MODELING TRANSPORTATION RESOURCE CAPACITY AND OPTIMIZING SECURE SHIPPING OPERATIONS

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ABSTRACT

The Department of Energy owns a number of nuclear materials that require physical protection. This protection is required for the materials in transit as well as in storage. The resource capacity for protecting these materials in transit was allowed to decline after the end of the cold war. As Records of Decision regarding the disposition of surplus special nuclear materials (SNM) are implemented, the Department’s secure transportation workload will increase dramatically. New resources cannot be added fast enough to support the growth in work scope unless secure shipping operations become more efficient. This paper describes our effort to model integrated secure shipping operations and to recommend changes to shipping plans that reduce workload and increase capacity.

INTRODUCTION

The Transportation Safeguards System, TSS, provides protected transport of the Department’s SNM. The protection is provided with engineered systems in the transport vehicles and with specially trained security forces that escort the shipments. The TSS maintains federal agents and special vehicle resources in three separate locations. These resources are chartered to support secure transportation between 37 shipper/receiver sites. The first challenge was to collect detailed shipping plans from each of these sites and integrate them into a comprehensive TSS workload forecast. The second challenge was to develop a model that could generate an optimized secure shipping solution set. The resulting model is called TRIPS – for Transportation Resource Integrated Planning System. TRIPS combines rules on TSS operations with workload projections and a detailed description of all the resources constraining transportation of these materials. The resource constraints include shipper and receiver site capabilities and the availability of federal agents, transporters, and certified packages to support the work.

This paper details the challenges of building such a model, and providing it with validated data on a regular basis. Although the model is still evolving, it has already provided critical data on supportable project schedules, as well as recommending where managers should focus limited assets to support overall Departmental commitments.

MODEL FORMULATION

The TRIPS model is a large-scale linear programming formulation. The baseline formulation determines the maximum workload that can be accomplished within constraints imposed by limited resources. However, the model can also be used in a “resources requirements” mode, in which it computes the set of resources that would be required to service a specified workload.

The model formulation relies on definition of several core terms. Most basic among these is definition of time periods considered in the model. Many of the variables in the model are defined over a set of discrete periods indexed by $t = 1,2,\ldots,T$. In the analyses performed to date, these periods are months, and the model planning horizon extends out ten years.

A second important definition is of a *campaign*. A campaign is the movement of a specific type of material in a specific type of package, from an origin point to a destination point. For example, a campaign might involve plutonium metal being moved in type 9975 containers from Rocky Flats to the Savannah River Site. A campaign will typically involve multiple shipments. Campaigns are the workload that drives the model solution. The model allows a shipment "window" to be defined for each campaign. This window represents the degree of scheduling flexibility that exists regarding when to move a particular shipment in that campaign. Because the basic time period in the model is one month, the minimum degree of flexibility assumed is that movements can occur any time within a single month. However, if greater flexibility is available for a specific campaign, the window can be expanded. If a shipment is not moved within its specified window, the packages not moved on time are said to be *deferred*. The model attempts to avoid deferral of shipments, but if resources are too constrained, deferrals can occur and are reported in the model output.

A third important concept in the model is that of a truck *fleet*. Each fleet is a particular physical trailer type. Material shipments are assigned by the model to truck movements by specific fleets, and we can restrict specific campaigns to move only in certain trailer types.

The model assigns packages and resources to *convoy deployments*. A convoy deployment involves the dispatch of TSS agents and transporters to move the contents for one or more campaigns. One convoy may move contents between a series of shipping and receiving sites before returning to its home base. The campaigns establish the workload, the convoy deployments determine how efficiently the workload is accomplished. The goals are to minimize deadhead miles, maximize the quantity of packages transported in each convoy, and minimize the overall resource requirements to support all of the requested work scope. All of these goals have to be met within the requirements of the missions being supported.

To describe the baseline model formulation, we can begin by defining a set of input parameters, as follows:

$Q_c(t)$: quantity (number of packages) of cargo for campaign c first available to move in time period t

$D_c(t)$: time period by which cargo for campaign c made available in period t must be moved

$V_k(t)$: trucks available in fleet k in time period t

$H(t)$: available agent-hours in time period t

v_c: packages for campaign c that can be shipped in one truck

π_k: vehicle-miles of productive use for a truck in fleet k per time period

d_{ij}: distance from node i to node j (miles)

g_c: distance from origination node to destination node for campaign c

ψ_c: relative priority of shipping a package from campaign c

γ_c: penalty cost for not moving a package of material for campaign c

The number of packages of material assembled into a single shipment varies across campaigns, and the proportion of a truck's capacity required for a single shipment also varies across campaigns. Because a whole truck must sometimes be used to carry a partial load, we transform the raw workload input, $Q_c(t)$, which is measured in number of packages, into workload demands measured in number of trucks, which we can denote $W_c(t)$. The transformation is:

$$W_c(t) = \left\lfloor \frac{Q_c(t)}{v_c} \right\rfloor \qquad \text{(Eq. 1)}$$

That is, the number of trucks demanded is the smallest integer number that is sufficient to carry the desired number of packages.

From the set of $W_c(t)$ and $D_c(t)$ values specified, we can compute two other sets of parameters:

$$A_c(t) \quad = \quad \sum_{\tau=1}^{t} W_c(\tau) \qquad \text{(Eq. 2)}$$

$$R_c(t) \quad = \quad \sum_{\tau=1}^{t} \{W_c(\tau) \mid D_c(\tau) \le t\} \qquad \text{(Eq. 3)}$$

$A_c(t)$ defines the cumulative number of truckloads for campaign c available for movement through the end of period t, and $R_c(t)$ represents the minimum requirement for movement of truckloads in campaign c through period t (i.e., in order to move packages within their allowable "time windows"). These values are used in the model to bound the actual movements. Material cannot be moved until it is available, and it should be moved by its deadline period. The values of $A_c(t)$ and $R_c(t)$ are used in the model as inputs, but they are computed from the actual data ($W_c(t)$ and $D_c(t)$).

The following decision variables are determined by the model:

$q_{ck}(t)$:	units of cargo (packages) of campaign c that are actually moved using fleet k in period t
$x_{ck}(t)$:	trucks from fleet k moved carrying cargo of campaign c in period t
$y_{ijk}(t)$:	number of trucks of fleet k that move empty from i to j in time period t
$N_c(t)$:	truckloads of cargo for campaign c that are deferred (i.e., not carried within the allowable time window) at time t

The objective of the model is to maximize total system completed workload. In addition, the actual objective function implemented contains penalty terms for deferred workload and empty truck-miles, so the actual objective is:

$$\text{Max} \sum_{c,k,t} \psi_c g_c e^{-\lambda t} x_{ck}(t) - \sum_{c,t} \gamma_c g_c N_c(t) - \theta \sum_{k,i,j,t} d_{ij} y_{ijk}(t) \qquad \text{(Eq. 4)}$$

The ψ_c coefficient in the first term provides a relative weighting based on the priority level of the campaign. The γ_c term in the second term reflects the relative penalty for deferring workload from campaign c. The $e^{-\lambda t}$ term creates a small time preference (e.g., using a small value of $\lambda = 0.01$), so that it is advantageous to carry shipments early in their allowable time window, rather than later. The penalty term on empty truck-miles is present to prevent solutions that move vehicles for no real purpose, and in implementation the value of θ is very small (0.001).

Two sets of constraints in the model are used to bound the workload and define deferred workload. The cumulative amount of cargo (in truckloads) for campaign c that is moved by the end of period t is $\sum_{\tau=1}^{t}\sum_{k} x_{ck}(\tau)$. We use that value, plus $R_c(t)$ and $A_c(t)$ defined by (2) and (3), to define deferred workload, $N_c(t)$. These constraints are as follows:

$$\sum_{\tau=1}^{t}\ \sum_{k} x_{ck}(t) + N_c(t) \geq R_c(t) \qquad \forall\, c, t \qquad \text{(Eq. 5)}$$

$$\sum_{\tau=1}^{t}\ \sum_{k} x_{ck}(t) \leq A_c(t) \qquad \forall\, c, t \qquad \text{(Eq. 6)}$$

Restrictions that certain campaigns must use specified types of trucks are implemented by constraining some of the flows to be zero:

$$x_{ck}(t) = 0 \qquad \text{for } ck \text{ combinations that are not acceptable} \qquad \text{(Eq. 7)}$$

Conservation-of-flow equations force the flow of trucks in each fleet k to balance at each network node, i, in each time period, t:

$$\sum_{j} y_{jik}(t) + \sum_{c\in\Delta_i} x_{ck}(t) = \sum_{j} y_{ijk}(t) + \sum_{c\in\Omega_i} x_{ck}(t) \qquad \forall\, i, k, t \qquad \text{(Eq. 8)}$$

The left-hand-side of (6) is the total flow of trucks (empty plus loaded) in fleet k into node i in time period t, using the notation that Δ_i represents the set of campaigns whose destination is node i. The right-hand-side of (6) represents the total flow of fleet k trucks out of node i in time period t, where Ω_i is the set of campaigns whose origin is node i.

The total resources available, represented as truck-miles and agent-hours, constrain the operations in each period:

$$\sum_{c} g_c x_{ck}(t) + \sum_{i,j} d_{ij} y_{ijk}(t) \quad \leq \quad \pi_k V_k(t) \qquad \forall k, t \qquad \text{(Eq. 9)}$$

$$\xi_0 + \xi_1 \left[\sum_{c} g_c x_{ck}(t) + \sum_{i,j} d_{ij} y_{ijk}(t) \right] \quad \leq \quad H(t) \qquad \forall\, t \qquad \text{(Eq. 10)}$$

The left-hand-side of (9) is the total truck-miles operated (including both loaded and empty miles) for fleet k in period t, and the right-hand-side is the available truck-miles from a fleet of size $V_k(t)$. The vehicle productivity parameter, π_k, is a critical input to the model, because it determines how much work an average vehicle can perform.

Constraint (10) expresses agent-hours required as a linear function of total truck-miles operated, using the parameters ξ_0 and ξ_1. For a variety of operational reasons, the relationship between truck-miles and agent-hours is not exactly linear in practice, but for long-range planning this is sufficiently accurate. The parameters ξ_0 and ξ_1 are estimated statistically from historical data and knowledge of the detailed operational rules in effect. Constraint (10) then limits operations to those that can be staffed with available agents.

In any given time period, either available truck resources or available agents to staff operations may be the limiting resource. The model allows investigation of both capital expenditure plans for acquiring more trucks over time, and training plans for increasing the agent pool, as means of relaxing resource constraints.

Equations (4)-(10) define a linear programming (LP) problem. For the purposes of long-term (i.e., multiple years of monthly periods) planning, we solve this problem as an LP even though the solution can generate non-integer flows of trucks. As long as we interpret the solution as a forecast of the general character of operations in future months, and do not try to infer from it that a specific truck is carrying a specific load at a specific time, this is an acceptable solution strategy. The model has been implemented in a PC environment, using a commercial linear programming software package.

SUPPORTING THE MODEL WITH VALID DATA

The modeling effort requires four main types of data:

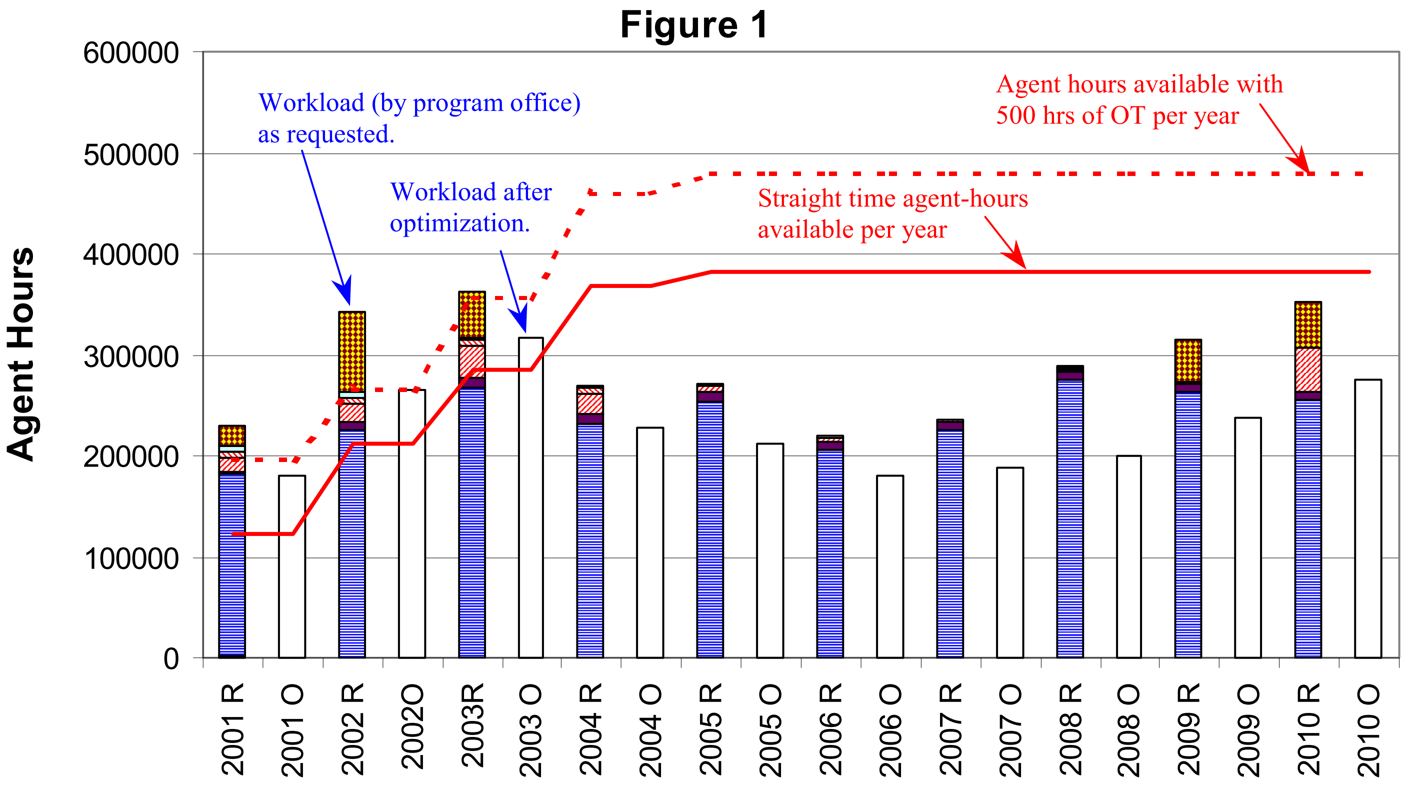
- Workload information, in the form of projected number of packages to be shipped, by package type, campaign and month, over the planning horizon (currently ten years)
- Resource availability (trucks and agents), by month, over the planning horizon
- Network data (locations, mileage, etc.)
- Operational data (loading limits for packages on trucks, vehicle productivity, parameter estimates for agent-hours calculation, etc.).

This data represented a large increase in the amount of planning information sites and program office were asked to provide. New data calls are not favorably received, so getting support for accurate and timely data inputs was challenging. We approached the problem on two fronts. First, we worked to inform the shippers that a significant problem with resource capacity was looming. We convinced shippers that providing long-range planning would allow us to develop solutions that would preclude, or mitigate resource problems before their campaigns were affected. Secondly, we worked with the resource provider, the Office of Transportation Safeguards, OTS, to support the planning requirement. Fortunately, they are the only source of secure transportation services approved for shipping the Department's materials of national security interest. OTS understood that having good workload data was key to obtaining support for increasing their resource capacity. To support our modeling, OTS made access to their shipping services contingent on shipper participation in the enhanced planning process. This requirement was formally instituted by direction of the Assistant Secretary for Defense Programs (the management organization that funds TSS operations) in November of 1999. The initial planning data we received had gaps in information, but it was complete enough to make clear and simple improvement recommendations for shipping plans. The adopted recommendations increased the efficiency of TSS operations by 28% for some campaigns with minimal impact to shipping sites. This success encouraged additional participation in the project. Currently, 19 shippers and/or program offices support this planning effort with accurate data revisions each quarter.

Resource availability, network and operational data were provided by the DOE Office of Transportation Safeguards. This has been an iterative effort. This organization has been working to recruit new agents and to enhance its security profile through better training, and improved equipment. OTS has worked closely with our TRIPS modeling team to establish recruitment goals, and to schedule procurements of new equipment. Operational constraints in OTS have been adjusted to mitigate impacts to requested shipping operations in the short term. This has been an iterative process. Analytical results from the model have driven changes to OTS resource allocation. Changes to resource allocation and operating rules have then affected inputs to the model.

USES AND IMPACTS OF THE MODELING EFFORT

The algorithms used by the model are of little direct use in guiding material disposition decisions. To support management analysis, a significant effort was invested in developing graphical output from the model that accurately summarized the analytical results. Graphical presentations highlight disconnects between workload and resource capacity. Good graphics also clarify the impacts of changing various parameters involved in managing these materials through disposition. Figure 1 shows one solution set created from the model for management review.



The "R" suffix on dates indicates workload as it was requested. The "O" suffix on dates shows the same workload after optimization. Once optimized, convoys loose their program specific character.

Fig. 1. One solution set created from the model for management review.

Our modeling effort has produced these benefits:

1. The planning for secure shipments now supports more efficient operations.
2. The planning data is now better aligned with the actual shipments than it was in the past. This increases confidence in modeling results and allows management to make effective decisions based on recommendations coming from the model.
3. The modeling data has supported budget requests to provide increased resource capacity
4. The effort has highlighted the importance of including transportation planning in any projects affecting the movement of DOE's cargoes that can affect national security.

CONCLUSIONS

The Transportation Safeguards System is a vital aspect of the Department's protection for materials of national security interest, but there are resource constraints. With the end of the cold war, many of the materials preserved for national defense activities are being declared surplus to production operations. Managing these materials through disposition is a complex endeavor. Transportation management is one of the complicated support functions in this process. Prior to creating this model, there was no way to assess the capacity of TSS resources to supported the integrated secure transportation workload under a variety of scenarios being considered. We now have a tool that can provide this information. Managers responsible for making disposition decisions for special nuclear materials can now review the costs and benefits of a variety of disposition scenarios. Transportation planning can be incorporated into that decision making process. Perhaps the greatest result is that the cost of collecting the data and running the model has been less than the opportunities for cost avoidance the model has presented to the Department. It is an elegant analytical tool that makes good business sense.

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