

SAE Technical Paper Series

821103

Crawler Transaxle with Differential Lock and Variable Steering

Saul Herscovici
Power Engineering & Mfg., Ltd.

Reprinted from SP-522—
“Analysis and Design of Off-Highway Powertrains”

**International Off-Highway Meeting
& Exposition
Milwaukee, Wisconsin
September 13-16, 1982**

Crawler Transaxle with Differential Lock and Variable Steering

Saul Herscovici
Power Engineering & Mfg., Ltd.

ABSTRACT

This transaxle is composed of two identical planetaries, a group of speed reducing gears that provide traction drive speed to each planetary through the sun pinions that are on a common shaft. Another group of steering, or differential lock gears provide power into the planetaries through the rotating ring gears.

This transaxle is powered by two hydraulic motors, one for straight line drive, or traction drive, and the other for steering or differential lock. The output shafts are driven by the planetary carriers of the two mirror image planetaries. The speed of the output shafts is independent of load, but is dependent on the speeds of the traction and steering motors.

This type of transaxle is most suitable for use on crawler track vehicles, or skid steer vehicles. It can also be used as a heavy-duty axle with differential lock option. It offers superior performance when used as a crawler drive transaxle, because its mechanical power split imparts the proper amount of required torque to each track at a steady track speed regardless of whether the vehicle travels in a straight line or in a curved line.

THERE ARE MANY APPLICATIONS that require precise steering control of crawler type vehicles so that the path that the vehicle travels does not deviate significantly from the required path. Perhaps 1/16th of an inch or 1/8th of an inch side deviation off the guide string is maximum permissible for a vehicle that weighs anywhere from 20,000 lbs. to 40,000 lbs. with a drawbar pull load that is not centered on the machine and that may be constantly shifting sideways or changing in magnitude. The machine shown in Figure 1 is a road paving machine made by C.M.I. Corporation of Oklahoma City, Oklahoma that is using the type of transmission described in this article.

Another application would be the formless curb

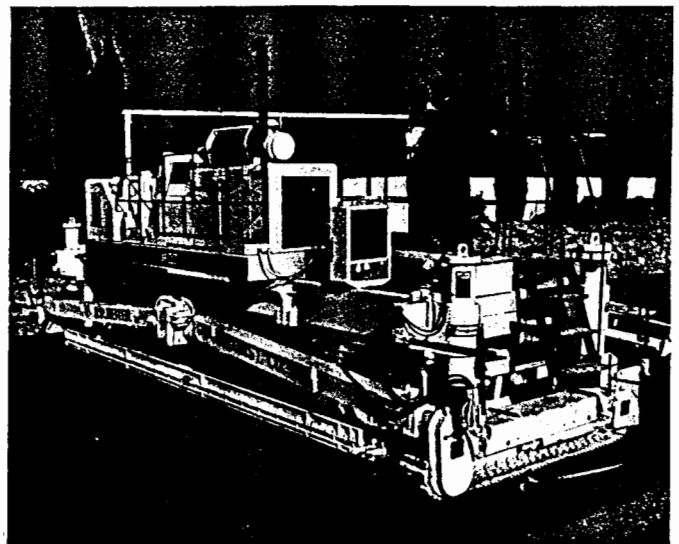


Figure 1. Road paving machine. Photo courtesy of C.M.I. Corp. of Oklahoma City, OK.

making machine, where abrupt steering will cause the curb, being made of soft cement, to actually break from the steering jolt. In other applications, such as trenching or ripping, where steering is done by clutches and brakes, the machine may see extremely high side loads that may be destructive to the machine frame as well as to the implement.

A popular method of propelling a crawler type vehicle is to provide power from the engine to the drive axles through a multiple speed transmission. The axle is composed of a set of bevel gears, two clutches, and two brakes as shown in Figure 2. One clutch and one brake on each side. When the vehicle travels in a straight line the two clutches are engaged and the two brakes are disengaged. When the vehicle is being steered to either side, the clutch is disengaged and the brake is simultaneously engaged on the track that is being slowed down. The amount of time that the clutch must remain disengaged and the brake

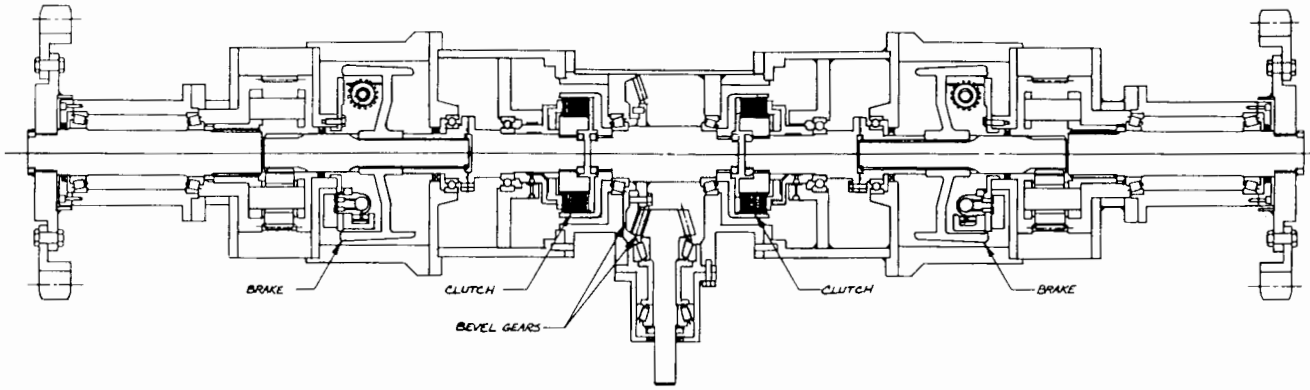


FIGURE 2
CLUTCH AND BRAKE DRIVE AXLE

engaged must be in direct proportion to the amount of steering desired. If the amount of steering is insufficient, then the action must be repeated. If there is oversteering, then the amount of steering must be reduced by disengaging the clutch and engaging the brake on the opposite side. This type of steering leads to a zig-zag pattern of short straight lines to attain the desired angle of travel as shown in Figure 4. Loss of steering control may occur on a steep incline if a significant amount of time elapses between the clutch release and brake engagement. For example, if the vehicle travels forward downhill and the right hand clutch is being disengaged to steer to the right, the vehicle may actually steer to the left due to free wheeling speed increase of the right hand track until the brake is engaged. It is practically impossible for the operator to perform the amount of steering desired with a single clutch disengagement and brake engagement because the rate of track speed reduction is affected by the amount of drawbar pull, coefficient of traction, vehicle weight distribution, and other

factors. For the above reasons, this type of steering is always a trial and error proposition. However, this type of axle has the advantage of being able to maintain a straight line when no steering is being done because there is no differential and the two clutches form an equal speed drive shaft towards each track if no clutch slip occurs.

With the advent of the high popularity of the hydraulic drives, many crawler type vehicles are being driven by two hydraulic motors, one on each side, through some type of speed reducing gear box as shown in Figure 3. There are many ways of steering such a track drive. A good way of controlling the speed of each track is by using two variable flow axial piston pumps and two constant flow axial piston motors in closed loops as shown in Figure 11. Here the angle of the pump swash plate is closely controlled so that each pump may deliver the proper amount of oil flow to its motor. This arrangement offers good steering control at moderate or high speeds, but it encounters difficulties at low speeds. The problems arise when the amount of oil leakage past the motor pistons and valves become significant in relation to the amount of working fluid. It may be further compounded by the fact that the two motors may have different volumetric efficiencies. The drive path made by such a drive is shown in Figure 5.

Electrical controls are available that sense the speeds of the hydraulic motors and automatically modify them to operate at the required speeds for good drive control. The vehicle is still traveling sideways when desiring to travel in a straight line, but in smaller side deviations. This makes the drive more expensive and more difficult to service.

Another way is to use a single pump and two motors with a variable flow divider so that when steering in a straight line equal amounts of working fluids are directed towards each motor. It is desired to have a low flow variation at the center which is the straight line drive so that a large motion of the control lever will make it easier to obtain equal flow for straight line drive. This type of variable rate of steering provides a higher sensitivity for maintaining a straight line.

Another method yet is to have two pumps and two motors connected in separate loops. Each loop will

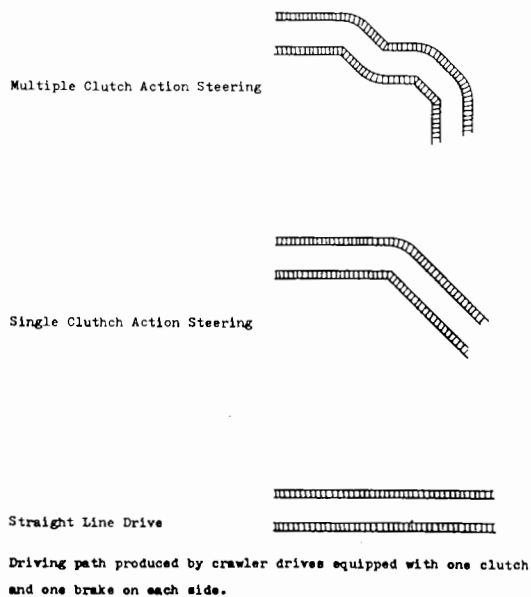
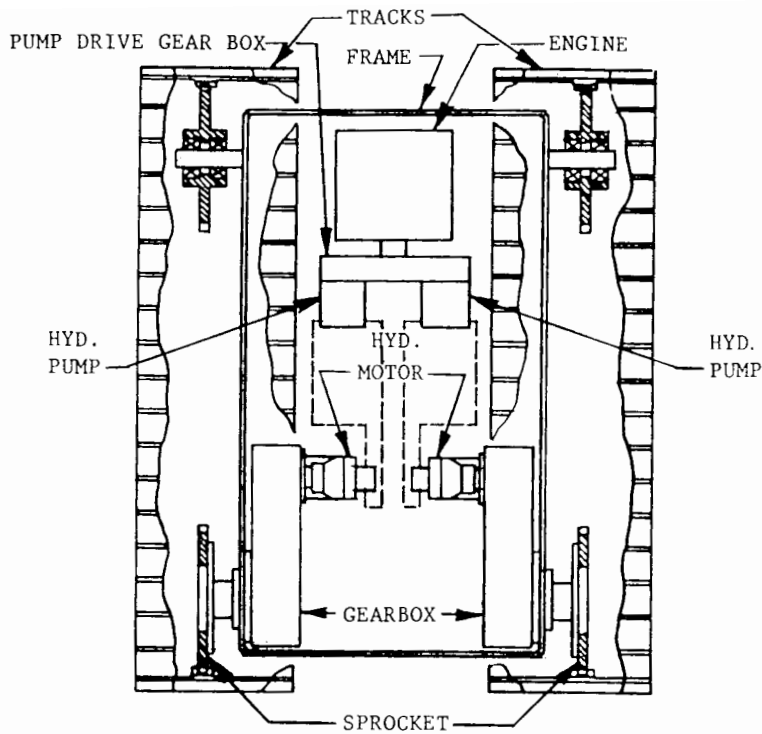
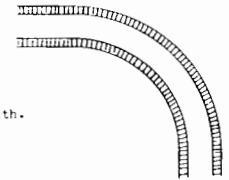


Figure 4



Steering produces a smooth curved path.



Straight line drive produces slight side deviations.



Driving paths produced by crawler vehicle equipped with individual hydraulic motor and speed reducing gear box on each track.

Figure 5

Figure 3
Individual Hydraulic Track Drive

TYPICAL HEAVY DUTY VARIABLE PUMP-FIXED MOTOR TRANSMISSION SCHEMATIC

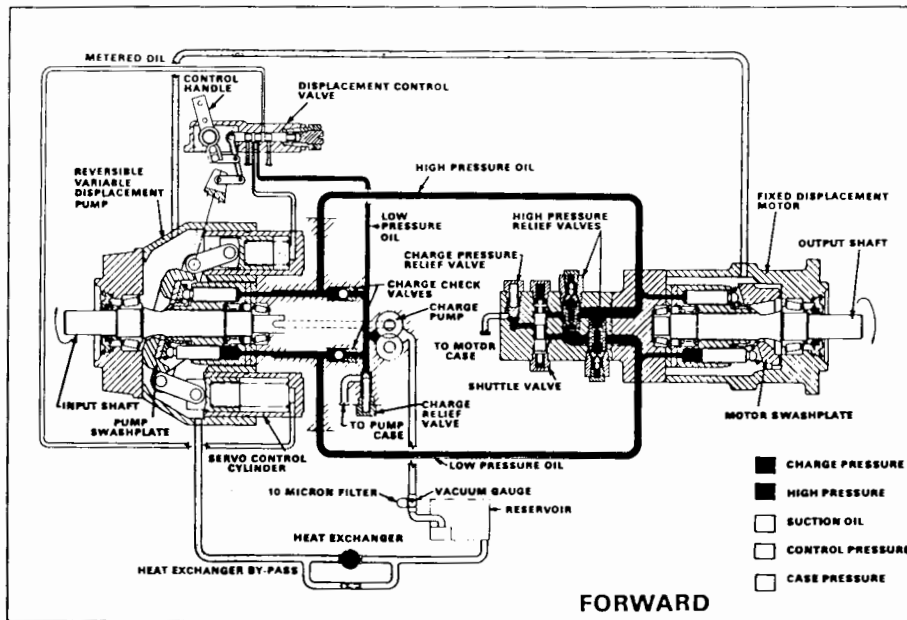


Figure 11 - Closed loop axial piston variable speed pump and constant speed motor. Courtesy of Sundstrand Corp.

have a valve through which oil can flow from the pressure line into the return line, thus bypassing the pistons and, consequently, slowing down one track. This is an inefficient method since the pressure flow is being diverted into the return line without doing any work, but at the same time generating heat. All of the hydrostatic methods that use separate motors for each track can perform properly down to a certain low speed below which the volumetric efficiency leakage consumes much of the flow in relation to the working flow.

The principle of operation of the double planetary transaxle is to use the power for straight line drive from a single source and mechanically divide it through proper gearing to each track. In the same manner, the steering power is being used from a single source and likewise, it is mechanically split through proper gearing to each track. This type of mechanical power split, with separate power sources for traction drive and steering drive, gives the crawler track vehicle the ability to maintain a straight line path when no steering is done, similar to the clutch and brake axle, yet eliminates the small side deviations that the individual hydraulic drive track produces. Likewise, this double planetary transaxle has the capability of steering the vehicle over a smooth path, unlike the zig-zag pattern that the clutch and brake axle produces.

The drive path made by this transaxle is shown in Figure 6 for comparison with that of the clutch and brake axle path shown in Figure 4, and that of the individual track hydrostatic drive shown in Figure 5.

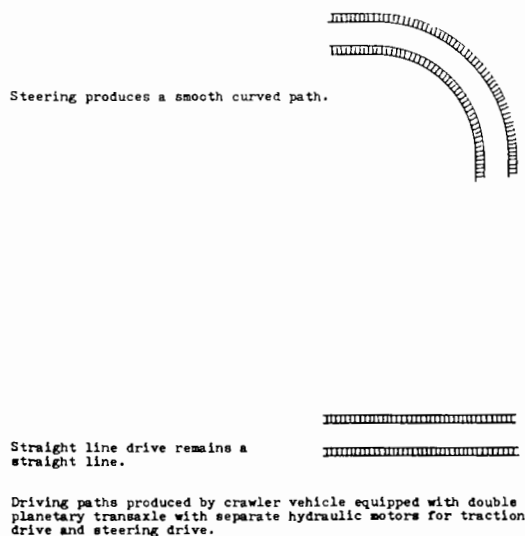


Figure 6

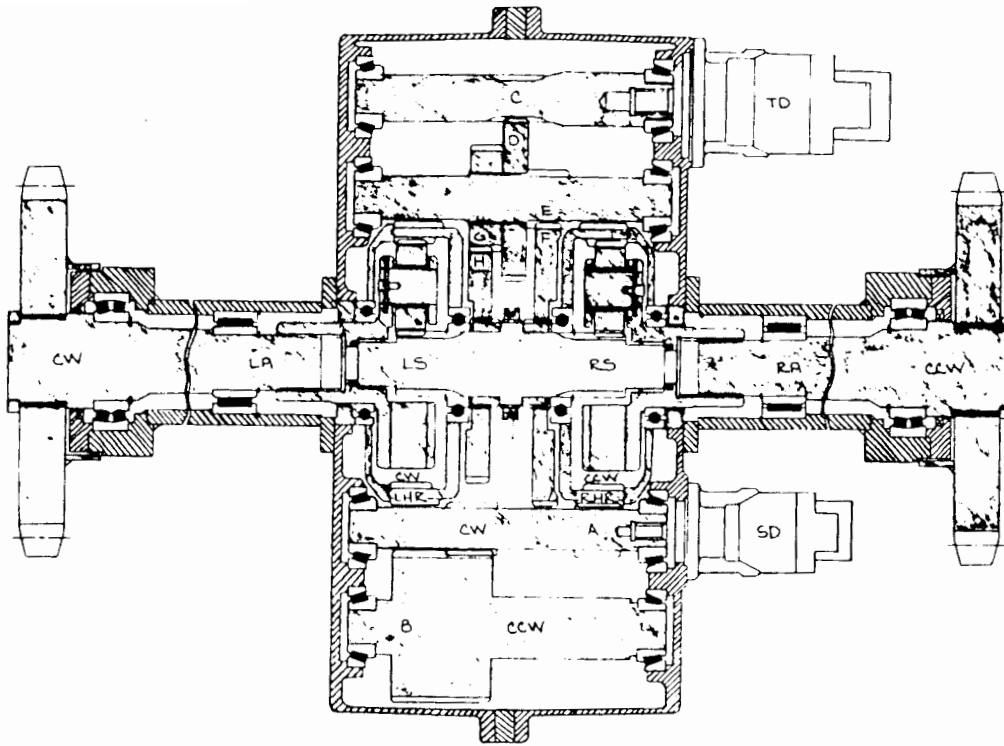
The only effect that the internal rate of leakage of the hydraulic motors has is to reduce proportionately the ground speed or the rate of steering because once the hydrostatic power is transmitted into the gear box, it is mechanically split to each track. The

straight line path remains straight but at a lower rate of speed, and the smooth steering path remains smooth and without zig-zag, but also at a lower steering rate.

Since the transaxle has two separate hydraulic motors for power sources, one for traction drive and one for steering, it is necessary to have two separate hydraulic circuits. Figure 11 is a schematic diagram of the Sundstrand variable speed pump and fixed speed motor. Both are axial piston type pump and motor. This type of motor is recommended for use for traction drive as it operates continuously and has high efficiency and high horsepower capability. The ground speed and direction is determined by the pump "control handle" shown in Figure 11. The control handle in turn operates the pump swash plate whose angle determines the amount of high pressure flow to the motor. The sign of the pump swash plate angle (positive or negative) determines the direction of vehicle travel.

The steering hydraulic circuit is shown in Figure 7. The pump and motor shown are of gear type. They are less efficient than the axial piston type, but are more economical and are used intermittently only. The steering pump and motor are connected through the steering valve in such a way that when the valve is in neutral, oil flow from the pump can pass through the valve unrestricted to the oil tank. At the same time, the pressure and return lines from the steering motor are blocked so that the motor cannot freely rotate. This is how the differential lock is automatically attained when the vehicle is not being steered.

To illustrate how easy it is to control a crawler type vehicle with this type of transaxle, imagine that the steering motor is at zero rpm (see Figure 10) and the traction motor is rotating at a certain speed. At this condition, the steering gears (A and B) act as a differential lock holding the ring gears (LHR and RHR) at zero rpm. At this point, the sun pinions (LS and RS) are being powered by the traction-drive hydraulic motor. The fact that both planetaries are identical and the sun pinions are on a common solid shaft, enables the output shafts to operate at identical speeds and consequently, the crawler drive path is a straight line. Pivot steering is attained when the traction hydraulic motor (TD) is at zero rpm and the steering motor rotates. Note that the steering idler (Gear B) is engaged with the ring gear (LHR) even though the cross sectional view shows it engaged to the steering pinion only. When the steering hydraulic motor rotates clockwise (CW), it rotates the steering input shaft CW. It is engaged with the steering idler B and the righthand ring (RHR) gear, causing both to rotate counter clockwise (CCW). The idler causes the left hand ring gear (LHR) to rotate clockwise. The net result is that when the right hand ring gear rotates clockwise, the left hand ring gear rotates counter clockwise, or vice versa, depending on the direction of rotation of the steering hydraulic motor. Because the speed reduction from the steering input shaft to the planetary is identical for both planetaries and the planetaries themselves are equal in reduction ratio,



- | | |
|--|--|
| TD - Traction drive motor speed, rpm | D - Number of teeth of input gear |
| C - Number of teeth of input pinion | F - Number of teeth of low range gear |
| E - Number of teeth of low range pinion | A - Number of steering pinion teeth |
| ITR - Number of internal ring gear teeth | H - Number of teeth on high range gear |
| ETR - Number of external ring gear teeth | G - Number of teeth on high range pinion |
| SD - Steering drive motor speed, rpm | B - Number of teeth on steering idler |
| LS - Number of sun pinion teeth | RS - Number of sun pinion teeth |

Figure 10 - Transaxle

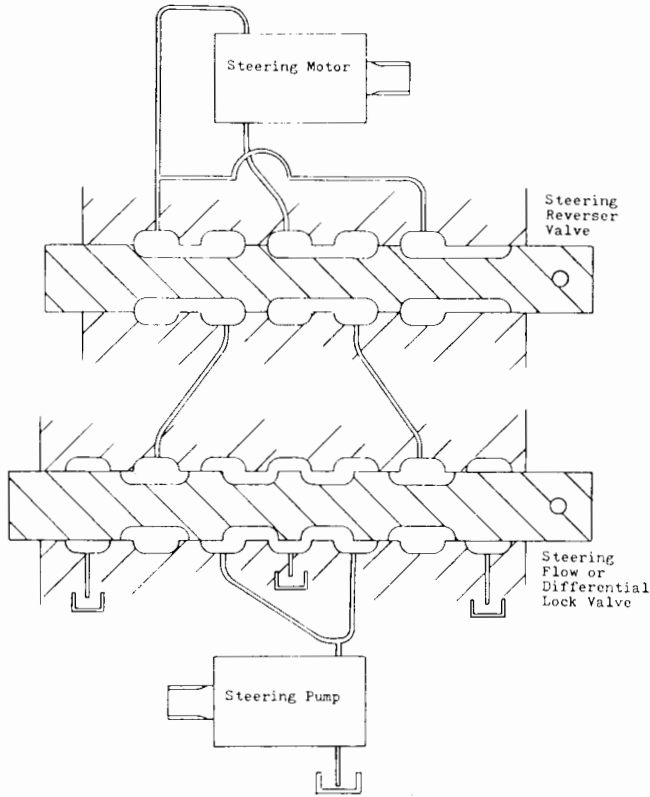


Figure 7
Hydraulic Circuit

the output shafts rotate at equal speeds but in opposite directions, and in turn, the crawler tracks rotate in opposite directions. This is how pivot steering is generated. The steering hydraulic motor, and the traction-drive hydraulic motor, can be operated simultaneously at any desired speed, as they are powered by different hydraulic pumps. The traveling speed and amount of steering can be combined in any way, depending on the operator's needs, to obtain a straight line path, or a gentle turn with a large radius, or a small radius, or pivot turn.

The following is the general equation for the output speed of each planetary carrier which directly drives the output shafts:

$$\text{Output Speed} = \left(\text{TD} \frac{D}{C} \frac{F}{E} \frac{\text{ITR} + \text{LS}}{\text{LS}} \right) \pm \left(\text{SD} \frac{\text{ETR}}{A} \frac{\text{ITR} + \text{LS}}{\text{ITR}} \right) \quad (1)$$

The first quantity in the equation to the right of the equal sign represents the output speed contributed by the traction drive motor and traction drive gears. The second quantity represents the output speed contributed by the steering drive motor and steering drive gears. It has a plus or minus because while it may add to one output shaft, it subtracts from the other output shaft because the idler is in mesh with the left hand ring gear even though the drawing does not show it. The function of any idler is to change direction of rotation. The direction of rotation of the steering motor in relation to the direction of rotation of the traction motor determines which output shaft increases in speed and which one decreases in speed.

When the second quantity in Eq. (1) becomes zero because the steering drive motor speed (SD) is zero, Eq. (1) can be simply written as follows:

$$\text{Output Speed} = \text{TD} \frac{D}{C} \frac{F}{E} \frac{\text{ITR} + \text{LS}}{\text{LS}} \quad (2)$$

This illustrates that both axles rotate at equal speeds and in the same direction as the modifying factor was removed from the equation.

In the same manner, when the traction drive motor speed (TD) is zero, the first quantity to the right of the equal sign in Eq. (1) becomes zero and it can be written as follows:

$$\text{Output Speed} = \pm \left(\text{SD} \frac{\text{ETR}}{A} \frac{\text{ITR} + \text{LS}}{\text{ITR}} \right) \quad (3)$$

This proves that when only the steering motor rotates, the two output shafts rotate at equal speed but in opposite direction of rotation. This is how pivot steering is accomplished.

Eq. (1) is written for output speed when driving in low range which is the working range. The same equation can be used for high range which is mostly used for transport by replacing the low range gear ratio F/E with the high range gear ratio of H/G.

Table one shows that for the same direction of steering wheel rotation the vehicle will actually steer in the opposite direction when changing the direction of vehicle travel from forward to reverse and vice versa, as determined by the traction drive motor. This can be confusing and dangerous if not corrected. One way to eliminate this problem is to add another valve to the steering hydraulic circuit whose function is to reverse the direction of flow to the steering motor when changing the forward and reverse direction of vehicle travel. Such a circuit is shown in Figure 7. It is best to connect this valve directly to the direction and speed control lever and slightly bias it to favor forward travel over the neutral zone in order to insure that the directions of pivot steering correspond to the directions of rotation of the steering wheel.

Direction of Steering Travel
Table 1

STEERING WHEEL DIRECTION OF ROTATION	TRACTION MOTOR ROTATION	STEERING MOTOR ROTATION	RIGHT HAND TRACK	LEFT HAND TRACK	TURN	DIRECTION OF TRAVEL
↻	+	+	FAST FORWARD	SLOW FORWARD	LEFT FORWARD	↻
↻	+	-	SLOW FORWARD	FAST FORWARD	RIGHT FORWARD	↻
↻	-	+	SLOW REVERSE	FAST REVERSE	LEFT REVERSE	↻
↻	-	-	FAST REVERSE	SLOW REVERSE	RIGHT REVERSE	↻

This ability of combining two different sources of power input at a variable speed rate is a unique feature of the planetary. It is made possible by the fact that a planetary is constructed from three principal components which are, the sun pinion, the planetary carrier and the ring gear as shown in Figure 8. One of these three members can be selected for

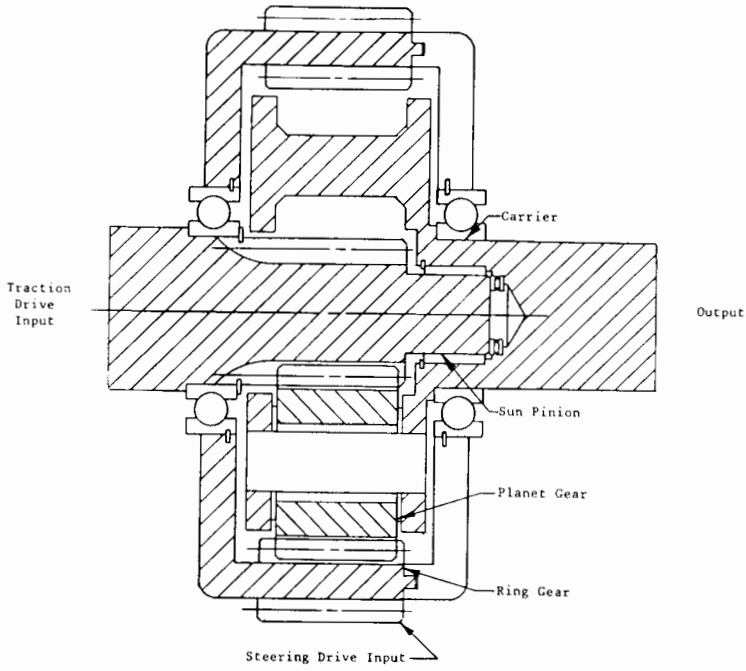


Figure 8 - Planetary

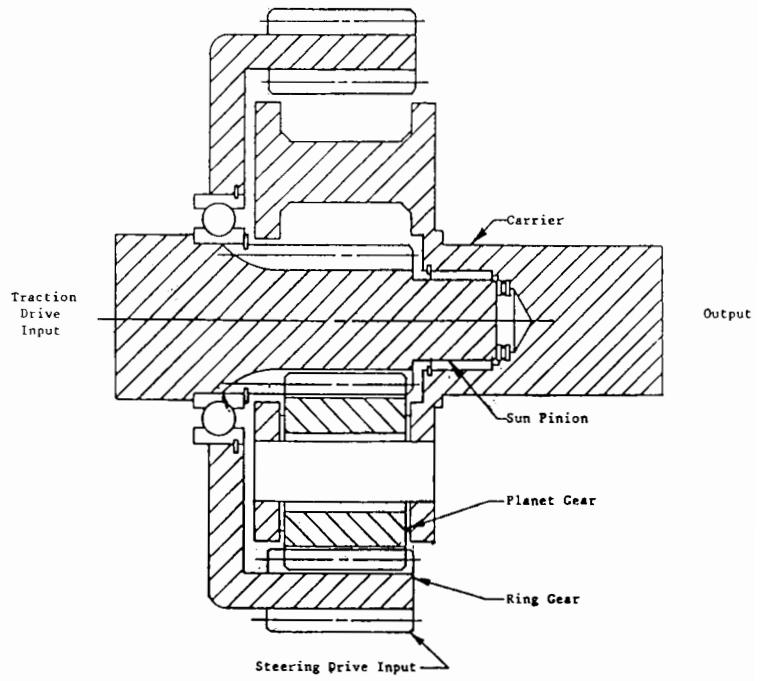


Figure 12 - Planetary

the output drive which in this case is the carrier, while the other two members are the traction input and the steering input which are the sun pinion and the ring gear respectively. In most applications, the ring gear is stationary and it is mounted in a housing. In this application, the ring gear is mounted on two bearings and it is rotating. It should be noted that the steering power is transmitted into the ring gear through a set of external gear teeth on the ring.

When the ring gear is mounted in a housing it is usually pressed in and the reinforcement of the housing makes it stable and free of deformation. In this transaxle, the ring gear lacks the reinforcement from the housing and is free to rotate on a bearing. The fact that the ring gear is constructed in a "C" shape, as shown in Figure 12, with one side wall only, and the gear teeth offset in relation to the side wall, caused it to have two significant deficiencies. One is that under heavy loads the ring gear tends to deform into a triangular shape by the loads of the three planet pinions. The second deficiency is that under heavy loads the ring gear tends to be pushed away from the steering gears by the gear separating forces. This caused the ring gear to overturn about the center of the bearing resulting in gear tooth end loading. Failure of gear teeth will result whenever the load is transferred in a concentrated form at the tooth end, rather than uniformly distributing it across the full face of the tooth. Such a failure can be seen in Figures 9a and 9b.

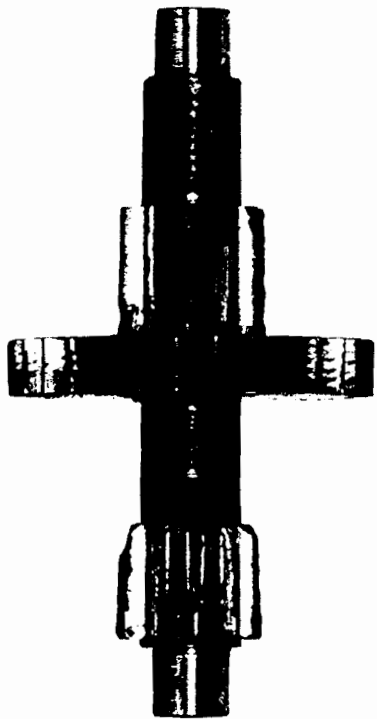


Figure 9a - Failed gear

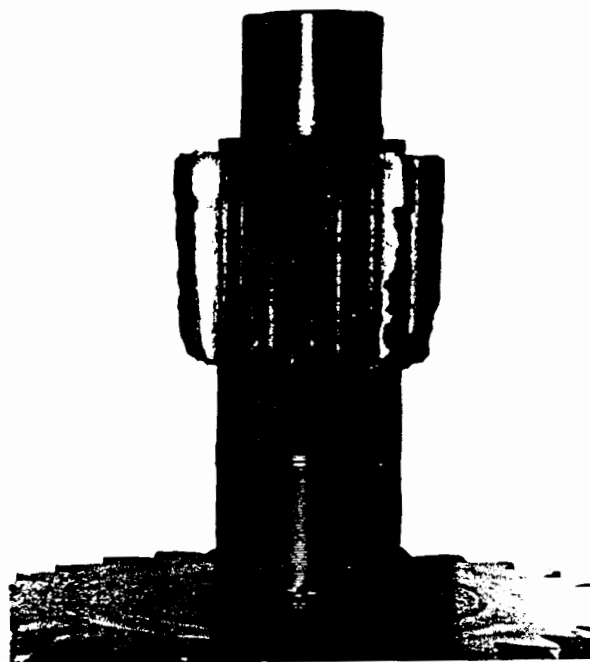


Figure 9b - Failed gear

The above two failures were eliminated by making a ring gear cover that is dovetailed with the ring gear and also mounted on a bearing as shown in Figures 8 and 10. This cover prevents the ring gear from becoming triangular, or from overturning under heavy loads. Field tests proved that these two problems were eliminated. This improvement is proprietary information of Power Engineering & Manufacturing, Ltd. and patent applications have been applied for and are pending.

This ability to drive a crawler in a straight line, or at a desired rate of curvature, but at a steady rate and without zig-zags, make it a good transmission for such applications as highway construction, pipe laying, highly curved residential street paving, and other applications that require precise steering. With the addition of the ring gear cover, the stability of the ring gear has been greatly improved, thus making this transaxle suitable for heavy duty crawler drive applications.

This paper is subject to revision. Statements and opinions advanced in papers or discussion are the author's and are his responsibility, not SAE's; however, the paper has been edited by SAE for uniform styling and format. Discussion will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Division.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Activity Board, SAE.

12 page booklet.

Printed in U.S.A.