AD-E500 392

Copy 3 of 90 copies

12

IDA PAPER P-1578

PROPULSION SYSTEM TECHNOLOGY FOR MILITARY LAND VEHICLES

Donald M. Dix
Frederick R. Riddell

August 1981

Prepared for
Office of the Under Secretary of Defense for Research and Engineering

IDA
INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION

IDA Log No. HQ 81-23426

The work reported in this document was conducted under contract MDA 903 79 C 0018 for the Department of Defense. The publication of this IDA Paper does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official position of that agency.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 2. GOVT ACCESSION NO. AD-A105411	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Propulsion System Technology for Military Land Vehicles	5. TYPE OF REPORT & PERIOD COVERED Final
	6. PERFORMING ORG. REPORT NUMBER IDA PAPER P-1578
7. AUTHOR(s) Donald M. Dix, Frederick R. Riddell	8. CONTRACT OR GRANT NUMBER(s) MDA 903 79 C 0018
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute for Defense Analyses 400 Army-Navy Drive Arlington, Virginia 22202	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task T-0-078
11. CONTROLLING OFFICE NAME AND ADDRESS OUSDRE (R&AT) The Pentagon Washington, D.C. 20301	12. REPORT DATE August 1981
	13. NUMBER OF PAGES 152
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) DoD-IDA Management Office 400 Army-Navy Drive Arlington, Virginia 22202	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE --

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

None

18. SUPPLEMENTARY NOTES

N/A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

propulsion system technology, military land vehicles, potential improvements, potential payoffs

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The primary purposes of this paper are to: (1) assess propulsion-system technology needs and opportunities for military ground-vehicle applications, and (2) examine the relationship of these needs and opportunities to current technology-base program activities. The scope of the paper includes consideration of all major types of vehicles: combat vehicles, combat support vehicles, and tactical

20. (cont'd)

wheeled vehicles. Both engines and transmissions are considered and, to a lesser extent, fuels; the only generic element of a propulsion system which is not considered here is the thruster--tracks or wheels.

The results indicate that: (1) the payoffs for potential improvements in propulsion systems are high; (2) with respect to tactical wheeled vehicles, there seens to be little to be sacrificed by relying on commercial propulsion systems; (3) with respect to armored vehicles, programs aimed at suitable propulsion system technology demonstrations in the mid-to-late 1980s are needed now; (4) such demonstrations need not be related specifically to either lightly armored vehicles or main battle tanks at this time, but rather to armored vehicles as a whole; (5) the power range of interest is 500-1500 hp, with the lower portion probably preferred; (6) technology-base programs should be directed toward purely military engines rather than commercial derivatives; and (7) major emphasis should be placed upon integrated power trains utilizing diesel engines with split-torque transmissions and gas-turbine engines with mechanical transmissions.

RE: Classified References, Distribution Unlimited
No change in distribution statement
per Ms. Betty Pringle, IDA

IDA PAPER P-1578

PROPULSION SYSTEM TECHNOLOGY FOR MILITARY LAND VEHICLES

Donald M. Dix
Frederick R. Riddell

August 1981

INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION
400 Army-Navy Drive, Arlington, Virginia 22202

Contract MDA 903 79 C 0018
Task T-0-078

ABSTRACT

The primary purposes of this paper are to: (1) assess propulsion-system technology needs and opportunities for military ground-vehicle applications, and (2) examine the relationship of these needs and opportunities to current technology-base program activities. The scope of the paper includes consideration of all major types of vehicles: combat vehicles, combat support vehicles, and tactical wheeled vehicles. Both engines and transmissions are considered and, to a lesser extent, fuels; the only generic element of a propulsion system which is not considered here is the thruster--tracks or wheels.

The results indicate that: (1) the payoffs for potential improvements in propulsion systems are high; (2) with respect to tactical wheeled vehicles, there seems to be little to be sacrificed by relying on commercial propulsion systems; (3) with respect to armored vehicles, programs aimed at suitable propulsion system technology demonstrations in the mid-to-late 1980s are needed now; (4) such demonstrations need not be related specifically to either lightly armored vehicles or main battle tanks at this time, but rather to armored vehicles as a whole; (5) the power range of interest is 500-1500 hp, with the lower portion probably preferred; (6) technology-base programs should be directed toward purely military engines rather than commercial derivatives; and (7) major emphasis should be placed upon integrated power trains utilizing diesel engines with split-torque transmissions and gas-turbine engines with mechanical transmissions.

CONTENTS

SUMMARY

A. PURPOSE AND SCOPE

This study resulted from a desire by OUSDRE(R&AT) to obtain an independent assessment of the needs, prospects, and potential technology-base programs for improved propulsion system technology for ground vehicles. The U.S. Army Tank-Automotive Command (TACOM) is the focal point for research and technology activities related to ground-vehicle propulsion systems, and TACOM typically spends, depending upon the vagaries of the budget process, $10-15 million* annually in support of such activities.

The objectives of this study are to:

1. Assess propulsion system technology needs and opportunities for ground-vehicle applications;
2. Examine the relationship of these needs and opportunities to current program activities; and
3. Recommend whatever steps, if any, appear appropriate for reorientation of current program activities.

The scope of the investigation includes consideration of all major types of vehicles: combat vehicles, combat support vehicles, and tactical wheeled vehicles. Both engines and transmissions are considered and, to a lesser extent, fuels; the only generic element of a propulsion system which is not considered here is the thruster--tracks or wheels.

B. APPROACH

The approach used consists of four major elements. First, future vehicle requirements are evaluated to ascertain

---

*Unless otherwise stated, all monetary amounts are in FY 81 dollars.

quantities, probable timing, power levels required, and the potential impacts of propulsion system improvements. Second, various advanced propulsion system options are evaluated in terms of estimated performance achievable and resultant military payoffs. Third, suitable goals, both technologically feasible and offering sufficient payoff to be of interest, are formulated for specific propulsion-system types. Fourth, technology-base activities needed to achieve these goals are identified and compared with current program activities.

Many parts of the analysis are quantitative; in particular, use is made of a simple model which relates costs and weights of vehicles to propulsion system characteristics, and this enables potential payoffs of propulsion system improvements to be evaluated in terms of reductions in cost and/or weight of vehicles with otherwise the same military capability. Inevitably, some of the findings which emerge from this approach are judgmental, and the judgments could perhaps be made differently. In all cases, however, the bases for the judgments are stated.

C. FINDINGS

1. Power Requirements for Armored Vehicles

Armored vehicles can be conveniently considered in two classes: main battle tanks (MBTs), distinguished by heavy armor, and lightly armored combat vehicles (LCVs). In both classes of vehicles, the specific power (maximum engine power/vehicle gross weight) which is practically useful is limited by two factors: the ability of soils to withstand the shearing force of the tracks, and the increased vehicle cost associated with increased power. On the basis of an analysis of these factors (Sections II-B and II-C), it is found that:

1. For future main battle tanks, the specific power requirement is unlikely to be greater than 25 hp/ton (which is the level of the current M1). Inasmuch as MBTs are practically limited to weights of no more

than 60 tons, this implies that maximum power levels will be no more than 1500 hp. Further, there is a current tendency to believe that future MBTs may be significantly less than 60 tons, and power requirements could be as low as about 1000 hp.

2. For lightly armored combat vehicles, the specific power requirement is unlikely to be greater than 30 hp/ton (50% greater than the current M2/M3). Given the current tendency toward smaller vehicles, it seems unlikely that future LCVs will exceed 30 tons, and thus the maximum power requirement is about 900 hp. Future LCVs may be considerably lighter, and power requirements may be as low as 500 hp.

2. Potential Needs for New Propulsion Systems

The potential need for ground-vehicle propulsion systems is large; future vehicle applications (Sections II-A, II-D) include:

Vehicle Application	Needed Power Level	Approximate Inventory Level	Estimated Production Date of New Vehicle
Main battle tanks	1000-1500 hp	15,000	≥ 1994
Lightly armored combat vehicles	500-900 hp	25,000	≥ 1994
Self-propelled artillery	500-900 hp	3,000	≥ 1988
Trucks (2-1/2- and 5-ton)	400	100,000	Any time

The future production dates are of course subject to considerable variation, both in forecasts and eventual reality, and to some extent depend upon the availability of a new propulsion system; nevertheless, it is clear that appropriate technology-base activities are needed now.

The potential leverage of advanced propulsion systems on these vehicles is high because the propulsion systems, including fuel, represent appreciable fractions of the vehicle weight, armored volume, and cost; thus rather modest improvements in propulsion systems can lead to appreciable reductions in weights and costs of vehicles with the same mobility, payload, and range characteristics. For example, it is estimated (in Section II-E) that a 10% improvement in each of the five major characteristics of engines and transmissions (engine specific fuel consumption or transmission efficiency, specific weight, specific volume, specific manufacturing cost, specific operation and maintenance cost) would produce reductions in vehicle life-cycle costs of 18, 15, and 11 percent for MBTs, LCVs, and 5-ton trucks, respectively; these reductions amount to about $450,000 per vehicle for MBTs, $125,000 for LCVs, and $30,000 for 5-ton trucks. It is not necessary, of course, that propulsion system improvements be used to reduce the costs of vehicles with the same mobility, range, and payload characteristics; nevertheless, the measure serves to indicate that relatively modest propulsion system improvements have large payoffs, however used.

As indicated in the previous table, there is a requirement for a large number of propulsion systems for tactical wheeled vehicles with power levels less than 400 hp. Unlike the other high-performance military applications, there is a large commercial market--both domestic and foreign--for vehicular propulsion systems in this power range. Thus, there is no doubt that relatively modern vehicular propulsion systems will always be available from purely commercial sources. Given this availability, and the facts that the relative leverage of propulsion system improvements is not as high in tactical wheeled vehicles as in armored vehicles and that the important commercial characteristics of specific fuel consumption, manufacturing cost, and operation and maintenance cost are also important military characteristics, there seems to be little to be sacrificed by relying on commercial propulsion systems for tactical wheeled vehicles.* Accordingly, technology-base efforts should be focused on propulsion systems for armored vehicles in the power range of 500-1500 hp.

In the context of desirable R&D directions, it is worth pointing out that an examination of the potential influence (in Section II-E) of the individual propulsion system characteristics permits the following observations:

1. Transmission efficiency is by far the most influential characteristic in all vehicles; this is simply because, for the same power delivered to the sprockets or wheels, the power required of the engine is inversely proportional to the transmission efficiency.
2. Apart from transmission efficiency, engine specific fuel consumption at representative part-power conditions is the most influential characteristic in main battle tanks.
3. Apart from transmission efficiency, engine and transmission specific weight are the most influential characteristics in lightly armored combat vehicles.

It is pointed out that the latter two observations are based on the gas-turbine installation in the M1 and the diesel installation in the M2/3, respectively, and hence reflect the relatively high part-power specific fuel consumption of gas turbines and the relatively high specific weight of diesel engines.

3. Advanced Propulsion System Options

There are many possibilities for advanced propulsion systems for armored vehicles in the 500-1500 hp range; the possibilities examined here are diesels, gas turbines, and rotaries for engines,

---

*Some sacrifices will be involved, of course: commercial engines will undoubtedly emphasize low pollutant emissions at some sacrifice in performance, and military needs for cold-start and multifuel capability may require modest modifications to commercial engines.

and mechanical, hydrokinetic, hydromechanical, and split-torque combinations for transmissions.* With respect to fuels, consideration is limited to liquid hydrocarbons (petroleum or non-petroleum based) as the only viable option for military ground vehicles.

For engines, we find (Section III-B-1) that substantial performance improvements are immediately foreseeable in diesel engines by means of: (1) large reductions in the heat rejection rate--that is, adiabatic or quasi-adiabatic operation--through the use of high-temperature metallic materials or perhaps ceramic materials; (2) high levels of turbocharging through the use of variable compression ratio, intake heaters, or the hyperbar technique; (3) higher piston speeds and rotational speeds through improved lubrication, injection, and combustion processes; and (4) turbocompounding.

Similarly, we find (Section III-B-2) that substantial performance improvements in gas turbines are immediately foreseeable by means of: (1) increased turbine inlet temperature through the use of newer superalloys or dispersion-strengthened superalloys; (2) higher combustor inlet temperatures through the use of high-effectiveness heat exchangers and improved heat-exchanger and combustor materials; (3) improvements in variable-geometry component performance; and (4) improved air filtration methods.

If the current rotary-engine development by Curtiss-Wright is completely successful, we find (Section III-B-3) that it

---

*Gears are the primary means of power transmission in all of these devices; mechanical transmissions transmit all power by means of gears; hydrokinetic transmissions have a fluid-driven torque converter through which all of the input power passes; hydromechanical transmissions utilize hydrostatic elements (pumps and motors) for speed ratio selection, and hence only part of the input power is transmitted by gears; and split-torque transmissions, as defined here, utilize a torque converter through which only part of the input power is transmitted.

offers substantial performance advantages as compared to existing and near-term engines of other types. If the rotary engine can be adapted to take advantage of turbocharging, further performance improvements are possible, but it does not offer significant performance advantages when compared to future advanced engines of other types.

For transmissions, we find (Section III-C-3) that the potential for significant improvements in conventional hydrokinetic and hydromechanical transmissions is distinctly limited. On the other hand, three different design concepts, none of them new, offer promise of significant improvements: (1) elimination of, or a large reduction of, power transfer through the torque converter to increase efficiency and decrease cooling requirements; (2) operation of the propulsion power splitting and steering controls at higher speeds (and lower torques) to decrease specific weight and volume; and (3) hybrid transmissions using low-torque devices (electrical converters or traction drives) with a high-speed input coupled with a geared final drive.

As a result of an assessment of the potential payoffs of these advanced propulsion system options in armored vehicles (in Section III-D), a few observations are pertinent:

1. Eliminating the torque converter from the transmission, or reducing its role, is a high-payoff area, and the additional potential offered by high-speed operation is significant. An important corollary is that the engine and transmission should be considered as an optimized unit, inasmuch as these payoffs cannot be fully achieved by a transmission adapted to operate with different types of engines or by the converse.
2. Among gas-turbine engines, the more-or-less conventional recuperated type is a much better candidate than the reheat-cycle type, by virtue of offering only slightly fewer payoffs at immensely lesser risk.

3. Advanced diesel and gas-turbine systems (with appropriate transmissions) offer comparable payoffs, the current rotary engine somewhat less. To be competitive, the rotary engine will require turbocharging and, given this necessity, the fundamental advantage of the rotary disappears. That is, with turbocharging, diesels and gas turbines cover the power range of interest completely, and the rotary engine has little to offer. Accordingly, we see no need for significant technology-base emphasis on the rotary engine.

On the basis of these observations, we conclude that the preferred advanced propulsion systems for future armored vehicles are (1) advanced diesel engines in combination with split-torque transmissions and (2) recuperated gas turbines in conjunction with mechanical transmissions.

4. Suitable R&D Goals

Although appropriate specific goals for either of the preterred propulsion system alternatives vary somewhat with application and power level, the following goals, appropriate to propulsion systems in the 800-hp class, are found (Section III-E) to provide payoffs in the range of 20-25% of vehicle life-cycle cost in LCV applications and would provide the necessary technological basis for achieving similar payoffs in MBT applications:

	Diesel/ Split-Torque	Gas Turbine/ Mechanical
Engine		
Specific fuel consumption @ 25% power, lb/hr/hp	0.35	0.42
Specific weight, lb/hp	2.2	2.2
Specific volume, ft^3/hp	0.032	0.033
Transmission		
Representative efficiency	0.87	0.90
Specific weight, lb/hp	2.5	2.3
Specific volume, ft^3/hp	0.033	0.030

These goals should not be interpreted too rigidly, of course, particularly since the individual goals can be traded off among themselves (e.g., lower specific fuel consumption for higher specific weight), depending upon future developments. Nevertheless, they appear to represent reasonable targets from the standpoint of technological possibility, and they offer payoffs which easily justify annual technology-base expenditures of the order of $10-$15 million.

5. R&D Program Needs and Recommendations

In examining the various relationships between and among technology-base activities and eventual system applications (Section IV-A), we conclude that: (1) 6.3A* programs aimed at suitable propulsion system technology demonstrations in the mid-to-late 1980s are needed now; (2) these efforts need not be related specifically to either LCVs or MBTs at this time, but rather to armored vehicles as a whole; (3) that the power range of interest is 500-1500 hp, with the lower portion probably preferred; (4) that technology-base programs should be directed toward purely military engines rather than commercial derivatives; and (5) that 6.2 programs should address critical component areas but with generally more ambitious goals than concurrent 6.3A programs. In accordance with these findings, the recommended major technology-base programs (Sections IV-B, IV-C) are as follows:

1. For the diesel-engine/split-torque-transmission power train, a 6.3A program to demonstrate the technology of a 600 gross horsepower (ghp) power train with the goals as indicated previously and with manufacturing and O&M costs consistent with current diesel power trains. While detailed tradeoff studies are necessary

---

*In the RDT&E program area (Program 6 of the DOD Budget), technology-base activities consist of Categories 6.1--Research, 6.2--Exploratory Development, and 6.3A--Advanced Development (Technology Demonstration).

to make particular choices, it appears that a quasi-adiabatic, high-speed, turbocharged and turbocompounded diesel with a matched high-speed, split-torque transmission could attain the desired performance without demanding unreasonable advances in component technology. At the 6.2 level the critical areas appear to be (1) improving the response of turbocharged systems, (2) improved cylinder breathing, fuel injection and combustion to accommodate higher speeds, (3) better materials and cooling/insulation schemes for quasi-adiabatic operation, and (4) improved lubricants.

2. For the gas-turbine-engine/mechanical-transmission power train, a 6.3A program to demonstrate the technology of a 800-900 ghp power train with the goals as indicated previously and with manufacturing and O&M costs consistent with current gas-turbine power trains. While detailed tradeoff studies are again necessary to make particular choices, it appears that a recuperated gas-turbine engine with turbine inlet temperature of 2200-2300°F, variable flow-path geometry and improved air filtration, with a matched high-speed, mechanical transmission could attain the desired performance without demanding unreasonable advances in component technology. At the 6.2 level the critical areas appear to be (1) high-temperature metallic recuperators, (2) high-inlet-temperature metallic combustors, (3) improved flow range of variable geometry components, and (4) compact air filtration systems.

Because of the variety of choices available in either of the power trains described above, it is recommended that in each case competitive engine-technology demonstrations be pursued. The funding requirements for such competitive demonstrations have not been analyzed here, but is is not readily apparent that they would be incompatible with reasonable budgetary expectations (e.g., $15 million per year).

The major differences between the R&D program recommended here and the proposed TACOM program are not so much in the power train performance goals (except possibly for transmissions) as in (1) the concept of demonstrating power-train technology for armored vehicles as a class rather than undertaking a prototype development directed at a specific application, as TACOM proposes, and (2) the emphasis accorded here to purely military engines, as opposed to derivatives of commercial engines, in the 500-1000 hp range. With respect to the first difference, the concept proposed here is to design the 6.3A program so that it can at a later date provide the technology needed when a specific application is more clearly focused. This not only leaves the technology options open, without possibly artificial restraints, as long as possible, but also removes the need to predict a specific application 12-14 years in advance. It is intended that such 6.3A demonstrator engines and transmissions fully utilize available component technology. The proposed 6.2 programs are then planned to advance the state of the art in critical component areas, but the 6.3A programs are not dependent on success of the 6.2 programs. With respect to the second difference, we believe that, although TACOM has been directed by both the Congress and the Department of the Army to make maximum use of commercial facilities, tooling, and engines, the relative payoffs associated with purely military engines for combat vehicles are such that complete reliance on commercial derivatives is unlikely to be a cost-effective approach.

The 6.2 programs proposed by TACOM are generally similar, but there is some difference in emphasis. In the diesel engine programs, in addition to the planned 6.2 work on advanced turbomachinery, programmable fuel injection, friction reduction, high-temperature materials and coatings, and integrated control systems, we would recommend some work on problems associated with high-speed operation.

In the 6.2 program for gas turbines the planned work emphasizes recuperators, reheat combustors, intercoolers, fuel control, high-temperature combustors, turbine nozzles and radial inflow turbine rotors, and thermal barriers. Our approach puts less emphasis on components for a reheat-cycle engine and more on recuperator and variable-geometry alternatives.

For transmissions the TACOM program is concentrated in 6.3A programs for hydrokinetic and hydromechanical transmissions. In addition, there is a planned advanced turbine transmission program, the details of which are unknown to us. Our proposed program would change emphasis to integrate the transmission more closely with the engine. This leads to possibly major design changes--i.e., possibly a high-speed mechanical transmission for the gas turbine or a high-speed, split-torque transmission for the diesel engine.

Finally, the planned TACOM program contains a substantial effort devoted to achieving a broad-range multifuel capability--from gasoline to heavy residuals--in engines. We find, however, that most of the benefits can be gained by providing a narrower middle-distillate range capability (boiling points between approximately 400° and 700°F), while the difficulties of developing a suitable engine for broader range capability increase greatly. Our recommendation is accordingly to concentrate on the more modest engine modifications and operator information needed to provide the narrower range capability.

I. INTRODUCTION

A. BACKGROUND

This study resulted from a desire by OUSDRE(R&AT) to obtain an independent assessment of the needs, prospects, and potential R&D programs for improved propulsion system technology for military ground vehicles. There are currently about 500,000 military ground vehicles in the inventory, ranging in size from main battle tanks to jeeps, all of which have propulsion systems of 1500 hp or less. Historically, these vehicles have been powered by either gasoline or diesel engines and remain so today, with the single exception of the main battle tank, where a gas-turbine engine has been introduced. Propulsion systems for ground vehicles have, with but few exceptions (the main battle tank being the most notable), consisted of commercially available engines and transmissions or derivatives of commercially available components.

The U.S. Army Tank-Automotive Command (TACOM) is the focal point for research and technology activities related to ground-vehicle propulsion systems, and TACOM typically spends, depending upon the vagaries of the budget process, $10-15 million* annually in support of such activities. The adequacy and disposition of these funds involve some thorny issues, including: (1) suitable goals, both technologically reasonable and offering sufficient payoff to be of interest; (2) power levels of interest; (3) the relative emphasis to be given to activities aimed at improving adaptations of commercial components versus those aimed at new military components; (4) the type of engine to be

---

*Unless otherwise stated, all monetary figures are in FY 1981 dollars.

pursued: diesel versus gas turbine versus other; (5) transmission types suitable for different engines; and (6) the nature of the program outputs needed to assure that the development of a new propulsion system for a specific vehicle can be undertaken with a satisfactory degree of confidence. These issues, and others, are examined here.

B. PURPOSE AND SCOPE

The objectives of this study are:

1. To assess propulsion system technology needs and opportunities for ground-vehicle applications;
2. To examine the relationship of these needs and opportunities to current program activities; and
3. To recommend whatever steps, if any, appear appropriate for reorientation of current program activities.

The scope of the investigation merits some discussion. With respect to R&D activities, the interest here is confined to so-called technology-base activities,* which are aimed at improving technology rather than providing a specific new propulsion system for a specific new vehicle. With respect to vehicles, all major types of vehicles are considered: combat vehicles (e.g., main battle tanks, armored personnel carriers), combat support vehicles (e.g., self-propelled artillery), and tactical vehicles (trucks). With respect to propulsion system components, both engines and transmissions are considered, and somewhat lesser consideration is devoted to fuels; from the standpoint of a generic definition of a propulsion system, the only major element not considered here is what could be called the thruster--tracks or wheels.

---

*In the RDT&E program area (Program 6 of the DOD Budget), technology-base activities consist of Categories 6.1-Research, 6.2-Exploratory Development, and 6.3A-Advanced Development (Technology Demonstration).

C. APPROACH

The approach followed here consists of five elements: (1) identification of future vehicle requirements; (2) synthesis of propulsion system options; (3) analysis of potential propulsion system payoffs; (4) formulation of appropriate R&D goals; and (5) identification of R&D needed.

The primary interest in identifying future vehicle requirements is in establishing both the propulsion-system power level needed and the potential impact of propulsion-system technology improvements on the vehicle. In the range of interest (less than approximately 1500 hp), the power level needed is an important quantity, inasmuch as it can affect the relative attributes of different types of propulsion-system components (e.g., diesel versus gas-turbine engines) as well as the technology areas requiring emphasis. Further, the nature of the propulsion-system development business is such that the output needed from 6.3A activities, in order to provide adequate confidence to undertake development, is a demonstration of the technology in a propulsion system environment at approximately the power level needed. As a specific example, demonstration of an advanced technology engine at, say, 1500 hp would not be considered adequate to undertake a new 750 hp engine development.* Similarly, the potential impact of propulsion-system improvements is important in evaluating appropriate R&D goals and/or the usefulness of technology improvements. For example, vehicles in which the combination of engine, transmission, and fuel do not constitute an appreciable fraction of the total vehicle weight or volume require more ambitious R&D goals than other kinds of vehicles in order to have the same overall impact. Projecting future vehicle requirements to the extent necessary

---

*This statement is more valid for gas-turbine engines than for other types of engines; for example, a smaller diesel engine can be obtained by merely reducing the number of cylinders, although an engine so derived will not generally be an optimum one.

to establish approximate power level and potential propulsion system impact is of course a hazardous business; the vehicles of interest generally will not enter into engineering development for another 8 to 10 years, and will not appear in the operational inventory until some 15 to 20 years hence. Such projections are made here on the basis of current and past trends as well as physical and practical limits governing the design of such vehicles.

Synthesis of propulsion system options entails not only estimating feasible technology improvements in both engine and transmissions, but also the resulting characteristics of suitable combinations of engines and transmissions. For example, the two major types of engines--diesel and gas turbine--differ significantly both in basic rotational speed level and in torque-speed characteristics; it is therefore unduly restrictive to evaluate the prospects of both engine types on the assumption that both use the same transmission, and this is avoided here. With respect to the individual characteristics of engines and transmissions, either separately or in combination, which can be affected by technology improvements, primary emphasis is given to five: (1) the specific fuel consumption and/or the transmission efficiency; (2) the specific weight (weight/output power); (3) the specific volume (volume/output power); (4) the specific hardware cost (cost/output power); and (5) the specific operation and maintenance cost (O&M cost/output power). Although there are many possible characteristics of interest, it is these five which have the largest potential impact on any ground vehicle. Possible improvements in technology are accordingly assessed in terms of effects on these five characteristics.

A key factor regarding any potential advanced-technology propulsion system is of course its military payoff, assuming that the technological goals will be satisfactorily achieved. This payoff is assessed here in terms of the impact that an improved propulsion system would have on the cost and weight of a relevant vehicle with otherwise the same military capability (i.e., a vehicle with the same payload, mobility, range, armor protection, etc.). This is accomplished here by means of a simple vehicle model, developed previously, which relates the five propulsion system characteristics mentioned above to the resulting cost and weight of vehicles. That the payoff measure is a reduction in cost or weight of a vehicle with unchanged military capabilty does not mean of course that advanced technology must be used for these purposes; it could equally well be used to provide greater vehicle payload for the same cost or weight, or greater range, or greater armor protection, etc. Reductions in cost (particularly) are, however, a convenient and accurate measure of payoffs, and they also avoid questions as to the military worth of increased payload and the like.

Identification of the R&D activities needed involves not only an assessment of those technology areas which need emphasis to achieve suitable goals, and a comparison of this assessment with the current and planned R&D program, but also consideration of the types of programmatic activities (e.g., engine component development versus engine-transmission technology demonstration) which seem best suited to produce results which can be used as a basis for a propulsion-system development decision.

Inevitably, some of the findings which emerge from this approach are judgmental, and the judgments could perhaps be made differently. In all cases, however, the bases for the judgments are stated.

II. FUTURE GROUND VEHICLES

Applications of potential advanced-technology propulsion systems are of course in vehicles which do not yet exist; hence, in order to determine the power levels needed, the importance of propulsion system improvements, and the timing required for the development of new propulsion systems, it is necessary to estimate some general characteristics of future ground vehicles. Such estimates are the subject of the following paragraphs.

A. PROJECTED REQUIREMENTS FOR GROUND VEHICLES

The current and projected inventories of ground vehicles is an obvious starting point for projecting future vehicle requirements. The Army currently has a bewildering array of different types, makes, and models of ground vehicles, to the extent that a detailed listing would be somewhat confusing. A reasonable aggregate representation of inventory levels for the next few years is as follows (Refs. 1-3*):

Vehicle	Power (hp)	Approximate Inventory Level
Tanks	750-1500	15,000
Armored personnel carriers	220-500	17,000
Other light, armored vehicles	220-	10,000
Self-propelled artillery	400-	3,000
Tactical wheeled vehicles	75-600	400,000
5-ton trucks	240	35,000
2-1/2-ton trucks	210	65,000
Less than 2-1/2-ton	75-100	290,000

---

*No classified material from these references has been used in this paper.

Obviously, in both numbers of vehicles and total installed horsepower, ground vehicles with less than 250 hp are dominant.

Major systems now in production are the main battle tank, M1, with a projected total buy of about 7,000 vehicles, and the infantry fighting vehicle and cavalry fighting vehicle, M2 and M3, also with a projected total buy of about 7,000 vehicles.

Current plans (Ref. 2*) indicate that new or modified vehicles are planned to be introduced as follows:

Vehicle	Year of First Production
Armored Combat Logistic Support Vehicle (ACLSV)	1986
Advanced Multipurpose Armor System	1987
Field Artillery Ammo Support Vehicle (FAASV)	1987
Enhanced Self-Propelled Artillery Weapons System (ESPAWS)	1988
Improved M1	1988
Improved M2	1989
Recovery Vehicle Family, Improved	1993
M1 Follow-On	1994
M2 Follow-On	1994
Advanced Multipurpose Armor System Follow-On	2000

In addition, procurement of tactical wheeled vehicles continues at an annual rate of about $300 million.

It should be emphasized, of course, that these plans are subject to appreciable departures before the vehicles become a reality. Nevertheless, it is apparent from the current inventory levels--assuming that they will remain essentially unchanged in the future--that new ground vehicles will be required in substantial numbers. The precise dates depend upon the expected

---

*No classified material from this reference has been used in this paper.

useful life of current vehicles, which depends not only on their durability, but also on changes in technology and in the nature of the threat. Unfortunately, as will be discussed later, these dates can have a large influence on propulsion system R&D activities.

B. CHARACTERISTICS OF GROUND VEHICLES

1. Classes of Vehicles

From the viewpoint of propulsion systems, it is fortunately not necessary to make subtle distinctions between types of vehicles; accordingly, it is convenient to consider vehicles in rather broad classes, wherein vehicle types in each class can be considered to use propulsion systems of the same power level and, further, the propulsion system is of about the same relative level of importance. Four classes of vehicles are examined here:

1. Main Battle Tanks (MBTs). These vehicles are characterized by heavy armor protection, and are typically in the range of 45-60 tons gross weight.
2. Lightly Armored Combat Vehicles (LCVs). These vehicles are characterized by light armor protection, and are typically in the range of 15-25 tons gross weight. This class will generally include a variety of vehicle types: armored personnel carriers (e.g., the M113), fighting vehicles (e.g., the M2 and M3), and various combat support vehicles (e.g., ammo carriers).
3. Self-Propelled Artillery (SPAs). These vehicles are also characterized by light armor protection and relatively large and heavy payloads, and are typically in the range of 25-35 tons gross weight.
4. Heavy Trucks. These vehicles are characterized by no armor protection, they are wheeled, and they are typically in the range of 10-20 tons gross weight. As defined here, this class includes trucks of the 2-1/2-

and 5-ton variety and excludes all other tactical wheeled vehicles, such as jeeps.

It is to be noted that only two levels of armor protection are considered: (1) light armor protection is assumed to give (selected) protection against 14.5 and perhaps 23 mm penetrator rounds, and protection against artillery fragments; (2) heavy armor protection is assumed to be as much armor as is feasible within other vehicle constraints. It is also to be noted that the first three classes of vehicles are generally tracked vehicles.

The first question to be addressed regards the power levels and the vehicle specific power (maximum engine power/gross vehicle weight) which will be representative of future vehicles in these classes. An obvious place to start is with existing vehicles representative of the classes. Selected characteristics of such vehicles are shown in Table 1 (see Appendix A for sources).

TABLE 1. TYPICAL CHARACTERISTICS OF VEHICLE CLASSES

Vehicle Class	MBT		LCV		SPA	Truck
Vehicle	M60	M1	M113	M2	M109	M813
Gross weight, tons	56	60	12.5	24	26	20
Power, hp	750	1500	220	500	405	250
Specific power, hp/ton	13.4	25	17.6	20.8	15.6	12.5
Vehicle mfg. cost,* FY 81 $	500K	880K	100K	360K	250K	50K
Propulsion system cost, FY 81 $	130K	310K	--	90K	--	17K
Representative quantity	--15,000---		--25,000---		3,000	35,000

---

*Excluding payload costs.

As might be expected, the trends exhibited by successive vehicles in the same class (M60, M1; M113; M2) are the usual military ones. The newer vehicles have higher specific powers, as evidenced by the M1 and M2, and, we believe, by the follow-on to the M109, for which specific power levels of 20 hp/ton have been mentioned; the newer vehicles tend to be heavier, as evidenced by the M2 and possibly the follow-on to the M109, which is presumably in the 35-40 ton range (the main battle tank is an exception to this trend, since the gross weight is limited by other considerations to about 60 tons); as a result, the newer vehicles have substantially higher power levels than the older ones (by a factor of about 2 or 3). Unfortunately, these trends seem difficult to extrapolate. A superficial extrapolation would indicate that, for example, the next main battle tank would have a power requirement of about 3000 hp, and the next LCV would have a power requirement of about 1150 hp. On the other hand, neither the vehicle specific power nor the power level is determined at the whim of either designers or users. Power is expensive, and the specific power which can be utilized by the vehicle is limited by the amount of shearing stress various kinds of soil can support. These subjects are examined below.

2. Relationship Between Vehicle and Propulsion System Characteristics.

A simplified model is used here to determine the impact of power on vehicle costs, and it is also used subsequently in determining the impact of potential improvements in propulsion systems on the overall weight and cost of vehicles. The model is completely described in Appendix A, but a brief description of its essential features is in order here.

The model consists of three parts: vehicle weight, vehicle manufacturing cost, and vehicle operation and maintenance (O&M) cost. Any vehicle is assumed to consist of five elements: payload, propulsion system, fuel, structure (including armor), and suspension, the first three being contained within the armored volume (if any). Structural weight is assumed to be a linear function of both the weight of the first three elements and the armored volume. For a fixed payload, the remaining elements are assumed to be linearly related to appropriate vehicle performance and design characteristics and to propulsion system performance characteristics. The net result is that the weight of a vehicle with fixed payload and range can be estimated as a function of vehicle specific power and three characteristics of the propulsion system: a specific fuel consumption representative of cruise conditions; the specific weight (weight/power), and the specific volume (volume/power). In the first instance, the characteristics of the propulsion system are based on the useful power delivered (thrust x velocity); these characteristics can in turn be related to the corresponding characteristics of the engine and the transmission. As indicated in Appendix A, the model yields results for gross vehicle weights which are in reasonable agreement with existing vehicles and more detailed design methods.

The vehicle manufacturing cost is defined here to consist of those nonrecurring and recurring costs associated with the direct production of the vehicle, excluding payload costs; as such, these costs do not include a variety of costs usually included in the so-called procurement cost (e.g., engineering changes, system test and evaluation, data system/project management, initial spares and repair parts) which typically are about an additional 20-25% of the manufacturing cost. The vehicle manufacturing cost is assumed to be a simple linear function of the empty vehicle weight (that is, the gross vehicle weight less the weights of payload and fuel) and the installed power; specifically, for armored vehicles

$$\$_p = 8000 W_{ve} + 275 P_i$$

for vehicles with diesel engines, and

$$\$_p = 8000\ W_{ve} + 310\ P_i$$

for vehicles with turbine engines, where W_{ve} is the vehicle empty weight in tons, and P_i is the maximum engine power in horsepower. It is to be noted that the coefficient of the power in the above relations includes not only the direct cost of the propulsion system but also a power-related cost of the structure (amounting to $95 per horsepower, as shown in Appendix A); further, the vehicle specific power at which the power-related costs exceed the weight-related costs is in the range of 26-29 horsepower per ton of empty vehicle weight. As indicated in Appendix A, these simple models provide results which are in reasonable agreement with both data for existing vehicles and results from more detailed cost-estimating methods.

Vehicle operation and maintenance costs are defined here to consist of the costs of the fuel, the direct costs of maintenance, including parts and labor, and an appropriate share of the indirect costs; the costs do not include the costs of the payload, crew, and ammunition. These O&M costs are intended to reflect those O&M costs which can reasonably be expected to be influenced by propulsion system characteristics and their resultant impact on the vehicle. Fuel costs are estimated on the basis of projected vehicle usage, and the remainder of the O&M costs are simply assumed to be proportional to the manufacturing cost (being somewhere between 10% and 20% of the manufacturing cost on an annual basis). A 20-year life is assumed for all vehicles.

The net result is that for a vehicle of a given class with a specified payload and range, the resulting vehicle weight, manufacturing cost, and O&M cost can be estimated as a function of vehicle specific power and propulsion system characteristics. The primary interest at this point is the impact of increasing vehicle specific power on vehicle weight and costs, and representative results for two vehicle classes--MBTs and LCVs--are shown in Fig. 1. In both cases, the payload weight and volume have been assumed equal to those in the current vehicles (the M1 as the MBT and the M2 as the LCV), and the characteristics of the propulsion systems are assumed to be those in the current vehicles. The interpretation of Fig. 1 is then that it portrays the weight and manufacturing cost of vehicles (for each class) with the same payload, range, and armor protection characteristics, and which differ only in specific power.

The results in Fig. 1 display the price--in terms of both vehicle weight and manufacturing cost--of increasing vehicle specific power.* The results suggest that the specific power of armored vehicles may be limited by cost considerations; to the extent that vehicle manufacturing cost is indicative of the costs, it is obvious that the incremental military value of increased specific power will have to increase continuously to offset the increased costs involved.

Vehicle manufacturing cost is but one element of costs; a more complete picture of the cost is obtained by estimating the system life cycle cost as a function of vehicle specific power, as shown in Fig. 2. Here, the system life cycle cost includes the vehicle manufacturing cost, the vehicle O&M costs for 20 years, the manufacturing cost of the payload, and all other operating and support costs associated with the system for every active vehicle (the latter costs amount to $3.3 million tor MBTs and $1.8 million for LCVs, as indicated in Appendix A).

---

*It is pointed out that two approximations used in the model tend to make the curves in Fig. 1 somewhat "steeper" than may actually be the case. The first is the assumption that armor weight $\sim$ armored volume, whereas a pure geometric scale would indicate armor weight $\sim$ (armored volume)$^{2/3}$; the second is the assumption that propulsion system characteristics are independent of power level, whereas, particularly in gas-turbine engines at the lower power levels ot interest here, these characteristics do improve somewhat as the power level increases.

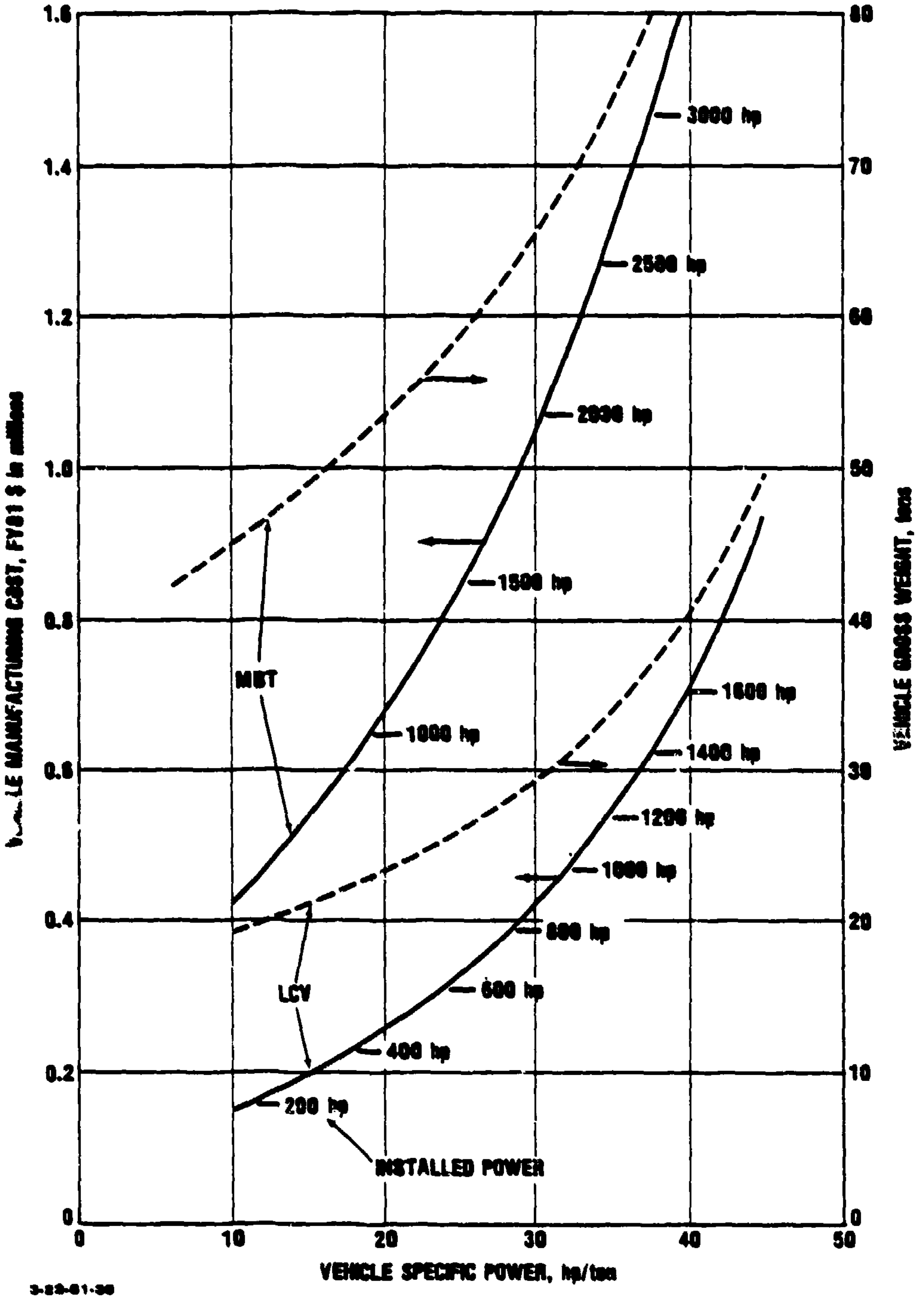


FIGURE 1. Impact of vehicle specific power on weight and manufacturing cost of armored vehicles.

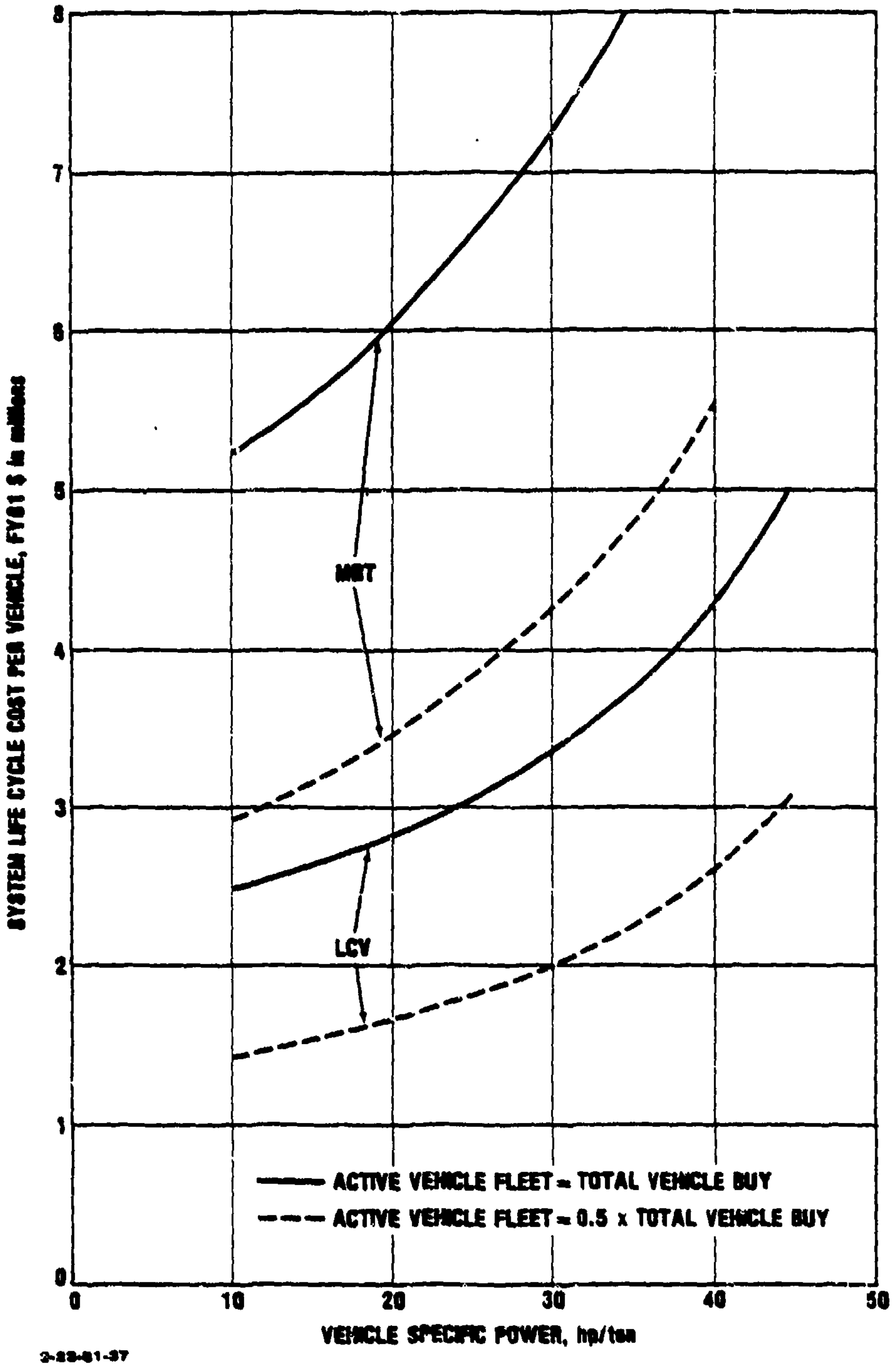


FIGURE 2. Impact of vehicle specific power on system life cycle costs of armored vehicles.

Two results are shown in Fig. 2: one on the assumption that all vehicles purchased will be active, and the other on the assumption that 50% of the vehicles purchased will be active vehicles; the latter is more representative of current plans for the M1 and M2/3. These results contain the same suggestion as the previous ones: unless the incremental military value of higher specific power continuously increases, the specific power of armored vehicles will be limited by the attendant increased costs. To complete the picture, some assessment of the military value of increased specific power is needed.

C. MOBILITY AND SURVIVABILITY CONSIDERATIONS

1. Ground Limits

The primary value of increased vehicle specific power is in the improved off-road performance obtained in the vehicle: greater acceleration and hill-climbing capabilities. These capabilities are in turn limited to some extent by the properties of the soil.

A basic feature of the interaction between a track (or a wheel) and a soil at the track-soil interface is that there is a limit to the shearing stress the soil can resist, which depends upon the properties of the soil, the ground pressure (vehicle weight/ground contact area), and the geometry of the track. This in turn limits the propulsive force a track can develop.

An analysis of these limits is presented in Appendix B; the essential results are shown in Fig. 3. Here the acceleration capabilities of 20- and 60-ton tracked vehicles are shown for two types of soils, in terms of level ground acceleration (right-hand scale) or normalized power available (left-hand scale) as a function of normalized sprocket power (sprocket power is the power supplied to the track). Normalized power (hp/ton/mph) is used here for convenience in inferring vehicle

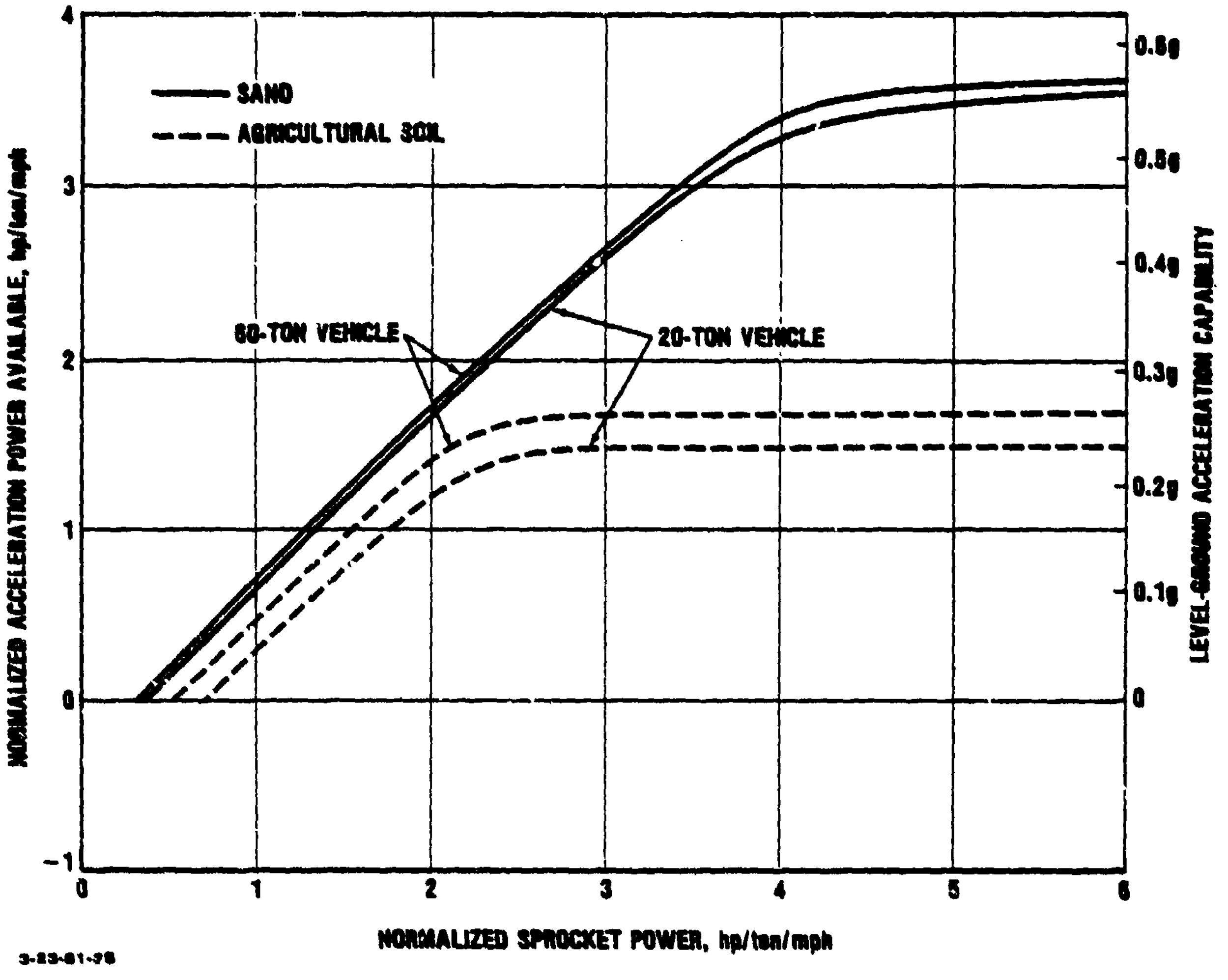


FIGURE 3. Useful power characteristics of tracked vehicles.

specific power; in reality, it is a force per unit mass, or an acceleration, e.g.

$$F = 375\ W_v\ \frac{HP/TON}{MPH}$$

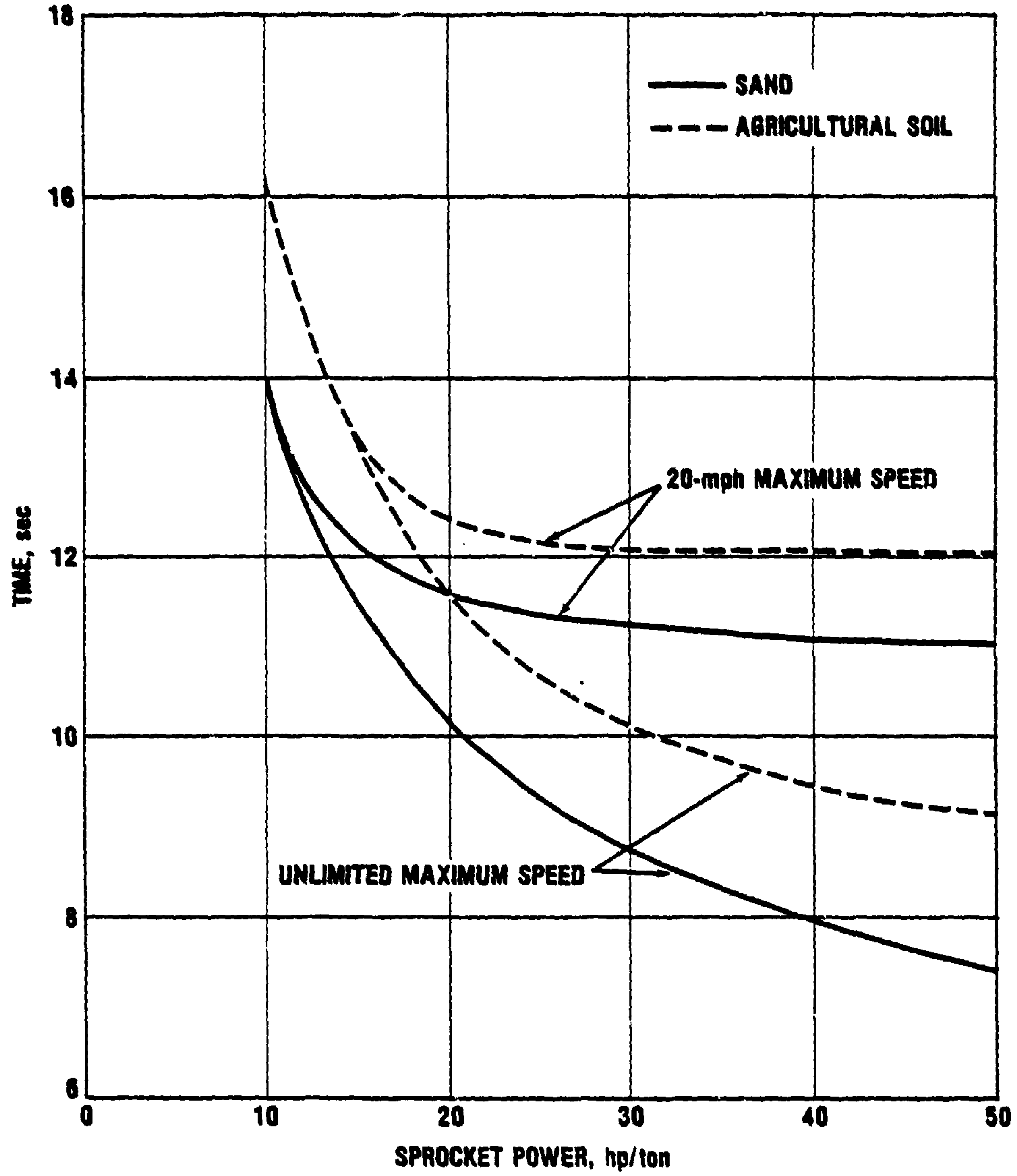
where F is in pounds and W_v is the vehicle gross weight in tons. Thus, for example, a normalized acceleration power of 2 hp/ton/mph for a 60-ton vehicle means that a force of 45,000 lb in excess of that required to overcome drag is developed in the soil.

The message contained in Fig. 3 is that the acceleration capability of a vehicle is limited by inherent properties of the soil; the more-or-less horizontal portions of the curves in Fig. 3 indicate a region where any increase in sprocket power is consumed by throwing the soil around (via spinning of the tracks), rather than in providing any increase in acceleration capability. The corollary is that the vehicle specific power which is useful depends upon the speed at which it is to be used. For example, in sand--a good soil for traction purposes--it is evident from Fig. 3 that a tracked vehicle cannot use more than about 4 hp/ton/mph at the sprocket; thus if maximum acceleration capability is needed at 20 mph, say, then 80 hp/ton could be used, or at 10 mph, 40 hp/ton, and so on. Similarly, in agricultural soil--a not-so-good soil for traction purposes, a vehicle cannot use more than about 2 hp/ton/mph at the sprocket, which leads to useful specific power levels that are 50% lower than those in sand.

A better portrayal of the significance of such specific power limits is obtained by converting the acceleration capabilities shown in Fig. 3 to vehicle time-to-distance characteristics. These are shown in Fig. 4,* in terms of the time required

---

*These time-to-distance characteristics have been obtained with the assumptions that maximum engine power is developed instantaneously and is maintained throughout the acceleration, and that 20% of the resulting power (continued on page 21)



3-23-81-39

FIGURE 4. Ideal standing start performance: time to 300 feet.

for an ideal vehicle to travel 300 feet, from a standing start. Results for two cases are shown. The first is based on the assumption that there are no limits on maximum vehicle speed, and the second is based on the assumption that the maximum vehicle speed is limited to 20 mph. It seems obvious from these results that, to the extent that time to 300 feet is a measure of military value, the incremental benefits of vehicle specific powers much in excess of 15-25 hp/ton at the sprocket are small indeed.

The shape of the curves in Fig. 4 would of course be different for different situations. The time to move greater distances at unlimited maximum speeds, or the time required to climb steep slopes at maximum sustainable speeds would show greater benefits for higher specific powers. However, it seems rational to suppose that, as a comparison of Figs. 3 and 4 indicates, acceleration capability is most useful at low vehicle speeds. Figure 4 is accordingly considered as reasonably representative of the utility of increased specific power.

2. Mobility Performance Versus Cost

The preceding results for the costs and acceleration capability of tracked vehicles can be combined to yield versions of cost-performance relationships for tracked vehicles, as shown in Figs. 5 and 6. Figure 5 portrays vehicle manufacturing cost, and Fig. 6 portrays a system life cycle cost (per vehicle). It should be pointed out that the parameter is now maximum engine power per ton of vehicle; in current vehicles the ratio of maximum sprocket power to maximum engine power is about 0.68.

---

*(continued from page 19) available for acceleration is needed to accelerate the rotating components of the drive train (Appendix B). In reality, of course, engine power is not developed instantaneously and varies throughout a vehicle acceleration due to discrete gear shifts, to an extent determined by the detailed characteristics of the transmission and the torque-speed characteristics of the engine. Although these details are important design considerations, they do not affect the conclusion made here.

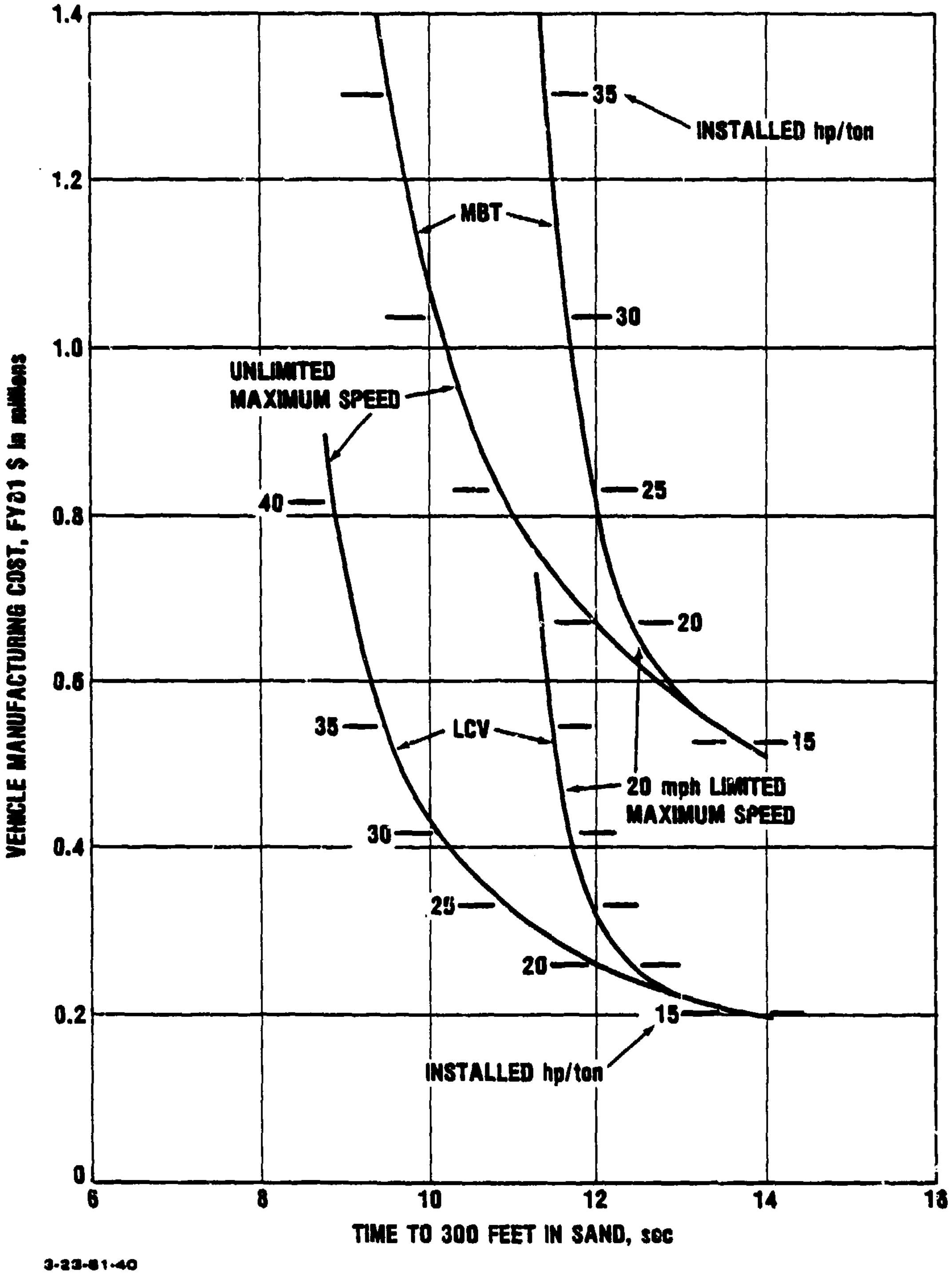


FIGURE 5. Acceleration performance and manufacturing cost of tracked vehicles.

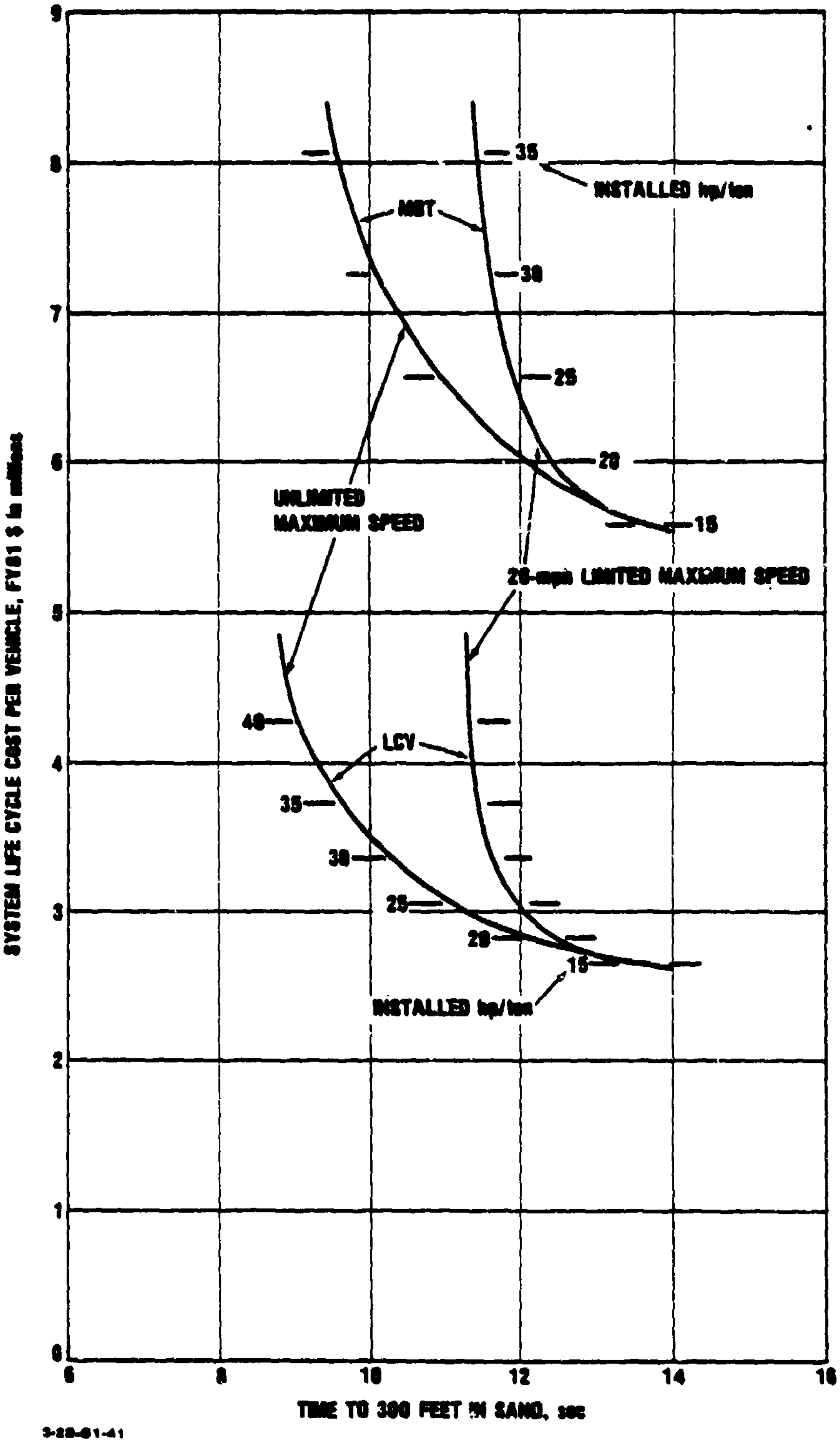


FIGURE 6. Acceleration performance and system life cycle cost of tracked vehicles.

An inescapable inference from either Fig. 5 or Fig. 6 is that it will be exceedingly difficult to justify a vehicle specific power of more than 25 hp/ton in main battle tanks and more than 30 hp/ton in lightly armored combat vehicles.

3. Current and Previous Studies on the Value of Mobility

As is evident from the foregoing, a key issue in determining useful limits on specific vehicle power is the military value of increased mobility.* Although we consider the analysis presented here to be adequately persuasive regarding the limits of specific power which will ultimately be found to be cost-effective, it is obvious that others could perhaps judge other situations differently. In this context, it should be pointed out that within the last decade, at least three major experimental efforts have been undertaken which included as a primary objective the determination of the military value of increased specific power (Ref. 4), and a few remarks on these efforts are perhaps in order.

The three efforts involved tests carried out in 1975 and 1976 on several vehicles, including Swedish S-tanks, [the S-Tank Agility/Survivability (STAGS) tests]; tests carried out in 1977 on a Chevrolet El Camino truck; and the current Armored Combat Vehicle Technology (ACVT) program which involves two vehicles: the High Mobility/Agility (HIMAG) vehicle and the High Survivability Test Vehicle-Lightweight (HSTV-L) vehicle. One phase of all of these efforts has been to operate the test vehicles over prescribed, representative terrain courses and maneuvers, and simultaneously have gunners and/or missile launchers endeavor to acquire and simulate fire at the vehicles, while recording both the mobility characteristics of the vehicle and the results of the simulated firing exercise.

---

*The term "mobility" is used here to describe either the ability of a vehicle to negotiate terrain at more or less a sustained speed or its ability to accelerate; sometimes only the former capability is referred to as mobility, with the latter capability referred to as agility.

Perhaps the analysis of these data that is most relevant to the purposes here is one of the possible tradeoffs between armor and mobility (Ref. 5*). Based primarily on STAGS data, the analysis endeavored to determine the change in survivability of various generic vehicles of fixed power level as armor protection was added (thereby decreasing the specific power). The analysis included: (1) a determination of average vehicle speed as a function of specific power which, as it happens, is in close agreement with those implied by the unlimited maximum speed results shown in Fig. 4; (2) a determination of hit probability as a function of average vehicle speed and size; and (3) the conditional kill probability as a function of increased armor protection (not based on the field data). The entire analysis was based on the assumption of one type of antitank round. The major results indicated that, starting from a vehicle weight of 20 tons, increases in armor protection were more than offset by decreases in mobility until weights in excess of about 40-50 tons were reached; that is, additional armor decreased survivability. Such a result was not unexpected, inasmuch as the assumed antitank round necessitated a large increase in armor to affect the conditional kill probability significantly. Although the analysis was not specifically aimed at deducing the benefits of increased specific power, interpolation of the results indicates that doubling the specific power from 20 to 40 hp/ton increased survivability about 10%--a result which would not be inconsistent with the analysis used in this report. The more important point, perhaps, is that any analysis of such data will portray the value of increased specific power subject to important constraints about which judgments will have to be made. That is, it seems reasonable to assume that situations can be analyzed which will show virtually any value of specific power to have large benefits, and the judgment to be made will be to what extent the situation analyzed is likely to be encountered by an armored vehicle in

---

*No classified material from this reference has been used in this paper.

combat (e.g., how representative are the soils and soil conditions, terrain features, tactics, enemy weapons, etc.?).

The current ACVT program is presumably addressing these matters with considerable thoroughness, and the results accordingly should be quite useful. Unfortunately, we have as yet not been able to obtain any results from the program.

4. Concluding Remarks

By way of summary, the preceding discussion involves some reasonable inferences regarding power requirements for future armored vehicles:

1. For main battle tanks, the specific power is unlikely to be greater than 25 hp/ton (which is the level of the M1). Inasmuch as MBTs are practically limited to weights less than 60 tons, this implies that future maximum power requirements will be less than 1500 horsepower. Further, there is of course some doubt as to the size of future "main battle tanks"; a current tendency is to believe they will be smaller--perhaps of the order of 45 tons or less. So it is possible that power requirements could be considerably less than 1500 horsepower; for example, a 45-ton vehicle at 25 hp/ton would require 1125 horsepower.
2. For lightly armored combat vehicles, the requirement for specific power is unlikely to be greater than 30 hp/ton (50% greater than the current M2/M3). Given the current tendency of considering smaller vehicles, it seems reasonable to suppose that future LCVs will not exceed about 30 tons; this implies a maximum requirement of about 900 hp. Future LCVs could be substantially lighter; a 16-ton vehicle (which would be transportable by helicopter) at 30 hp/ton might be possible, in which case the power requirement would be 480 hp.

It should be pointed out that these observations are at variance with some previous efforts aimed at identifying future armored combat vehicles and their power requirements (e.g., Refs. 6-8*). Specific power requirements of future vehicles are conjectured to be in the range of 35-50 hp/ton, and consequently the power requirements for future vehicles tend to be about 50% larger than indicated by the present analysis.

D. PROJECTED REQUIREMENTS FOR GROUND-VEHICLE PROPULSION SYSTEMS

The previous information regarding the projected nature and timing of future vehicles, and their powering requirements, can be combined to produce a reasonably representative picture of potential needs for new propulsion systems, as shown in Table 2. In broad terms, the power levels which appear probable are in the range of 500-900 hp for LCVs and SPAs (on the basis that the quantity and nature of SPAs are such that a new propulsion system development would not be justified specifically for these vehicles), 1000-1500 hp for MBTs, and less than 400 hp for trucks.

TABLE 2. POTENTIAL NEEDS FOR NEW PROPULSION SYSTEMS

Vehicle Application	Power Level	Year of First Production
MBTs		
M1 Retrofit	1500?	1988
New MBT	1000-1500	1994
LCVs		
M2/3 Retrofit	≤750	1989
New IFV/CFV	500-900	1994
Advanced Multipurpose Armor System	≤600	2000
SPA		
Improved M109	Same range as LCV	1988
ESPAWS		1988
Trucks		
5-ton, 2-1/2-ton	≤400	Anytime

---

[*] No classified material from these references has been used in this paper.

The first-production dates shown in Table 2 represent the earliest dates for which there is some documentation; such dates are of course subject to considerable variation, both in present forecasts and eventual reality. Nevertheless, these dates do define a problem with respect to new propulsion systems. Engineering development of a new propulsion system must typically precede first-production dates by about 5-7 years; as indicated in Table 2, initial production of major new systems is currently forecast to be as early as 1994 (new MBT and new IFV/CFV). Accordingly, the implication is that any improved propulsion system technology must be demonstrated to an extent sufficient to provide confidence for development in the 1987-89 time period. As will be discussed subsequently, this does not allow ample time for the required technology-base activities to be completed.

E. POTENTIAL LEVERAGE OF PROPULSION SYSTEM CHARACTERISTICS

A final question that needs to be addressed is with regard to the propulsion system characteristics, which, if improved, will have the most impact on future vehicles. Some appreciation of the relative importance of various propulsion system characteristics in typical vehicles can be gained from the weight and volume distributions of the vehicles.

Such distributions are shown in Table 3. In MBTs, the propulsion system plus fuel amounts to 12% of the weight and 40% of the interior volume; in LCVs, 17% of the weight and 27% of the volume; in trucks, 12% of the weight. Reasonable inferences would be that reductions in propulsion system specific volume and fuel consumption would offer the largest improvements in main battle tanks, that reductions in propulsion system specific weight and specific volume would probably yield similar benefits in LCVs, and that reductions in propulsion system specific weight would offer the most benefit in trucks. On a broader scale, improvements in propulsion systems for

MBTs would seem to have the highest leverage, followed by LCVs, and then trucks.

TABLE 3. TYPICAL WEIGHT AND VOLUME DISTRIBUTIONS OF GROUND VEHICLES

	MBT				LCV				Truck	
	Weight		Interior Volume		Weight		Interior Volume		Weight	
	Tons	%	ft^3	%	Tons	%	ft^3	%	Tons	%
Structure	32.5	54.6	--	--	7.9	32.9	--		3.7	18.5
Suspension	10.9	18.4	--	--	5.3	22.0	--		4.0	20.0
Propulsion	5.3	9.0	178	28.7	3.4	14.1	108	21.6	2.0	10.2
Fuel	1.8	3.0	68	11.0	0.8	3.3	26	5.2	0.3	1.5
Payload	8.9	14.9	374	60.3	6.6	27.7	366	73.2	10.0	50.0
TOTAL	59.4	100.0	620	100.0	24.0	100.0	500	100.0	20.0	100.0

These inferences can be made more quantitative by means of the simplified model described in Section II-B-2 and Appendix A, with the results shown in Table 4. Here the results are shown in the form of sensitivity factors, defined as the ratio of the fractional change in vehicle cost or weight to fractional changes in propulsion system characteristics; thus, for example, Table 4 indicates that a 10% reduction in specific fuel consumption will produce a 2.6% reduction in the cost and a 2.0% reduction in the weight of a main battle tank. The costs are the vehicle life-cycle costs defined previously, and the overall characteristics of the propulsion system are based on output power (that is, the power delivered to the tracks or wheels).

The results in Table 4 indicate that for MBTs all propulsion system characteristics have about equal leverage (with the exception of procurement cost); in particular, contrary to intuition, the specific volume is not the dominant characteristic. This is simply because some structure is required to support the weight of the propulsion system whether armor protection is desired or not, and the resulting combination must be supported by the suspension system.

TABLE 4. SENSITIVITY OF VEHICLE LIFE-CYCLE COSTS AND WEIGHTS TO OVERALL PROPULSION-SYSTEM CHARACTERISTICS

	MBT		LCV		30 hp/ton LCV	Truck	
	Cost	Weight	Cost	Weight	Cost	Cost	Weight
Specific fuel consumption	.26	.20	.15	.10	.10	.71	.25
Specific weight	.27	.25	.43	.36	.73	.32	.22
Specific volume	.29	.27	.10	.08	.17	--	--
Procurement cost	.12	--	.11	--	.12	.06	--
O&M Cost	.23	--	.21	--	.24	.23	--
TOTAL	1.17	.72	1.00	.54	1.44	.71	.25

For the current LCV, on the other hand, the specific weight is by far the most dominant propulsion system characteristic. This is in part due to the lightly armored nature of the vehicle, and in part due to the fact that the sensitivity factors are based on the current propulsion system characteristics; the current propulsion system in the M2 and M3 is quite heavy (e.g., its weight is about 65% of that of the M1, but it produces only one-third as much power). Results are also shown in Table 4 for an LCV with a specific power of 30 hp/ton, but with the same payload, armor, and range as the current M2; these results illustrate the familiar theme that more stringent vehicle requirements result in greater payoffs for propulsion system improvements.

The totals indicated in Table 1 can be interpreted as the impact on the vehicle resulting from equal fractional improvements in each characteristic listed. Thus, for example, a 10%

improvement in each of the five characteristics will yield a reduction of 11.7% in vehicle life-cycle cost of a main battle tank. It is evident that with respect to existing vehicles, propulsion system improvements have greatest leverage in the MBT application, followed by the LCV, and then the truck; a hypothetical high-specific-power (30 hp/ton) LCV offers the greatest leverage of all. To provide some perspective on the absolute numbers, a 10% improvement in vehicle life-cycle cost represents about $225,000 per vehicle for an MBT, $85,000 per vehicle for the current LCV, and $28,500 per vehicle for a 5-ton truck. Considering the various fleet sizes, it is obvious that relatively modest improvements in propulsion system characteristics can have large payoffs.

The potential impact of individual characteristics of engines and transmissions (as opposed to those for the propulsion systems as a whole) can be readily obtained from the sensitivities shown in Table 4, giving the results shown in Table 5. A few observations worth making, in the context of desirable R&D directions, are:

1. Transmission efficiency is by far the most influential characteristic in all vehicles. This is simply because, for the same power delivered to the sprockets or wheels, it affects the power level required of the engine. Obviously, if improvements appear possible, they should be pursued.
2. In MBTs, engine sfc is the next most influential characteristic; again, this is with reference to the existing AGT-1500 gas-turbine engine.
3. In LCVs, engine and transmission specific weight are the most influential characteristics (other than transmission efficiency).
4. In trucks, the engine specific weight is the next most influential characteristic; again, this is with

TABLE 5. SENSITIVITY OF VEHICLE LIFE-CYCLE COSTS AND WEIGHTS TO ENGINE AND TRANSMISSION

	MBT		LCV		30 hp/ton LCV	Truck	
	Cost	Weight	Cost	Weight	Cost	Cost	Weight
Engine							
Specific fuel consumption	.26	.20	.15	.15	.18	.09	.03
Specific weight	.10	.09	.22	.18	.37	.24	.16
Specific volume	.13	.12	.06	.05	.10	--	--
Procurement cost	.06	--	.05	--	.06	.03	--
O&M Cost	.13	--	.10	--	.11	.02	--
Total	.68	.41	.58	.33	.82	.48	.19
Transmission							
Efficiency	.68	.41	.58	.33	.82	.48	.19
Specific weight	.18	.16	.21	.17	.36	.08	.05
Specific volume	.16	.11	.04	.03	.07	--	--
Procurement cost	.05	--	.06	--	.06	.03	--
O&M Cost	.11	--	.11	--	.13	.12	--
Total	1.18	.68	1.00	.53	1.44	.71	.24
Total	1.86	1.09	1.58	.86	2.26	1.19	.43

reference to the existing NHC-250 engine, which is quite heavy.

Finally, as observed previously, it is apparent that rather modest improvements in these individual characteristics will produce high vehicle payoffs.

III. ADVANCED PROPULSION SYSTEM OPTIONS

The preceding analysis enables a reasonable forecast to be made of the requirements for future propulsion systems for ground vehicles in terms of both power levels needed for various classes of vehicles and those propulsion system characteristics which have the most leverage on potential payoffs. An assessment of technological possibilities for improvements in the relevant propulsion systems then permits an evaluation of potential payoffs for various kinds of propulsion systems, and the formulation of some rationally based technological goals; such an assessment is the subject here.

As indicated previously, there is a requirement for a large number of propulsion systems for tactical wheeled vehicles with power levels less than 400 hp. Unlike many other high-performance military vehicle applications, there is a large commercial market--both domestic and foreign--for vehicular propulsion systems in this power range (for trucks and off-highway vehicles at the higher power levels, and for automobiles at the lower power levels). Thus, there is no doubt that relatively modern vehicular propulsion systems in this power range will always be available from purely commercial sources. The question then becomes one of what kind of payoffs a military R&D program aimed at propulsion systems in this power range could offer as compared to commercially available engines, and we think that the answer is: not much, for at least two reasons. First, the relative leverage of the propulsion system on the cost or weight of the vehicle is not as great as for armored vehicles, and second, the important commercial characteristics of specific fuel consumption, manufacturing cost, and O&M cost are also important military characteristics. Although commercial systems can be expected to compromise these characteristics somewhat for the purpose of emission control, it seems unlikely that a specific military development will offer large advantages in payoffs over commercially available systems. There are of course some advantages, more difficult to quantify, which could accrue to military engines in this power range; two of the most important would appear to be more uniformity in makes and models and a wider fuel tolerance in the engines. Still, policy changes in commercial system acquisition could produce the former also. On balance, then, it appears that there is little to be sacrificed by relying on commercial propulsion systems for tactical wheeled vehicles, and there is no further consideration here of systems in this power range.

Accordingly, the emphasis is on propulsion systems for armored vehicles in the power range of 500-1500 hp. Although these systems must be ultimately treated as whole systems, the following assessment of potential technology improvements is, for convenience, organized in terms of the major elements: fuels, engines, and transmissions.

A. FUELS

1. Introduction

The question to be addressed here is to what extent the developing restrictions on the availability and quality of petroleum fuels* impact R&D on power trains for Army combat vehicles. There are two aspects to this problem. One relates to the desirability of broadening military fuel specifications (mil specs) in order to ensure easier supply in "normal" situations, and the other relates to the need for multifuel capability

---

*"Petroleum fuels" are those made from natural crudes as distinct from "synfuels," which are made from oil shale, tar sands or coal. "Liquid hydrocarbons" include both petroleum fuels and synfuels.

to meet emergency situations when military specification fuels may not be available.

It is assumed that liquid hydrocarbons are the only viable fuels for Army ground vehicles. Various studies have shown that alternate fuels are not attractive for military use in ground vehicles. Even in the less-demanding civil arena viable alternative fuels for ground transportation have not yet been found, and it appears that liquid hydrocarbons will continue to be the primary fuels for the foreseeable future.

2. Normal Supply Situations

By normal supply is meant a situation where there are no restricted (i.e., embargoed) sources of supply of fuels. In the short term the rise in crude prices has brought new types of crudes into the market. Many of these are heavy, sour crudes with unusual kinds of contaminants. It is a refinery problem to produce from these crudes products to meet existing specifications. On the other hand, since the commercial market does not have such tight specifications as the Army does, it may be advisable to consider broadening the milspecs so as not to restrict the sources of supply unnecessarily. This is a question to be addressed in the Army Fuels R&D Program.

In the longer run, it is clear that syncrudes (i.e., crudes from shale oil, tar sands or coal) are projected to come into greater use in the next 10 to 15 years. Certainly this time scale is well within the lifetime of any new Army engine. The extent to which these changes will affect the refinery outputs is therefore also a matter of concern. Current studies are being done by all the Services to monitor this problem and decide what fuel specs are acceptable. The problem exists, of course, also for civilian users of diesel and turbine engine fuels, so there is considerable pressure to solve in the refinery any problems connected with changes in available crudes and hence to avoid a requirement for engine modifications.

3. Emergency Situations

The other fuel problem, which is related to emergency use for non-spec fuels, is commonly referred to the engine designer as a need for multifuel capability. This requirement has received a great deal of attention since the oil embargo of 1973, but in fact it has been an Army interest at least since World War II. The significant question to be addressed here is how wide a range of fuel options should be included in multifuel capability for future Army combat vehicles. This question was treated in a previous IDA study (Ref. 9) with the following results. It was found convenient in that study to consider multifuel capability in two ranges: a narrower range that would allow use of civilian fuels of equivalent distillate range but not meeting other military specs (e.g., freezing point or cold start), and a wider range that would permit use of fuels of different distillate ranges (e.g., gasoline and diesel fuel, or diesel fuel and residual oils) in the same engine. It was found that, if engines are to be multifuel in the narrower sense, then there is little impact on the basic engine design. There may, however, be a need to add fuel or intake heaters or fuel valve adjustments to accommodate off-spec fuels without degrading performance below requirements. On the other hand, if the broader sense of multifuel capability is required (i.e., the ability to use fuels from different distillate ranges), then major engine redesign is necessary. In fact, such a specification should be made at the outset of the engine development. The report referenced above also examined the relative benefits of the narrower and wider ranges of multifuel capability in conceivable emergency situations. It was concluded that the narrower range of multifuel capability had a tremendous impact on broadening emergency fuel availability for ground vehicles, and the further gain by going to the wider capability was not worth its cost. A basic reason for this conclusion is the very large* commercial market in middle distillate fuels which are usable in diesel or gas turbine engines with the narrower range of multifuel capability defined above. Since there does not appear to be any viable fuel option other than liquid hydrocarbons, it is expected that this market will continue indefinitely even if it is eventually supported largely by syncrudes.

4. Conclusions

The conclusion, insofar as fuels themselves are concerned, is a continuing need to monitor the possible changes in refinery products due to changes in natural crudes and also the eventual introduction of syncrudes. Associated R&D should be done to evaluate the impact of changes on engine performance and O&M costs. The possible gains in availability and cost of milspec fuels that may be attained by relaxing the specifications should also be investigated.

The conclusion, insofar as the impact of fuel requirements on engine development is concerned, is that the major factor to be considered is the need for multifuel capability. As pointed out above, only the narrower, middle distillate multifuel capability is needed to reap most of the benefits. This does not have an impact on the basic engine design in diesels or gas turbines but may affect auxiliary systems. For example, fuel systems need to be able to accommodate the appropriate viscosity range, and fuel or oil heaters may be needed to meet cold start and minimum temperature operating requirements. It is easier to supply these capabilities during the engine development than as a retrofit. Hence the desirable distillate range should be specified early.

---

*Compared to any conceivable military demand. Currently it is about 30 times the military usage and constitutes 40-50% of petroleum fuels production. Thus, going to the wider multifuel capability adds little benefit in availability of supplies. Even if only crudes were available, they could be easily converted to middle distillates in portable refineries (see Ref. 9).

B. ENGINES

The interaction of an engine and a transmission in a vehicle causes some difficulties in treating one element in isolation from the other. The most pronounced difficulty is perhaps in characterizing the usable power-producing capabilities of an engine. The capabilities are characterized here by the maximum power of an engine, although it is realized that the useful power developed by an engine depends also upon other engine characteristics, the transmission characteristics, and the specific vehicle maneuver. For example, in a maximum acceleration from a standing start, the average power produced by an engine will be less than its maximum power to an extent determined largely by its torque-speed characteristics and the number of gear ratios in the transmission--for engines with the same maximum power, those for which the torque-speed characteristics are such that the power produced drops rapidly with decreasing engine speed, operating in conjunction with transmissions with few gear ratios will produce less average power than those with more favorable torque-speed characteristics operating in conjunction with transmissions with a greater number of gear ratios. Although these matters are of obvious importance in considering specific vehicle installations, we feel that maximum engine power is an adequate characterization for the more general comparisons of interest here.

1. Diesel Engines

The characteristics of some representative modern diesel engines for military applications are shown in Table 6, as compiled from various sources (Refs. 10-14). All of these engines are intended for, or are being used in, armored vehicles; in particular, the AVCR-1360 was intended for the M1, and the VTA903 is the engine in the M2/3. All of the engines except the AVCR-1360 are water-cooled, and the characteristics shown refer to the engine without the cooling system; thus, the weight and volume of the AVCR-1360 are not directly comparable

TABLE 6. REPRESENTATIVE DIESEL ENGINES FOR MILITARY APPLICATIONS

Characteristics	Designation and Manufacturer[a]					
	AVCR-1360 TCM	MB873 MTU	CV12TCA RR	VTA903 Cummins	MB870 MTU	CV8TCA RR
Power, hp	1500	1500	1200	500	750	750
Speed, rpm	2600	2600	2300	2600	2600	2300
Displacement, in^3	1360	2430[b]	1593	903	1215	1061
Bore/stroke, in.	5.4/5.0	6.5/6.1	5.3/6.0	5.5/4.8	6.5/6.1	5.3/6.0
Piston speed, fpm	2170	2640	2300	2060	2640	2300
Boost pressure, atm	4	--	--	~ 2	--	--
Best sfc, lb/hp-hr	.40	.37	.35	.36	~ .37	~ .35
Weight,[c] lb	4750	4280	3600	2400	2733	2780
Volume,[c] ft^3	95	58.3	59.1	43	37.1	38.4
Cylinder disp., in^3	113	202	133	113	202	133
Specific weight, lb/hp	3.2	2.9	3.0	4.8	3.6	3.7
Weight/disp., lb/in^3	3.5	1.8	2.3	2.7	2.3	2.6
Power/disp., hp/in^3	1.1	0.62	0.75	.55	0.62	0.71
Specific volume, ft^3/hp	.063	.039	.049	.086	.049	.051
Volume/disp., ft^3/in^3	.070	.024	.037	.048	.031	.036
Power/piston area, hp/in^2	5.5	3.8	4.5	2.6	3.8	4.2
Bmep, psia	336	188	259	169	188	243

---

[a] Cummins = Cummins Engine Co., MTU = Motoren und Turbinen Union, RR = Rolls-Royce, TCM = Teledyne Continental Motors.

[b] Later versions of the MB 873 have a displacement of 2899 in^3 and bore/stroke equal to 6.69/6.9.

[c] Weights and volumes do not include cooling systems, except for the AVCR-1360, which is air cooled.

to the others. In detail, the engines have remarkably little similarity (except within families); for the purpose of providing a starting point for an assessment of possible technology improvements, however, two observations are pertinent. First, within the power range of interest, there is a tendency for lower power engines to have somewhat inferior weight and volume characteristics; both the MTU and Rolls-Royce engines exhibit such a trend. Unfortunately, it is not clear how much of this effect is due to the fact that the engines are members of a family, rather than specific designs for individual power levels. Second, the AVCR-1360 can be considered to be representative of current diesel engine technology, but the VTA903 cannot. For example, a reasonable estimate of the result of halving the number of cylinders in the AVCR-1360 would be a 750 hp engine with a weight of perhaps 2800 lb; making allowances for the cooling system required for the VTA903 (0.8 to 1 lb/hp), its weight would also be about 2800 lb but with an output of 500 hp rather than 750 hp. Thus, the technology level from which to begin is represented by the AVCR-1360.

The physical origins of potential improvements--or potential limitations--in diesel engines provide the basis for assessing magnitudes of possible improvements, and these physical origins can be described in many ways. One such description is as follows.

From a purely thermodynamic standpoint, peak cylinder pressures and air-fuel ratios essentially dictate performance. Higher peak cylinder pressures produce higher power outputs and slightly higher efficiencies; peak cylinder pressures are currently in the range of 2000 psi. Lower air-fuel ratios produce higher power outputs and slightly lower efficiencies and are currently equivalent to about 50% excess air, being limited by mixing and combustion processes within the cylinder. The benefits of improving either peak cylinder pressures or air-fuel ratios are generally limited.

Power output of a diesel can be increased, of course, by increasing the volumetric flow rate for a given displacement; this can be accomplished by either reducing cylinder size or increasing piston speed. That is, the volumetric flow rate per cylinder is proportional to (linear dimension)^2 x piston speed, while the displacement per cylinder is proportional to (linear dimension)^3. To maintain constant relative velocities of both mechanical parts and gas flows and hence, to first order, constant fractional losses, piston speed must be constant; thus, for geometric scaling, both the volumetric flow per unit displacement and the rotational speed are inversely proportional to the linear dimension. As cylinder size is decreased, the increase in rpm complicates the mixing and combustion processes, lower Reynolds numbers increase the losses, and mechanical complexity increases; these effects have led to an empirically observed optimum cylinder size in the range of 60-100 in.^{3} (Ref. 15), corresponding to 20-30 hp/cylinder for naturally aspirated engines. The other way of increasing volumetric flow rate--increasing piston speeds--tends to increase both the losses and the mechanical loads; current piston speeds are limited to about 2600 fpm, although old aircraft diesels have operated with piston speeds in excess of 3000 fpm.

Historically, the most effective way of increasing the specific power of diesels has been through turbocharging: increasing the inlet pressure and density by means of a compressor driven by an exhaust-gas turbine. Two factors currently limit the amount of turbocharging which can be accomplished. As turbocharging is increased, either the maximum cylinder pressure must be increased, which leads to increased stresses, or the compression ratio of the diesel must be reduced; the drop in compression ratio has a slight adverse effect on the efficiency, but more importantly it makes the engine difficult to start. This difficulty has been overcome to some extent by the use of variable-compression-ratio diesels (namely, the AVCR-1360), in which the compression ratio is high at starting conditions and low at full-load conditions. A newer idea addressing the same problems is the so-called hyperbar system, which uses a gas-turbine-like combustor placed before the exhaust-gas turbine; this system also permits the intake manifold conditions to be maintained at lower loads, thus improving the response of the turbocharged system. The other factor limiting the amount of turbocharging is the thermal load on the cylinder; as turbocharging is increased, the power generated per unit surface area increases, and the necessary cooling becomes more difficult to accomplish. As a result, current turbocharging levels do not exceed boost pressures of about 4 atmospheres, and thermal loadings do not exceed about 6 hp/in^2.

Finally, a diesel engine typically rejects about 30% of the fuel energy to the cooling medium, which exacts a large penalty in performance: typically, 20 to 25% of the weight and perhaps 30-40% of the volume of a diesel-engine installation is devoted to the cooling system, and 10% of the gross engine power output is required by the cooling system. This has led to recent efforts to eliminate the cooling system by means of so-called adiabatic operation, and it requires that the material temperature capabilities be increased substantially.

Eliminating, or sharply reducing, the heat transfer losses from the cylinder does not have a dramatic effect on the engine efficiency; the absence of heat transfer to a cooling medium results largely in an increased temperature of the exhaust gases. This increased exhaust-gas energy has reactivated interest in turbocompounding: extracting as much available energy as possible from the exhaust gases (more than is needed to drive the compressor) at the expense of gearing the diesel and the turbine together.

Various efforts at overcoming these limitations on diesel engine improvements, or opportunities for improvements, have been proposed and/or are currently under way. The goals and resulting engine characteristics of such efforts are shown in Table 7, as gathered from several sources (Refs. 14, 16-18).

The uprating of the VTA903 to 1000 hp is currently being conducted by Cummins with TACOM funding. The elements involved are (1) increasing cylinder pressures to 2000 psi, (2) increasing piston speed to 2500-2600 fpm (and rpm to 3200), (3) increasing the boost pressure to about 4 atmospheres, and (4) turbocompounding. If successful, the resulting engine specific weight and specific volume (including cooling system) would be somewhat greater than the AVCR-1360, but the sfc would be substantially improved.

Uprating of the VHO engine to 1000 hp is currently being pursued by Teledyne Continental Motors. The VHO series of engines is distinguished by cylinder pressures of 3000 psi, and the primary element involved in the current effort is ultimately increasing boost pressures to the order of 6 or 7 atmospheres. If successful, the resulting engine specific weight and specific volume would be roughly comparable to the AVCR-1360, with a somewhat better specific fuel consumption.

The adiabatic engine is being pursued by Cummins with TACOM funding. The major elements involved are the elimination of the cooling system by means of the use of high-temperature materials, and turbocompounding. The "near adiabatic" is based on the modification of the current NHC-250 engine,* and the more mature version is presumably based on some unspecified new design. The current and previous efforts appear to have emphasized the use of ceramic materials in the cylinder and piston, although some efforts using high-temperature metallic materials (superalloys) also have been mentioned. If successful,

---

*More recently, TACOM proposed to base an adiabatic engine on a new Cummins engine, the L10 (10-liter displacement). This would result in a substantial improvement in specific weight and volume, as compared to the NHC-250.

TABLE 7. POTENTIAL MILITARY DIESEL ENGINE CHARACTERISTICS

	VTA-903 Uprate	VHO Uprate	Near Adiabatic	Adiabatic	Advanced Diesel	Proposed A/C Diesel
Power, hp	1000	1000	700	1000	625	400
Speed, rpm	3200	2800	--	--	4000	3500
Displacement, in.^{3}	903	700	--	--	342	287
Bore/stroke, in.	5.5/4.8	4.5/5.5	--	--	4.3/4.0	3.9/3.9
Piston speed, fpm	2530	2570	--	--	2600	2300
Boost pressure, atm	~4				~4-5	~4
Best sfc, lb/hp-hr	.33	.36	.28	.28	.36	.37
Weight, lb	3000	2400	3500	2500	1163	457
Volume, ft^3	50	31			18.8	16.3
Cylinder disp., in.^{3}	113	88			57	48
Specific weight, lb/hp	3.0	2.4	5	2.5	1.9	1.1
Weight/disp., lb/in.^{3}	3.32	3.4			3.4	1.6
Power/disp., hp/in.^{3}	1.1	1.4			1.8	1.4
Specific volume, ft^3/hp	.050	.031	.080	.034	.030	.041
Volume/disp., ft^3/in.^{2}	.055	.044			.055	.057
Power/piston area, hp/in.^{2}	5.3	7.9			7.2	5.6
Bmep, psi	274	404			362	

it is quite obvious that an adiabatic engine represents a significant advance in diesel-engine performance.

The "advanced diesel" is a speculation synthesized here as a representative example of reasonable objectives for a quasi-adiabatic, metallic diesel. The major elements include (1) scaling down the cylinder size of the AVCR-1360 by a factor of two, (2) increasing the piston speed to about 2600 fpm, (3) significant reduction in cooling requirements, and (4) turbocompounding. The rationale is that the reduced heat loss and higher metal temperatures in the cylinder will alleviate combustion and heat loss difficulties associated with the smaller cylinder; the piston speed and boost level are at the limit of the current state of the art. With a cooling system of perhaps 0.5 lb/hp, this would represent an engine with specific weight and specific volume of perhaps 25% less than the AVCR-1360, and a somewhat improved specific fuel consumption. The "proposed aircraft diesel" (from Ref. 18) is a two-stroke, adiabatic, hyperbar configuration, and the proposed characteristics in terms of piston speed, thermal loading, etc., are in the ranges of those suggested for the advanced diesel.

In detail, there are of course many other diesel-engine alternatives which could be synthesized, representing somewhat different design choices. The basic point, however, is that significant improvements in performance appear possible (with, to be sure, some uncertainty) in diesel engines by means of (1) large reductions in the heat rejection rate, (2) high levels of turbocharging, (3) high piston speeds and rotational speeds, and (4) turbocompounding.

The bottom line here is the payoff to the relevant vehicles and, to this end, the engine characteristics as installed in the vehicles are of interest. Such estimates are shown in Table 8, as compared to the existing installations in the M1 and the M2/M3. These characteristics are based on total installation weights and volumes, and on the basis of power delivered

TABLE 8. POTENTIAL INSTALLED CHARACTERISTICS OF MILITARY DIESEL ENGINES COMPARED TO EXISTING INSTALLATIONS IN THE M1 and M2/3

	VTA903 M2/3	AGT1500 M1	VTA903 Uprate	VHO Uprate	Near Adiabatic	Adiabatic	Advanced Diesel
Sfc at 25% power, lb/hp-hr	.41	.60	.37	.40	.34	.34	.40
Specific weight, lb/hp	7.45	2.82	5.01	4.37	5.95	3.0	2.97
Specific volume, ft^3/hp	.14	.058	.097	.073	.099	.050	.050
Manufacturing cost, $/hp	91.8	124.5*	91.8	113	91.8	105	109
O&M cost, $/hp	184	184	184	205	184	190	198

---

*Projected average cost over a buy of approximately 7000 units.

to the transmission (including the power necessary to cool the transmission). Specifically, it has been assumed that 8% of the gross engine power is required to cool conventional engines, 4% to cool the advanced diesel, and none at all to cool the adiabatic engines.* The specific fuel consumption is also based on the power delivered to the transmission, at 25% power (taken as representative of the duty cycle). The differences in manufacturing and O&M costs are rather crude estimates of the differences likely to be encountered between engines derived from a commercial engine and new, purely military engines. It can be observed that the installed characteristics of the advanced engines are also substantially better than the VTA903 in the M2, but less so for the AGT1500 in the M1; in the latter case, of course, the largest difference is in specific fuel consumption.

2. Gas-Turbine Engines

Gas-turbine engines are not widely used in vehicular applications, either military or civilian. The vehicular turbine which is probably the most widely used at present is the Avco-Lycoming AGT1500 in the M1 tank; another vehicular turbine intended for truck use, still in commercial development, is the Garrett GT601. Characteristics of those two engines, as obtained from Refs. 10, 14, 19-21, are shown in Table 9. Both engines are recuperated engines. A few remarks on some of the other characteristics are in order.

The specific fuel consumption values shown in Table 9 are those at 25% of full power; this condition is considered here to provide a reasonable representation of the fuel consumed during a typical duty cycle. For turbine engines, in particular, this is quite important since the part-power fuel consumption tends to degrade rapidly (e.g., the best sfc of the AGT1500

---

*In actuality, roughly 1% of gross engine power is required for compartment and fuel cooling, but this will not affect relative differences between engines.

is about 0.45 lb/hp-hr). Thus, for the purposes here, it is the 25% power condition that is of interest; as a practical matter, the full-power sfc is of virtually no interest at all.

The specific power (power/air flow rate) indicated in Table 9 reflects a basic characteristic of turbine engines which has received much attention in the M1 program; that is, compared to diesel engines, current gas turbines require much larger airflows through the engine (diesel engines typically produce about 300 hp/lb/sec), and this air must be well filtered to prevent damage to the engine. This leads to bulky air filtration systems which, within current design philosophy, are contained within the armored volume.

TABLE 9. REPRESENTATIVE GAS-TURBINE ENGINES FOR MILITARY APPLICATIONS

	AGT 1500	GT601
Power, hp	1500	550
Cycle pressure ratio	14.5	7:1
Turbine inlet temperature, °F	2150°F	1900°F
Recuperator effectiveness	.72	0.85
Airflow, lb/sec	12	5
Sfc at 25% power, lb/hp-hr	0.60	0.46
Weight, lb	2500	2200
Volume, ft^3	47	53.6
Specific weight, lb/hp	1.67	4.0
Specific volume, ft^3/hp	.031	.097
Specific power, hp/lb/sec	125	110

It should further be noted that the characteristics shown in Table 9 illustrate the difficulty of comparing engines of perhaps not dissimilar state-of-the-art technological levels, but of certainly different power levels and containing different design choices. There is a well-known tendency for the performance of turbine engines in the power range of interest here to degrade as power level is decreased; these effects of scale do not, however, account for the different performance levels of the AGT1500 and the GT601. By far the largest effect is due to the different design choices made in the respective engines; specifically, in the GT601, weight and volume have been sacrificed to obtain better specific fuel consumption characteristics via a relatively larger recuperator. This tradeoff between size and weight, on the one hand, and specific fuel consumption, on the other, is always present in any kind of heat engine (a topic explored at length in Ref. 22), and is particularly evident in recuperated gas-turbine engines. Thus, despite the differences in performance between the engines, both are more or less representative of current in-use technology in their respective sizes.

The physical origins of, and limitations to, performance improvements in gas-turbine engines are somewhat easier to describe than those for diesel engines. The traditional sources of improvement in gas-turbine engines are the basic thermodynamic ones of increased maximum temperatures and increased cycle pressure ratios. Higher temperatures have a large impact on specific power and further permit the cycle pressure ratio to be increased to obtain lower specific fuel consumption. Temperatures have always been basically limited by materials; currently, this limit for uncooled operation is in the vicinity of 2000°F, and the introduction of blade cooling permits maximum temperatures in the range of 2200-2400°F for turbines in the sizes of interest here. These (high) temperature capabilities have accounted in large part for the scale effects mentioned above. In nonrecuperated engines, to take full advantage of high temperatures, high pressure ratios are needed. This in turn produces small passage sizes and consequent high turbomachinery losses which are further aggravated by any blade cooling requirements, so that high pressure ratios cannot be efficiently achieved in small engines. As a consequence, smaller engines tend to operate at lower pressure ratios, with greater component losses, and at slightly lower temperatures than larger engines. Hence the performance characteristics of smaller machines, including part-power performance characteristics, are somewhat poorer than those of larger machines.

In recuperated engines, however, these effects of scale are not so marked, for at least two good reasons. First, a more fundamental requirement than increased pressure ratio in any gas-turbine engine is an increased temperature before combustion begins; that is, turbine engines of any type which have the same value of this temperature also have about the same value of specific fuel consumption. This temperature can be increased either by increasing pressure ratio or by adding or increasing recuperation. Thus, in recuperated engines, the pressure ratios need not be as high as in nonrecuperated engines; in turn, the problems associated with smaller passage sizes in smaller engines are alleviated, and at the same time the component efficiency levels are of less importance because relatively less power is handled by the turbomachinery components. Further, the scaling laws of heat exchangers dictate that their relative size decreases as maximum temperatures are increased and as power level decreases (providing that heat exchanger passage sizes can be made sufficiently small). The net result is that in recuperated engines, marked degrading effects of reduced power levels will occur at significantly lower power levels than in nonrecuperated engines; a corollary is that recuperated engines are the only type of gas-turbine engine suitable for armored vehicle applications.

More generally, then, the basic limits to improved performance in recuperated engines are associated with the turbine inlet temperature, the combustor inlet temperature, and recuperator size. These in turn imply potential limits concerned with both recuperator and combustor material-temperature capability. Current recuperators are made of stainless steel, with a useful operating temperature limit of about 1400°F; as turbine inlet temperatures increase, such a limit requires higher pressure ratios, otherwise detrimental to performance, to maintain a suitably low recuperator operating temperature. Thus, there is a need for higher temperature capability in recuperators. Nickel-based superalloys and dispersion-strengthened superalloys offer significantly higher temperature capabilities. Similarly, as the combustor inlet temperature rises, the difficulty of cooling the combustor increases because the inlet air is the source of cooling for the liner. Thus, improved materials and cooling schemes for combustors are needed. Current combustor materials are nickel-based superalloys, and dispersion-strengthened superalloys offer some prospect of improvement.

The part-power characteristics of a gas turbine are dictated primarily by the operating characteristics of the compressor, which do not permit a reduction in mass flow rate proportionate to the power decrease nor maintenance of the pressure ratio. As a consequence, the maximum temperature must be reduced, the pressure ratio falls, the combustor inlet temperature drops, and part-power sfc rises. The effect is less pronounced in recuperated engines since the combustor inlet temperature does not completely depend upon compressor pressure ratio (still another reason why recuperated engines are the only type of gas-turbine engines suitable for armored vehicle applications). To maintain low part-power sfc, it is essential to introduce variable geometry into the engine components: variable nozzle vanes in the turbines and, eventually, variable inlet guide vanes and/or stator vanes in the compressors. Decreasing the efficiency penalties and increasing the range of flow rates over which variable-geometry elements will provide efficient operation is an important area of potential improvement.

Reducing air filtration requirements is another potential source of significant improvement in turbine engines. In the M1 the filtration system occupies a volume equal to about half that of the engine; in addition, the barrier filters require considerable maintenance. Dual-stage inertial filters in combination with less sensitive compressor components offer significant size reductions, and self-cleaning barrier filters offer a reduction in maintenance requirements.

A more direct way of reducing air filtration requirements if of course to increase the specific power of the engine. In this context, intercooled reheat cycles have been studied. Reheat cycles entail adding another combustor after the gas-generator turbine, thus increasing power output, and inter-cooling entails adding a heat exchanger between compressor stages to reduce the power required for compression, thus further increasing net power output.

Various efforts at overcoming these limitations on gas-turbine engine improvements, or opportunities for improvements, have been proposed. The engine characteristics resulting from such efforts are shown in Table 10, as gathered from various sources (Refs. 19, 20, 23).

The two versions of the GT1801 have been proposed by Garrett; in the first version, the primary elements involved are (1) operation of a radial inflow turbine at 2230°F with no internal cooling, by means of the use of a directionally solidified superalloy; (2) use of a high-effectiveness recuperator; (3) variable nozzle vanes on both power-turbine stages and variable, articulated inlet guide vanes for the compressor; and (4) the use of two-stage inertial filters in conjunction with no axial compressor stages. If successful, the resulting engine specific fuel consumption (at 25% power) would be greatly improved over the AGT1500 and the specific volume would be significantly reduced, as would the maintenance requirements for the air filter. The second version of the engine primarily entails: (1) turbine operation at 2480°F, by means of the use of oxide-dispersion-strengthened superalloys in the turbine components; and (2) operation at higher recuperator temperatures, by means

TABLE 10. POTENTIAL GAS-TURBINE ENGINE CHARACTERISTICS

	GT1801 MK1	GT1801 MK11	AGT800	Reheat	Advanced Gas Turbine
Power, hp	1450	1800	800	1800	900
Cycle pressure ratio	12	12		22.5	~ 8-10
Turbine inlet temperature, °F	2230	2480	~ 2000	2500	2300
Recuperator effectiveness	.8	.8	.83	.78	.8
Airflow, lb/sec	9.4	8.6	7	6.1	5
Sfc at 25% power, lb/hp-hr	.42	.39	.42	.39	.42
Weight, lb	3100	3100	2000	2925	1900
Volume, ft^3	47	47	~ 31	37	28
Specific weight, lb/hp	2.14	1.72	2.5	1.63	2.1
Specific volume, ft^3/hp	.032	.026	.039	.021	.031
Specific power, hp/lb/sec	154	209	111	295	180

of the use of a nickel-based superalloy (instead of stainless steel) as the recuperator material. If successful, the resulting engine specific fuel consumption, weight, and volume characteristics would be further significantly improved.

The AGT800 has been proposed by AVCO. As far as is known, its major elements include: (1) completely uncooled turbine operation at an inlet temperature of about 2000°F; and (2) the use of a high effectiveness recuperator (as compared to the AGT1500). If successful, the engine specific fuel consumption would be a great improvement over that of the current AGT1500 and a significant improvement over that of the GT601, and the AGT800 would also provide a reduction in specific weight and volume compared to the GT601.

The reheat cycle characteristics have been taken from one design study sponsored by TACOM (Ref. 23), and it is more or less representative of other concurrent studies. In addition to the intercooling and reheat features, the primary elements include: (1) uncooled turbine operation at 2500°F by means of ceramic materials; (2) recuperator operation at maximum average inlet temperatures of 1760°F, with a ceramic material proposed; and (3) burner operation at 1500°F inlet temperature in the primary burner and 1740°F inlet temperature in the reheat burner, again with ceramic materials proposed. This is obviously a very futuristic engine, inasmuch as ceramic materials are far from the current state of the art for these applications. If successful, it would represent a considerable improvement over the AGT1500 in all respects. As compared to the GT1801 MK11, a considerably more conservative proposal, the most significant improvements are in specific volume and airflow.

The advanced gas turbine is a speculation synthesized here as representative of reasonable objectives for a recuperated gas turbine at the 900 hp level. Its major elements include: (1) operation with minimum cooling at the 2300°F level, using oxide-dispersion-strengthened superalloys; (2) a high effectiveness recuperator made of either stainless steel or superalloy, depending upon detailed design studies; and (3) variable geometry in both power turbine stages and at the compressor inlet. If successful, it would represent a slight improvement over the AGT800.

As was the case with diesel engines, there are of course many other engine alternatives, differing in detail, which could be synthesized, representing various design choices. Nevertheless, the basic point is that significant improvements appear possible by means of (1) increasing turbine inlet temperatures through the use of newer superalloys or dispersion-strengthened superalloys, (2) higher combustor inlet temperatures through the use of higher effectiveness heat exchangers and, if necessary, improved heat exchanger and combustor materials, and (3) improvements in variable-geometry component performance. The use of ceramic components for even higher temperature capabilities may be a distant possibility, of course, but they do not appear to be feasible in the nearer term.

The ultimate interest is in the payoffs offered by these prospects and, to this end, the characteristics of the engines as installed in the vehicle are shown in Table 11, as compared to the existing installations in the M1 and M2/M3. Again, the characteristics are based on the power delivered to the transmission, including that necessary for cooling; the power delivered was estimated to be 95% of the base engine power, with the 5% remainder accounting for inlet/exhaust losses and external engine cooling requirements.

3. Rotary Engines

The rotary, or Wankel, engine has received a great deal of attention recently as a potential engine for combat vehicles. Development of a military rotary engine is currently being conducted by Curtiss-Wright with Marine Corps funding. The essential advantage offered by the rotary engine is a significant improvement in volumetric flow capability as compared to

TABLE 11. POTENTIAL INSTALLED CHARACTERISTICS OF MILITARY GAS-TURBINE ENGINES COMPARED TO EXISTING INSTALLATIONS IN THE M1 AND M2/3

	VTA903 M2/3	AGT1500 M1	GT1801 MK1	GT1801 MK 11	AGT800	Reheat Cycle	Advanced Gas Turbine	GT601
Sfc at 25% power, lb/hp-hr	.41	.60	.43	.40	.43	.40	.43	.47
Specific weight, lb/hp	7.45	2.82	2.97	2.38	3.55	2.28	3.04	5.54
Specific volume, ft^3/hp	.14	.058	.043	.035	.053	.028	.042	.123
Manufacturing cost, $/hp	91.8	124.5*	120.8	120.3	121.0	121.0	121.0	110.5
O&M cost, $/hp	184	184	178.6	177.9	179	179	179	168

---

*Projected average cost over a buy of approximately 7000 units.

the reciprocating engine. The price paid for this improvement is an increase in sealing dimension, an increase in difficulties associated with combustion and mixing due to the shape of the combustion volume, and an increase in heat transfer and thermal loading problems because that portion of the engine block under which combustion occurs is never exposed to ambient air.

The bare engine and installed characteristics of the stratified-charge, spark-ignition rotary that would result if the current Curtiss-Wright development were completely successful are shown in Table 12. These characteristics represent a substantial improvement in specific weight and volume as compared to the existing VTA903 engine and the Garrett GT601 turbine, at the expense of a somewhat degraded specific fuel consumption. As with other positive displacement devices, rotary engines are in principle amenable to diesel operation and turbocharging, although both are considerably more difficult in the rotary than in reciprocating devices. Diesel operation is hindered by the high surface-to-volume ratio of the combustion chamber, to such an extent that several major corporations have been unsuccessful in various attempts. Turbocharging is hindered by high metal temperatures in the combustion zone, and its effects are not so marked as in reciprocating devices simply because the basic engine is relatively smaller.

TABLE 12. ROTARY ENGINE CHARACTERISTICS

	Bare Engine	Installed
Power, hp	750	690
Sfc at 25% power, lb/hp-hr	0.48	0.49
Specific weight, lb/hp	1.8	3.2
Specific volume, ft^3/hp	.040	0.055

4. Other Engines

Other engines, most notably the Stirling and the closed-Brayton-cycle, have been considered for vehicular engines from time to time. Both of these engines suffer from the fact that relatively large amounts of heat exchange are required per unit power output. The net result is that the potential gains in specific fuel consumption offered by those engines are more than offset by their size and weight, at least for armored vehicle applications. In short, we do not know of any other promising engine types for armored vehicle applications other than the diesel, the recuperated gas turbine, and the rotary.

C. TRANSMISSIONS

1. Introduction

Modern tracked vehicles in the U.S. inventory all use either hydrokinetic or hydromechanical transmissions. These are combinations of mechanical gears with hydraulic units in the form of either torque converters or hydraulic pumps and motors. Various combinations of these units are used, as will be discussed below. A general point to be made first, however, is that in spite of the fact that a transmission is in principle less complicated than an engine, in the latest combat vehicles the transmission can be as big and costly as the engine (Tables A-3, A-4, Appendix A). There is thus a strong impetus to look for ways to reduce its size, and/or improve its efficiency, as is discussed above in Section II. Unfortunately, there are not many avenues for making large improvements through technological advances in the components. Thus it is expected that significantly smaller or more efficient transmissions will only be attained by overall changes in design concept. This point of view will be developed below in more detail by examining the characteristics of current transmissions.

It is of interest to note that historically there have been very large reductions in the size of armored vehicle transmissions since World War II. In a gross sense this progress can be tracked by observing that the CD-850 transmission in the M60 was about one-half the specific weight and two-thirds the specific volume of the M26 Pershing tank transmission components (Ref. 24). A further reduction of about 40% in specific weight and slightly less in specific volume from the CD-850 was attained in the X-1100 transmission for the M1 tank. These improvements were partially due to improved component performance, e.g., more compact brakes, but were mostly accomplished by different design concepts using different components, e.g., planetary gears, torque converters, and hydrostatic steer units. Gains were made initially in the design of the CD-850, of course, by combining gear shifting, braking and steering units into one package, which again is a change in design concept. History thus reinforces the point that significant transmission improvements are more likely to come from changes in design concept than from improved component technology.

2. Current Transmissions

The CD-850 transmission and the lower-powered XTG-411 and XTG-250 of similar vintage are in extensive use in the current fleet of tracked vehicles. However, newer vehicles are using either the X series hydrokinetic transmission, of which the X-1100 in the M1 is an example, or the hydromechanical transmission such as the HMPT-500 in the M2. These represent the most advanced transmissions in use today and will be used in this study as the baseline designs in examining what the potential for further improvements may be.

The hydrokinetic X series transmissions are made by the Detroit Diesel Allison Division of General Motors. They have the following family characteristics: a hydraulic torque converter with a lock-up clutch in combination with planetary gearing providing four forward and two reverse speeds, hydrostatically controlled differential steer, and hydraulic service and parking brakes. The series includes the X-200 rated at

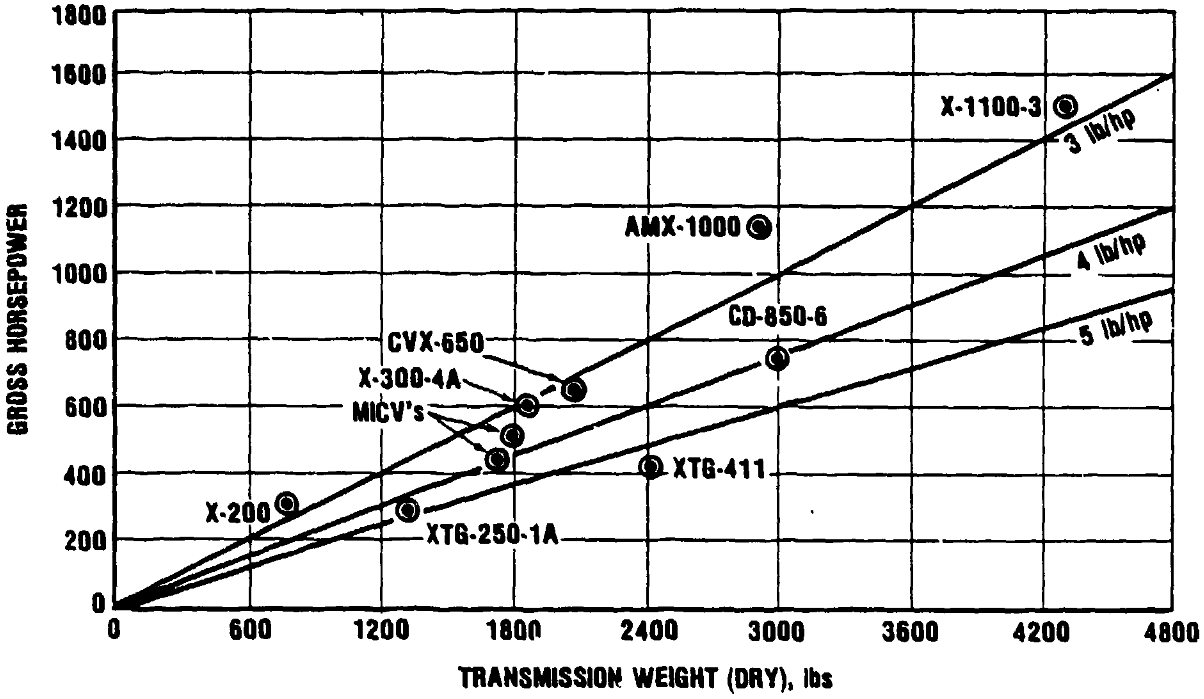
300 gross horsepower (ghp), the X-300 rated at 650 ghp, and the X-1100 rated at 1500 ghp. An advanced model designated the AMX-1000 is also under development. It incorporates six forward speeds and one reverse, as well as improved brakes using retarders, but it is not a fundamentally different concept.

The HMPT-500 hydromechanical transmission is made by the General Electric Co. It differs in concept from the X series mainly in that the propulsion power is not carried through a torque converter but instead is transmitted through split hydrostatic-mechanical paths which also include the steering function. The HMPT-500 is rated at 500 ghp. There is also another advanced hydromechanical transmission designated the CVX-650, under development by Detroit Diesel Allison Division.

The weights and volumes of all the transmissions discussed above are shown in Figs. 7 and 8 as a function of gross horsepower (i.e., maximum rated input horsepower). Note that the weights and volumes shown are values for the bare units. For our purposes here installed weights and volumes for the baseline vehicles, the M1 and the M2, are required. These are shown in the following table.

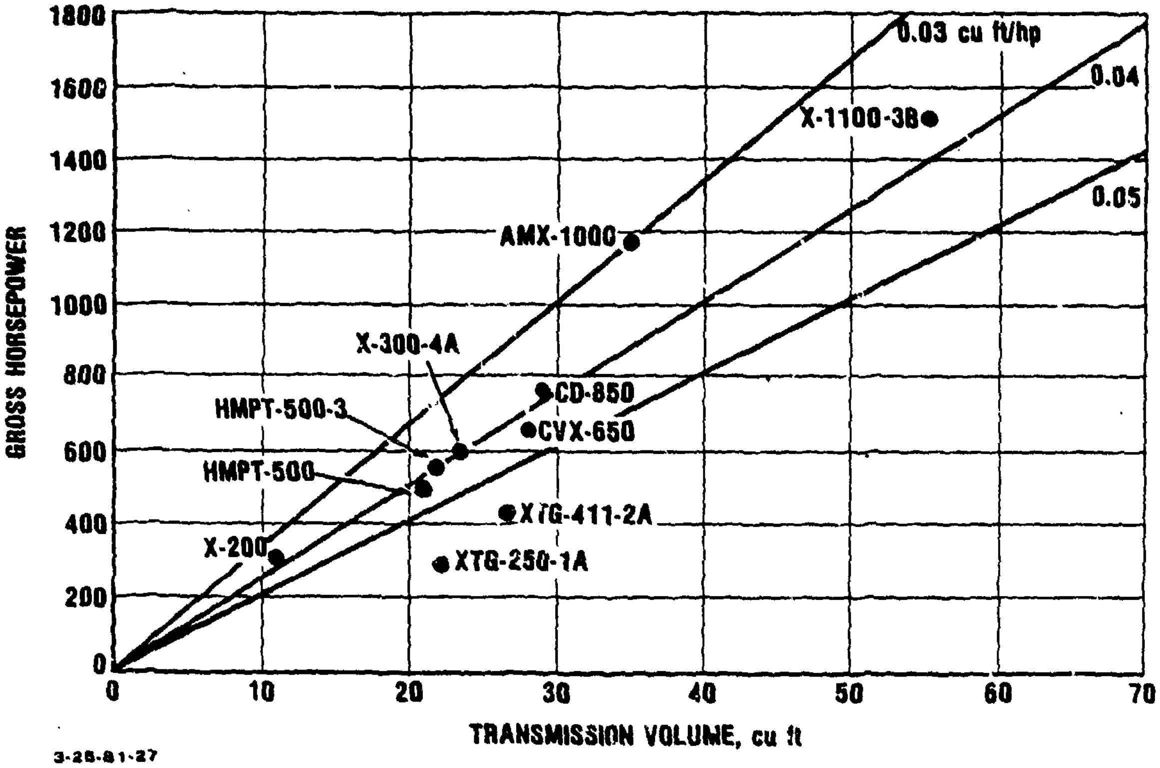
	Bare		Installed	
Vehicle/Transmission	Wt (lb)	Vol (ft^3)	Wt (lb)	Vol (ft^3)
M1/X-1100	4000	56	6770	98
M2/HMPT-500	1900	22	3300	43

The major part of the increments in installed over bare weights and volumes is due to inclusion of the final drive and an allocated portion of the cooling system. While these elements depend somewhat on the particular installation, one would expect to first order that proportionate differences between installed and bare weights and volumes would apply to other transmissions in the same class of vehicle.



3-25-81-28

FIGURE 7. Weights of bare transmissions (i.e., uninstalled) as a function of gross vehicle horsepower. The points marked MICV's refer to the versions of the HMPT-500 transmission. (Source: Data furnished by TACOM)



3-28-81-27

FIGURE 8. Volumes of bare transmissions as a function of gross vehicle horsepower. (Source: Data furnished by TACOM)

All the above transmissions contain hydraulic elements, and it is these that have the greatest influence on the overall efficiency (i.e., ratio of output power to input power) of the transmission. Gears typically have losses of about 1% per mesh,* and this is relatively independent of speed. In torque converters, on the other hand, efficiency varies inversely with torque ratio and reaches a maximum (of almost 90%) when the torque ratio is 1.2 or less (i.e., at high rotational speeds). The efficiency-speed characteristics of a torque converter can be varied considerably by blade design; selecting the best configuration is part of the overall transmission design optimization to meet given operating conditions. When the torque converter is combined with a planetary gear shifting assembly, as in the X series transmissions, the efficiency becomes a complicated function of the power level, as is shown in Fig. 9 (Ref. 25). Also shown in Fig. 9 is the output power/speed relationship for the CVX650. Though this transmission uses hydraulic pumps and motors instead of torque converters in the propulsion power path, the overall output level is not greatly different, which indicates that the loss of efficiency is compensated by the ability to operate the engine near its best output point. This can be seen by comparing Figs. 9a and 9b.

The baseline vehicles used in this study, i.e., the M1 and M2, use the latest hydrokinetic and hydromechanical transmissions. For these vehicles the representative power output at the sprocket was taken to be 76% of engine power. This reflects the power output shown in Fig. 9 corrected for the power used in cooling the transmission and the efficiency of the final drive (98%). Roughly half of the losses in the hydrokinetic transmission were found to be due to the torque converter, giving a representative power output of 87% of engine power if the torque converter were removed. This concept is being

---

*For spur gears the range is 0.5-0.75%; for spiral bevel gears the loss per mesh is about 1.5%.

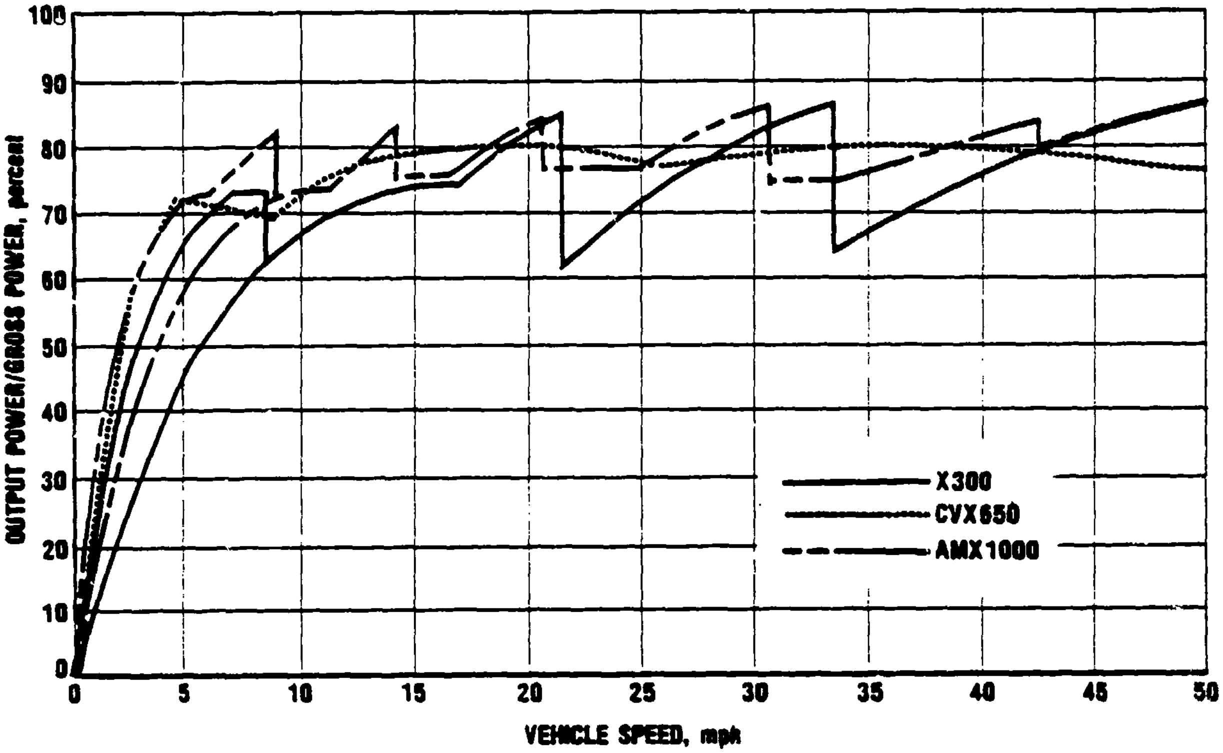


FIGURE 9a. Comparison of output powers for advanced transmissions as a function of vehicle speed. (Source: Personal communication, Detroit Diesel Allison)

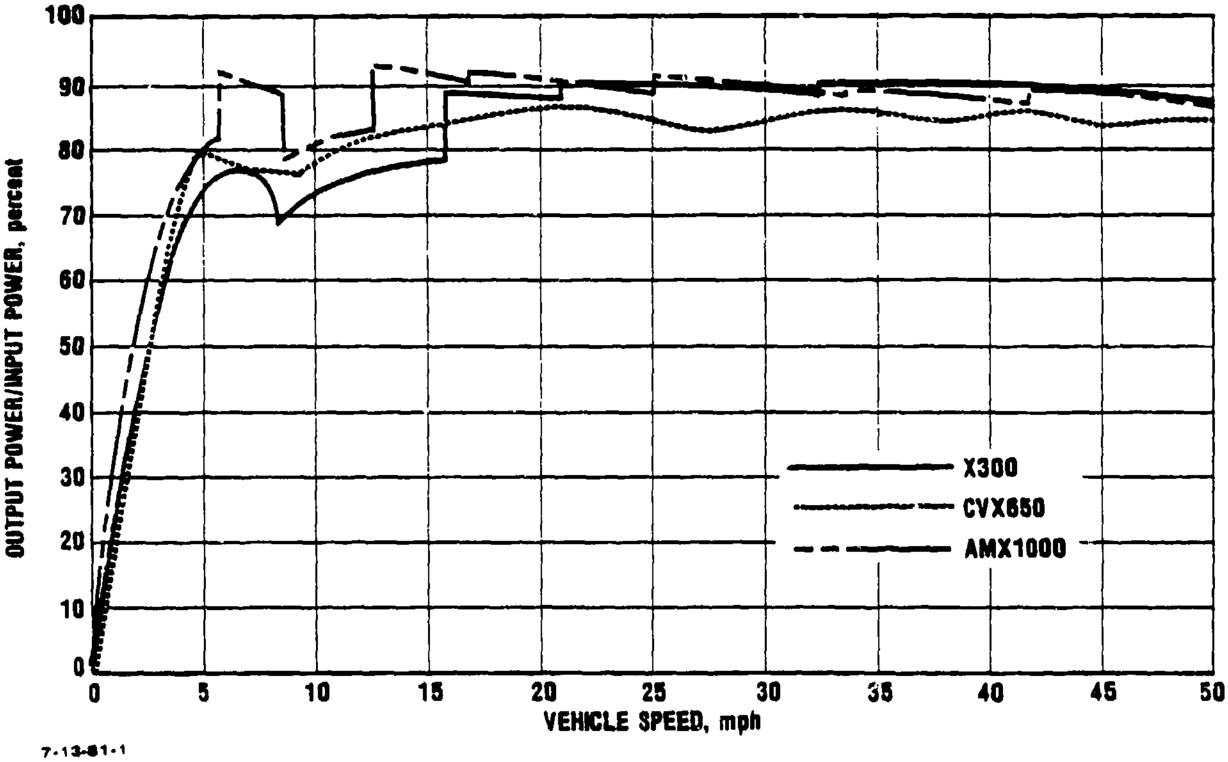


FIGURE 9b. Comparison of efficiencies for advanced transmissions as a function of vehicle speed. (Source: Personal communication, Detroit Diesel Allison)

tested in a TACOM demonstration program using the GT601 engine with a modified X300 transmission in a MICV chassis. In analyzing this installation Garrett arrived at sprocket power figures for the M2 similar to the ones established here, i.e., 75% of engine power for the overall transmission with the torque converter unlocked and 86% if the torque converter were removed (Ref. 21).

3. Potential for Future Improvements of Current Transmissions

The question to be addressed here is to what extent improvements in weight, size and efficiency of current transmissions can be expected from technology advances in the components. The possibilities inherent in different design concepts will be treated in the next section.

In a previous IDA study (Ref. 22) a simple model of a hydrokinetic transmission was used to evaluate the potential for technology advances in the components. The reference transmission was the X-1100, and the results are shown in Fig. 10, where the specific weight is based on the output power. For the "present technology" line the variation in size and efficiency was due to changing the size of torque converter. It was assumed that the gears had constant efficiency. The 1950s technology refers to the CD-850 transmission. The "potential limit" line was obtained by assuming that technology advances might ultimately reduce the losses in the torque converter by the amount indicated and that improved materials might ultimately reduce the size of the gears and housing. The potential limit line was intended to represent what was physically conceivable--not what could be achieved by foreseeable means. The R&D goals were thus set between the current technology and potential limit figures. The conclusion was that even if optimistic R&D goals were met, they would not achieve the percentage gains made in the past, i.e., in arriving at the X-1100 device.

This trend toward diminishing returns is evident in the advanced programs currently under way, i.e., the AMX1000 advanced

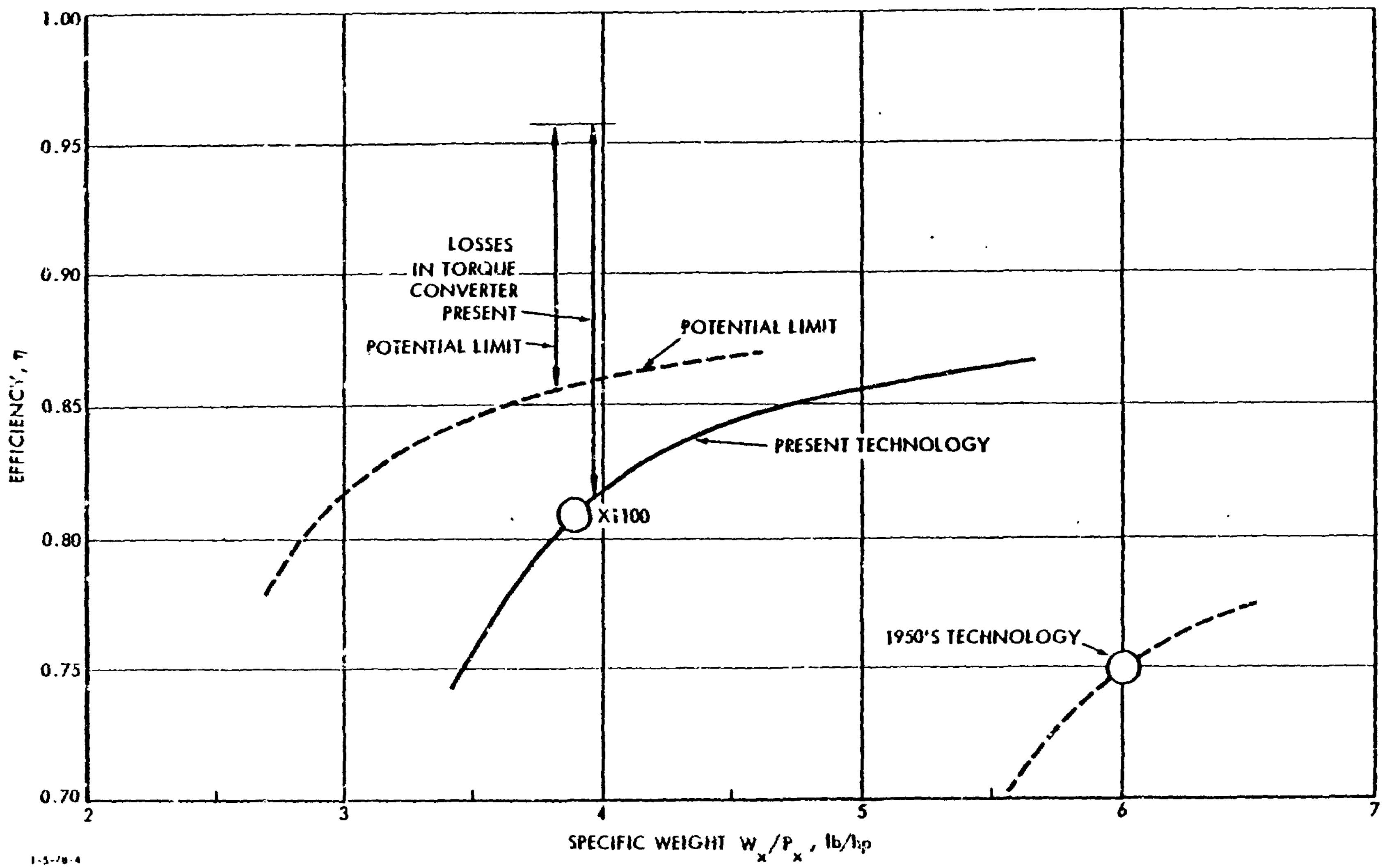


FIGURE 10. Estimated efficiency and specific weight characteristics of hydrokinetic transmissions.

hydrokinetic and the CVX650 advanced hydromechanical transmissions. The indications from Figs. 7-9 above are that only marginal improvements in size, weight or efficiency are projected. For our purposes here it is assumed that a 5% improvement in specific weight and a corresponding improvement in specific volume is possible. Of course, these new units do incorporate other features such as electronic controls, six speeds, retarders, etc., which improve other features of the transmission.

4. Alternate Transmission Concepts

As noted above, the potential for greater size and efficiency improvements in transmissions lies in different design concepts. Three concepts, none of them new, which appear to offer promise for significant impact on the size or efficiency of a tracked vehicle transmission are as follows:

1. Eliminate or greatly reduce the power transfer through the torque converter by using the power turbine of a gas turbine engine or a turbocompounded diesel as a hydraulic unit in the transmission input. The potential payoff would be a large increment in efficiency, i.e., from 76% to 87% as noted above, accompanied by a reduction of 10% in weight and volume.
2. Operate the propulsion power splitting and steering controls at higher speeds (lower torques). The payoffs would be potential reductions in gearing weight and better matching with the output of a gas turbine or high-speed diesel engine. An estimated 25% reduction in weight and volume would be a reasonable goal.
3. Use traction torque converters or electrical power conversion devices for steering control and/or main propulsion power. This concept is probably tied to the high speed input suggested in 2, above, since traction and electric devices compare more favorably in size and weight with hydraulic devices and gears

for power conversion at the lower torque levels inherent in the higher speed device. More detailed study is needed to assess the size and efficiency trade-offs in this concept.

With regard to the possibility of removing the torque converter, there is a current TACOM demonstration program which uses a gas turbine (the Garrett GT601) coupled to an X300 transmission with the torque converter removed, in an MICV chassis. The concept appears very powerful. It is estimated that the net sprocket horsepower can be increased about 11%* by removing the torque converter. The basic problem with this program is that it is funded at a level which assumes everything will go right the first time, which is unlikely. Some years ago a similar demonstration was done using the AGT600 engine and the X-700-T transmission, with inconclusive results (Ref. 26). Though the same problems may be unlikely to occur in the current demonstration, others should be anticipated and proper funding provided.

The possibility of eliminating the torque converter in a power train using a turbocompounded diesel has been previously examined (Ref. 27). The conclusion was that the torque converter could not be completely removed but the propulsion power through it could be greatly reduced in a differential compounding arrangement referred to here as a split-torque transmission.

D. POTENTIAL PAYOFFS OF ADVANCED PROPULSION SYSTEM OPTIONS

The previous estimates of the installed characteristics of various engine and transmission alternatives, in combination with the vehicle sensitivity factors estimated in Section II, permit an evaluation of their ultimate impact on vehicle cost and/or weight. These results are shown in Table 13, in terms of fractional reductions in vehicle life-cycle costs which could

---

*See discussion, p. 65.

TABLE 13. POTENTIAL PAYOFFS OF SOME ADVANCED PROPULSION SYSTEMS IN ARMORED VEHICLES

	Fractional Improvements in Vehicle Life-Cycle Cost	
	MBT	LCV
Diesel Engines		
VTA903	(.05)**	.10
VHO uprate	(.01)	.10
Near adiabatic	(.08)	.08
Adiabatic	.13	.19
Advanced diesel	.09	.15
Gas-Turbine Engines		
GT601	(.18)	.04
GT1801 Mk1	.10	.14
GT1801 Mk11	.15	.17
AGT800	.06	.12
Reheat cycle	.16	.20
Advanced gas turbine	.10	.15
Rotary Engine		
RC2-350	.03	.10
Transmissions		
Improved conventional (D, T, R)*	.02	.01
Improved w/o torque converter (T)	.08-.14	.06-.11
High-speed (T)	.12-.18	.09-.14
Split-torque (D, T, R)	.06-.10	.05-.08

---

*D denotes that the transmission is applicable to diesel engines; T, applicability to gas-turbine engines; R, applicability to rotary engines.

**Parentheses denote an adverse impact.

be achieved, for all of the alternatives considered. Results are shown for both LCV and MBT applications for all alternatives, by assuming that the specific characteristics (specific fuel consumption, specific weight, etc.) are applicable at either power level. It is realized of course that, for example, the GT1801 is not applicable to an LCV, nor would the characteristics of a scaled-down version be as favorable; nevertheless, the results for both applications serve to illustrate the range of payoffs which might be achieved for armored vehicles of different design characteristics. To a first approximation, the total payoff resulting from a particular engine/transmission combination can be obtained by adding the individual payoffs, provided of course that the engine and transmission are compatible.

The range of payoffs shown in Table 13 for various transmission options reflects the differences between possible design conditions which determine the installed power requirements. That is, the higher numbers in Table 13 are applicable if the installed power required is governed by a design condition in which a torque converter would not be locked up (as in low-speed hill-climbing), and the lower numbers are applicable if the installed power required is governed by a design condition in which a torque converter would be locked up (as in higher-speed acceleration).

The first observation to be made is that removing the torque converter from the transmission, or reducing its role, offers high payoffs in both applications; this single potential improvement offers payoffs which can be of the same magnitude as those offered by many of the advanced engines. In addition, for gas-turbine engines which can operate without a torque converter, the additional potential offered by high-speed operation is significant. Thus, the transmission is a high prospective payoff area indeed. An important corollary is that the engine and transmission should be considered as an optimized unit; for example, it seems evident that diesel engines and gas-turbine engines prefer different kinds of transmissions, and it is a penalty to both propulsion sytems to require the same transmission.

A second observation to be made concerning the results in Table 13 is that the payoffs offered by the reheat-cycle engine are not overwhelmingly greater than the payoffs offered by considerably less adventuresome gas-turbine engines. This in turn suggests that, in the nearer term at least, primary R&D efforts would be better placed on the lesser-risk alternatives.

The rotary engine currently under development offers payoffs comparable to the other near-term engines (the first two diesels and the first gas turbine in Table 13). Presumably some other potential improvements could also make an advanced version offer payoffs comparable to the other advanced engines. On the other hand, as a class, rotary engines do not appear to offer significant advantages over diesels and gas turbines.

The differences in payoffs for the MBT and LCV applications are of interest because they provide some indication of how the payoffs might change as a function of more specific vehicle design characteristics. The implication of the results in Table 13 is that although the four nearer-term engines offer substantial payoffs as compared to the present M2 configuration, the payoffs may decrease when compared to alternatives for a future combat vehicle which requires a higher power level and may perhaps be more heavily armored. The inference is that R&D efforts would be better placed on alternatives which offer payoffs in both applications, to provide to some degree for the uncertainty in future vehicle characteristics.

Finally, a more general observation is that there are advanced propulsion system alternatives which appear to offer high payoffs in combat vehicle applications. These payoffs are in the range of being equivalent to 25% of the vehicle life-cycle cost for either application, for appropriate combinations of engines and transmissions. Thus, propulsion systems for these applications have not yet reached the point of practical maturity.

E. SUITABLE R&D GOALS

The evaluation of potential payoffs of various alternative propulsion systems provides some basis for arriving at suitable goals for R&D programs in the propulsion area. Such goals should of course satisfy at least two criteria: (1) they should be technologically feasible, in that there should be a reasonable chance of attaining success within the resource and time constraints likely to be imposed, and (2) they should offer sufficient payoff to justify the investment necessary.

Some idea of the economics of the return on investment can be gained by a simple example. For an LCV, say, a 10% reduction in vehicle life-cycle cost for at total fleet of 25,000 vehicles amounts to approximately $2.2 billion over the life of the vehicles. This is of course a return in the future; if it is assumed that 7 years of technology-base effort will be required, followed by 7 years of full-scale engineering development, followed by 5 years of production, and that the vehicles have a 20-year life, then the full $2.2 billion will not be realized for 39 years. On this basis, assuming a discount rate of 5% (above the inflation rate), then the discounted value of this $2.2 billion is $530 million. If a technology-base investment of 10% of the discounted return is deemed prudent, in view of the various risks and uncertainties, then a discounted investment of $53 million would be justified. This translates into an annual technology-base investment of about $9 million for the next seven years. A similar example exists for main battle tanks. Although a variety of different assumptions in these examples could be made which would significantly affect the detailed numerical values, it seems reasonable to infer that R&D goals which offer 10%-15% reduction in combat vehicle life-cycle costs will easily justify expenditures of $10-15 million annually in technology-base efforts.

Of course, the payoffs offered by the fruits of technology-base efforts should be measured relative to those likely to be obtained in the absence of technology-base expenditures; if it is assumed that the latter amount to perhaps 5-10% of the vehicle life-cycle cost, then suitable R&D goals should offer 15-25% in vehicle life-cycle cost reductions relative to current systems to justify the investment.

As it happens, goals satisfying this criterion are consistent with some of the advanced propulsion system alternatives examined here. Specific goals will of course vary with the application and the power level. To simplify matters, goals appropriate to propulsion systems in the 800-hp class are considered which, if successfully achieved, would provide payoffs in the range of 20-25% in the LCV application and would also provide the necessary technological basis for achieving similar payoffs in the MBT application. Such goals are indicated in Table 14 and represent reasonable expectations for (1) diesel engines with characteristics in the range between the adiabatic diesel and the so-called advanced diesel, both in combination with a split-torque transmission; and (2) gas turbine engines with characteristics in the range between the AGT800 and the so-called advanced gas turbine, in combination with a transmission without a torque converter, perhaps operating at higher speeds. These goals should not be interpreted too rigidly, of course, particularly since the individual goals can be traded off among themselves (e.g., lower specific fuel consumption for higher specific weight) depending upon future developments. Nevertheless, they appear to represent reasonable targets from the standpoints of both technological possibility and adequate payoffs.

TABLE 14. SOME SUITABLE GOALS FOR PROPULSION SYSTEMS FOR ARMORED VEHICLES AT THE 800-HP LEVEL

	Diesel/ Split-Torque	Gas Turbine/ Mechanical
Engine (Bare)		
Specific fuel consumption @ 25% power, lb/hp-hr	.35	.42
Specific weight, lb/hp	2.2	2.2
Specific volume, ft^3/hp	.032	.033
Transmission (Bare)		
Representative efficiency	.87	.90
Specific weight, lb/hp	2.5	2.3
Specific volume, ft^3/hp	.033	.030

IV. R&D PROGRAM POSSIBILITIES

A. INTRODUCTION

The variety of alternative advanced propulsion systems, the nature of technology demonstration, and the uncertainties regarding specific applications permit consideration of many alternative technology-base programs. The selection of an appropriate program(s) depends strongly on the degree of interrelationship which exists between (1) advanced development (6.3A) activities and eventual application, (2) military development and commercial development, and (3) exploratory development (6.2) activities and advanced development activities, as well as on the more technical matters of (1) propulsion system types to be pursued, (2) appropriate goals, and (3) constituent component technology to be emphasized. Thus, in order to identify needed technology-base activities in a rational way, and to evaluate the extent of their differences with the current program, it is necessary to establish the degrees of these interrelationships.

1. Relationship Between Technology-Base Activities and Engineering Development

Ideally, the output of the technology-base activities is validated design information: a demonstration that the physical phenomena involved in the advanced technology are sufficiently well understood that the relevant characteristics can be reproduced in a range of specific component/system designs. In principle, then, exploratory development activities would consist of acquiring the necessary component information over a suitable range of parameters, and 6.3A advanced development activities would consist of characterizing and improving those interactions between components which are significant in the system environment. In particular, there would be no a priori need to demonstrate advanced technology in a complete system which is representative in great detail of an actual system.

Technology-base activities in propulsion systems have not yet conformed to this ideal picture. As a practical matter, in order to provide sufficient confidence to justify undertaking engineering development, it has been necessary to demonstrate reasonably satisfactory operation of a system (or at least separate operation of the engine and transmission) which very closely approximates the system proposed for engineering development. In some cases, this demonstration has been achieved through 6.3B advanced development activities; in other cases it has not. In any case, it still seems necessary for the 6.3A activities to demonstrate reasonably satisfactory operation of advanced engines and transmissions at power levels and in configurations which are not too dissimilar from those of an intended application; thus, 6.3A activities must be structured around such demonstrator configurations.

Such a program structure means, of course, that 6.3A activities will encompass component development activities; for example, not all components involved in a 6.3A engine will originate directly from 6.2 exploratory development efforts, and these components, although not necessarily representing advances over the demonstrated state of the art, must be developed. Conversely, not all exploratory development activities will be devoted to component goals consistent with a concurrent 6.3A program. The net result is a greater degree of independence between concurrent 6.2 and 6.3A programs than might be supposed; an appreciable portion of the 6.2 activities will be directed at more ambitious goals than 6.3A activities, and in any case should be directed at only the critical component areas rather than all component areas.

2. Focus on Power Level and Eventual Application

Unfortunately, the practical requirement of 6.3A system demonstration causes considerable difficulties in the timing of technology-base activities and in the selection of specific power levels on which to focus. As we have seen, the current estimates are for major new armored vehicles to enter production in 1994; inasmuch as about 5-7 years are required for full-scale engineering development of a propulsion system, a suitable demonstration must be available in the period 1987-89. If 2-3 years are allowed for a 6.3B program (or its equivalent), then the 6.3A demonstration--to provide sufficient confidence--must be completed in the period 1984-87; the earlier of these two dates allows very little time for relevant technology-base activities between now and then. This time pressure is alleviated somewhat by two factors: (1) plans for some 7-14 years in the future inevitably tend to be optimistic; and (2) the leverage of the propulsion system on these vehicles is so large that unless a substantially improved propulsion system has been demonstrated, new vehicle developments are unlikely to be undertaken. Nevertheless, the technology-base program must be reasonably responsive to future plans, and hence there is time pressure.

Given this time pressure, there is a tendency to begin, in the technology-base program, what amounts to the development of specific propulsion systems for these new vehicles. Such an approach has certain advantages, and is particularly appealing in the sense that it is difficult to question the relevance of technology-base activities to specific military goals. However, it has some significant disadvantages, in that the power level, and perhaps other propulsion system characteristics as well, must be specified within a very narrow range, and this is very difficult to do for vehicles which have not even reached the conceptual design stage. For example, the analysis here indicates probable power ranges of 500-900 hp for LCVs and

1000-1500 hp for MBTs, and, as pointed out, there are other views which require uniformly higher power levels; adding to this, say, the uncertainty regarding the future of the MBT, makes the selection of a suitably specific power level very difficult indeed. Thus, we believe that an approach of closely relating technology-base programs to specific characteristics of undesigned future vehicles is not the preferred one.

A more appropriate approach would seem to be to delay such specific decisions. It can be said with a reasonable degree of certainty, we believe, that major new armored vehicles requiring propulsion systems in the range of 500-1500 hp will enter production in the mid-to-late 1990s, with values in the lower part of the power range preferred (500 to 1100 hp, say). This means that there should be suitable 6.3A demonstrations of advanced propulsion systems in the mid-to-late 1980s which provide sufficient confidence to undertake 6.3B advanced development, or its equivalent, of more specific propulsion system configurations for specific vehicle concepts which will be identified at that time. Obviously, this implies that the requisite 6.3A programs be initiated without delay, but it does permit the selection of power level to be based largely on that which best demonstrates the propulsion system technology being pursued, as discussed below.

3. Military Development Versus Commercial Development

For engines other than those for MBT applications, there has been a tendency for the military to rely on commercial sources, either by purchasing purely commercial engines directly or by modifying them (generally by increasing the power output) for military uses. The chief argument in favor of such a policy has been one of decreased cost, and ample commercial engine models have been available in the past when horsepower requirements were well below 500 hp. Accordingly, one approach would be to continue this policy and focus technology-base efforts primarily on MBT power levels, with a modest effort devoted to techniques for modifying commercially available engines for LCVs.

The difficulties with this approach concern the availability of commercial engines, the confluence of military and commercial performance criteria, and the opportunities for modification. Above 500 hp, the number of commercial vehicular diesel engines is not great, and there are of course no commercially available vehicular gas turbines. The Garrett GT601 is intended for commercial truck application but has not as yet achieved that status. It has been a long-time dream of gas-turbine advocates to replace diesel engines in the commercial vehicular market, but this has not yet occurred. Thus, at the moment, the choice of diesels is limited, and the choice of gas turbines, or any other type of engine, is nonexistent.

Further, commercial performance criteria are not consistent with military ones; for example, specific volume and specific weight are of considerably less importance in commercial applications and, in the truck market particularly, the specific fuel consumption at very low power levels is also of lesser concern. Hence it is not clear that commercial engines would produce sufficient payoffs in military applications, even with their favorable price differential, to justify their selection over purely military engines. This point is exemplified by the VTA903, which, as we have seen, does not compare favorably with advanced diesels that presumably could have been developed for the M2/3 application. Evidence of similar difficulties can be observed in the GT601; it has a T-shaped frontal cross section, which is of course well adapted to trucks but leads to a substantially larger envelope volume than is desirable for armored vehicles.

Finally, there are limitations on the types of modifications that can be implemented on commercial engines. In particular, they cannot be "scaled down" nor can their normal geometry be changed; basically, only modifications to increase power output can be undertaken.

Although a case could possibly be made for reliance on adaptation of commercial diesel engines for LCVs, we do not believe that such adaptations are likely to compare favorably with purely military designs; and we do not believe any case can be made for relying on adaptations of commercial engines of any other type for LCVs. Thus, on balance, we believe that the technology-base efforts should be directed primarily toward purely military engines for armored vehicles of any kind.

4. Type of Propulsion System

The analysis here has indicated advanced propulsion system alternatives incorporating two basic engine types--diesel and gas turbine--and corresponding transmissions which offer substantial and essentially equivalent payoffs in armored vehicles ranging from LCVs to MBTs; further, with but little extrapolation, a rotary engine could also offer equivalent payoffs. An obvious issue is to what extent the technology-base program should include all three alternatives.

Briefly, the arguments for diesel systems are that they are inherently cheaper, that they have a substantial commercial vehicular base, that their specific fuel consumption at very low power levels--around idle--is superior, and that there are some power levels under 2000 hp at which they are superior to gas turbines. The major argument against the diesel is of the nature that its basic technology is well developed and that further improvements arise primarily from incorporating more turbine elements (i.e., turbocharging, turbocompounding, hyperbar); thus it relies on turbine technology and will hence eventually defer to it.

Similarly, arguments in favor of the gas turbine are that the power level at which gas turbines are superior to diesels becomes lower as their technology improves, that their maintenance characteristics are superior, that they are more adaptable to improved transmissions, and that inasmuch as the turbine is already in the MBT, further advantages would accrue by powering all armored vehicles by gas turbines. On the other hand, it can be argued that gas turbines are inherently more expensive than diesels, and that their fuel consumption at very low power levels is excessive.

The major argument in favor of the rotary engine is that it provides for a volumetric flow capacity intermediate between the diesel and gas turbine, which is useful precisely in the horsepower range of interest here, and thus it eliminates the size and weight difficulties of the diesel while retaining the diesel's fuel consumption characteristics. The major argument against the rotary is that its sealing, combustion, and heat transfer problems are such that it will not be able to achieve the forecast performance levels reliably, as evidenced by the significant amount of commercial R&D resources that have been expended on the engine without producing a suitable commercial product.

All of the above arguments are to significant degrees true. However, the fact remains that we find the advanced diesel and gas-turbine alternatives, with respectively suitable transmissions, to be competitive, we find the rotary engine to be less so, and we are guided by these findings. With respect to the rotary engine, it seems clear that even if the current development effort is successful, it will be necessary to turbocharge the engine if it is to be competitive with the others and, given this requirement, the fundamental advantage over other engines disappears. That is, with turbocharging, diesels and gas turbines cover the power range completely, and the rotary engine has little to offer. Accordingly, we see no need for significant technology-base emphasis on the rotary engine.

With respect to the diesel versus the gas turbine, their relative merits have been debated warmly for the past several years, specifically with regard to the M1. Our view is that the primary reason the issues remain unsettled is that there is little to choose between them--now or in the immediately foreseeable future. The matter of high fuel consumption at idle conditions in gas turbines seems to be a popular one currently; however, we believe that if the specific fuel consumption of a gas turbine at 25% power is in the range of 0.40-0.45 lb/hp-hr, as seems reasonable, the differences in idle fuel flow between the two types of engines will not have a significant military impact. There does seem to be some appeal to having all armored vehicles powered by the same type of engine, inasmuch as this would inevitably ease those operation and maintenance difficulties caused by different engine types; however, this does not seem to be a decision which should be dictated by the technology-base program. Further, the uncertainties in future performance levels are sufficiently great that substantive elimination of either the diesel or the gas turbine from the technology-base program would jeopardize the chances of obtaining the magnitude of performance improvement which could reasonably be expected. Thus, we think that the technology-base program should include major efforts directed at both diesels and gas turbines.

To recapitulate briefly, we conclude that: (1) 6.3A programs aimed at suitable propulsion system technology demonstrations in the mid-to-late 1980s are needed now; (2) these efforts need not be related specifically to either LCVs or MBTs at this time, but rather to armored vehicles as a whole; (3) the power range of interest is 500-1500 hp, with the lower end probably preferred; (4) technology-base programs should be directed toward military engines rather than commercial derivatives; and (5) major emphasis should be given to both diesels and gas turbines and their respectively suitable transmissions. The nature of the technology-base effort needed is indicated in the following paragraphs.

B. DIESEL ENGINE/SPLIT-TORQUE TRANSMISSION SYSTEM

The primary need is a 6.3A program to provide a demonstration of basic propulsion system technology for the goals indicated previously,

	Engine	Transmission
Efficiency	0.35 (sfc @ 25%)	0.87 (representative)
Specific weight, lb/ghp	2.2	2.5
Specific volume, ft^3/ghp	.032	.033

with manufacturing and O&M costs at or below the levels of current military diesel systems. The appropriate power level seems to us to be in the vicinity of 600 hp, for three reasons. First, future light, lightly armored combat vehicles are likely to have power requirements close to the low end of the range 500-900 hp; second, the scaling laws of diesels are such that a demonstration at 600 hp permits a reasonable extrapolation to the performance achievable at higher power levels; and third, the lower horsepower levels are more favorable to diesels than to gas turbines, and therefore constitute more likely applications for diesels.

With respect to the engine, it appears that it should incorporate some or all of the following features: high turbocharging; turbocompounding; adiabatic or quasi-adiabatic operation; and high piston speeds and rotational speeds. The particular choices and tradeoffs among these features would seem to be best made by prospective engine manufacturers, with of course closer integration with the transmission in mind. A key ingredient, however, is that the configuration or configurations should incorporate as much current state-of-the-art or minimum-risk technology as is consistent with achieving the program goals; in this connection, we are not convinced that the widespread use of ceramic materials satisfies this criterion, and we are certain that some attention should be devoted to high-temperature metallic materials. Given the various alternatives, we conclude that two competing engine-technology demonstration programs would seem to be appropriate.

With respect to the transmission, there seems to be no feasible way to eliminate a hydraulic element to accommodate the slip necessary at very low power levels, while retaining automatic operation; there do appear to be ways to reduce the power which such an element must transmit. There are also advantages to be gained from matching the higher rotational speeds of an advanced engine. These matters would seem to be best resolved by prospective transmission manufacturers, working with the engine developers.

The needs at the exploratory development (6.2) level are a little less clear. With respect to engines, the critical areas, present and future, appear to be: (1) improving the response of turbocharged systems; (2) improved cylinder breathing, fuel injection, and combustion associated with higher piston and rotational speeds; (3) better materials and improved cooling/insulation schemes associated with adiabatic or quasi-adiabatic operation; and (4) improved lubrication associated with higher piston speeds. The first area could be handled largely by appropriate component work, properly integrated with similar needed activities for gas-turbine engines; the latter three areas could be handled by appropriate single-cylinder work. With respect to transmissions, it is not clear that any advanced component work can be identified.

C. GAS-TURBINE ENGINE/MECHANICAL TRANSMISSION SYSTEM

The primary need is a 6.3A program to provide a demonstration of basic propulsion system technology for the goals indicated previously,

	Engine	Transmission
Efficiency	0.42 (sfc @ 25%)	0.90 (representative)
Specific weight, lb/ghp	2.2	2.3
Specific volume, lb/ghp	.033	.030

with manufacturing and O&M costs at or below the levels of current gas-turbine systems. The appropriate power level seems to us to be in the vicinity of 800-900 hp, for three reasons. First, future heavily armored vehicles are likely to have power requirements close to the low end of the range 500-900 hp; second, the scaling laws of gas turbines are such that a demonstration at 800-900 hp permits a reasonable extrapolation to the performance which is achievable at higher power levels of possible interest, and also to lower power levels in the 600-700 hp range; and third, the higher horsepower levels are more favorable to gas turbines than to diesels and therefore constitute more likely applications for gas turbines.

With respect to the engine, which must be recuperated, it should contain the following features in various degrees: (1) a turbine inlet temperature in the 2200-2300°F range, with minimum cooling; (2) a high-effectiveness recuperator; (3) variable geometry in both turbine and compressor stages; and (4) improved air filtration. Again, specific choices and tradeoffs among these features would seem to be best made by prospective engine manufacturers, in conjunction with transmission integration considerations. Two key ingredients are, however, that the configuration or configurations should provide insofar as possible features which are applicable to both lower and higher power engines, and as with diesels, these configurations should incorporate as much current state-of-the-art or minimum-risk technology as is consistent with achieving the program goals. In the latter context, the widespread use of ceramic materials, such as that proposed for the reheat-cycle engine, is not suitable at this time; further, it is not clear that the reheat-cycle offers significant advantages over the conventional recuperated engine at the same basic technology levels. Given the choices available, it again seems that two competing engine-technology demonstration programs would be appropriate.

With respect to the transmission, emphasis should be given to eliminating the hydraulic element entirely and to taking advantage of the inherently higher output speeds of gas turbines. Again, specific choices relating to these matters would seem to be best resolved by prospective transmission manufacturers working with the engine developers.

The engine needs at the exploratory development (6.2) level are primarily those directed at the unique features of vehicular recuperated gas turbines, as opposed to other types of turbines. Specifically, effort is needed on (1) high-temperature recuperators incorporating improved high-temperature materials such as nickel-based superalloys and dispersion-strengthened superalloys; (2) high-inlet-temperature combustors incorporating dispersion-strengthened superalloys or similar improved materials; (3) improved flow range capabilities of variable-geometry components; and (4) compact air-filtration systems. Effort associated with more conventional compressor and turbine performance and higher turbine temperature capabilities seems to be best left to other gas-turbine technology-base programs. With respect to transmissions, it is again not clear that any needed advanced component work can be identified.

D. THE CURRENT TACOM TECHNOLOGY-BASE PROGRAM

The current TACOM technology-base program is based on an engine acquisition strategy of (Ref. 14): relying purely on commercial engines at power levels below 500 hp; considering either modified commercial engines or specific military designs for power levels between 500 and 1000 hp; and relying exclusively on military designs at power levels greater than 1000 hp. In general, we think that this strategy is sound; the only area of disagreement is in the 500-1000 hp range, where, for reasons indicated earlier, we think that little emphasis should be given to modification of commercial engines.

The specific goals for propulsion systems are given by TACOM as follows (Ref. 14), with our suggested goals in parentheses:

	TACOM	Present Analysis
Engine		
Sfc, lb/hp-hr	<.36 (at max power)	.32-.42 (at 25% power)
Specific weight, lb/hp	2.4	2.2
Specific volume, ft^3/hp	.033	.032-.033
Transmission		
Representative efficiency	--	.87-.90
Specific weight, lb/hp	3.25	2.3-2.5
Specific volume, ft^3/hp	.029	.033-.035

As can be observed, there is substantial agreement in goals for engine specific weight and volume; the engine sfc goals are not necessarily inconsistent, but as stated earlier, the emphasis appears to be more proper at representative part-load conditions. On the other hand, the transmission goals are substantially at variance; in particular, we think that efficiency and specific weight improvements are both achievable and desirable. Thus, more emphasis on integrated engine and transmission systems would seem to be necessary.

More substantive aspects of the TACOM program are somewhat difficult to address, due primarily to the fact that the initial appropriation of 6.3A funds for FY81 consisted entirely of $1.56 million for the CVX-650 transmission; no other 6.3A activities related to engines and transmissions were funded. To provide some basis for evaluation, the planned TACOM technology-base program for FY82-86 related to engines and transmissions is shown in Table 15 (Refs. 28, 29).

With respect to 6.3A programs for engines, the major efforts are apparently the adiabatic diesel and the advanced MBT engine. The adiabatic diesel includes the demonstration of a

TABLE 15. PLANNED TACOM TECHNOLOGY-BASE PROGRAM FOR ENGINES AND TRANSMISSIONS, FY 82-86 ($1000)

	Fiscal Year				
	1982	1983	1984	1985	1986
Diesel Engines	7,237	7,400	6,347	6,845	6,510
Adiabatic diesel (6.3A)	(4,800)	(6,000)	(4,947)	(4,445)	(2,356)
Advanced diesel (6.3A)	(1,887)	(0)	(0)	(0)	(0)
Adiabatic technology (6.2)	(550)	(1,400)	(1,400)	(2,400)	(4,154)
Gas Turbine Engines	3,041	7,251	9,765	11,218	8,678
AGT-1500 (6.3A)	(0)	(2,200)	(1,000)	(0)	(0)
*Advanced MBT engine (6.3A)	(1,200)	(3,321)	(7,390)	(9,518)	(7,578)
Turbine air cleaner (6.3A)	(720)	(630)	(850)	(850)	(500)
Advanced air filtration (6.2)	(600)	(100)	(100)	(100)	(100)
Advanced *turbine components* (6.2)	(521)	(1,000)	(425)	(750)	(500)
Transmissions	2,778	5,599	5,299	5,428	5,901
CVX-650 (6.3A)	(900)	(780)	(0)	(0)	(0)
AMX-1000 (6.3A)	(878)	(2,319)	(2,049)	(1,000)	(0)
Component development (6.3A)	(500)	(1,000)	(500)	(928)	(1,000)
Advanced turbine transmission (6.3A)	(500)	(1,000)	(1,250)	(2,000)	(2,401)
Other	(0)	(500)	(1,500)	(1,500)	(2,500)
Alternate fuel concepts	2,739	3,451	2,277	2,077	2,300
Other	1,672	1,590	2,558	1,370	1,600
Total	17,467	25,291	26,246	26,968	24,989

---

*The advanced MBT engine could be a diesel, also.

250-hp engine in a truck, and the demonstration of a 750-hp engine and one other power level in a vehicle. The advanced MBT engine is aimed at a 1500-1800 hp demonstrator engine. The favored concepts appear to be an adiabatic engine using ceramic components and the reheat-cycle gas turbine. As discussed earlier, some reorientation would appear to be desirable: lower power levels for the gas turbine; more emphasis on engine-technology demonstration rather than prototype engine development; more emphasis on a high-temperature metallic diesel alternative; and a focus on the recuperated gas-turbine rather than the reheat-cycle engine. The planned levels of funding reflect, in our view, the emphasis on prototype engine development, and they would be more than adequate for two competitive diesel programs and two competitive turbine programs of the engine-technology-demonstration type.

The 6.2 programs for engines emphasize, in the case of diesels, advanced turbomachinery, programmable fuel injection, friction reduction by elimination of piston rings and use of ceramic bearings, high-temperature material, thermal barrier coatings, and an integrated control system. All of these areas merit attention; in addition, some effort on the problems associated with high-speed operation would be beneficial.

In the case of gas turbines, the planned 6.2 programs emphasize advanced recuperators, reheat combustors, intercoolers, fuel control, high-temperature (2500°F TIT) components including combustor, turbine nozzle, and a radial inflow turbine rotor, and thermal barrier coatings. It seems that the effort devoted to components of the reheat-cycle engine is overemphasized; a better use of the resources would be in recuperator and variable-geometry alternatives.

With respect to 6.3A programs for transmissions, the efforts devoted to the CVX-650 and the AMX-1000 have previously been discussed. The planned activity for the advanced turbine transmission is not known to us in detail; we hope it will include effort devoted to a high-speed mechanical transmission closely integrated with the relevant 6.3A gas-turbine efforts. The most noticeable lack in the planned transmission program is any effort devoted to a split-torque transmission suitable for the diesel engines at which the 6.3A efforts are directed; it appears that the resources planned for the AMX-1000 could be redirected for this purpose.

With respect to the program for alternate fuels concepts, the details are not known to us. However, one objective was stated to be to provide multifuel capability for "a wide range of hydrocarbon fuels--from gasoline to diesel, including shale-oil or coal-derived fuels, with a wide spread of octane and cetane tolerance." As pointed out above, the cost/benefits tradeoff on multifuel capability drops off rapidly as the multifuel distillate range is broadened. There does not seem to be any basis for the wide range specified above. In our view the multifuel range should be limited and the R&D targeted at the limited engine modifications needed to accommodate the narrower range of fuels.

REFERENCES

1. Department of Defense, Sustainability Study Draft Final Report, Volume 3, March 1979 (SECRET/NOFORN).

2. Department of the Army, The Army Program Objective Memorandum FY 82-86, Annex Q: Extended Planning Annex (U), 31 October 1980 (SECRET).

3. Various undated viewgraphs received from TACOM, February 1981.

4. R.M. Ogorkiewicz, "The U.S. Armoured Combat Vehicle Technology Program," International Defense Review, pp. 811-815, May 1979.

5. USARADCOM, Ballistic Research Laboratory, Mobility and Armor Protection Trade-Off (U), C. Masaitis, G. Francis, V. Woodward, Memorandum Report ARBRL-MR-02933, July 1979 (CONFIDENTIAL).

6. O.C. Decker and E.N. Petrick, "Component Development for Future Combat Vehicles," Journal of Defense Research, Special Issue 79-1, pp. 169-194, January 1980 (UNCLASSIFIED).

7. F.L. Bagby and C.D. Bradley, "Advanced Systems Concepts (U)," Journal of Defense Research, Special Issue 79-1, pp. 245-290, January 1980 (SECRET/NOFORN).

8. U.S. Army Tank-Automotive Research and Development Command, Armored Combat Vehicle Development Plan (U), December 1978 (CONFIDENTIAL).

9. Institute for Defense Analyses, DOD Energy R&D, Part II: Military Fuel Options--Performance and R&D Implications, IDA Paper P-1116, F.R. Riddell, R.C. Oliver and R.E. Reichenbach, March 1977.

10. U.S. Army Tank-Automotive Research and Development Command, Study on Up-Power of M60 Tank, 28 January 1977.

11. U.S. Army Materiel Development and Readiness Command, Foreign Science and Technology Center, Automotive Engine

Technology - Foreign, M.S. Mingledorff and S.J. Thompson, DST-1850S-402-77-Chg 1, 22 October 1979.

12. R.M. Ogorkiewicz, "Gas Turbines or Diesels for Tanks?," International Defense Review, pp. 913-916, June 1978.

13. Motoren-und-Turbinen-Union Friedrichshafen GMBH, High-Performance Diesel Engines for Armoured Vehicles, Undated brochure.

14. Various undated viewgraphs received from TACOM, February 1981.

15. Institute for Defense Analyses, Survey of Advanced Propulsion Systems for Surface Vehicles, IDA Paper P-1073, F.R. Riddell, January 1975.

16. U.S. Army Tank-Automotive Research and Development Command, Development of an Adiabatic Diesel Engine, R. Kamo et al, Technical Report 12448, March 1979.

17. U.S. Army Tank-Automotive Research and Development Command, Propulsion Systems Requirements Study for Armored Combat Vehicles, C.A. Moses, Technical Report 12447, June 1979.

18. National Aeronautics and Space Administration, 150 and 300 kW Lightweight Diesel Aircraft Engine Design Study, A.P. Brouwers, NASA CR-3260, April 1980.

19. AVCO/Lycoming Division, private communication, July 1980.

20. The Garrett Corporation, A New Turbine Engine for Heavy Military Tracked Vehicles, Brochure, Revision 1, May 1979.

21. The Garrett Corporation, Gas Turbine Power for Infantry Fighting Vehicles, Annotated briefing document, May 1980.

22. Institute for Defense Analyses, Technology Assessment of Advanced Propulsion Systems for Some Classes of Combat Vehicles; Volume I: Summary and Main Text; Volume II: Appendices A-F; Volume III: Appendices G-M, IDA Paper P-1278, F.R. Riddell and D.M. Dix, September 1978.

23. U.S. Army Tank-Automotive Command, Tracked Vehicle Gas Turbine Engine Combined Programs, Volume 1, Engine Systems Studies, S.W. Mitnik, Technical Report 12141, March 1976.

24. Society of Automotive Engineers, The Evolution of Power Trains and Steering in High Speed Military Track Laying Vehicles, Edward Hamparian, SAE Paper 670726, September 1967.

25. Descriptive material for the AMX-1000 Program prepared by Allison Division of General Motors Corporation.

26. General Motors Corporation, Allison Division, Vehicle Performance Comparison of X-700 Series Power Trains, Report on Contract No. DA-33-008-AMC-327(T), 31 January 1967.

27. TARADCOM, Diesel Component Technology--Variable Area Turbocharger--Differential Compounding, Technical Report No. 12410, September 1978.

28. U.S. Army Tank-Automotive Command, TACOM 6.3/6.4/6.5 Project Listing, 1 December 1980.

29. U.S. Army Tank-Automotive Command, Tank-Automotive Technology, 1L182601AH91, PE 6.26.01A, 4 November 1980.

APPENDIX A

RELATIONSHIP OF GROUND VEHICLE CHARACTERISTICS TO PROPULSION SYSTEM CHARACTERISTICS

CONTENTS

APPENDIX A

RELATIONSHIP OF GROUND VEHICLE CHARACTERISTICS TO PROPULSION SYSTEM CHARACTERISTICS

In order to evaluate the utility, or payoff, of various propulsion system improvements, an analysis is needed which provides a quantitative, first-order view of the impact of such improvements on the cost, size, and/or performance characteristics of the overall vehicle. Such an analysis is developed here; its essential features are identical to those of an analysis developed previously in Ref. A-1.

A. VEHICLE PERFORMANCE AND COST MODELS

1. Vehicle Performance

A ground vehicle is defined here to consist of only five elements: payload, propulsion system, fuel, structure, and suspension. In an armored vehicle, the first three elements are assumed to be contained within the armored volume. The gross vehicle weight is accordingly

$$W_v = W_\ell + W_{ps} + W_f + W_s + W_{su} \quad , \qquad \text{(A-1)}$$

where W_v = gross vehicle weight
W_ℓ = payload weight
W_{ps} = propulsion system weight
W_f = fuel weight
W_s = structural weight
W_{su} = suspension weight.

The payload weight is considered a vehicle performance characteristic here, and the remainder of the analysis consists of relating the weight of the other elements to other vehicle performance characteristics, vehicle design characteristics, and/or propulsion system performance characteristics.

The structural weight, which by definition includes armor, is considered to consist of two parts: that necessary to support the weight of the payload, propulsion system, and fuel; and that necessary to provide and support any required armor protection. Thus, one obtains

$$W_s = \alpha(W_\ell + W_{ps} + W_f) + \beta(\nabla_\ell + \nabla_{ps} + \nabla_f) \quad , \qquad \text{(A-2)}$$

where ∇_i is the volume of the ith element, and α and β are considered to be vehicle design characteristics. In principle, of course, the weight of armor protection should be proportional to the 2/3 power of the enclosed volume for geometrically similar vehicles; for simplicity, the linear form is used here, which will tend to overestimate somewhat the structural weight of larger vehicles and underestimate somewhat the structural weight of smaller vehicles.

The weight of the suspension system, which by definition includes the tracks or wheels as appropriate, is assumed to be proportional to the weight required to be supported:

$$W_{su} = \left(\frac{W_{su}}{W_v}\right) W_v \quad , \qquad \text{(A-3)}$$

where (W_{su}/W_v) is considered a design characteristic of the vehicle.

The fuel weight is based on the assumption of a single representative operating condition:

$$W_f = \overline{D} \cdot \overline{V} \cdot \overline{SFC} \cdot \frac{R}{\overline{V}}^{*} \quad , \tag{A-4}$$

$$W_f = \frac{\overline{SFC}\ R}{(W_v/\overline{D})} W_v \quad , \tag{A-5}$$

where $\overline{D}$ = average vehicle drag (= average vehicle thrust)
$\overline{V}$ = average vehicle speed
$\overline{SFC}$ = average specific fuel consumption, based on delivered power ($\overline{D} \cdot \overline{V}$)
R = vehicle range.

Here the weight-to-drag ratio of the vehicle is considered a design characteristic, and the specific fuel consumption a propulsion system characteristic. It is to be noted that $\overline{SFC}$ is based on delivered power, and is related to the more familiar sfc based on engine output by

$$\overline{SFC} = \frac{sfc}{\eta_x \eta_t} \quad ,$$

where η_x is the transmission efficiency and η_t is the thruster efficiency at representative cruise conditions. The fuel weight could equally well be represented by

$$W_f = \frac{(hp\text{-}hrs)_{cruise}}{W_v} \overline{SFC}\ W_v \quad ,$$

where $(hp\text{-}hrs)_{cruise}$ defines the combination of thrust power and endurance needed to provide the desired range, in which case $(hp\text{-}hrs)_{cruise}/W_v$ would be considered a vehicle performance characteristic.

---

*If $\overline{D}$ is in pounds, R in miles, and $\overline{SFC}$ in lb/hr/hp, then W_f = .00267 RD $\overline{SFC}$ pounds.

The weight of the propulsion system, which by definition includes the engine, transmission, and final drive, can be written as

$$W_{ps} = (P_{max}/W_v)(W_{ps}/P_{max})\, W_v \quad , \qquad \text{(A-6)}$$

where P_{max} is the maximum delivered power. Here, (P_{max}/W_v) is considered a vehicle performance characteristic (e.g., delivered horsepower/ton), and (W_{ps}/P_{max}) is considered a propulsion system performance characteristic (i.e., the specific weight based on delivered power). As was the case with specific fuel consumption, the specific weight of the propulsion system is related to the more familiar specific weights of the constituents by

$$\left(\frac{W_{ps}}{P_{max}}\right) = \frac{w_e}{\eta_x \eta_t} + \frac{w_x}{\eta_t} \quad , \qquad \text{(A-7)}$$

where w_e is the specific weight of the installed engine based on engine output power, w_x is the specific weight of the installed transmission (including final drive) based on transmission output power, and η_x, η_t are the transmission and thruster efficiencies at representative maximum power condition.

Combining Eqs. A-1, A-2, A-3, A-5, and A-6 then produces the entire vehicle performance model used here:

$$W_v = \frac{\left(1 + \alpha + \frac{\beta}{\rho_\ell}\right) W_\ell}{1 - \left(\frac{W_{su}}{W_v}\right) - \left(1 + \alpha + \frac{\beta}{\rho_{ps}}\right)\left(\frac{P_{max}}{W_v}\right)\left(\frac{W_{ps}}{P_{max}}\right) - \left(1 + \alpha + \frac{\beta}{\rho_{pf}}\right)\frac{\overline{SFC}\ R}{(W_v/D)}} \quad , \qquad \text{(A-8)}$$

where appropriate densities have been introduced, i.e.,

$$\rho_\ell = \nabla_\ell / W_\ell$$

$$\rho_f = \nabla_f / W_f$$

$$\rho_{ps} = \nabla_{ps} / W_{ps} = \frac{(\nabla_{ps}/P_{max})}{(W_{ps}/P_{max})} \quad .$$

This relationship enables the total vehicle weight to be estimated for specified vehicle performance characteristics $[W_\ell, \rho_\ell, (P_{max}/W_v), R]$ from a knowledge of vehicle design characteristics $[(W_{su}/W_v), \alpha, \beta, (W_v/D)]$ and propulsion system characteristics $[(W_{ps}/P_{max}), \rho_{ps}$ or $(\nabla_{ps}/P_{max}), \overline{SFC}, \rho_f]$. All that remains is a determination of the values of the vehicle design characteristics representative of various classes of vehicles; this is based on data for actual vehicles and is accomplished in Section B below.

2. Vehicle Costs

Costs have three elements of interest: manufacturing, operation and maintenance, and fuel. The interest here is in identifying and estimating those costs which depend upon the characteristics of the propulsion system either directly, or indirectly through the dependence of vehicle characteristics on propulsion system characteristics. Thus, the payload costs are excluded. The vehicle life-cycle cost is then defined as

$$\$_L = \$_p + \$_{OM} + \$_f \quad . \tag{A-9}$$

The unit manufacturing cost,* $\$_p$, is considered to be a linear function of the empty vehicle weight (the gross weight

---

*In the parlance of cost analysis, the unit manufacturing cost as defined here includes only initial investment and recurring production costs and excludes costs associated with initial spares, training, engineering changes and the like; typically, manufacturing costs are of the order of 85% of the total investment costs.

less the weight of payload and fuel) and the maximum delivered power, P_{max}:

$$\$_P = \left(\frac{\$}{W}\right)\left(W_v - W_\ell - W_f\right) + \left(\frac{\$}{P}\right) P_{max} \quad . \tag{A-10}$$

In turn, the costs which are power dependent are assumed to consist of the propulsion system cost and a structural cost which is power dependent:

$$\$_P = \left(\frac{\$}{W}\right)\left(W_v - W_\ell - W_f\right) + \left[\left(\frac{\$}{P}\right)_S + \left(\frac{\$}{P}\right)_{ps}\right] P_{max} \quad . \tag{A-11}$$

The manufacturing costs are thus determined by two vehicle cost characteristics--the structural cost factor associated with weight, ($/W), and the structural cost factor associated with power $(\$/P)_S$--and one propulsion system cost characteristic--the proulsion system cost factor $(\$/P)_{ps}$. In actuality, the latter cost factor depends upon other characteritics of the propulsion system, simply because the cost per unit of maximum engine power is a better cost characteristic of a propulsion system. The propulsion system cost factor can be expressed as

$$\left(\frac{\$}{P}\right)_{ps} = \frac{1}{\eta_x \eta_t}\left(\frac{P_e}{P_{inst}}\right)\left(\frac{\$}{P_e}\right)_{ps} \quad , \tag{A-12}$$

where η_x and η_t are the transmission and thruster efficiencies at representative maximum power conditions, (P_e/P_{inst}) is the ratio of maximum engine-power output to that delivered to the transmission (including any power required for cooling the latter), and $(\$/P_e)_{ps}$ is the propulsion system cost factor based on maximum engine power. This distinction is only important, however, in the subsequent considerations of the dependence of costs on the characteristics of the individual components of the propulsion system.

Operation and maintenance costs (excluding fuel costs) are assumed to be directly proportional to manufacturing costs and are considered separately for structural and propulsion elements; thus one has

$$\$_{OM} = K_{MS} \left[\left(\frac{\$}{W}\right) \left(W_v - W_\ell - W_f\right) + \left(\frac{\$}{P}\right)_S P_{max} \right] + K_{MP} \left(\frac{\$}{P}\right)_{ps} P_{max} \quad , \qquad \text{(A-13)}$$

where K_{MS} and K_{MP} are the proportionality constants for structure and propulsion, respectively. These constants include the effect of the duration of the life cycle; e.g., if the annual structural maintenance cost is 10% of the manufacturing cost and the life cycle is 20 years, then $K_{MS} = 2.0$.

The fuel costs are based on vehicle usage over its life cycle, as follows:

$$\$_f = \overline{SFC} \cdot P_{max} \cdot \overline{DC} \cdot \left(\frac{\$}{W_f}\right) \quad , \qquad \text{(A-14)}$$

where $(\$/W_f)$ is the cost per pound of fuel, $\overline{DC}$ is the equivalent usage at maximum power of the vehicle over the life cycle, and $\overline{SFC}$ is based on a representative operating condition (which is assumed here to be at 25% of maximum power). That is, if the usage of the vehicle is represented, say, by 300 hours per year at 25% power over a life of 20 years, then $\overline{DC}$ would be 300 x 20 x .25 = 1500 hours.

Equations A-9, A-11, A-13, and A-14 enable the vehicle life-cycle cost to be estimated from a knowledge of its gross weight, payload weight, fuel weight, representative specific fuel consumption, and maximum delivered power, provided that seven cost or operational characteristics are known [$(\$/W)$, $(\$/P)_S$, $(\$/P)_{ps}$, (S/W_f), K_{MS}, K_{MP}, $\overline{DC}$]. These characteristics are determined for various classes of vehicles on the basis of data for representative actual vehicles in Section B below.

3. Sensitivity Factors

Of primary interest here is the sensitivity of vehicle weight and cost to changes in propulsion system performance and cost characteristics. This can be portrayed by means of weight and cost sensitivity factors, defined by

$$SW_i = \frac{\Delta W_v/W_v}{\Delta Q_i/Q_i}\ ^*$$

and

$$SC_i = \frac{\Delta \$_L/\$_L}{\Delta Q_i/Q_i} \quad ,$$

where Q_i is any relevant propulsion system characteristic and SW_i and SC_i are the weight and cost sensitivity factors, respectively. These sensitivity factors can be derived from the preceding relationships by straightforward differentiation, with the (selected) results shown in Tables A-1 and A-2. It is to be noted that each sensitivity factor indicates the fractional change in vehicle weight or cost due to a fractional change in a propulsion system characteristic, on the assumption that all vehicle characteristics and all other propulsion system characteristics are unchanged. That is, in the most general case, the vehicle life-cycle cost is a function of 19 such characteristics, as follows:

Vehicle Performance Characteristics: W_ℓ, ∇_ℓ, P_{max}/W_v, R

Vehicle Design Characteristics: α, β, W_v/D, W_{su}/W_v

---

*More precisely, $SW_i \equiv \partial(\ell n\ W_v)/\partial(\ell n\ Q_i)$.

TABLE A-1. WEIGHT SENSITIVITY FACTORS

$$\frac{\Delta W_v}{W_v} = SW_i \frac{\Delta Q_i}{Q_i}$$

Parameter Q_i	Weight Sensitivity Factor SW_i
$\overline{SFC}$	$\frac{(1 + \alpha + \beta/\rho_f)W_f}{(1 + \alpha + \beta/\rho_\ell)W_\ell}$
$\frac{W_{ps}}{P_{max}}$	$\frac{(1 + \alpha)W_{ps}}{(1 + \alpha + \beta/\rho_\ell)W_\ell}$
$\frac{\nabla_{ps}}{P_{max}}$	$\frac{(\beta/\rho_{ps})W_{ps}}{(1 + \alpha + \beta/\rho_\ell)W_\ell}$
ρ_f	$\frac{(\beta/\rho_f)W_f}{(1 + \alpha + \beta/\rho_\ell)W_\ell}$

TABLE A-2. COST SENSITIVITY FACTORS

$$\frac{\Delta \$_L}{\$_L} = SC_i \frac{\Delta Q_i}{Q_i}$$

Parameter Q_i	Cost Sensitivity Factor SC_i
$\overline{SFC}$	$\left[1 + \left(1 + K_{MS}\right)\left(\frac{\$}{W}\right)\right]\left[\frac{(1 + \alpha + \beta/\rho_f)W_f}{(1 + \alpha + \beta/\rho_\ell)W_\ell}\right] + \left(\frac{\$}{W_f}\right)\frac{(\overline{DC})\ \overline{SFC}\ P_{max}}{\$_L} - \left(1 + K_{MS}\right)\left(\frac{\$}{W}\right)\frac{W_f}{\$_L}$
$\frac{W_{ps}}{P_{max}}$	$\left[1 + \left(1 + K_{MS}\right)\left(\frac{\$}{W}\right)\frac{W_\ell}{\$_L}\right]\left[\frac{(1 + \alpha)W_{ps}}{(1 + \alpha + \beta/\rho_\ell)W_\ell}\right]$
$\frac{\nabla_{ps}}{P_{max}}$	$\left[1 + \left(1 + K_{MS}\right)\left(\frac{\$}{W}\right)\right]\frac{W_\ell}{\$_L}\left[\frac{(\beta/\rho_{psp})W_{psp}}{(1 + \alpha + \beta/\rho_L)W_L}\right]$
ρ_F	$-\left[1 + \left(1 + K_{MS}\right)\left(\frac{\$}{W}\right)\right]\frac{(\beta/\rho_f)W_f}{(1 + \alpha + \beta/\rho_\ell)W_\ell}$
$\left(\frac{\$}{P}\right)_{ps}$	$\left(\frac{\$}{P}\right)_{ps}\frac{P_{max}}{\$_L}$
$\$_F$	$\left(\frac{\$}{W_f}\right)\frac{(DC)\ \overline{SFC}\ P_{max}}{\$_L}$

Vehicle Cost Characteristics: $\overline{DC}$, $\$/W$, $(\$/P)_S$, K_{MS}

Propulsion System Performance Characteristics: $\overline{SFC}$, W_{ps}/P_{max}, ∇_{ps}/P_{max}, ρ_f

Propulsion System Cost Characteristics: $(\$/P)_{ps}$, K_{MP}, $\$/W_f$.

Thus, for each sensitivity factor in Tables A-1 and A-2, all of the above characteristics except the relevant propulsion system characteristic are assumed to be constant. In more physical terms, each sensitivity factor is merely the change in vehicle weight or cost attributable to a change in a propulsion system characteristic for a vehicle with fixed performance capabilities.

As could be anticipated, the various sensitivity factors directly reflect the relative magnitudes of weights or costs associated with the propulsion system characteristics. This is particularly evident in the weight sensitivity factors, wherein each factor is the ratio of the total weight attributable to the characteristic to the total weight attributable to the payload (including the weight required to armor the volume).

These sensitivity factors refer of course to overall characteristics of the propulsion system, rather than to the characteristics of the engine and transmission separately. The sensitivities of the vehicle weight and cost to these latter characteristics can be obtained from the following relationships between the overall characteristics and engine and transmission characteristics:

$$\overline{SFC} = \frac{sfc_e}{\eta_x \eta_t} \qquad \text{(A-15)}$$

$$\frac{W_{ps}}{P_{max}} = \left(\frac{W_e}{P_e}\right)\frac{1}{\eta_x \eta_t} + \left(\frac{W_x}{P_x}\right)\frac{1}{\eta_t} \qquad \text{(A-16)}$$

$$\frac{\nabla_{ps}}{P_{max}} = \left(\frac{\nabla_e}{P_e}\right)\frac{1}{\eta_x\eta_t} + \left(\frac{\nabla_x}{P_x}\right)\frac{1}{\eta_t} \qquad \text{(A-17)}$$

$$\left(\frac{\$}{P}\right)_{ps} = \left(\frac{\$}{P}\right)_e \frac{1}{\eta_x\eta_t} + \left(\frac{\$}{P}\right)_x \frac{1}{\eta_t} \qquad \text{(A-18)}$$

$$K_{MP}\left(\frac{\$}{P}\right)_{ps} = K_{Me}\left(\frac{\$}{P}\right)_e \frac{1}{\eta_x\eta_t} + K_{Mx}\left(\frac{\$}{P}\right)_x \frac{1}{\eta_t} \quad , \qquad \text{(A-19)}$$

where the subscript e refers to the engine and the subscript x refers to the transmission (including the final drive). Thus, for example, the sensitivity of vehicle weight to transmission efficiency is given by

$$\frac{\Delta W_v/W_v}{\Delta\eta_x/\eta_t} = -SW_{SFC} - \frac{W_e}{W_{ps}}\, SW_{(W_{ps}/P_{max})} - \frac{\nabla_e}{\nabla_{ps}}\, SW_{(\nabla_{ps}/P_{max})} ,$$

since the transmission efficiency affects all of the overall propulsion system characteristics.

B. CHARACTERISTICS OF VEHICLE CLASSES

As indicated previously, the vehicle design and cost characteristics used in the vehicle weight and cost models are determined on the basis of data from actual vehicles. These determinations are indicated below.

1. Performance and Cost Characteristics of Selected Ground Vehicles

Physical characteristics of actual ground vehicles are shown in Table A-3. The sources of the data are indicated in the table. The data are not complete in all cases, and estimated values have been used where necessary. Further, inasmuch as the data have been gathered from a variety of sources, there are

TABLE A-3. PHYSICAL CHARACTERISTICS OF SELECTED GROUND VEHICLES

VEHICLE CLASS	MBT	MBT	LCV	LCV	SPA	5-Ton Truck
VEHICLE DESIGNATION	M60A1	M1	M113A1	M2	M109	M813A1
WEIGHT (lb)						
Structure	54,915	64,890	9,040	15,794*	18,035*	17,402*
Propulsion	12,576	10,670	3,100	6,750	6,276	4,075
Engine	(4,700)	(2,500)	(1,500)	(2,450)	(2,336)	(2,460)
Transmission	(3,025)	(4,000)	(500)	(1,600)	(2,390)	(415)
Final drive	(1,000)*	(2,000)*	(500)*	(750)*	(550)*	(400)
Other	(3,751)	(2,170)	(600)*	(1,950)	(1,000)*	(800)*
Fuel	2,800	(3,600)	724	1,600	1,000	600
Suspension	22,008	21,880	5,407	10,560*	11,541*	8,000*
Payload	17,101	17,760	6,072	13,296*	15,609*	20,000*
TOTAL	109,400	118,800	24,343	48,000	52,461	40,000*
ARMORED VOLUME (ft^3)						
Propulsion	205	178	65	108	120	--
Engine	(105)	(40)	(29)	(40)	(54)	--
Transmission	(36)	(53)	(17)	(23)	(30)	--
Induction	(10)	(31)	(2)	(5)	(4)	--
Cooling	(55)	(45)	(15)	(35)	(28)	--
Other	(9)	(9)	(2)	(5)	(4)	--
Fuel	50	68	13	26	18	--
Payload	395	374	322*	366*	462*	--
TOTAL	650	620	400	500	600	--
OTHER						
Engine type	D	T	D	D	D	D
Engine designation	AVDS-1790	AGT-1500	6V53	VTA-903	8V71T	NHC-250
Gross horsepower	750	1500	216	500	405	250
Transmission designation	CD-850	X-1100	TX-100	HMPT-500	XTG411	Dana 6453
References	A-2,A-3,A-4	A-3,A-4,A-5	A-3,A-5,A-1	A-3,A-4,A-6	A-3,A-4,A-7	A-3,A-4,A-7,A-8

---

*Estimated

undoubtedly some discrepancies between the values indicated in the table and the actual vehicle values.

Similarly, data for the manufacturing costs of these same vehicles are shown in Table A-4, from the sources indicated in the table. The data are intended to be representative of the average manufacturing costs pertaining to full production of a typical number of vehicles and thus do not perhaps correspond to the actual cost of the vehicle at the present time. The total cost indicated for the vehicle is the cost of the vehicle excluding the cost of the payload.

Finally, operating and support cost data for these same vehicles are shown in Table A-5, from the sources indicated in the table. The values indicated in the table for System O&M, Vehicle O&M, and Propulsion O&M require some explanation. System O&M is defined as the total operating and support costs less the cost of crew (the latter includes crew pay and allowances and the attributable portions of indirect pay and allowances, permanent change of station, and indirect support costs when these latter costs are allocated among crew, direct maintenance, and depot maintenance labor costs). Vehicle O&M is defined as System O&M less the costs attributable to the payload (including ammunition). Propulsion O&M is defined as that part of Vehicle O&M which is attributable to the engine and transmission (but not including the cost of the fuel). As with the other data, and more so, discrepancies among the various sources exist; thus, the data in Table A-5 should only be interpreted as representative.

2. Design and Cost Characteristics for Vehicle Classes

Based in part on the data presented in the previous section, and in part on more generic data from previous studies (Refs. A-1 and A-15), vehicle design characteristics for three representative classes of vehicles have been selected as follows:

TABLE A-4. MANUFACTURING COSTS OF SELECTED GROUND VEHICLES

VEHICLE CLASS	MBT	MBT	LCV	LCV	SPA	5-Ton Truck
VEHICLE DESIGNATION	M60A1	M1	M113A1	M2	M109	M813A1
MANUFACTURING COST (FY 81 $)						
Propulsion	129,500	394,100	N.A.*	89,000	N.A.	17,400
Engine	63,900	247,300	7,600	21,800	13,931	12,400
Transmission	35,000	108,900	N.A.	34,300	N.A.	2,500
Final Drive	14,310	18,400	N.A.	4,600	N.A.	2,000
Other	16,290	19,500	N.A.	28,300	N.A.	1,000
Vehicle w/o propulsion	371,890	568,100	N.A.	274,100	N.A.	35,200
Payload	143,050	261,500	N.A.	218,200	N.A.	0
Total	644,440	1,223,700	120,672	581,300	318,000	52,600
Vehicle Total	501,390	962,200	N.A.	363,100	N.A.	52,600
References	A-1,A-9	A-10	A-11,A-12	A-13	A-11,A-12	A-12,A-14

---

*N.A. = not available.

TABLE A-5. ANNUAL OPERATING AND SUPPORT COSTS OF SELECTED GROUND VEHICLES (FY 81 $)

VEHICLE CLASS	MBT	MBT	LCV	LCV	SPA	5-Ton Truck
VEHICLE DESIGNATION	M60A1	M1	M113A1	M2	M109	M813A1
MILITARY PERSONNEL	92,100	105,800	N.A.	56,400	N.A.	44,300
Crew payload allow.	(51,100)	(51,100)	"	(28,000)	"	(19,300)
Maintenance payload allow.	(7,400)	(10,400)	"	(6,600)	"	(8,400)
Indirect pay & allow.	(26,400)	(36,700)	"	(17,100)	"	(9,200)
Perm. change of station	(7,200)	(7,200)	"	(4,700)	"	(7,400)
CONSUMPTION	27,600	66,400	N.A.	25,300	N.A.	2,100
Replenishment spares	(25,700)	(40,580)	"	(11,800)	"	1,300
POL	(1,900)	(2,440)	"	(400)	"	800
Ammo, etc.	N.A.	(23,300)	"	(13,100)	"	--
DEPOT MAINTENANCE	27,200	34,300	N.A.	9,300	N.A.	--
Labor	(11,400)	(11,000)	"	(2,800)	"	--
Material	(14,600)	(22,100)	"	(4,200)	"	--
Transportation	(1,200)	(1,200)	"	(2,300)	"	--
MODIFICATIONS, MATERIEL	--	1,900	N.A.	2,200	N.A.	200
OTHER DIRECT	--	3,900	N.A.	700	N.A.	--
INDIRECT SUPPORT	45,900	52,000	N.A.	25,600	N.A.	15,800
TOTAL	192,800	263,900	22,674	119,500	153,500	62,400
SYSTEM O&M	83,500	120,100	N.A.	40,800	N.A.	19,700
VEHICLE O&M	N.A.	79,900	N.A.	27,000*	N.A.	19,700
PROPULSION O&M	N.A.	22,300	N.A.	6,600*	N.A.	2,400*
References	A-9	A-10	A-11	A-13	A-11	A-14

---

*Estimated.

Vehicle Class	α	β (lb/ft^3)	(W_{su}/W_v)	W_v/D
Main Battle Tank (MBT)	0.3	84.0	0.20	17.9
Light Combat Vehicle (LCV)	0.3	18.6	0.22	17.9
Truck	0.3	0	0.20	40.0

The ratio of structural weight necessary to support the combined weight of payload, propulsion, and fuel to this combined weight (α) is assumed to be 0.3, consistent with the structural weight required in non-armored vehicles. The armor weight per unit armored volume (β) has been determined from the data for the M1 and M2, respectively, presented in Table A-3, on the assumption that the armor weight is the weight of the structure indicated in the table less the structural weight necessary to support the combined weight of payload, propulsion, and fuel. The ratio of the weight of the suspension system to gross vehicle weight (W_{su}/W_v) is generally assumed to be 0.2, consistent with the results of previous studies (Refs. A-1, A-15); in the case of trucks, this suspension weight includes the weight of the axles. The vehicle weight-to-drag ratio typical of cruise conditions (W_v/D) is based on the results of these same studies.

Similarly, the cost characteristics of the vehicles and propulsion systems have been selected as shown in the following table:

Vehicle Class	$\overline{DC}$ (hrs)	(\$/W) (\$/lb)	$(\$/P)_s$ (\$/hp)	$(\$/P)_{ps}$ (\$/hp)	$(\$/W_f)$ (\$/lb)	K_{MS}	K_{MP}
MBT	1440	4.0	150	340	0.14	2.0	2.0
LCV	1440	4.0	150	290	0.14	2.0	2.0
Truck	1440	1.4	54	100	0.14	4.0	4.0

In the case of the MBT and LCV, the effective duty cycle (DC) is based on 288 hours/year of operation at an average power level of 25% and a 20-year life. The result, 1440 hours, also appeared to be a reasonable estimate for trucks based on 3000 miles/year. The next three characteristics--related to the manufacturing cost of the vehicle--have, for MBTs and LCVs, been selected so as to provide a reasonable match with the available data, as well as a reasonable match with more detailed cost estimates, of which more will be said later. In particular, the power-related cost factors are based on a structural power cost of $95 per gross engine horsepower, an engine cost of $85 per gross engine horsepower for diesel engines and $115 per gross engine horsepower for gas turbine engines, a transmission cost of $95 per gross engine horsepower, and a ratio of useful power delivered (P_{max}) to gross engine horsepower of 0.62--assuming a ratio of power delivered to the transmission to gross engine horsepower of 0.9, a transmission efficiency of 76%, and a thruster efficiency of 91%. These same cost characteristics for trucks have been obtained by scaling down the factors for MBTs and LCVs to provide a reasonable match with the manufacturing cost of the M813 shown in Table A-4 (the rationale being that the larger production quantities of trucks accounts for the unit cost reduction). The factors determining the operation and maintenance costs, K_{MS} and K_{MP}, have been based largely on the assumption that annual O&M costs are between 10% and 20% of the manufacturing costs; these values are reasonably consistent with the data shown in Table A-5.

3. Selected Results

In order to assess the adequacy of the vehicle performance and cost models developed here, at least to some degree, the results obtained from these models have been compared to other available information for combat vehicles.

With respect to performance, detailed weight breakdowns of preliminary designs for a variety of conceptual armored vehicles are presented in Ref. A-6. A comparison of the gross vehicle weights resulting from the model developed here with the gross vehicle weights estimated in Ref. A-6 is shown in Fig. A-1. To obtain model results, it has been necessary to estimate the payload volume from the payload weight given in Ref. A-6, based on the assumption of a payload density of 40 lb/ft^3. It can be observed from Fig. A-1 that the discrepancies are appreciable; they are attributed here largely to differences in armor protection in the conceptual vehicles. That is, the model results have been obtained by assuming armor protection levels of either 18.6 lb/ft^3 or 50 lb/ft^3, whereas the conceptual vehicles have a greater variety of armor protection levels. In view of the fact that the vehicles range in weight from 16 to 40 tons, in power from 375 to 1500 horsepower, and in specific power from 21.7 to 37.5 hp/ton, the quality of agreement is considered adequate.

Manufacturing cost estimates for the conceptual vehicles of Ref. A-6 have been presented in Ref. A-15, on the basis of a detailed cost-estimating method for armored combat vehicles. The results of Ref. A-15 are compared in Fig. A-2 with corresponding results from the model developed here. Also shown in Fig. A-2 is a comparison of model results with the data in Table A-4 for four vehicles: M1, M60, M2, and M113A1. The quality of agreement indicated in Fig. A-2 is considered quite satisfactory.

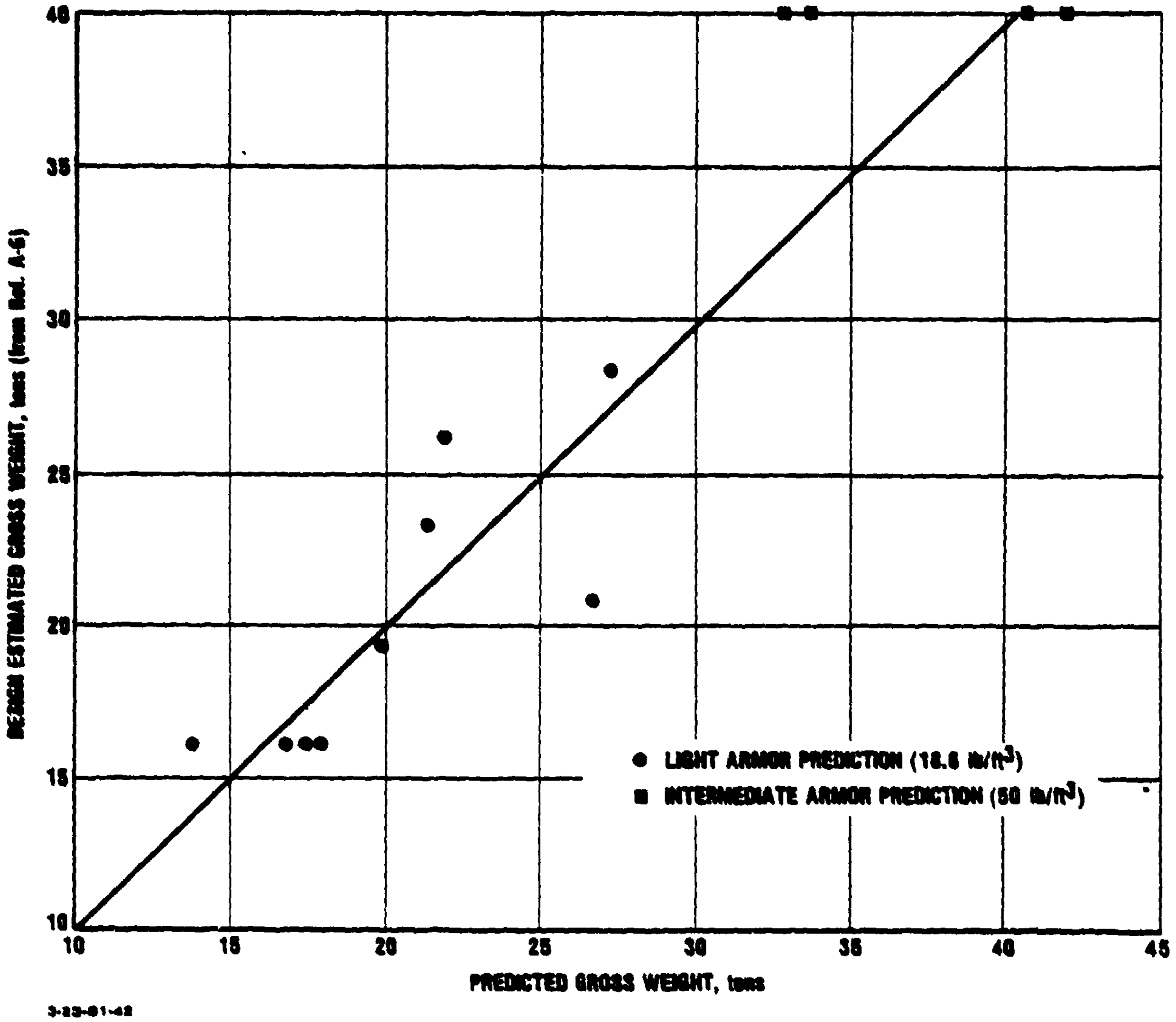
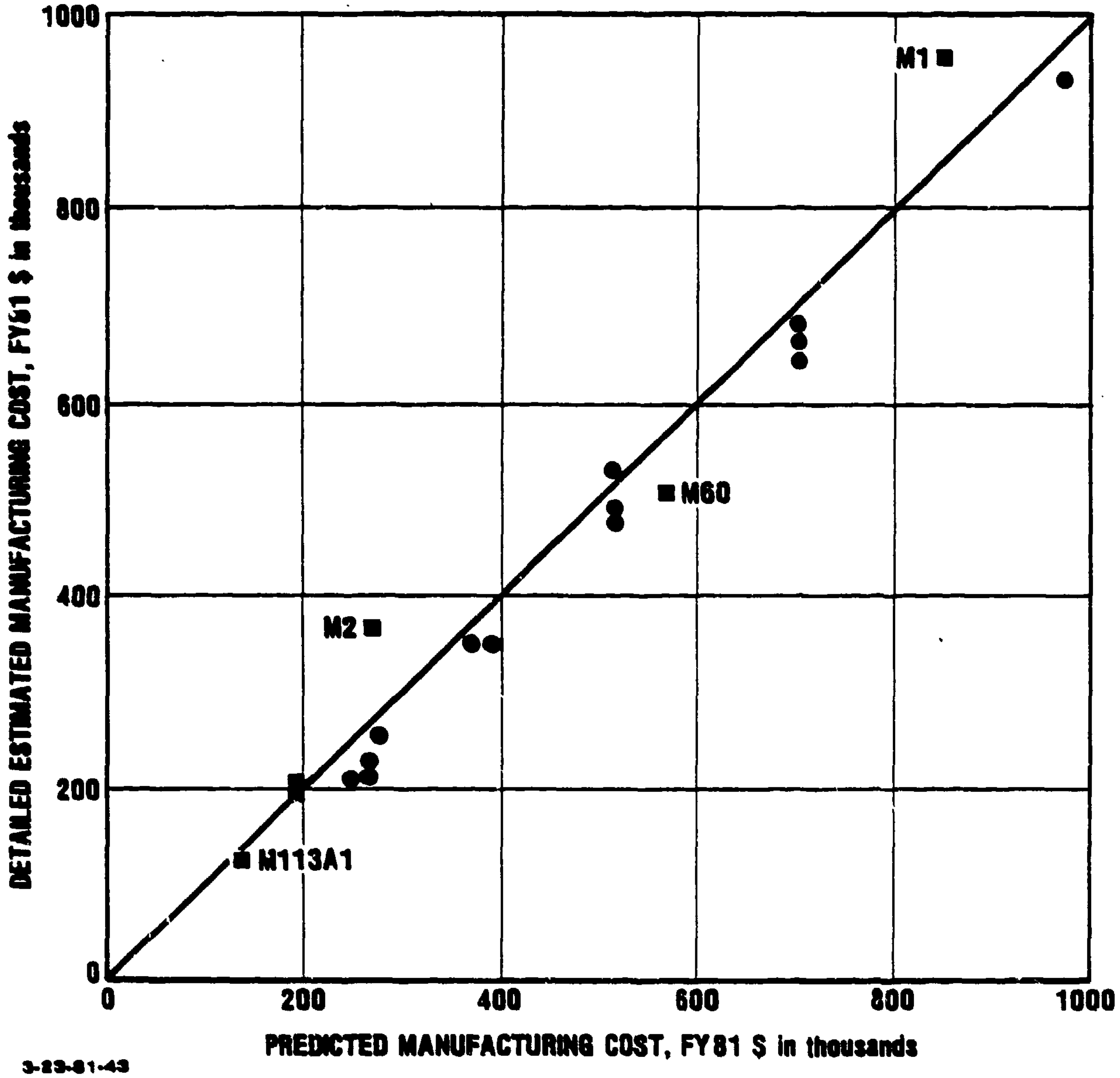


FIGURE A-1. Comparison of estimated gross weights of vehicles.



3-23-81-43

FIGURE A-2. Comparison of estimated manufacturing costs of vehicles.

REFERENCES, APPENDIX A

A-1. F.R. Riddell, D.M. Dix, *Technology Assessment of Advanced Propulsion Systems for Some Classes of Current Vehicles*, IDA Paper P-1278, September 1978.

A-2. *M60A1 Weight Summary*, Undated sheet received from TARADCOM, July 1980.

A-3. *Combat Vehicle Propulsion System Volumes*, Undated viewgraph received from TACOM, February 1981.

A-4. Data obtained from Clifford Moses of the Advanced Concepts Laboratory, 6 June 1977.

A-5. *Tank Weight Comparisons: Threat Concept vs. XM1*, Undated sheet received from TARADCOM, July 1980.

A-6. T.H. Puuri, H.C. Motlin, W.J. Seyfort, *Armored Combat Vehicle Technology Study*, Technical Report 12495, U.S. Army Tank-Automotive Research and Development Command, March 1980.

A-7. *Handbook of Army Materiel*, U.S. Army Ordnance Center and School, May 1972.

A-8. *Engine Horsepower vs. Gross Vehicle Weight*, Undated viewgraph received from TACOM, February 1981.

A-9. *M60AN Tank: Annual Operating and Support Cost per Vehicle*, Project Manager, M60 Tank Development and TACOM Cost Analysis Division, April 1976.

A-10. XM1 Cost Estimates received from TACOM, February 1981.

A-11. *Investment and O&S Costs for Selected Track Vehicles*, Undated sheet received from TACOM, February 1981.

A-12. Average Unit Hardware Cost Data for Engines received from TACOM, February 1981.

A-13. *FVS COEA Life Cycle Cost Matrix*, and supporting data received from TACOM, February 1981.

A-14. *Cost Analysis, 5-Ton Cargo Truck, XM939 Series vs. M809 Series (XM923 Cargo vs. M813A1 Cargo)*, Viewgraph copies, TACOM, 27 June 1979.

A-15. F.R. Riddell, *Survey of Advanced Propulsion Systems for Surface Vehicles*, IDA Paper P-1073, January 1975.

A-16. B. Kornhauser, A.J. Provenzano, A.E. Schneider, *Manufacturing Cost Estimates--Armored Combat Vehicle Technology Program Conceptual Vehicles*, SPC 550, System Planning Corporation, December 1979.

APPENDIX B

SOME MOBILITY CONSIDERATIONS FOR TRACKED VEHICLES

CONTENTS

APPENDIX B

SOME MOBILITY CONSIDERATIONS FOR TRACKED VEHICLES

The specific power of a vehicle (e.g., hp/ton) is an important characteristic in determining both the power level needed from the propulsion system and the impact that the propulsion system has on the overall vehicle. In the past, the specific power of tracked vehicles has been limited by the power density (i.e., weight or size per unit power) of the propulsion system; as the propulsion system power density has increased through technological improvement, the specific power of newer vehicles has increased accordingly. The utility of increased vehicle specific power is, however, limited to a large extent by the ability of the soil to resist the motion of a track. These limitations are developed here; the development follows previous treatments in Refs. B-1 and B-2.

A. MATHEMATICAL MODELS OF SOIL-TRACK INTERACTIONS

The maximum shearing stress that a soil can support can be written as

$$\frac{\tau_m}{p} = \frac{c}{p} + \tan \phi \quad , \qquad \text{(B-1)}$$

where τ_m = maximum soil shearing stress
c = coefficient of cohesion
ϕ = angle of soil friction
p = ground pressure (vertical load/contact area).

This maximum shearing stress translates into a limit on the useful thrust that a vehicle can produce; noting that the contact area is W_v/p, where W_v is the gross vehicle weight, one has

$$T_{max} = \tau_m \left(\frac{W_v}{p}\right)$$

or

$$\frac{T_{max}}{W_v} = \frac{c}{p} + \tan\phi \; . \qquad \text{(B-2)}$$

To produce thrust, relative motion between the track and the soil is generally required, and the actual thrust produced depends upon the magnitude of this relative motion. This motion is characterized by the vehicle slip, i_o, where

$$i_o \equiv 1 - \frac{V_v}{V_t} \; , \qquad \text{(B-3)}$$

where V_v = actual vehicle speed

V_t = theoretical vehicle speed (the linear speed of the track relative to the vehicle).

The actual thrust produced can be written as

$$\frac{T_s}{W_v} = \left(\frac{c}{p} + \tan\phi\right)\left[1 - \frac{K}{i_o \ell}\left(1 - e^{-i_o \ell / K}\right)\right] , \qquad \text{(B-4)}$$

where T_s = vehicle thrust

K = coefficient of soil shear

ℓ = length of track in contact with the ground.

It is convenient to express Eq. B-4 in terms of the useful propulsive power per unit weight (i.e., thrust × vehicle speed ÷ vehicle weight):

$$\frac{P_u/W_v}{V_v} = 5.333\left(\frac{c}{p} + \tan\phi\right)\left[1 - \frac{K}{i_o\sqrt{\frac{1000W_v(\ell/b)}{p}}}\left(1 - e^{-\frac{i_o}{K}\sqrt{\frac{1000W_v(\ell/b)}{p}}}\right)\right] \qquad \text{(B-5)}$$

where P_u = propulsion power in horsepower
W_v = vehicle weight in tons
V_v = vehicle speed in miles per hour
ℓ/b = the length-to-width ratio of the track
with the units of c and p being psi, and K in inches.

The power required at the sprocket [the track-driving wheel(s)] is related to the useful propulsive power through the losses due to slip and internal track friction. The power required at the track surface is

$$\frac{P_T/W_v}{V_v} = \frac{1}{1 - i_o}\,\frac{P_u/W_v}{V_v} \; . \qquad \text{(B-6)}$$

The internal track friction is characterized by a friction coefficient, f_n, which is the ratio of the force required to overcome track friction to the gross vehicle weight; thus the power at the sprocket can be written as

$$\frac{P_s/W_v}{V_v} = \frac{P_T/W_v}{V_v} + 5.333\, f_n$$

or

$$\frac{P_s/W_v}{V_v} = \frac{1}{1 - i_o} \frac{P_u/W_v}{V_v} + 5.333 f_n \quad , \qquad \text{(B-7)}$$

where P_s is in horsepower, W_v is in tons, and V_v in mph.

The delivered propulsive power is used of course to overcome drag at a constant vehicle speed or to overcome drag and provide excess thrust for acceleration. The drag of a tracked vehicle can be expressed as

$$\frac{D}{W_v} = \frac{2b \; p^{n+1/n}}{W_{v.}\left(1 + n\right)\left(\frac{k_c}{b} + k_\phi\right)^n} \quad , \qquad \text{(B-8)}$$

where D = vehicle drag (lb)
b = track width (in.)
k_c = "cohesive" modulus of soil deformation (lb/in.$^{n+1}$)
k_ϕ = "frictional" modulus of soil deformation (lb/in.$^{n+2}$)
n = exponent of soil consistency

and p is in psi and W_v in pounds. The power required to overcome drag is accordingly

$$\frac{P_D/W_v}{V_v} = 5.333 \left(\frac{D}{W_v}\right) \quad , \qquad \text{(B-9)}$$

where P_D is in horsepower, W_v in tons, and V_v in mph. Thus the power available for acceleration is

$$\frac{P_A/W_V}{V_v} = \frac{P_u/W_V}{V_v} - \frac{P_D/W_V}{V_v} \quad . \qquad \text{(B-10)}$$

The power available for acceleration is in turn used, on level ground, for vehicle acceleration and acceleration of all of the rotating masses in the power train; typically, the latter is about 20% of the former--somewhat greater for heavy tanks and somewhat less for light combat vehicles. The acceleration capability can be accordingly expressed as

$$a(\text{mph/sec}) = 21.9 \left(\frac{a}{g}\right) = \frac{4.114}{1.2} \frac{P_A/W_v}{V_v} , \qquad \text{(B-11)}$$

where g is the acceleration due to gravity. This level-ground acceleration capability is also a measure of hill-climbing ability, in that the maximum slope negotiable is given by

$$\tan \alpha = 1.2 \left(\frac{a}{g}\right) .$$

B. QUANTITATIVE RESULTS

Equations B-5, -7, -8, -9, -10 define a relationship between the power delivered to the sprocket of a tracked vehicle and the ultimate power available for acceleration or hill-climbing purposes. The quantitative nature of this relationship is of interest in assessing potential limits on the useful specific power of tracked vehicles. Representative results are developed here for two different types of soils and two types of vehicles.

The soil types are taken to be sand--a reasonably good soil for locomotion purposes--and a plowed agricultural soil. Their representative characteristics are as follows:

	c (psi)	ϕ (deg)	K (in.)	k_c (lb/in.$^{n+1}$)	k_ϕ (lb/in.$^{n+2}$)	n
Sand	0	35	1	0	8	0.8
Agricultural soil	0.1	20	1	6	4	0.5

The vehicles are a 60-ton vehicle and a 20-ton vehicle with the following representative characteristics:

	(psi)	ℓ/b	ℓ (in.)	b (in.)
60-ton vehicle	14.5	5.6	152	27
20-ton vehicle	14.5	5.6	88	16

The results are shown in Fig. B-1. The essential feature is that for any given speed at which vehicle acceleration is desired, there is a limit to the vehicle specific power (in terms of sprocket hp/ton) beyond which no significant increase in acceleration capability is obtained. For example, in sand, this limit is about 4 hp/ton/mph; thus if maximum acceleration capability is desired at a speed of 10 mph, say, then sprocket powers of more than 40 hp/ton will accomplish essentially nothing. For agricultural soil, the limit is about 2 hp/ton/mph, and the corresponding 10 mph value would be 20 hp/ton. Any sprocket power in excess of these values would be consumed in merely moving the soil about, via the spinning of the tracks. It can be verified by direct calculation that the results shown in Fig. B-1 are not sensitive to the vehicle characteristics of ground pressure, p, and track length-to-width ratio, ℓ/b, over the ranges of values permitted by reasonable vehicles.

A more informative picture of the limited utility of very high specific vehicle power in providing acceleration capability is perhaps gained by examining the ideal standing-start performance of a vehicle. The requisite time-distance relationship can be obtained by straightforward numerical integration of Eq. B-11, and representative results--for any size of vehicle--are shown in Fig. B-2. Here, the time required for a vehicle to traverse a distance of 300 feet is shown as a function of sprocket hp/ton, for two cases: the first presumes an unlimited maximum vehicle speed, and the second presumes that the maximum

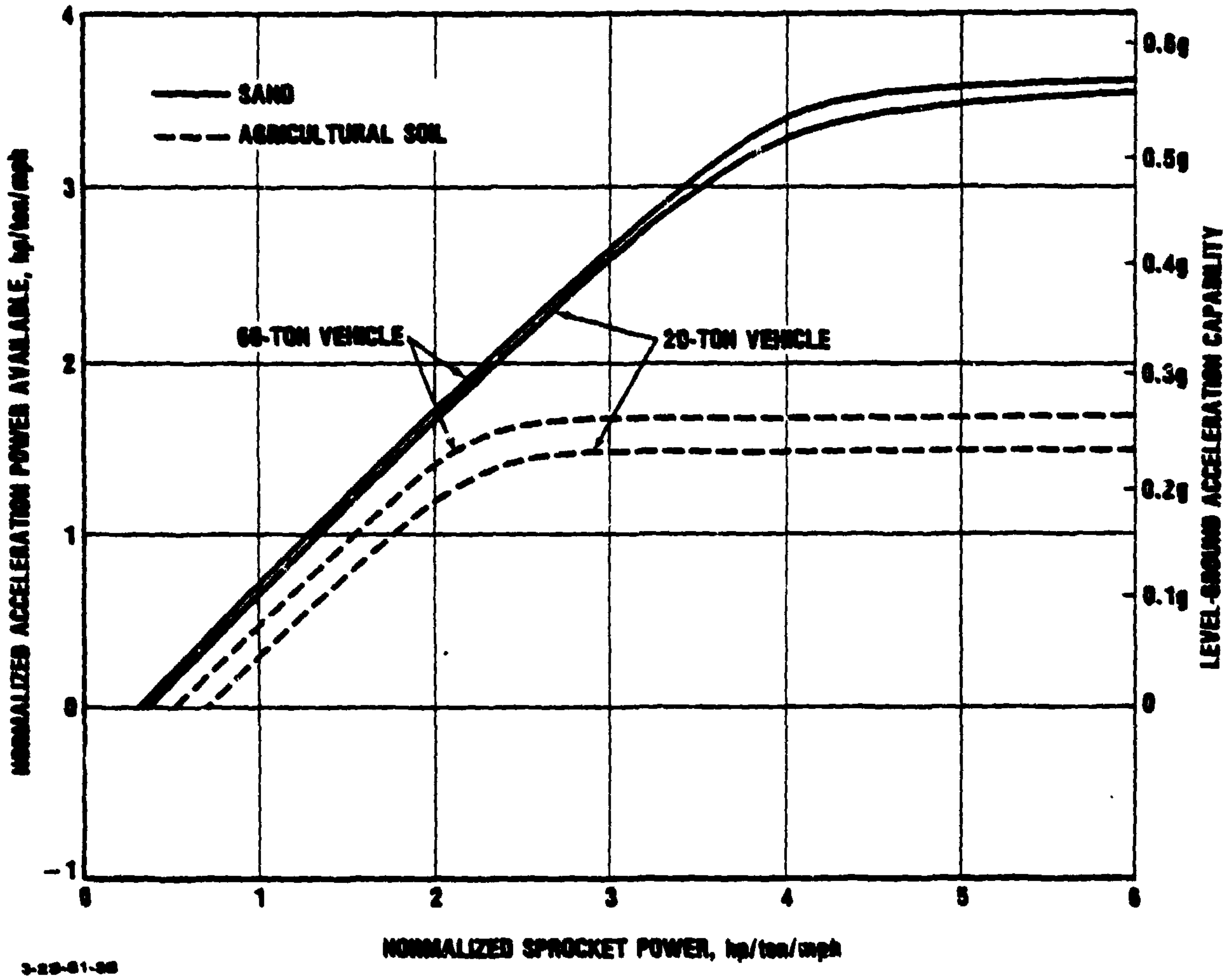


FIGURE B-1. Useful power characteristics of tracked vehicles.

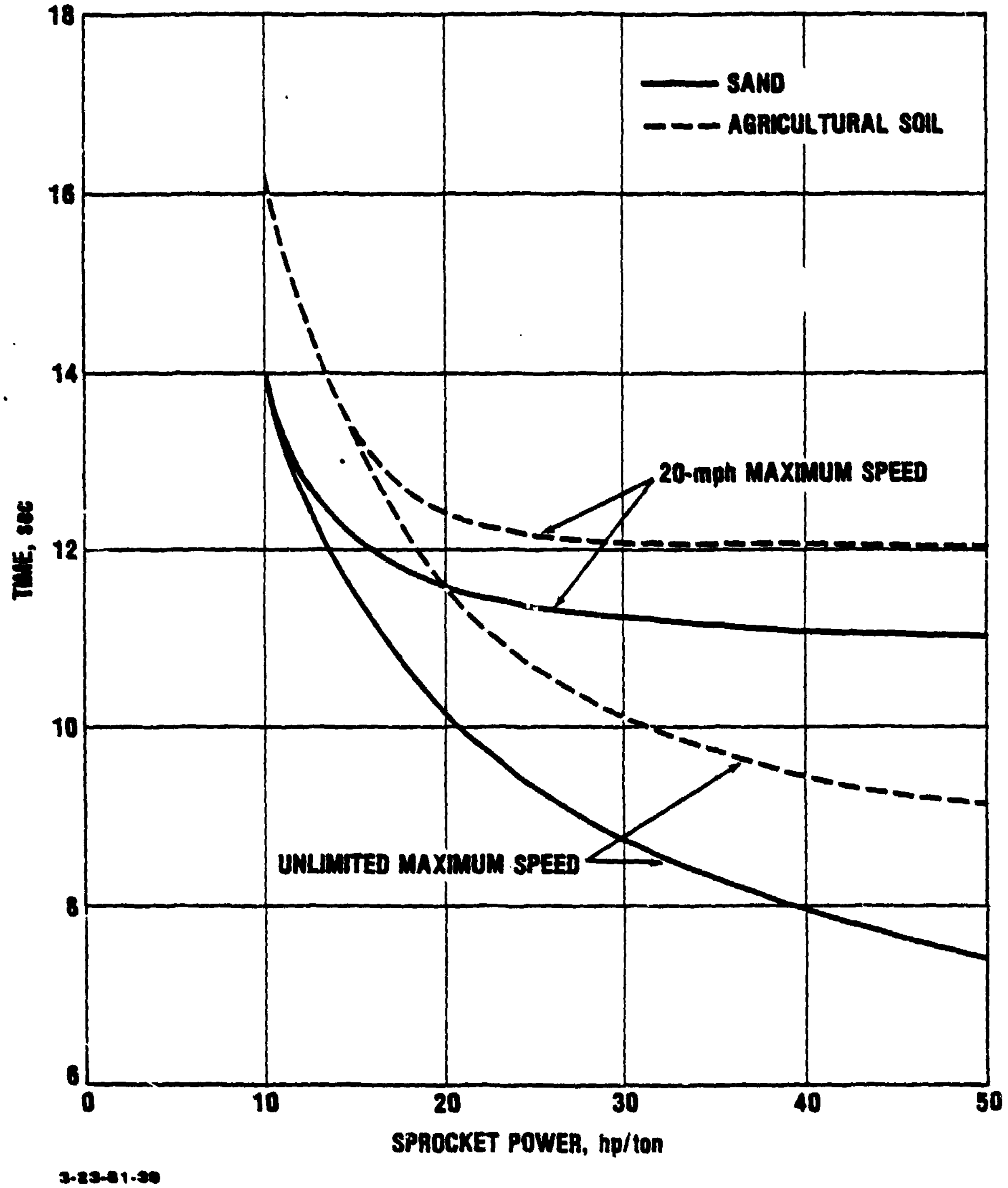


FIGURE B-2. Ideal standing start performance: time to 300 ft.

vehicle speed is limited to 20 mph (which seems reasonable for off-road conditions).

It can be observed from Fig. B-2 that the benefits of increased vehicle specific power above rather modest levels diminish considerably; in particular, if the maximum vehicle speed is limited to 20 mph, sprocket powers in excess of 15-20 hp/ton yield virtually no reduction in elapsed time. Similar results for longer distances, or for non-zero initial speeds, would of course show larger relative gains for higher vehicle specific powers.

REFERENCES, APPENDIX B

B-1. M.G. Bekker, "Thrusters for Ground Combat Vehicles," Appendix K of *Technology Assessment of Advanced Propulsion Systems for Some Classes of Combat Vehicles*, Institute for Defense Analyses, IDA Paper P-1278, F.R. Riddell and D.M. Dix, September 1978.

B-2. Institute for Defense Analyses, *Survey of Advanced Propulsion Systems for Surface Vehicles*, IDA Paper P-1073, F.R. Riddell, January 1975.