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CROSS-COUNTRY VEHICLE WITH AUTOMATIC INCLINATION COMPENSATION*

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MOST of the serious and fatal accidents occur in agriculture and forestry when tractors (prime movers) tip over while driving along sloping terrain. The Federal Association of Agricultural Professional Associations has recorded all reported accidents and has investigated the causes in a study covering the period from 1 August 1962 until 31 July 1963. During this period of time, there were 1316 serious and 183 fatal accidents. Compared to the number of tractors in West Germany at that time, this means that we have about 1000 serious and fatal accidents per 100,000 tractors annually.

It was found that 41 per cent of all serious accidents and 70 per cent of all fatal accidents can be blamed on the fact that tractors tipped over while driving along inclines. These accidents can be reduced in terms of design by means of tipproof tractor hoods (tops) or suitable protective frames (loops, bars). But the basic trouble —the tipping over of the tractors—cannot be eliminated in this way.

In the following we want to show how it is possible to design cross-country vehicles through the suitable suspension of the wheels and through the special steering of these wheels, in their position with respect to the vehicle body; these vehicles would automatically adapt to the particular slope inclinations so that the vehicle body will always have a perpendicular position.

1. WHEEL AND AXLE ARRANGEMENT

Figure 1 is a diagram showing a conventional vehicle as it is driven along a slope in a lateral direction. The diagonal position of the vehicle means that wheel pressures

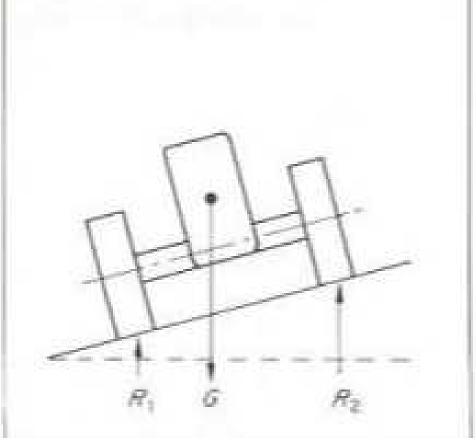

FIG. 1.
Conventional vehicle on slope.

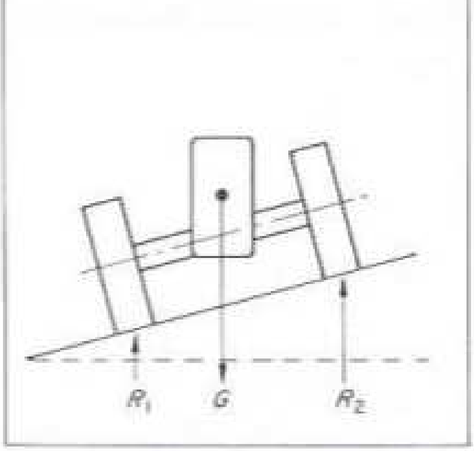

FIG. 2.
Vehicle with pendulum suspension.

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R_1 and R_2 differ. The lower wheel R_1 is heavily stressed. On the one hand, this creates a particularly heavy stress on the supporting earth, so that the wheel either sinks deeper or slides down the slope, and, on the other hand, the effective diameter of the wheel is reduced because of the load on the tires. As a result, the vehicle inclines even further downward and this in turn, increases the effects described above.

In addition to the danger of tipping over, this design also results in poor traction conditions because the small wheel pressure at R_2 can produce only small traction forces and because the overloading at R_1 causes the soil to be pushed downward.

Figure 2 shows a vehicle with an axle in a pendulum suspension whose position with respect to the vehicle body is assumed to be fixed by means of special devices such as, for example, hydraulic cylinders.

Compared with the arrangement in Fig. 1, the conditions are improved inasmuch as the wheel pressure R_2 is now greater, while the pressure R_1 is lower than in the arrangement illustrated in Fig. 1. The basic principle, according to Fig. 2, creates design difficulties to allow greater axle inclinations because there is only very little free space left for the vehicle body itself. But the traction and stability conditions are definitely improved.

Figure 3 shows a vehicle with a parallelogram-type location for the rear axle, whose position with respect to the vehicle body is fixed similar to the setup in Fig. 2. Because of the parallelogram arrangement of the wheels, the wheels are always parallel to the body of the vehicle and have the same distance from the vehicle. As a result, wheel pressures R_1 and R_2 are equal to each other in any axle position, which gives us optimum traction conditions. The stability of such a vehicle is definitely improved, compared to the abovementioned possibilities, because the center of gravity G can never be outside the contact surface, inasmuch as the axle can be adjusted so far that the wheels and the vehicle body will always be perpendicular However, one disadvantage in this arrangement resides in the fact that there is a change in the track when the axle is adjusted on the run. When the axle is in the extreme position, we only have a reduced contact surface available and this surface is no longer sufficient to meet the stringent requirements (for example, a forest tractor, equipped with a cable winch, will pull a load toward itself laterally in this position).

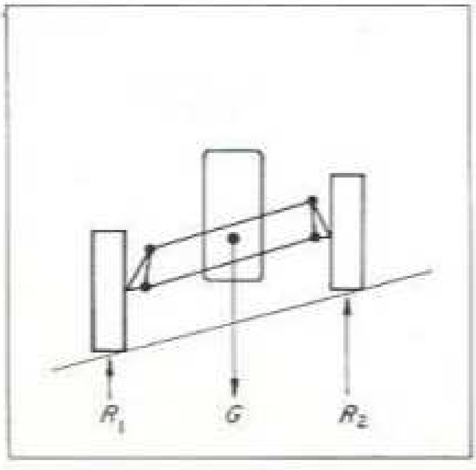

FIG. 3.
Vehicle with parallelogram type suspension.

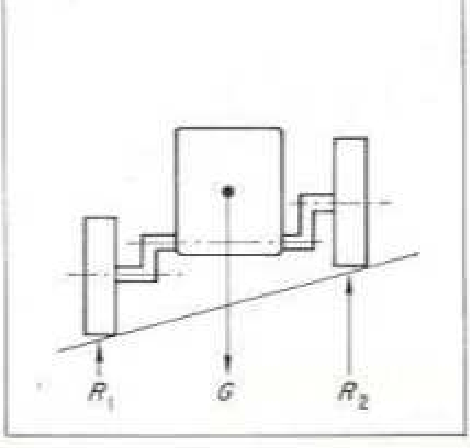

FIG. 4.
Changing vertical location of wheels.

Figure 4 shows a wheel arrangement in which, when the vertical position of the wheels is changed, there will be no change in the track of the wheels. The wheels are positioned individually on rotatable wheel shafts (locking arms) and they are, for example, fixed in their elevation position, with respect to the vehicle body, by means of hydraulic cylinders.

Instead of a change in the track or gauge, we get a change in the wheel base in such a vehicle, which however it not important when we drive across slopes, laterally with respect to the line of steepest gradient. Furthermore, the change in the wheel base can be reduced further either by means of longer swing arms or by means of special wheel suspensions. As regards stability, this solution represents the optimum. The traction ratios and conditions then correspond to the arrangement in Fig. 3.

2. VEHICLES WITH CONTROLLED [STEERED] AXLE

A vehicle, which is equipped with a steering system requires a third contact point, to make it possible to continually adjust one axle, while driving across a slope (Fig. 3 or 4) in such a way that the vehicle body in each case remains in a vertical position. This contact point is created very simply in accordance with Fig. 5 in that the vehicle is designed as a three-wheeler with a rotatable front wheel. The stability is that of a vehicle with a front axle in pendulum suspension without any stops, because on such a vehicle we only have a contact triangle (no contact square) available.

The above considerations are basically generally known but they are related to our problem here, the problem of creating a steering system which is in a position to keep the vehicle body in a perpendicular position during all operational states.

3. STEERING SYSTEM

Let us first of all consider only the metering element of the control circuit. The function of the metering element consists in determining the deviation of the position of the vehicle body with respect to the center of the earth. This measured value must not be falsified by static or dynamic interference which occurs when the vehicle moves on the terrain.

Figure 6 shows a vehicle with a simple pendulum for the recording of the angle of inclination α. The pendulum is suspended at its point of rotation 1. If the vehicle with its wheel 2 drives over an obstacle, for example a rock, then it assumes the angle

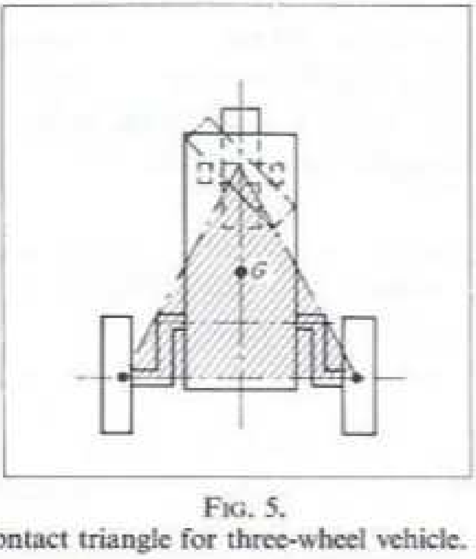

FIG. 5.
Contact triangle for three-wheel vehicle.

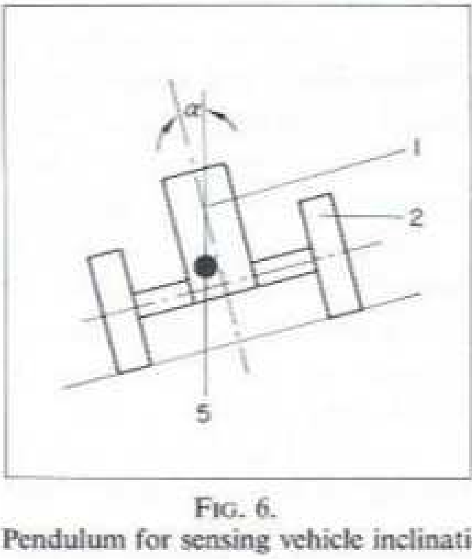

FIG. 6.
Pendulum for sensing vehicle inclination.

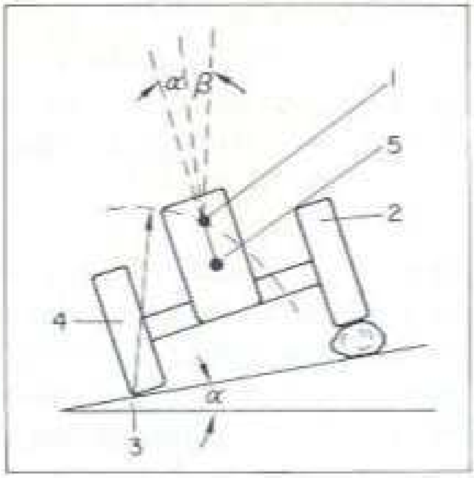

FIG. 7.
One wheel riding over obstacle.

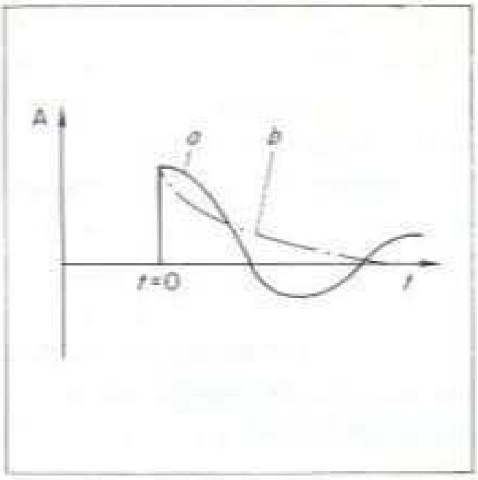

FIG. 8.
Variation of error signal with time.

$\alpha+\beta$ with respect to the vertical, when wheel 2 stands on top of the obstacle, as can be seen from Fig. 7. The entire vehicle has moved around contact point 3 of wheel 4. All points, including suspension point 1 of the pendulum, have described a circular movement around point 3. However, the inert pendulum mass 5 has remained in its original position so that we briefly get the pendulum position as drawn in Fig. 7. We can see that the pendulum, during the very first moment, swings straight toward the wrong side in the sense of a coverage of the angle of the vehicle toward the vertical.

Figure 8 shows the variation with time of the indication error when one side is driven over a beam. Prior to time $t=0$, wheel 2 is in front of the beam; the indication error is $A=0$. At time $t=0$, the wheel climbs on the beam and the vehicle suddenly assumes the additional inclination β. At this moment there develops an indication error A, which depending upon attenuation, pendulum length, and pendulum weight, will decay according to a time function and will become zero. This decay can take place in case of weak damping in the form of oscillatory motion (curve *a*) whereas in case of strong damping it is aperiodic (curve *b*). It must therefore be the function of a metering element to avoid the influence of circular accelerations around one of the wheel contact points. These accelerations occur in any change in the inclination of the slope.

Figure 9 shows a double pendulum arrangement. At a point of rotation 1, a pendulum with weight 5 is suspended, as in Fig. 6. Attached to this pendulum we have an indicator 7 by which means the vehicle inclination can be read off on a degree scale 4 attached to vehicle body 3. An additional pendulum, with weight 7, pivots about point 6. Side arms 8 and 9 are attached to both pendulums and these arms end in pivot points 10 and 11. Rotation points 10 and 11 are connected by tie 12. Assuming we have equal geometric dimensions in both pendulums, it is necessary to make sure that weight 5 is greater than weight 7 so that stable conditions will prevail in the resting state. For the static behavior of this arrangement, the additional upper pendulum 7 creates a disturbing effect because it reduces the adjusting force of the lower pendulum.

When we drive over an obstacle (as in Fig. 7) we see that radius described by the suspension point 1 around rotation point 3, is smaller than the rotational radius described by the suspension point 6 of the upper pendulum. In case of a sudden angle

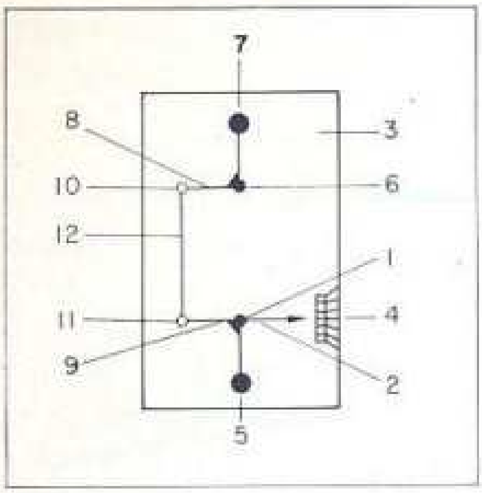

FIG. 9.
Double pendulum arrangement.

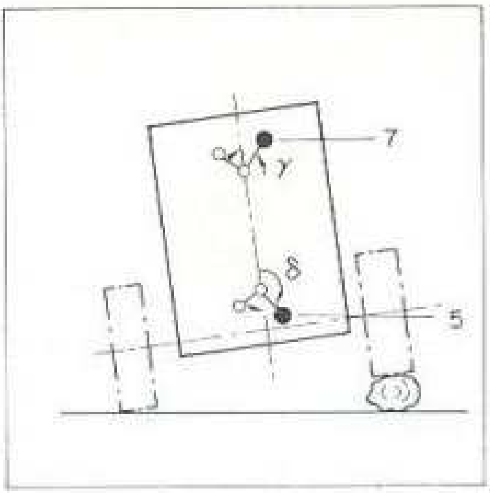

FIG. 10.
Position of individual pendulums when wheel rides over obstacle.

change β, the suspension point 6 thus covers a longer distance on its circular arc than suspension point 2. The pendulum with weight 7 thus endeavours to assume a greater angle change than the pendulum with weight 5 because the suspension point of the latter only describes a smaller path on its arc.

Figure 10 shows which pendulum positions the individual pendulums want to assume when the right wheel suddenly runs over an obstacle—if they were not connected by tie rod 12. Here, the imaginary angle γ which is described by the upper pendulum with weight 7, is greater than the imaginary angle δ, which is described by the lower pendulum with weight 5.

The two pendulums however are connected via joints 10 and 11 (Fig. 9) by the tie rod 12, so that there cannot be any differing angle change. The greater angle change γ (Fig. 10) in the upper pendulum (smaller weight) is matched by the larger weight 5 in the lower pendulum (smaller angle δ). If weights 5 and 7 are correctly balanced—assuming that the individual pendulums have the same geometric dimensions—then we do not get a faulty angle change due to dynamic accelerations on the metering element when we drive over obstacles and as a result of the associated rotational movement of the vehicle body.

In summary, the pendulum system can be so interpreted that one can compensate for the deceleration on the main pendulum by means of a second pendulum with a smaller weight, which however experiences a greater deceleration on the basis of its local arrangement. Through this sensing element it is possible—regardless of slope changes—to always obtain the same angle between the vehicle body and the vertical axis, indicated by the pendulum system, even at high operating speeds. According to Fig. 9, this angle can be read off on scale 4. The adjusting member of the regulating circuit now has the function of accurately compensating the angular deviations between the vehicle body and the pendulum system as quickly as possible.

Figure 11 shows one possible version of the adjusting element. Via control arm 1 of the metering element, a control valve 2 is activated and the housing of this valve is firmly connected with the vehicle body. The valve is supplied from an accumulator 3, which is intermittently fed via a pipeline 4 in such a way that the accumulator always has roughly constant pressure inside. The flow takes place via tank pipeline 5. On the output side, valve 2 controls the two hydraulic cylinders 6, which are connected

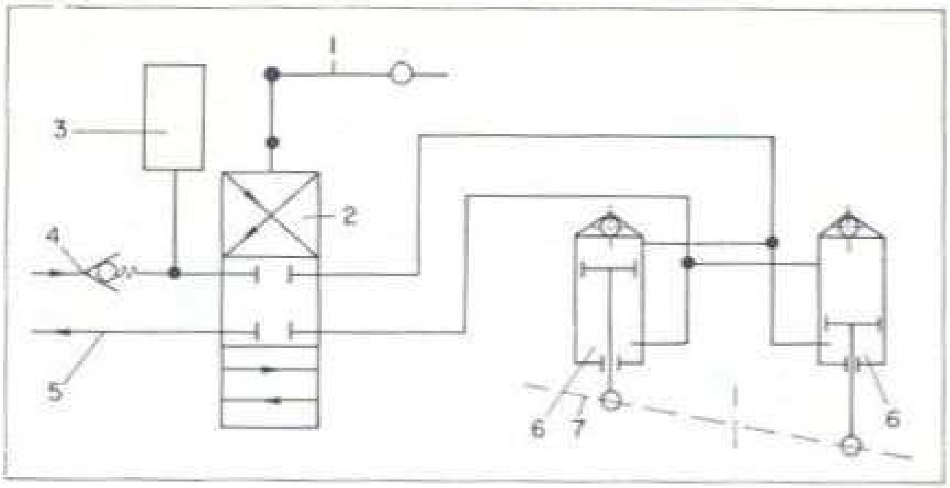

FIG. 11. Hydraulic circuit of compensating system.

in the manner shown; these cylinders are flexibly connected, on the one hand, with the vehicle body, and on the other hand, with the axis which is positioned in pendulum fashion.

If the vehicle body is in a vertical position, then the control arm 1 of the metering element does not give any indication at all and control valve 2 is in the neutral position shown. The oil flow is blocked all around, and the cylinders are locked, and axle 7 is thus fixed in position with respect to the vehicle body. If the vehicle, while being driven across country, reaches a point which reveals an inclination different from the one across which the vehicle has been driven earlier, then the position of the vehicle body changes while the pendulum system always indicates the vertical direction. Control arm 1 of the metering element thus changes its position with respect to the vehicle body and so activates the control slide of the valve. Pressurised oil from the accumulator flows into the hydraulic cylinders, as a result of which the vehicle body is adjusted to its angular position with respect to axle 7. The adjustment is arranged so that the vehicle body will approach the vertical position and stops when the control valve is in the neutral position, that is to say, when the vehicle body once again stands exactly vertical.

The above described arrangement thus makes it possible to keep a vehicle body in a pre-determined position—in this case a vertical position—while driving across constantly changing terrain. The dynamic problems occurring here are solved satisfactorily by the metering element, as described above. As regards the adjusting member, the adjustment times have been reduced to a minimum in that an abundant energy storage facility is available in the form of the accumulator 3. The requirement of such an energy storage facility is described by the following considerations:

An angular change of 20° is to be compensated for within 0·5 sec. On the basis of the design features, we might assume that this requires an oil volume of 2 l. at a pressure of 150 atm. This corresponds to a short-time performance of 80 h.p. If we wanted to divert this output without energy storage from the drive motor, then the entire drive motor would be stressed with this output performance during the adjustment time. On the basis of the fact that we drive very slowly when moving across particularly difficult terrain, we find that the angle changes occurring here within the unit of time are always small so that it is entirely sufficient to provide an engine output of about 6 h.p. available for the intermittent energy storage. On the basis of the available pressure storage unit, the adjusting member of the regulating system can meet all dynamic requirements it is expected to meet.

4. SAFETY PRECAUTION

In addition to the generous allowance in the safety interval, which all hydraulic parts must naturally reveal between operating and the spot pressures, and in addition to the reliable design of all mechanical parts of the entire control system, the following additional precautions have been incorporated.

The oil flows in the adjustment cylinders of the axle are turned off by means of mechanical servo-valves when there is no pressure in the pressure storage. Furthermore, the hydraulic cylinders are likewise locked in their position as soon as the container pressure is 30 per cent lower than the operating pressure. This fact is indicated to the driver by a warning light. Finally there is a possibility of fixing manually from the dashboard of the vehicle the axle in any position with respect to the vehicle by locking the hydraulic cylinders via electromagnetic locking valves. This locking takes place anyway when the vehicle is driven on the road, so that other drivers on the road will not be alarmed by the unusual compensating movements of the vehicle.

5. UTILIZATION POSSIBILITIES

Vehicles designed according to the above principle can be used wherever the terrain inclination is either so great that we can no longer use conventional equipment or where the work to be done requires a certain fixed position for the vehicle body.

The following utilization possibilities have emerged in agriculture and forestry so far: moving lumber and timber; removing tree cutting waste; layout of new forest cultivation areas by means of an attached step milling device; working marginal soils in agriculture, that is, soils which are marginal-yield soils, not because of their nature but because of their inclined position; in under-ground and road construction. Vehicles with automatic inclination compensation are particularly suitable for levelling work on level stretches and along embankments.

With control systems which provide stabilization along two planes, it is possible to build vehicles which have a platform that is stabilized in a lateral and longitudinal direction. Such a platform can accommodate a crane superstructure, so that the crane can be driven over terrain with a load suspended from it, without requiring any rails for this purpose.

Figures 12 and 13 show a vehicle with a controlled rear axle and a steerable front wheel. The vehicle is specially designed for the requirements of the forest industry. It can do all timber moving work because it is equipped with a cable winch and a bulldozer blade. Equipped with a fork of its own, it can push the cutting waste left on areas where the trees have been cut and this waste is then burned.

For new tree growth areas, a special forest cutting tool has been developed; it makes step-shaped terraces in the slopes. In reforestation areas, the young trees are planted in places exposed by the cutting tool. The following figures provide information to assess the success to be achieved in this field.

Time required to work 1 ha—about 13 hr; time saving compared to manual labor, consisting all operational and mechanization costs—about 1000 DM.

These figures clearly show what possibilities are offered by the use of machines in such places which until now could be worked only by hand.

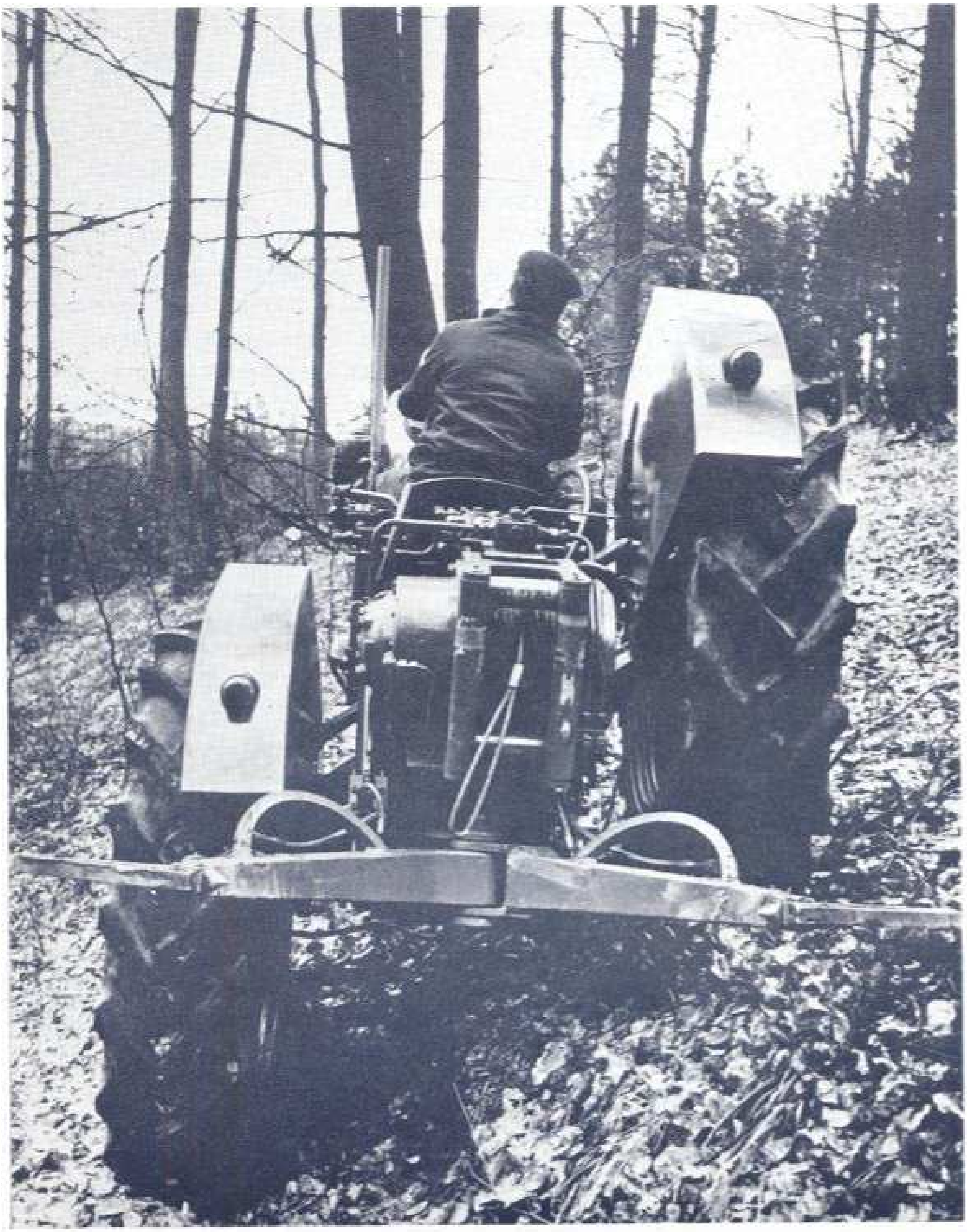

Fig. 12

FIG. 13

6. FURTHER DEVELOPMENT OUTLOOK

At this time, work is being done on wheel suspension and control systems, providing for several controlled axles in one vehicle. Here, it is possible to achieve a complete weight distribution over all individually suspended wheels so that the contact surface of such a vehicle with, for example, two controlled axles represents a genuine contact square, compared to the hitherto known contact triangle. The improvements which can be obtained here with respect to stability and traction behavior are quite obvious.

The abovementioned axle arrangement furthermore improves the dynamic behavior while driving over obstacles because the vehicle body initially describes only the alteration angle α_n, when one axle is turned around the angle α_{av} with respect to the vehicle body because of unevenness in the terrain, where n represents the number of controlled axles. The control system can thus compensate for the angle change of the vehicle body before the next controlled axle reaches the same obstacle. We can thus build vehicles which can move at considerable speeds even in very difficult terrain, without producing any disturbing or dangerous inclinations to the side which would jeopardize the driver.

By means of a special metering element it now seems also possible to regulate not only the side inclination but also the longitudinal inclination of such a vehicle so that we can create platforms stabilized in both directions, platforms which can be universally used as special equipment carriers.