THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Final Report

FLEXIBLE VERSUS RESPONSIVE ENGINES

Part II. Transmission System for Flexible Engines

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INTRODUCTION

This report is a study of power transmissions that are primarily intended for use in military tanks. However, as a basis for such an analysis the report looks at the transmission as a basic mechanical device. Thus, the study serves several purposes.

It first reviews the fundamentals of power transmitting devices: mechanical, electrical, hydraulic, etc. These operating parameters and goals are investigated in themselves, and also with regard to some of the more practical aspects of transmission performance and application. This gives a picture of what would be ultimately desired of a theoretically perfect transmission and what can be reasonably expected in light of practical limitations.

The second step in this investigation is a definition of operational goals and a criterion or procedure for evaluating general transmission types. This was done to provide a uniform approach to all varieties of transmissions and to help insure that the potentialities of some of the new or less developed devices would not be overlooked.

The resulting criterion was then used as a basis for a general survey of the various types of transmissions and an evaluation of their good and bad points.

Finally, the particular power requirements of tanks were investigated. These in combination with the transmission survey were used as a basis for recommendations for possible improvements in tank power transmissions.

SECTION 1

TRANSMISSION FUNDAMENTALS

1.1. BASIC FUNCTION

The primary function of a power transmission is to transmit the energy generated by a prime mover to the places desired, whether it be in the form of heat energy, as in heating a house; chemical, as in charging a battery; or mechanical, as in driving a tank. Ideally, a transmission would permit maximum utilization of the prime power source and would absorb no energy itself during its operations.

In a tank, the transmission's function is entirely a mechanical one. It must convert the speed and torque developed by the engine to the speed and torque combination required at the driving tracks. In addition, it must facilitate steering, but this is a special function and will be discussed separately.

1.2. PRIMARY FACTORS

The perfect tank transmission would fulfill two performance requirements as well as satisfy numerous practical considerations. First, it would minimize fuel consumption, and second, it would enable the engine to operate throughout its full power range regardless of vehicle speed or operation.

The first of these factors, maximum fuel economy, involves two considerations. One is the actual engine performance economy. This is best illustrated by the specific fuel consumption plots seen in Fig. 1. An examination of this will reveal a composite optimum specific fuel consumption versus brake horsepower curve tangent to the individual minimum fuel consumption curves for selected engine speeds. This has been cross-plotted, as seen in Fig. 2, to give an optimum engine performance curve, along which the engine will always operate for best fuel economy. Thus, the desired output horsepower would dictate engine speed, regardless of vehicle speed or other considerations.

The other factor influencing fuel economy is the tare horsepower requirement of the transmission itself. Ideally, it would be frictionless and inertialess, requiring no power to operate or accelerate it. Obviously, this can only be approximated in actual practice.

The second primary factor, optimum power utilization, is best illustrated through Fig. 3. Usual engine-transmission combinations permit the engine to

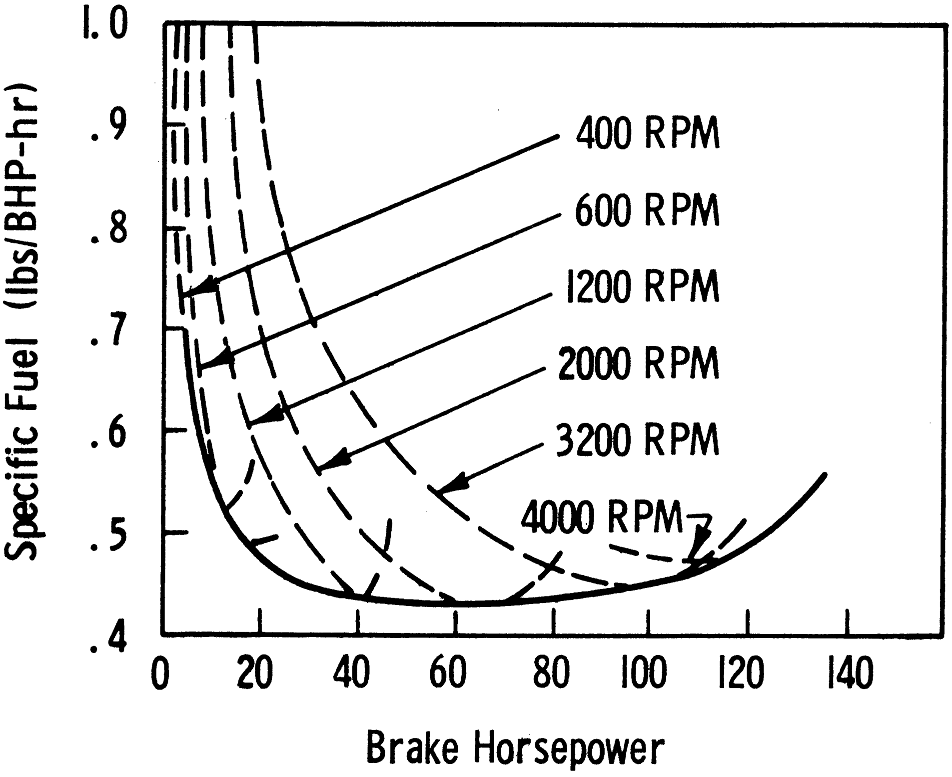

Fig. 1. Maximum engine economy (I).

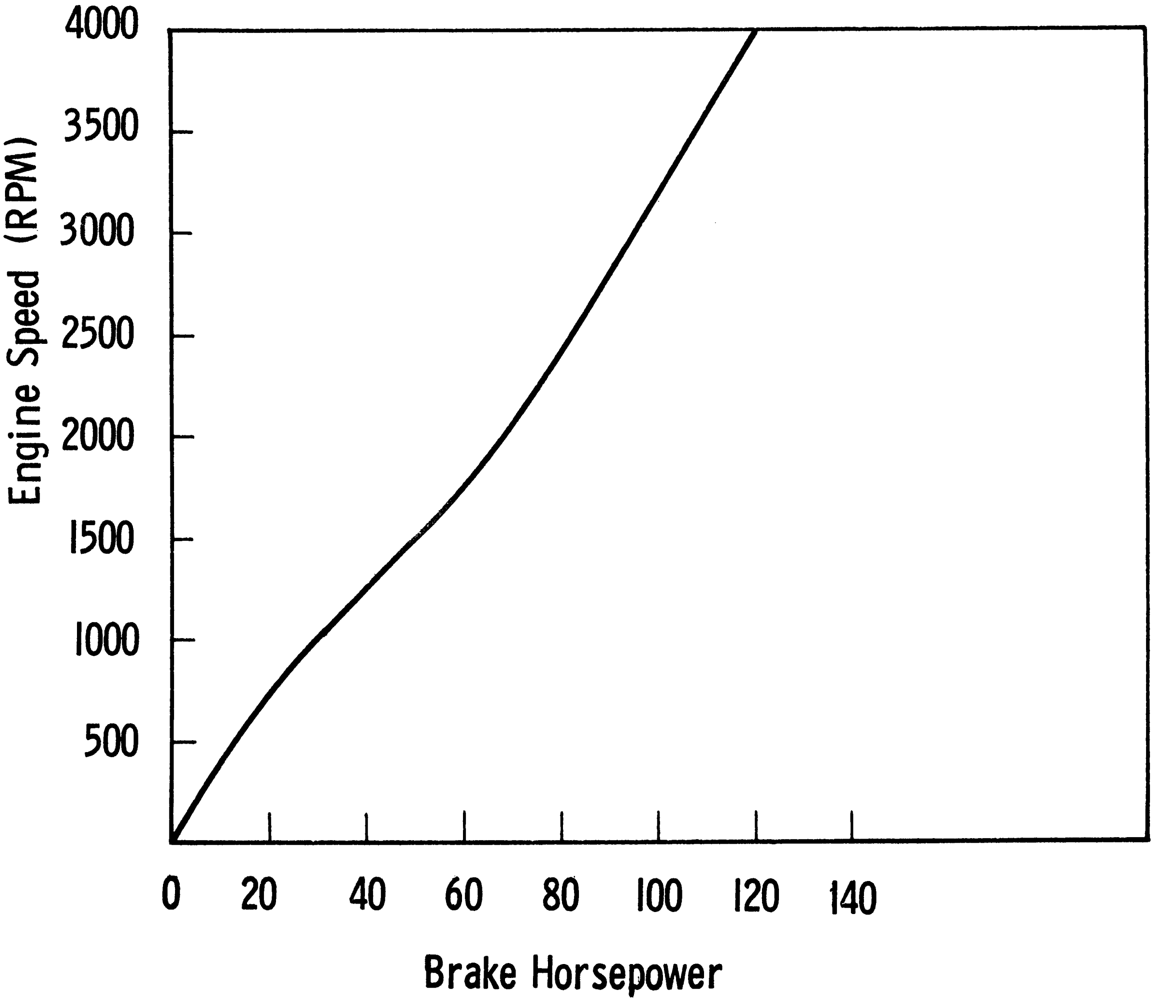

Fig. 2. Maximum engine economy (II).

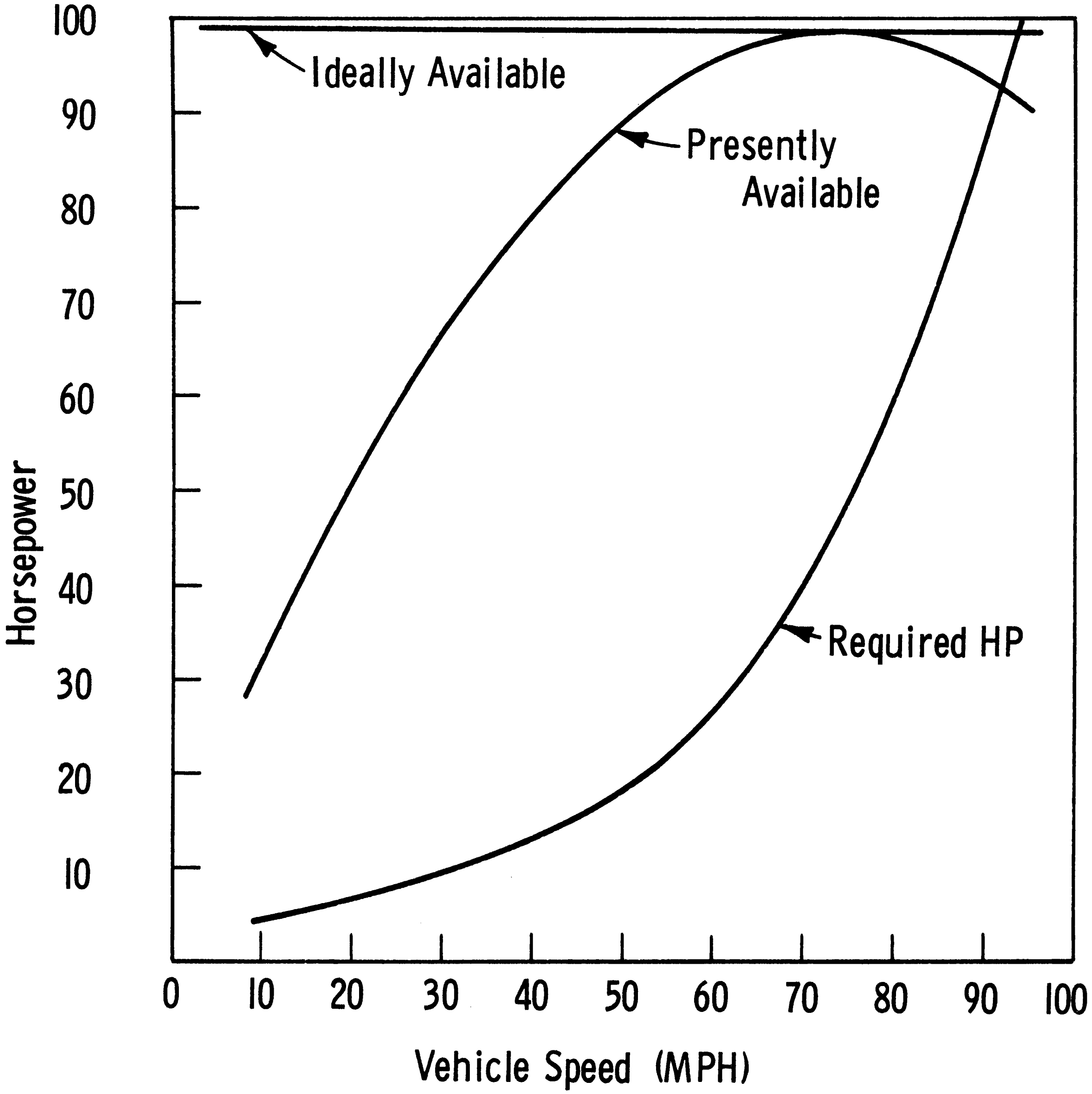

Fig. 3. Maximum power utilization (typical automotive data).

develop its maximum power over a very restricted speed range because of the limitation of fixed gear combinations. This could mean that a 100 hp engine, for instance, is only able to develop its full power at a few discrete vehicle speeds, and that its actual average output power would be considerably less than 100 hp. This problem can be partially alleviated by an increased number of gear steps, but the practical limitations to such an approach seriously restrict the full utilization of engine potential. Ideally, the engine would be able to produce maximum power at all vehicle speeds, as represented by the horizontal maximum power line in Fig. 3. Operationally, such a vehicle would have much better acceleration and hill climbing abilities than present vehicles, especially at lower speeds. It would also have a slightly higher maximum speed if its engine developed its maximum power at less than its maximum speed, as most engines do.

Both minimum fuel consumption and optimum power utilization are functions of the transmission and the engine. That is, the two components should be matched for best performance. Thus, a transmission that gives good performance with one engine may be unsatisfactory with a different power plant, even of the same size, if the second engine has different specific fuel consumption and speed-power curves.

1.3. SECONDARY FACTORS

In addition to the two primary operating factors, there are a number of practical considerations that affect the over-all desirability of any specific transmission. The major ones are:

1. Size
2. Weight
3. Reliability
4. Operator skill and fatigue
5. Maintenance
6. Simplicity
7. Cost

Although the relevance of these factors is reasonably clear, some comment is pertinent.

1.3.1. Size

For tanks, the primary concern with size is that the transmission fit in the present available space. Smaller transmissions would probably not permit a smaller vehicle, but might permit additional fuel tanks.

1.3.2. Weight

Weight, in a sense, is similar to size in that excess weight is to be avoided, although no particular emphasis is on lightness. Reduced weight could be used to advantage but should be incidental to the primary objectives.

1.3.3. Reliability

Much thought has been given recently to the reliability considerations of mechanical devices, such as minimum operating hours before replacement or servicing. This is a field by study of its own, well beyond the scope of the present investigation.

1.3.4. Operator Skill and Fatigue

This factor was included because it seemed to have been the primary basis for changing to a torque converter type of transmission. Such human factors are always difficult to express in other than general terms, but an attempt was made here to make an "ease of driving" comparison. The transmission's role in tank steering is as important as its primary motive power function in judging what effect it will have on driver skill and fatigue.

1.3.5. Maintenance

This is related to reliability, but it involves other areas as well. The difficulty of making adjustments and repairs as well as the frequency with which they are needed is of importance. Also involved is the type and present availability of maintenance personnel. Quite obviously, some exotic device that required, for example, specially trained electro-physicists to maintain it would be less desirable than a simple gearbox, regardless of the comparative performance characteristics.

1.3.6. Simplicity

The over-all simplicity of a mechanism is a good indication of how well it will perform in service. Such things as the number of moving parts, the complexity of motions, and the fits and tolerances required all have an effect on how well a transmission will perform on a long tour of rugged service

1.3.7. Cost

Other things being equal, cost is always a deciding factor. For commercial situations, cost considerations are primary reasons for deciding what kinds of transmissions are developed for wide application. Although performance and getting the job done is of first importance in a military vehicle, cost still has an effect in weighing one device against another.

This list of secondary factors is certainly not an exhaustive one, but it does cover some of the practical considerations and it represents the kind of approach that was taken in this phase of the study.

1.4. IDEAL SOLUTION

The most important features of an ideal transmission are its performance characteristics. As pointed out in Section 1.2, the ideal transmission would keep the engine operating along the optimum fuel economy line (Fig. 2) at all times. Thus, it would have to "know" what that line is, and when the engine is on it. Secondly, the transmission would permit the engine to operate at any power output regardless of vehicle speed.

In present vehicles the primary control is the throttle, via the accelerator pedal. This throttle speed control is broadened by the few finite gear ratios that might be available, but the speed of the vehicle and its acceleration characteristics are still primarily dependent on the engine speed.

With an ideal transmission speed, selection would be by power control. The driver would merely select whatever power output he desired, either for acceleration or to meet road load, and the engine speed and transmission ratio would adjust automatically. This could be incorporated in an accelerator-like pedal so the actual driving would be very similar to present methods. However, the driver would immediately feel the extra available power at his command.

The major question is what kind of a transmission would do all of these things? First and foremost, it would be infinitely variable, probably ranging from almost 0:1 to nearly infinity:1 at the other end of the scale. It would have to have some method of knowing engine power output so that it would know what the engine speed should be. Furthermore, it would have to correlate engine and vehicle speed continuously in order to supply the optimum ratio. In addition, it would be small, lightweight, and completely reliable. Although it would be easy to drive, it would also require no maintenance, be simple, and cheap. Lastly, it would be 100% efficient under all conditions.

Quite obviously, such a device does not exist. Although there are various infinitely variable drives, none, except perhaps electric, have been widely developed thus far. Moreover, any device used would need some sort of controlling "brain" to perfect its operation, probably an electronic computer with appropriate feedback and servo regulation. All this is interesting speculation but of little practical importance in itself. However, it does serve as a useful comparison standard for actual working transmissions.

1.5. PRESENT SOLUTION

Today's tank transmissions are based on a finite gear ratio type of operation. The introduction of a torque converter smoothes out the power flow and modifies the ratios somewhat, but the fuel economy suffers in the process because of converter inefficiency. Also, the full engine power is still available at only a few parts of the total operating range.

SECTION 2

PROJECT AIMS

2.1. GOALS

Most of the goals of this study have been hinted at in the preceding general discussion. The actual goals are to improve the transmission without years of drawn-out research. These goals are threefold:

(1) Maximize ton miles per gallon. This is primarily a question of fuel economy. It was shown that transmissions reduce fuel economy by absorbing power themselves and by forcing inefficient engine operation. Therefore, the foremost aim of this study is to reduce these two factors.

(2) Maintain or improve performance. It was assumed that present tank performance (i.e., acceleration, gradeability, speed range, etc.) is satisfactory. Therefore, the primary effort in this area was to insure the maintenance of present standards, as well as improving them when possible.

(3) Provide acceptable size, weight, reliability, operator skill and fatigue, maintenance, simplicity, and cost qualities. This statement is self explanatory. The question of what is acceptable is a difficult one to determine in any context. For the most part, present solutions were used as a comparison guide when examining various transmissions.

2.2. BASIS OF EVALUATION

2.2.1. Prohibitive Factors

First, all transmissions studied were examined to see if they could be made to function in a tank. Many of the less developed or unusual varieties were immediately eliminated because they were definitely unsatisfactory for one reason or another.

2.2.2. Efficiency

Once it was determined that a transmission was able to function in a tank, its efficiency was examined. Its efficiency is primarily a question of how much energy is lost in the transmission. The matter of matching engine characteristics cannot be realistically done without knowing the the engine type. Moreover, the most desirable transmissions on an efficiency basis all have about the same flexibility in matching the engine.

2.2.3. Other Factors

This involves evaluating the relative advantages (size, weight, etc.) of one transmission over another. These were quite influential considerations in some cases.

2.2.4. Development Status

Because some transmissions have had a great deal more development than others, they have a definite advantage as far as immediate improvements in present tanks is concerned. A gross attempt was made to estimate the time needed to develop various improvement recommendations into working equipment.

2.3. PRESENT STATUS

It is understood that this study is primarily concerned with improving the T95 tank equipped with four forward and 2 reverse speed planetary gear sets and torque converter type transmission and clutch steering. However, the study is equally valid for any tank which has these general characteristics.

SECTION 3

TRANSMISSION EVALUATIONS

The transmissions investigated in this study have been grouped under the classifications of mechanical, hydrodynamic, hydrostatic, and electric. A discussion of combined drives, or power shunt transmissions was also included.

3.1. MECHANICAL TRANSMISSIONS

The numerous mechanical devices that transmit power have been subdivided here into very practical categories. First is the collection of mechanisms that illustrate various principles but have for one reason or another proved impractical for general commercial application. Representative of this category are the variable throw, mechanical differential, and inertia transmissions, which are surveyed herein. The Curtiss-Wright toroidal drive is a special case and may prove to be commercially satisfactory. The second category is that of the well developed mechanical transmissions. This includes the harmonic drive, conventional countershaft gearsets, and planetary gearset transmissions.

3.1.1. Variable Throw Transmission

This type of transmission provides continuous or infinite variation of the torque ratio. It consists of two or more members to which a reciprocating or oscillating motion can be imparted by the engine, and which in turn imparts a corresponding angular motion to a rotating member connected to the driving axle. Usually only one phase of the motion is transmitted to the rotating member; a roller clutch or equivalent device is used for this purpose.

Since 1903, when a transmission of this type was used in an experimental truck, other transmissions have been developed but no commercial success has been realized. All of the transmissions use roller ratchets or similar devices which are subjected to severe stress cycles and hence have very short lives.

<u>Advantages</u>:

(1) Continuously variable gear ratio.

Disadvantages:

1. (1) Short-lived ratchet devices.
2. (2) Irregular power flow.
3. (3) High power loss at low reductions.

The ratchet drive makes this transmission unsuitable for the rugged high-power demands of tank application.

3.1.2. Mechanical Differential Transmission

It is possible to build a transmission in which the power is divided and transmitted mechanically along two paths. An arrangement of this type is illustrated in Fig. 4, and although it may not have practical value for commercial applications, it provides a good explanation of the principles involved. The apparatus comprises a mechanical differential, shown here as of the bevel-pinion type, with a spur-type crown gear that meshes with another spur gear on a countershaft parallel with the differential shafts. In this case the two spur gears happen to have the same number of teeth, but they need not. The shaft carrying the left-hand differential side gear is the input; the shaft carrying the right-hand side gear is the output. There are conical pulleys on the countershaft and the output shaft, and a belt runs over these pulleys.

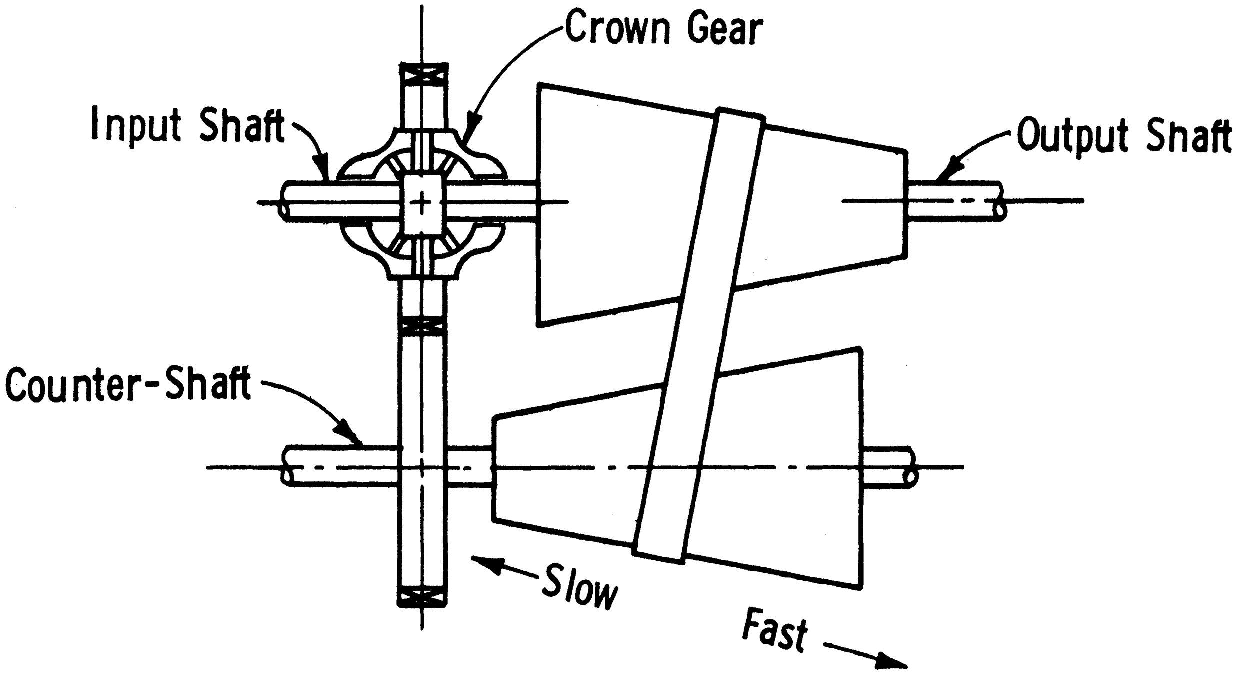

Fig. 4. Mechanical differential transmission.

Speed and torque conversion ratios for such a transmission are readily computed. Assuming the belt to be removed, if the crown gear is held stationary, the input shaft will have to make one right-hand revolution for every left-hand revolution of the output shaft, and if the output shaft is held stationary, the input shaft will have to make two right-hand revolutions for every right-hand revolution of the crown gear. Normally, with the speed relation between the output shaft and countershaft fixed by the belt, the crown gear will turn in the opposite direction to the output shaft; the number of revolutions of the input shaft required for one revolution of the output shaft is then equal to the sum of the revolutions which would be required: (1) to impart one revolution to the output shaft with the crown gear stationary, and (2) to impart to the crown gear—with the output shaft stationary—that number of revolutions which, owing to the drive ratio in the power shunt, corresponds to one revolution of the output shaft. In a differential of the type illustrated in Fig. 4, the output shaft always turns in the direction opposite to that of the input shaft.

Advantages:

(1) Continuously variable gear ratio.

Disadvantages:

(1) Short-lived ratchet or friction devices.
(2) Irregular power flow.
(3) Low power capacity.

The dependency on friction connections makes this transmission unsuitable for tank use.

3.1.3. Inertia-Type Transmission

This is another device that mechanically provides continuous or infinite variation of gear ratio. Continuous variation is possible with such devices as expanding and contracting pulleys, and friction discs and wheels. These methods were used in the early years of the automobile, when powers to be transmitted were small and users had to be satisfied with cumbersome, inefficient transmission mechanisms because nothing better was available. Only the Dutch Daf automobile now has such a drive, and this is possible because of its very low power and low expense.

There are two types of mechanisms regarded as positive in action, both of which incorporate roller ratchets or equivalent devices. Figure 5 is a diagram illustrating how mechanical inertia can be made to transmit power from one shaft to another in such a manner that the torque ratio changes automatically in accordance with variations in the torque load. "A" is the driving shaft—a crankshaft—from which a connecting rod extends to a balance lever. One arm of the balance lever connects through a link to the pendulum "C," while from the other arm two links connect to oscillating levers fulcrumed on the driven shaft "B." These levers carry pawls that engage with a ratchet wheel on the driven shaft.

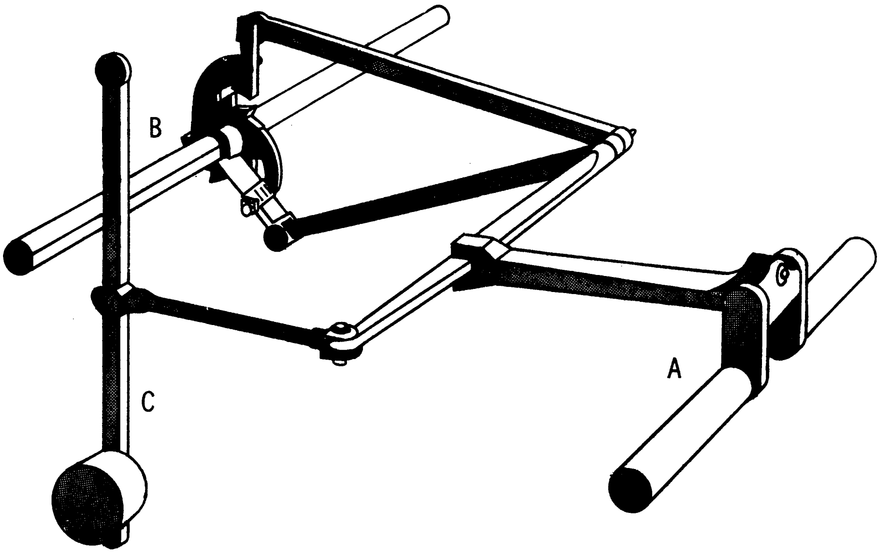

Fig. 5. Inertia-type transmission.

First assume the forward ends of the pawl links to be connected directly to the crank. The driven shaft will be moved through a definite angle by the pawls during each crankshaft revolution, hence there will be a definite speed ratio and also a definite torque ratio between the driving and driven shafts. ("Torque ratio" refers to the average torque on each shaft during one revolution of that shaft, and not to the instantaneous torques.)

The introduction of the balance lever and pendulum will have the following effect on the transmission of power. Assume that the crank is in its dead center position and the pendulum at the end of its swing toward the left, so that it is momentarily at rest. As the dead center position is passed, the pendulum must be accelerated, which requires that its inertia be overcome. The force required to overcome this inertia is proportional to the acceleration. From the theory of crank trains it is known that the acceleration is maximum at the beginning of a stroke or swing. The pull of the link on the pendulum will be a maximum at the beginning of the swing toward the right. While the pendulum is being accelerated, work is being done on it and energy stored in it. Owing to the balance lever, the pull on the pendulum during the period of acceleration is equaled by the pull on one of the pawl links, or, more precisely, by that component of the pawl-link pull which is parallel with the pendulum link.

Advantages:

(1) Continuously variable gear ratio.

Disadvantages:

(1) Dependent on friction or ratchet devices and are accordingly short lived.
(2) May have irregular power flow.
(3) Low power capacity.

Here again the defects of friction or ratchet-type mechanisms make inertia transmissions unsatisfactory for tank application.

3.1.4. Toroidal Drive

The toroidal drive developed by the Wright Aeronautical Division of Curtiss-Wright Corporation is shown in Fig. 6. Torque is transmitted through this drive by the rollers, which roll on both the driven and driving discs. The position of the roller determines the speed ratio between input and output shafts. Although it is referred to as a friction-type drive, this device does not have sliding elements. The contact between moving parts is a rolling-type contact, such as that found in anti-friction bearings. As in anti-friction bearings, the local Hertzian stress is quite high, in the neighborhood of 250,000 psi. However, the life of the drive has not been found to be limited by this stress, but rather by the stress in other bearings in the unit. Satisfactory life can be obtained, but at the cost of the drive. The loading cam shown between the input shaft and the driving disc

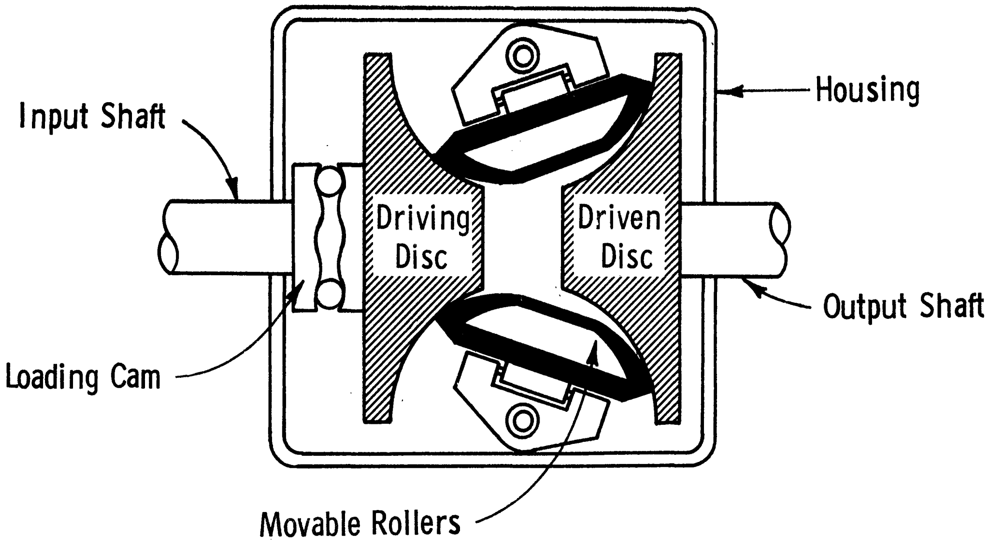

Fig. 6. Toroidal drive.

applies a compressive force between the two discs which is roughly proportional to the input torque, so that the load on the rolling members of the drive is proportional to the torque transmitted. Therefore, the loads at low power and low torques are lower, thereby extending the life of the unit.

The speed ratio is changed by varying the rolling radius of the roller on the driving and driven discs. Because of the loads, the rollers cannot merely be rotated to change the speed ratio. Instead, they are translated in their plane of rotation to get off the tangential rolling point of the disc. A reaction force is then generated between the rollers and the discs, which causes the roller to seek a new position. A full change in ratio is accomplished within twenty revolutions of the input shaft by this means. The current model has a 2.83:1 ratio possible at full inclination of the roller. Since the drive is symmetrical, this ratio is available as an increase or decrease in the input-output speed ratio, so that the over-all drive ratio is 8:1. The translation of the rollers is accomplished by means of hydraulic pressure which acts on a piston to move the rollers.

Various types of control systems may be built to control the ratio in any predetermined program. For instance, in a vehicle application, the ratio may be held so that the maximum fuel economy point of the engine is used as the operating point at any particular horsepower.

This drive differs from existing toroidal drives in that (1) only the inner half of the toroid is used, and (2) the rolling diameter of the rollers is less than the diameter of the toroid section. All parts of the drive are constantly wetted by lubricating oil.

Accelerated life tests have been run on the unit and satisfactory life has been found, without failure of the rolling surfaces. As mentioned earlier, the bearing failures are the prime failures. The efficiency of the unit varies between approximately 83 and 93% over the full speed range.

Advantages:

(1) Continuously variable gear ratio.
(2) Compact and lighter in weight than comparable countershaft gearsets.

Disadvantages:

(1) Very new and undeveloped.
(2) Efficiency drops off at extreme reduction ratios.

Because the toroidal drive is new and as yet unproved, it is hard to evaluate. The high Hertzian stresses of 250,000 psi would seem to be the limiting factor common to other friction drive devices, but this may not be prohibitive. Otherwise the drive has good efficiency and could be very promising.

3.1.5. Harmonic Drive

In the harmonic drive, a travelling deflection wave is generated which is capable of producing extremely high torque leverage, high thrust, and positive power transmission. A harmonic drive provides unusually high reduction ratios and torque capacities for a given physical volume and weight (1/3 the volume and 1/2 the weight of similar spur gear reduction units).

While a harmonic drive can be applied to many forms of motion conversion systems, it is most easily explained in terms of rotary-to-rotary mechanical transmission. A schematic form of rotary-to-rotary harmonic drive is shown in Fig. 7. Two toothed parts are employed which mesh together in a manner similar to splines. The outer part is a rigid, fixed, circular ring with internal spline teeth. The inner part, called a "flexspline," is a flexible ring carrying external spline teeth. The third element is a "wave generator" which rotates within the flexspline and deflects it slightly from its natural circular form into an ellipse-like shape called an "elliptoid." For the two-lobe wave generator shown, the flexspline is deflected into splined engagement with the circular spline at two diametrically opposite regions on the major axis of the elliptoid. Teeth of the two splines are fully disengaged at the minor axis.

The teeth on the flexspline and circular spline are usually cut to the same circular pitch, with the smaller flexspline carrying slightly fewer teeth than the circular spline. For a two-lobe system having two regions of tooth engagement, the difference in number of teeth on the two splines must be 2, 4, 6,...i.e., an integral multiple of the number of lobes. The pitch circle of the undeflected flexspline is made smaller than that of the circular spline by an amount corresponding directly to the difference in the number of teeth.

As the wave generator is rotated clockwise, the flexspline rotates slowly in a counterclockwise direction relative to the circular spline. For a full rotation of the wave generator, the flexspline counter-rotates by the difference in the number of the teeth on the two splines, which corresponds to the difference in the circumferences of their two pitch circles.

So far only the case in which the circular spline is fixed with the flexspline and wave generator free to rotate has been considered. For this case the result is a high negative reduction ratio. If the flexspline were fixed the output would be a high positive reduction ratio. For the case where the wave generator is fixed the reduction ratio is near unity and positive.

The present minimum reduction ratio is 60/1 with practically no limit on the high side. Therefore, the primary use of the harmonic drive is with turbine power sources. The efficiencies of the units are quite high until very high reduction ratios ($10^5/1$) are reached (see Fig. 8).

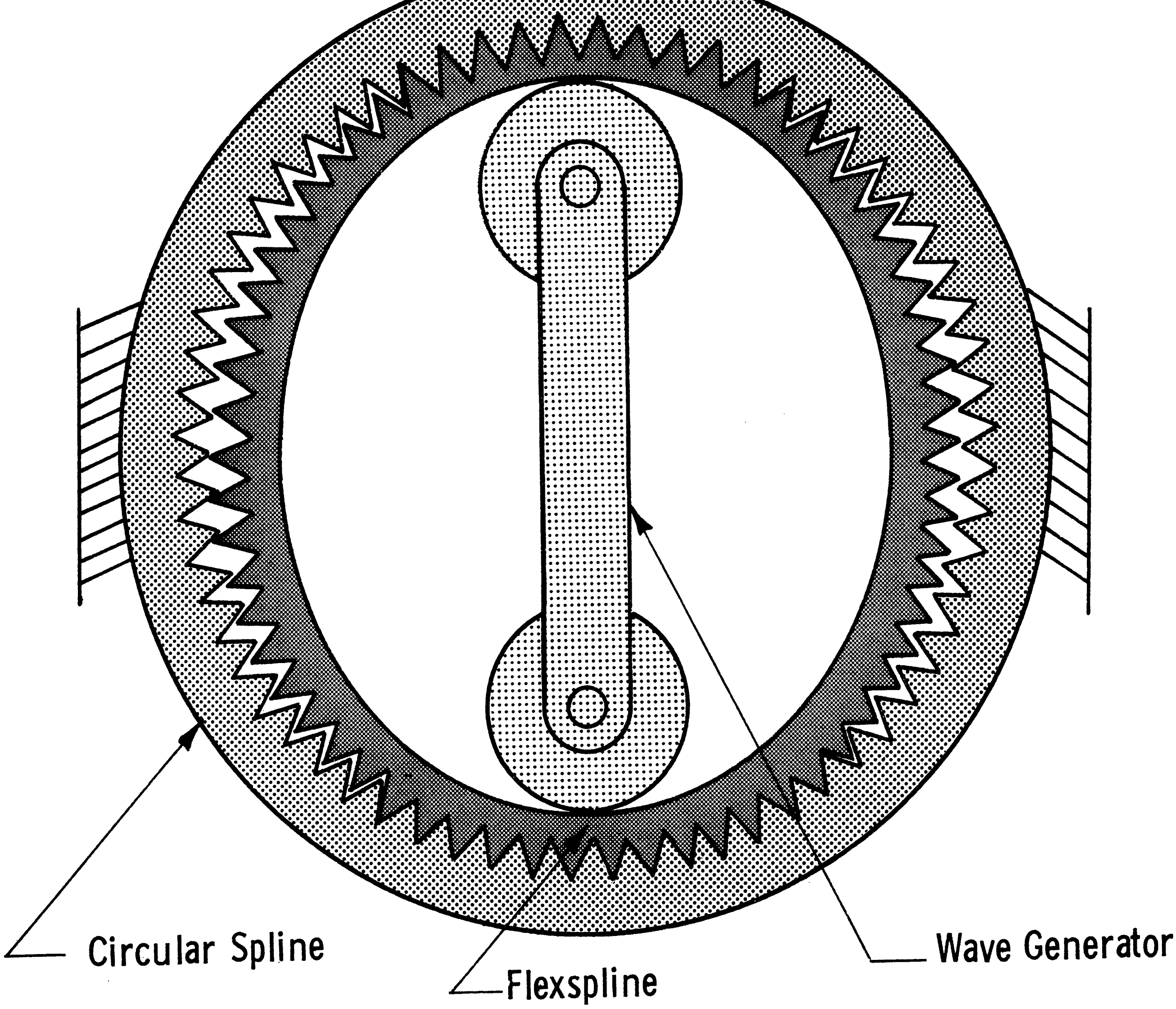

Fig. 7. Rotary-to-rotary harmonic drive.

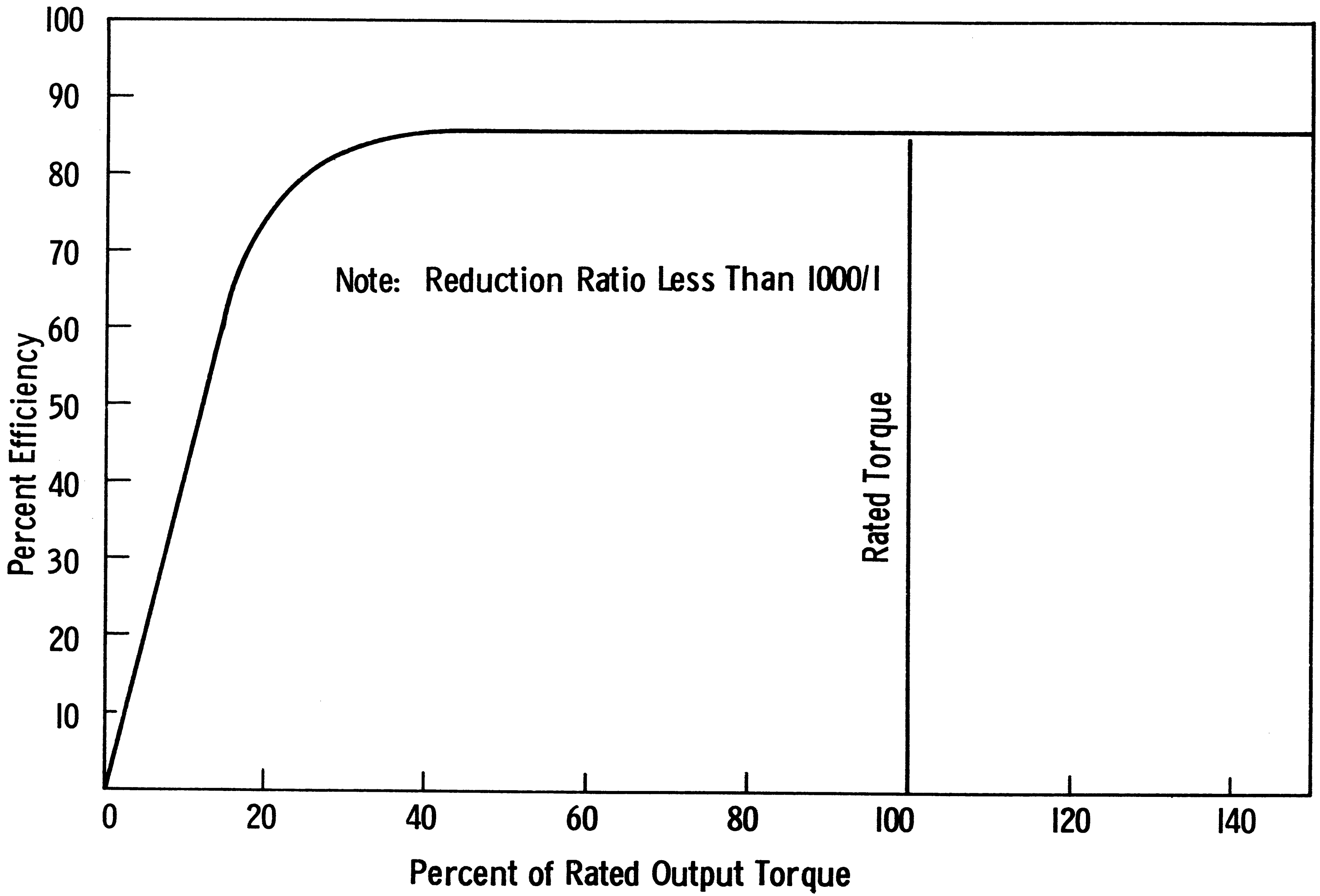

Fig. 8. Single-stage harmonic drive efficiency.

Advantages:

(1) Extremely high gear reduction.
(2) High torque capacity.
(3) Favorable efficiency.
(4) Very compact.
(5) Low wear.

Disadvantages:

(1) Minimum reduction ratio of 60/1.
(2) Very high reductions have low efficiencies.

For a turbine-powered vehicle the advantages of a harmonic drive would merit serious consideration. However, for conventional piston-powered vehicles the large reduction ratio is no longer necessary and other transmission types could very well be more desirable.

3.1.6. Countershaft Gearsets

The relative simplicity and low cost of the mechanical gearbox established the countershaft gearset type of transmission in the earliest days of the automotive industry and until recent years has kept it ahead of most of its competitors. It has the advantage of very high efficiencies while remaining simple and inexpensive to manufacture. Since it has been in use for many years it has been adapted to many applications and is very reliable.

The reason for the decline of the mechanical gearbox in recent years is that automatic transmissions have eliminated shifting and thereby made operation simpler and less fatiguing.

Advantages:

(1) High efficiency.
(2) Very reliable, well developed.
(3) Simple, rugged.

Disadvantages:

(1) Limited to finite gear steps.
(2) Operator shifting can become complicated and fatiguing.

The very wide use and application of countershaft gearsets are the best testimonial of their desirability that a transmission could have. Therefore, they are a prime contender in any evaluation.

3.1.7. Planetary Gearsets

The planetary gearset is essentially a variation of the countershaft gear arrangement with a rotating countershaft (planet carrier) and a ring gear. Because it is more expensive than countershaft gearsets it has not been used as widely. However, automatic transmissions invariably utilize planetaries as they are constantly in mesh and are consequently adaptable to hydraulic clutch control.

Since countershaft and planetary gearsets are merely variations of the same principle drive mechanism, they are best evaluated in comparison to each other.

Advantages:

(1) More compact than countershaft gearsets.
(2) Slightly more efficient than countershaft gearsets.
(3) Usually in constant mesh, which facilitates shifting under power and with less chatter than countershaft gearsets.
(4) Quieter than countershaft gearsets.
(5) Shifting is easier than with countershaft.

Disadvantages:

(1) Limited to finite ratios.
(2) Some ratios difficult to obtain with planetary.
(3) Additional clutches are necessary which are expensive and complicated.

From an operational point of view, planetary gearsets are somewhat more desirable than countershaft gearsets. With hydraulic clutch shifting, operator fatigue can be reduced considerably compared with a manual countershaft transmission. This along with their excellent efficiency makes planetary gearsets the leading contender for basic power transmission.

3.2. HYDRODYNAMIC METHODS (Torque Converter)

A hydrodynamic torque converter is a device for converting torque by making use of the kinetic energy of a fluid in motion. The simplest form of a torque converter consists of three vaned wheels: (1) an impeller secured to the input shaft, (2) a runner secured to the output shaft, and (3) a reaction member fixed in position. All three are enclosed in a housing filled with hydraulic fluid. The impeller serves to impart a whirling motion to the fluid, and the reaction member changes the direction of the whirling motion between the runner outlet and the impeller inlet in such a way that the kinetic energy left in the fluid helps to drive the impeller. Without a reaction member in the converter, only the input torque would be transmitted, and no torque multiplication could take place.

The chief advantage of the hydrodynamic torque converter is that its torque ratio changes automatically in accordance with load conditions and without interruption in the flow of power. In a motor vehicle the torque ratio of the converter is a maximum when the vehicle is being started from rest or, in general, when the greatest difference exists between the driving and driven speeds. Torque ratios on the order of 6:1 have been reached for three-stage converters. Torque converters are usually combined with a reducing gear when high ratios are desired since they do not operate best when designed for high ratios. From developments carried out to date it does not seem practical to use a torque converter as the sole means of power transmission in automotive vehicles under all operating conditions, because the requirements of a high starting torque, a wide range of torque multiplication, and a high mean operating efficiency cannot be satisfactorily met. However, the converter can be used as a means for accelerating the vehicle to a speed at which it can be handled by the engine in direct drive. It permits continuous shock-free acceleration and eliminates wear and tear on friction clutches.

Hydrodynamic torque converters can be used in all applications from small vehicles through heavy trucks.

Advantages:

(1) A wide range of variable ratio allows the torque converter to vary speed and torque ratios gradually while under load (see Fig. 9).
(2) The torque converter provides smooth starting and shockless acceleration, which adds to engine and drive line life by damping vibrations.
(3) A torque converter in the drive line eliminates engine lugging and overspeeding, which increases engine and drive line life.
(4) A feature may be incorporated to provide downhill braking.
(5) By eliminating or minimizing gear shifting, the torque converter reduces driver fatigue.

Disadvantages:

(1) Higher first cost.
(2) Usually an increase in weight.
(3) Generally higher fuel consumption. This is usually true in passenger cars, in which the utmost in smoothness and a minimum of driver attention has been achieved. Under certain conditions trucks and buses have improved fuel economy, although this is not to be expected.
(4) The torque converter cannot compete with gears for continuous steady operation.

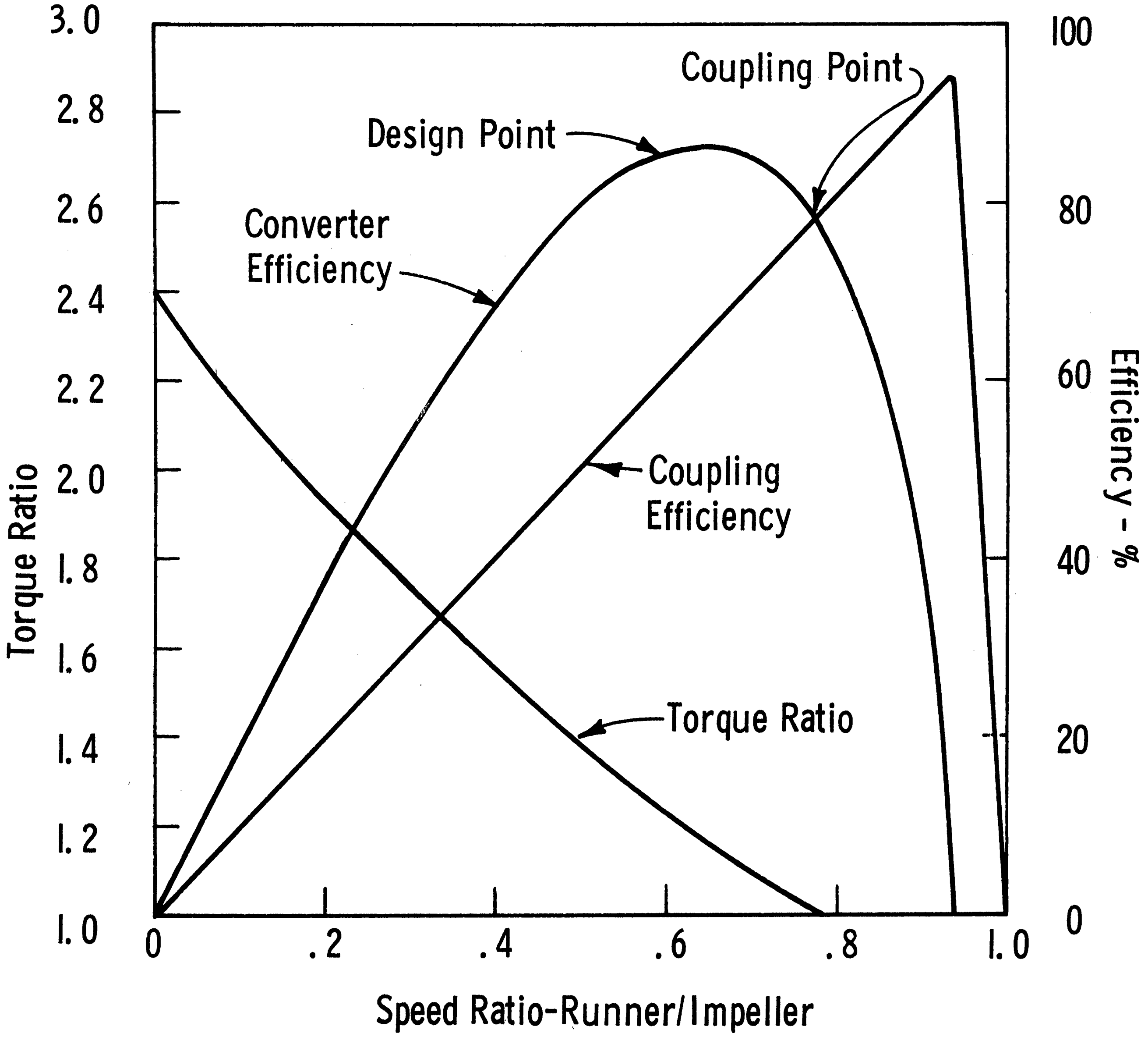

Fig. 9. Characteristics of a conventional three-element converter.

Since a torque converter alone is almost never used as power transmission, a fair appraisal of its merits should be made on the basis of a torque converter and some sort of gearset. This is done in Section 3.3.

3.3. HYDRO-MECHANICAL TRANSMISSION

A hydro-mechanical transmission is one in which a hydrodynamic torque converter is combined with a mechanical transmission (planetary gearset) providing two or more gear ratios and permitting a reverse drive. (Figure 10 gives some typical performance characteristics.) In some cases the hydrodynamic torque converter is combined with a friction clutch, which renders the torque converter ineffective and gives a direct drive under normal operating conditions.

Most of the automotive transmissions of today are of this type and include gear ratio changes to supplement the hydrodynamic drive unit. The functional arrangements of the fluid units with the gearsets fall into three classes:

(1) Input gears in series.
(2) Output gears in series.
(3) Split torque.

These arrangements are discussed here to demonstrate the effect of gears on the combined operation of the engine or vehicle with the fluid unit when gearsets are used in the system. In no instance does the use of the gearset, as discussed here, affect the operational characteristics of the hydrodynamic drive device. Changes in these characteristics can only be accomplished by changing the function of one or more of the components—for example the special use of a reactor as a reverse drive turbine or as a rotating reactor.

Input Gearing. When a gearset is interposed between the engine and the fluid unit, the input engine characteristics vary in a manner directly related to the gear ratio. With an underdrive input the engine performs at lower speeds and higher torque than at normal 1:1 input. Correspondingly, with an overdrive input the engine runs faster and with a torque lower than normal.

Output Gearing. Although in this case the gears are between the torque converter and the road, the over-all effect on engine operation is the same as with input gearing. That is, underdrive causes low-speed, high-torque operation and overdrive causes just the reverse. Therefore, considerations other than engine operation are important when considering the merits of these two possibilities.

Split-Torque Gearing. The term "split torque" describes an operational condition in which the power flow through the transmission is divided between

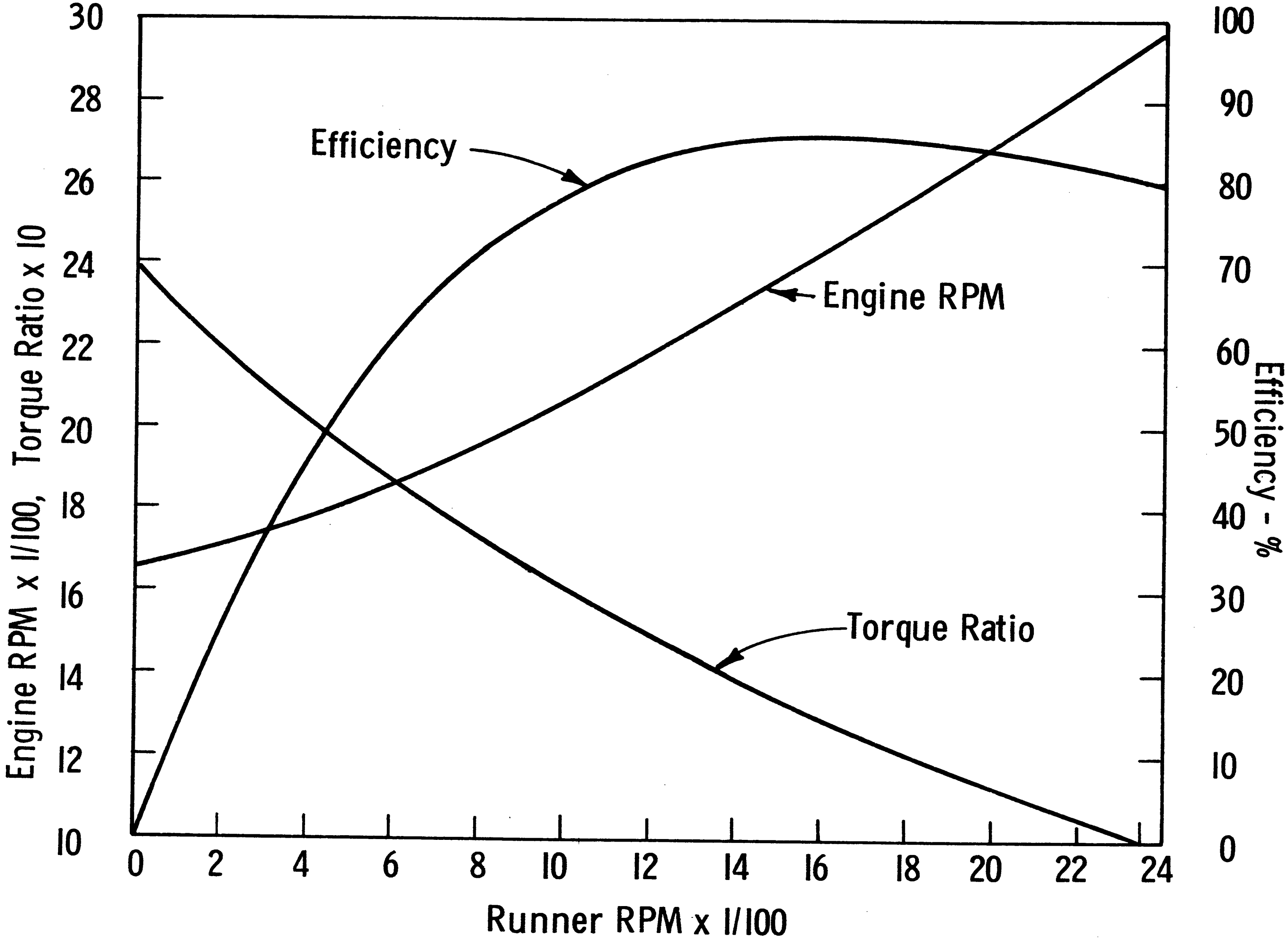

Fig. 10. Typical performance curves of hydro-mechanical transmission for a constant-input torque of 265 lb-ft.

two or more parallel paths: a mechanical path and a hydrodynamic path or paths. Split-torque systems can be divided into two basic arrangements: input splits and output splits. Each of these arrangements can be further divided into pure splits and regenerative or recirculation splits. Pure splits are those in which the torque flow through the hydrodynamic unit is normal and not augmented by feedback torque from the mechanical path. A more complete discussion of this type of transmission is found in Section 3.6, which surveys the basic characteristics of the entire range of multiple-power transmission types.

The advantages and disadvantages are essentially the same as those listed for pure hydrodynamic drive (Section 3.2).

Although torque converters are becoming more common in everyday use, their poor fuel consumption is felt to be some handicap for a tactical vehicle.

3.4. HYDROSTATIC TRANSMISSIONS

Hydrostatic transmissions transmit power by means of fluid under pressure acting upon a moving piston. Energy is given to the fluid by a positive displacement pump and is transmitted to a positive displacement motor, where it is converted to useful work. (Figure 11 gives a comparison of hydrostatic and torque-converter transmissions; Figs. 12 and 13 give some typical operating characteristics for hydrostatic transmissions.) If a variable displacement pump is used with a fixed displacement motor, a transmission is available that can deliver constant torque throughout the full speed range (see Fig. 14). This type of transmission is easily matched to any normal internal combustion engine characteristic. If a fixed displacement pump is used with a variable displacement motor, the transmission is capable of delivering constant horsepower independent of the output speed (see Fig. 15). This type of transmission can be used with an engine running at a governed speed and putting constant horsepower into the transmission.

The hydrostatic transmission is more responsive than any other type of power transmitting device. Vickers has marketed a 50 hp hydrostatic transmission capable of reversing from 8600 rpm clockwise rotation to 8600 rpm counterclockwise rotation, five times a second.

In comparison with the torque converter, the hydrostatic transmission offers a high efficiency curve over a much wider range of speed ratios with very much lower losses in the stalled or near-stalled condition; but because of the absence of a mechanical driveline it does not offer the possibility of lockup or direct drive.

So far transmissions of this type have found use in farm and industrial machinery in the range of small vehicles (farm tractors) through medium

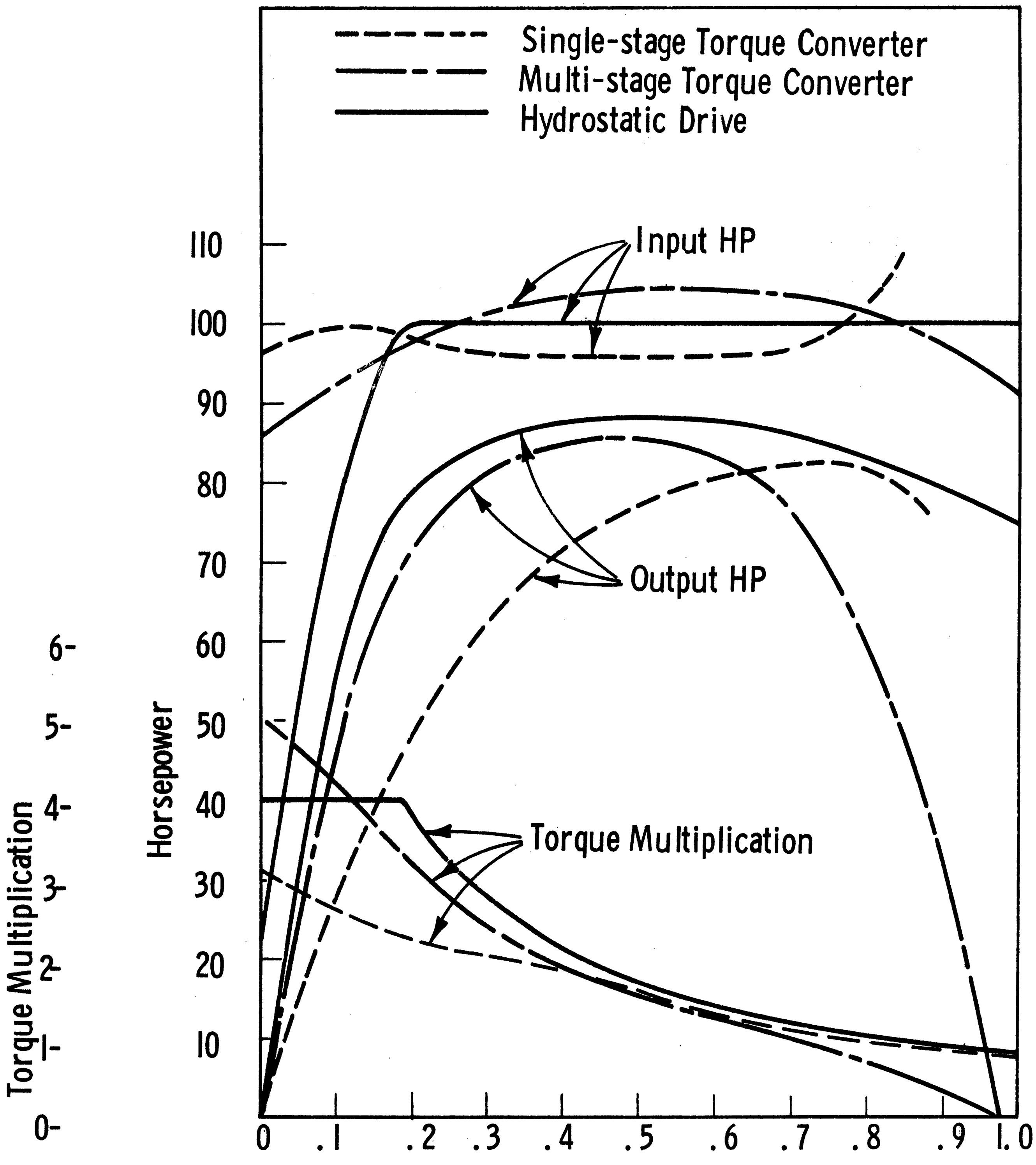

Fig. 11. Comparison of hydrostatic and torque-converter transmissions.

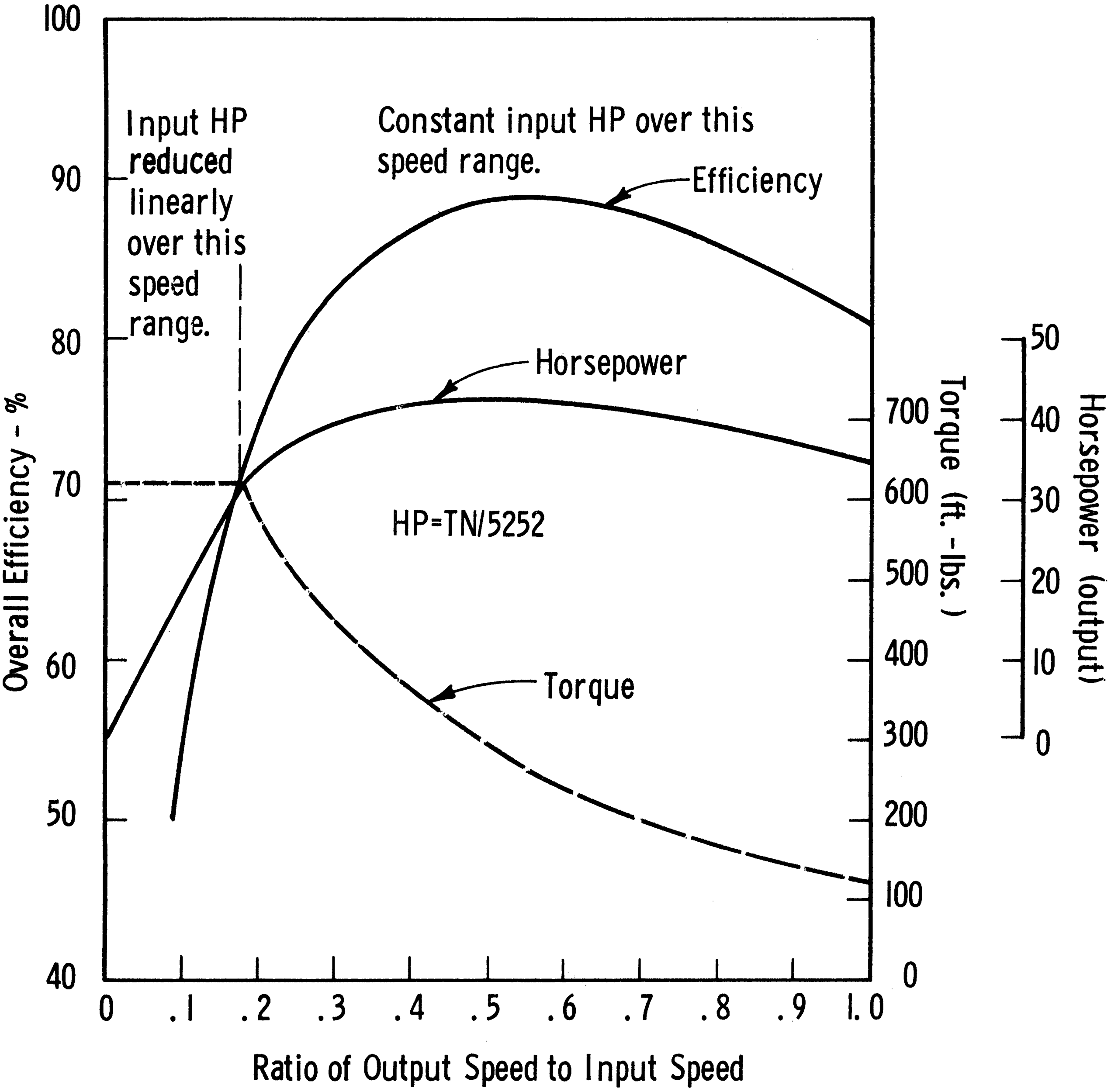

Fig. 12. Performance of complete hydrostatic transmissions (input 45 BHP at 1500 rpm).

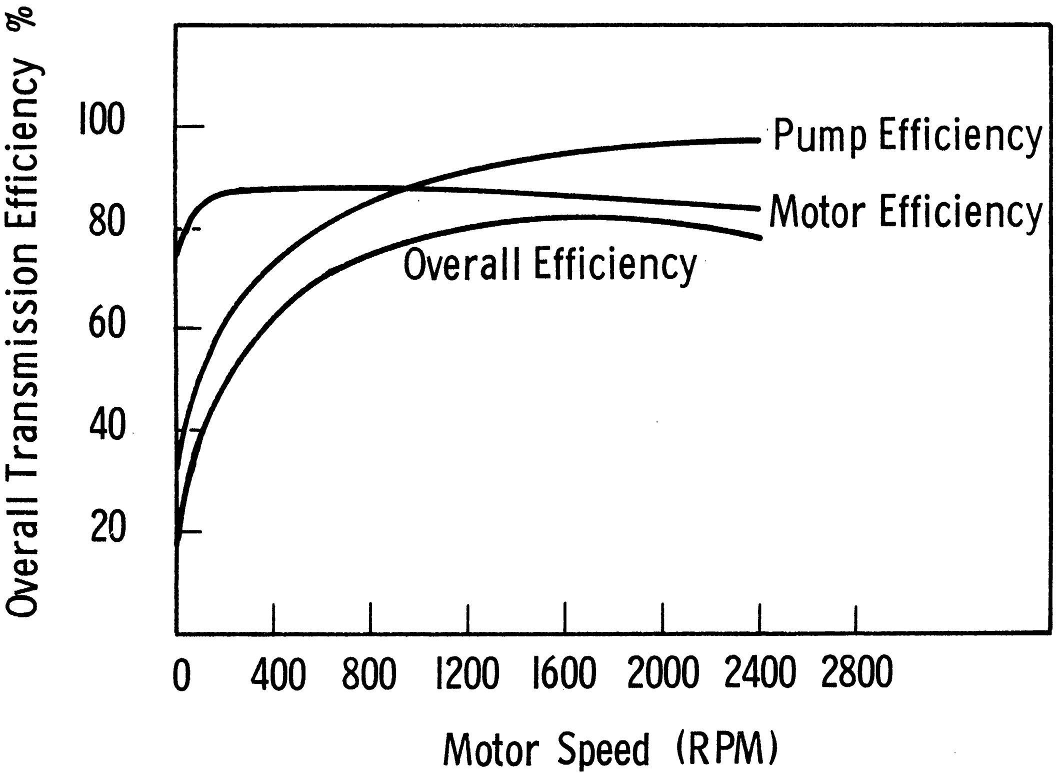

Fig. 13. Efficiency characteristics of hydrostatic transmission for farm tractor (constant 75 hp input; 1 variable displacement pump—2 fixed displacement motors).

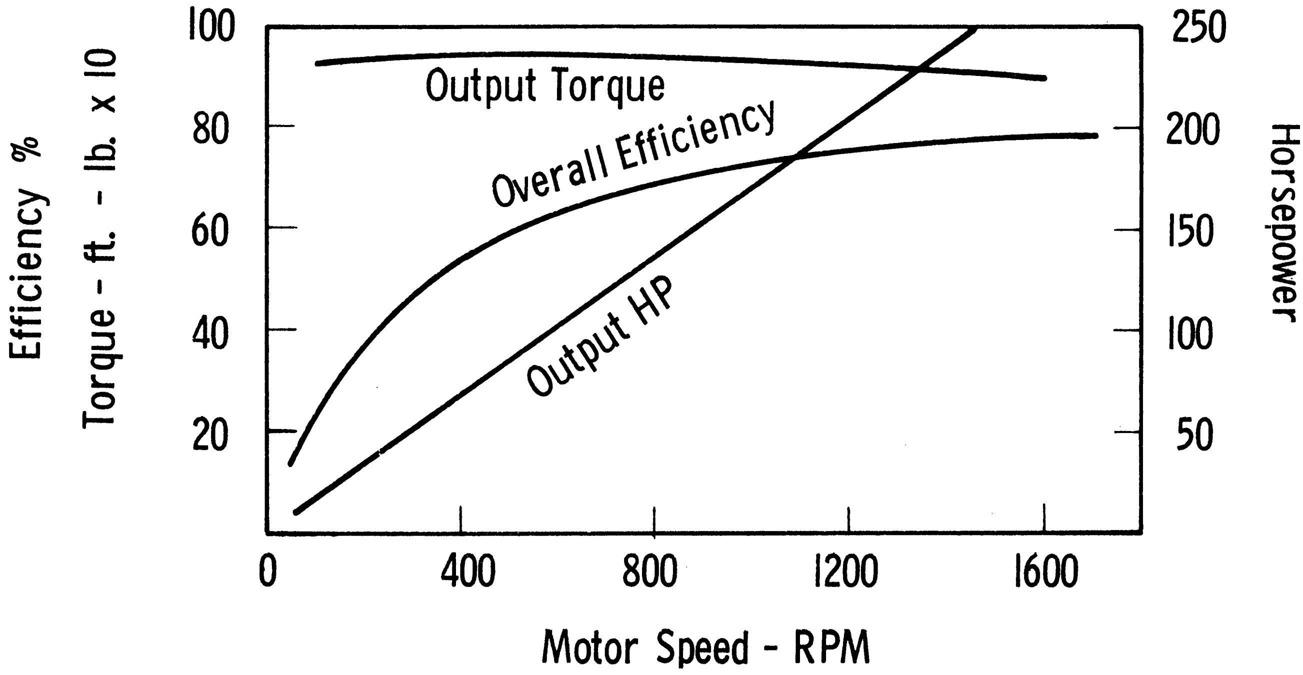

Fig. 14. Typical performance characteristics of variable displacement pump-fixed displacement motor (hydrostatic transmission).

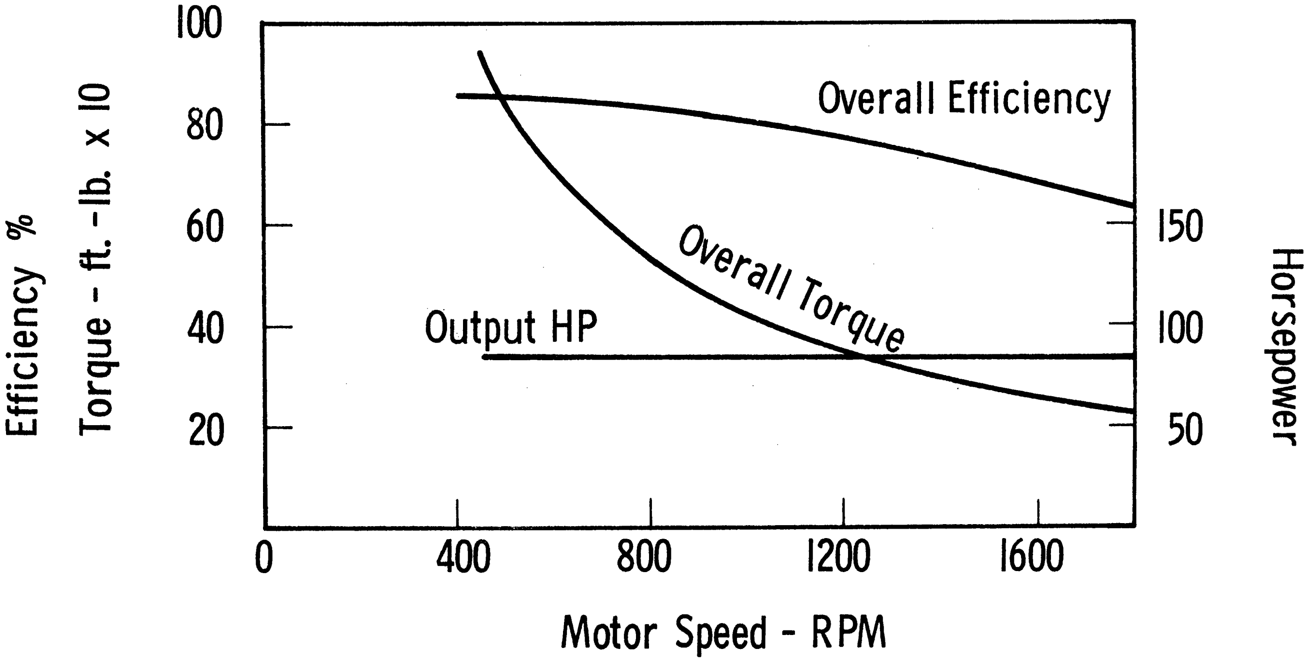

Fig. 15. Typical performance characteristics of fixed displacement pump-variable displacement motor (hydrostatic transmission).

trucks and construction equipment (crawler tractors, shovel loaders, road rollers, and locomotives).

Advantages:

(1) Efficient operation over wide torque and speed range (see Fig. 13).
(2) Infinite, stepless speed and/or torque ratio control.
(3) Produces more torque for less space and weight than any other type of remote actuator transmission.
(4) Withstands full load stall without damage and with low power loss.
(5) Holds selected speed ratio accurately against driving or braking torques up to design limits.
(6) Effortless, shiftless operation.
(7) Remote location of driving motors.
(8) Driving motor can act as a regenerative power source.

Disadvantages:

(1) Relatively new and undeveloped.
(2) High efficiencies require high-pressure (2000-3000 psi) system and precision manufacture—expensive.

The primary disadvantages of hydrostatic drive are first that it has a lower efficiency than pure mechanical drive, and second that it is new and not fully developed. However, it is the most promising of the infinite ratio devices and has the potential to become quite an important transmission.

3.5. ELECTRIC DRIVE

The basic electric drive system consists of a motor-generator set and a number of motorized wheels. The motor-generator set usually consists of a diesel engine driving a generator, the size and types of these components being determined by the output desired from the electric driving motors at the wheels.

The motorized wheel is the heart of an electric drive system and is basically a heavy steel barrel joined to a large mounting flange. The d-c series wound motor and brake are mounted within this heavy steel barrel, which doubles as the vehicle wheel axle and the motor magnet frame. The necessary bearings and reduction gears are contained in the barrel, which makes the whole system complete and compact. From this brief description it is seen that with electric drive, power can be applied to any wheel where a set of power lines can be run.

The d-c series wound motor has the characteristic of high torque at low speeds (see Figs. 16 and 17) so coupled with the proper gear reduction that

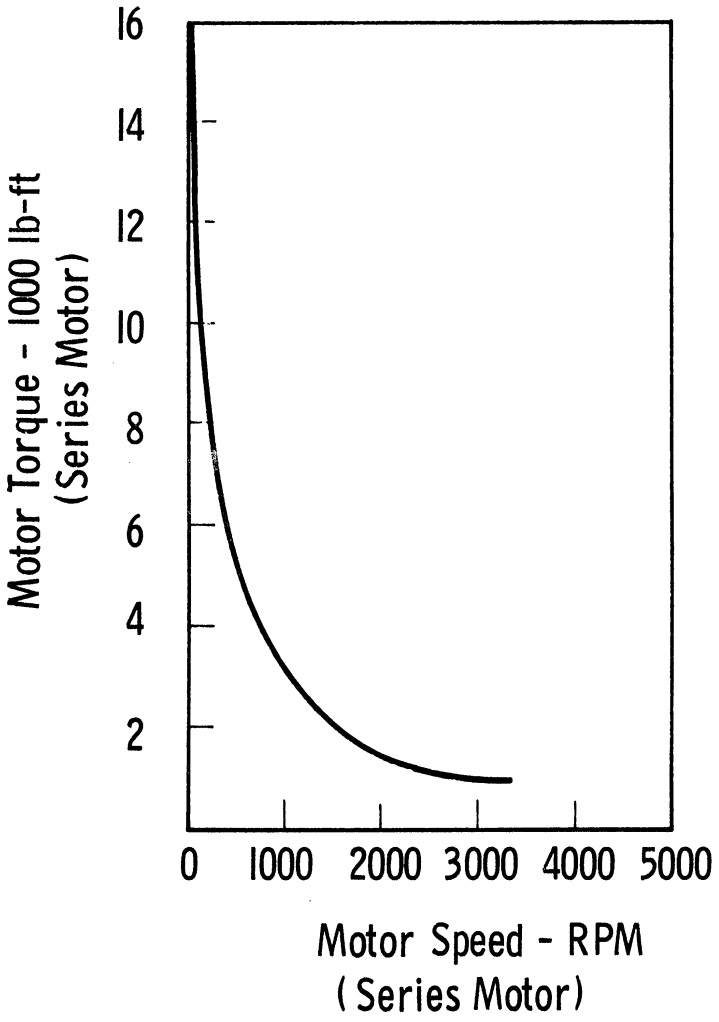

Fig. 16. Speed torque characteristics (4-motor equipment with 600 hp engine). Type: Off highway truck; Tires: 44.5-45, 103 in. rolling diameter; Vehicle Wt.: Approx. 100 tons (loaded).

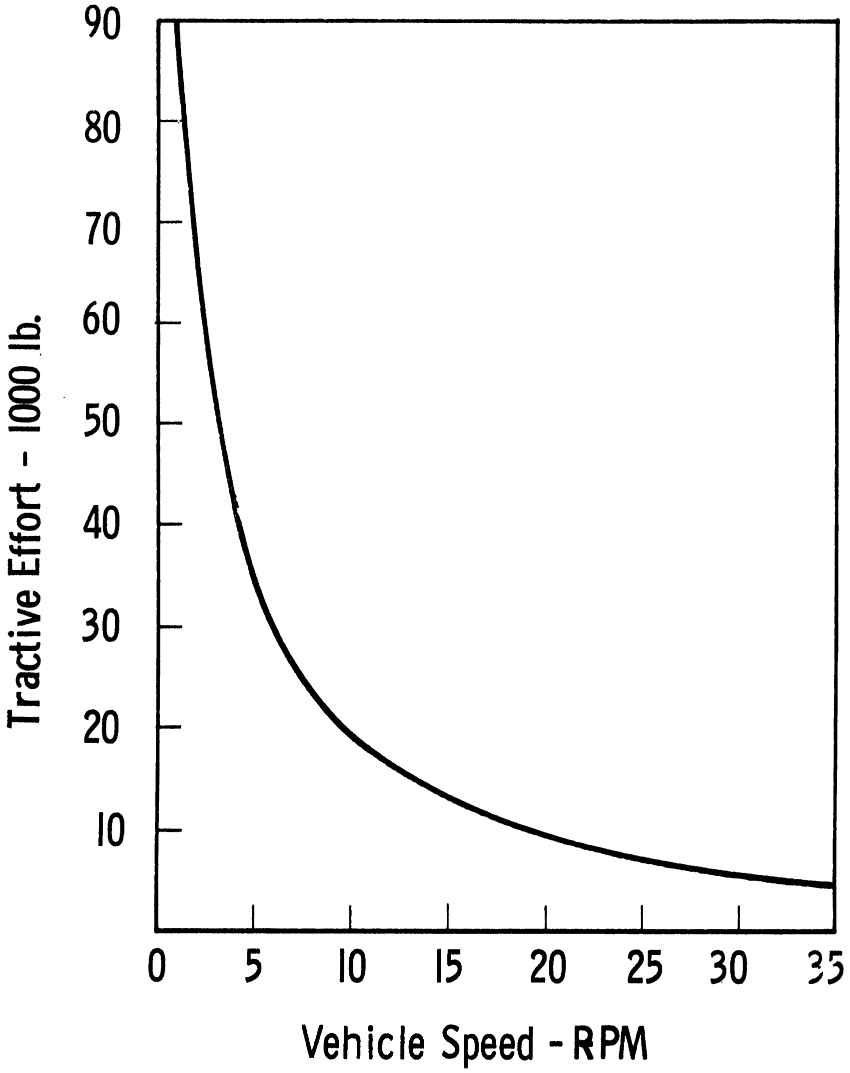

Fig. 17. Vehicle speed-tractive effort curve (4-motor equipment with 600 hp engine). Type: Off highway truck; Tires: 44.5-45, 103 in. rolling diameter; Vehicle Wt.: Approx. 100 tons (loaded).

a high starting torque can be generated. In the particular case of a General Electric unit a gear reduction of 40:1 is used. This provides vehicle speeds up to 35 mph and a maximum tractive effort of 32,400 lb, corresponding to 60% adhesion with 54,000 lb on the 44.5-45 tire at standstill. This means that the maximum allowable motor current at standstill produces a torque that gives a tractive effort of 32,400 lb per wheel.

Vehicles using electric drives are usually the heavy duty or off-highway types.

Advantages:

(1) Reasonably good efficiency (see Fig. 18).
(2) Infinite gear stepping.
(3) Effortless, shiftless operation.
(4) Remote actuator location.
(5) Simple servicing and motor replacement.

Disadvantages:

(1) Prohibitively large and heavy in the past, although recent developments may have eliminated this.
(2) Insulation (for fordability) and cooling problems.
(3) Generator needed at each remote location for pure electric power regeneration.

Although electric drives have received attention from time to time, they have not been very prominent in vehicular applications. Their basic qualities are satisfactory, but the practical limitations have been prohibitive. As more advances are made this may yet become a competitive transmission.

3.6. POWER-SHUNT TRANSMISSIONS

In transmissions of this type engine power is divided, part of it being transmitted mechanically and the remainder being converted into another form—generally either electric or hydraulic—that permits continuous variation of the torque ratio in suitable equipment, and then reconverted into mechanical power and combined with the part transmitted directly. There is a device—usually mechanical (some form of differential or planetary gear) although electric or hydraulic methods may be used—to divide power between the two paths.

These transmissions permit continuous variation of the torque ratio without using a roller ratchet (see Section 3.1.3). With these transmissions only a small part of the total power is subjected to a double conversion so losses incurred in conversion are small. The fraction of the total power which must be converted varies with the torque multiplication required. It is large

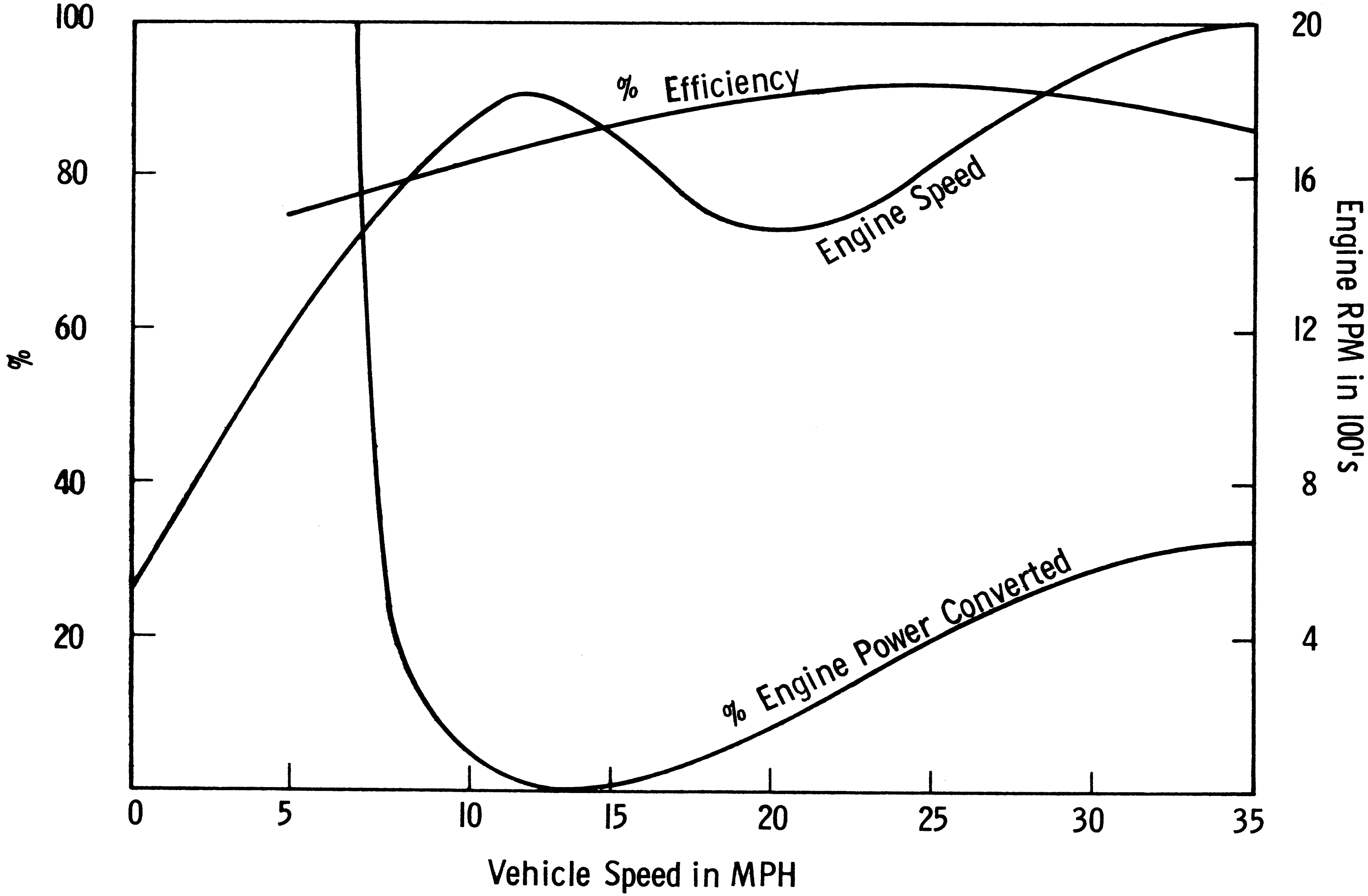

Fig. 18. Characteristics of bus-type, power-shunt transmission (electric). Bus wt. = 18,500 lb; rear axle: $6\frac{1}{6}/1$.

when the vehicle starts from a standstill but reaches a minimum of about 5% when the torque required is only slightly greater than the engine torque.

Possibly equipment for power conversions of this size can be made lighter and smaller than the electric or hydraulic equipment which is necessary when all of the power developed by the engine must be converted. A few transmissions of this type have been built and used in automobiles, buses, and railcars, but the recent trend to hydrodynamic transmissions has slowed their development.

In discussing hydrodynamic split-torque transmissions it is necessary to distinguish between "true split" and "recirculative" arrangements. A true split arrangement is one in which the power is divided and then transmitted through the drive system or transmitted through the drive system and then divided. In a recirculative or regenerative system part of the output power is returned to the input mechanism.

For split-torque arrangements, the following advantages and disadvantages in comparison to straight converter drives may be listed:

<u>Advantages</u>:

(1) The peak efficiency is increased.
(2) The economy ratio is increased.
(3) The converter size is reduced, down to 50%, depending on magnitude of split ratio and converter match point.
(4) The engine speed is reduced as transmission stall is approached.
(5) Some mechanical inertia effects are available which can be useful for various applications, but fluid drive smoothness is still maintained.
(6) On sustained-type converters, the power absorption at low-load, high-speed conditions is reduced.
(7) The planetary gear can be used for an overdrive or other purposes.

<u>Disadvantages</u>:

(1) The availability ratio ($\frac{\text{upper output speed}}{\text{lower output speed}}$ at which output power equals 70% of the engine rated power) is reduced.
(2) The stall torque ratio is reduced.
(3) There is less downhill braking available.
(4) The design is more complicated; there are additional elements which compensate for the reduction of converter size.
(5) The additional losses in gears and clutches may detract from the theoretical efficiency gains.
(6) Torsional vibrations may occur in the driveline because there are additional elements connected to the engine flywheel which are not damped by the converter.

For recirculative systems, the following features are different:

Advantage:

(1) The stall torque ratio is increased for output splits, at least within certain limits.

Disadvantages:

(1) The peak efficiency is reduced.
(2) The economy ratio is reduced.
(3) The converter size is increased.
(4) The engine speed is reduced as high transmission ratios are approached.

Power-shunt transmissions have an advantage in cases such as tracked vehicles where the primary motive power can be transmitted mechanically with low associated losses and the steering power can be transmitted either electrically or hydraulically with much greater flexibility of control. The over-all efficiency in this type of vehicle would be a compromise between the low efficiencies of a hydro-mechanical transmission and the high efficiencies of a pure mechanical unit. The gain would come in the much easier and more flexible control over the vehicle. Figure 19 shows comparisons between the types of transmissions which could be coupled in such a power-shunt transmission.

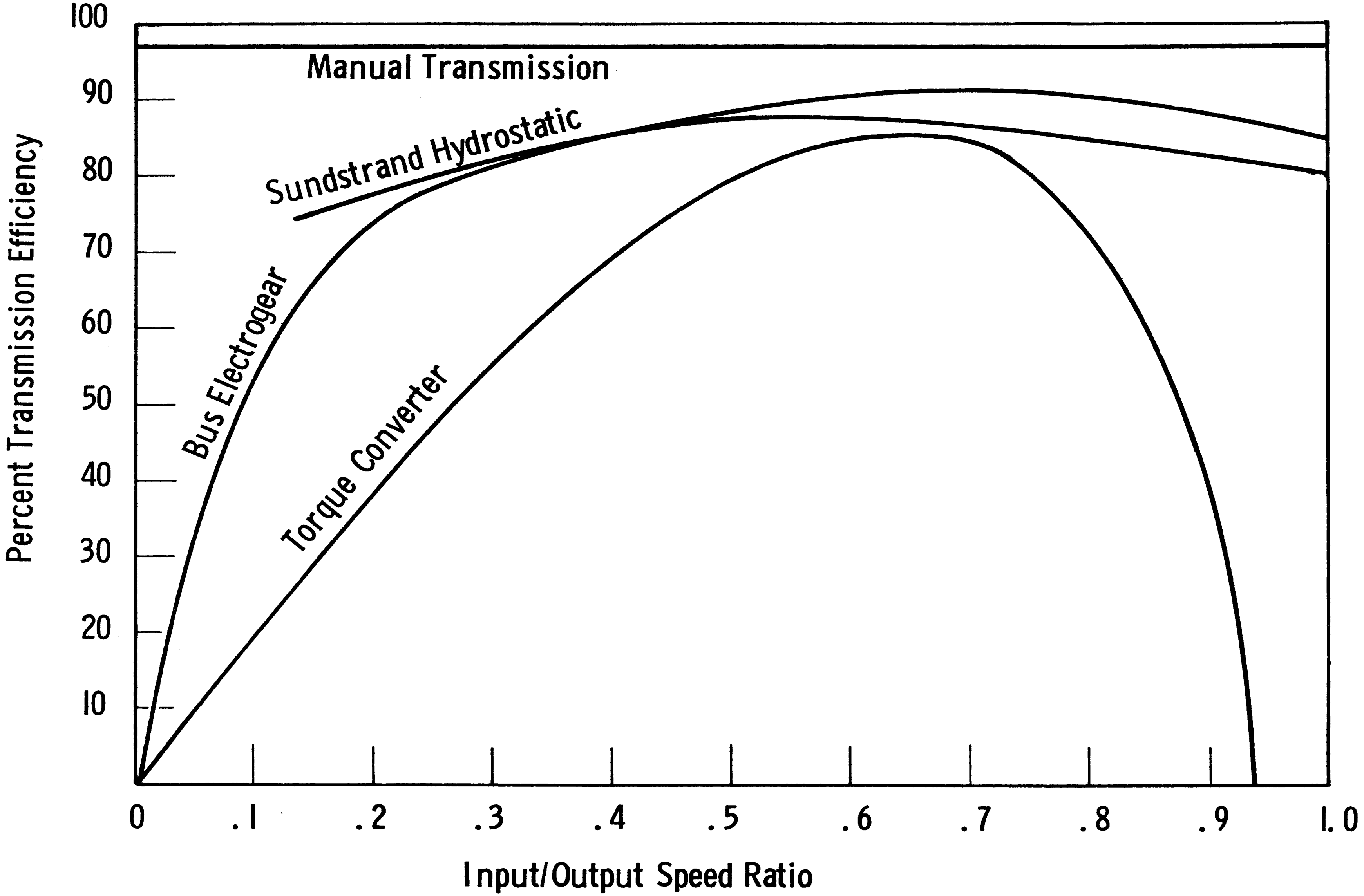

Fig. 19. Comparative transmission efficiencies.

SECTION 4

TANK REQUIREMENTS

Thus far the transmission has been investigated as a separate entity, without reference to its application. However, tanks present rather unique demands because the transmission must not only control the tank's motive power flow but also facilitate steering. Therefore it is appropriate that the steering requirements be studied and the associated transmission needs be formulated.

4.1. STEERING CRITERION

When a tracked vehicle executes a turn it is obvious that the track on the outside of the turn must go faster than the track on the inside. Moreover, this speed difference is not caused by the turn, it is what causes the turn. Thus, the basic problem in effecting a tank turn is efficiently powering and controlling this difference in track speeds.

Furthermore, it is also obvious that if a straight track is to move along a curved path, it must slip sideways, or "slew," as it is called. Naturally, to do this the track must overcome the sideways-resistance forces. These slewing forces vary considerably according to the nature of the terrain and may be in the order of half the tank's weight.

The next point is perhaps best visualized by considering the tank hull as the coordinate reference point. Then, when the tank is turning, the earth describes a curved path under it, and the outside track is moving forward faster than the inside track. In other words the inside track, altough it is moving forward, is the drag or braking force that causes the curved path. Thus during a turn the inside track, relative to the earth, is moving forward but is pulling backward. It is receiving power from the ground. In a sense the ground is being driven by the outside track and is driving the inside track.

As has already been mentioned, the slewing forces range to half the tank's weight. Moreover, the dynamic force needed just to change the direction of the tank's motion can be quite large. Thus the total power for turning can be very high. In fact, according to Merritt, the total steering power can be as much as three times the maximum propulsive power needs. Obviously, it is undesirable to build a 1500 hp engine in a tank that needs only 500 hp to drive it.

Fortunately there is a way to avoid this. As previously described, while the inside track is turning it receives power from the ground. Therefore, if a means is provided for transmitting this power across to the outside track the remaining steering power needs will be within the normal engine capacity.

An effective tank transmission must consequently have a means of creating and manipulating regenerative power and differential speeds between the two tracks. Naturally, the method of steering must be continuous rather than stepped in order to provide satisfactory maneuverability.

4.2. PRESENT SOLUTION

Current tank steering is controlled through a clutch or brake slip power drive to some sort of regenerative steering differential. Figure 20 shows a typical American tank layout. The steering power is taken off the main cross axle by a constant mesh gear and shaft. This then drives the steering differential through clutch connections to either side of the differetial. As a steering clutch is let out, the associated differential pinion starts to drive the two halves of the steering cross axle in opposite directions. These are connected to the output planetary sun gears at either track During straight line operation these sun gears are stationary. However, during turning their opposite rotations are superimposed on whatever motive power rotation may be taking place and give rise to different track speeds and turning. The two tracks are directly interconnected through the steering cross axle and differential, and although the differential is being driven to cause steering, it is still able to transmit the regenerative power from the inside track to the outside one.

The present steering mechanism provides an infinitely variable steering ratio through clutch slip. Accordingly, the maximum turning effort occurs when a steering clutch is completely engaged. Beyond this, individual track braking can provide sharper pivot turns, but only at the expense of total vehicle speed.

The primary disadvantages of clutch controlled steering are twofold. First, until the clutch is completely engaged power is lost via friction heating at the slipping clutch surfaces. Secondly, operating these steering clutches requires considerable skill and can be quite fatiguing, depending on the circumstances. Thus, any changes in steering arrangements should strive to eliminate or reduce these two factors without sacrificing the desirable features of the present solution.

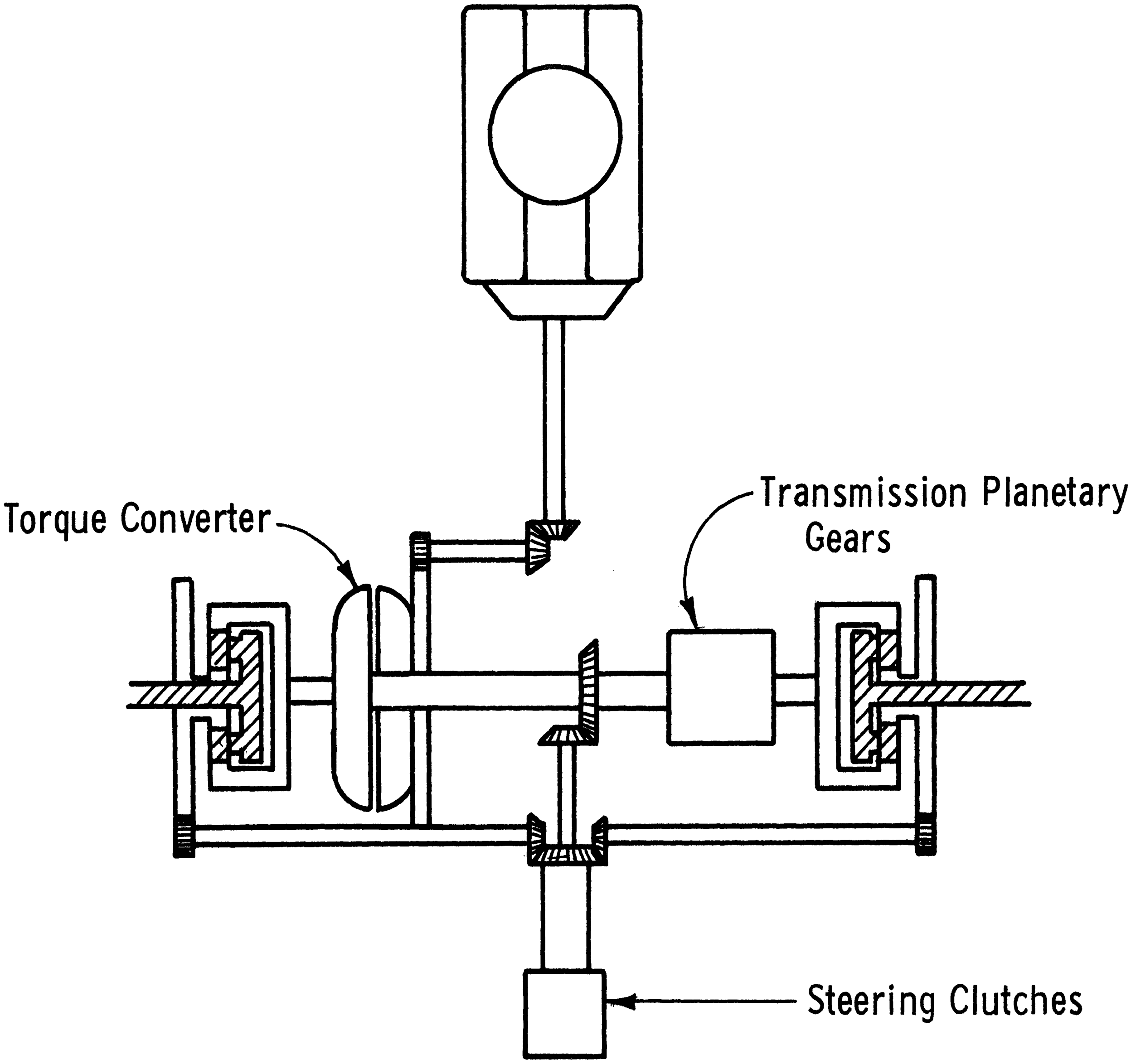

Fig. 20. Current cross-drive transmission.

SECTION 5

RECOMMENDATIONS

Now that the transmission field has been surveyed and the particular needs that tanks impose have been investigated, some improvements in present equipment may be suggested.

5.1. MOTIVE POWER

It is felt that since maximum fuel economy is the primary objective of this study, the advantages of a completely mechanical gear type transmission cannot be ignored. Comparative efficiency curves make it obvious that the consistent high efficiency of a gear transmission will definitely reduce fuel consumption below that of present torque converter arrangements.

Apparently, the primary reason that torque converters were introduced into tank transmissions was to reduce driver fatigue and skill requirements. However, much of the ease of operating the present hydro-mechanical transmission can be maintained in an all-mechanical drive by using constantly meshed planetary gears and appropriate clutch arrangements for shifting. Although conventional gearbox transmissions use sliding gear layouts, planetary gears are not prohibitive and further work along this line may eliminate some of the difficulties of the former mechanical transmissions. Therefore, if fuel economy is to be significantly improved, the present state of transmission development strongly indicates the utilization of a mechanical drive arrangement of some sort.

5.2. STEERING

Obviously, present steering arrangements are adequate. However, here too some improvements might be possible. It is felt that the basic qualities of hydrostatic powering can be used to good advantage to reduce power loss and to improve operating characteristics. As mentioned before, present methods achieve infinitely variable steering through power wasting clutch slip connections. And although steering power performance data were not available, it is a safe assumption that the efficiency of slipping steering clutches is certainly no better than that of a hydrostatic drive and is probably much worse. Thus, a hydrostatic steering drive would save power and fuel consumption. In addition, hydrostatic steering would provide positive, stepless, and most important, almost effortless control. The wide range of torque, speed, and power characteristics possible with hydrostatics can give almost any steering qualities desired, and can make operation nearly fingertip control.

Because hydrostatic drives are so flexible, there are a number of possible arrangements for applying them to tank steering. Figures 21 and 22 illustrate two such methods of facilitating hydrostatic steering. In the first layout the steering clutches have simply been replaced with a reversible hydrostatic motor, with the cross axle and differential left as they were. In the second design each final output sun gear is driven by a hydrostatic motor. Here, power regeneration is hydraulic. Probably the first arrangement would be the easiest to convert to. Moreover, since turret drives are already hydrostatic, the addition of a steering motor could probably be facilitated merely by modifying the already existing pump.

Finally, it is felt that the resulting vehicle, a tank with mechanical power drive and hydrostatic steering, would be no harder to operate than a highway truck, either from the standpoint of skill or fatigue. These changes could probably be effected in a reasonable period of time.

5.3. ALTERNATE STEERING POSSIBILITY

Another method of approaching the steering requirements is through the use of electric motors. These have roughly the same characteristics as hydrostatic motors and could be introduced into the system in much the same manner as hydrostatics. That is, the pump would be replaced by a generator and the motors would be electric instead of hydrostatic.

Hydrostatic steering was given preference over electric because of superior efficiency and secondary advantages. Moreover, present vehicles seem more conducive to hydrostatic conversion than to electric. Here again, the development time is estimated as being quite reasonable.

5.4. FUTURE DEVELOPMENT

Although the preceding recommendations may result in an improvement over present vehicles, they still utilize finite gear ratios and thus cannot let the engine operate along its best efficiency line. However, further research and development could possibly reduce this inefficiency. In fact, several methods of obtaining infinite speed ratios look promising.

One possibility is illustrated in Fig. 22. Although the hydrostatic motors are primarily for steering, there is no reason why they cannot supplement the basic power drive as well. Thus, their variable speeds could be applied with the basic gear drive to give an over-all spectrum of ratios much wider than those offered by conventional gearing. The control mechanism for this or any other infinitely variable transmission would need considerably more development than that needed to guide steering only. Roughly two to three years are estimated for the time needed to adequately develop this system.

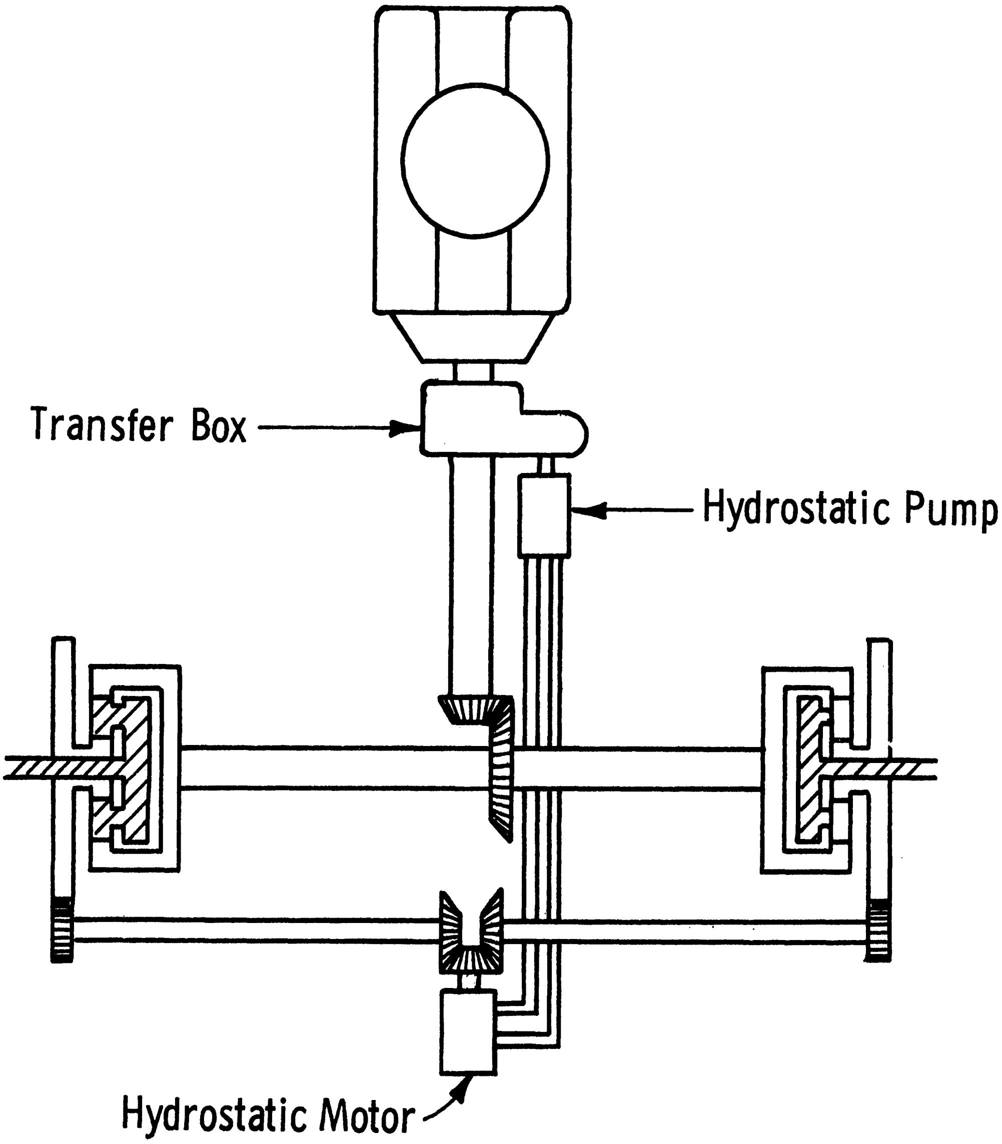

Fig. 21. Power-shunt transmission with hydrostatic steering (I).

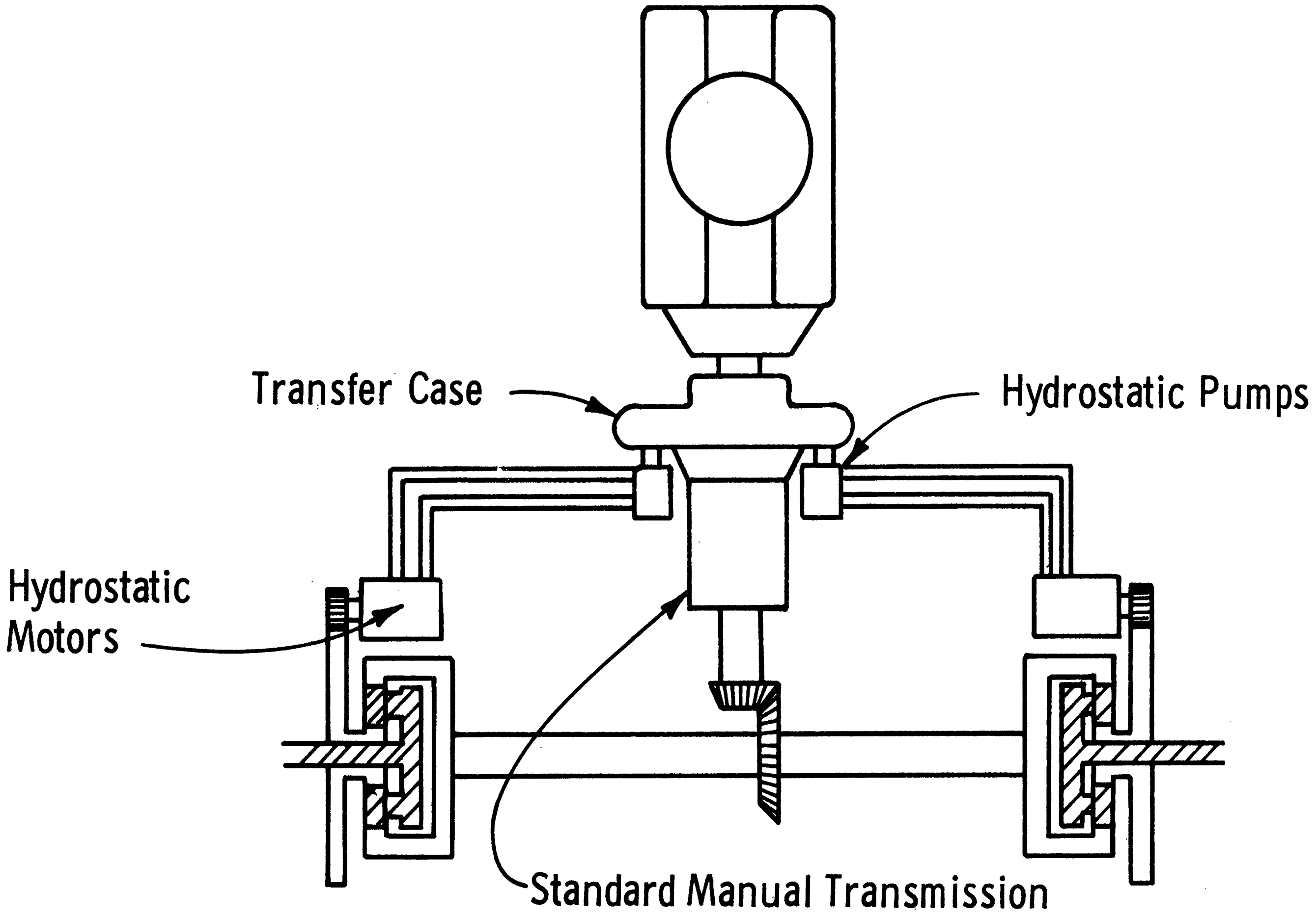

Fig. 22. Power-shunt transmission with hydrostatic steering (II).

After the mechanical-hydrostatic combination comes the next step, a completely hydrostatic transmission. Because hydrostatics are still new and only partially developed, research would be needed to properly exploit the best characteristics of such a system. However, some high-horsepower hydrostatic units—as high as 1500 hp, according to one source—are already in use today. However, an all-hydrostatic tank drive unit would need careful power and steering control not found in today's large power models. This combined with present precision manufacturing and high oil-pressure techniques probably would require from three to five years for proper development.

Lastly, an all-electric drive is also a possibility. This would be similar in nature to an all-hydrostatic drive and would require about the same development time.

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APPENDIX

I. MECHANICAL TRANSMISSIONS

A. Countershaft Gearsets

1. Fuller Transmissions
   Fuller Manufacturing Co.
   Kalamazoo, Michigan

2. Spicer Transmissions
   Dana Corp.
   Toledo 1, Ohio

B. Harmonic Drive Transmission

1. United Shoe Machinery Corp.
   Boston, Massachusetts

C. Planetary Gearsets

1. Allison Torqmatic Drives—TG Series
   Allison Divison
   General Motors Corp.
   Indianapolis 6, Indiana

II. FLUID TRANSMISSIONS

A. Hydrodynamic: Torque Converters

1. Allison Torqmatic Drives—TC Series
   Allison Division
   General Motors Corp.
   Indianapolis 6, Indiana

2. Allison Torqmatic Converter—Series 800-900

3. Borg-Warner Torque Converter
   Long Mfg. Division
   Borg-Warner Corp.

4. Clark Converters
   Clark Machinery Division
   Benton Harbor 13, Michigan

5. Hydra-Drive Torque Converters
Rockwell-Standard Corp.
Transmission and Axle Division
Detroit 32, Michigan

B. Hydro-Mechanical Transmissions

1. Allison CT-CLT-CBT and CLBT Series
Allison Division
General Motors Corp.
Indianapolis 6, Indiana

2. Allis-Chalmers
Allis-Chalmers Construction Machinery Division
Milwaukee 1, Wisconsin

3. Case Terramatic Drive
J. I. Case Co.
Racine, Wisconsin

4. Vari Draulic
Hydraulics, Inc.
Parsons, Kansas

5. Hydra-Drive Transmissions
Rockwell-Standard Corp.
Transmission and Axle Division
Detroit 32, Michigan

C. Hydrostatic

1. Sundstrand Hydrostatic Transmission
Sundstrand Hydrostatic Division
Sundstrand Corp.
Rockford, Illinois

III. ELECTRIC TRANSMISSIONS

1. Electric Transmissions
LeTourneau-Westinghouse Co.
Peoria, Illinois

IV. APPLICATIONS TO HEAVY MACHINERY

1. Allis-Chalmers Construction Machinery Division
Milwaukee 1, Wisconsin

2. Clark Equipment Co.
   Construction Machinery Division
   Benton Harbor 13, Michigan

3. J. I. Case Co.
   Racine, Wisconsin

4. Euclid Division
   General Motors Corp.
   Cleveland 17, Ohio

5. LeTourneau-Westinghouse Co.
   Peoria, Illinois