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Transportability in the Defense Department Research, Development, and Acquisition Process

Benjamin Zycher, David Morton

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PREFACE

This study considers the formal role that transportability plays in the Department of Defense research, development, and acquisition process. Several specific systems are reviewed for insights into practical aspects of transportability planning and analysis. The report is a portion of a project aimed at formulating a conceptual design for a future DoD materiel distribution system.

Other parts of the Future Distribution System Study are exploring distribution of cargo during mobilization and deployment of forces (including mixes of strategic transportation assets and the related operating procedures), the civil transportation systems on which DoD will rely in a major contingency, alternative concepts for managing the distribution of military resupply cargo in wartime, and the affordability of distribution alternatives. RAND was asked to do this study by the Under Secretary of Defense for Acquisition, who called for a "blueprint" for a materiel distribution system that would serve the needs of all the U.S. military. This call was inspired by the concerns of the Under Secretary of the Army and others about like problems during mobilization and deployment.

This report was prepared within the Acquisition and Support Policy Program of the National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense and the Joint Staff. The research reported here was jointly sponsored by the Assistant Secretary of Defense (Production and Logistics), the military services, the Joint Staff, the Defense Logistics Agency, and the institute's Defense Advisory Group, whose members are key policymakers in the Office of the Secretary of Defense and the Joint Staff.

The work should be of interest to researchers, participants, and policymakers concerned with design of DoD materiel and equipment, logistics planning, and systems effectiveness.

SUMMARY

There is inherent tension between the goals of greater effectiveness for Department of Defense (DoD) equipment, systems, and weaponry on the one hand, and greater ease (or reduced cost) of transport on the other. To put it differently, greater combat effectiveness in the theater usually carries with it increases in weight, size, and other parameters affecting transportability adversely.

Tradeoffs between these desirable goals somehow must be made, and DoD devotes considerable attention to them. Unlike such choices in the private sector, however, the DoD Research, Development, and Acquisition (RDA) process is not constrained in important ways to make design decisions reflecting the preferences of the ultimate users of the equipment. In part, this is due to the absence of a profit motive; in part, it is due to the much greater complexity inherent in the identity of the "users." Because of this feature of the RDA process—a relative weakness in the decision voice of users—examination of tradeoffs tends to be replaced by imposition of a series of physical constraints. In the transportability context, the constraints are defined in terms of the physical characteristics of the existing or prospective transport system or assets.

Thus, DoD defines transportability as "the inherent capability of materiel to be moved by towing, by self-propulsion, or by carrier via railways, highways, waterways, pipelines, oceans, and airways." The central question addressed by the RDA process in the context of transportability is whether a given item can be moved; a related issue often addressed is the number of specific items that can be moved to a given theater in some number of days.

Analytically, the way that transportability is defined in the RDA process leads to treatment of transportability as a constraint rather than as a parameter to be optimized along with other goals. This means that from the viewpoint of the users, design decisions are likely to miss the optimal combination of weapon effectiveness and transportability in favor of a mix that assigns too heavy a weight to effectiveness and one that is too small to transportability. Overall system "quality," then, is lower than otherwise would be the case in light of user preferences.

Among the military services, the Army confronts the transportability problem most directly, and nonoptimization is evident in the development histories of several important systems. Weight growth was a constant problem afflicting the development history of the M1 Main Battle Tank (MBT) series; that history reveals an overwhelming (and important) concern about the ability of existing or prospective transport modes simply to move the tanks. Tradeoffs among transportability and other goals received far less attention, and the preferences of ultimate users seem to have played only a minor role in design decisions.

The design history of the Light Helicopter Experimental (LHX) displays similar characteristics. Important transportability issues were presented by choices on the number of pilots, the choice between a conventional and tilt-rotor design, the maximum allowable weight, and self-deployment versus air transport. As with the M1 tank, the design process for the LHX was driven largely by efforts to satisfy physical constraints established by administrative decision or inherent in the transport system. The preferences of users did not play a prominent role in the LHX design history.

Design decisions on other important systems, among them the Bradley Fighting Vehicle System and the High-Mobility Multipurpose Wheeled Vehicle, had similar features. Design decisions may or may not be "correct," but they are not constrained in important ways by user preferences. For the military, the "users" are the individuals in the foxholes, but their preferences may be impossible to determine in the absence of an internal market driving decisions in the RDA process. An imperfect proxy for the actual users may be the theater commanders (CINCs), who clearly are concerned with both the availability and performance of equipment in their theaters. Thus, one way to increase the degree to which "user" preferences are represented in the RDA process might be to include the CINCs on the Army System Acquisition Review Council (ASARC) Board, just as the Military Traffic Management Command (MTMC) now is included. An indirect but perhaps better way might be to charge any new lift requirements and their attendant cost against budgets or cost projections for proposed systems. This would induce planners to evaluate cost tradeoffs between lift and other goals, thus indirectly asking the tradeoff question from the user perspective.

Further improvement in the outcomes yielded by the RDA process might be obtained by making analyses of the relevant tradeoffs more explicit. Financial incentives might be provided for creation and

comparative evaluation of alternative parameter packages by contractors, MTMC, and the CINCs. Incentive fee contracts promoting such analyses could be written for designers/contractors.

DoD has been moving in this direction with its analytic concept of *unit* transportability as part of total force deployment analysis. It differs from the more traditional analysis of ~~item~~ transportability described above in terms of the kind of information yielded, but user preferences again do not constrain decisions. The experience with transportability as it actually fits into the RDA process suggests that DoD resource use would be improved by a change in focus from transportability as a constraint to transportability as an optimization parameter, with the chosen "optimum" constrained by and reflecting the preferences of the users affected most directly.

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1. INTRODUCTION

TRANSPORTABILITY VERSUS COMBAT EFFECTIVENESS

Getting there "the firstest with the mostest" certainly is a laudable goal, but it also carries inherent contradictions. By attempting to get "there" (e.g., Saudi Arabia) with equipment of the greatest effectiveness, the Department of Defense (DoD) inevitably will find it more difficult to get there quickly. Thus, the military is faced with a common tradeoff: how much combat potential should be forgone as a means of increasing the ease or speed—or reducing the cost—of deployment? Increasing the speed of deployment, or reducing its cost, is termed in this report "transportability."¹ To put it differently, how much extra difficulty or cost in transport of materiel and equipment should be accepted in return for enhanced combat effectiveness? More generally, what are the tradeoffs among the multitude of equipment attributes, only one of which is ease (i.e., cost or time requirement) of transport?

Thus, the tradeoff between effectiveness and transportability—the measurement of which, by the way, is shrouded by uncertainty in any given case—can be viewed as a standard optimization problem among competing goals. And, as discussed in more detail below, DoD devotes considerable attention and resources to the transportability issue as it arises during the development process for materiel and equipment. To say, however, that transportability "matters" to DoD does not mean that the development process systematically optimizes among competing goals. To put it differently, the way that transportability enters the materiel development process does not appear to constrain decisions—or decisionmakers—to evaluate the tradeoffs "correctly."²

What does "correctly" mean in this context? Conceptually, it means the tradeoff that balances the marginal benefits of capability and transportability from the user perspective. Consider a private sector

¹More detailed definitions are noted below. Note, however, that the transportability issue centers on the problem of deployment to the theater. Thus, it differs from the problem of tactical mobility, although the two clearly are related.

²This does not mean that DoD fails to consider tradeoffs. Quite to the contrary, the case examples discussed in the later sections of this report reflect real efforts to evaluate them. And the formal Research, Development, and Acquisition (RDA) process mandates such analysis; for example, Army Regulation 70-47 (effective August 19, 1985), Chapter 2, 2-1b, states explicitly that "Tradeoffs between transportability and combat effectiveness may be appropriate."

producer of goods and services, the design of which necessarily carries tradeoffs among desirable characteristics. For example, design of an automobile engine forces a choice between power and fuel economy. That tradeoff can be avoided only if greater cost is accepted; an example is the use of four valves per cylinder. Perhaps more to the point, design of private sector equipment often must consider tradeoffs between power—in a word, usefulness—on the one hand, and ease or cost of transport on the other.

The profit motive induces private sector designers—faced with customers, themselves driven by a profit motive, who seek an optimum among conflicting goals—to consider the preferences of their customers. How much is greater size or power worth at the margin? How much extra transport cost or delay is implied by that additional capacity? What is the marginal cost of avoiding, through specialized design features, the transport cost penalties that otherwise would be imposed by the additional size and power? To put it differently, the designer constrained by a profit motive is led to ask, whether implicitly or explicitly, both how much customers are willing to pay for the extra capacity *and* how much they are willing to pay to avoid the extra transport cost or delay associated with it.

The central point is the critical role in the private sector of the preferences of users as the set of criteria with which to evaluate such tradeoffs at the margin. For DoD there is no profit motive, and the identity of the “users” is more complex. This yields the set of issues with which this report is concerned. What is the extent to which the preferences of users shape and constrain the DoD RDA process as it makes choices among transportability and other characteristics in the design of equipment and materiel? Does the existing process substitute a decision procedure that tends to produce the same choices among conflicting goals? What evidence can be brought to bear on this issue? And how can the RDA process be shaped to provide analogous incentives and decision constraints?

TRANSPORTABILITY IN THE DOD RDA PROCESS

The Department of Defense defines transportability as “the inherent capability of materiel to be moved by towing, by self-propulsion, or by carrier via railways, highways, waterways, pipelines, oceans, and

airways."³ Specific policies and guidance are provided for the purpose of "assuring that items of materiel, equipment, and transportation systems are so designed, engineered, modified, and constructed that the required quantities can be efficiently moved by available means of transportation."⁴

The DoD Integrated Logistics Support (ILS) system is designed to incorporate logistics considerations, including transportability factors, into RDA processes and decisions.⁵ "The primary objective of the ILS program shall be to achieve system readiness objectives at an affordable life-cycle cost."⁶ Transportability is one of 12 ILS elements, as defined in DoD Directive 3224.1,⁷ and is to be assessed with respect to "the impact on strategic deployment."⁸ Moreover, Milestone III (Production and Deployment) of the acquisition process is incomplete unless "transportability approval has been given by the appropriate transportability agent, and strategic mobility requirements have been met."⁹ The duties of the program manager include development of "an ILS plan by Milestone I," which "shall document readiness and support objectives and demonstrated achievements, operating concepts and deployment requirements (including transportability). . . ."¹⁰ Transportability considerations, as part of logistic supportability requirements, "shall be established early in the acquisition process and be considered in the formulation of the acquisition strategy. They shall receive emphasis comparable to that accorded to cost, schedule, and performance objectives and requirements."¹¹

Among the services, the Army and the Marines are affected most heavily by the transportability problem. Thus, it is useful to concentrate upon Army procedures and experience. Since the Training and Doctrine Command (TRADOC) develops statements of materiel and

³See Department of Defense Directive 3224.1, "Engineering for Transportability," November 29, 1977. This document has been replaced by DoD Directive 5000.1, "Defense Acquisition," February 23, 1991, and by DoD Directive 5000.2, "Defense Acquisition Management Policies and Procedures," February 23, 1991.

⁴Directive 3224.1.

⁵See Department of Defense Directive 5000.39, November 17, 1983, "Acquisition and Management of Integrated Logistic Support for Systems and Equipment."

⁶Ibid., p. 2.

⁷See footnote 3 above.

⁸See footnote 5, p. 3-2.

⁹Ibid., p. 3-5.

¹⁰Ibid., p. 4-1.

¹¹See Department of Defense Directive 5000.1, "Major and Non-Major Defense Acquisition Programs," September 1, 1987, p. 6.

equipment requirements in light of the threat, TRADOC officially "represents the user in the materiel acquisition process" and is to "[e]stablish user priorities on reliability, availability, and maintainability."¹² The Military Traffic Management Command (MTMC) is charged with the provision of transportability approval or delineation of "corrective actions required to obtain approval for all transportability problem items."¹³ The Transportation Engineering Agency of MTMC (MTMCTEA) has as its charge the provision of transportability assessments for items, units, and systems, as well as the provision of engineering advice to developers of materiel and equipment.¹⁴

To say that TRADOC represents the user, or that MTMC is charged with the responsibility for transportability analysis, verification, and approval, does not imply that decision processes are driven systematically to optimize among transportability and other competing goals. Whatever the dedication of the professional analysts and the care given the relevant analyses, neither TRADOC nor MTMC enjoys the future benefits of correct decisions. Nor do they bear—at least directly—the adverse effects of prior decisions that turn out to have been nonoptimal. Thus, at least as far as transportability is concerned, the RDA process does not simulate the constraints inherent in markets.

To put it differently, the RDA system does not simulate a market process in which the preferences of the ultimate-users serve as constraints operating through their perceived effects upon profitability. The "users" are those who bear the consequences of the design decisions and tradeoffs. In the DoD context, the identity of the users is multidimensional and thus more complex, since the nature and timing of future events are highly uncertain. Equipment and materiel must be designed for heterogeneous events in disparate locales under varying conditions. Moreover, design decisions affect not only the soldiers in the foxholes and their commanders, but also others in the defense system who operate transport equipment, bear responsibility for logistics, and otherwise perform numerous important functions. The people responsible for air mobility, for example, have voices that are heard other than through TRADOC. These groups are affected in significant ways by design decisions on equipment and materiel produced by the RDA process, and their interests force the evaluation

¹²Army Regulation 70-1, *Systems Acquisition Policy and Procedures*, October 10, 1988, Sec. 2-20, p. 10.

¹³*Ibid.*, Sec. 2-22.

¹⁴*Ibid.*, Sec. 2-31.

of tradeoffs.¹⁵ Thus, the interests of the ultimate users may be served implicitly other than through the formal efforts of TRADOC.

Nonetheless, there exists no formal mechanism through which the preferences of the users in the theaters on the "firstest/moestest" tradeoff impose *constraints* on the choices that are made. The "users" fundamentally are those affected most directly by prior decisions. In this context, then, the users might be viewed as the various commanders-in-chief (CINCs) with important uses for the equipment under consideration in the RDA process. Instead, the weight given transportability considerations is determined by the preferences of those actually involved in the RDA process. Should a disagreement among these parties and interests yield an impasse, disputes typically are "kicked upstairs" for resolution, perhaps to the ASARC or even to the Chief of Staff.¹⁶

The RDA process does not now optimize systematically among transportability and other competing goals. Nor is it constrained in ways that would tend to drive it to evaluate such tradeoffs in a manner reflecting the preferences of users. Instead, those responsible for ensuring that equipment meets transportability constraints are concerned with the (important) issue of whether a given design is consistent with height, weight, width, and other such constraints inherent in the existing transport infrastructure or in existing (or prospective) transport equipment. The RDA histories of the systems discussed in this report indicate that additional system features assumed to contribute to capability usually add to size and weight. The approval process is defined in terms of these constraints rather than in terms of tradeoffs between transportability and other goals. Indeed, the Transportability Engineering Analyses prepared by MTMCTEA deal specifically with the ability to move equipment given the characteristics of the transport system, rather than with the relevant tradeoffs.

This study has as its central goal a review of transportability analysis as it actually influences the evolution of equipment designs in the RDA process. The goal is a clearer understanding of the extent to which user

¹⁵For example, MTMC for the last few years has been represented formally on the Board of the Army Systems Acquisition Review Council (ASARC).

¹⁶Indeed, Army Regulation 70-1 (Sec. 5-6a, p. 29) states that "[t]he purpose of convening the ASARC is to provide a structured forum at which issues requiring top-level consideration can be presented to the senior Army leadership." This section of Regulation 70-1 provides for involvement in an ASARC session or in prior ASARC *ad hoc* working group meetings of a number of commands, services, and other interests. Conspicuously absent from the list are the users as defined above.

preferences constrain RDA decisions in the transportability context. The next section discusses briefly a concept of transportability that may have some analytic advantages over the dimensions/constraints dichotomy now so prevalent. The ensuing sections review some design histories as a means of gaining insights into the role of transportability considerations in the RDA process as actually practiced. Finally, some conclusions and policy recommendations are offered.

2. TRANSPORTABILITY AND THEATER CAPABILITY

It may be useful at this point to illustrate with a small amount of formality the concept of transportability, the tradeoff between transportability and other goals, and the possible effect of exclusion from the RDA process of the preferences of the users affected most directly by decisions on design tradeoffs. An item of equipment or materiel i has some value (or capability) v_i in the theater, but imposes some marginal cost c_i for transport to the theater.¹⁷ These values v_i and c_i are predetermined in the sense that they are functions of the design features and prior investments in the equipment and the transport system that are fixed in the short run. However, they may change during hostilities, or even beforehand as the nature of the impending crisis becomes clearer; but for purposes of the RDA system, predetermination is the appropriate assumption. Moreover, v_i and c_i are functions of each other such that $\partial c_i / \partial v_i > 0$ and $\partial v_i / \partial c_i > 0$. In words, design features that add value—that is, combat capability—also by assumption increase the cost or difficulty of transport, and an attempt to design equipment so as to reduce transport costs also reduces combat value.¹⁸

It is reasonable to assume also that faster transport, say, by air rather than by sea, is more costly, that is, $\partial c_i / \partial t_i < 0$, where t is the time required to transport a given piece of equipment. But faster transport also increases the value of the equipment in the theater; if v_i is the value of the equipment under instantaneous deployment (or predeployment), we can define $v_i' = v_i / e^{r_i t}$, where r_i is the rate per time period at which the value of equipment type i declines due to transport delay.¹⁹ Thus, $v_i' \leq v_i$, $\partial v_i' / \partial t < 0$, and $\partial v_i' / \partial r_i < 0$. The

¹⁷These parameters may be only notional in the sense that they resist attempts at measurement. Nonetheless, it is useful for conceptual purposes to discuss them.

¹⁸Of course, both theater capability and transportability can be increased with enhanced investment in the transportation system, thus increasing total cost. The conceptual model discussed here assumes a fixed RDA budget, thus focusing attention upon the crucial tradeoffs.

¹⁹Thus, r_i in effect is the rate of return to faster transport. It may be high at the outset of hostilities, and may increase as the crisis approaches a climax. Once the issue is settled, r_i may fall to zero. More generally, some types of equipment are more likely than others to "turn the course of the battle" expectationally, that is, in the context of uncertainty before crises and wars arise. Thus, the discount rate applying to the transport of such "crucial" assets is likely to be relatively high. The key analytic

greater the time required for transport, the lower the net value; the same is true for higher discount rates, which vary by equipment type because some military goods are more urgent than others.

The inclusion of transportability as a conceptually separate dimension yields an important distinction between *capability* and *value*. Such typical measures of capability as indices of weapon effectiveness or firepower potential implicitly assume availability in the theater of interest. Since such availability prospectively is a stochastic variable, value differs from capability as a function of availability—or transportability. Our definition $v_i' = v_i/e^{r_i t}$ makes this distinction explicit. Net value v_i' can be increased by enhancing capability or transportability, or both; but increases in either or both are costly. Moreover, our explicit assumption above is that enhanced capability reduces transportability, and vice versa. Thus, optimal design equates the ratio of the net marginal values of greater capability and greater transportability with the ratio of their marginal costs.

Consider Fig. 1. The budget line AB maps the combinations of capability and transportability available given the RDA budget for some type of equipment or materiel. The slope of AB is the marginal rate at which more capability can be acquired at a cost in terms of forgone transportability, or vice versa; this slope does not have to be constant, but such an assumption simplifies the analysis without loss of generality.²⁰ In principle, the points A (maximum capability, zero transportability) and B (zero capability, maximum transportability) are available, but are difficult to define operationally; in any event, a standard convexity assumption guarantees an interior optimum. Isoquant v_i' is the maximum net value available given the fixed budget AB; each point on v_i' is a different combination of capability and transportability yielding that net value. The optimal combination of capability and transportability is c^* and t^* . Since the tradeoff between capability and transportability is a choice variable, the isoquant mapping V_i (not shown explicitly in Fig. 1) simultaneously is an indifference mapping. Thus, the slope of v_i' is the marginal rate of substitution between capability and transportability; at the optimum, this marginal rate of substitution is equal to the marginal rate of transformation of capability into transportability, or vice versa.

issue is the expected values of the r_i during the RDA process, from the viewpoint of the users, or demanders.

²⁰In other words, given the dollar costs of additional capability and of additional transportability, the slope of AB is the cost of one in terms of the other given the fixed budget $OA = OB$.

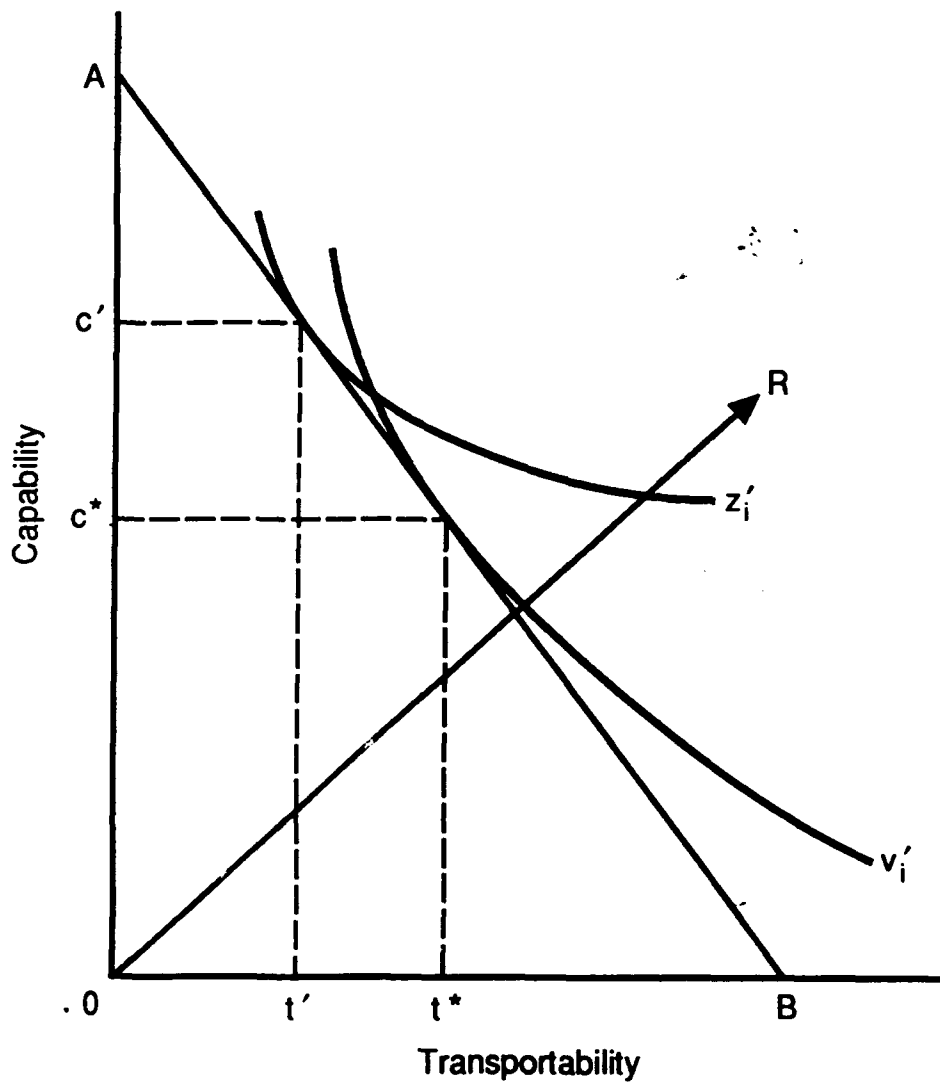


Fig. 1—Tradeoffs and preferences between capability and transportability

Consider isoquant (or indifference curve) z'_i . It represents a higher marginal valuation of capability in terms of transportability than does v'_i , and thus has a smaller (flatter) slope than v'_i along any ray OR. The chosen optimum would combine capability c' and transportability t' , a combination yielding less net value in terms of the original preference mapping V_i . In this simple model, the preferences of the

direct users are represented by this latter preference mapping.²¹ The substitution of other preferences yields a loss of net value from the viewpoint of the direct users.

Figure 2 illustrates the capability/transportability choice as it tends to be shaped by the RDA process in practice. As a standard

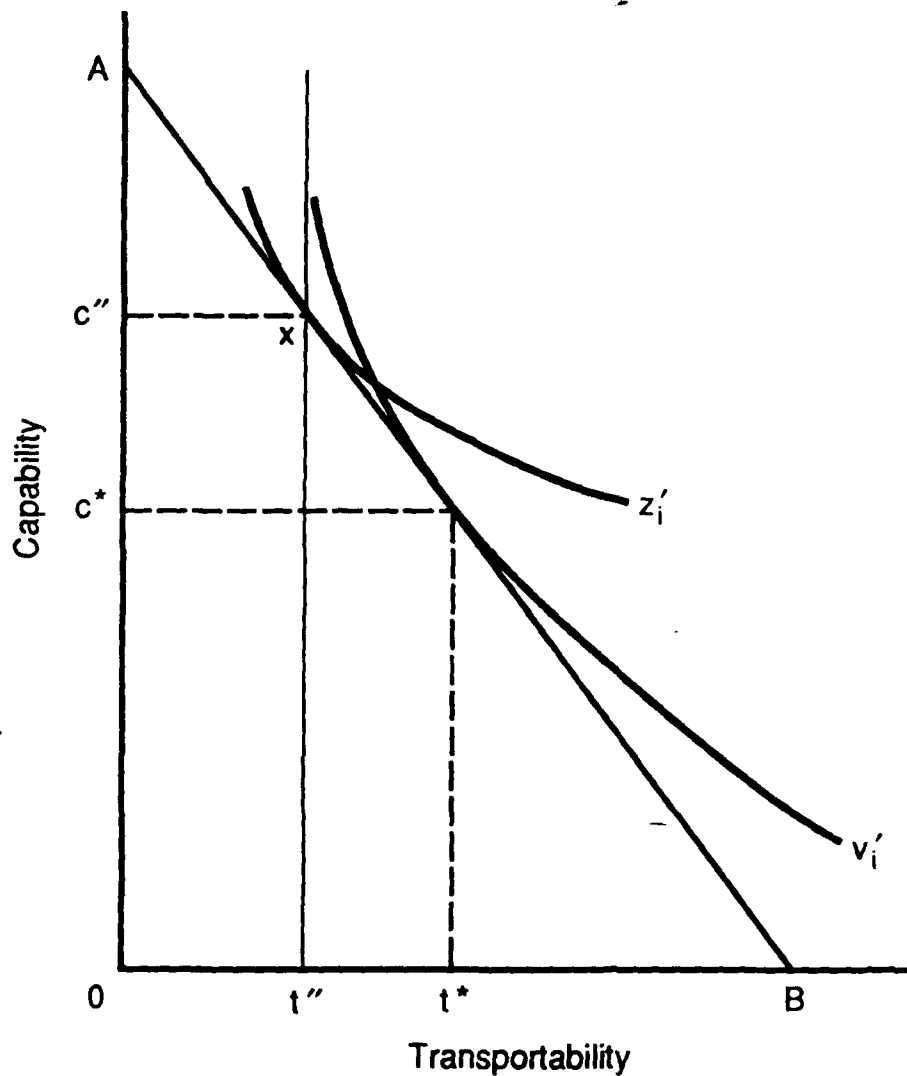


Fig. 2—Capability/transportability choice under a minimum transportability constraint

²¹We ignore here the side issue of how the preferences of the users are aggregated to yield the indifference mapping V_i . It is realistic to assume that V_i represents the preferences of the commanding decisionmaker.

operational focus, MTMCTEA and other agencies concerned with transportability matters attempt to see to it that equipment designs are compatible with the constraints presented by the existing or prospective transportation system. Thus, for example, armored vehicles must not be too heavy for existing highways and bridges or too large for existing (or expected) planes and ships. More generally, various physical dimensions are treated as upper bounds, with some flexibility allowed by potential choices on disassembly/reassembly, the use of more transporter axles per pound, and similar procedures. Analytically this means that the RDA process has an inherent minimum transportability constraint, and equipment design can proceed to maximize capability subject to that constraint as well as others posed by budgetary and similar considerations.

This variant of the analytic problem may be seen in Fig. 2. Suppose that the minimum transportability constraint implies a transportability level of t'' ; thus, no combination of capability and transportability is allowable to the left of the vertical line at t'' . Hence, the portion of the budget constraint to the left of t'' is irrelevant, and the true budget constraint becomes $c''xB$, with a kink at x . Given this constrained formulation of the choice problem, decisionmakers with preferences represented by z_i' are led to choose the corner solution c'', t'' as the preferred mix of capability and transportability.

The central argument of this report is that the RDA process currently treats transportability as modeled in Fig. 2: equipment designs are constrained to satisfy parameters inherent in the existing or prospective transport system. That is, transportability is viewed as a series of physical constraints rather than as one of several sets of conflicting goals pursued by users. This approach is illustrated by Department of Defense Directive 3224.1, "Engineering for Transportability," which assigns the service secretaries the task of "assuring that items of materiel and equipment are so designed, engineered, and constructed that the required quantities can be efficiently moved by *available means of transportation*."²²

The following sections examine design decisions for several systems in terms of transportability tradeoffs. The goal is to examine the degree to which the preferences of users tended systematically to constrain decisions.

²²Emphasis added. The MTMC commander discharges this responsibility for the Secretary of the Army. See footnote 3 above.

3. TRANSPORTABILITY OF THE M1 ABRAMS MAIN BATTLE TANK

The development history of the M1 Abrams Main Battle Tank (MBT) concentrated on the weight issue, although such other issues as height and width dimensions affected design decisions in important ways as well.²³ As discussed below, what is interesting about the development history is the overwhelming concern with the ability of existing or prospective transport modes simply to move the tanks; *tradeoffs* among transportability and other goals received far less attention. The effect of rising weight upon battlefield mobility received considerable attention, particularly because the decision to incorporate the Chobham armor carried a large attendant weight penalty. This explains in part the decision to adopt the turbine engine rather than a diesel engine; the former yields much greater speed and thus battlefield mobility.

That the greater weight affected transportability considerations was obvious to all, but the central question continued to be the *ability* of the tank to be transported, rather than the *tradeoff* between greater survivability and greater ease of transport.²⁴ This approach perhaps was implicit within the list of priorities among numerous objectives given to designers and contractors.²⁵ The priority list for full-scale engineering development/production-engineering-produc-

²³Weight was a prime constraint throughout the development history of the M1, although technical developments and other factors resulted in slow but inexorable upward movement of the allowable weight. The successive weight goals were driven in substantial part by the importance of battlefield mobility; until the decision to incorporate the Chobham armor, it was felt that homogeneous rolled steel armor had reached its limit in terms of crew protection and that increases in survivability required enhanced battlefield mobility. Additional reasons for the prominence of weight constraints in the early design of the M1 were transportability and cost considerations, since total system cost is correlated strongly with weight. See, for example, Orr Kelly, *King of the Killing Zone*, Norton & Co., New York, 1989, Chap. 4.

²⁴See Kelly, 1989.

²⁵The Mission Need Engineering Development document listed 11 parameters in order of priority, of which transportability was tenth. The Validation Contract listed 16 priorities; transportability was not among them. The priorities for full-scale engineering development/production-engineering-producibility were, in descending order, crew survivability, surveillance and target acquisition performance, first and subsequent round hit probability, time to acquire/hit, cross-country mobility, complementary armament integration, equipment survivability, environmental, silhouette, acceleration/deceleration, ammunition stowage, human factors, producibility, range, speed, diagnostic aids, growth potential, support equipment, and transportability.

ibility contained 19 entries, of which transportability was listed last. There is nothing inherently wrong with that choice among priorities relative to some other potential choice, but the very concept of priorities tends to deemphasize tradeoffs among conflicting goals; instead, it encourages promulgation of minimum (or maximum) goals for each successive priority, leaving each lower priority to "fend for itself" given the achievement of higher goals. This yields the suboptimization problem illustrated in Fig. 2.

It is useful to review briefly the history of weight growth in the evolution of the M1 tank.²⁶ The original Material Need document for the Abrams tank written in 1972 specified a maximum weight of 58 tons when fully loaded for combat. This weight included incorporation of the Chobham armor into the design. A review was conducted by a Tank Special Study Group (TSSG) after the 1973 Arab-Israeli war, the results of which were recommendations for increased range (i.e., more fuel) and 10 additional main gun rounds, thus requiring an increase in the storage capacity of the ammunition racks. The Material Need document was amended accordingly. The design changes, finalized in 1975, added about 0.9 tons to the weight of the tank. In 1978 a number of small ballistic protection changes were made in the tank design; these changes were significant collectively, raising the total projected weight to 59.8 tons, as reported in the System Acquisition Review of December 31, 1978. The Material Need document was revised to 60 tons the following month, and later in 1979 a number of changes were incorporated that added a total of about 0.5 tons.²⁷ The total projected weight then stood at about 60.3 tons.

The Army approved the M1 Product Improvement Program for initial development planning in June 1979. This led to a product improvement annex to the M1 Material Need document, which was approved and incorporated in the Material Need document in May 1982. These changes were designed to incorporate technological advances and to deal with changes in the threat that had arisen since the TSSG changes were approved in 1975. These Block I improvements²⁸ raised the maximum tank weight specified in the Material Need document

²⁶The term "M1" is used as a general classification for all the successive generations of the M1: the M1, the Improved Performance M1 (IPM1), the M1A1 (formerly M1E1), and the forthcoming M1A2. Distinctions will be maintained among these generations when useful for purposes of analysis or avoidance of confusion.

²⁷These changes resulted from the development test/operational test II.

²⁸These improvements included improved armor, the 120-mm gun, and the nuclear/biological/chemical filtration system.

to 63 tons. Several additional changes raised the maximum weight projected in 1985 to over 63.5 tons.

A Block II series of changes was approved early in 1985 for various purposes of combat effectiveness and cost savings in operations and support. Although the Material Need document did not specify weight increases associated with each of the Block II changes, the total projected gross vehicle weight for the M1A1 was raised to over 66 tons (with the standard track). It was decided at that point that the contractor should develop a weight control program with a goal of 65 tons, incorporating the Block II changes.²⁹ There was concern that uncontrolled gross vehicle weight could reach 68 tons with addition of the long gun and the heavy track, affecting reliability, availability, maintainability, and durability, as well as transportability. Maintenance of those parameters "at acceptable levels" was the goal, in pursuit of which "trade-offs may become necessary."³⁰ The "acceptable levels" approach leads away from optimum solutions, and the outlook of the Army planners was not necessarily the same as that of the ultimate users.

The production experience of the M1 reflects the inexorable upward movement in system weight. At initial production of the M1 in February 1980, gross vehicle weight (combat-loaded) was 61.4 tons. By November 1984, gross vehicle weight for initial production of the IPM1 was 62.5 tons. The M1A1 at initial production in May 1986 weighed in at 64.9 tons. M1A1 weight rose to 65 tons in April 1988 with the addition of a new gunner position sight. A further armor improvement raised M1A1 weight to 66.2 tons in September 1989, and a new track in November 1989 raised the weight further to 67.6 tons. Production of the M1A2 is projected for November 1992, with the gross vehicle weight now estimated at 68.9 tons.³¹

What is of interest here is not the weight growth per se, but is instead the consistent approach used by DoD and the Army to examine the potential problems posed by weight growth for transportability. The central issue addressed in virtually all analyses of weight growth and attendant effects was the effect on the ability of the tank to be moved by highway, rail, sea, and air modes of transport. This is clearly a crucial

²⁹This figure was for a combat-loaded tank, but excluded the extra weight associated with an improved track.

³⁰See the July 1985 letter from Ronald McCullough, Chief, Systems Engineering Division, Tank Systems, U.S. Army Tank-Automotive Command, to Headquarters, Department of the Army.

³¹Source: Correspondence with General Dynamics, Land Systems Division.

question requiring detailed attention, but one that differs substantially from the evaluation of *tradeoffs* among transportability and other important goals. Such tradeoffs are choices that ought to be influenced heavily by the preferences of the users, but there is little in the development history of the M1 suggesting that tradeoffs between transportability and other goals received more than minor attention.³²

The major analytic documents relating to transportability of the M1 reflect this approach. The *Transportability Engineering Analysis* of the M1E1,³³ prepared by the Transportation Engineering Agency of MTMC, deals exclusively with the compatibility of the tank with transport assets available to DoD, both in the continental United States and overseas. Indeed, the report has as its central objectives evaluation of "the capability of the M1E1 tank to be handled and secured for transport by highway, rail, marine, and air modes of transportation," and identification of "potential transportation shortcomings that could adversely affect the deployment and routine movement of M1E1."³⁴ M1 weight growth became an issue of such importance and concern that MTMC TEA in 1987 was directed to prepare a special study of the impact of weight growth in the M1 series of tanks upon transportation operations worldwide by all transport modes.³⁵ The analysis was conducted in increments of one ton from 60 to 80 tons. Each increment was examined in terms of reduced transportability, that is, the ability of the tank to be moved by existing transportation assets. Again, the tradeoffs between weight or transportability and other desirable features—reflecting the preferences of users—were unexamined.³⁶

³²Again, transportability received a great deal of attention, but it was defined as nonviolation of such physical constraints posed by the transport system as the weight limits of highways and the heavy equipment transporters. This approach can exclude the preferences of users from analysis, since satisfaction of the constraints essentially is a yes-or-no question. Among the 19 priorities established for M1 characteristics (noted above), the Army established weights ranging from .160 for crew survivability to .004 for transportability. These weights reflected the descending priorities of the 19 factors, but the record leaves unclear the origin or derivation of the weights or their ordering. In particular, the role that user preferences may have played is ambiguous at best; this very lack of prominence in the record suggests that it was not important.

³³The report was issued in May 1983, at which time the M1A1 was denoted the M1E1.

³⁴Again, the compatibility issue is crucial but differs from the tradeoff issue, which fundamentally is a choice among conflicting user preferences.

³⁵See MTMC, *Transportability Engineering Analysis of the M1-Series Tanks Weight Growth (60 to 80 Tons)*, July 1987.

³⁶This is not the role of MTMC, and so no criticism of that organization is intended here. The central point is, however, that the treatment of transportability as a parameter with given "priority" in the DoD RDA process leads inexorably to the problem stressed above.

Section 4 reviews the development history of the Light Helicopter Experimental (LHX), with the emphasis again given to the manner in which transportability was defined and the ways in which it affected design decisions.

4. TRANSPORTABILITY OF THE LHX

Several issues affecting the transportability of the LHX were prominent during the design evolution of the aircraft. They can be summarized as follows:

- The number of pilots.
- The choice between a conventional and tilt-rotor design.
- The maximum allowable weight.
- The issue of self-deployment versus air transport.

As with the M1 tank, the design process for the LHX was driven largely by efforts to satisfy physical constraints established by administrative decision or inherent in existing or prospective transport assets. Tradeoff analyses reflecting the preferences of users are not prominent in the design history; as with the M1, there seems to have been an effort to satisfy a descending series of priorities, with weight foremost among them.

THE NUMBER OF PILOTS

An advanced Rotorcraft Technology Integration (ARTI) program was initiated in 1983 to determine the feasibility of a single-pilot design for the LHX. A reduction in crew size would reduce the weight by 1000–1300 lb, and cost savings per helicopter were estimated at \$500–\$1000 per pound. Further study led to a decision that the development risks attendant with a single-pilot LHX were too high to justify the benefits obtained; the ASARC directed the Army to develop an LHX with two pilots, but with a single-pilot operational capability. This decision was made in 1987, by which time other design decisions had reduced the number of LHXs transportable on a C-141 from four to three. The weight penalty associated with the two-pilot design was not sufficient by itself to reduce that figure to two, but could contribute to such an outcome if combined with another design decision adding to the weight of the aircraft. There is little evidence that transportability considerations affected this decision in other than minor or indirect ways.

CONVENTIONAL VERSUS TILT-ROTOR DESIGN

The Army in 1985 opted for a conventional helicopter airframe rather than a tilt-rotor design. This decision had important implications for transportability factors, since the conventional design generally has advantages in terms of air transport, whereas the tilt rotor has greater capabilities for self-deployment.

What is of interest is the role that transportability considerations played in the decision on airframe design. For the tilt rotor, transport via C-141 would require removal of the wing or pivoting of the wing along the length axis of the aircraft. The pivoting option—"swing wing"—was estimated to impose a 325-lb weight penalty as well as some increase in unit and life-cycle cost. Wing removal imposed a requirement for ground support equipment estimated to cost \$50 million (fiscal 1984 dollars), assuming one deployment per aircraft every four years. Under either approach, two tilt-rotor aircraft could be transported on a C-141, whereas the C-141 could accommodate three or four conventional helicopters.

On the other hand, the tilt-rotor aircraft were perceived to have a significant advantage in terms of self-deployment—the tilt-rotor design could self-deploy both further and more quickly. This is discussed in more detail below; the central point is that there is no evidence that the air transportability issue played a significant role in the choice of the conventional design. The Army believed that 85 percent of the LHX's operations would be conducted in "nap-of-earth" flight, for which the tilt rotor burns more fuel and has other disadvantages. The higher cruise speeds of the tilt rotor were projected to be useful during only a minor portion of the aircraft's operational life. The tilt rotor has higher manufacturing costs, whereas relative operating costs were disputed by the competing developers. It seems clear that the decision favoring the conventional design was influenced strongly by the lower development risk and manufacturing cost. These findings were supported by studies conducted by RAND and the Institute for Defense Analyses (IDA), which argued that the only advantage of the tilt rotor was its greater ability to deploy itself, with perhaps an additional gain in terms of maneuverability.

In short, transportability considerations played only a small role at most in the decision on airframe design and seem to have carried little weight in terms of priority. As in the case of the M1, there is nothing inherently wrong with that set of values, but the origin of the priorities does not necessarily reflect the potential preferences of the ultimate users.

MAXIMUM ALLOWABLE WEIGHT

The 1983 System Attributes Document for the LHX listed a desired gross weight (GW) of 6000–8000 lb. This was revised to 7500–8500 lb in 1984, as requirements for the LHX became defined more clearly. New requirements raised the figure to 9500 lb at the end of 1986, and the two-pilot decision in 1987 increased estimated GW to 10,500 lb. Since GW is dependent in important ways upon choice of primary mission, the decision was made to use empty weight (EW) as the weight measure. At the same time, maximum EW was fixed at 7500 lb.³⁷

The primary effect of LHX weight is the number of aircraft that can be transported on a C-141.³⁸ Because the dimensions of the aircraft shift in predictable ways upon changes in empty weight, weight is a good proxy for “cube”—physical dimension specifics and size relative to space available on a C-141. At 6000 lb EW, four LHXs can be transported on a C-141; that figure declines to three as EW rises to 7000 to 8500 lb, and to two at an EW above 8500 lb. As the design history of the LHX—as with much DoD equipment—is one of gradual weight growth, it is unlikely that EW will decline to 6000 lb, allowing a fourth aircraft onto a C-141. Similarly, the cost penalty associated with weight increases—\$500–\$1000 per pound—is likely to prevent a decline to two LHXs per C-141. Thus, the air transportability of the LHX—in terms of the number that can be moved on a C-141—in a sense has been an outcome dictated by other considerations. Again, this is not inherently adverse, but does not emphasize the evaluation of tradeoffs from the viewpoint of the ultimate users.³⁹

AIR TRANSPORT VERSUS SELF-DEPLOYMENT

It was recognized early in the LHX design process that air and sea lines of communication would be congested with troops, weaponry, materiel, and supplies during the mobilization/deployment phase of a

³⁷Empty weight includes only the airframe and mission equipment package, and excludes crew, fuel, and armament.

³⁸The feeling of the Army seems to have been that C-5s and (forthcoming) C-17s during a mobilization/deployment crisis would not be readily available, and that other Army materiel would have higher priority than LHXs. Thus, attention centered largely upon the C-141.

³⁹The final transportability characteristics of the LHX may benefit from other design goals. Efforts to reduce radar signatures may tend to reduce size, thus enhancing transportability. The same can be said for efforts to reduce weight by avoiding such features as the stub wings found on the Apache or the heavy external missile launchers of the EH-60.

crisis. Thus, a self-deployment capability was specified at the outset.⁴⁰ Self-deployment was required for the North Atlantic route and desired for the longer South Atlantic route; the still-longer Pacific route was not specified.

The Concepts Analysis Agency (CAA) completed in 1986 a Light Helicopter Fleet (LHF) study, part of which examined comparative self-deployability for the LHX and for the tilt rotor. The study illustrated the superior self-deployment characteristics of the tilt rotor; along the North Atlantic route, deployment time for the tilt rotor was predicted at two days and at four days for the conventional design. By day 10 of the mobilization, about twice as many tilt-rotor aircraft as conventional helicopters would be ready for combat; it is not until day 16 that combat readiness in terms of numbers of helicopters would be equated. Moreover, deferred maintenance required by the tilt rotor would be lower since such maintenance is determined by flight hours.

This study was complemented by the 1988 Total Army Analysis, also conducted by CAA. Under very conservative assumptions, self-deployment for the Apache, Black Hawk, and Chinook delivered 75 percent of the helicopter fleet to the theater by day 24 of the mobilization period (D-day); airlift delivered only 50 percent. Other advantages include reduced helicopter attrition and release of airlift assets for other purposes. At the same time, other helicopter unit equipment would have to be transported (or deployed in advance), and the helicopters must be deployed with units in the theater. Nonetheless, the analyses, even with their limitations and assumptions, suggested that self-deployment can reduce the need for air transport of the LHX over Atlantic routes. The longer distances of the Pacific route make this option far more problematic, as a flight from Fort Ord to Hickam Air Force Base is 2080 n mi. The Defense Science Board argued that a requirement for such a self-deployment capability would impose too many constraints in terms of other design parameters.⁴¹

Thus, the combination of Pacific theater requirements and a single design for all theaters makes air transportability an important concern, since as a practical matter self-deployment is not an option for that theater. Nonetheless, the air transportability characteristics of the LHX seem to be the outcome of other design decisions, rather than an independent parameter subject to optimization. This does not mean that three LHXs per C-141 is the wrong number; but as in

⁴⁰See, for example, the 1983 System Attributes Document for the LHX.

⁴¹Report of the Defense Science Board task force on LHX requirements.

the case of the M1, the tradeoffs between air transportability and other goals seem not to have been examined from the viewpoint of users in the theater.

5. OTHER EXAMPLES

THE BRADLEY FIGHTING VEHICLE SYSTEM (BFVS) (M2A2/M3A2)

Weight growth has afflicted the Bradley as it has evolved over time, particularly as a result of upgraded armor added after recent live-fire survivability tests. Indeed, the new BFVS, at about 67,000 lb, presents a serious air transport problem in that the removal of armor and other items needed to reduce weight to 44,000 lb—the upper weight limit for transport on a C-141B—has added six hours to the two already required for flight preparation and reassembly.⁴² That time estimate by itself does not demonstrate poor planning or a lack of optimization; in principle, the benefits of the added armor may compensate for the additional logistic difficulty, although eight hours for flight preparation/reassembly is unusually long. Moreover, air transportability may be unimportant, particularly relative to marine transport. But what is of interest in the transportability context is the unintended nature of the problem; nowhere in the record is there an examination of the tradeoffs between transportability and other BFVS design features.⁴³

A review of the design/development history of the Bradley reveals striking similarities to the cases discussed in previous sections. Various features were specified as goals or requirements, with little explicit examination of tradeoffs among them, although such tradeoffs implicitly must affect the overall system "effectiveness" evaluations used to compare competing designs.⁴⁴

⁴²Items to be removed from the BFVS for C-141 airlift preparation are the air defense secondary sight, the air intake grille, the backup sight, the cargo hatch assembly, the commander's hatch, the driver's hatch assembly, the engine access-door assembly, the final drive armor, the front glacis armor, the gunner's hatch, the headlight assemblies, the integrated sight unit and its ballistic cover, the mine armor plate, the rear sponson boxes, the side armor skirts and skirt bracket, the squad seats, the swim curtain tripods and bipods, the TOW (tube-launched optically tracked wire-guided) missile launcher assembly, the turret armor plates, the turret periscopes, and the work platform. The Army is considering removal of the turret assembly instead of the items listed above, a change that would save about four hours but would increase the probability of mistakes during reassembly.

⁴³With respect to the adverse preparation/reassembly effects of the added armor, Lt. Col. Tom Hutson, Bradley action officer for the Deputy Chief of Staff for Operations and Plans (DCSOPS), remarked that "[i]t was an unintended effect of survivability improvements." Quoted in *Defense Week*, April 24, 1989.

⁴⁴For example, a Mechanized Infantry Combat Vehicle Alternatives Cost-Effectiveness (MICV ACE) study was conducted in 1969–1970, comparing the existing M113, a different MICV meeting the earlier Qualitative Material Requirements (the

For example, the Qualitative Material Requirements for the MICV specified in 1968 included frontal protection against 23-mm armor-piercing ammunition, side and rear protection against 14.5-mm ammunition, overhead protection against 155-mm artillery fire, a cruising range of 400 miles, a crew of 10, and others, among them a requirement for transportability aboard a C-5 aircraft. The Army subsequently modified the latter requirement in favor of a C-141.

As with the systems discussed in earlier sections, the central transportability analyses of the Bradley centered on the ability of the system to be moved on existing transport assets; tradeoffs among transportability and other goals were decidedly secondary.⁴⁵ As the system has evolved, the Bradley has posed increasing problems for various transport modes.⁴⁶ The system exceeds dimensional or weight limits on most road networks in the United States and overseas. Rail outline diagrams are exceeded in the M2A2/M3A2 operational configuration. Only the reduced configuration is transportable on a C-141. As with the examples discussed in previous sections, these outcomes are not necessarily "wrong," and this report does not purport to demonstrate that transportability receives a priority or weighting that in some sense is too low. The point is that optimization analysis weighted by user preferences is absent (or nearly so) from examination of tradeoffs among transportability and other desirable goals in the RDA process. Thus, there is no reason to believe that transportability among other goals is optimized systematically by the design process.

KM723), and an "austere" MICV. The definitions or algorithms that measure "effectiveness" in such studies must carry weights reflecting some system of priorities or preferences among system attributes. There is little evidence that these weights systematically reflected the preferences of users. Indeed, in the available development histories of the Bradley, the only explicit reference to user input was concern expressed in 1969 by the Commander-in-Chief USAREUR about the level of protection provided by the MICV designed in the mid- and late 1960s, one of the early evolutionary models of the Bradley.

⁴⁵See, for example, MTMCTEA, *Final Transportability Engineering Analysis for the M2A2/M3A2 Bradley Fighting Vehicle System*, August 1989. Note that such trade-off analysis is not the function of MTMCTEA; its function is to examine the compatibility of particular defense systems with the existing transport network and available transport assets.

⁴⁶For example, the evolution from the M2 to the M2A1HS to the M2A2 has been accompanied by an increase in operational weight from 50,259 lb to 66,845 lb, in operational height from 117.0 in. to 119.3 in., and in operational width from 126.0 in. to 139.5 in.

THE HIGH-MOBILITY MULTIPURPOSE WHEELED VEHICLE (HMMWV)

In the transportability context, weight growth has afflicted the HMMWV as it has so many other systems. Envisioned originally as transportable in one sortie by a Black Hawk helicopter, the fully loaded weapons carrier model of the HMMWV now exceeds the lift capacity of the Black Hawk—8000 lb—by 150 lb.⁴⁷

As a result, the Army may be required to procure a new set of vehicles for light infantry units, seemingly a rather extreme solution for a weight limit breach of less than 2 percent. In any event, the available transportability analyses of the HMMWV reflect the approach noted with respect to the other systems discussed above: the central question again has been posed in terms of the ability of the HMMWV to be moved, rather than the tradeoffs among design features enhancing contributions to combat capability and those yielding greater transportability.⁴⁸

⁴⁷See the discussion in *Military Forum*, March 1989.

⁴⁸See MTMC TEA, *Final Transportability Engineering Analysis for the High-Mobility Multipurpose Wheeled Vehicle (HMMWV)*, September 1989.

6. CONCLUSIONS

Transportability now enters the Defense Department RDA process as a set of constraints reflecting the physical characteristics of existing or prospective transport assets. Analytically, this is the same as satisfaction of a minimum transportability requirement without explicit allowance of increases in transportability coupled with decreases in other desirable parameters. This may yield combinations of transportability and other system characteristics—however measured—different from those that would be chosen by ultimate system users if their preferences systematically could constrain or shape choices made in the RDA process.

Who are the “users?” For a number of systems the users are the individuals “in the foxholes,” so to speak, but it may be impossible to register their preferences in the absence of an internal market driving the design of DoD equipment. An imperfect proxy for the actual users may be the theater CINCs, who obviously are concerned with both the availability and performance of equipment over time in their theaters. Thus, one way to increase the degree to which “user” preferences are represented in the RDA process might be to include the CINCs on the ASARC Board, much as MTMC now is so included.

Such inclusion of the CINCs is likely to prove imperfect as a representation of “user” preferences. First, the CINCs themselves may have poor information about the relevant tradeoffs and may be advised by staff officers constrained by budget competition within their respective services. More important, the various CINCs are likely to differ in their assessments of the relevant tradeoffs; since the “users” represent a multitude of preferences and considerations, foreign policy goals among them, decisions ultimately must be highly centralized. However, to the extent that the CINCs collectively can be expected to receive and register user preferences to a degree greater than is the case currently, explicit inclusion of the CINCs in decision-making may yield net improvements.

An indirect approach might further user interests more fully. At present the requirements formulation process is not constrained by budgets; indeed, it is arguable that requirements often are written as a means of justifying budgets. Marginal requirements for lift inherent in new systems and requirements—and the future costs associated with such lift requirements—are not reflected in cost

projections for the new systems or in choices among requirements. By charging marginal lift costs against the new systems' budgets or cost projections, planners indirectly would have stronger incentives to evaluate transportability tradeoffs; in the present RDA process, marginal lift is treated as if it is "free," and so planners have incentives to maximize other objectives (capability) subject only to minimum transportability constraints. That is the problem outlined in Sec. 2. By this indirect route, planners would have stronger incentives to evaluate tradeoffs, thus indirectly evaluating options from a user perspective to a greater extent.

Further improvement in the outcomes yielded by the RDA process might be obtained by making analyses of the relevant tradeoffs more explicit. This could be done by providing financial incentives for creation and comparative evaluation of alternative parameter packages by contractors, MTMC, and the CINCs. Incentive fee contracts promoting such analyses could be written for designers/contractors.

The Department of Defense has been moving in this direction with its analytic concept of *unit* transportability as part of total force deployment analysis. This differs from the traditional analysis of *item* transportability described above in terms of the kind of information yielded, but user preferences again do not constrain decisions. The experience with transportability as it actually fits into the RDA process suggests that improvement in DoD resource use would be forthcoming with a change in focus from transportability as a constraint to transportability as an optimization parameter, with the chosen "optimum" constrained by and reflecting the preferences of the users affected most directly.