The Fuel Multiplier in Multi-Stage Supply Chains

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Abstract

Fuel requirements on the battlefield impose direct costs associated with the resources necessary to transport the fuel and protect logistics assets, in addition to indirect energy security costs. Estimating the enterprise-wide demand for fuel associated with fuel consumption on the battlefield is a challenging, but necessary, step to making good decisions. This paper presents a modeling framework for estimating the enterprise-wide fuel requirements associated with a multistage fuel supply chain, demonstrating a multiplicative increase in fuel demand with additional stages, and examining the fuel impact of protecting the supply chain.

Key Words: fully burdened cost; supply chain; fuel; energy; cost estimation

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1. The Impact of Battlefield Fuel Demand

In the last five years, the U.S. Department of Defense (DoD) has begun to pay great attention to its energy requirements and, in particular, its operational fuel requirements. The monetary cost of fuel to the DoD made up 2.5% of its total budget in fiscal year (FY) 2011, or approximately $17 billion, and both the percentage and absolute cost have been increasing [1]. About 75% of DoD's energy consumption is classified as operational (and 25% is installation energy [2]).

The demand for fuel on the battlefield requires logistics support to deliver that fuel where and when it is needed, which imposes three major types of costs: resources, capability reductions, and additional vulnerability [3]:

> **Resources:** Logistics activities required to meet battlefield fuel demand are themselves resource-intensive, requiring transport and force-protection assets, personnel, and consumables. An Army study found that only 2 of the top 10 fuel-consuming platforms are combat platforms [4]. 4 transport trucks and 2 cargo helicopters appear in the top 10, while the only combat platforms are the Abrams tank at number 5 and the Apache helicopter at number 10 [5].
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> **Capability Reductions:** Logistics support, while highly capable, is not necessarily available in unlimited capacity at every time and place; therefore, fuel demand may reduce capabilities such as range and endurance. As the 1st Marine Division Commander during the rapid 2003 invasion of Iraq, then-Major General James Mattis,[1] is widely quoted as saying, "Unleash us from the tether of fuel." [1]. As General John Allen, who was the Commander of ISAF/USFOR-A (International Security Assistance Force/U.S. Forces in

[1] General Mattis later served as Commander, U.S. Central Command.

> Afghanistan), added in the following handwritten exhortation to a memo calling for greater energy efficiency: "Operational energy equates exactly to operational capability" (emphasis in the original).
>
> **Vulnerability:** Finally, the logistics network itself becomes a vulnerability. This was demonstrated clearly in July 2012 when a Taliban bomb destroyed 22 fuel tankers in the Samangan Province of Afghanistan. The tankers were transporting supplies to coalition forces [6]. In addition to the risk of the supply lines being cut off, the vulnerability of the supply chain exposes personnel to attack. The Army Environmental Policy Institute (AEPI) estimated that the United States incurred one casualty for every 24 fuel resupply convoys in Afghanistan [7]. Citing the Center for Army Lessons Learned, AEPI (2009) estimates that historically, about 10%-12% of Army casualties may be attributed to resupply [7].

Yet, battlefield fuel demand is increasing. Technological advances have increased the capability deployed with the warfighter. However, more advanced platforms and systems consume more fuel and electrical power. These increases have more than overwhelmed improvements such as more efficient engines and lighter materials. Total warfighter fuel demands have been steadily increasing for decades—a 175% increase since the Vietnam conflict [8].

A Defense Science Board (DSB) report (2008) highlighted the failure of DoD management processes to properly account for the enterprise-wide costs of fuel [3]. 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.

In addition, estimates of performance and capability were almost certainly overstated in acquisition analyses, as war games and simulations implicitly assumed that the required supplies, including fuel, would be available with certainty. The DSB task force "was unable to identify any case where the logistics reductions or deployment and sustainment enhancements achievable from improvements in platform efficiency were quantitatively included as capability improvements and factored into trade-off decisions." [3].

The fully burdened cost (FBC) of fuel (more recently generalized to energy) is the construct designed to fix this bias in the acquisition process. The DSB (2008) made five recommendations for changing management processes, the first of which was to base investment decisions on the "true cost of delivered fuel" [3]. This recommendation led to a mandate in the 2009 National Defense Authorization Act that defined the FBC of fuel (FBCF) as

> "the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use"

and called for the FBCF to be estimated and used in acquisition decisions [9].

The FBCF (now Fully Burdened Cost of Energy, FBCE) is the most influential analytic construct in operational energy. It is officially defined in terms of resources, and it has been interpreted as a measure in units of dollars. It is therefore a summary of the resources required to assure delivery of fuel to the platform or system requiring it. Since there are, however, two other more important types of costs associated with battlefield fuel demand—capability reductions and vulnerability—the FBCF has been interpreted to have a broader meaning. For example, Lovins (2010) argues that "FBCF is a wartime capability planning factor, not a peacetime cost estimate" [10]. While the FBCF (or FBC of energy) is correlated with capability reduction and vulnerability associated with the heavy logistics requirements of battlefield fuel demand, as defined, it is clearly the cost of resources consumed in the delivery of fuel.

The FBC is currently required to be used in acquisition decisions. A framework for calculating the FBCE was developed by the office of the Assistant Secretary of Defense for Operational Energy Plans and Programs (ASD (OEPP)) [2] and promulgated in Section 3.1.6 of the Defense Acquisition Guidebook (DAG) [11] in July 2012. The guidance specifies that the FBCE will be estimated alongside the total ownership cost, but will be based on short combat scenarios. In other words, the FBCE should be calculated for a combat environment, rather than for peacetime use of the platform being evaluated. It specifies that in most planning scenarios, logistics will be *organic* (i.e., that DoD assets, rather than contractor assets, will be used). This implies that they may need to be fueled from within the supply chain.

The DAG codifies but does not standardize the calculation of FBCF, and itemizes three price elements that must be included [11]:

1. the fuel itself (used by the platform being analyzed);
2. tactical delivery assets, to include Operations & Support (O&S), depreciation, and infrastructure costs of those assets; and
3. security (which we call force protection).

The guidance calls for price element #1, the fuel itself, to be priced at the DLA-E standard price. This assumption ignores differences in DLA costs for delivery to DFSPs, in different regions of the world, and, in general, will understate the costs for fuel at remote DFSPs outside the United States [12]. DLA-E provides contractor delivery of bulk fuels to DoD services at DFSPs. For contractor-provided delivery, it is relatively easy to estimate the FBCF, because contractors must build all their costs (with the exception of environmental externalities) into their rates in order to operate profitably. Contractor rates are, therefore, fully burdened with the cost of transport assets and any protection provided. Although it is straightforward [12] to estimate the FBCF delivered to DLA-E DFSPs, most FBC analyses do not do this. Instead, they use the DLA-E standard price as the cost of fuel at the DFSP.

Estimating price elements 2 and 3 of the FBC of delivered fuel or other energy sources is not easy. Organizational and record-keeping systems are not always set up to separate assets (equipment, personnel, and supplies) involved in logistics from other assets; costs of unit-level logistics activities, for example, may not be easy to separate from costs for other activities. Logistics assets used in delivering fuel are also used for other logistics activities. Even dedicated logistics units supply many types of items. Although fuel is generally the single largest demand item during sustainment, in extreme forward positions with few mechanized platforms, water demand may exceed fuel demand [13]. Apportioning costs among the different delivered items is one challenge. Some assets that are used in the logistics network are also used for non-logistics purposes, so determining what portion of their costs should be attributed to the logistics function is a further challenge. For example, mine-resistant ambush protected vehicles (MRAPs) and Apache helicopters, and the personnel that operate them, are used in convoy protection but are also used in other warfighting activities. Moreover, every asset has its own sustainment requirements (e.g., personnel require water, food, and other supplies in theater).

The above estimation challenges tend to push analysts toward a focus on the easy-to-measure costs, leading to an underestimate of the total resource cost of the logistics network required to deliver fuel.

This paper addresses one further factor that leads to systematic underestimates in the FBCE. Estimates that include more than one stage in the supply chain conducted by service-owned assets leave out the cost of transporting and protecting fuel that is consumed by the downstream (later) stages in the network. These costs can be extremely large in long supply chains. Estimates that leave out the analysis of this fuel and its assured delivery costs systematically understate the enterprise-wide costs associated with battlefield fuel consumption. If underestimates are used in the acquisition process, the DoD risks continuing to rely on over-consuming weapons and platforms for decades into the future.

2. Monetary and Nonmonetary Costs Associated With Enterprise-wide Fuel Requirements

This paper focuses on enterprise-wide fuel requirements that are incurred by fuel consumption on the battlefield. Every gallon of fuel burned in a vehicle, aircraft, or generator in theater must be transported there, requiring fuel for transportation platforms (vehicles, aircraft, or vessels) and force-protection platforms. The enterprise-wide fuel requirement—the amount that must be purchased by the DoD—is therefore necessarily greater than the amount consumed on the battlefield.

This paper introduces models that estimate the fuel multiplier—the total amount of fuel the DoD must procure per gallon delivered to the battlefield. The ratio is called the fuel multiplier, and multiplying it by the commodity price of fuel provides a lower bound on the FBCF. It leaves out all other costs, including procurement of logistics platforms and personnel costs. This paper does not quantify other costs associated with sustainment logistics, such as platform depreciation and maintenance, personnel, or deployment.

As discussed earlier, the DLA-E's costs to provide bulk fuels at remote DFSPs are higher than their costs to provide fuels inside the United States. In Afghanistan, for example, the U.S. DoD purchased contractor-delivered fuel for $6.39/gallon in Helmand Province in 2009 [13].

Market fuel prices are also far more volatile than prices for other items purchased by the DoD. Volatility is costly because it makes planning difficult. Recent price increases have forced the DLA-E to impose out-of-cycle increases in their standard price, after the services have budgeted at the lower rate. The DoD can ask Congress to increase the defense appropriation to cover the additional cost when fuel prices rise, but in the short term, rising fuel prices cause replanning and disruptions [14].

Finally, environmental and other costs associated with greenhouse gas emissions are incurred proportionally to the total amount of fuel purchased (and consumed) by the DoD, regardless of how it is used (e.g., powering generators, fuel trucks or combat vehicles).

Underestimating the enterprise-wide fuel requirement associated with battlefield fuel consumption will underestimate all the above costs. This paper demonstrates that most FBCF analyses systematically underestimate the enterprise-wide fuel consumption associated with battlefield fuel consumption and, therefore, underestimate the incurred logistics costs and any additional costs related to the total amount of fuel consumed.

2.1 Estimating and Apportioning Enterprise-wide Costs of Battlefield Consumption

Following the terminology of the guidance in the DAG, we will use the term "assured delivery price (ADP)" to refer to the FBC (including transport and force-protection assets) per unit of fuel delivered to a given location in the supply chain. The DAG specifies that the ADP for liquid fuel is in units of $/gallon and is the value commonly referred to as FBCF. The DAG uses FBCF to refer to the ADP times the daily quantity of fuel required by the system, and would be measured in units of $/day. In the DAG, the term "apportionment" is used to describe the determination of what portion of the logistics tail cost to attribute to the platform or system being evaluated.

2.2 Apportionment in Multistage Logistics Chains

In a multistage supply chain, the transport of fuel from the source (usually a DFSP) to the battlefield is not accomplished in a single round-trip. Rather, the trip is broken down into multiple stages, because the distance is very long or because terrain, quantities required, or force-protection requirements differ across stages.

Consider a very simple, hypothetical model of a three-stage logistics chain that provides fuel to a single battlefield, as shown in Table 1, and first presented in [15]. Fuel delivered is the total number of gallons of fuel that each stage delivers to the beginning of the next stage. The battlefield fuel demand at the end of Stage 3 is 1,000 gallons. In each stage, the transport and force-protection assets require fuel to operate. The fuel consumption by each stage is a given percentage of the amount delivered at the end of the stage. In Stage 1, for example, logistics activities directly consume 0.15 gallons for every gallon delivered to the end of Stage 1. Fuel costs are calculated as the fuel consumption, in gallons, multiplied by the current DLA-E fuel price for diesel, $2.30/gallon.[2]

[2] For F-76 diesel fuel; current as of September 16, 2012. Retrieved from http://www.energy.dla.mil/DLA_finance_energy/Pages/dlafp03.aspx.

Table 1 **Here**

Nonfuel operating costs are all other O&S costs, depreciation, infrastructure and recapitalization, and infrastructure for tactical delivery assets and associated security (force protection)—everything attributable to the logistics sector, and capturing the DAG-defined price elements #2 and #3 (excluding fuel consumed directly by logistics activities on this stage). Nonfuel operating costs are set to $2/gallon delivered to the next stage. This value is included purely to illustrate the multiplier effect, but is much lower than the other costs estimated in the AEPI (2008) scenario by stage (they use the term “leg”) [16]. The last column in Table 1 shows the total operating cost, including fuel, per gallon delivered to the next stage.

A straightforward way to estimate the ADP would be to take the sum of the per-gallon operating costs of all three stages, plus the DLA-E commodity price. This would yield an estimated ADP of 7.50 + 2.30 = 9.80.

A quick check, however, shows that this understates the costs attributable to battlefield fuel demand. This supply chain delivers 1,000 gallons of fuel to the battlefield, at a total cost of 9,346. The total operating cost per gallon delivered to the battlefield is, therefore, $9,346/1,000 gallons, or $9.35/gallon. The ADP is therefore 9.35 + 2.30 = 11.65. The difference between the correct ADP, 11.65, and the incorrect estimate of 9.80 is due to the *multiplier effect*: the phenomenon in which increases in fuel consumption will cascade back through the supply chain. As we will show later, this effect increases dramatically as the number of stages becomes large.

Figure 1 illustrates the consumption of fuel by stage. On Stage 3, 1,000 gallons is transported directly to the battlefield, and Stage 3 consumes 20% of 1,000 gallons, or 200 gallons. On Stage 2, however, 1,200 gallons must be transported—1,000 gallons for eventual delivery to the battlefield, plus the 200 gallons required to supply the logistics activities on Stage 3. Therefore, Stage 2 consumes 30% of 1,200, or 360 gallons of fuel. Similarly, Stage 1 must transport the battlefield’s 1,000-gallon demand, plus 200 gallons for Stage 3, plus 360 gallons for Stage 2. The total amount of fuel required at the beginning of Stage 1 just to provide the 1,000 gallons to the battlefield is 1,794 gallons, and the fuel multiplier for the warfighter in this example is 1,794/1,000 = 1.79.

FIGURE 1 HERE

2.3 Defining the Fuel Multiplier

The fuel multiplier reflects that logistics activities themselves consume fuel. In general, if organic assets are used to deliver fuel, transport and force-protection platforms will not be able to refuel commercially or at DLA-E prices for stages that do not originate at a DFSP. Fuel multipliers quantify the impact of the fuel requirements of the supply chain itself. We use the following notation:

s is the index of a given stage in the supply chain

a_s = the ratio of fuel consumed by logistics activities (e.g., transport vehicles) on Stage s to the amount delivered to the end of Stage s

b_s = the multiplier for Stage s, $b_s = 1 + a_s$, i.e., the number of gallons of fuel that must be provided at the beginning of Stage s 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).

Since $a_s > 0$, and $b_s > 1$, allocating the costs of resources associated with fuel supply logistics on early stages proportionally to the amount required on the battlefield will underestimate the resources incurred by battlefield demand.

The multiplier effect is cumulative along the supply chain. One gallon of fuel that is used at the end of the third stage in the above example, for instance, incurs a system-wide requirement of 1.79 gallons of fuel: $1.79 = 1.15 \times 1.30 \times 1.20$. We denote this cumulative multiplier as B_s = the amount of fuel required throughout the chain per gallon consumed at the end of Stage s, defined as

$$B_s = \prod_{t=1}^{s} b_t . \qquad (1)$$

In this example, B_3 =1.79. One gallon of fuel used at the end of the second stage incurs a system-wide fuel requirement of $1.50 = 1.15 \times 1.30$ gallons, i.e. B_2 =1.50.

The concept of a multiplier has been noted by others. For example, [10] notes that, "Savings downstream in a long logistics chain save more fuel: delivering 1 gallon to the Army speartip consumes about 1.4 extra gallons in logistics." However, the cumulative multiplier for each stage is simply the product of the stage-by-stage multipliers. This means that improving the efficiency of any stage would have the same proportional impact on the fuel multipliers at all downstream locations in the network. A reduction in battlefield fuel requirement downstream, however, has a bigger impact on the organization-wide fuel requirement, as multipliers are strictly increasing along the chain, i.e. $s > s' \Rightarrow B_s > B_{s'}$.

Many analyses (e.g., [18]) model a single-stage supply chain, in which the multiplier effect is not relevant. Other calculations neglect the multiplier effect. Early versions of the Army's FBC methodology specifically apportioned logistics costs on each stage (or leg) based on the amount consumed by the end user. As described in [17], for Leg 1, the total cost of convoys on this leg is calculated, and a percentage of that (10.7%) is counted towards the cost of fuel for the warfighting unit, a Stryker Brigade Combat Team (SBCT). The percentage is the two-day fuel consumption by the SBCT, divided by the total payload capacity of the convoys, which are assumed to go every two days. The cost to transport additional fuel to supply the convoys traveling on Legs 2, 3, and 4 is explicitly not attributed to the SBCT.

Although the early Army FBC methodology did not capture the fuel multiplier effect, the Army's current FBC Tool does capture the fuel multiplier effect without calculating it directly. In the current implementation of the model[3], the FBCF is calculated at the beginning of each stage, and is used in cost estimates for later stages. This means that

[3] Jan Montgomery, Logistics Innovation Agency, personal communication. October 1, 2012.

although the quantity of fuel that the supply chain must transport is not directly calculated, the fuel multiplier effect would be accounted for in each stage's FBCF. Denoting the fully burdened cost at the end of stage s as C_s, the formula should be $C_s = (1+\alpha_s)C_{s-1}$ plus stage s non-fuel logistics costs per gallon delivered on stage s. Using the example in Table 1, C_1 = \$4.65, C_2 = \$8.04, and C_3 = \$11.65, thus matching our calculation.

To get a more accurate estimate of the total cost, the DAG [11] explicitly calls for the FBC to include "costs directly and indirectly attributable to the system (i.e., costs that would not occur if the system did not exist), regardless of funding source or management control." Therefore, the cost to transport the fuel required for downstream stages of the supply chain should be included in FBC estimates.

The remainder of this article estimates the fuel multiplier for three example supply chains and examines the impact of the fuel multiplier on the fully burdened monetary cost of delivered fuel, as well as the impact of force-protection requirements on the fuel multiplier and on the capability available for other warfighter missions.

3 Estimating the Multiplier Effect

3.1 The Model

To estimate the fuel multiplier for fuel delivered to each point in a supply chain, the fuel consumed by the logistics activities, per unit of fuel delivered to the end of the stage, must be estimated for each stage. In this paper, we estimate the fuel consumed to propel transport vehicles and force-protection vehicles used to escort the transport vehicles. This ignores fuel consumed for other purposes that support the logistics chain, such as fuel consumed to deploy the platforms to the theater. The estimates here, however, provide lower bounds on the fuel multipliers for the modeled supply chains.

We define the following new parameters:

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

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

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 (Apache AS-64A assumed)

Thus, the amount of fuel consumed on Stage *s* per unit of fuel delivered to the end of Stage *s* can be written as:

$$\alpha_s = \frac{\overbrace{n_s^T g_s^T d_s}^{\substack{\text{fuel consumed}\\ \text{by transport}\\ \text{vehicles,}\\ \text{per convoy}}} + \overbrace{n_s^P g_s^P d_s}^{\substack{\text{fuel consumed by}\\ \text{force-protection}\\ \text{vehicles,}\\ \text{per convoy}}} + \overbrace{r_s g_s^A}^{\substack{\text{fuel consumed by}\\ \text{helicopter air,}\\ \text{support,}\\ \text{per convoy}}}}{\underbrace{n_s^T p_s}_{\substack{\text{total fuel delivered}\\ \text{to Stage } s+1\text{, per convoy}}}} \tag{2}$$

Time is not represented in this model. The multiplier b_s is a ratio of the quantity of fuel entering a stage to the quantity fuel leaving that stage; that quantity could be a daily, weekly, or annual consumption, or, as in our calculations and Equation (2), the amount delivered per convoy. The model presumes the convoy composition on a given stage does not change. However, the composition may differ across stages, and the total payload may differ across stages. The cumulative multiplier B_s may be interpreted as an average over many convoys on each stage, where the number of convoys required on each stage may differ. Below, we show results for three scenarios.

3.2 Results

3.2.1 Helmand Province Scenario

Dubbs [18] modeled a portion of the United States Marine Corps (USMC) logistics network in Helmand Province in Afghanistan, from Kandahar to all downstream forward operating bases (FOBs) and combat outposts (COPs). Below, we show results for a three-stage chain from Camp Leatherneck to the Now Zad FOB to the Bar Now Zad COP. The other FOB in this supply chain is Deleram, and the two FOBs serve a total of 11 COPs.

Dubbs described typical convoy compositions for each stage based on information provided by Jeffrey Kausek, a former USMC Captain [18].[4] Fuel is delivered in convoys consisting of fuel trucks and force-protection vehicles. Vehicle characteristics for all scenarios in Section 3.2 are given in Table 2. Table 3 shows the convoy compositions and stage distances for the Bar Now Zad supply chain, and calculates the stage-wise and cumulative multipliers, showing that 1.71 gallons of fuel must be delivered to Kandahar for each gallon that the warfighter requires at Bar Now Zad. The Kandahar to Leatherneck stage consumes only 4% as much fuel as it delivers, while the Leatherneck to Now Zad stage consumes 37% as much fuel as it delivers. In 2009, the USMC was able to contract for delivery of fuel at Camp Leatherneck for \$6.39/gallon [13].[5] At this rate, and removing the Kandahar to Camp Leatherneck stage, the ADP at Bar Now Zad would be at least $6.39\times1.37\times1.20=10.45$, excluding all other costs (personnel, depreciation, etc.) associated with USMC logistics assets. Moreover, the \$6.39/gallon

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[4] Jeffrey Kausek separated from active service on May 30, 2011, as Battalion Logistics Officer for 3rd Battalion, 4th Marines, 7th Marine Regiment, 1st Marine Division. Mr. Kausek served two tours in Afghanistan as a supply officer for the USMC.

[5] According to MEAT (2010), in 2009, contracted fuel was delivered as far as Camp Leatherneck, which would mean that no fuel multiplier was incurred for organic logistics between Kandahar and Leatherneck, and only two stages of the logistics chain from Leatherneck to Bar Now Zad would be organic, which is a cumulative multiplier of 1.57 [13].

rate was for 2009, when market oil prices were roughly half what they were in late 2012 and the vast majority of fuel was shipped through Pakistan. Pakistan closed the fuel routes for seven months, ending in July 2012, during which time the supply traveled either by air or along the Northern Distribution Network (NDN), a supply route to Afghanistan from the Baltic and Black Seas through Central Asia. Contracted transport prices on the NDN are substantially higher–estimated at $17,000 per container, vs. $7,000 on routes through Pakistan [19].

Table 2 **Here**

Table 3 **Here**

The difference between the fuel multipliers for Stage 1 from Kandahar to Leatherneck and the later stages is meaningful. The road infrastructure in the Helmand Province logistics network is varied. For example, some of the FOBs and COPs lie directly along the A1 (Kandahar-Herat) Highway. Now Zad, on the other hand, lies off the highway, and the terrain separating it is very difficult. Therefore, it is estimated that it takes three hours for a convoy to travel 60 miles from Camp Leatherneck to Deleram, but 18 hours for a convoy to travel 40 miles from Camp Leatherneck to Now Zad. Vehicles' fuel efficiencies decline in poor terrain; therefore, Dubbs modeled fuel consumption as proportional to the duration of the trip. This makes the logistics network supplying Bar Now Zad very fuel intensive, and highlights that in remote areas and in an immature theater, the fuel requirements of the logistics support itself may be a serious consideration.

3.2.2 Army Sustain the Mission Project Iraq Scenario

AEPI [16] describes the methodology behind the Army's FBC Tool, developed as part of the Sustain the Mission Project (SMP). The document details the calculations for a base case scenario—a four-stage logistics chain transporting fuel a total of 550 miles (one way) from Kuwait to an SBCT in Iraq, with transfers at the convoy-support FOB Cedar II, an Expeditionary Sustainment Center (ESC), and the Brigade Support Battalion (BSB).

The convoy compositions differ by stage, and airborne force protection is included for a fraction of each stage. The details are provided in Table 4 together with fuel consumption and multiplier calculations. In the SMP scenarios, air protection is provided by two Apache (AH-64) helicopters over a portion of the trip on each stage (20% on Stage 1, and 40% on the remaining stages). The helicopters' fuel consumption is counted toward the stage's total fuel consumption only during the portion in which they are used.

Table 4 **Here**

The cumulative multiplier at the end of Stage 4 (the SBCT) is B_4 = 1.07. This means that based exclusively on the fuel consumed directly in transport and force protection platforms (vehicles and aircraft), an extra 0.07 gallons is required for every gallon consumed by the SBCT. The impact of this on fuel purchase costs (price element #1 in the DAG) is that the DLAE standard price of $3.19/gallon [16] should be multiplied by 1.07, for a cost of $3.41/gallon used by SBCT.

3.2.3 Army Sustain the Mission Project Immature-Theater Scenario

AEPI [16] also describes an immature theater scenario. In an immature theater, we would expect a longer supply chain (greater distance between commercial sources of supply and the battlefield), as well as greater fuel consumption on each stage. This is due primarily to the need for force protection, but also due to the likely delays and compromised fuel efficiency associated with poor roads and other infrastructure challenges.

The immature-theater scenario is shorter (1,700 miles round-trip, versus 1,100 miles round-trip for the Iraq scenario), uses 5,000-gallon capacity transport vehicles along the entire supply chain instead of the larger tanker trailers used on the first two (long) legs in the Iraq scenario, and requires more air support. The ratio of transport vehicles to force-protection vehicles (4:1) is the same in the two scenarios, and the convoy speed (35 miles per hour [mph]) is the same. The analysis uses standard fuel consumption rates per vehicle, and so they are not affected by the potential reduction in fuel efficiency due to potentially compromised infrastructure in an immature theater [16].

Table 5 shows our analysis of this scenario, which assumes four identical stages; the number of stages was specified but the breakdown by distance was not [16]. As expected, the multipliers are larger for the immature theater. The multipliers b_s = 1.043 on each stage and cumulatively, B_4 = 1.18. For every gallon of fuel consumed by the warfighter, an extra 0.18 gallons must be provided at the beginning of Stage 1 to sustain the supply chain.

Table 5 **Here**

3.3 Discussion

3.3.1 Impact on Fully Burdened Cost Calculations

Fuel is not the only resource consumed in the transport of fuel. Due to the multiplier effect, extra fuel to sustain downstream logistics must be transported and protected in each stage. Therefore, other costs—such as vehicle depreciation, personnel, maintenance, and deployment of the logistics vehicles to the theater—associated with those platforms should also be charged to the FBC of battlefield fuel consumption. If we assume other costs, quantified for the SMP base-case scenario and allocated proportionally to the length of the stage, then the revised ADP, including the fuel multiplier, should be $15.53/gallon, rather than the $14.13/gallon calculated in [16]—a 10% difference.

3.3.2 Sensitivity to Force-Protection Requirements

As highlighted in the DAG FBCE discussion, the logistics footprint is especially important in high-threat environments. In these environments, not only will long portions of the supply chain be organic, without access to commercial fuel or contracted delivery services, but the vulnerable supply network may require force protection to ensure delivery. In general, there is an inverse relationship between force protection and asset attrition. In this paper, we model the additional costs in high-threat environments via force protection. We assume that force protection is sufficient for the given environment; if it were insufficient, we would expect to see substantial additional costs due to attrition.

In order to explore the impact of the level of force protection required, we separate the transport function from the force-protection function on each stage, and introduce the concept of a *sector*. Following the conventions of input-output (IO) analysis, sectors require each other's inputs, and meet the requirements of all other sectors. First conceived and most often applied to the analysis of national economies [20,21], using industries and subindustries as the units of analysis (sectors), IO is a simple, but powerful, tool.

In recent years, IO analysis has been extended to model greater detail in the material and economic relationships in the economy, and to trace the resource and environmental impacts through economic systems. The research literature is rich with applications to Life Cycle Assessment (LCA), which is the estimation of the environmental impacts of consumption of products and services, traced back through the economy [22]. Physical IO analyses represent the transformation of materials through production processes to trace resource requirements and environmental impacts throughout a system [23].

In our supply-chain model, each sector provides a particular type of output on a particular stage. Thus, for a supply chain with four stages requiring transportation and force protection, there are eight sectors. The origin may also be interpreted as a sector; when another sector requires output from the origin, this simply means that the output must be provided at the start of the supply chain. As previously, the transport sector's output in each stage is fuel delivered to the end of the stage. The force-protection sector's output is a measure of force protection provided on that stage; we will use vehicle-hours. A convoy that requires two force-protection vehicles along a 100-mile stage will, therefore, require 200 vehicle-miles of force protection.

Previously, each Stage s required one input (fuel) from an external source (for $s=1$) or from the preceding stage. In the IO model, each sector may now require output from more than one other sector to be used as input. In particular, each force-protection sector requires fuel provided by the prior stage's transport sector. It is assumed that force-protection sectors do not demand further force protection.[6] 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. The associated notation is given below:

i,*j* indices of sectors
x_i = the quantity of output produced by Sector *i*
a_{ij} = the amount of output from Sector *i* required by Sector *j* to produce one unit of Sector j's output. The a_{ij}'s are called the IO coefficients.

For convenience, we also define

$s(i)$= 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

[6] This assumption is not required to analyze the model. The IO framework allows for a sector to demand its own input.

Now, the IO coefficients may be calculated. For a transport Sector j and $i = i^T\left(s(j) - 1\right)$,

$$a_{ij} = \frac{n^T_{s(j)} p_{s(j)} + n^T_{s(j)} g^T_{s(j)} d_{s(j)}}{n^T_{s(j)} p_{s(j)}} = \frac{p_{s(j)} + g^T_{s(j)} d_{s(j)}}{p_{s(j)}} \quad . \tag{3}$$

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

$$a_{ij} = \frac{n^P_{s(j)} g^P_{s(j)} d_{s(j)}}{2 n^P_{s(j)} d_{s(j)}} = g^P_{s(j)} . \tag{4}$$

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

$$a_{ij} = \frac{n^P_{s(j)} d_{s(j)}}{n^T_{s(j)} p_{s(j)}} . \tag{5}$$

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 a set of mass-balance equations, given in Equation (6) below, for all i whose output is not exogenous:

$$x_i = \sum_j a_{ij} x_j . \tag{6}$$

Table 6 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.

Table 6 Here

Rather than viewing force protection as logistics activity, we may take the perspective that these platforms are in theater for their warfighting capability and may be diverted to protect the supply chain if necessary. In this view, the quantity of force-protection output produced does not change based on the size of the supply chain. Instead, the force-protection output available to provide warfighting capabilities declines as more force protection is allocated to protecting the supply chain.

Assume that the warfighter produces force-protection output (measured in hours) at the same resource intensity (here, 0.13 gallons per mile) as the force-protection vehicles operating on the supply chain. With 5,000 gallons, for example, the warfighter produces 1,093 hours of warfighting output. In the baseline scenario, in each stage, each convoy consists of n^P_s = 4 force-protection vehicles and $n^T_s = 16$ transport vehicles—a force-protection ratio $\left(\frac{n_s^P}{n_s^T}\right)$ of 0.25. In the baseline scenario shown, for every 5,000 gallons delivered to the battlefield, the warfighter produces 1,093 hours on the battlefield, plus 439 hours total protecting the four stages, for a total of 1,531 hours. The supply chain, therefore, requires 29% of the total warfighter output. Figure 2 shows the effect of the force-protection ratio on the percentage of force-protection output used by the supply chain.

FIGURE 2 HERE

In this model, this percentage approaches 100% asymptotically as the number of fuel-protection vehicles per transport vehicles increases. With a small change in Equation (4) describing the assumption about where force-protection vehicles refuel, the percentage is no longer bounded by 100%. If the force-protection vehicles along the supply chain refuel at the destination node, they consume fuel delivered by the transport vehicles they are protecting. The force-protection vehicles can consume all the fuel delivered by the transport vehicles they protect; the single-stage multiplier goes to infinity and the supply chain becomes a self-licking ice cream cone.

3.3.3 Factors Driving the Multiplier

Three factors determine the size of the multiplier in each stage: resource intensity, length, and availability of supplies.

The greater the resource intensity of the chain—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 drive up the enterprise-wide multiplier considerably. Transport over difficult terrain, which leads to lower vehicle fuel efficiency, has this effect as well.

In addition, greater force-protection requirements drive greater resource intensity in the supply chain. A high-threat environment, with the enemy targeting the supply chain in an attempt to deny access, is likely to have a very high fuel multiplier. The SMP base case scenario has much bigger convoys, including larger-capacity fuel vehicles and fewer force-protection vehicles per transport vehicle. The fuel requirement per gallon delivered in each stage is, therefore, lower, and the multipliers are lower than for the Bar Now Zad supply chain. Even in the SMP base-case scenario, however, convoys get smaller downstream, with a higher ratio of force-protection to transport vehicles, and smaller transport vehicles are used downstream (near the "point of the spear"). Fuel consumption in extreme forward positions is the most costly.

The length of the organic portion of the supply chain is a driver. For n identical stages with $b_s = b$ in each stage, following Equation (2), $B_n = b^n$ –in other words, the multiplier increases exponentially with the number of stages in the organic portion of the supply chain.

Moreover, the distance between sources of fuel (or other supplies) and points of consumption (by both the end user and logistics platforms) drives the multiplier. If the length of a stage exceeds the distance the vehicles can travel on their non-payload fuel tank, they must consume fuel they are transporting, and the payload delivered at the end of the stage declines. In fact, the amount of fuel consumed on a stage increases rapidly as the length of the stage becomes large, as described in [24]. Fuel consumption imposes an upper bound on the possible length of each stage, determined by the fuel capacity of the vehicles. Fuel consumption per gallon delivered (a_s) increases asymptotically as the length approaches this upper bound.

The estimates in this paper exclude the logistics costs for delivering supplies, other than fuel that sustain transport and force-protection vehicle.

4. Future Directions

Sustainment of these vehicles and personnel requires other inputs besides fuel, such as food and water. Thus, since additional fuel consumed downstream requires additional transport and force protection earlier in the supply chain, the fuel multiplier also increases requirements for these other inputs. Similarly to the other factors excluded from the analysis in this paper, incorporating this would increase the multipliers.

Moreover, the estimates in this paper cover only the sustainment phase of operations. A more complete analysis would include asset depreciation, and the resources required for deployment, which may be quite substantial. Inclusion of these factors would increase the multipliers.

A natural question is: how much cost is not captured if the fuel (or other) multiplier effect is ignored? If it is on the order of 10%, for example, then it is a much smaller impact than the uncertainty regarding the future price of fuel, and so perhaps insignificant from a decision-making perspective. We would argue, however, that because it causes a systematic underestimate (rather than just imprecision) in FBCF estimates, it is a cause for concern. That is, whether multiplier effects account for an error in an FBCF estimate of 10% or 100%, that error will always be an underestimate of overall costs.

In addition, for reasons described above, the estimates here should be considered lower bounds on the impact of the multiplier effect, as they exclude resource consumption in deployment, consumption of non-fuel supplies by logistics activities, and attrition of the assets themselves. We recommend more detailed studies to estimate the magnitude of the logistics multiplier effect to determine how important it is to incorporate it into FBC estimation methods.

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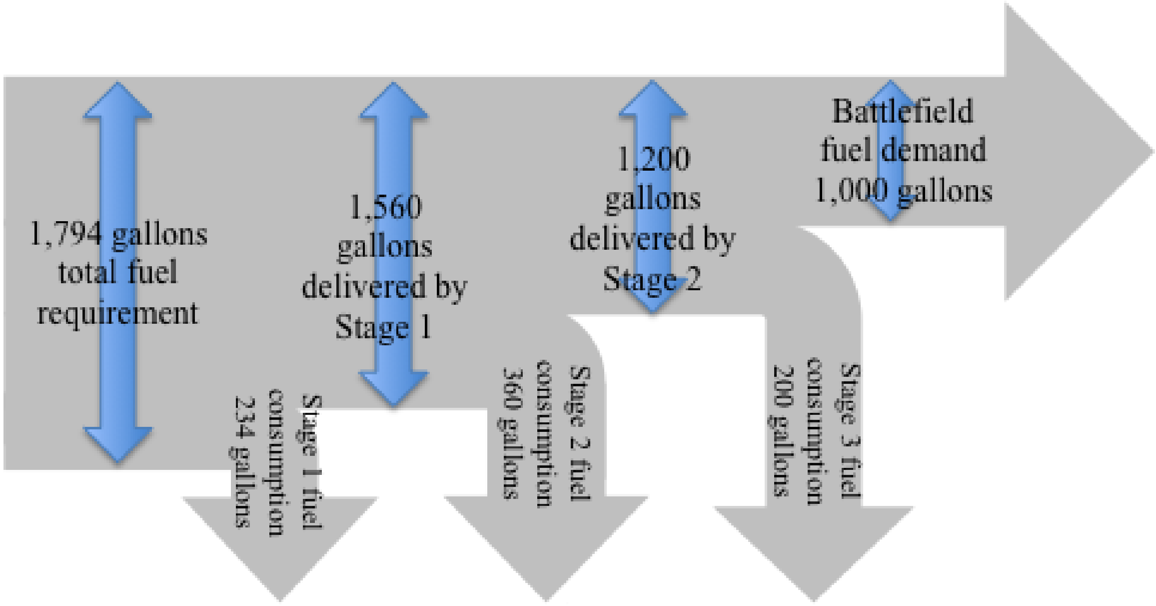

Figure 1: Illustration of fuel consumption in three-stage supply chain from Table 1.

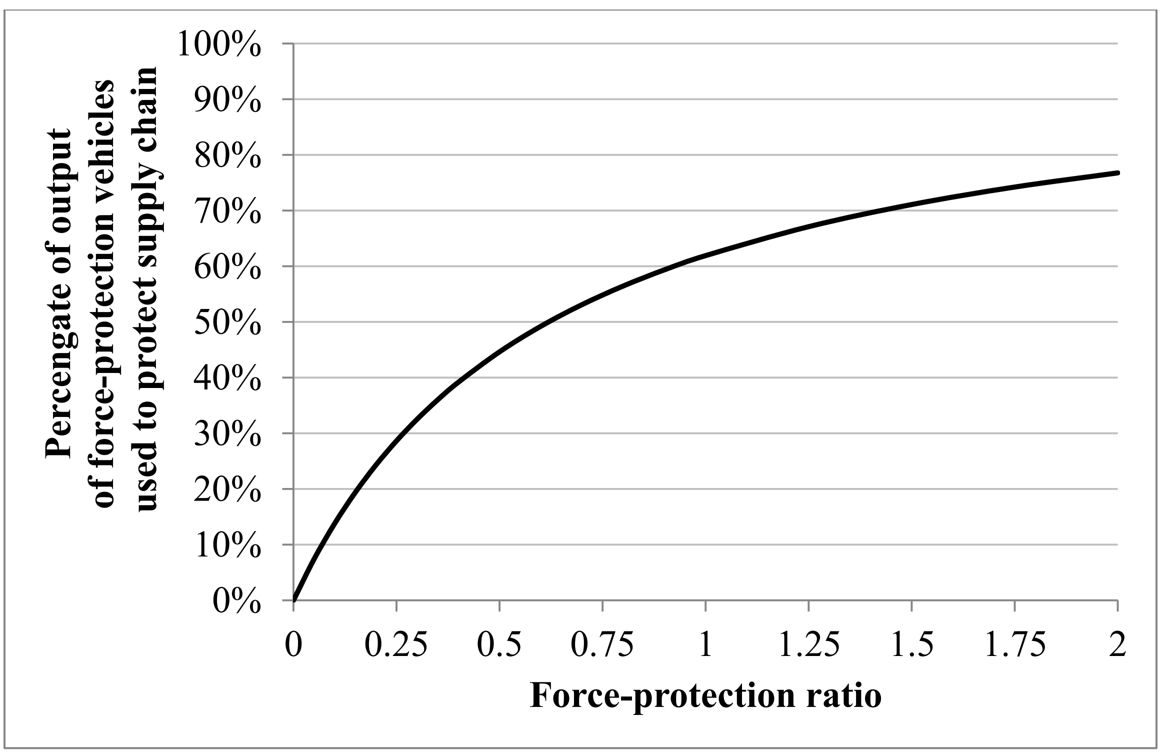

Figure 2: The impact of the force-protection ratio on the percentage of warfighter output required to protect the fuel supply chain.

Table 1: Hypothetical three-stage supply chain.

Stage	Fuel Delivered (gallons)	Fuel Consumption (% of delivered)	Operating Costs Non-Fuel	Fuel	Total	Total Operating Costs per Gallon Delivered
1	1,560	15	$3,120	$538	$3,658	$2.35
2	1,200	30	$2,400	$828	$3,228	$2.69
3	1,000	20	$2,000	$460	$2,460	$2.46
		Total	$7,520	$1,826	$9,346	

Table 2: Vehicle characteristics used in the scenarios. The hourly consumption rates used in the Helmand Province scenario are based on poor terrain and low speeds and are from Dubbs (19). 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 derive from AMSAA.

Type	Fuel Consumption Rate (gallons per mile)	Fuel Consumption Rate (gallons per hour)	Payload (gallons)
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		

Table 3: Analysis of the Bar Now Zad supply chain in Helmand Province.

Stage	d_s (round-trip hours)	Convoy Composition: Vehicle Type: Transport	Force Protection	Vehicle Quantity n_s^T	n_s^P	Air Support (hours)	Total Fuel Consumption (gallons)	Total Payload (gallons)	Stage Multiplier b_s	Cumulative Multiplier B_s
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 4: Analysis of the Army Sustain the Mission Project base-case scenario, a supply chain in Iraq.

Stage	d_s (round-trip miles)	Convoy Composition: Vehicle Type: Transport	Force Protection	Vehicle Quantity n_s^T	n_s^P	Air Support (hours)	Total Fuel Consumption (gallons)	Total Payload (gallons)	Stage Multiplier b_s	Cumulative Multiplier B_s
1 (Kuwait to Cedar II)	450	8000	M1117	16	4	5.1	2,700	128,000	1.02	1.07
2 (Cedar 2 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 5: Analysis of the Army Sustain the Mission Project immature-theater scenario, a 1,700-mile round-trip organic supply chain.

Stage	d_s (round-trip miles)	Convoy Composition: Vehicle Type – Transport	Vehicle Type – Force Protection	Vehicle Quantity n_s^T	Vehicle Quantity n_s^P	Air Support (hours)	Total Fuel Consumption (gallons)	Total Payload (gallons)	Stage Multiplier b_s	Cumulative Multiplier B_s
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 6: An input-output matrix for a supply chain with transport (T) and force-protection (FP) components. The fuel consumption rates match the Sustain the Mission Project immature-theater scenario, with no air support.

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	1.018	0.131
3	FP	0	0	0	0	0	0.021	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	105
	(units)	(gallons)	(gallons)	(hours)	(gallons)	(hours)	(gallons)	(hours)	(gallons)	(hours)