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Estimating Supply-Chain Burdens in Support of Acquisition Decisions

20 March 2013

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Abstract

Acquisition decisions drive supply-chain requirements that incur financial costs and other critical impacts. To account properly for the resource impacts of demand for fuel and other supplies for new weapon systems and platforms, the Services are required to estimate the fully burdened cost of energy in acquisition analyses, including the resources required for the logistics activities necessary to deliver supplies to the warfighter in an operational scenario. This research uses economic input/output analysis to model the Department of Defense supply chain to estimate the fully burdened cost of fuel and other supplies as a function of the locus of demand to support acquisition decisions. This year's accomplishments include (1) modeling logistics with force protection for fuel delivery to Navy assets in a threat environment and applying the results to real-world examples and (2) modeling the impact of consumption of multiple supply commodities by logistics activities themselves.



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Disclaimer: The views represented in this report are those of the author and do not reflect the official policy position of the Navy, the Department of Defense, or the federal government.



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Table of Contents

Introduction	1
The Burden of Supply.....	2
Multi-Commodity Logistics Model.....	3
Naval Logistics Model	3
Activities.....	4
Convoy-Based Model of Fuel Multipliers for Ground Operations	5
Basic Fuel-Multiplier Model	5
Results	6
Impact of Diverting Combat Assets to Force Protection	8
Optimal Depot Placement	9
Multi-Commodity Logistics Model	10
Naval Resupply Under Threat.....	12
Model	13
Network	13
Consumption Rates	13
Scenario	14
Input-Output Model	15
Operating and Support Costs.....	15
Results.....	16
Conclusions	16
Drivers of the Fuel Multiplier—and FBCE.....	16
Future Directions	17
References	19
Appendix: Fuel-Multiplier Model Scenarios.....	21



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List of Figures

Figure 1.	Stage-Wise Fuel Multiplier	10
Figure 2.	Schematic of Three-Stage Self-Sustaining Supply Chain That Consumes Two Commodities: Fuel and Water	11



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List of Tables

Table 1.	Vehicle Characteristics Used in the Scenarios in Tables 2–4	21
Table 2.	Analysis of the Bar Now Zad Supply Chain in Helmand Province..	22
Table 3.	Analysis of the Army Sustain the Mission Project Base-Case Scenario (A Supply Chain in Iraq)	22
Table 4.	Analysis of the Army Sustain the Mission Project Immature-Theater Scenario, a 1,700-Mile Round-Trip Organic Supply Chain.....	23
Table 5.	An Input-Output Matrix for a Supply Chain With Transport (T) and Force-Protection (FP) Components	23



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Estimating Supply-Chain Burdens in Support of Acquisition Decisions

Introduction

Department of Defense (DoD) policy and federal statute call for using the fully burdened cost of energy (FBCE) in cost estimates in analyses of alternatives (AoAs) that support acquisition decision-making, so that decisions reflect all of the costs throughout the DoD organization that will be incurred (or saved) by a given acquisition decision. In August 2012, the Assistant Secretary of Defense for Operational Energy Plans and Programs (ASD[OEPP]) issued specific guidance promulgated in Section 3.1.6 of the *Defense Acquisition Guidebook* (DAG; OSD, 2012) on how to estimate the FBCE for a system (ASD[OEPP], 2012). This guidance specifically calls for the inclusion of the logistics costs associated with delivering fuel (or other energy supply) to its point of consumption. Moreover, it specifies that the FBCE should be calculated for combat scenarios and that, in most planning scenarios, logistics will be organic (i.e., that DoD assets, rather than contractor assets, will be used). The use of organic assets has implications for the FBCE: although contractors must build all of their costs (except environmental externalities such as greenhouse gas global-warming potential) into the rates that they charge the DoD, their rates are fully burdened with respect to the cost of transport assets and any force protection, if necessary. However, DoD accounting systems and conventions do not necessarily assign all implied costs to logistics assets. In particular, transport assets and any force-protection escorts may need to be fueled and otherwise supplied from within the supply chain, using infrastructure and supply.

The DoD's focus on energy consumption and the logistics costs of delivering fuel and other energy-related supplies is justified by the dominance of fuel in total supply to both naval and land-based forward operations, both current and historical. Moreover, the fuel requirements associated with warfighting have been increasing; for example, current engineering estimates are that the Joint Strike Fighter will consume 110% more fuel than the Harrier that it replaces. The Littoral Combat Ship similarly consumes far more fuel than existing comparable vessels. On the ground, Deloitte (2010) estimated that total fuel consumption for troops in Operation Iraqi Freedom in 2007 was 22 gallons per soldier per day, as compared with about one gallon per soldier per day at the end of World War II (WWII).

Although energy is the largest component of supply by both weight and volume in most ashore and naval missions, we note that the supply of any item to



the forward-operating warfighter requires logistics support, which requires resources, may limit capability when supply lines cannot be maintained, and is vulnerable to enemy attack. We therefore generalize our analysis to address the fully burdened cost of supply (FBCS).

The Burden of Supply

As discussed by Regnier, Simon, Nussbaum, and Whitney (2013), the logistics activities required to deliver fuel to the warfighter impose three major types of costs:

1. **Resources:** The logistics activities required to meet fuel needs on the battlefield are themselves resource intensive because they require transport and force-protection assets, personnel, and consumables such as fuel and water. An Army study (Haggerty, 2008) found that only two of the top 10 fuel-consuming platforms are combat platforms, which highlights the magnitude of the resource costs involved with logistics activities.
2. **Capability Reductions:** Logistics support is highly, but not infinitely, capable. Fuel and power demand therefore limit range and endurance. During the 2003 rapid push to Baghdad, General James Mattis¹ is widely quoted as saying, “Unleash us from the tether of fuel” (Schwartz, Blakely, & O’Rourke, 2012, p. 11). General John Allen, Commander of the International Security Assistance Force/U.S. Forces in Afghanistan (ISAF/USFOR-A), added the following handwritten statement to a memorandum calling for improved energy efficiency: “Operational energy equates exactly to operational capability” (emphasis in the original).
3. **Vulnerability:** There is also a danger of losses to the logistics assets themselves. For example, a Taliban bomb destroyed 22 fuel tankers in the Samangan Province of Afghanistan. The tankers were transporting supplies to coalition forces in July 2012 (“Afghanistan: Taliban Bomb”, 2012). In addition to the risk of supply lines being stopped, there is also a risk of attacks on personnel. The Army Environmental Policy Institute (AEPI) estimated that the United States incurred one casualty for every 24 fuel resupply convoys in Afghanistan (Eady, Siegel, Bell, & Dicke, 2009). Citing the Center for Army Lessons Learned, Eady et al. (2009) estimated that historically, about 10%-12% of Army casualties may be

¹ In 2003, General Mattis was serving as the 1st Marine Division Commander. General Mattis later served as Commander, U.S. Central Command.



attributed to resupply. Moreover, strategic guidance indicates that threatened logistics networks should be anticipated in the future.

Despite these costs, battlefield fuel demand is increasing. New technologies continue to increase the capability deployed with the warfighter. Unfortunately, more advanced platforms and systems tend to consume more fuel and electrical power. These increases have significantly outweighed the savings from technological improvements such as more efficient engines and lighter materials. Total warfighter fuel demands have been increasing steadily for decades—a 175% increase since the Vietnam conflict (Deloitte, 2010).

Regnier et al. (2013) also explained the shortcomings in fuel demand estimates:

A Defense Science Board (DSB) report (2008) highlighted the failure of DoD management processes to properly account for the enterprise-wide costs of fuel. Before 2009, DoD analyses dramatically understated the total costs associated with fuel demand for new weapons systems and platforms. In cost analyses, fuel requirements were monetized at the Defense Logistics Agency-Energy (DLA-E, formerly Defense Energy Support Center) standard fuel price, regardless of where in the world the system was anticipated to be used, and whether DLA-E defense fuel supply points (DFSPs) could realistically be expected to provide fuel. The service-specific fuel logistics costs were neglected, therefore implicitly estimated at zero.

Multi-Commodity Logistics Model

As noted in previous research, logistics activities themselves consume fuel that must be transported in an organic supply chain, thus requiring fuel to transport and creating a fuel-multiplier effect (Regnier & Nussbaum, 2011; Dubbs, 2011). In the work reported here, we expand the analysis to reflect the fact that logistics activities consume supplies other than fuel. For ground-based operations, water is a particularly important supply item, and for extreme forward positions, water may be consumed in volumes comparable to fuel. We therefore expand the economic input/output (EIO) model of Regnier & Nussbaum (2011) to reflect a multi-commodity (more than one type of supply) self-sustaining (organic) supply chain. This expansion to model multiple commodities is one major contribution of the 2012 work, and the elaboration of this model and application of it to generate numerical results is part of our 2013 effort.

Naval Logistics Model

The second major contribution of the 2012 work is to build a model of naval resupply, with a capability to explore the impact of force-protection requirements. Current strategic guidance indicates that the U.S. Navy should anticipate operating



in regions where the enemy attempts to deny access. Historical experience from WWII indicates that fuel supply lines would be a prime enemy target, and therefore, exploring the impact of force-protection requirements for logistics vessels is critical to understanding the consequences of acquisition decisions that affect naval forces' future fuel demands. Reinforcing the criticality of logistics to warfighting capability, in June 2010, the Chief of Naval Operations (CNO) released OPNAV Instruction 3380.5, which designated Military Sealift Command (MSC) sealift vessels carrying munitions, unit movements, or military-essential materiel in support of actual combat operations as high-value units, a designation assigned to U.S. and NATO aircraft carriers, guided-missile submarines, and other strategic assets.

Activities

Under this award, we expanded the EIO model of a self-sustaining supply network, and reported on these results at the Ninth Annual Acquisition Research Symposium (Regnier, Simon, & Nussbaum, 2012), and explored the model's applicability to humanitarian assistance and disaster response (HADR) missions. We described the model in terms of a ground-based supply chain, but it could also be applied to a naval network and a mixed-mode network, including air transport.

Nussbaum and Regnier traveled to Washington, DC, in June 2012 to meet with staff of the ASD (OEPP) who are developing the FBCE guidance for the DAG, as well as other stakeholders. In September 2012, Regnier traveled to the Naval Research Laboratory in Washington, DC, to participate in the Fuels-at-Sea Research Workshop organized by the CNO's Strategic Studies Group.

Nussbaum and Regnier are supervising a thesis student who has built a Navy-specific model of logistics, based on the EIO framework, that estimates the total supply requirements for naval resupply, allowing the user to adjust the location of the warfighter and the threat scenario. The student, LT Brendon Hathorn, is in the Operations Analysis program at the Naval Postgraduate School (NPS). He is also a member of the first cohort of NPS students expected to receive an energy certificate.

We have submitted a paper titled "The Fuel Multiplier in Fuel Supply Logistics" to the *Journal of Defense Modeling and Simulation*. This paper has come back to us with a request for minor revisions and resubmission. The model in this paper includes the impact of force-protection requirements on total fuel demand. Regnier and Simon also presented research results at the 2012 annual meeting of the Institute for Operations Research and the Management Sciences on October 17, 2012, in Phoenix, AZ.

A further paper introducing the multi-commodity self-sustaining supply network model is under preparation; we anticipate submitting it in early 2013.



Convoy-Based Model of Fuel Multipliers for Ground Operations

As reported in Regnier et al. (2013), we extended work from Dubbs (2011) to build a more general convoy-based model of logistics activities in a multistage supply chain, implemented in an Excel spreadsheet. In this model, we can vary

- force-protection requirements, which are captured by including combat vehicles as part of the convoy;
- transport and force-protection vehicle characteristics, including payload and fuel efficiency;
- the number of stages; and
- the length of stages.

We used this model to explore the Dubbs (2011) scenario as well as two scenarios from the AEPI's Sustain the Mission Project (Siegel, Bell, Dicke, and Arbuckle, 2008).

Basic Fuel-Multiplier Model

In this model, supply is transported over multiple stages using organic assets. Stages are indexed by s . Each stage begins and ends at a depot. Fuel that is required by transportation or force-protection assets is provided at each stage's originating depot. Therefore, this fuel, which is required to operate the logistics assets, must also be transported to the originating depot. The model is as follows:

Convoy

n_s^T = number of transport vehicles in convoy for Stage s

n_s^P = number of force-protection vehicles in convoy for Stage s

Fuel Consumption Rates

g_s^T = fuel consumption per unit length for each transport vehicle on Stage s

g_s^P = fuel consumption per unit length for each force-protection vehicle on Stage s

Other Stage Characteristics

d_s = round-trip length of Stage s (may be measured in units of time or distance, with consumption rates specified accordingly)

p_s = fuel payload per transport vehicle on Stage s (the type of transport vehicle may differ by stage)



g_s^A = fuel consumption per hour by force-protection aircraft on Stage s

r_s = air support requirement (aircraft hours) on Stage s (the air support is assumed to be provided by an Apache AS-64A)

Fuel Multiplier

The stage-wise fuel multiplier (i.e., the amount of fuel consumed on Stage s per unit of fuel delivered to the end of Stage s) can be written as $\beta_s = 1 + \alpha_s$, where

$$\alpha_s = \frac{\overbrace{n_s^T g_s^T d_s}^{\text{fuel consumed by transport vehicles, per convoy}} + \overbrace{n_s^P g_s^P d_s}^{\text{fuel consumed by force-protection vehicles, per convoy}} + \overbrace{r_s g_s^A}^{\text{fuel consumed by helicopter air support, per convoy}}}{\underbrace{n_s^T p_s}_{\text{total fuel delivered to Stage } s+1, \text{ per convoy}}}, \quad (1) \text{That is, Equation 1 is the}$$

ratio of the amount of fuel consumed to the amount of fuel delivered. We also define the cumulative multiplier, β_s , as the number of gallons of fuel that must be provided at the beginning of Stage 1 for one gallon to reach the end of Stage s (the beginning of Stage $s + 1$, or the battlefield, if Stage s is the final stage).

The multipliers β_s and B_s are dimensionless (in units of gallon/gallon) and may be used to estimate daily, weekly, or annual systemwide consumption by multiplying them by the appropriate rate of warfighter demand. The convoy composition on a given stage is modeled as constant over the period of interest. However, the model allows the convoy composition as well as the total payload to differ across stages. The cumulative multiplier B_s should be interpreted as a long-run average of the incremental consumption per additional gallon of fuel demanded.

Note that B_s increases geometrically with the number of stages. For example, for n identical stages with $\beta_s = \beta$ constant, $B_n = \beta^n$.

Results

In Regnier et al. (2013), we applied this model to several scenarios, specifically the following:

- transportation from Kandahar to a Bar Now Zad combat outpost (COP) in Helmand Province Afghanistan, following Dubbs (2011);
- transportation from Kuwait to a Stryker Brigade Combat Team (SBCT) in Iraq, following Siegel et al. (2008); and
- a 1,700-mile round-trip immature-theater supply chain, also following Siegel et al. (2008).



The results for these scenarios are included in Tables 2–4 in the appendix. The highlights are as follows:

- As expected, larger convoys using high-payload transport vehicles and a lower ratio of force-protection assets to transport vehicles are more efficient. Therefore, the Kuwait-to-SBCT scenario, which uses sixteen 8,000-gallon trucks with four escort vehicles and has the lowest multiplier effect—only 7% “extra” fuel is required, despite a round-trip distance of 1,100 miles.
- In immature theaters and remote locations, infrastructure may not support large trucks or large convoys, and therefore, logistics is less efficient. Large convoys may also be impractical because the quantities demanded and storage facilities at forward locations are small. Therefore, for immature theaters and remote locations, fuel multipliers are likely to be much higher. In the immature theater scenario, 18% “extra” fuel is required per unit delivered to the warfighter.
- In the Kandahar to Bar Now Zad scenario, road quality also slows down the convoy. This greatly increases the resource requirements, and therefore the multipliers, relative to a supply chain covering a similar distance but on better roads. In the Bar Now Zad scenario, which does not include air support, 71% “extra” fuel is required, despite the stage lengths being relatively short. If air assets are used in force protection, the impact of longer travel times is magnified.

Since expeditionary units are likely to operate in remote environments with limited infrastructure and small convoys, the value of reducing fuel requirements for expeditionary units is very high, especially if their supply lines may be contested.

It should be noted that although early Army fully burdened cost (FBC) methodologies did not capture the fuel-multiplier effect, the Sustain the Mission Project (Siegel et al., 2008) has led to the development of the Army’s FBC Tool, which does capture the single-commodity (fuel) multiplier effect, using a different approach. In the current implementation of the model (J. Montgomery, personal communication, October 1, 2012), the cost of fuel is calculated at the beginning of each stage and is used in cost estimates for later stages. This means that although the quantity of fuel (and other supplies) that the system must transport to support the warfighter is not directly calculated, the costs of fuel used in early stages are accounted for and allocated to later-stage logistics activities. Later versions of the tool will do the same for water, thus capturing at least the two-commodity multiplier effect.



Impact of Diverting Combat Assets to Force Protection

Rather than looking at the total fuel requirements associated with transport and force-protection assets, another perspective is to consider combat capability as fixed; using combat assets in force protection diverts them from other missions. To explore the impact that force-protection requirements would have on capability available for other missions, we expanded the model. As described in Regnier et al. (2013), we used input-output (IO) analysis to represent force-protection assets as a “sector.” This sector’s output (measured in hours of patrol) may be applied to force protection (and be consumed by the transport sector), or it may be applied to other missions.

IO analysis (Leontief, 1986) represents the flows of goods and services in a system—usually, a national, industrial economy—and assumes constant ratios of inputs are required per unit of output from each sector. For example, the automobile sector might require a certain amount of the steel sector’s output and a certain amount of the coal sector’s output per unit of steel produced. Letting sectors be indexed i, j , the input requirements are denoted with coefficients a_{ij} , where a_{ij} = the amount of output from Sector i required by Sector j to produce one unit of Sector j ’s output.

The total amount of output (denoted x_i) required by each sector i is determined by a set of mass-balance equations:

$$x_i = \sum_j a_{ij}x_j, \forall i, \text{ except consuming sectors} \quad (2)$$

We built an IO model of the immature-theater supply chain described in Siegel et al. (2008) and in Table 4 in the appendix. Each stage was modeled as two sectors: a transport sector and a force-protection sector. In the model, each force-protection sector requires fuel provided by the prior stage’s transport sector, and each transport sector requires fuel provided by the prior stage’s transport sector, as well as force protection provided by the same stage’s force-protection sector.

For convenience, we also defined the following:

$s(i)$ = the stage associated with Sector i

$i^T(s)$ = the transport sector for Stage s

$i^P(s)$ = the force-protection sector for Stage s

For transport Sector j and $i = i^T(s(j) - 1)$,

$$a_{ij} = \frac{n_{s(j)}^T P_{s(j)} + n_{s(j)}^T g_{s(j)}^T d_{s(j)}}{n_{s(j)}^T P_{s(j)}} = \frac{P_{s(j)} + g_{s(j)}^T d_{s(j)}}{P_{s(j)}}. \quad (3)$$



Similarly, for force-protection Sector j , $i = i^T(s(j) - 1)$, when the units of force-protection output are the same as the denominator of the fuel consumption rate, g_s^P ,

$$a_{ij} = \frac{n_{s(j)}^P g_{s(j)}^P d_{s(j)}}{n_{s(j)}^P d_{s(j)}} = g_{s(j)}^P. \quad (4)$$

For transport Sector j , and $i = i^P(s(j))$,

$$a_{ij} = \frac{n_{s(j)}^P d_{s(j)}}{n_{s(j)}^T P_{s(j)}}. \quad (5)$$

All other $a_{ij} = 0$. The amount of output required for each stage, x_i , is either determined exogenously (e.g., warfighter demand is the output of the transport sector in the final stage) or determined as the solution to the set of mass-balance equations given in Equation 2, for all i whose output is not exogenous.

Table 5 shows an IO coefficient matrix that matches the AEPI immature-theater example, except that no air protection is used and, therefore, the multiplier effect is lower than it would be in the original scenario. In particular, it is 5,439 gallons/5,000 gallons = 1.09.

Constructing the IO matrix allowed us to examine the amount of force protection required and how those requirements are affected by particular characteristics of the supply chain.

Optimal Depot Placement

In the basic fuel-multiplier model, the stage-wise multipliers increase only linearly with distance, as implied by Equation 1. The model treats the logistics assets' internal fuel tanks as separate from the transport vehicles' payload. This is consistent with operations on relatively short stages. However, as we noted in Regnier et al. (2012), if logistics assets are allowed to resupply from the payload of the fuel transport assets (which would be realistic for longer stages), the stage-wise fuel multiplier would increase faster than linearly in the length of the stage because the denominator—the amount of fuel delivered at the end of the stage—would decrease as the logistics assets consumed the payload. Specifically, if the internal fuel tank capacity is included in the payload, β_s would become

$$\beta_s = \frac{\text{payload per convoy}}{\text{fuel consumed by logistics assets, per convoy}} = \frac{\overbrace{n_s^T P_s}^{\text{payload per convoy}}}{\underbrace{\overbrace{n_s^T P_s} - \overbrace{n_s^T g_s^T d_s + n_s^P g_s^P d_s + r_s g_s^A}_{\text{total fuel delivered to stage } s+1, \text{ per convoy}}}}. \quad (6)$$



Figure 1 shows the impact of increasing the length of the stage, d_s , on the stage-wise multiplier β_s . As discussed earlier, the cumulative (enterprise-wide) multipliers increase geometrically with the number of stages. However, constructing the supply chain with fewer and longer stages does not necessarily solve the problem; there will be fewer individual stage multipliers, but they will be larger. In addition, we must consider the costs of establishing and operating each depot. In setting up a new supply chain, therefore, an important question is, How many depots should there be, and how should they be positioned?

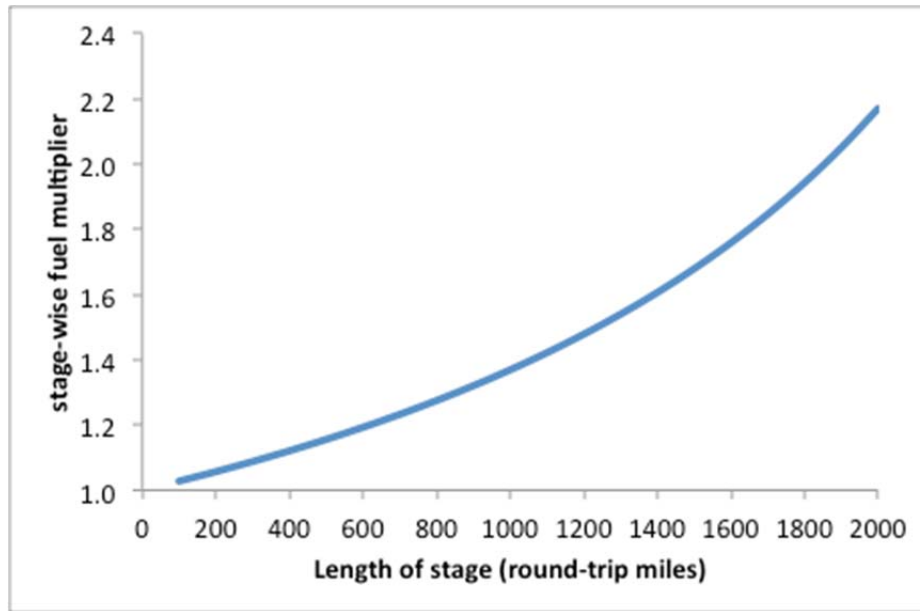


Figure 1. Stage-Wise Fuel Multiplier

Note. This figure shows a stage-wise fuel multiplier as a function of the length of the stage. It is based on Equation 7 and the immature-theater scenario (see Table 4 in the appendix) with four transport vehicles and four force-protection vehicles.

We have begun to address this question in work this year. In particular, we proved that in a simple fuel supply chain with only one type of transport vehicle and constant terrain, the minimum cost is obtained using stages of equal length. We developed a cost function that computes an overall cost for any given number of equal-length stages; this function can be used to determine the optimal number of stages.

Multi-Commodity Logistics Model

As noted previously, neglecting the fuel multiplier in a multi-stage supply chain leads to a systematic underestimate of the total resource requirement—and the total amount of logistics activity—required to provide supply to the warfighter.



Moreover, logistics activities consume additional resources, such as water, that must also be supplied internally in a self-sustaining supply chain. Not only does supply type (commodity) consumed by logistics activities have its own multiplier but the multipliers interact. As shown in Figure 2, the transportation of each commodity requires consumption of the other commodity.

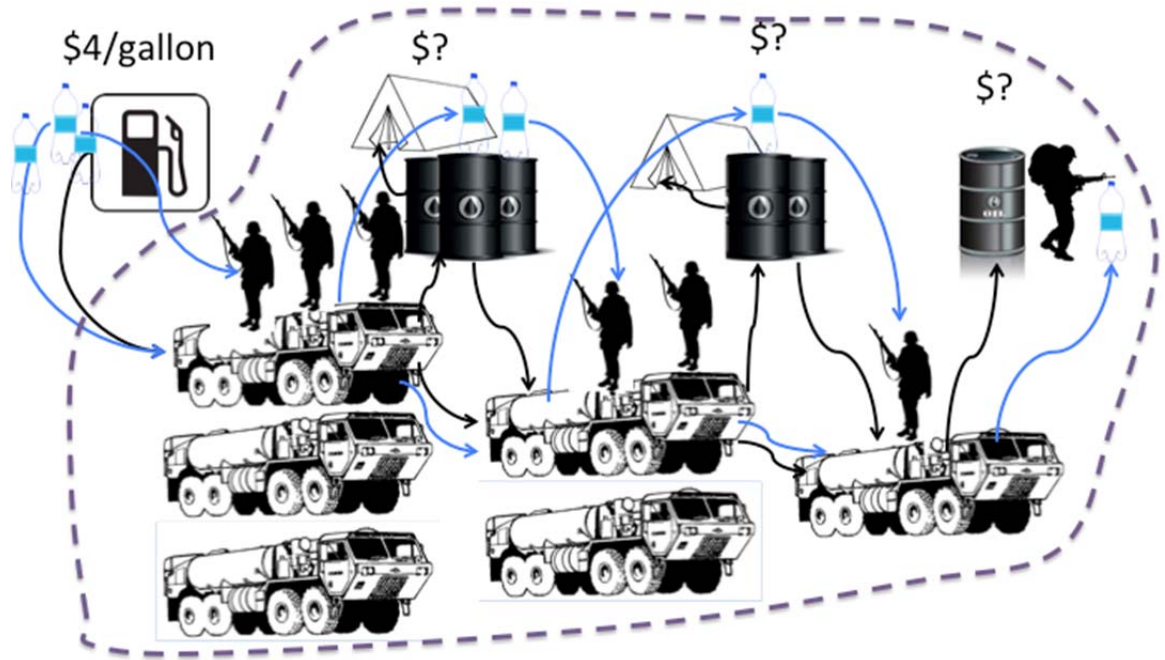


Figure 2. Schematic of Three-Stage Self-Sustaining Supply Chain That Consumes Two Commodities: Fuel and Water

Note. Logistics assets (personnel and fuel trucks) are shown for each stage, and stocking at each depot is shown. The arrows represent flows of supply to logistics assets and (at the far right) to the warfighter, with blue arrows for water and black arrows for fuel.

We have developed a basic model of the multi-commodity supply chain that may be used to estimate these cross-commodity multipliers and the associated enterprise-wide resource requirements. In this model, a supply chain has n nodes, indexed i ; we now index stages according to their originating node, so stage i connects node i with node $i + 1$. There are m commodities (units are normalized), indexed c , transported and consumed by this supply chain.

- x_n^c = the amount of Commodity c needed at the destination (given)
- x_i^c = the amount of Commodity c required at Node i
- X_i = the total resource requirement at Node i

$$= \sum_{c=1}^m x_i^c$$

d_i = length of Stage i
 r_i^c = the amount of Commodity c consumed per unit length on Stage i
 R_i = the total amount of resources consumed per unit length on Stage i

$$= \sum_{c=1}^m r_i^c .$$

This model is designed to provide an estimate of monetary costs, including both the resource requirements and other costs of logistics activities—such as labor. Labor requirements are proportional to the amount of logistics activity required in the supply chain, but labor is not transported by the network. Future work may include modeling the deployment phase; such a model would include the transportation of personnel.

This work is ongoing, and dissemination of this work is part of our research effort in 2013.

Naval Resupply Under Threat

Although the U.S. Navy has operated nearly unopposed since the end of WWII, the experiences during WWII demonstrate that supply lines, and especially fuel, are a key vulnerability that a capable enemy can exploit to severely undermine and potentially defeat U.S. forces. Goralski and Freeburg (1987) and Yergin (1991) narrated vividly how many of the key decisions on all sides were motivated by the objective of securing access to petroleum supplies. Japan's domestic energy resources were (and remain) limited, and its entry into the war was largely motivated by its goal to secure petroleum supplies; at the time, it had only two years of reserves, even without wartime demand.

The focus on petroleum supplies continued throughout the war, quite justifiably, as limits on the availability of petroleum also drove key decisions—for example, the U.S. did not have enough fuel to steam both its destroyer and its carrier fleets and had to choose between them (Goralski & Freeburg, 1987). The need to refuel contributed to the loss of 793 U.S. Navy lives and three destroyers sunk by Typhoon Cobra in December 1944. The fleet was attempting to refuel when it was overtaken by the storm (Drury & Clavin, 2007).

A large part of the Germans' war strategy was to disrupt supply traveling from the U.S. to the UK as well as from the U.S. Gulf Coast and the Caribbean to ports on the U.S. Atlantic Coast. Yergin (1991) quoted British Intelligence's official history, saying that "It was only by the narrowest of margins that the U-boat campaign failed to be decisive during 1941" (p. 356).



In his thesis, provisionally titled *Resource Burden of Logistics to Navy Ships Under Threat Scenarios* (anticipated graduation is March 2013), LT Hathorn develops an EIO-based model of Navy logistics using a global network based on the Combat Logistics Force Planner (CLFP) (see Brown and Carlyle, 2008) and supply consumption factors for each U.S. Navy and MSC vessel class.

Model

Motivated by historical experiences of the centrality of threats to fuel supply lines in WWII strategy and by the potential for U.S. naval operations in a high-threat (anti-access) environment anticipated by the 2010 Quadrennial Defense Review Report (DoD, 2010), Hathorn's model estimates the IO multipliers as a function of threat scenarios.

Network

Hathorn's model uses the global network model used in the CLFP. The CLFP is described in Brown and Carlyle (2008). Nodes are indexed by i and j , and arcs connect the nodes. Each possible threat level (t = low, med, or high) on each arc is represented by a stage. Since stages are directional, each arc and threat level require two stages, one for each direction. Stages are denoted as follows: $s_{i,j,t}$ = the stage transporting supply from node i to j , under threat level t , and $t(s)$ is the threat level of stage s . We also write $i(s)$ and $j(s)$ to represent the source and destination nodes, respectively, associated with stage s .

Consumption Rates

Each stage has a resource-consumption level that is estimated based on planning factors, also from the CLFP. The planning factors for each vessel class, indexed k , are the daily consumption rates of each type of supply—fuel (jet fuel and diesel fuel), dry stores, and ordnance.

FPF_k = daily fuel consumption rate from the CLFP for vessel class k (barrels)

SPF_k = daily stores consumption rate from the CLFP for vessel class k (pallets)

OPF_k = daily ordnance consumption rate from the CLFP for ship class k (short tons)

Fuel is by far the dominant supply type—for example, for a guided-missile destroyer (DDG), over 95% of daily supply consumption (by weight) is fuel. Therefore, in Hathorn's thesis, all supply is normalized by weight so that all units are in short tons. All supply is treated as identical and priced at the price of the F-76 Diesel Fuel Marine (DFM).



Consumption rates for each vessel class are calculated as follows:

$$r_k = \text{daily consumption rate of the normalized commodity by vessel class } k \text{ (short tons/day)}$$

$$= (7 \text{ lbs/gallon}) \times (42 \text{ gallons/barrel}) \times (\text{short ton}/2,000 \text{ lbs}) \times FPF_k + SPF_k + OPF_k$$

To calculate consumption rates for each stage, we need to model the impact of the threat level on resource consumption. It is assumed that Combat Logistics Force (CLF) vessels are protected by an escort of combat vessels. The composition of the convoy for each threat level is determined as part of the scenario and is denoted using $v_{k,t}$ (i.e., the number of vessels of class k) in the convoy under threat level t , assumed constant within a scenario. The ratio of consumption to payload is

$$R_s = \frac{\overbrace{\sum_k v_{k,t(s)} r_k d_s}^{\text{supply consumption during on stage } s}}{\underbrace{\sum_k v_{k,t(s)} cap_k}_{\text{total payload capacity of convoy on stage } s}}, \quad (7)$$

where cap_k = the payload capacity for vessel of class k (short tons) and d_s = the length of stage s (days), including transit as well as time to load transport vessels and to replenish warfighting vessels at the destination.

Scenario

A scenario consists of

- the position of warfighter demand (for fuel or any other supply);
- the availability or non-availability of ports as sources of supply; and
- a threat level for each arc.

For a given scenario, Hathorn's model estimates the total amount of supply from source nodes required per unit of supply delivered to the warfighter. The results show how the total resource requirements increase with the length of the supply chain and with the force-protection requirements and increase as supply nodes become unavailable due to threat. This implies that the value of reducing warfighter fuel requirements is higher than estimated in a low-threat scenario. The Navy has counted on uncontested supply lines for decades; therefore, historical costs to deliver fuel to forward-deployed ships will not reflect the costs in an access-denial scenario.



Input-Output Model

Hathorn used an IO model to estimate the total resource requirement (TRR) at each node and ultimately for the entire network, associated with a particular scenario. As can be seen in Figure 3, there may be many possible paths that supply could take through the network. The IO model must be based on one such path. Therefore, Hathorn used a linear programming optimization to select a single path through the network, for a given scenario. The decision variable is $z_s \in \{0,1\}$, a binary variable indicating whether stage s ($s = 1$) is used in the scenario or not. Let j^D represent the destination node. The linear programming formulation is

$$\min \sum_s d_s z_s \left(\sum_k r_k v_{k,t(s)} \right) \quad (8)$$

subject to

$$\text{demand constraint: } \sum_{s:j(s)=j^D} z_s \geq 1, \text{ and} \quad (9)$$

$$\text{mass – balance constraints: } \underbrace{\sum_{s:j(s)=n} z_s}_{\text{flow in to node } n} \geq \underbrace{\sum_{s:i(s)=n} z_s}_{\text{flow out of node } n}, \quad (10)$$

for all transshipment nodes n (i.e., nodes that are neither sources nor destinations).

Now, the IO coefficients for each pair of stages (sectors) can be calculated as

$$a_{s',s} = z_s (1 + R_s), \quad (11)$$

and the total amount of output required of stage s , per short ton of supply delivered to the node, is

$$x_s = \sum_{s':i(s')=j(s)} a_{s,s'} x_{s'}. \quad (12)$$

The TRR of the logistics system is equal to the total, system-wide, supply requirement per unit of supply delivered to the destination. The TRR = x_{s^*} , where s^* is the supply node.

Operating and Support Costs

Although this model may be used to estimate the total amount of supply required by the logistics system per unit delivered to the warfighter, FBC includes



other cost elements as well. Moreover, these other elements are also affected by the multiplier effect—specifically, for long paths from the source node to the destination node, the early stages will need to deliver larger amounts of supply to sustain later-stage logistics activities. The other cost elements should go up proportionally with the amount of supply that early stages deliver. One of the biggest cost elements is other operating and support (O&S) costs required to operate CLF and escort vessels. The *DAG* calls for O&S costs, as well as depreciation and infrastructure costs, of delivery assets to be included in FBCE estimates. Hathorn used the Navy Visibility and Management of Operating and Support Costs (VAMOSC) database to estimate these costs; he avoided double-counting the cost of supplies that are captured in the TRR by excluding cost elements for fuel and other supplies.

Results

Hathorn's thesis will be completed in March 2013. Results are therefore preliminary. However, for a long transportation, from San Diego to the Spratley Islands, with high threat in the region beyond Guam, and with the most common MSC vessel, the FBC of fuel is over \$11/gallon, comparable to the FBC of fuel at remote COPs in Afghanistan (Moore et al., 2011). This estimate uses the VAMOSC database for O&S costs, excluding supply (which is captured by the IO model), for the CLF and escort vessels. This is a conservative underestimate of the true cost because it includes only costs for the one-way trip to the warfighter and excludes other costs such as vessel depreciation and environmental costs.

Conclusions

Drivers of the Fuel Multiplier—and FBCE

FBCE analyses that implicitly or explicitly assume that supply of fuel, water, food, and spare parts will be available along the supply line systematically underestimate the FBCE if the assumption does not hold.

In new theaters, it is generally unrealistic to assume that fuel, drinking water, and other supplies required by logistics activities will be readily available. The same is true for austere and post-disaster environments where HADR operations are likely to occur. As reported in Regnier et al. (2013), two factors are the primary drivers of the cumulative (enterprise-side) fuel multiplier:

1. **Resource Intensity:** The more fuel, labor, spare parts, ammunition, and other resources required per unit of supply delivered by each stage, the larger the single-stage multiplier and the larger the multiplier for all downstream points. This means that logistics and force-protection platforms that are relatively inefficient and terrain that lowers platforms' fuel efficiency drive up the fuel multiplier. A high-threat



environment that requires force protection for transport assets drives greater resource intensity in the supply chain, in turn increasing the fuel multiplier.

2. **Length:** The distance between sources of fuel (or other supplies) and points of consumption (by both the end user and logistics platforms) drives the multiplier. Both the number of stages in the organic supply chain and the length of each stage drive the cumulative fuel multiplier. In particular, the multiplier increases faster than linearly with the number of stages in the organic portion of the supply chain and with the length of each stage (Regnier et al., 2012).

Future Directions

We have already begun expanding our work on the resource demands of multi-commodity supply chains. We plan to apply our model to a real-world supply chain and to submit this work to an academic journal in 2013. We will also explore the use of the multi-commodity model in HADR supply chains as part of our work in 2013. This will involve adding the deployment phase to the model, since it represents a significant proportion of the overall costs of HADR logistics.

In addition, we will extend our analysis of depot placement to more complex self-sustaining supply chains, and we will continue to develop Hathorn's naval resupply model and use it to analyze acquisition-relevant scenarios.



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Appendix: Fuel-Multiplier Model Scenarios

This appendix shows results of the fuel-multiplier model for three scenarios reported in Regnier et al. (2013):

- transportation from Kandahar to a combat outpost (COP) named Bar Now Zad in Helmand Province Afghanistan, following Dubbs (2011);
- transportation from Kuwait to a Stryker Brigade Combat Team (SBCT) in Iraq, following Siegel et al. (2008); and
- a 1700-mile round-trip immature-theater supply chain, also following Siegel et al. (2008).

Table 1. Vehicle Characteristics Used in the Scenarios in Tables 2–4

Type	Fuel Consumption		Payload (gallons)
	Rate (gallons per mile)	Rate (gallons per hour)	
Medium Tactical Vehicle Replacement (MTVR)		13.3	1,800
8000-gallon tanker trailer, towed by M967 tractor	0.22		8,000
5000-gallon tanker trailer, towed by M967 tractor	0.22		5,000
TRUCK TANK FS 2500G M978A	0.19		2,500
Mine-Resistant Ambush Protected vehicle (MRAP)		10.2	
MRAP All-Terrain Vehicle (MATV)		6.9	
Apache (AH-64D)		175.0	
M1117 Armored Security Vehicle	0.13		

Note. The hourly consumption rates used in the Helmand Province scenario are based on poor terrain and low speeds and are from Dubbs (2011). Consumption rates for the platforms used in the Sustain the Mission Project scenarios are from the current version of the Army's Fully Burdened Cost Tool and are derived from AMSAA.



Table 2. Analysis of the Bar Now Zad Supply Chain in Helmand Province

Stage	d_s	Convoy Composition				Air Support (hours)	Total Fuel Consumption (gallons)	Total Payload (gallons)	Stage Multiplier β_s	Cumulative Multiplier B_s
	(round-trip hours)	Vehicle Type		Vehicle Quantity						
		Transport	Force Protection	n_s^T	n_s^P					
1 (Kandahar to Leatherneck)	5	MTVR	MRAP	43	11	0	3,423	77,400	1.04	1.71
2 (Leatherneck to Now Zad)	36	MTVR	MRAP	8	4	0	5,305	14,400	1.37	1.64
3 (Now Zad to Bar Now Zad)	8	MTVR	MRAP	1	3	0	352	1,800	1.20	1.20

Table 3. Analysis of the Army Sustain the Mission Project Base-Case Scenario (A Supply Chain in Iraq)

Stage	d_s	Convoy Composition				Air Support (hours)	Total Fuel Consumption (gallons)	Total Payload (gallons)	Stage Multiplier β_s	Cumulative Multiplier B_s
	(round- trip miles)	Vehicle Type		Vehicle Quantity						
		Transport	Force Protection	n_s^T	n_s^P					
1 (Kuwait to Cedar II)	450	8000	M1117	16	4	5.1	2,700	128,000	1.02	1.07
2 (Cedar II to ESC)	500	8000	M1117	16	4	11.4	4,000	128,000	1.03	1.05
3 (ESC to BSB)	100	5000	M1117	16	4	2.3	800	80,000	1.01	1.02
4 (BSB to SBCT)	40	M978A	M1117	16	4	0.9	301	128,000	1.01	1.01



Table 4. Analysis of the Army Sustain the Mission Project Immature-Theater Scenario, a 1,700-Mile Round-Trip Organic Supply Chain

Stage	d_s	Convoy Composition				Total Fuel Consumption (gallons)	Total Payload (gallons)	Stage Multiplier β_s	Cumulative Multiplier B_s	
	(round-trip miles)	Vehicle Type		Vehicle Quantity						Air Support (hours)
		Transport	Force Protection	n_s^T	n_s^P					
1	425	5000	M1117	16	4	9.7	3,400	80,000	1.04	1.18
2	425	5000	M1117	16	4	9.7	3,400	80,000	1.04	1.13
3	425	5000	M1117	16	4	9.7	3,400	80,000	1.04	1.09
4	425	5000	M1117	16	4	9.7	3,400	80,000	1.04	1.04

Table 5. An Input-Output Matrix for a Supply Chain With Transport (T) and Force-Protection (FP) Components

Component (Stage and Type)		Component (Stage and Type)								
		Origin	1 T	1 FP	2 T	2 FP	3 T	3 FP	4 T	4 FP
Origin		0	1.018	0.131	0	0	0	0	0	0
1	T	0	0	0	1.018	0.131	0	0	0	0
1	FP	0	0.021	0	0	0	0	0	0	0
2	T	0	0	0	0	0	1.018	0.131	0	0
2	FP	0	0	0	0.021	0	0	0	0	0
3	T	0	0	0	0	0	0	0	0.131	0.131
3	FP	0	0	0	0	0	0	0	0	0
4	T	0	0	0	0	0	0	0	0	0
4	FP	0	0	0	0	0	0	0	0.021	0



Output	5,439	5,326	113	5,215	111	5,106	109	5,000	5,000
(units)	(gallons)	(gallons)	(hours)	(gallons)	(hours)	(gallons)	(hours)	(gallons)	(hours)

Note. The fuel consumption rates match the Sustain the Mission Project immature-theater scenario, with no air support.





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