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FOR A LONG TIME, truck manufacturers have been working to improve the productivity of the truck for the owner and to increase the driving ease for the driver. An automatic transmission can potentially do both, providing weighted consideration is given to the various truck requirements at the time of the transmission design.

This paper deals with the design of a fully automatic heavy-duty truck transmission employing hydromechanical principles. Truck requirements are analyzed, features of hydromechanical transmissions are explained, and the specific design chosen is compared with these requirements.

HEAVY-DUTY TRUCK REQUIREMENTS

Of all the requirements, life reliability is probably most important. Heavy-duty trucks require a long life with a high average load. Many are designed for an average life of 400,000 miles or 10,000 h before major overhaul. All transmissions should be designed to meet that criterion.

Efficiency requirements from application to application vary. Long haul, or line haul, trucks require very high efficiency. Automatic transmissions which cause a 5% or greater increase in fuel consumption have a hard time replacing gear boxes. Other heavy-duty trucks, such as cement mixer trucks, have less concern for efficiency due to the high percentage of idle time and generally low overall mileage.

Weight and volume are obvious requirements in order to

fit all the various truck chassis. The weight should not be so excessive as to rob substantially from the pay load. While weight is important in some market areas, a good many of the trucks are now volume limited, either because of the item being shipped or the packaging involved in the shipment. Only a small percentage of the truck market seems to pay for weight savings.

Increasingly, trucking companies are thinking in terms of total cost, and to them, first cost is only one factor along with productivity, fuel consumption, resale value, maintenance, etc. But there are still many truck markets where first cost is the major consideration in the purchase of a transmission. So, if the transmission price is too high, much market potential is endangered.

Recently, certain requirements have been legislated to make trucks more socially acceptable. The particular legislation that would apply to transmissions is on noise. Many laws have been passed in this country, as well as in others, to define the maximum noise allowed on truck drive-by, as well as in-cab considerations. It appears there will be more legislation, and the required noise levels will continue to go down. Results of some of the legislation can be seen in Fig. 1.

FEATURES OF HYDROMECHANICAL TRANSMISSIONS

Hydromechanical is used in this paper to mean, in effect, a two path or split torque type of transmission, where one path

ABSTRACT

A new automatic transmission for heavy-duty trucks is going into production. It is a dual mode, hydromechanical transmission, incorporating a control system to minimize en-

gine fuel consumption. The size, weight, and price are generally competitive with other automatic and manual transmissions.

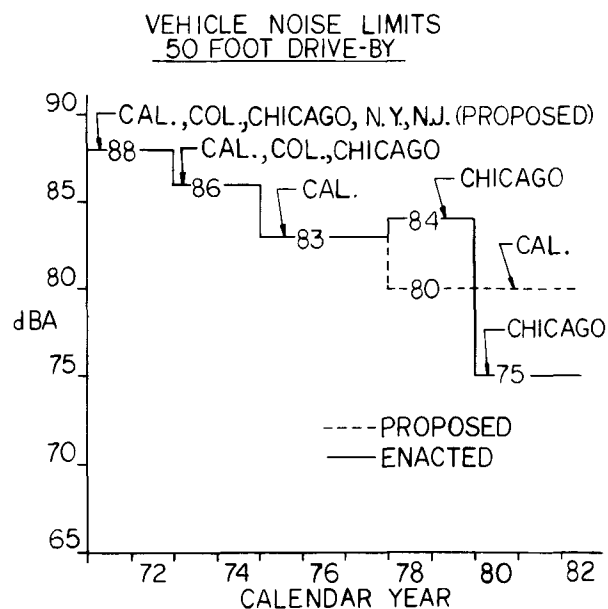


Fig. 1 - dBA versus calendar year (noise legislation)

is mechanical, consisting of shafts and gears, and the other is hydrostatic, consisting of a high-pressure pump and motor.

These two paths are tied together or summed by means of epicyclic gearing (a differential). The operation of a differential is, in effect, to add algebraically speeds of its various inputs and outputs, as shown in Fig. 2. A simple differential can be in three modes of operation:

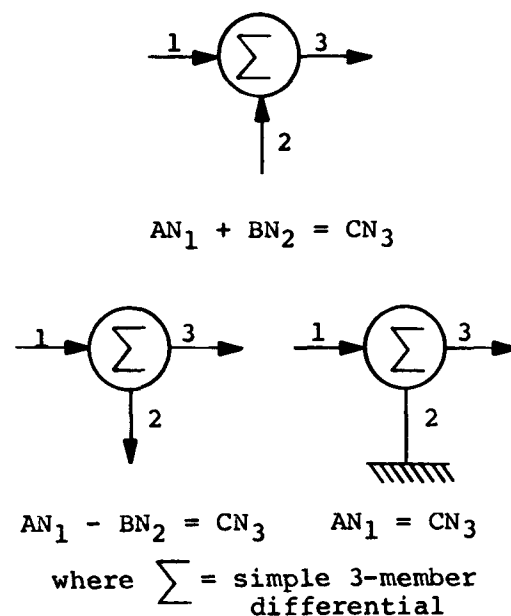
1. Two inputs and one output.
2. One input and two outputs.
3. One input, one output, and one reaction member.

All three play a part in the design of this hydromechanical transmission.

Probably the main feature of hydromechanicals is that they can be fully automatic, with infinitely variable speed. This means that the output of a hydromechanical transmission can be varied from zero to some maximum speed, with no change in input speed to the transmission. In effect, it has an infinite number of output/input speed ratios. This capability can exist in the hydromechanical transmission as long as you have one variable displacement hydraulic unit (Fig. 3). It is obvious that the flow can be varied from the variable displacement pump to run the fixed displacement motor to any speed up to the capacity of the pump. It is this hydrostatic building block that is fundamental to hydromechanical transmissions. Also, if the proper hydraulic unit design is chosen, the variable displacement pump can move to negative displacement, reversing the flow to the motor, and so give a reverse rotation of the motor output.

Inherent in a hydromechanical transmission is its higher efficiency over a narrow speed range relative to a hydrostatic transmission. This efficiency improvement is based on the fact that varying amounts of the engine power are transmitted mechanically, based on the speed ratio. In Fig. 4, the output/input speed ratio is plotted against the percentage of hydraulic or hydrostatic power to the total power. If all the power goes through hydrostatically,

OPERATION OF A DIFFERENTIAL



N = speed

A , B , & C = constants

Fig. 2 - Speed adding with a differential

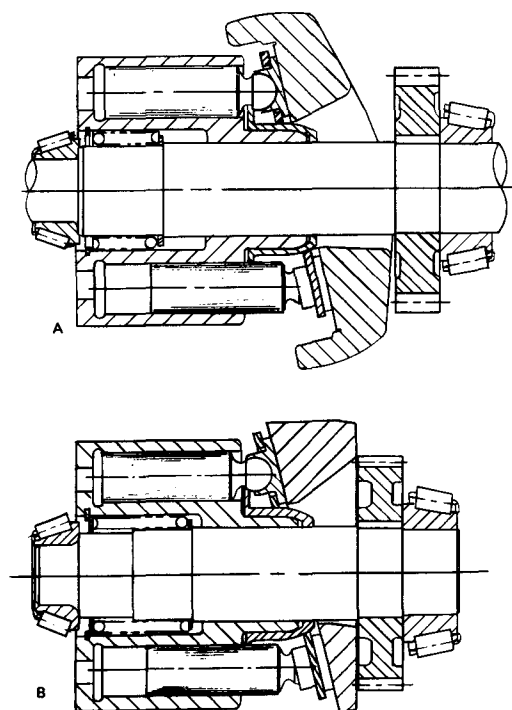


Fig. 3 - Hydraulic units, A-variable; B-fixed

$$\frac{\text{Hydraulic hp}}{\text{Engine hp}} = 1 \quad (1)$$

the transmission efficiency would be in the range of 80-85%. The mechanical section of the transmission is about 95-98% efficient. As the hydrostatic power flow is reduced, there is

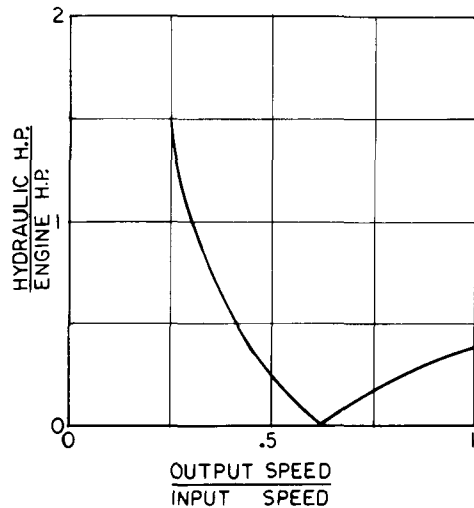


Fig. 4 - Typical hydraulic horsepower over a 4:1 hydromechanical speed ratio

generally a proportionate increase in efficiency. The efficiency peaks in the area where the hydraulic power is zero. However, this does not mean that there are no hydraulic losses just because the hydraulic power is zero. Working pressure, and, hence, torque, is generated in the hydrostatic section to create a reaction member for the differential. (See Fig. 11.)

More subtle, and yet a fundamental feature of hydromechanical transmissions, is the potential to shift synchronously, where there is more than one mode or speed range. A synchronous shift is that condition when speed difference across a clutch is essentially zero at the time of its engagement. This can result in longer clutch life and smoother shifts. Hydromechanical transmissions can be made to do synchronous shifting because they have infinitely variable speeds and the hydraulic units are bidirectional in power flow. For example, a hydromechanical transmission is shown in Fig. 5 with two modes of operation. The first mode is all hydrostatic, and the ring and sun gears of the differential are locked together, resulting in no independent action among its members. The gearing can be designed so that the speed difference across clutch 1 is essentially zero at the time the variable unit gets to full displacement and the fixed unit gets to full speed. This means the input speed, or a fixed ratio to it, is going the same speed as the locked-up differential. Clutch 1 can then be fully engaged before clutch 2 is released. Upon release of clutch 2, the differential is unlocked, allowing it to do its algebraic additions of speeds. With a slowing down of the fixed displacement unit, the output will continue to increase in speed. A shift, or mode change, has been accomplished which is synchronous and with no engine speed change or power interruption to the vehicle.

One other feature of the hydromechanical, where there is at least one variable unit, is that torque is generated essentially without slip. Torque is created with a pressure drop across the hydraulic motor by placing the pump in displacement sufficient to make up leakage and fluid compressibility in the hydraulic system. In fact, one can create maxi-

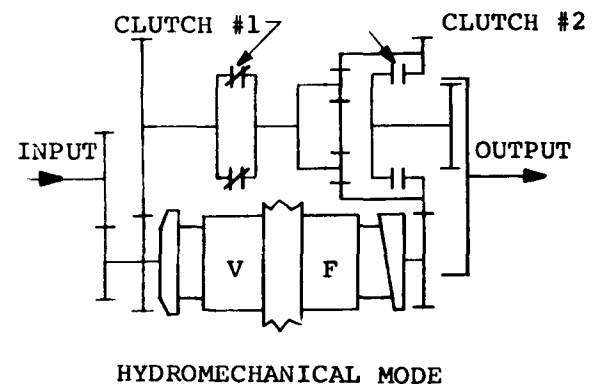
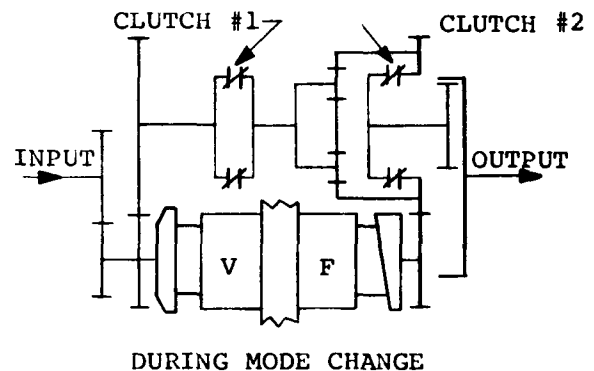
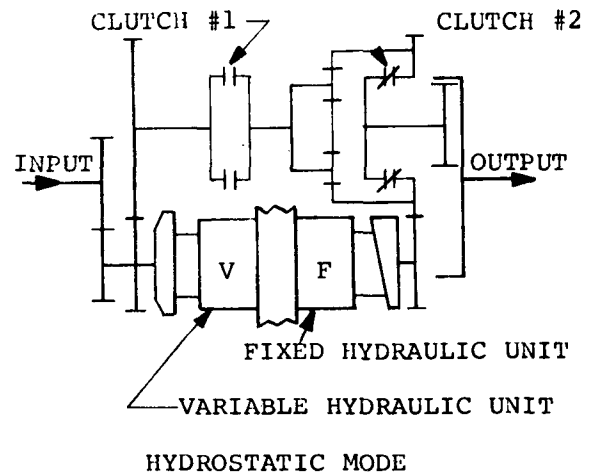


Fig. 5 - Synchronous shift with dual mode transmission schematic

mum torque at vehicle stall conditions with so little power from the engine that it can be running virtually at idle. This also means there is no thermal time limit for this condition, as is generally the case with torque converter transmissions.

CHOOSING THE RESPONDER-DUAL MODE TRANSMISSION

GENERAL - Choosing the right hydromechanical transmission to meet the truck requirements means deciding the

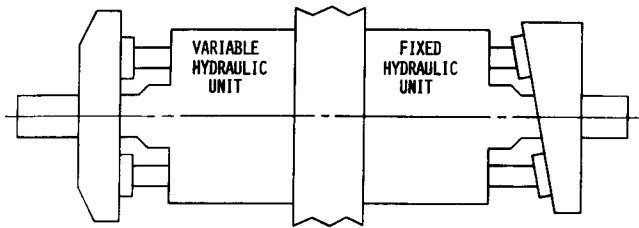


Fig. 6 - Back to back hydraulic units

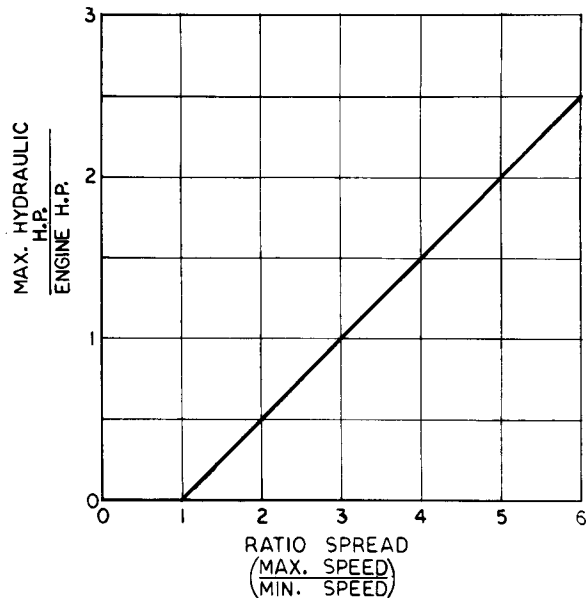


Fig. 7 - Maximum hydraulic horsepower at various hydromechanical speed ratio

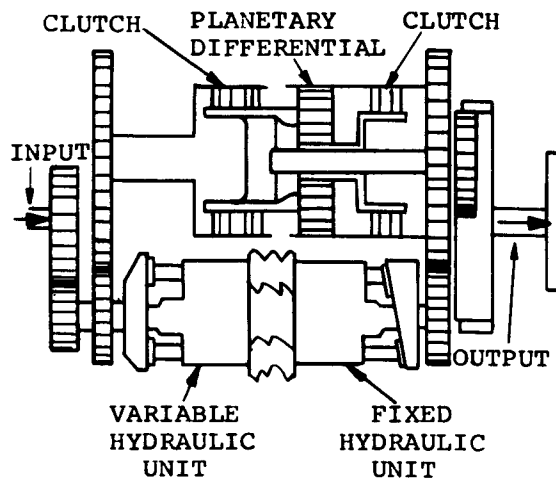
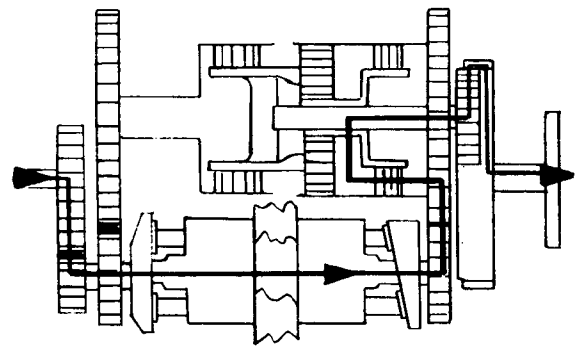


Fig. 8 - Dual mode transmission schematic

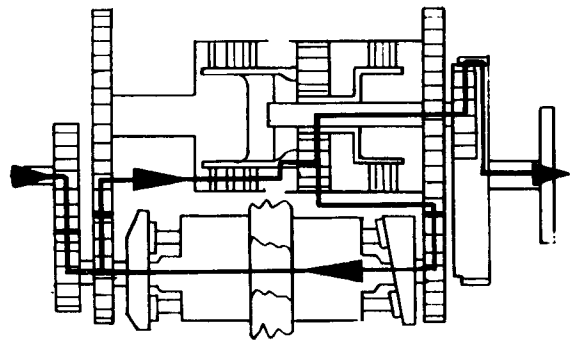
approach in each of these areas: hydraulic unit, hydromechanical schematic, controls, and noise considerations.

Each is a major factor in the transmission design, and it is necessary to know the logic behind them to understand the advantages of the complete transmission.

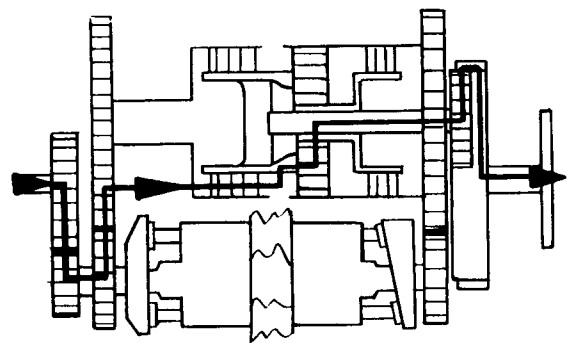
HYDRAULIC UNIT - The basic building block of the hydromechanical transmission is the hydraulic unit. The hydraulic unit should have good efficiency, be simple to package, have long life, and have low first cost. Our company got into production on this type of unit in the early 1960s. This



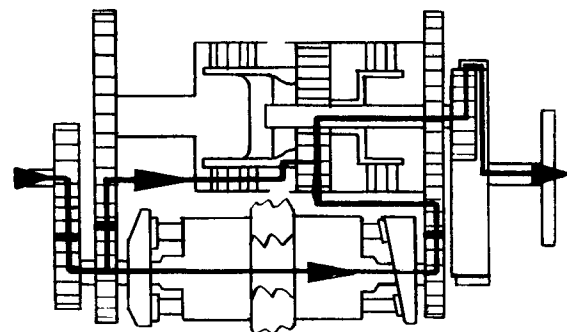
HYDROSTATIC MODE



HYDROMECHANICAL MODE (RECIRCULATING)



HYDROMECHANICAL MODE (MECHANICAL ONLY)



HYDROMECHANICAL MODE (ADDITIVE)

Fig. 9 - Power flow diagram of dual mode transmission

unit was designed for hydrostatic transmissions (Fig. 3), and, with minor modifications, is used in our new hydromechanical transmission for trucks. The hydraulic unit is an axial piston, rotating cylinder block design with the thrust loads carried by the hydrostatically balanced slippers and block face. It operates at working pressures up to 6000 psi, giving it the power density desirable for a small package. Two of these units are easily mounted back to back, that is, with the block faces facing one another and a port plate in between. The only calculable life limit items in the design are the two shaft bearings. The variable and fixed displacement units have identical parts, with the exception of the swashplate and its mounts. Fig. 6 shows a variable and fixed displacement unit mounted back to back.

HYDROMECHANICAL SCHEMATIC - Another variable in the hydromechanical design is the number and type (variable or fixed displacement) of hydraulic units to be used. The simplest and least expensive way is to use one variable and one fixed displacement unit. For every additional variable unit, a control actuator and control logic must be added to the system. More than two hydraulic units require more gearing and often load division controls.

There is a very large number of hydromechanical transmission schematics or designs that can be created. The hydromechanical schematic or design is really a tradeoff on first cost versus efficiency. If the speed range of the hydromechanical transmission is narrow, the maximum hydraulic power that must be transmitted is very low, with consequently higher efficiency (Fig. 7). Narrow speed ranges, however, require more modes, more shafts, more clutches, and more control complexity, resulting in higher first cost. A major factor in this tradeoff is the annual mileage of the truck.

The schematic chosen was a dual mode transmission (DMT), comprising a hydrostatic startup mode which synchronously shifts into a hydromechanical mode. It requires two hydraulic units of the same rated displacement, two clutches, and one planetary differential (Fig. 8).

The operation of the DMT can best be explained by referring to the power flow sketches in Fig. 9. During vehicle startup, the power is transmitted hydraulically, bypassing the locked-up differential. As the variable unit displacement is increased, the fixed unit, and the vehicle, increases in speed. When the variable displacement unit reaches full displacement, the fixed unit is now going virtually the same speed as the variable unit. At this point, a synchronous mode change can take place, since both elements of the mechanical path clutch are at synchronous speeds. After the clutch is engaged, the differential clutch is disengaged (completing the transition to the hydromechanical mode). During the first part of the hydromechanical mode, there are decreasing amounts of recirculating power within the transmission until an output is reached where all the power is transmitted mechanically. As the vehicle goes to maximum speed, power in the hydraulic path gradually increases. Vehicle reverse is done without gear changes or shifts by going over center or reversing the displacement of the hydraulic unit. There is no reverse operation in the hydromechanical mode.

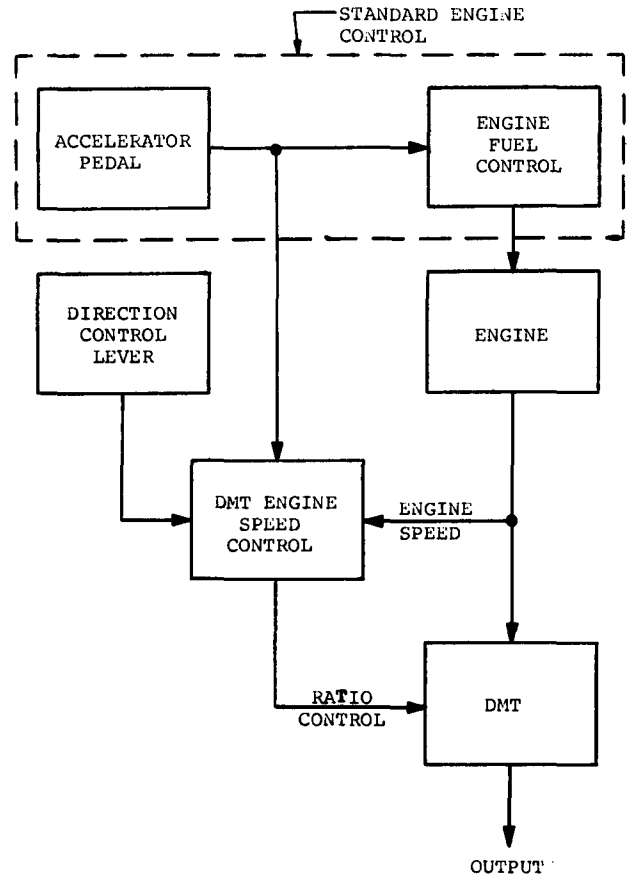


Fig. 10 - Control block diagram

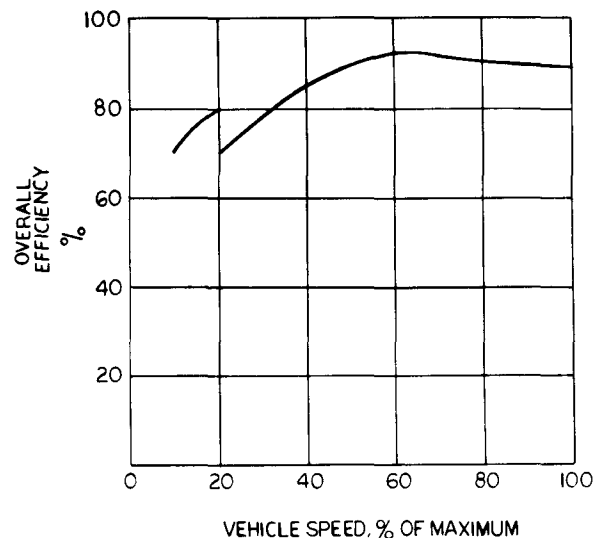


Fig. 11 - Efficiency for dual mode transmission

CONTROLS - The controls chosen for our hydromechanical transmission are subdivided into startup, driving, braking, mode change, and protective or limiting controls. The driving and braking controls are the ones that should be discussed here due to their key role in the overall vehicle performance.

The driving-braking control block diagram is shown in Fig. 10. An engine speed-sensing governor located within the transmission is signaled by the accelerator pedal, concurrent

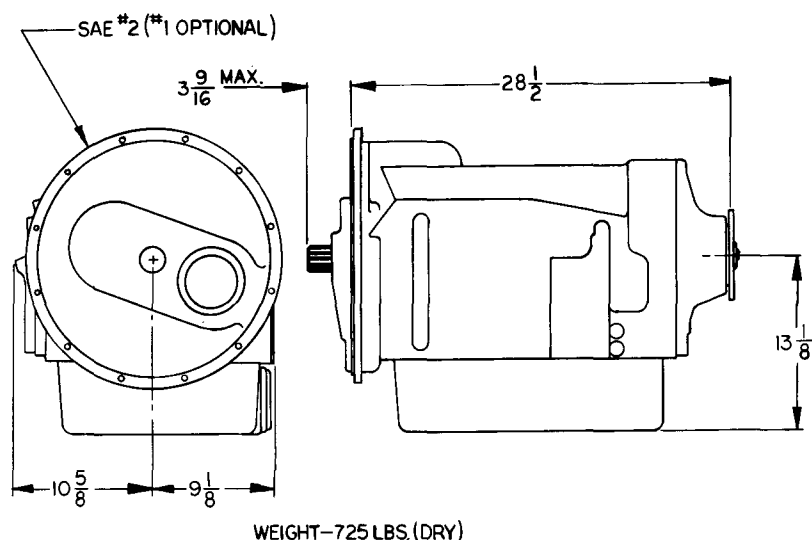


Fig. 12 - Dual mode transmission outline and weight

with its signaling to the engine fuel control. This means that for a given accelerator pedal position, there is, in effect, a certain engine speed which is established by varying the load on the engine, using the transmission as a variable loading device.

Since an infinitely variable speed transmission like the dual mode does not require any variation in engine speed for torque multiplication or speed range, the speed can be varied for other purposes, for example, minimizing the fuel consumption. The engine speed and fuel control setting relationships are established by a simple cam. The cam design is generated by knowing the fuel consumption map of the engine and the operation of the fuel control. There has been no attempt to make this a very precise control. Its aim is generally to depress the engine speed for part-load operation. If an engine has good part-load fuel consumption, like a diesel, reduction in fuel consumption of about 5% can be expected. If a gasoline engine is used, where part-load consumption is relatively poor, reductions are more impressive, and many applications result in better fuel consumption than a gasoline-gear box combination.

DUAL MODE TRANSMISSION (RESPONDER)—MEETING TRUCK REQUIREMENTS

The best way to judge the Responder transmission design is against the truck requirements.

LIFE-RELIABILITY - This is achieved in the Responder by choosing a hydraulic unit design which minimizes the use of life-limited bearings, by picking a simple scheme which has relatively few parts, and by designing the gears and bear-

ings with a composite life to meet the requirements of over-the-road and on/off highway duty cycles.

EFFICIENCY - The efficiency of the Responder is shown in Fig. 11. That efficiency, coupled with the 5% improvement in engine fuel consumption by means of the Responder controls, offers acceptable fuel consumption for most heavy-duty trucks. While the Responder is not the best hydro-mechanical transmission for efficiency, it is an appropriate choice in the first cost-efficiency tradeoff, considering that the immediate market need is for automatics in mixer, dump, and short-haul trucks, where annual mileage is relatively low.

SIZE AND WEIGHT - The Responder appears to be competitive with other heavy-duty transmissions (Fig. 12). The bell housing to output flange dimension is probably the most important, and the Responder is generally less than other transmissions.

FIRST COST - The price of the Responder is 10-20% above a heavy-duty 10-speed gearbox. This price is largely the result of choosing a simple schematic with a minimum number of low-cost hydraulics.

The Responder has been equipped with an acoustical enclosure which tends to dampen the noise that is generated within the transmission. Based on truck tests so far, this should meet the present legislation to 1975. The contribution to in-cab noise appears to be low, so that the total in-cab noise is not adversely affected.

It is felt that the Responder hydromechanical transmission offers the owner an automatic transmission which is abuse tolerant, low in maintenance, and competitive in fuel consumption and first cost. The driver benefits from ease of operation and a performance that can be achieved only by a transmission which makes full engine power available whenever the accelerator is fully depressed.



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