TOLLWAYS IN SPACE: FROM SCI-FI TO SAVING GRACE

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ABSTRACT

With unprecedented space activity, skyrocketing collision risks, and falling debris increasingly in the public eye, the need for decisive action on space debris has never been more urgent. While active debris removal (ADR) presents engineering challenges, the real stumbling block is the lack of binding regulations and financial incentives for sustainable use of orbital environment. ADR remains trapped in a vicious circle: high development costs and unproven technology deter investment, yet industry support & funding is necessary for further advancements. Without intervention, the market has no inherent need to break this cycle.

This paper proposes the ***Orbital Tollway Framework***, a scalable economic model that funds debris removal through mandatory fees in congested LEO regions, creating clear incentives and a self-sustaining cycle for orbital cleanup. Built on existing spectrum management mechanisms, the framework is a partnership between the International Telecommunication Union (ITU) and national authorities, each playing a key role. The ITU provides stewardship by setting global guidelines and coordination mechanisms, while national authorities manage administration, enforcement, and investment allocation. This approach strikes a delicate balance between global cooperation and national interests while aligning environmental benefits with industry growth.

1. THE MILLION DOLLAR QUESTION

As we enter the next era of space exploration, the focus is shifting from launching missions to constructing advanced in-space infrastructure, with one major obstacle standing in the way: the growing threat of space debris. The million-dollar question of who bears the cost of space debris cleanup has been a longstanding issue, directly tied to uncertainty about liability and the lack of incentives. Over the past decades, this issue has been a game of hot potato between governments, space agencies, and the industry with marginal progress. Currently, there's no clear funding mechanism for active debris removal (ADR) beyond the space agencies' investments, leaving the "tragedy of the commons" unresolved. Various models, including regulatory fees, taxes, tradeable permits, clean-up funds, have been suggested, highlighting the need for international cooperation. However, achieving consensus remains challenging especially in current geopolitical environment. Additionally, balancing environmental sustainability with industry impact is crucial for successful adoption. What follows is a framework that aims to strike this delicate balance.

2. THE ISSUE OF INCENTIVE

The growing problem of space debris has been debated for decades and is now at the forefront of sustainability discussions. Currently, there are aprx. 40,000 tracked objects in space [1]. With a record-high 223 launches in 2023 and projections of another 36,900 objects entering space by 2033, the collision risk is increasing exponentially [2], [3]. Recent incidents of space junk hitting Earth are increasingly making headlines, raising public awareness. With unprecedented space activity, rising collision risks, and the debris issue now in the public eye, it's necessary to transition from discussions to actions.

Managing space debris requires an integrated approach, combining debris avoidance, limiting debris creation (mitigation), and debris removal (remediation). Significant progress has been made in debris avoidance, through improved tracking and development of Space Situational Awareness (SSA) capabilities. While various debris mitigation guidelines exist, they are all non-binding, leading to voluntary and thus sub-optimal compliance especially in LEO. Initiatives like ESA's Zero Debris Charter and the UK's Astra Carta are aimed at encouraging sustainable practices, but participation remains voluntary, attracting industry players with existing commitment to sustainability[4]. These initiatives also do not address accumulation of debris over the past decades.

While debris avoidance and mitigation efforts have seen some momentum, the remediation, or ADR, has significantly lagged behind. The root of the issue lies in the regulatory environment, which lacks both incentives and penalties to promote compliance and sustainable practices. Despite widespread recognition of the problem, the absence of binding regulations, financial incentives, and proven technologies continue to hinder meaningful progress. ADR faces a catch-22: high development costs and unproven technology make it difficult to attract investment, while the industry is hesitant to commit without validated, cost-effective solutions. This creates a vicious cycle, with supply side requiring demand to mature, but the demand side is reluctant to invest without proven capabilities and regulatory pressure. Without intervention, the market has no inherent need to bridge this gap. Therefore,

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government action—through binding regulations and incentives—is essential to break this deadlock and enable the development of the ADR market.

Pioneering companies like ClearSpace, Astroscale, Starfish Space, and Kall Morris, are diligently working to demonstrate the technology, relying on a handful of government sponsored missions. The question remains: can they sustain their efforts long enough for the necessary market conditions and regulatory framework to materialize?

3. ORBITAL TOLLWAY FRAMEWORK

The proposed Orbital Tollway Framework draws from the concept of Orbital-Use Fees and terrestrial congestion measures [5]. It introduces mandatory fees for highly congested LEO subregions, assessed annually and based on an object's duration in orbit. The fee structure operates on a deposit-refund model to incentivize operators to deorbit objects and improve compliance with debris mitigation guidelines. Operators receive partial refunds upon successful deorbiting, while non-compliance results in penalties. Collected fees and fines must be allocated to sustainability initiatives, primarily debris removal.

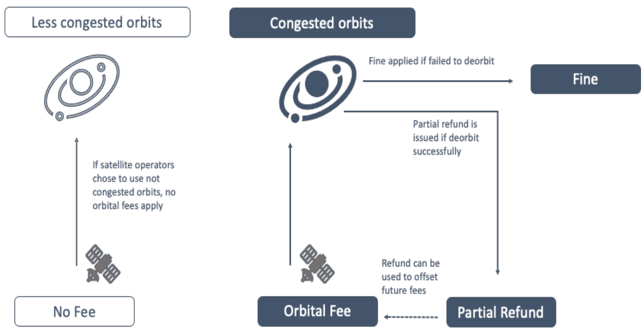

Figure 1: The Orbital Tollway Framework *illustrates an orbital fee for congested zones and no fee for less congested regions. Satellite operators in congested orbits pay annual fees in exchange for access to spectrum. Partial refunds are granted for successful deorbiting and fines levied for non-compliance. The collected funds are reinvested into sustainability programs and debris removal, establishing a self-sustaining cycle for orbital cleanup.*

While the framework establishes a global fee structure, management remains with national governments, similar to the existing spectrum management and usage fees. It empowers national authorities to collect and reinvest the funds into local or regional space sustainability efforts, allowing each state to control funds and their national activities. Given the urgency of needed action and the fact that global consensus will remain a challenge for the forseeable future, structuring this way emerges as the only viable option.

The management of spectrum and orbital resources is currently disconnected. While spectrum management is governed by well-defined rules, the orbital environment lacks similarly clear regulations[6]. This framework aims to align the two, recognizing that both should be managed in a comparable manner to ensure the efficient use and equitable access to space. The Outer Space Treaty (OST) was designed to preserve national sovereignty in space activities, yet Article IX emphasizes the importance of avoiding harmful contamination of both Earth's environment and outer space, as well as preventing harmful interference with the activities of other states. This provision offers a solid foundation for fostering international collaboration, without the need to reinvent existing constructs.

Overall this framework seeks a dynamic equilibrium between global cooperation and national interests, while balancing industry impact with practical environmental benefits.

3.1 Financials: How Much Can This Generate?

A simplified model estimates that the Orbital Tollways framework could generate $5-10 billion over the next decade. This is based on annual fees ranging from $75,000 to $200,000, differentiated by orbital region, with a 40% refund for successful deorbiting, and a very conservative estimate on number of fines ranging between $750,000 and $3M. The number of objects is based on Novaspace forecast, and assumption was made that 80% of the objects in LEO would be in congested orbits and thus subject to the Tollway fee[3]. While the model provides a high-level feasibility indication, more detailed analysis is required to refine the assumptions.

3.2 Viability: Is It Enough to Clean Orbits?

The short answer is YES for critical orbital areas, but NO for removing all debris. Estimating the cost of debris removal remains challenging since no commercial service exists yet, and pricing depends on factors like size, mass, and orbit. KMI is the only company that published estimates ranging from $4M to $62.5M per object[7]. Assuming an average removal cost of $20M per object, allocating 60% of the lower-end projection of $5B to ADR, the scheme could fund the removal of 150+ objects over a decade, or 15 objects per year. It is assumed that 60% of the funds generated will be allocated to ADR activities, with the remaining 40% reserved for the administration of the scheme and other sustainability measures.

To put this figure in perspective, the studies generally suggest that removing 5 to 10 large debris objects per year could significantly reduce the risk of Kessler

Syndrome, a cascade of collisions that could make certain orbits unusable[8][9].

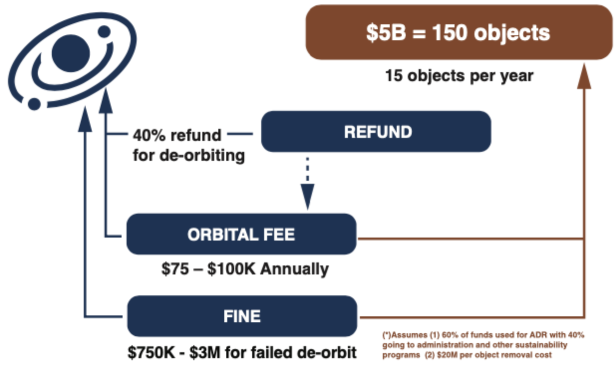

Figure 2: The Orbital Tollway Revenue Model *details the financial mechanics behind a conservative $5B estimate. Satellite operators pay an annual orbital fee ($75K–$100K), with a 40% refund for successful deorbiting and fines of $750K–$3M for non-compliance. Over a decade, collected fees and fines could generate up to $5B, funding the removal of 150+ high-risk debris objects.*

While this seems like a small fraction of the total debris problem, with focus on the most critical orbital zones and objects, the impact will be significant. Congestion is anticipated to peak at 400-600km altitudes, but atmospheric drag naturally deorbits objects within a decade, while debris above 600km poses greater long-term challenges that future deployments will exacerbate[3][10]. The highest debris concentration is at altitudes of 800 to 1000km and 1400km, where objects can remain for centuries[11]. The global expert community has already identified the top 50 most-concerning derelict objects, nearly all are in these debris-dense bands[12]. Focusing on these critical zones and objects will make the overwhelming problem more manageable, enabling effective change.

3.3 Ownership: Who Can Take on This Weight?

The success of any mechanism relies heavily on international collaboration but balancing the common good with sovereign interests amid geopolitical tensions remains a challenging task. Global collaboration, particularly at the UN level, is essential to ensure the effectiveness of this framework. Without such coordination, there is a risk of "forum shopping," where parties seek more lenient regulations in different jurisdictions, undermining the overall effort. A united approach is necessary to build a comprehensive and enforceable system that can address the debris problem globally.

The International Telecommunication Union (ITU) emerges as the pivotal organization to establish binding global regulations, given its strategic control over the space sector's most valuable resource: frequencies. Any reform will still require the approval of its members, but if structured as a collaborative partnership between ITU and national authorities, it stands a chance. Member States play a leading role in this scheme, with national authorities responsible for reinvesting collected funds into ADR and other sustainability initiatives at the national or regional level. This approach empowers national authorities as they retain control over their activities while addressing a pressing global issue.

Although the ITU does not regulate physical objects in space, its authority and experience position it as the ideal body to lead the development of binding global regulations. In September, ITU held its first Space Sustainability Forum to gather experts and stakeholders to discuss responsible space usage. Its proven track record, such as introducing a milestone-based approach to regulate mega-constellation deployments, demonstrates its ability to adapt to emerging challenges and drive necessary reforms.

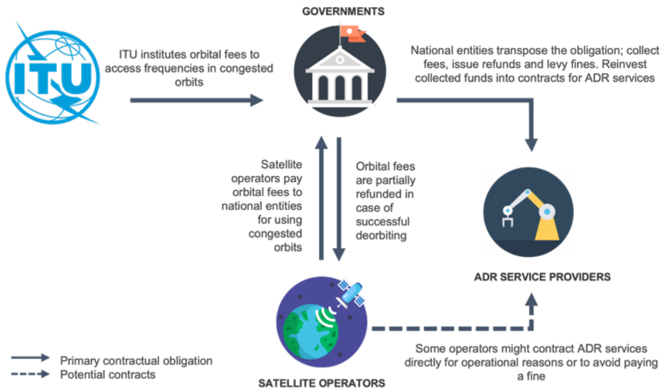

Figure 3: The Orbital Tollway Key Players *and their primary roles and contractual obligations. The ITU establishes an orbital use fee for congested orbits, linked to frequency allocation. In partnership with ITU, the national regulators implement and administer the system by collecting fees, issuing refunds for successful deorbiting, and imposing fines for non-compliance. The collected funds are allocated to sustainability measures and debris removal missions.*

4. PATH FORWARD: TURNING CONVERSATIONS INTO ACTIONS

As space exploration accelerates, binding international regulations incentivizing sustainable practices becomes essential. The Orbital Tollway framework presents a practical, scalable solution to address space debris by introducing incentives and generating funding for debris removal. While it won't eliminate all debris, it focuses efforts on critical orbital zones and high-risk objects, making the issue more manageable and actionable.

This framework, as any paradigm shift, might seem daunting but reforms are inevitable – the debris issue won't magically sort itself out. Moving from discussions to actions will require a commitment to change from industry, governments, and regulators, acknowledging that any progress will take funding and resources. Fortunately, much groundwork already exists in charters, space-agencies sponsored studies, and other research. The process is also already established given the framework's similarity to frequency licensing procedures. What remains is to thoughtfully bring these elements together and address any remaining gaps.

Next steps could involve further economic modeling to address industry concerns about cost burdens while demonstrating potential benefits. A pilot program involving key space-faring nations under the auspices of the ITU could then be launched to test the Orbital Tollway concept on a smaller scale. This would help overcome obstacles and refine the framework for a more practical and equitable design. Space agencies, with their extensive expertise, can actively contribute alongside industry, bringing regulators into the fold to ensure alignment and collaboration in implementing this transformational reform.

Although a debris-free orbit is unrealistic in the near term, this framework sets a viable path for progress, striking a delicate balance between global cooperation and national interests, while aligning tangible environmental benefits with realities of industry growth.

Figure 4: *Orbital Tollway Booths, image generated with Dall-E*

This proposal offers a structured response to the space debris problem, but the author acknowledges that the framework requires further refinement. Feedback and collaboration are welcome to help design a viable solution. For any questions or inquiries, please contact polina.shtern@community.isunet.edu.

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