Appendix: The U.S.-China Military Balance in Space

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Figure 1

The single-shot probability of hit (SSPh) on a circular target is:[1]

$$\text{SSPh} = 1 - 0.5^{(\text{r}/\text{CEP})^2}$$

Where:

- r is the radius of the target in meters
- CEP is the circular error probable of the weapon in meters

Figure 2

The cumulative probability of hitting a target (Ph) is:[2]

$$\text{Ph} = 1 - (1 - \text{SSPh})^{\text{N}}$$

Where:

- SSPh is the single-shot probability of hit
- N is the number of weapons fired

Figure 3

The line of sight to the horizon measured in kilometers is:[3]

$$\text{Line of Sight} = \sqrt{2\text{Rh}} \approx 3.57 * \sqrt{\text{h}}$$

Where:

- R is the radius of the Earth
- h is the height of the transmitting antenna in meters

[1]For this equation, see: Joshua R. Itzkowitz Shifrinson and Miranda Priebe, "A Crude Threat: The Limits of an Iranian Missile Campaign Against Saudi Arabian Oil," *International Security*, Vol. 36, No. 1 (Summer 2011), p. 187, fn. 90.
[2]For this equation, see: Jacob L. Heim, "The Iranian Missile Threat to Air Bases: A Distant Second to China's Conventional Deterrent," *Air and Space Power Journal*, Vol. 29, No. 4 (July/August 2015), p. 47, fn. 28.
[3]See, for example, EverythingRF, https://www.everythingrf.com/rf-calculators/line-of-sight-calculator, No Date.

To calculate the line of sight distance between two antennas, add the height of the receiving antenna:

$$\text{Line of Sight} \approx 3.57 * (\sqrt{h_1} + \sqrt{h_2})$$

Where:

- h_1 is the height of the transmitting antenna
- h_2 is the height of the receiving antenna

Figure 4

The model of amphibious lift capacity for Figure 4 adapts the approach from RAND's 2015 *U.S.-China Military Scorecard* report.[4] The model provides a way to estimate how many troops China can transport to Taiwan via military sealift and how different rates of attrition to China's fleet would reduce its capacity to deliver reinforcements over time. Table A1 below summarizes the updated data for 2024. Because the model does not incorporate China's dual-use civilian ships or its airborne and air assault forces, readers should not interpret Figure 4 as a comprehensive model of China's lift capacity in a Taiwan scenario.[5] The model relies on several simplifying assumptions that are particularly influential for the estimates it produces, so this section of the appendix makes those assumptions transparent and discusses their implications.[6]

Table A1: China's Military Amphibious Lift Capacity

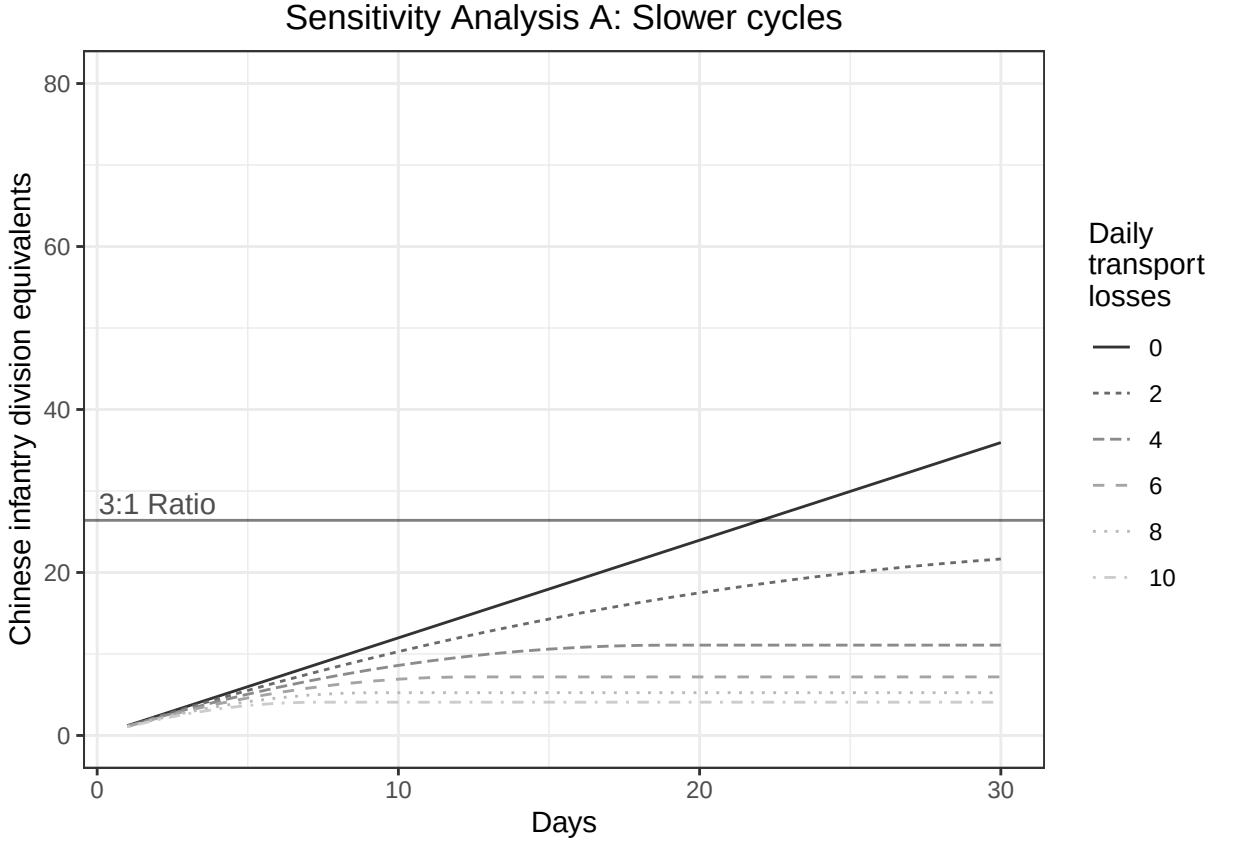
Ship	**Type**	**Troops**	**Tanks/AFVs**	**Active Ships**
Type-075 (Yushen)	LHD	1,200	50-60	3
Type-071 (Yuzhao)	LPD	730	24	8
Type-072-II (Yukan)	LST	200	10-11	4
Type-072-III (Yuting I)	LST	250	10	9
Type-072A (Yuting II)	LST	250	10	9
Type-072B (Yuting II)	LST	260	10	6
Type-073-II (Yudeng)	LSM	180	6-7	1
Type-073A (Yunshu)	LSM	180	8-10	10
Type-074 (Yuhai)	LSM	250	2-3	11
Type-074A (Yubei)	LCU	70	4	11
Type-958 (Zubr)	LCAC	360	3	6
Total Capacity		23,960	792+	78

SOURCE: Conor Kennedy, "Getting There: Chinese Military and Civilian Sealift in a Cross-Strait Invasion," in *Crossing the Strait: China's Military Prepares for War with Taiwan*, Joel Wuthnow et al., Eds. (Washington, D.C.: National Defense University, 2022), pp. 226-227; Robert Wall, ed., *The Military Balance* (London: International Institute for Strategic Studies, 2024), p. 258; Heginbotham et al., *The U.S.-China Military Scorecard*, p. 203.
NOTE: The "total capacity" estimates are the capacity of each class of transport multiplied by the number of ships in service. In some cases, the ship can likely carry either that many vehicles or that many troops but not both simultaneously. AFV – Armored fighting vehicle; LHD – Landing helicopter dock; LPD – Landing platform/dock; LST – Landing ship, tank; LSM – Landing ship medium; LCU – Landing craft utility; LCAC – landing craft air cushion.

[4] Eric Heginbotham et al., *The U.S.-China Military Scorecard: Forces, Geography, and the Evolving Balance of Power, 1996–2017* (Santa Monica, CA: RAND, 2015), p. 205. It also draws some inspiration from: David A. Shlapak et al., *A Question of Balance: Political Context and Military Aspects of the China-Taiwan Dispute* (Santa Monica, CA: RAND, 2009).
[5] On China's airlift capabilities, see: Cristina L. Garafola, *The PLA Airborne Corps in a Joint Island Landing Campaign*, China Maritime Report No. 19 (Newport, RI: China Maritime Studies Institute, 2022).
[6] These are not the only relevant assumptions, but they are the most important ones.

(A) Operational tempo

The model's estimates depend heavily on assumptions about the tempo at which Chinese transports could operate. For simplicity, the model assumes that China's fleet of amphibious transports could complete one cycle per day in which they transport forces to Taiwan, unload, and return to China to prepare for the next transit.[7] This assumption is likely overly generous to China given its lack of real-world experience with these operations and based on historical cases of amphibious landings.[8] The figure below shows the results of a sensitivity analysis that decreases China's offload rate by 50 percent, such that each day half the fleet is able to deliver Chinese forces to Taiwan. The results highlight that the operational tempo of amphibious landings will have a major impact on China's ability to establish a large presence on Taiwan before the United States and Taiwan hollow out China's lift capacity. If China manages to cycle transports to Taiwan faster, the United States and Taiwan would need to achieve faster attrition in turn. Conversely, a slower landing tempo creates more breathing room. The precise tempo of amphibious landings is ultimately difficult to forecast because it depends on many factors, including the training and proficiency of Chinese personnel, the weather, the status of the fighting on Taiwanese beaches and how congested they become, whether China has captured a Taiwanese port and how long it takes to repair potential damage to the port's infrastructure, the quality of China's logistical capabilities to reload and repair transports when they revisit Chinese ports between transits, and how much risk China is willing to accept by operating its transports in ways that maximize speed at the cost of greater vulnerability to U.S. and Taiwanese attacks.



[7]For different modeling assumptions about the operational tempo of an amphibious fleet, see: Heginbotham et al., *The U.S.-China Military Scorecard*, p. 205; Shlapak et al., *A Question of Balance*, p. 109.

[8]Mark F. Cancian, Matthew Cancian, and Eric Heginbotham, *The First Battle of the Next War: Wargaming a Chinese Invasion of Taiwan* (Washington, D.C.: Center for Strategic and International Studies, 2023), pp. 73-74.

(B) Civilian sealift capacity

The model applies to China's military sealift, but extending the scope to include dual-use civilian ships would significantly increase the estimates. Researchers, such as Conor Kennedy and Thomas Shugart, have extensively documented Chinese preparations to use civilian shipping to support an invasion of Taiwan.[9] But simply adding Chinese civilian ships to the baseline model is not straightforward for two reasons.

First, the operational tempo would likely differ significantly for purpose-built military transports and dual-use civilian transports. Civilian ships are designed to deliver people and supplies to well-established ports in peacetime conditions, not directly to contested beaches. The results would be extremely sensitive to different assumptions about whether China captured a Taiwanese port, how long it took to capture the port, and how long it took to repair the port from potential Taiwanese sabotage. China could also try to establish temporary port infrastructure such as erecting floating piers off beachheads, similar to the two Mulberry portable harbors the Allies used at Normandy in World War II.[10] Modeling this process would require generating estimates of the speed at which China could use this equipment to offload forces and the vulnerability of China's temporary infrastructure to attack or bad weather. China has reportedly modified some civilian roll-on/roll-off (RO/RO) ships to enable in-water launches of amphibious combat vehicles, bypassing the need for fixed infrastructure but creating bottlenecks based on the number of amphibious vehicles and what they can carry.[11] Only a subset of China's civilian RO/ROs have reportedly received these modifications. This highlights the additional modeling challenge that not all civilian ships are fungible. There will be distinctions between different types of ships, such as RO/ROs versus container ships, which generally require large cranes to unload their supplies rather than having vehicles simply drive off.

Second, there is much greater uncertainty about how many civilian ships China would use to support an invasion fleet and how much capacity those civilian ships would offer for transporting personnel and equipment. Conor Kennedy, Thomas Shugart, and others have provided invaluable early research, but further data collection and refinement is necessary to create a comparable order of battle for China's civilian sealift as for its military sealift.

With these caveats in mind, the figure below shows the results of a sensitivity analysis that provides a very rough sense of how the estimates might change because of civilian sealift. As illustrative numbers, the sensitivity analysis considers the impact of adding 100 civilian vessels to China's invasion fleet, each of which can carry 400 Chinese troops and their associated vehicles.[12] Adding 100 civilian ships would bring the total invasion fleet to 178 transports. To account for the reduced operational tempo of unloading from civilian ships, the greater complexity of the operation, and the potential for backlogs of ships waiting to unload forces onto a finite amount of beach space, the sensitivity analysis reduces China's offload rate to 33 percent. That is, the model assumes that China's entire fleet of both military and civilian ships could finish offloading reinforcements to Taiwan every three days. Again, this is not meant to provide an actual estimate of China's civilian lift capacity. But it is important to acknowledge the potential contributions of China's

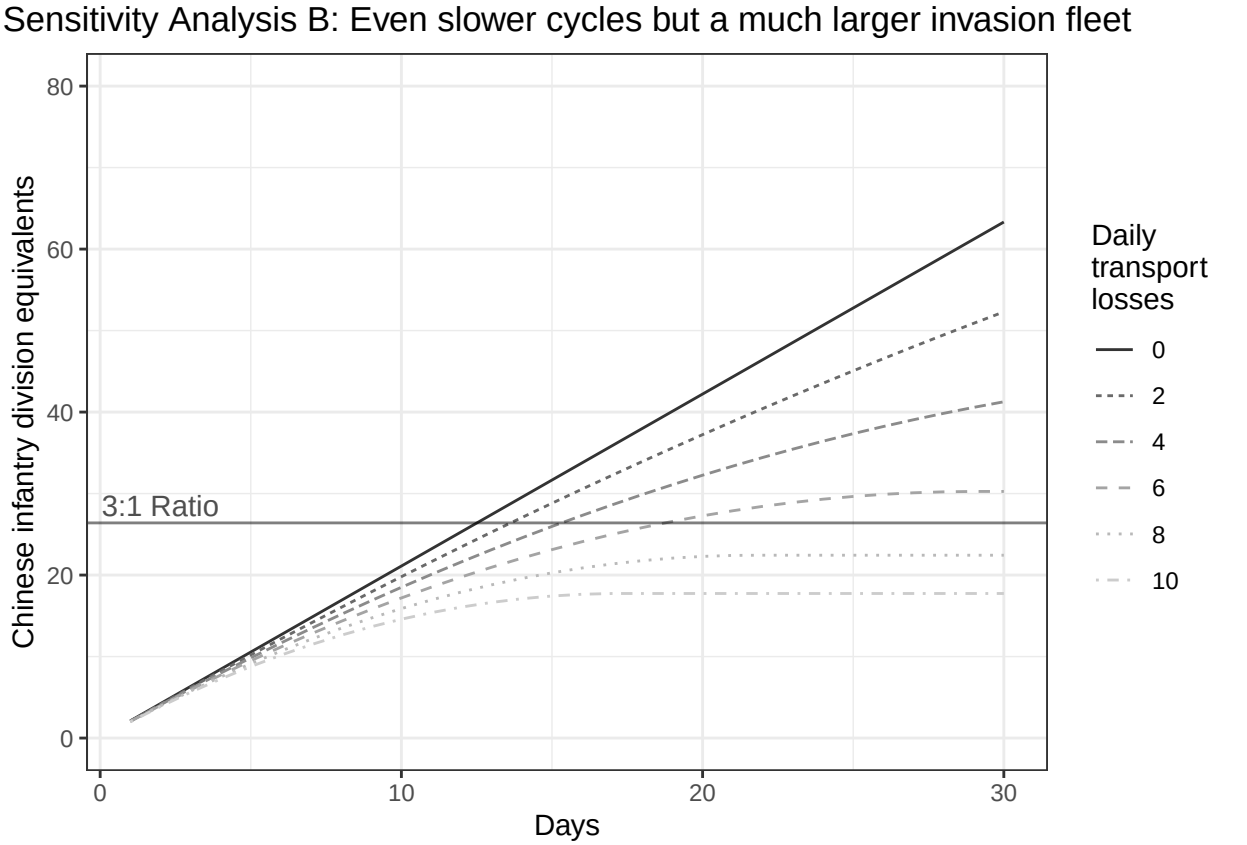
[9] See, for example, Conor Kennedy, *Civil Transport in PLA Power Projection*, China Maritime Report No. 4 (Newport, RI: China Maritime Studies Institute, 2019); Conor Kennedy, "Ramping the Strait: Quick and Dirty Solutions to Boost Amphibious Lift," *China Brief*, Vol. 21, No. 14 (2021); Kennedy, "Getting There;" Conor Kennedy, *Deck Cargo Ships: Another Option for a Cross-Strait Invasion*, CMSI Note No. 4 (Newport, RI: China Maritime Studies Institute, 2024); Thomas Shugart, "Mind the Gap: How China's Civilian Shipping Could Enable a Taiwan Invasion," *War on the Rocks*, August 16, 2021, https://warontherocks.com/2021/08/mind-the-gap-how-chinas-civilian-shipping-could-enable-a-taiwan-invasion/; Lonnie D. Henley *Civilian Shipping and Maritime Militia: The Logistics Backbone of a Taiwan Invasion*, China Maritime Report No. 21 (Newport, RI: China Maritime Studies Institute, 2022); Office of the Secretary of Defense, *Military and Security Developments Involving the People's Republic of China 2023* (Washington, D.C.: Department of Defense, 2023), pp. 142-144.

[10] Kennedy, "Getting There," pp. 237-239.

[11] Kennedy, "Ramping the Strait."

[12] Kennedy reports that China had around 63 civilian roll-on/roll-off (RO-RO) ships that were "suitable for use in transporting military units" in 2019. Kennedy, "Ramping the Strait." The sensitivity analysis uses 100 ships for 2024 simply because it is a round and plausible number. For another example of a notional Chinese invasion fleet including "60 amphibious and 100 cargo vessels," see: David A. Ochmanek et al., *Inflection Point: How to Reverse the Erosion of U.S. and Allied Military Power and Influence* (Santa Monica, CA: RAND, 2023), p. 30. In 2022, Shugart estimated that Chinese civilian ships could add around 40,000 troops to the first wave of an amphibious assault. Thomas Shugart, "Mind the Gap, Part 2: The Cross-Strait Potential of China's Civilian Shipping has Grown," *War on the Rocks*, October 12, 2022, https://warontherocks.com/2022/10/mind-the-gap-part-2-the-cross-strait-potential-of-chinas-civilian-shipping-has-grown/. The sensitivity analysis simply distributes this capacity across the 100 civilian ships in the notional fleet. Again, this is meant to be illustrative rather than exact.

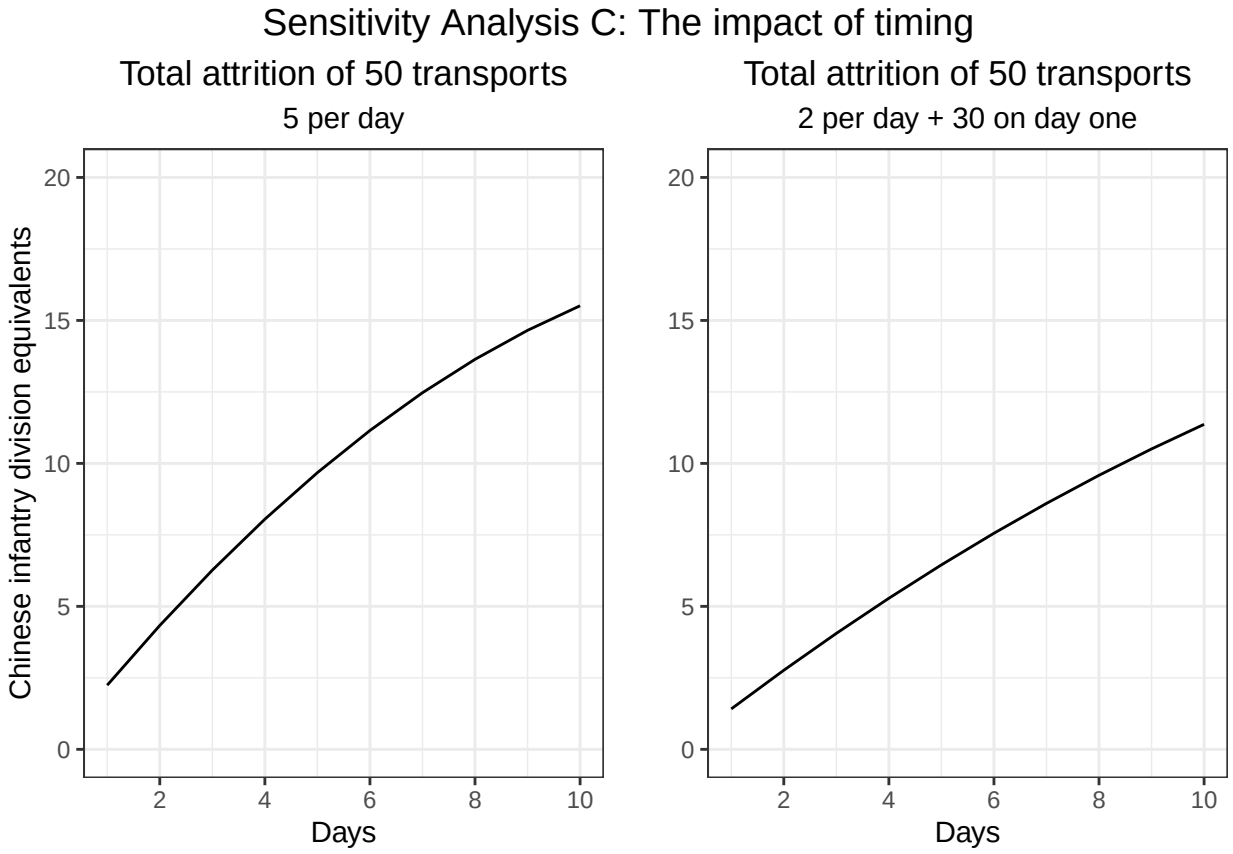
civilian sealift and illustrate how adding more capacity could influence the model's estimates. The figure below should be interpreted with caution because of the explicit and implicit assumptions that it is making, including about the number and capacity of civilian transports, the rate at which China can offload forces from those civilian ships, and that China is ready and able to do so starting on the first day of the invasion.



(C) Variation in the timing of attrition

The model assumes that the attrition to Chinese ships occurs at a consistent rate over time. For example, in the case where the attrition rate is two ships per day, this means that China loses two ships every day for 30 days (or until it has run out of transports); China does not lose one ship on day 1, three ships on day 2, etc., for an average loss rate of two ships per day. The assumption of consistent loss rates keeps the illustration in Figure 4 clear because otherwise variation in the exact timing of attrition would cause large fluctuations in the results.

But there are significant rewards if the United States and Taiwan can front-load attrition against transports earlier in the conflict. This is because every day a Chinese transport survives is another day that it has an opportunity to bring more forces to Taiwan. To illustrate the importance of timing, the figure below shows the results of sensitivity analysis where the attacker achieves the same total amount of attrition over a 10-day period but the pace of attrition is different. The results highlight that there are large advantages to front-loading attrition even if it means that subsequent attrition rates are much lower. This underscores the value of early, concentrated efforts to interdict the invasion fleet.



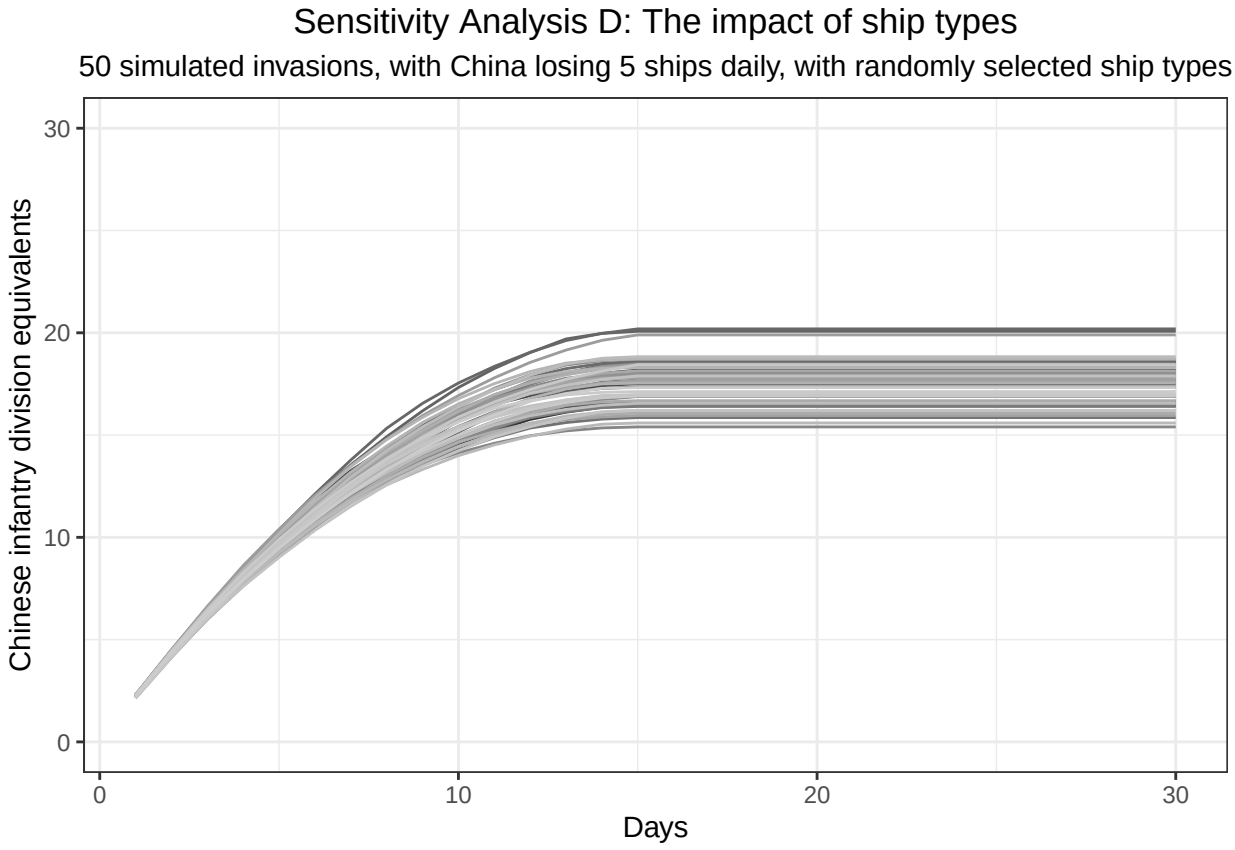
(D) Variation in the types of ships lost

The model estimates lift capacity using a notional "average" Chinese transport.[13] Because different types of transports have different capacity levels, this assumption is useful to show clear trends and avoid fluctuations based on randomness in what types of ships are lost in what order. But, in reality, the order in which different types of ships are lost matters. For example, China losing its large Type-075 transports on day 2 versus day 22 would produce a notable difference.

The figure below shows the results of a sensitivity analysis that accounts for variation in which types of transports China loses to U.S. and Taiwanese attacks. The adjusted model keeps track of each of the 78 Chinese transports listed in Table A1 above, randomly selecting N ships for removal from the fleet based on the specified attrition rate. Once a ship of a certain class (e.g., one of China's Type-075s) is lost, that means that specific ship is no longer available to China for subsequent transits across the Taiwan Strait. Because the model assumes that ships are targeted randomly rather than the United States prioritizing high-value transports, each run of the simulation will include fluctuations in the estimates based on the randomly selected order of attrition.[14] The figure includes the results from 50 simulated Chinese amphibious invasions. In each run, the United States and Taiwan achieve a fixed attrition rate of 5 transports per day. The 50 lines represent how changes to the order in which certain transports are lost in turn changes the size of the military presence China establishes on Taiwan. In a scenario where the United States could consistently prioritize targeting the largest and most capable ships first, rather than settling for random attrition, that would much more significantly and rapidly reduce China's lift capacity.

[13]Based on the data from Table A1, this means China starts the simulation with 78 transports that can each carry 307 troops and their associated vehicles. (1200*3 + 730*8 + 200*4 + 250*9 + 250*9 + 260*6 + 180*1 + 180*10 + 250*11 + 70*11 + 360*6)/78

[14]The removal is actually pseudo-random, setting MIT's zip code (`02139`) as the seed.



Summarizing the implications for the analysis

Taken together, changing the baseline values the model uses or else modifying the model's assumptions could significantly change the estimates it produces. The baseline model is likely overly generous to China in its assumptions about operational tempo but overly generous to the United States by including only China's dedicated military transports. The extent to which these two dynamics offset each other depends on assumptions about how much slower China would likely operate in practice, how many civilian ships China could use, how much capacity those civilian ships offer, and what tempo China could achieve with civilian ships depending on its access to a Taiwanese port or its use of temporary port infrastructure. Spreading out the losses of Chinese ships over time and treating attrition across different classes of transports as effectively random may also be assumptions that benefit China. The model also does not estimate China's requirements to transport supplies such as food, fuel, and ammunition to keep the forces it already has on Taiwan combat effective over time. At least some share of China's dual-use civilian ships might focus on supporting these logistical requirements so that China's military transports could maximize reinforcements in their load planning.[15] Despite these caveats, the baseline model may still very well underestimate China's overall sealift capacity without modifications to incorporate China's civilian ships.[16] Further work on modeling China's overall lift capacity that accounts for a wider range of capabilites, including dual-use civilian vessels and airlift, and more diverse assumptions and conditions, including the addition of sustainment requirements and temporary port infrastructure, is a valuable area for future research.

To the extent that the baseline model understates China's lift capacity, what are the implications for the article's findings? The key implication is that the requirements for successful anti-surface warfare operations against a Chinese invasion fleet become more demanding if that invasion fleet has more ships and can carry

[15] See, for example, Henley, *Civilian Shipping and Maritime Militia: The Logistics Backbone of a Taiwan Invasion*.

[16] Again, airlift is another vector to consider, but this would also require an order of battle for airlifters and a range of assumptions to model their operational tempo and survivability.

more troops. Offsetting China's improved lift capacity would require the United States and Taiwan to generate a larger volume of anti-ship fires along faster timelines. If the requirements are more demanding and there is less room for error, that means that the inefficiencies from degraded access to space could generate increased risks of operational failure. Even if kill chains that have low dependence on space, such as submarines and undersea mines, achieve high rates of attrition, a bigger fleet means that this would translate into China losing a smaller share of its overall lift capacity. Adding the lethality and safety of long-range kill chains could become particularly important to help satisfy these growing requirements by rapidly delivering anti-ship cruise missiles at scale, but this comes with the trade-off that striking from over the horizon depends more on space to find targets that aircraft and ships cannot see themselves, to communicate with widely dispersed sensors and shooters, and to guide weapons over long distances.[17]

While the requirements for successful anti-surface warfare operations matter for assessing the exact magnitude of U.S. dependence on space, the article's overall conclusions about key trends are still compatible with increased estimates of China's lift capacity: China's military modernization and expansion have created negative trends that have made the United States more dependent on space to maximize the effectiveness of its operations to defend Taiwan, but there are still promising ways for the United States to make its terrestrial anti-ship kill chains more robust in the future.

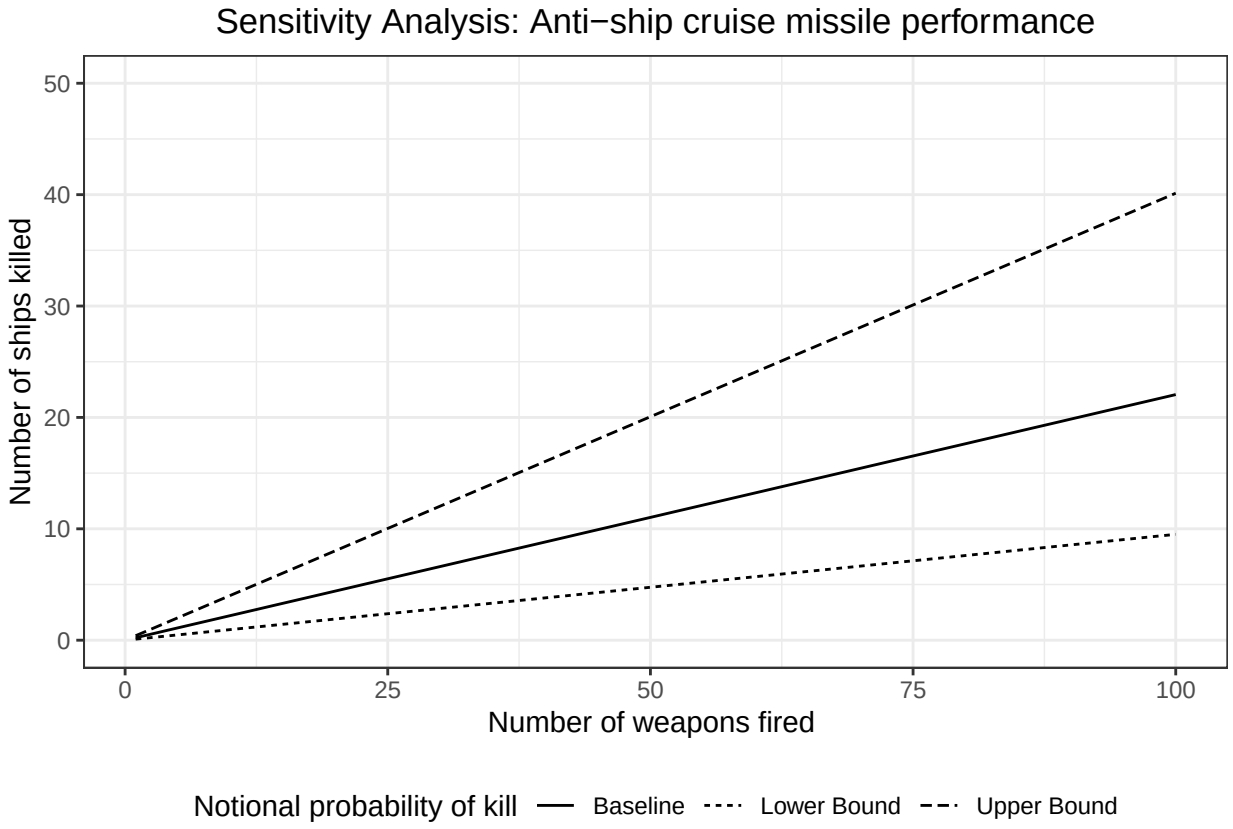
Model 5 (No corresponding figure)

Model 5 (p. 98) is a salvo engagement model for anti-ship cruise missiles. This replicates a "back-of-the-envelope" model from a 2009 RAND report on the U.S.-China military balance.[18] The model includes the following parameters and baseline values:[19]

- Missile reliability – baseline 90 percent
- Penetrating ship-based air and missile defenses – baseline 50 percent
- Achieving at least a mission kill that disables the target – baseline 70 percent
- Achieving a unique hit (not hitting a ship that has already been "killed") – baseline 70 percent
- Salvo size – baseline 50 missiles

At baseline, the model estimates that a salvo of 50 anti-ship cruise missiles would disable around 11 ships. Disabling the ships does not require sinking them, just damaging them enough to achieve a "mission kill" that prevents the transports from continuing to support the invasion's operations within an operationally relevant timeframe. Because the original model uses notional numbers rather than actual estimates of specific U.S. or Chinese capabilities, it is important to acknowledge that the model's estimates are inherently uncertain. The figure below provides sensitivity analysis to show what upper and lower bounds might look like. The upper bound is a potential best-case scenario for missile performance against ships, and the lower bound is a potential worst-case scenario. The adjusted values on the parameters are still notional, but they help provide a sense of the overall range of plausible outcomes. For example, if the model's baseline is that half of the attacker's missiles penetrate the defender's missile defenses, the lower bound is that one-third succeed and the upper bound is that two-thirds succeed. The uncertainty in the range of possible outcomes underscores the importance of procuring and employing anti-ship cruise missiles at scale.

[17] Ochmanek et al., *Inflection Point*, p. 30; Shlapak et al., *A Question of Balance*, p. 115.
[18] Shlapak et al., *A Question of Balance*, pp. 115–116n40.
[19] It assumes statistical independence of shots in the salvo.


Sensitivity Analysis: Anti−ship cruise missile performance
Number of ships killed
0
10
20
30
40
50
0
25
50
75
100
Number of weapons fired
Notional probability of kill
Baseline
Lower Bound
Upper Bound