14] http://www.oosa.unvienna.org/pdf/limited/AC105C12011CRP14E.pdf

[15] Liou, 2011

[16] Wright (2007), and also McKnight (2010) who observes that the destructiveness of the impact depends on both the mass of the objects as well as the encounter geometry.

suggests centuries would pass before the region is self-cleaned (assuming no additional debris is added during that time).[17]

The quantity of trackable debris (> 10 cm) in earth orbit increased substantially after 2007. This increase was largely due to two events: the intentional destruction by the Chinese of a Chinese-made weather satellite (FengYun 1C) in January 2007, and the accidental collision between the Cosmos 2251 and Iridium 33 satellites in February 2009. The destruction of the FengYun weather satellite generated more than 3,000 trackable objects and over 150,000 additional pieces of debris over 1 cm in size, at an altitude approximately 540 miles above the surface of the earth (i.e., low earth orbit). The Cosmos-Iridium collision generated at least 2100 additional pieces of trackable debris, at an altitude approximately 490 miles above the earth's surface.[18]

Unlike standard terrestrial pollution, debris propagates additional pollution. Thus, for example, a collision between a satellite and a piece of debris, or even between two pieces of debris, creates additional debris which further increases the likelihood of other debris creating collisions. Kessler (1991) proposed the possibility of a sufficiently dense debris cloud that would lead to a cascade of collisions, ultimately rendering space unusable.[19] The probability of such an event is unknown, although the probabilities increase in the density of the debris field. A recent National Academy of Sciences report states that:

> ...the current orbital debris environment has already reached a "tipping point." That is, the amount of debris, in terms of the population of large debris objects, as well as overall mass of debris currently in orbit, has reached a threshold where it will continually collide with itself, further increasing the population of orbital debris. This increase will lead to corresponding increases in spacecraft failures, which will only create more feedback into the system, increasing the debris population growth rate. The increase thus far has been most rapid in low earth orbit (LEO), with geosynchronous earth orbits (GEOs) potentially suffering the same fate, but over a much longer time period. The exact timing and pace of this exponential growth are uncertain, but the serious implications of such a scenario require careful attention...[20]

[17] History of On-Orbit Satellite Fragmentations, 14th Edition, Orbital Debris Program Office, NASA/TM2008

[18] Limiting Future Collision Risk to Spacecraft: An Assessment of NASAs Meteoroid and Orbital Debris Programs; http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i2.pdf

[19] Kessler (1991). This is analogous to the "shallow lake" problem explored in Brock and Starrett (2003) or a bit more popularly, a "black swan" event.

[20] Limiting Future Collision Risk to Spacecraft: An Assessment of NASAs Meteoroid and Orbital Debris Programs, Committee for the Assessment of NASAs Orbital Debris Programs, Aeronautics and

In what follows, we formally model private incentives to launch satellites and mitigate space debris. While the physics community and the popular press have provided abundant literature on this subject, to our knowledge, this is the first theoretical economic model that analyses the issue of satellite launches and space debris. Our results suggest that there are two main economic factors contributing to the increase in space debris. First, competitive firms tend to launch more satellites than socially desirable because they do not take into consideration the damaging effects of increased debris generated by launch vehicles on other satellites. Second, competitive firms tend to select more polluting technology because they only compare individual marginal benefits and costs of their technology choice and fail to take into account social benefits and costs. These findings suggest that the policy makers need to address both of these negative externalities in order to effectively address the problem of space pollution. To this end, our model could serve as a useful economic framework for policy-makers when analysing the effects of various policy options designed to reduce the impact of space debris on consumers, firms, and social welfare.

1.2 Paper Outline

In the next section, we present a model of debris creation in which orbital debris is a negative externality, and solve for the satellite launch rate which emerges in a decentralized setting. After solving for the decentralized launch rate, we compare that rate with the socially optimal level of launches and debris creation that would be chosen by a social planner who internalizes the negative effects of debris. We then endogenize debris creation, allowing firms to explicitly choose a level of debris creation, and compare this to the socially optimal level. We next discuss proposals for debris remediation. Finally, we conclude.

2 Model

2.1 Structure and Assumptions

In this section, we construct a two-period model in which competitive firms choose their launch rate. Firms and consumers are modelled using a Salop circle, where each

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participant has a preferred location in the market corresponding to their particular services or demands.

Consumers of satellite services are private individuals, private firms (such as Verizon, AT&T, Google, etc.), academic and scientific institutions, and governmental agencies of various kinds (including military and civilian institutions, such as NOAA). Suppliers are satellite operators who provide a variety of information services to these consumers, including television, radio, broadband, mobile voice and data, environmental and mapping services, and GPS, to name a few. Product differentiation is captured in the model by the distance a consumer is from their most preferred location on the circle.[21]

After constructing the basic two-period competitive model, we introduce a social planner who internalizes the debris externality, and compare launch rates. We then relax our assumption of a homogeneous debris creation rate, and extend the model by allowing firms to explicitly choose technologies that embody differential debris creation rates, and explore firms' incentives. We then compare the launch and debris creation rate chosen by the firms to the social optimum.

2.1.1 Consumers

Following Salop (1979) we assume that consumers are uniformly distributed with unit density on a circle of perimeter one.[22] We assume that satellites are located around the circle and each consumer buys one unit of the good from the closest satellite. Consumer $i's$ utility from purchasing a unit from satellite j is $s - p_j - td(i, j)$, where s is the consumer's gross surplus, p_j is the price charged by satellite j, $d(i, j)$ is the distance between consumer $i's$ and satellite $j's$ locations, and $t > 0$ is a parameter that measures the dis-utility (cost) consumer i experiences because satellite $j's$ location differs from consumer $i's$ ideal location.[23] For simplicity, we assume $t > 0$ is a linear cost. Following Salop (1979) and Tirole (1988), it is assumed that s is large enough so that consumers

[21] It is important to note, simply for the purpose of accuracy, that substantial demand for satellite services exist for military and para-military organizations in the United States and elsewhere. At least some of the demand of these institutions is self-supplied i.e., these organizations have their own satellites in orbit.

[22] See Tirole (1988) for a discussion on the appropriateness of a circular model when analysing the number of firms in a differentiated product industry.

[23] It is important to note that location is not to be taken literally in our model. Distance is stylized and represents the loss of satellite service quality which is experienced as a consequence of buying service from a provider which is less-than ideal (i. e. not "located" immediately in the neighborhood of a consumer.

purchase from one firm or another, i.e., the market is complete.

2.1.2 Firms

At the beginning of period one, we assume there is no human-created debris or satellites in space.[24] During period one, firms simultaneously decide whether (or not) to launch a satellite. Each firm pays $r > 0$ to launch a satellite, a fixed per period cost of $F > 0$ to maintain a satellite in orbit, and a marginal cost of $c \geq 0$ to serve each consumer. Once the satellites are launched, we assume that they are located equidistant from one another on the circle. In period one, each firm j chooses price $p_{j,1}$ while profit is $(p_{j,1} - c)q_{j,1} - r - F$, where $q_{j,1}$ is firm $j's$ quantity demanded at price $p_{j,1}$.

At the end of period one, a fraction of the satellites are destroyed by debris generated by launch vehicles. Assuming L is the number of satellites launched in period one, the quantity of debris equals $D = \phi L$, where $\phi > 0$ represents the debris generated per launch.

In period two, firms do not launch new satellites, but receive revenues from the remaining satellites in orbit. The number of remaining satellites is given by $S = L - kD$, where $k > 0$ and $0 < k\phi < 1$. The parameter k represents the rate at which satellites are lost due to collision with debris. We assume that each satellite faces an equal probability of destruction and that the remaining satellites remain located equidistant from one another in period two. Based on the parameters specified above, the probability that a satellite remains in orbit in period two is $1 - k\phi$. Each firm j chooses its price for period two, $(p_{j,2})$, if satellite is still in orbit, and incurs fixed cost of F and a marginal cost of c as before. Period two profits are discounted by β, where $0 < \beta < 1$. The sum of firm $j's$ expected profits from both periods is $(p_{j,1} - c)q_{j,1} - r - F + \beta(1 - k\phi)((p_{j,2} - c)q_{j,2} - F)$.

2.2 Launch Rate: Competitive Market Structure

We next calculate the equilibrium prices and number of satellites for each period, where, following Salop (1979), we restrict our analysis to the symmetric zero-profit Nash equilibrium. Because we assume free entry with identical firms, equilibrium economic profit is zero.

[24] We abstract throughout from naturally occurring orbital debris.

To begin, first fix the number of satellites at L, and consider firm $j's$ pricing decision in period one when other firms are charging p. A consumer i located between firm $j's$ and the adjacent satellite $j+1$ would purchase from firm j if $s-p_{j,1}-td(i,j) > s-p-td(i,j+1)$ and from firm $j+1$ if $s-p_{j,1}-td(i,j) < s-p-td(i,j+1)$. Consumer i is indifferent to purchasing from firm j or $j+1$ if $s-p_{j,1}-td(i,j) = s-p-t(1/L-d(i,j))$.

Then, the demand for firm j in period one is:[25]

$$D_j(p_{j,1}, p) = (p + t/n - p_{j,1})/t \tag{1}$$

and firm j maximizes profit by solving:

$$\max_{p_{j,1}} (p_{j,1} - c)\left(\frac{p + t/L - p_{j,1}}{t}\right) - F - r \tag{2}$$

Differentiating (2) with respect to $p_{j,1}$ and equating to zero yields $p_{j,1} = (p + t/L + c)/2$. Then, setting $p_{j,1} = p$ yields:

$$p = c + t/L \tag{3}$$

where t/L is the mark-up over cost.

The period two pricing decision for firms is similar to that of period one. In the second period, because only $(1-k\phi)L$ satellites remain in orbit, firms charge $p = c + \frac{t}{(1-k\phi)L}$, which implies that each firm's sum of expected profits from both periods is:

$$\pi = \frac{t}{L^2} - r - F + \beta(1-k\phi)\left(\frac{t}{((1-k\phi)L)^2} - F\right) \tag{4}$$

To determine the equilibrium number of satellite launches in a competitive market structure, we assume a zero economic profit condition $\pi = 0$. This implies that the equilibrium number of launches in a competitive market is:

$$L_{Com} = \sqrt{\frac{(\beta + (1-k\phi))t}{(1-k\phi)(r + F + \beta(1-k\phi)F)}} \tag{5}$$

Proposition 1. The launch rate in a competitive market is increasing in parameters t, β, ϕ and k, and decreasing in parameters r and F.

[25] See Salop (1979) or Tirole (1988) for further discussion on the derivation of the demand curve in a circular model.

Proof.

$$\frac{\partial L_{Com}}{\partial t} = \frac{1}{2t}\sqrt{\frac{(\beta + (1-k\phi))}{(1-k\phi)(r+F+\beta(1-k\phi)F)}} > 0 \tag{6}$$

$$\frac{\partial L_{Com}}{\partial \beta} = \frac{1}{2\sqrt{L_{Com}}} \cdot \frac{t}{(1-k\phi)} \cdot \frac{r + Fk\phi(2-k\phi)}{(r+F+\beta(1-k\phi)F)^2} > 0 \tag{7}$$

$$\frac{\partial L_{Com}}{\partial \phi} = \frac{1}{2\sqrt{L_{Com}}} \cdot \frac{k\beta t(r + F + 2\beta F(1-k\phi) + F(1-k\phi)^2)}{[(1-k\phi)(r+F+\beta(1-k\phi)F)]^2} > 0 \tag{8}$$

$$\frac{\partial L_{Com}}{\partial k} = \frac{\partial L_{Com}}{\partial \phi} > 0 \tag{9}$$

$$\frac{\partial L_{Com}}{\partial r} = \frac{1}{2\sqrt{L_{Com}}} \cdot \frac{-(1-k\phi)(\beta + (1-k\phi))t}{[(1-k\phi)(r+F+\beta(1-k\phi)F)]^2} < 0 \tag{10}$$

$$\frac{\partial L_{Com}}{\partial F} = \frac{1}{2\sqrt{L_{Com}}} \cdot \frac{-(1-k\phi)(1+\beta(1-k\phi))(\beta + (1-k\phi))t}{[(1-k\phi)(r+F+\beta(1-k\phi)F)]^2} < 0 \tag{11}$$

The intuition behind these results is relatively straightforward. For example, when the parameter t increases, it lessens price competition among firms because it is more costly for consumers to switch between competing satellites. This allows firms to increase prices, and thus, their expected profits. The increased expected profits encourage more satellite launches. Similarly, an increase in the discount factor, β, increases expected firm profits and encourages new satellite launches.

Next, consider the effects of a change in the debris creation parameter ϕ and in the debris damage parameter k. An increase in ϕ or in k reduces the number of satellites that remain functional in period two, which increases expected firm revenues due to reduced competition in period two. On the other hand, the firms' expected costs also increase due to more satellite collisions with the debris. Our model suggests that the increase in expected revenues is greater than the increase in expected costs. Therefore, greater ϕ or greater k increases expected firm profits and encourages more launches.[26] Finally, increasing costs, both F and r, reduce firm profits and the number of launches in equilibrium.

2.3 Launch Rate: Social Planner

We next explore the industry's optimal number of satellite launches as determined by a social planner who maximizes the discounted sum of expected firm profits and consumer surplus. The discounted sum of expected firm profits equals:

$$\sum \pi_i = p - c - L(r+F) + \beta(p - c - (1-k\phi)LF) \tag{12}$$

and the discounted sum of expected consumer surplus equals:

$$CS = s - p - 2tL\left(\int_0^{\frac{1}{2L}} xdx\right) + \beta\left(s - p - 2tL(1-k\phi)\left(\int_0^{\frac{1}{2L(1-k\phi)}} xdx\right)\right) \tag{13}$$

Because we assume that s is large enough so that all consumers are served, deriving the social optimum is equivalent to minimizing the sum of consumers' transportation costs and firms' launch and fixed costs. Specifically, the social planner solves the following optimization problem:

$$\max_L \quad \sum \pi_i + CS \Leftrightarrow$$

$$\Leftrightarrow \min_L \quad L(r+F) + 2tL\left(\int_0^{\frac{1}{2L}} xdx\right) + \beta(1-k\phi)LF + 2\beta tL(1-k\phi)\left(\int_0^{\frac{1}{2L(1-k\phi)}} xdx\right) \tag{14}$$

This simplifies to the following minimization problem:

$$\min_L \quad L(r+F) + \frac{t}{4L} + \beta(1-k\phi)LF + \frac{\beta t}{4L(1-k\phi)} \tag{15}$$

the first-order condition of which implies that:

[26] Our model suggests that the risk of collisional cascades is high, since an increase in debris creation (or satellite loss risk) induces more launches which further increases the probablility of more collisions. Thus, there is a positive feedback loop which, without mitigation, can lead to a "Kessler syndrome" (see Kessler, 1978).

$$r + F + \beta(1-k\phi)F - \frac{((1-k\phi)+\beta)t}{4L^2(1-k\phi)} = 0 \tag{16}$$

or:

$$r + F + \beta(1-k\phi)F = \frac{((1-k\phi)+\beta)t}{4L^2(1-k\phi)} \tag{17}$$

The left-hand side (LHS) of equation (17) is an increase in firms' costs when one more satellite is launched. The right-hand side (RHS) is a decrease in consumers' transportation costs when an additional satellite is launched. At the social optimum, these (marginal) costs should be equal. Solving for L yields the socially optimal level of launches:

$$L_{soc} = \frac{1}{2}\sqrt{\frac{(\beta+(1-k\phi))t}{(1-k\phi)(r+F+\beta(1-k\phi)F)}} \tag{18}$$

Because the launch rate of a social planner is simply half the rate of a competitive market, the results from Proposition 1 still apply.

Corollary 1. The launch rate for the social planner is increasing in parameters t, β, ϕ and k, and decreasing in parameters r and F.

Proof.

$\frac{\partial L_{soc}}{\partial t} = \frac{1}{2}\frac{\partial L_{Com}}{\partial t} > 0$, $\frac{\partial L_{soc}}{\partial \beta} = \frac{1}{2}\frac{\partial L_{Com}}{\partial \beta} > 0$, $\frac{\partial L_{soc}}{\partial \phi} = \frac{1}{2}\frac{\partial L_{Com}}{\partial \phi} > 0$, $\frac{\partial L_{soc}}{\partial k} = \frac{1}{2}\frac{\partial L_{Com}}{\partial k} > 0$, $\frac{\partial L_{soc}}{\partial r} = \frac{1}{2}\frac{\partial L_{Com}}{\partial r} < 0$, and $\frac{\partial L_{soc}}{\partial F} = \frac{1}{2}\frac{\partial L_{Com}}{\partial F} < 0$.

The intuition for these results is as follows. As noted earlier, the social planner minimizes the sum of consumers' transportation costs and firms' launch and fixed costs. When the parameter t increases, consumers' transportation costs increase, and thus, the social planner launches more satellites to reduce the RHS of equation (17). An increase in the parameter β increases the consumers' discounted sum of transportation costs at a faster rate than an increase in firms' expected costs. Thus, the optimal number of launches increases when β increases. When the parameter ϕ or k increases, more satellites are damaged by debris and fewer satellites remain in period two. This increases consumers' transportation costs (and the RHS of equation (17)), while firms' expected costs in period two (and the LHS of the equation) decrease. Thus, the social planner would choose to launch more satellites. An increase in the launch cost r or the fixed cost F only increases the LHS of equation (17), which reduces the socially optimal number of launches.

2.4 A Comparison of Launch Rates

We next use the results obtained from sections 4.2 and 4.3 to compare the competitive launch rate to the social optimum. The main finding is:

Proposition 2. Competitive firms launch more satellites than the social optimum.

Proof. Comparing L_{Com} and L_{soc} yields $L_{soc} = \frac{1}{2}L_{Com} < L_{Com}$.

This result implies that a satellite industry with competitively determined launch rates will result in a loss of social welfare. Profit maximizing behavior results in excess launching since firms fail to internalize the impact of debris on industry profits and consumer welfare. A launch will generate lower expected profits since it increases the risk to existing satellites.

2.5 Endogenous Choice of the Debris Creation Rate

Until now, we have assumed that launches are homogeneous in the debris creation rate. Next, we assume the debris creation rate is endogenous, and each firm chooses the debris creation rate parameter ϕ, where $\phi \in [0, \phi_H]$ and $\phi_H < 1$. This assumption is meant to capture the notion that launchers can choose technologies which increase, or decrease, the amount of debris associated with a launch. The choice of ϕ directly impacts the firm's launch cost r, where $r = h(\phi)$. The function h is decreasing in ϕ at a decreasing rate, where $h'(\phi) < 0$ for $\phi < \phi_H$, $h'(\phi_H) = 0$, $h''(\phi) > 0$, and $h(\phi_H) > 0$. In other words, it is increasingly more costly to reduce the debris creation rate by an additional unit.

Let ϕ_i be the debris creation rate chosen by firm i. Then, the quantity of debris generated equals $D = \sum_{i=1}^{L} \phi_i = \bar{\phi}L$, where $\bar{\phi} = \frac{\sum_{i=1}^{L} \phi_i}{L}$ is the *average* rate of debris creation. In period two, the number of satellites equals $S = L - kD = L - k\bar{\phi}L = (1 - k\bar{\phi})L$.

2.5.1 Competitive Market

In a competitive market, under the assumption a firm can choose the debris creation rate, firm i's expected profit equals:

$$\max_{\phi_i \in (0,\phi_H]} \pi_i = \max_{\phi_i \in (0,\phi_H]} \frac{t}{L^2} - h(\phi_i) - F + \beta(1 - k\bar{\phi}) \left(\frac{t}{((1 - k\bar{\phi})L)^2} - F \right) \tag{19}$$

Proposition 3. Competitive firms choose the highest rate of debris creation, $\phi_1 = \phi_2 = ... = \phi_L = \phi_H$.

Proof. Differentiating π_i defined in (19), with respect to ϕ_i yields:

$$\frac{\partial \pi_i}{\partial \phi_i} = -h'(\phi_i) - \frac{\beta k}{L}\left(\frac{t}{((1 - k\bar{\phi})L)^2} - F\right) + \frac{2k\beta t}{L^3(1 - k\bar{\phi})^2} = \tag{20}$$

$$= -h'(\phi_i) + \frac{k\beta t}{(1 - k\bar{\phi})^2 L^3} + \frac{\beta k F}{L} > 0 \tag{21}$$

This implies that firm $i's$ profit is strictly increasing in ϕ. Therefore, it is optimal for each firm i to choose $\phi_i = \phi_H$ regardless of what other firms choose. This completes the proof.

Proposition 3 implies that competitive firms choose the least costly technology, which generates the most debris, because the firms cannot increase their profits by reducing ϕ.

Next, we set each firm's ϕ equal to ϕ_H and calculate the equilibrium number of launches (by equating expected firm profits to zero). This yields:

$$L_{Com} = \sqrt{\frac{(\beta + (1 - k\phi_H))t}{(1 - k\phi_H)(h(\phi_H) + F + \beta(1 - k\phi_H)F)}} \tag{22}$$

Note that the formula for the equilibrium number of launches is the same as in the case of exogenous ϕ, with the simple amendment that the debris creation rate for firms is set at ϕ_H.

2.5.2 The Social Planner

Next, we analyze the optimal level of debris creation under a social planner. Specifically, we assume that the social planner chooses both a launch rate and debris creation rate that maximizes the sum of producer and consumer surplus.

Let $L(\phi)$ be the optimal rate of launches under a social planner for a given parameter ϕ as given in equation (18). Then, the optimal ϕ solves:[27]

$$\min_{\phi\in[0,\phi_H]} V = \min_{\phi\in[0,\phi_H]} L(\phi)h(\phi)+L(\phi)F+\frac{t}{4L(\phi)}+\beta(1-k\phi)L(\phi)F+\frac{\beta t}{4L(\phi)(1-k\phi)} \quad (23)$$

Proposition 4. The social planner's optimal rate of debris creation is $\phi_{soc} < \phi_H$, and its launch rate is below the competitive launch rate, $L_{soc} < L_{Com}$.

Proof. First, we note that the problem defined in (23) has a solution because the value function V is continuous in ϕ on its closed and bounded domain. Differentiating V with respect to ϕ, while noting that $\frac{\partial V}{\partial L} = 0$, yields:

$$\frac{dV}{d\phi} = L(\phi)h'(\phi) + \frac{\beta k}{4L(\phi)(1-k\phi)}(t - 4F(1-k\phi)(L(\phi))^2) \qquad (24)$$

To prove that $\phi_{soc} < \phi_H$, it suffices to show that $\frac{dV}{d\phi}|_{\phi_H} > 0$. Evaluating (24) at ϕ_H yields $\frac{dV}{d\phi}|_{\phi_H} = \frac{\beta k}{4L(\phi_H)(1-k\phi_H)}(t - 4F(1-k\phi_H)(L(\phi_H))^2)$. This expression is positive if $t - 4F(1-k\phi_H)(L(\phi_H))^2 > 0$.

$$t - 4F(1-k\phi_H)(L(\phi_H))^2 =$$

$$t - 4F(1-k\phi_H)\frac{(\beta+(1-k\phi_H))t}{4(1-k\phi_H)(h(\phi_H)+F+\beta(1-k\phi_H)F)} =$$

$$\frac{(h(\phi_H)+(1-\beta)k\phi_H F)t}{h(\phi_H)+F+\beta(1-k\phi_H)F} > 0$$

[27] The formula for the social planner is the same as in (15) with the modification that the social planner can endogenously choose parameter ϕ.

Next, we compare the launch rates. According to Corollary 1, $L_{soc}(\phi_{soc}) < L_{soc}(\phi_H)$ because $\phi_{soc} < \phi_H$. Furthermore, according to Proposition 2, $L_{soc}(\phi_H) < L_{Com}(\phi_H)$. Therefore, $L_{soc}(\phi_{soc}) < L_{Com}(\phi_H)$. This completes the proof.

In our model, the launch rate for a competitive market is greater than the social planner's rate for two reasons. First, competitive firms have a higher debris creation rate (ϕ) because the benefits of lowering debris accrue to others as an externality while the costs are borne by the launcher. Second, even if the debris creation rate ϕ were set at the social optimum, a competitive market launches more satellites than the social optimum because a competitive firm does not take into account the negative externality its satellite launches impose on other firms. In short, relative to the social optimum, firms launch too many satellites and under-invest in debris mitigation technologies.

3 General Proposals for Mitigating Orbital Debris

In this section, we discuss mechanisms that might tighten the correspondence between the launch and debris creation rates of competitive firms to the social optimum. From a policy perspective, reducing the rate of growth in debris is essential for the long-term health of orbital resources, since the debris field in important orbits continues to grow. As we noted in the introduction, unlike 'standard' terrestrial pollution, debris propagates additional pollution. Thus, for example, a collision between a satellite and a piece of debris, or even between two pieces of debris, creates additional debris which further increases the likelihood of other debris-creating collisions. Don Kessler, an astrophysicist, and former director of NASA's Orbital Debris Program Office, proposed the possibility of a sufficiently dense debris cloud that would lead to a cascade of collisions, ultimately rendering certain orbital space unusable.[28] Such a scenario is popularly referred to as the "Kessler Syndrome." The probability of such an event is unknown, although the probabilities increase in the density of the debris field. Remediation techniques, such as active debris removal, have been proposed as a means of reducing the probability of impacts and a collisional cascade, but even if these measures were fully implemented, debris densities are projected to increase substantially over the next century.[29]

[28]Kessler and Cour-Palais, 1978
[29]Liou (2010).

In what follows, we discuss various means of remediating orbital debris, including voluntary guidelines, command and control approaches, and active debris removal, as well as approaches that utilize economic incentives, such as Pigovian taxes.[30] It is beyond the scope of this paper to do more than organize remediation proposals, and provide a framework for evaluating the general efficacy and drawbacks of various mechanisms. We suggest, however, that a blend of active debris removal along with another mechanism that would reduce the production of orbital debris and the number of launches might be a useful approach. In particular, active debris removal appears to have broad support within the scientific community, but will require funding. Thus, a paired measure that is designed to passively reduce debris creation by reducing the number of launches and provide a source of funding for active debris removal might be helpful. To that end, we calculate the socially optimal Pigovian tax. We note that policy proposals require somewhat uniform consent among divergent interest groups, including those across national boundaries, which adds substantial complexity and nuance.

3.1 Voluntary Guidelines

In 2010, the United Nations Office for Outer Space Affairs issued mitigation guidelines for operators within member states. The guidelines suggest that operators should (1) limit debris released during normal operations, (2) minimize the potential for breakup during operational phases, (3) limit the probability of accidental collision in orbit, (4) minimize potential for post-mission breakups resulting from stored energy, (5) avoid intentional destruction and other harmful activities, (6) limit the long-term presence of spacecraft and launch vehicle orbital stages in low earth orbit at the end of their mission, and (7) limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit region at the end of their mission.

Note that these guidelines are recommendations, which no member state or operator is obligated to follow. Given that at least some of the guidelines impose direct costs but confer only indirect benefits on operators, the marginal costs of compliance will exceed marginal benefits. In short, it will not be individually rational for operators to voluntarily undertake (at least some of) the costs of mitigation. This is precisely what was found in Proposition 3 of our model: profit-maximizing commercial operators choose the least costly mitigation technology, which in turn generates the most debris.

[30] See also Macauley (2003) for a policy discussion on remediating debris.

It is important to note that even given heterogeneity among operators in their choice of technology, voluntary guidelines will not be effective, because firms will still launch too many satellites relative to the social optimum.

3.2 Command and Control

Command and control measures, such as those regulations issued by the Environmental Protection Agency, are a standard feature of much domestic (US) environmental regulation, and often utilize emission limits and technology standards. Thus, in a command and control regulatory environment, firms are required to meet an emissions or technological standard. However, even in relatively simple regulatory settings, command and control measures can lead to efficiency losses. Such is the case, for example, with uniform emission standards with cost heterogeneity among firms. In this case, the government must know the marginal abatement costs for each firm, which is infeasible. Thus, command and control approaches may fail to meet the requirement of static efficiency. Moreover, if firms are required to use certain abatement technologies, it potentially reduces the incentives to innovate, and induces dynamic inefficiencies. If, however, a command and control approach were feasible, our model predicts that this would only partially solve the problem of excess debris creation because the firms would launch more satellites than socially optimal.

3.3 Active Debris Removal

Liou and Johnson (2006) observe that (even) absent new launches, the debris population in low earth orbit will continue to increase over the next 200 years as a result of collisions between extant space objects. Moreover, they note that new, additional satellite launches further increase the growth rate in debris. Liou (2011) explores the implications of active debris removal, and suggests that:

> The future debris environment is likely to be dominated by accidental collision fragments. This phenomenon is popularly known as the "Kessler Syndrome" after the pioneering work by Kessler and Cour-Palais (1978). If the ADR objective is to reduce the population growth, then the effort should focus on limiting accidental collision fragments. In other words, the best ADR strategy to meet this mission objective is to target objects with the highest collision probabilities and objects with the potential of generating the greatest amount of fragments upon collision.

To put a fine point on this, Liou suggests active debris removal should focus on extant objects that have the greatest probability of collision and that will also produce the greatest fragmentation in the event of a collision. The technology for active debris removal is largely conceptual, and proposed removal systems appear, operationally at least, somewhat distant. Moreover, it is not clear how the cost of the debris removal systems will be borne. As Liou (2010) notes, "the idea of ADR is not new, but it has never been widely accepted as necessary or feasible, primarily due to the tremendous technical challenges and cost involved." Assuming that active debris removal becomes technologically feasible, the costs are likely to be high, and it is not clear how they might be apportioned among (various government and private) users.[31]

3.4 Taxes

A Pigovian tax is a classic economic approach to internalizing external costs. The regulator can affect firms' costs and therefore the firms' incentives for launches and debris mitigation technology choices via the tax structure. Assume that the regulator announces a tax schedule T prior to period one and that firms launching satellites pay the tax in period one. (We assume that the rest of the model is unchanged and the same as described in section 2.5.) We assume that the tax schedule has two parts: a per launch tax w and a variable tax $\gamma(\phi)$ that varies with the parameter ϕ. Then, the total tax T equals $w + \gamma(\phi)$. Suppose L_{soc} and ϕ_{soc} denote the socially optimal level of launches and the parameter ϕ, respectively. Then, as shown in equation (18), the socially optimal level of launches equals:[32]

$$L_{soc} = \frac{1}{2}\sqrt{\frac{(\beta + (1 - k\phi_{soc}))t}{(1 - k\phi_{soc})(h(\phi_{soc}) + F + \beta(1 - k\phi_{soc})F)}} \tag{25}$$

Proposition 5 below demonstrates that the regulator can choose a tax schedule that induces the competitive market to choose the optimal levels of launches and debris creation rate.

Proposition 5. There exists a tax schedule T^* such that the competitive market yields $L = L_{soc}$ and $\phi = \phi_{soc}$.

[31] McKnight (2010), among other things, provides an overview of active debris programs and proposals.
[32] Note that $r = h(\phi_{soc})$ when the social planner can select ϕ.

Proof. Provided in the appendix.

Thus, there exists a tax schedule that induces competitive firms to choose the socially optimal level of launches and the parameter ϕ. Moreover, the revenues generated by the optimal tax might be additionally rationalized by funding a program of active debris removal. However, the practical problem of getting various economic actors to agree to a launch tax is daunting, to say the least.

4 Conclusion

Space debris, an externality generated by expended launch vehicles and damaged satellites, reduces the realized value of space activities by increasing the probability of damaging existing satellites or other space vehicles. Unlike terrestrial pollution, debris created in the production process interacts with firms' final products, and is, moreover, self-propagating: collisions between debris or extant satellites creates additional debris. In the limiting case, collisional cascading could reduce the realized value of certain earth orbits to zero.

Voluntary guidelines regarding debris remediation have been employed over the past 50 years, but, as we showed in our model, voluntary guidelines provide insufficient incentives. In fact, competitive firms will generally choose the least-costly mitigation technology, which in turn generates the most debris, because it carries the lowest cost for the firm. In our model, a social planner that takes into account the welfare of both producers and consumers would generate fewer launches as compared to the competitive market, and it would employ technology that reduces the rate of debris creation.

Active debris removal technology is pre-emergent and costly; funding will likely require the cooperation of governments of space-faring nations. Since active debris removal is retrospective, nations that have created the majority of extant debris, the United States, Russia, and China, might provide funding commensurate with created debris. A tax on launches provides a straight-forward economic solution to externalities. Future research might formally investigate the effectiveness of various policy remedies to space pollution.

References

[1] Brock, W. A., and D. Starrett, “Managing Systems with Non-convex Positive Feedback,” *Environmental and Resource Economics*, 26, 575-602, 2003.

[2] Demsetz, Harold, “Toward a theory of property rights,” *American Economic Review* 57 (May): 347-359, 1967.

[3] Fehr, Ernst, Susanne Kremhelmer, and Klaus M. Schmidt, “Fairness and the Optimal Allocation of Ownership Rights,” *The Economic Journal*, 118 (August), 2008.

[4] Gabrynowicz, Joanne Irene, “One Half Century and Counting: The Evolution of U.S. National Space Law and Three Long-Term Emerging Issues,” 4, *Harvard Law and Policy Review*, 901 (2010).

[5] Hardin, Garrett, “The Tragedy of the Commons,” *Science*, Vol. 162, No. 3859,(1968), pp. 1243-1248

[6] Hitchens, Theresa, “Multilateralism in Space: Opportunities and Challenges for Achieving Space Security,” *Journal of Space and Defense*, Volume Four, Number Two, Summer 2010.

[7] Kessler, Donald J., “Collisional cascading: The limits of population growth in low earth orbit,” *Advances in Space Research*, Volume 11, Issue 12, 1991.

[8] Kessler, Donald J., N.L. Johnson, J.-C. Liou, M. Matney, The Kessler Syndrome: Implications to Future Space Operations, AAS 10-016, *Advances in the Astronautical Sciences*, v. 137, 2010, pp.47-62.

[9] Liou, J.C., “A Parametric Study on Using Active Debris Removal for LEO Environment Remediation,” *Advances in Space Research*, Volume 47, Issue 11, 2011.

[10] Liou, J.C., N.L. Johnson, and N.M. Hill, “Controlling the Growth of Future LEO Debris Populations with Active Debris Removal,” *Acta Astronautica*, Volume 66, Issues 5-6, March-April 2010, pp. 648-653.

[11] Lyall, Francis, “On the Privatisation of INTELSAT,” *Journal of Space Law*, pp.101-19, 2001.

[12] Lyall, Francis and Paul B. Larsen, “Space Law: A Treatise,” Ashgate, 2009.

[13] Macauley, Molly, "Regulation on the Final Frontier," *Regulation*, Vol. 26, No. 2, pp. 36-41, Summer 2003.

[14] McKnight, Darren,"Pay Me Now or Pay Me More Later: Start the Development of Active Orbital Debris Removal Now," Paper presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, September 2010.

[15] Ostrom, Elinor, "Governing the Commons: The Evolution of Institutions for Collective Action," Cambridge University Press, 1990.

[16] Roberts, Lawrence D., "Addressing the Problem of Orbital Space Debris: Combining International Regulatory and Liability Regimes," *Boston College International and Comparative Law Review*, 15, 51, 1992.

[17] Salop, Steven C., "Monopolistic Competition with Outside Goods," *The Bell Journal of Economics*, Volume 10, Issue 1, pp. 141-156, 1979.

[18] Schwartz, Evan, "Waste MGMT," The Best American Science and Nature Writing, Houghton, Mifflin, Harcourt, 2011.

[19] Senechal, Thierry, "Orbital Debris: Drafting, Negotiating, Implementing a Convention," MBA Thesis, MIT, 2007.

[20] Tirole, Jean, "The Theory of Industrial Organization," The MIT Press, 1988.

[21] Warf, Barney, "Geopolitics of the Satellite Industry," *Journal of Economic and Social Geography*, Vol. 98, No. 3, pp. 385397, 2007.

[22] Wong, Henry, "2001: A Space Legislation Odyssey - A Proposed Model for Reforming the Intergovernmental Satellite Organizations," *American University Law Review*, Volume 48 Issue 2, 1998.

[23] Wright, David, "Space Debris," *Physics Today* 60: 35-40, 2007.

[24] Zee, Chong-Hung, "Theory of Geostationary Satellites," Springer-Verlag, New York, 1989.

A Appendix: Proof to Proposition 5

Suppose the regulator selects a variable tax rate $\hat{\gamma}(\phi) = \{\gamma(\phi) = 0$ if $\phi = \phi_{soc}$, $\gamma(\phi) = s$ if $\phi \neq \phi_{soc}\}$. Because s is the maximum consumer surplus value for the market (as introduced in section 2.1.1), $\phi = \phi_{soc}$ is the only choice for firms that could yield non-negative profits. Thus, any firm that chooses to launch a satellite would select $\phi = \phi_{soc}$. Next, suppose the regulator sets a per launch tax rate $\hat{w} = 3(h(\phi_{soc}) + F + \beta(1 - k\phi_{soc})F)$. Then, the tax schedule equals $\hat{T} = 3(h(\phi_{soc}) + F + \beta(1 - k\phi_{soc})F) + \hat{\gamma}(\phi)$. Equation (5) from section 2.2 describes the number of launches in the competitive market for a given ϕ. Then, under the tax schedule $\hat{T}$, the number of launches in the competitive market would equal:

$$
\begin{aligned}
L_{Com} &= \sqrt{\frac{(\beta + (1 - k\phi_{soc}))t}{(1 - k\phi_{soc})(h(\phi_{soc}) + \hat{T} + F + \beta(1 - k\phi_{soc})F)}} \\
&= \sqrt{\frac{(\beta + (1 - k\phi_{soc}))t}{(1 - k\phi_{soc})(4)(h(\phi_{soc}) + F + \beta(1 - k\phi_{soc})F)}} \\
&= \frac{1}{2}\sqrt{\frac{(\beta + (1 - k\phi_{soc}))t}{(1 - k\phi_{soc})(h(\phi_{soc}) + F + \beta(1 - k\phi_{soc})F)}} = L_{soc}
\end{aligned}
$$

Thus, $L_{Com} = L_{soc}$ and $\phi_{com} = \phi_{soc}$ under the tax schedule $\hat{T}$.