

SOME NOTES ON THE STEERING OF TRACKED VEHICLES BY ARTICULATION

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The steering of tracked vehicles by articulation is defined and explained, and its basic advantages over skid-steering are illustrated. The principal mobility gain is shown to result from the elimination of any necessity to 'put on the brakes' to steer at the very moment when all available traction may be needed simply to avoid bogging down. The chronology of the development, which in the past six years has taken on new life, is briefly traced. The general characteristics and field performance of several new vehicles currently exploiting this principle are reviewed. It is concluded that the successful introduction of practical vehicles steered by articulation is the most important development in off-road vehicles in the past several decades.

1. INTRODUCTION

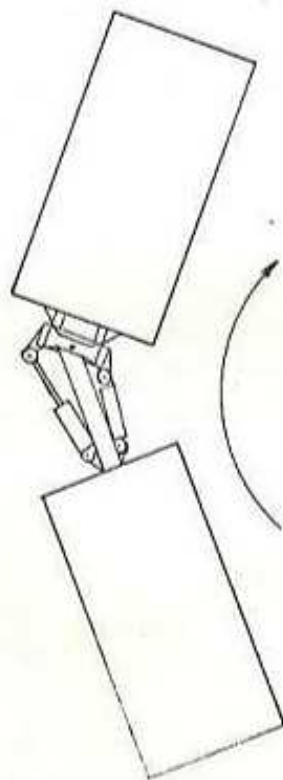
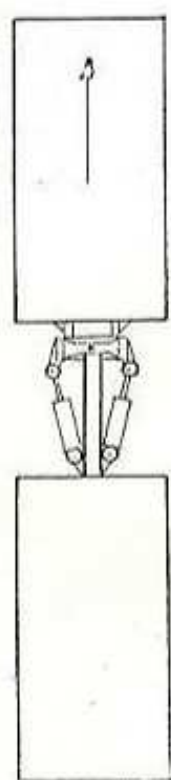
The very *raison d'être* for tracked vehicles of all types is their increased level of performance over wheeled vehicles in off-road operations, particularly in terrains characterized by muds, snows, and similarly weak surface materials. It is, therefore, surprising to find that the serious basic limitations on that performance which are imposed by the use of skid-steering - almost universally used since about 1910 - have been clearly stated and demonstrated only in the past few years. (1,2) In skid-steering, the large moment necessary to change the heading of a vehicle against the resistance (primarily) of frictional and/or soil shear forces generated in its extensive contact area with the ground is supplied by reducing the net longitudinal thrust of one track and (when possible) increasing that of the other. Where the vehicle-soil contact is already stressed close to failure, the increase in thrust from the one track is not possible; and steering is accompanied by a net reduction in total forward thrust. In cases where operation is marginal as a result of ground weakness (usually accompanied by large sinkages which increase turning resistance) attempting to steer by this means often leads to complete immobilization.

Over the years many ingenious mechanisms have been devised and developed at great cost to reduce the internal braking losses which accompany this basic type of steering action, and this work still goes on (e.g. Reference 3). The vehicle-soil interaction is fundamentally unchanged by any of these remarkable devices, however. A vehicle equipped with the latest regenerative steering axle will become immobilized, while steering in weak terrains, in the same places and by the same mechanism as its most antiquated clutch-brake cousin.

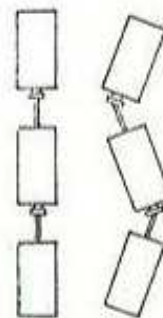
The alternative is to construct the vehicle so that the stable direction of thrust of its running gear may, by means of internal forces, be controllably disposed in the steering plane to make the vehicle follow a curved path, after the general fashion of ordinary motor cars. One version of this approach is illustrated in Figure 1. The general method

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STEERING OF TRAIN-JOINT VEHICLES



TWO UNITS



THREE UNITS - IN PLACE

Fig. 1. Tracked vehicle steering by articulation

PRINCIPAL ARTICULATE CONFIGURATIONS

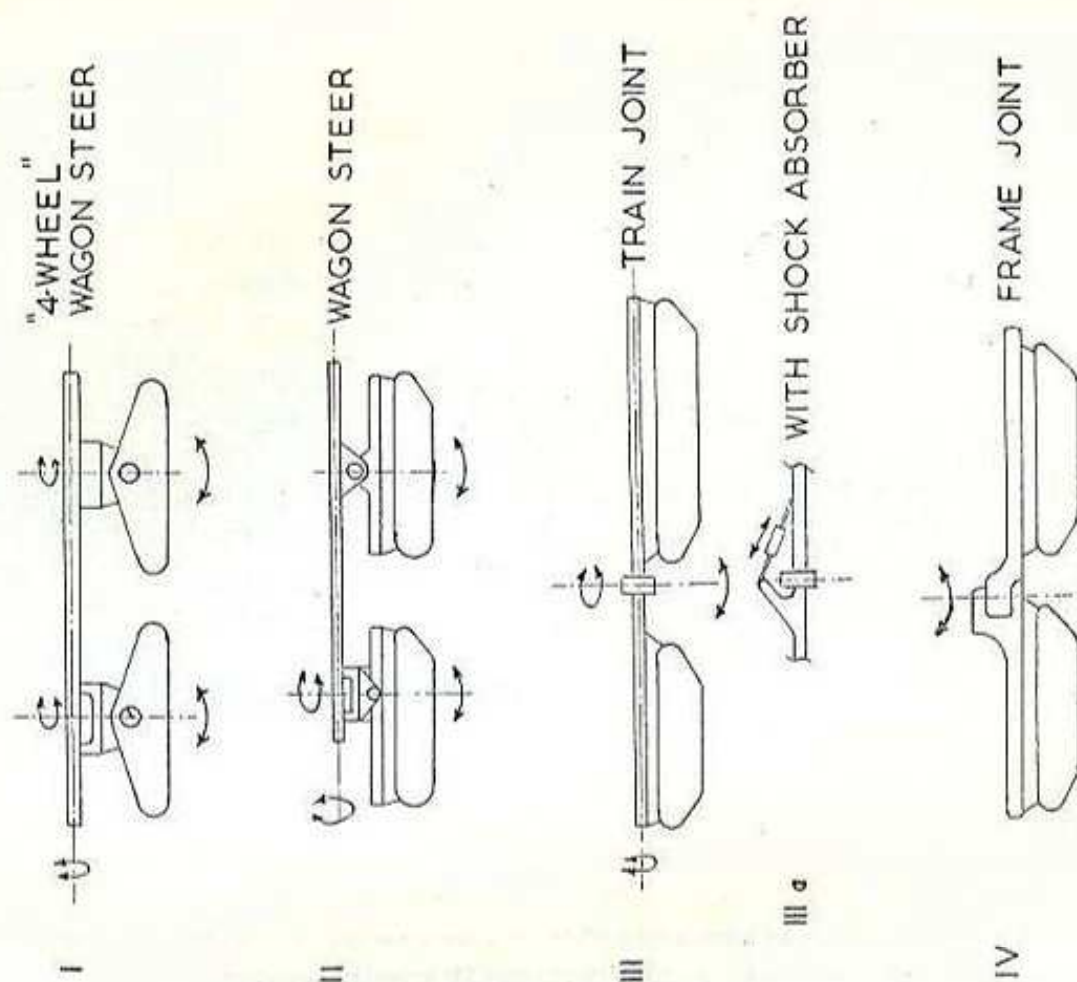


Fig. 2. Several articulation schemes

illustrated therein for steering tracked vehicles will be referred to as 'steering by articulation', or simply 'articulated steering'.

There are a number of possible vehicle articulations which will accomplish this in a practical manner. The three main types of articulated steering configuration now in use are illustrated in Figure 2. A fourth, the form originally proposed by Bekker from considerations of the best 'ride' in rough terrain⁽²⁾ is also shown, although it has not been tried in the field. The ultimate in 'ride' improvement which it offers is bought at the expense of considerably increased structure, track, and running gear loadings. A compromise, in which a heavy damper or shock absorber is used across a joint otherwise free in the pitching plane (III-a), has demonstrated a substantial improvement in cross-country ride, and has proved eminently practical as well.

In the remaining sections of this paper, the history of articulated steering for tracked vehicles will be briefly outlined. Some of the advantages of this type of steering over skid-steering will be discussed and demonstrated, and experience and data on some recent vehicles which have successfully exploited this means of steering will be presented.

2. ARTICULATED STEERING THROUGH WORLD WAR I*

The earliest tracked vehicles were great, smoke-belching, steam traction engines, closely related to their contemporaries which operated on large, often ingeniously devised wheels. Like their wheeled cousins, these primitive tracked machines were generally steered via wagon-steered, unpowered front wheels, or by a single pivoting, unpowered front wheel or track [Minnis, U.S., 1867⁽⁵⁾; Parvin, U.S., 1873⁽⁵⁾; Baxter (or Batter), U.S., 1888^(4,5); Edwards, England, 1888⁽⁴⁾; Stratton, U.S., 1893⁽⁵⁾]. They were, broadly speaking, steered by a form of articulation. One of the last commercial machines of this type appears to have been the Killen-Strait tractor, investigated by the British in 1915 as a possible basis for the development of their tank (Figure 3).

Towards the turn of the century, however, two alternatives had appeared on the horizon: steering by track-setting, and skid steering.

Proposals to steer by controlled lateral placement of the tracks as they are progressively laid on the ground (i.e. by track-setting) were first advanced, in patents, by Page [1884⁽⁴⁾] and Justice and

* An authoritative historical review of the development of tracked vehicles appears yet to be compiled. This brief reconstruction of the early history of tracked vehicles steered by articulation is pieced together largely from a small number of previous compilations (4,5,6,7) each of which is patently limited in one way or another. A modest effort was made to get at more original source material such as patents, the published works of the early protagonists (8,9,10), etc., but far more remains to be done. The author will be happy to serve as a clearing center for any further information which anyone cares to offer.

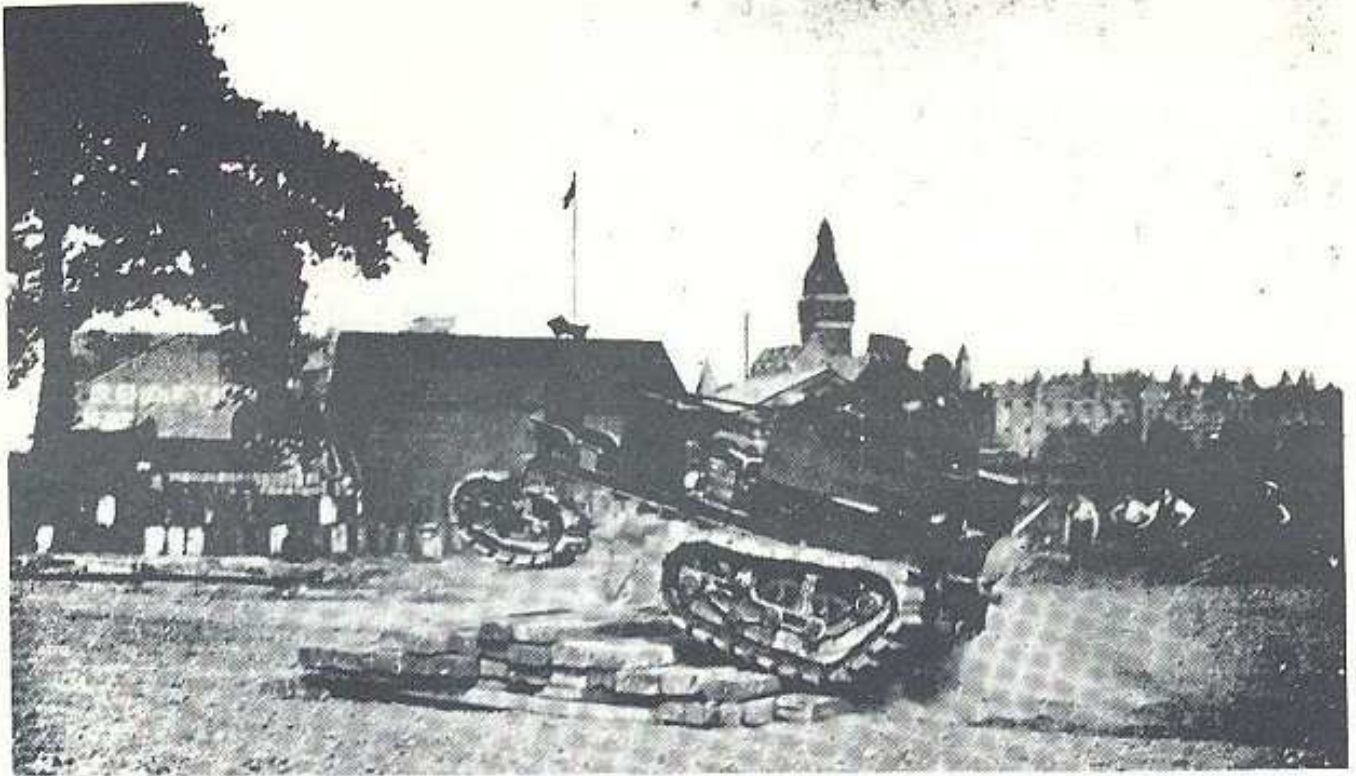


Fig. 3. Killen-Strait tractor under test by the British in 1915

Johnson [1896⁽⁴⁾]. Practical trials of the method, however, were not forthcoming until the early 1920's. Subsequently, several military vehicles employing this steering system were built by the British. Some of these saw service in World War II. All vehicles using track-setting ultimately incorporated the dual complexity of some form of supplementary skid steering for close manoeuvring, however. Thus, not only did weight and complexity of the track-setting vehicle increase (as compared to a skid-steered vehicle) but its potential mobility advantages in soft ground could not be exploited in precisely those situations where they were most needed. So far as is known, no modern tracked vehicles employ track-setting.

Skid steering, on the other hand, has been employed on the great majority of tracked vehicles since about 1910. Gray refers to Holt's having proposed to replace the differential in his early machines with a clutch-brake system as early as 1891⁽⁵⁾. A practical steam-powered machine utilizing a clutch-brake mechanism to supplement the steering provided by front wheels appears to have been demonstrated by Holt in 1904, and offered commercially in 1906. A smaller gasoline-engined version was demonstrated in 1906 and went into production in 1908. By 1915, the front wheels were totally dispensed with; and in 1916, the U.S. Army had a number of Holt gasoline tractors, looking much like modern D-4's, for pulling artillery⁽⁶⁾.

In England, Roberts dispensed with front wheels altogether and demonstrated skid steering via a braked differential in 1904. In 1907, he patented a power servo to aid application of the steering brakes; and in 1909, with James, demonstrated and patented a clutch brake mechan-

ism⁽⁴⁾. By the time of World War I, skid steering had been largely accepted in commercial vehicles. Although, as will be discussed later, steering by articulation was considered during the early stages of development by the British of their World War I tanks, the several versions finally put in the field were all skid steered, as were the contemporaneously developed French tanks. The very first British tanks (MKI-1916) were controlled by a cumbersome arrangement of clutches and dual transmissions (augmented by hydraulically steered tail wheels) which required the full-time attention of two or three crew members^(8, 10). The tail wheels were soon dispensed with, and following trials in early 1917 of some six various drive systems - ranging from electric through hydrostatic to various mechanical arrangements - a more manageable epicyclic geared-steer system was adopted for the late MKIV's (1917) and all subsequent models⁽⁸⁾.

Post-World War I commercial tractors and military vehicles were likewise skid steered. The main advances in tracked vehicle steering in the years that followed were in the sophistication of the interior mechanism by which the relative track speeds were controlled. In 1918, Cleveland Tractor offered a tractor employing the controlled differential mechanism⁽⁵⁾, of the type almost universally used on military tracked vehicles well into World War II. By 1930, the first of the deliberately regenerative axles, of which the U.S. Army cross-drive is a latter day example, were on the scene⁽¹¹⁾.

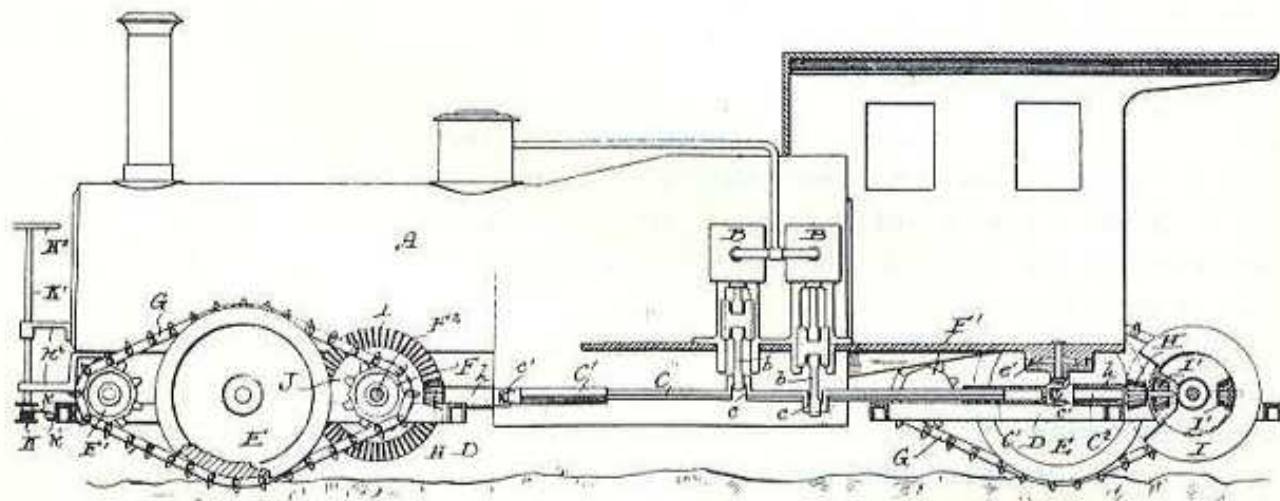


Fig. 4. Stewart's 1892 four-track proposal

By the turn of the century, the steering of tracked vehicles by articulation was clearly on the wane; although Stewart, in an 1892 U.S. patent, proposed a relatively modern concept (Figure 4). The only person to buck the tide seriously appears to have been Diplock, who in 1902⁽¹²⁾ patented a steering joint configuration for use with either wheels or tracks (Figure 5). In 1913, he offered an articulated Pedrail tractor and trailer on the commercial market. This vehicle is shown in Figure 6, which is reproduced from *The Engineer* of 25 July 1913, and schem-

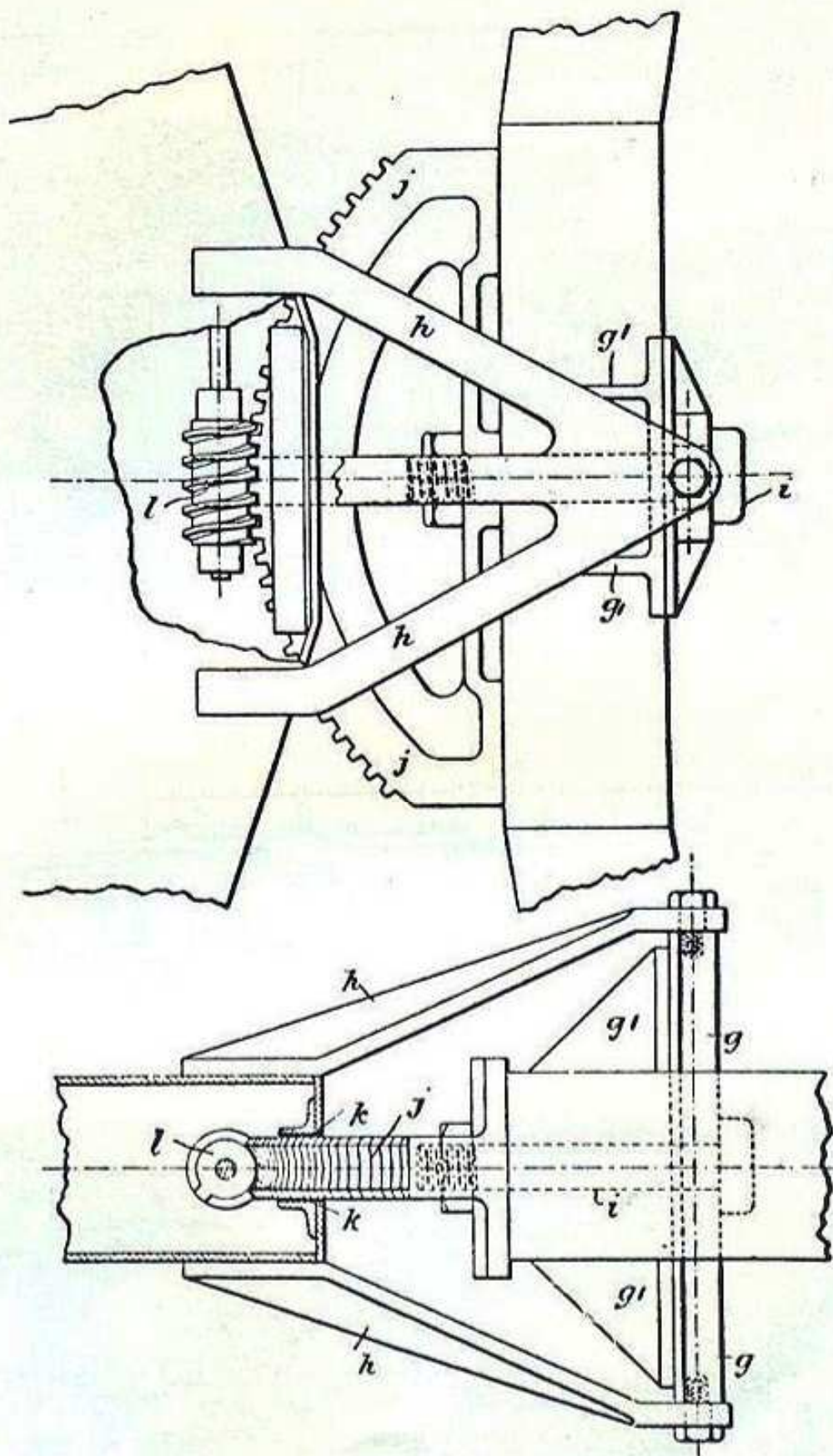


Fig. 5. Diplock's 1902 steering joint

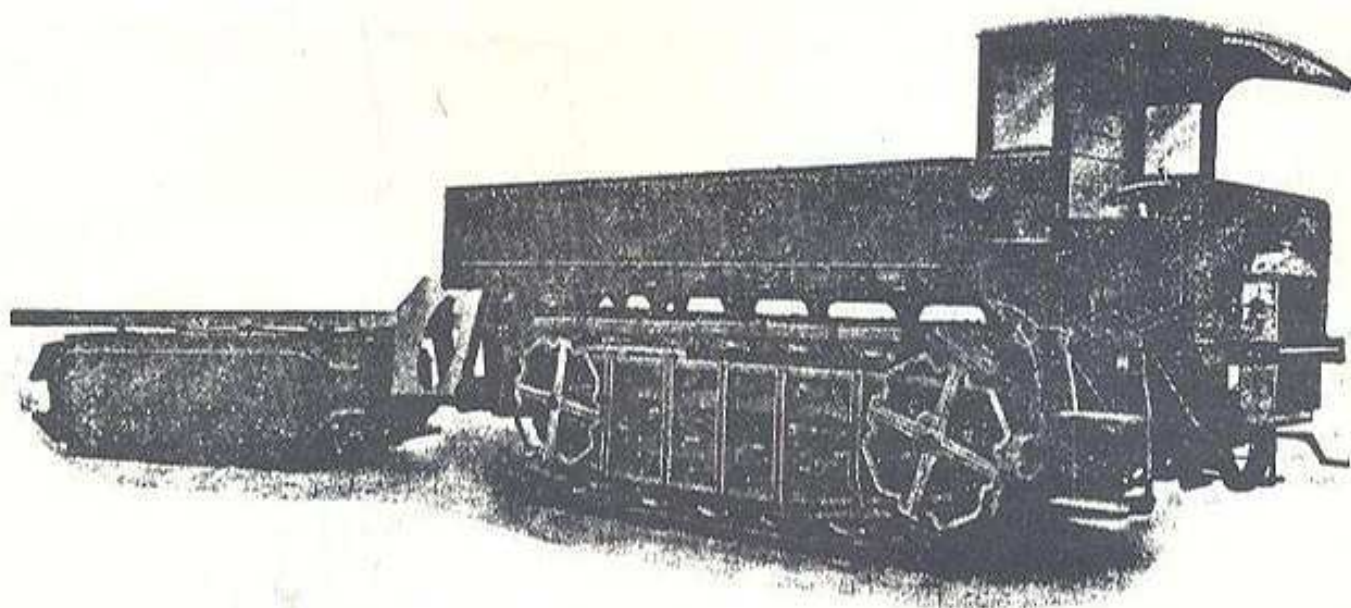


Fig. 6. 1913 Pedrail Tractor and Trailer (Diplock)

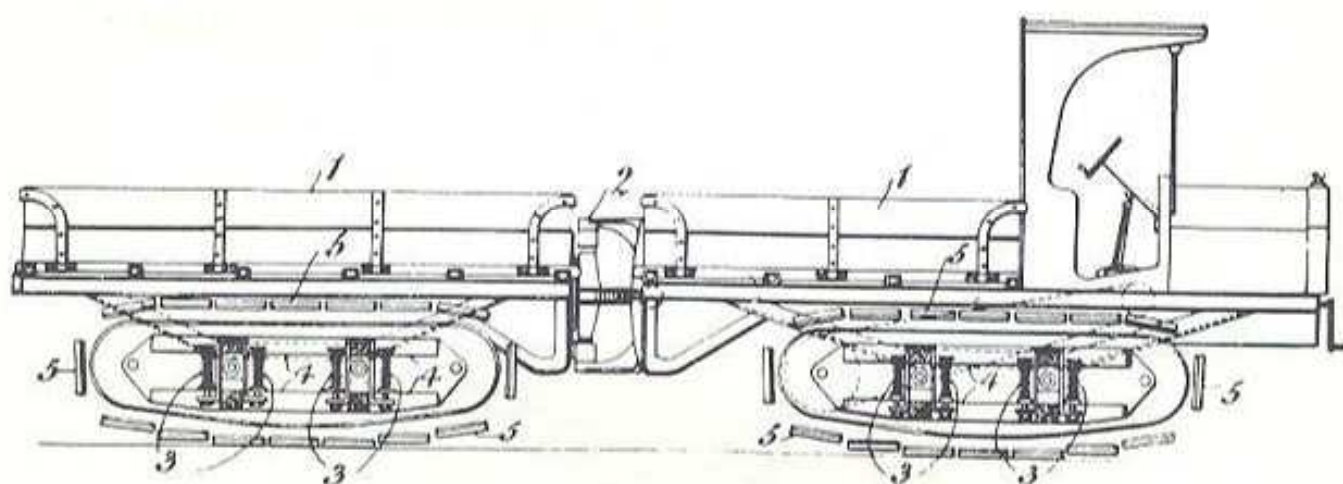


Fig. 7. Diplock tractor-trailer articulated vehicle as shown in a 1912 patent pertaining to his Pedrail track system

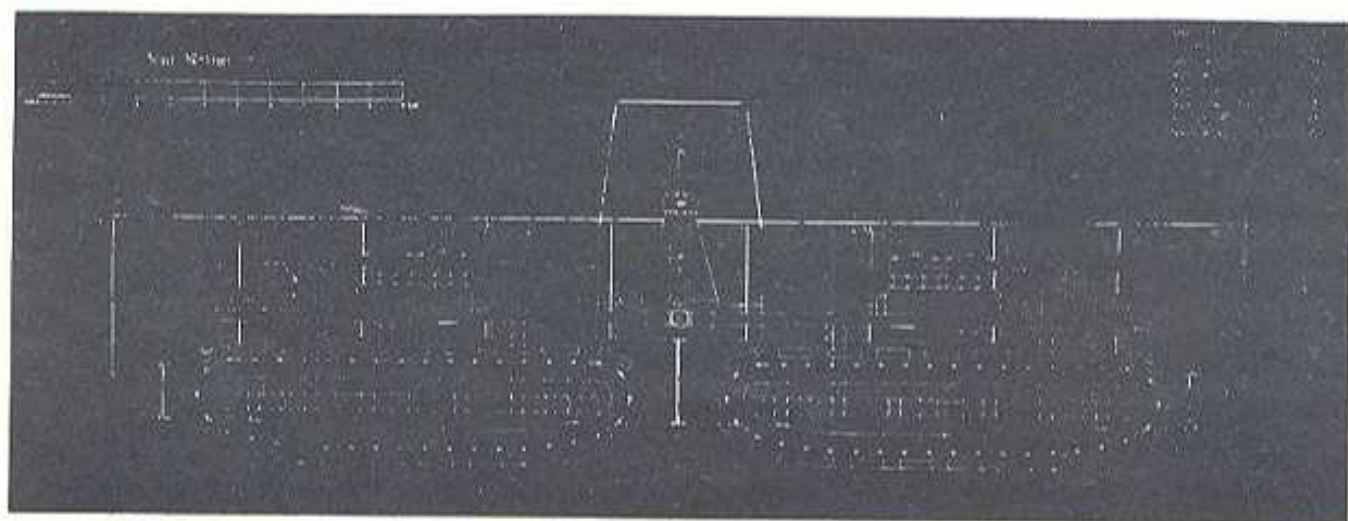


Fig. 8. First actual design for a tank as prepared by Diplock following the suggestions of Sueter

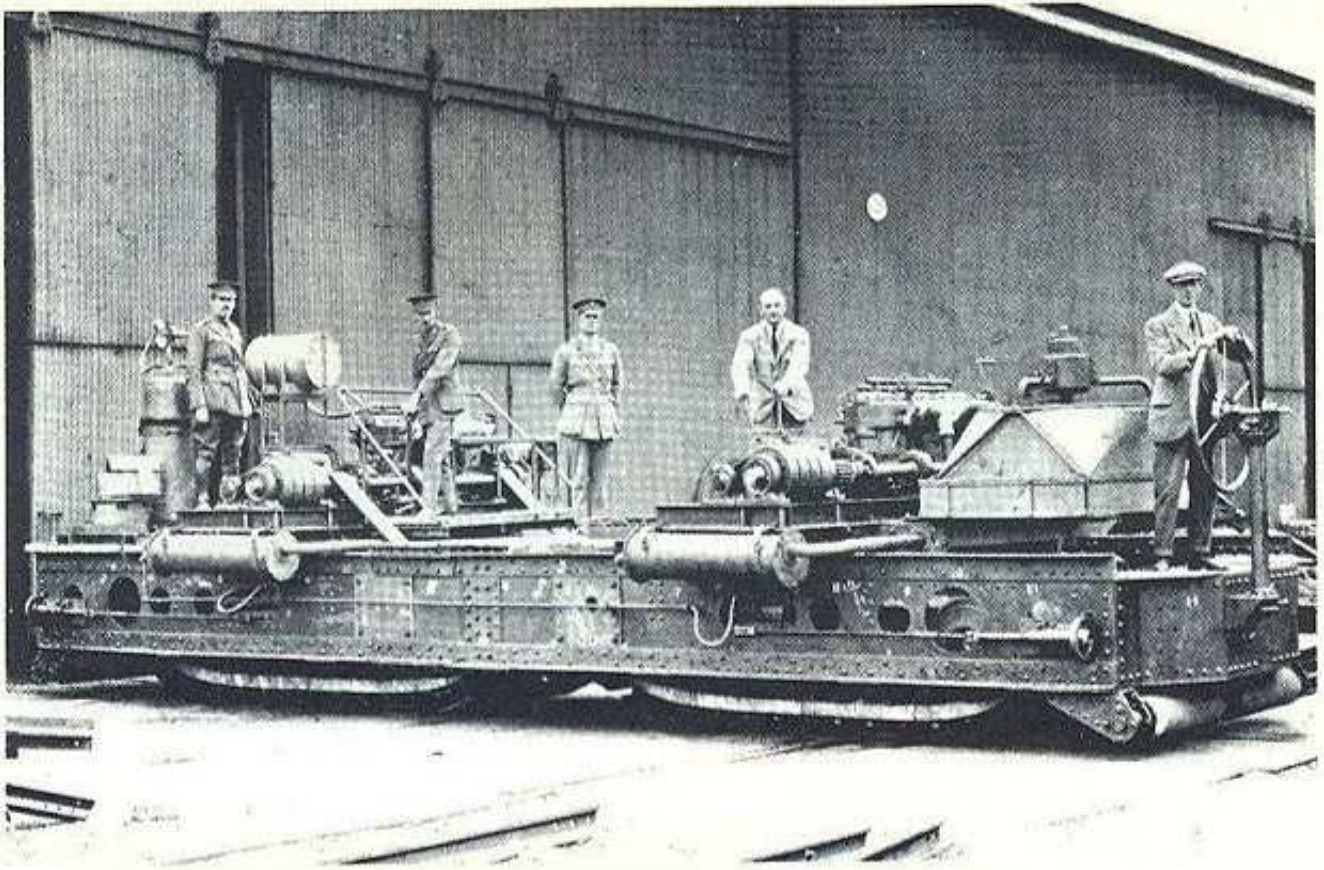


Fig. 9. Overgrown Pedrail landship chassis, 1915, as developed by Crompton, apparently following Diplock's earlier concept, albeit loosely

atically in Figure 7, taken from Diplock's 1912 patent on some improvements to his Pedrail track system, in which the articulation is only mentioned in passing. This machine is a tractor with unpowered trailer. Although it is implied that the tractor was operable alone, this is not certain; and steering when coupled was accomplished by means of the joint, 'using....(the trailer)....after the fashion of a rudder'⁽¹⁰⁾. The fact that the joint was controlled in yaw, for steering, free in roll, but locked against interunit pitch, would seem to indicate that the two units were not truly intended to be separated. This machine may not have been a commercial success for when, some 18 months later - after the outbreak of the war - it was desired to demonstrate a tracked vehicle to Winston Churchill, the device shown him was a small, horse-drawn cart on a single Pedrail.

As is well known, the British armoured, tracked military vehicle which became known as the tank, which played a decisive tactical role in the defeat of the German Armies in 1918, and which was the ancestor of our present fighting tanks, began life as a 'landship' under the official protection of Churchill, then First Lord of the British Admiralty. It is not so widely remembered that the very first design (Figure 8) was prepared by Diplock⁽¹⁰⁾. Note, however, that although Diplock's first layout shows a four-tracked vehicle, it was not intended at this time to steer it by articulation, but rather by skid-steering. The four-tracks were adopted because Diplock could not offer a larger single track

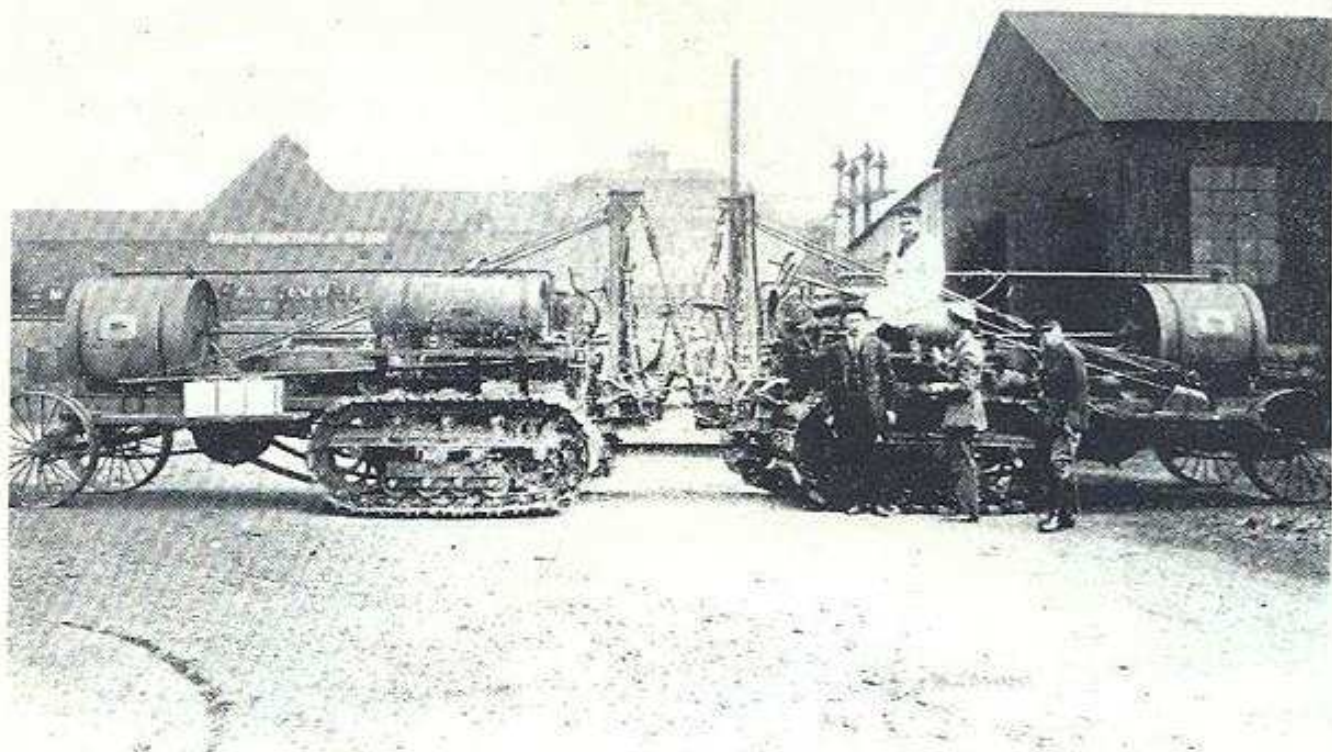


Fig. 10. 'Lash-up' of two Bullock 'Creeping Grip' tractors to test articulation concept

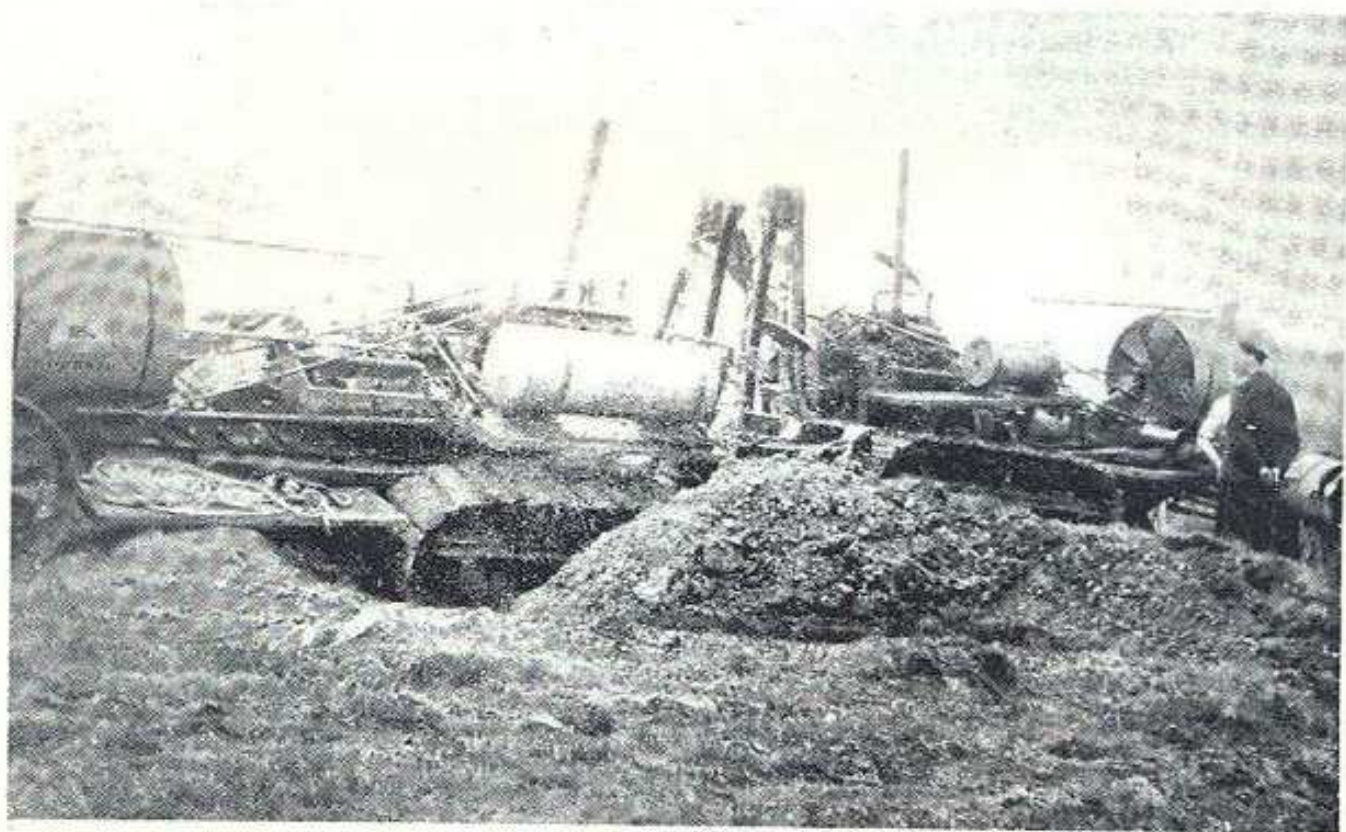


Fig. 11. Articulated 'Lash-up' fails to cross an obstacle

structure for each side. This design grew during 1915 into the monstrosity shown in Figure 9, which was still not articulated. The idea of articulating it by placing a joint in the frame appears to have come only after it was decided that it would have difficulty manoeuvring in the narrow streets of French villages^(8,10) (overall length was 65 feet, and its L/T ratio about 3.5).

In order to determine the feasibility and merits of such an articulation, the lash-up shown in Figure 10 was made using two U.S.-made Bullock 'Creeping Grip' farm tractors. The connection appears to have allowed considerable interunit freedom, did not incorporate internal steering means, and was in no perceptible manner related to Diplock's earlier-published concepts. Encumbered with two sets of undriven wheels and with a joint which (via 20-20 hindsight) was totally unsuited for the obstacle-climbing, trench-crossing job envisioned for it, the rig was a failure^(8,10) (Figure 11). History marched on.

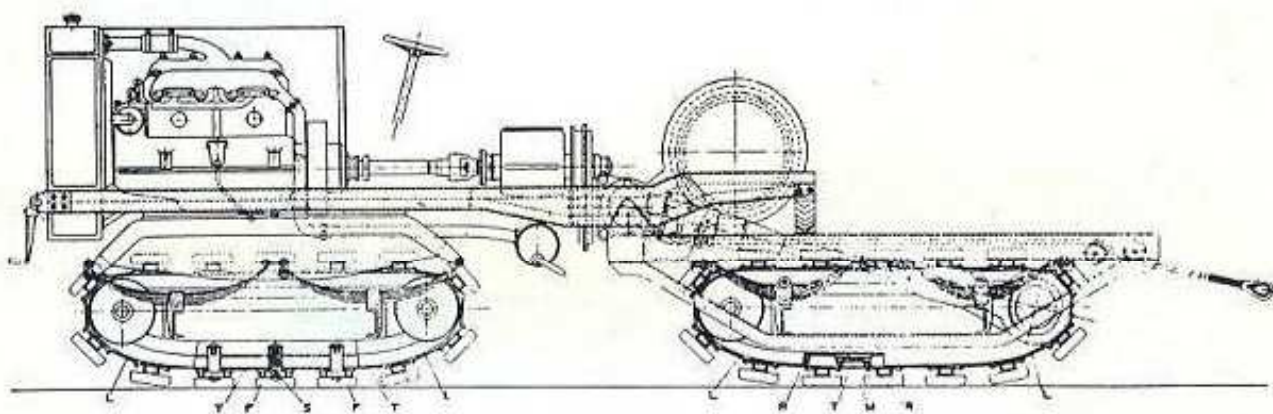


Fig. 12. 1917 Diplock Tractor

Diplock apparently continued (unsuccessfully) to offer articulated, Pedrail vehicles commercially as late as 1917. Figure 12 shows a 'Present Day Diplock Chain-Track Tractor' as illustrated in *The Engineer* that year⁽⁴⁾. The 1917 Diplock machine is steered by means of a wagon-steered, unpowered front track unit, and appears, in addition, to incorporate spring-controlled frame flexibility permitting some pitch and roll motion between units. Like all of Diplock's tracked machines, it uses his Pedrail track system, which appears to have been his principal pre-occupation, rather than articulated steering.

3. 1919 - 1957

There followed a virtual hiatus in the development of articulated tracked vehicles until after World War II. Such few experiments as were undertaken between the wars, including several in which trucks were modified to use tracks in place of their wheels⁽⁷⁾, did not lead far. Awareness of the potential of this type of steering in extremely weak terrains was stirring, however (Figure 13).

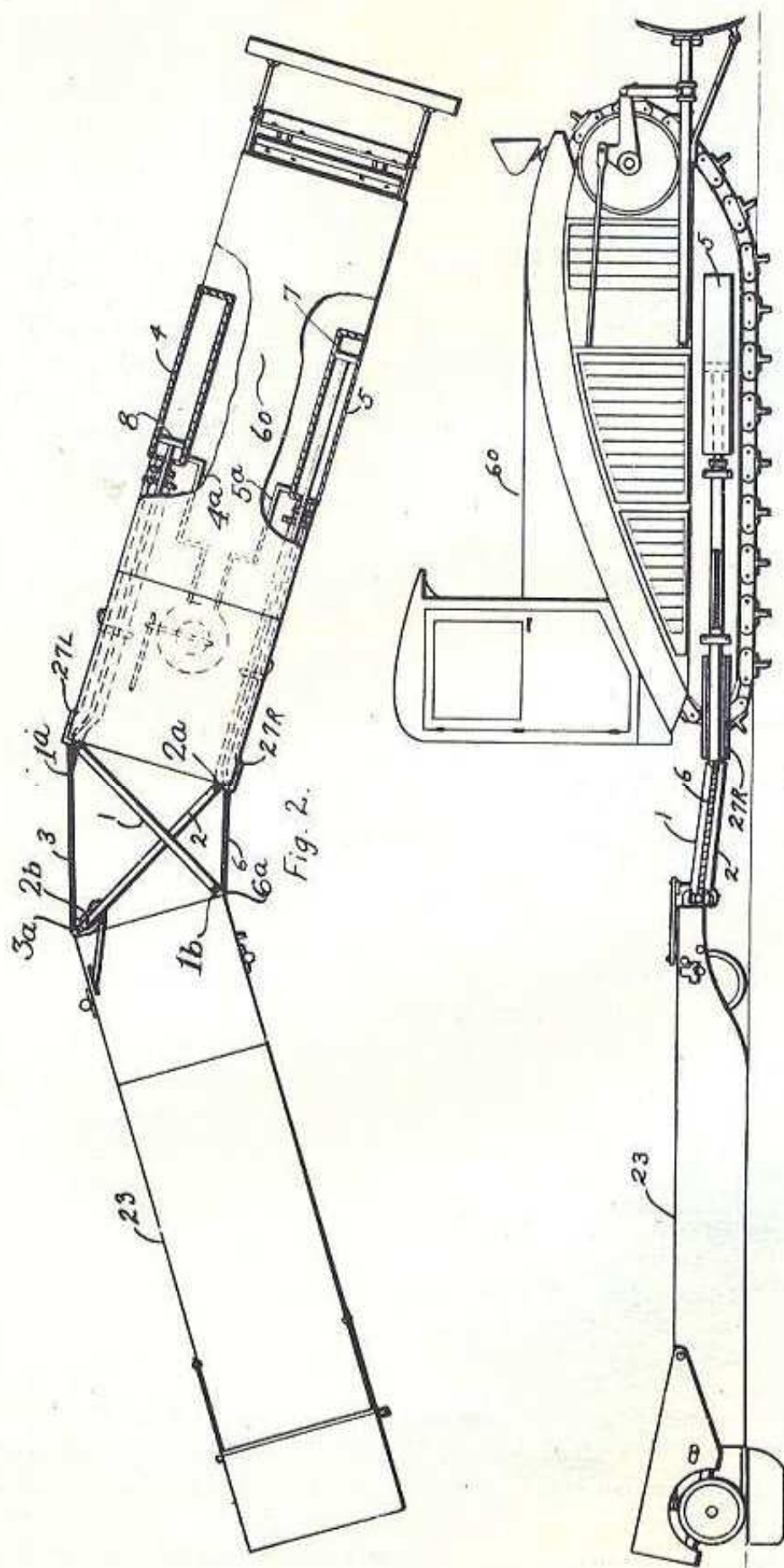


Fig. 1.

Fig. 13. Davidson Sno-Tractor, from U.S. Patent filed in 1935



Fig. 14. Prototype Tucker SNO-CAT, about 1948

Activity during World War II on this line of development was trivial. In the U.S. a proposal was studied for a large caliber Gun Motor Carriage, based on articulating two M-4 tank chassis. Work also began on two 8x8 trucks (T20, T26) employing wagon steering on the front, four-wheel bogies. This permitted their use with tracks, and they were so tested in the late 1940's. But the fuse was still damp.

During the late stages of World War II, the frequent bogging of allied armoured vehicles in northern Europe led to the formation in Great Britain of the 'Mud Committee'. One of the final (post-war) reports of this group calls attention to the fact that most immobilizations occurred while the tanks were attempting to steer⁽¹⁴⁾. Beyond recommending that this seemed a pregnant area for research, no suggestions were made, however.

The thread was picked up by Bekker, in 1952, when he called attention to the limitations on form and hence 'ride' imposed by the 'stubby' geometry necessary for successful skid steering⁽²⁾. Growing out of this, some crude scale-model tests were conducted at Stevens



Fig. 15. Current commercial SNO-CAT

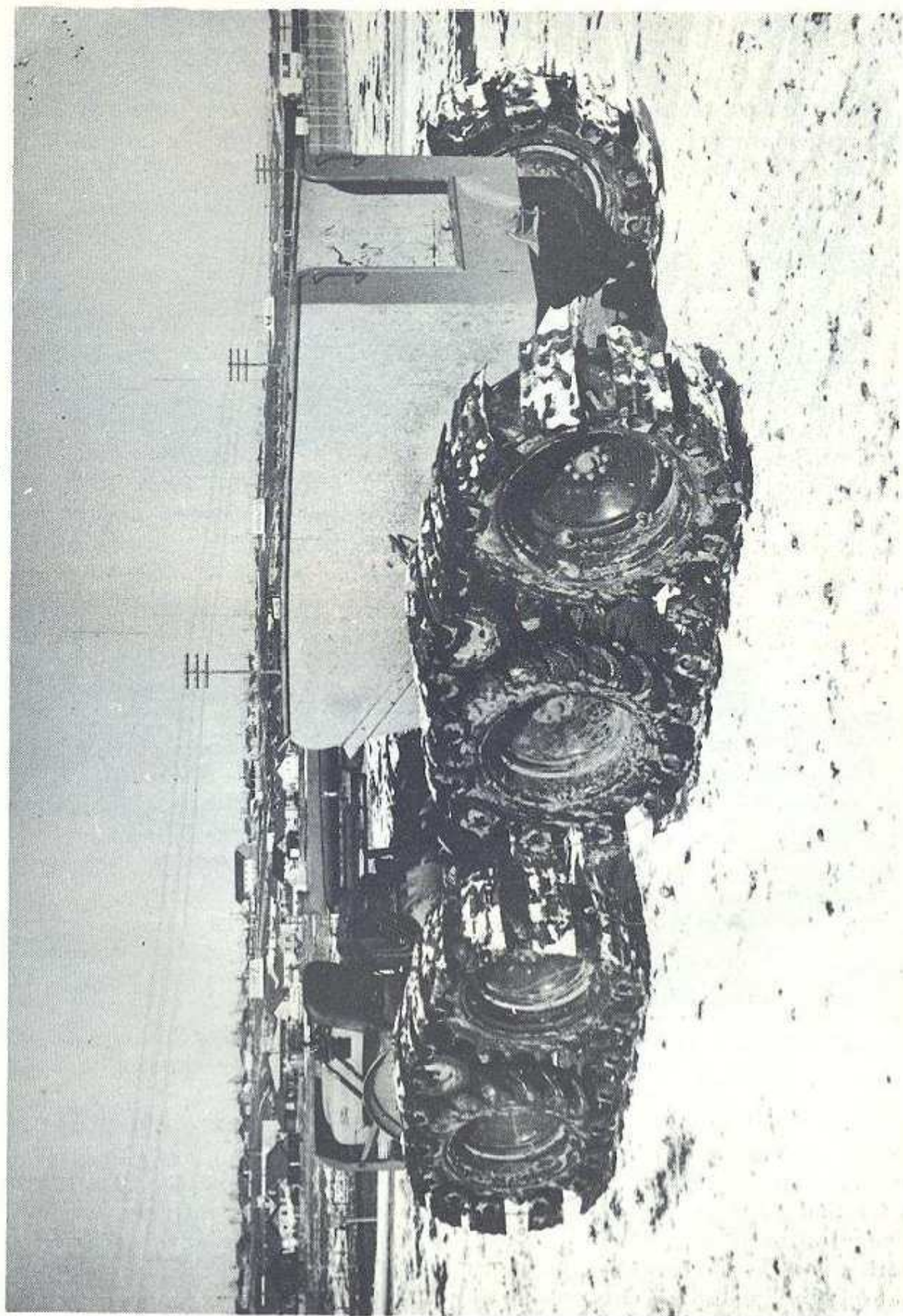


Fig. 16. Prototype 'North King', 1952

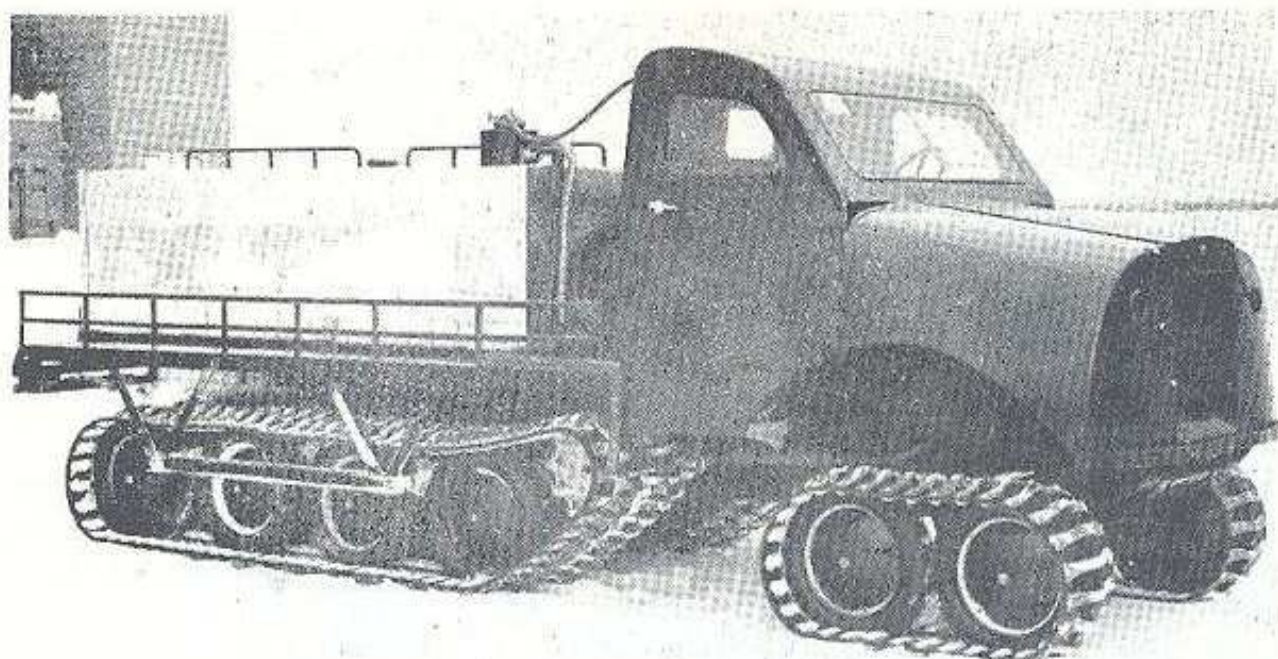


Fig. 17. Bombardier Snomobile with front tracks (unpowered), 1954



Fig. 18. Preprototype RAT

Institute of Technology; and static, 'friction circle' based equations were developed relating joint forces and vehicle turning radii to joint steering angles and to vehicle geometry⁽¹⁵⁾. It was concluded from this work that articulated steering of tracked vehicles was entirely feasible. There followed a number of design studies in which the advantages of articulated steering were stressed, and the resulting change in tracked vehicle morphology was demonstrated (e.g. References 2, 16).

The first practical modern tracked vehicle incorporating articulated steering antedates all of these later studies, however. The four-tracked Tucker SNO-CAT, which evolved from World War II experience with several small half-track/half-ski machines, was successfully introduced in rugged, public utilities maintenance work in the Rocky Mountains during the late 1940's (Figures 14,15). The remarkable over-snow mobility of this low-ground-pressure machine led to an abortive line of military development during the early 1950's. It is to the credit of no one involved that it was not recognized for several years that the better-than-expected mobility of this vehicle stemmed largely from its use of articulated steering (Type I, Figure 2).

Several unrelated minor machines ensued in quick order. Although not one could be classed as an outstanding development, they all lead to further and better machines. Viewed in retrospect, they indicated that the time was ripening for full-fledged articulated tracked vehicles. In 1952, Nodwell introduced the North King vehicle (Figure 16). At about the same time, Bombardier replaced the skis of his successful snowmobile with unpowered tracks (Figure 17); the U.S. Navy Civil Engineering Research and Evaluation Laboratory experimented with a powered, tracked trailer behind a construction tractor; and Wagner obtained a Canadian patent on some features of a tracked vehicle steered by articulation (1954).

A more fruitful line of development was begun in 1955 by the Canadian Army Directorate of Vehicle Development. During 1955 and 1956, they designed and extensively tested a preprototype, 600-pound-payload carrier for use in Canada's extensive snow country. Dubbed the RAT, it was 'bellyless' and steered by articulation of two 'train' units about a common ball-joint between (Type III). Articulation was controlled manually by means of cables. In the first experimental rig (only) there was an engine in each unit (Figure 18).

The preprototype 'lash-up' proved highly mobile in the deep, soft snow of the northern Canadian tree-line country, which had hitherto been impassable to practical, load-carrying small vehicles. As a result of this success, the Canadian government undertook an extensive development program on the device with Canadair Ltd. (17). (Figure 19). Although the RAT never went into production, it led more or less directly to the current development of the XM-571, about which more later.

4. THE PACE QUICKENS - 1957 TO THE PRESENT

The next development was the introduction by Wilson, Nuttall, Raimond Engineers, Inc. (WNRE), in late 1957, of the POLECAT, a conversion of two World War II Weasels. The original POLECAT was powered by a single engine mounted in the rearmost of two 'train' units. Power for the front tracks was transmitted on standard universal-jointed shafts through the centre of the train-type connecting/steering



Fig.19. Pilot model Canadian Army RAT

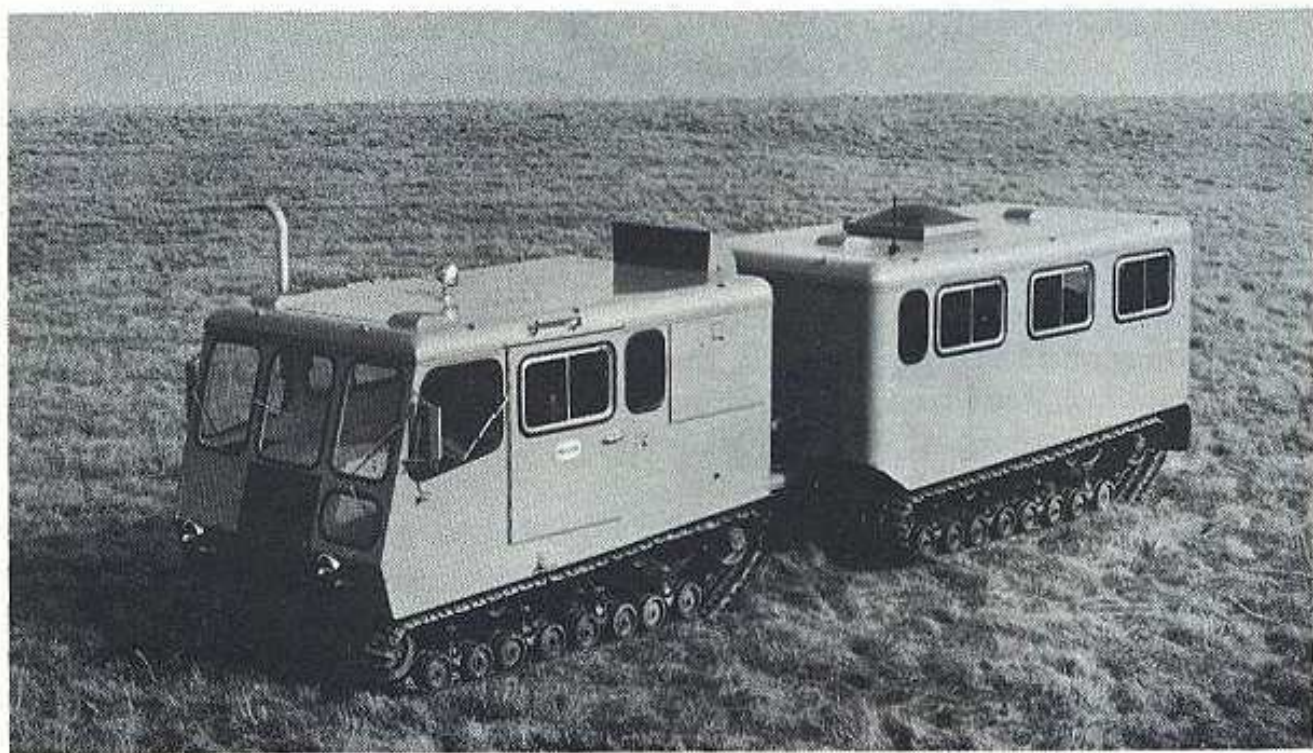


Fig.20. Current model POLECAT Personnel Carrier for Greenland icecap service

joint. The joint design permitted full roll and (co-ordinated) pitch freedom between the two units, but motion in the steering plane was at all times under full hydraulic servo control (Type III).

The six-ton GVW POLECAT demonstrated better performance in snow country than the original Weasel, which had stood for the previous 14 years as the U.S. Army's standard of comparison. Manoeuvrability, ride, and side-slope performance of the POLECAT were better than for the parent vehicle. Towing and mobility performance were particularly impressive. The POLECAT was able to maintain speed in deep snow with a relatively large towed load, even while manoeuvring violently. It was demonstrated that a nominally comparable skid-steered vehicle could approach this performance only while going straight ahead, and lost headway and frequently became immobilized when a turn was attempted. This behaviour clearly reflected the loss of tractive capacity resulting from skid-steering in the already severely stressed snow cover.

In 1959, a redesigned, front-engine POLECAT was introduced for high-speed personnel movement by the U.S. Army in Greenland (Figure 20). This was the first vehicle in its weight and speed class to cope successfully with the total range of Greenland operational, maintenance, terrain, and environmental problems. For the past four years, POLECATS of this type have been the backbone of the U.S. Army's high-speed surface communications system on the Greenland icecap. These vehicles have demonstrated superior 'ride' characteristics and improved track and suspension life, as a result of their articulated configuration, as well as distinctly superior mobility in all types of snow conditions.

Concurrent with these developments, Nodwell began to supply to the Canadian oil industry a low-ground-pressure, tracked tractor, the SCOUT, and a companion, separately-powered, tracked trailer. The combination was capable of moving two- to four-ton loads in summer muskeg operations (Figure 21). While not fully capitalizing on the principles either of articulated steering or of train operation, the combination derived a little advantage from each. For example, the skid-steered tractor applied tongue forces to steer the trailer. Thus, the trailer continued to work with full effectiveness during a turn, even though the tractor did not. Also, each unit was free to pitch as an individual, thereby failing to provide the ride and mobility advantages of a long co-ordinated unit. The coupling did, however, add to the mobility of the combination in those instances when one unit was on a firmer footing than the other.

At about this same time, Bombardier introduced his MM muskeg freighter for oil field use. This was a light-duty, single-engine, five ton payload machine based upon two Bombardier Muskeg Tractor chassis. Articulation was Type II (Figure 2), and steering was controlled via cables, hydraulically actuated.

During late 1957, Imperial Oil, Ltd. (Canada), built an articulated test rig from two of the Nodwell, powered, tracked trailers, train-

coupled by means of a WNRE-designed joint similar to that on the POLECAT. The resulting two-engine rig, called the CENTIPEDE, and subsequently rated a five- to six-ton carrier, demonstrated the soundness of the 'train-joint' type of articulation (Type III) for summer muskeg operation (Figure 22). Based upon the CENTIPEDE's success as a test rig, Imperial Oil, in 1958, commissioned the design and construction of the 20-ton-payload MUSK-OX.

While Imperial Oil was still testing its CENTIPEDE, however, Nodwell introduced a 'wagon-steer', Type II, articulated, 10-ton carrier (Figure 23). The Nodwell TRANSPORTER entered muskeg service with the Shell Oil Company during the summer of 1958. Following a season of mechanical 'teething' troubles, these two-engined vehicles have given excellent service⁽¹⁸⁾. Currently rated for 12-ton payloads, they are in wide use in the Canadian and Alaskan oil fields, and under extensive test by the U.S. Army.

The largest and technically most successful articulated vehicle built to date is the MUSK-OX, designed and built by WNRE for Imperial Oil as a direct result of the performance demonstrated by the smaller CENTIPEDE. The MUSK-OX is a 20-ton-payload carrier, grossing 45 ton. It is 'bellyless', 49 feet long, 10 feet wide, and 10 feet high over the cab. Its four tracks are powered at all times by a single, 375 horsepower Diesel engine mounted on the front unit⁽¹⁹⁾ (Figure 24). Now beginning its fifth season in the field, it has successfully logged in excess of 55,000 cross-country miles⁽²⁰⁾ in Canada and Alaska, in both summer and winter operation. In this service, it has regularly carried 15- to 25-ton payloads in summer muskeg conditions (Figure 25), and has often handled loads of 30 ton or more in winter operations. In addition to carrying really big loads through terrains hitherto thought impassable, it has been working in these areas at a total cost (including capital charges) of the order of \$0.60/ton-mile (one-way loads only).

During the winter 1961-62, the MUSK-OX successfully took part in the U.S. Army exercise GREAT BEAR in Alaska. This exercise showed that 'overall performance of the MUSK-OX in deep snow and over unbroken trails is exceptional', and that 'fuel and oil consumption is lower than on some vehicles of less payload capacity. Vehicle design is good. It is comfortable, durable, and fairly maintenance-free despite its size'. Unfortunately, it was judged much too large to be of use to the U.S. Army⁽²⁰⁾ (see Table 1).

In 1958, WNRE began construction, for the U.S. Army Ordnance Tank and Automotive Center, of the first three-unit, articulated, tracked vehicle, the COBRA (Figure 26). This experimental vehicle, which grossed 12 tons, was powered by a single engine mounted in the front unit. All six tracks were powered at all times through an extended, universal-jointed-shaft drive-train which normally included five active differentials to insure proper power distribution. Two of these differentials were lockable at the driver's option. The COBRA was equipped with a spaced-link-track⁽²¹⁾, and proved highly mobile in a variety of terrains.

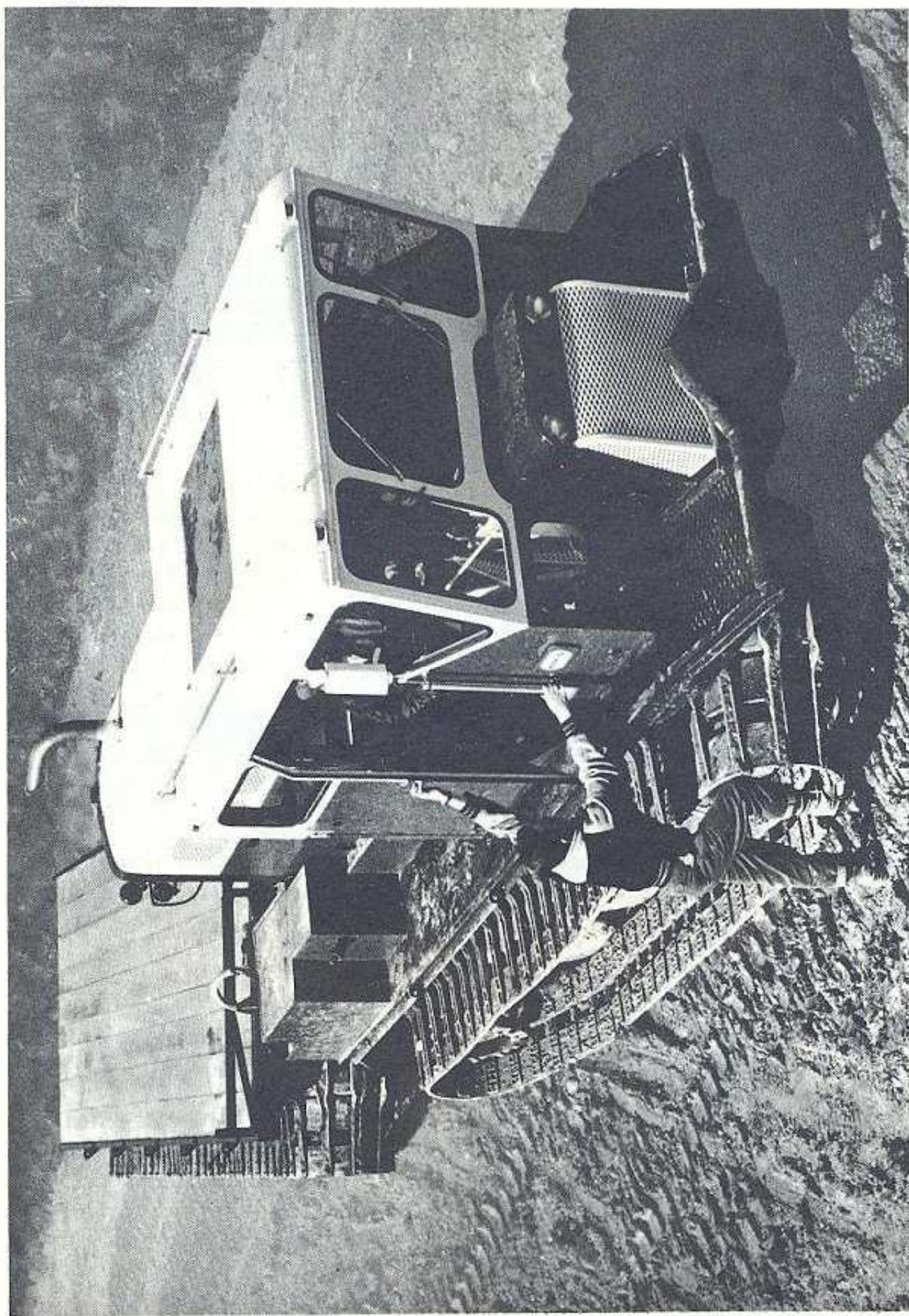


Fig. 24. 20-ton-payload MUSK-OX, 1959



Fig. 25. MUSK-OX at work in summer muskeg conditions

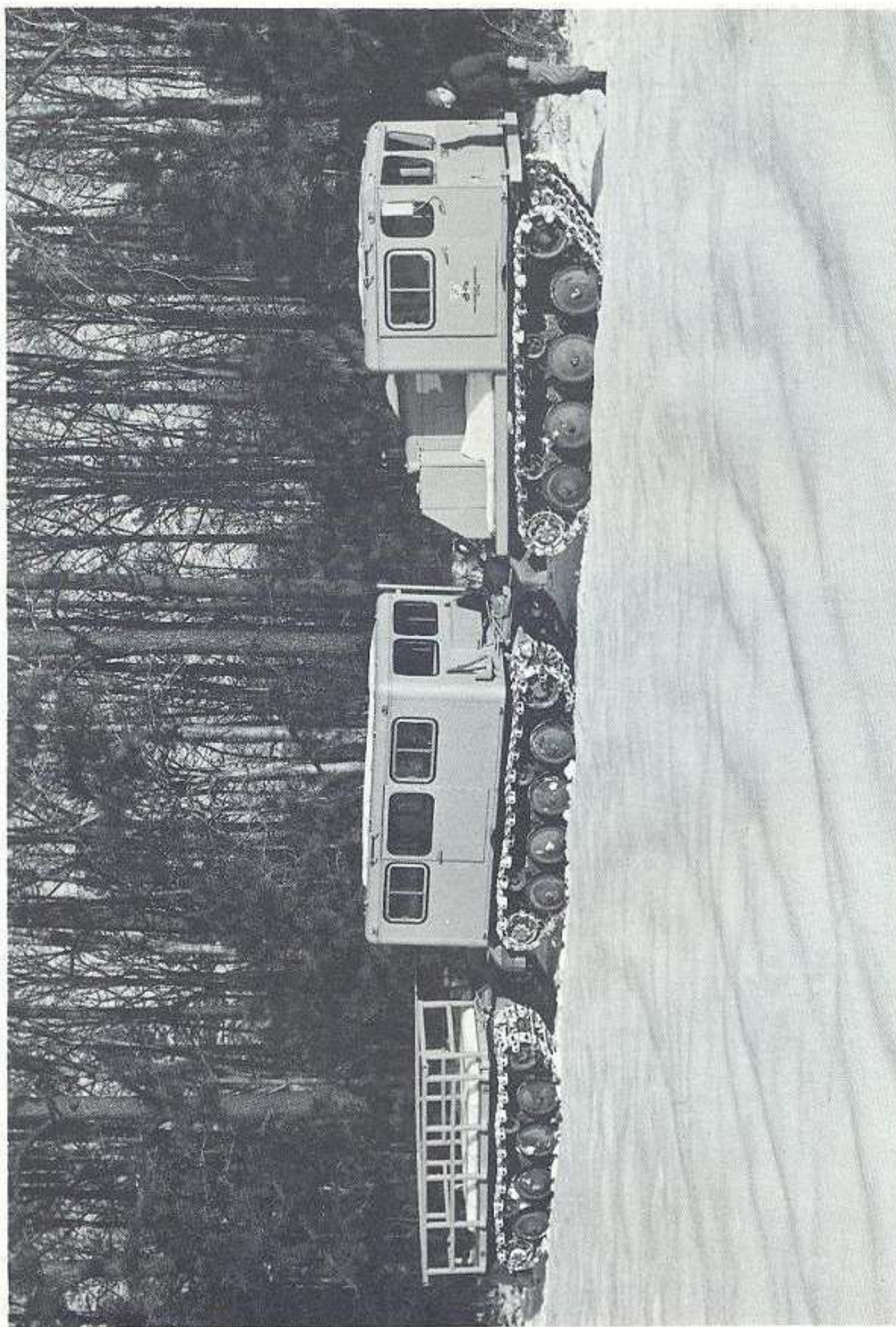


Fig. 26. Three-unit, train-articulated COBRA, 1959

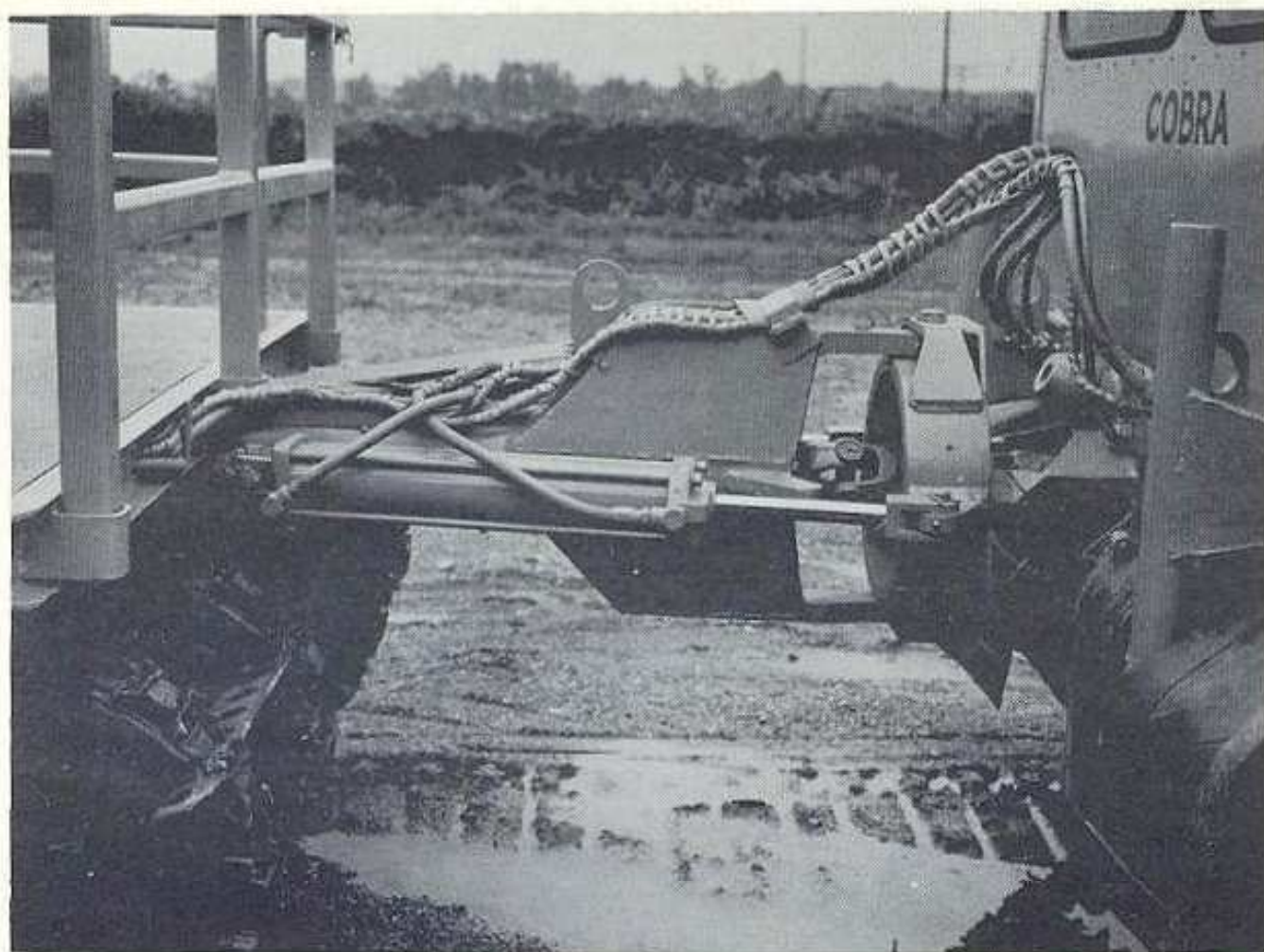


Fig. 27. 'Train-type' steering joint on the COBRA (Type III)

Steering of the COBRA utilized a 'train-joint' (Type III) between the first and second train units (Figure 27) and another between the second and third. Both joints were hydraulically controllable for steering, but under normal circumstances only the first was controlled. The second ordinarily trailed freely. When the working pressure in the front-joint hydraulic system exceeded a pre-set value, however, the second joint was activated for a brief period until the front-unit pressure was reduced again. The second joint, when it 'kicked in', was so arranged that its contribution tended to rotate the second unit in the train in the same direction that the first joint did. Thus it aided the turning of the first joint. The effect, when turning in place, was to put the three units in an 'S' shape, which was precisely what happened when only the front joint was activated (if track-to-ground friction was low enough to permit this action with only one joint powered). (See Figure 1.) Advantage was taken of the hydraulic control available at each joint to reverse the entire control sequence when the vehicle was reversed, making backing up of this long train as simple as backing a motor car.

The entire system worked well, and successive units of the COBRA tracked the first closely, even when snaking along narrow trails. However, experience demonstrated that the three-unit configuration made

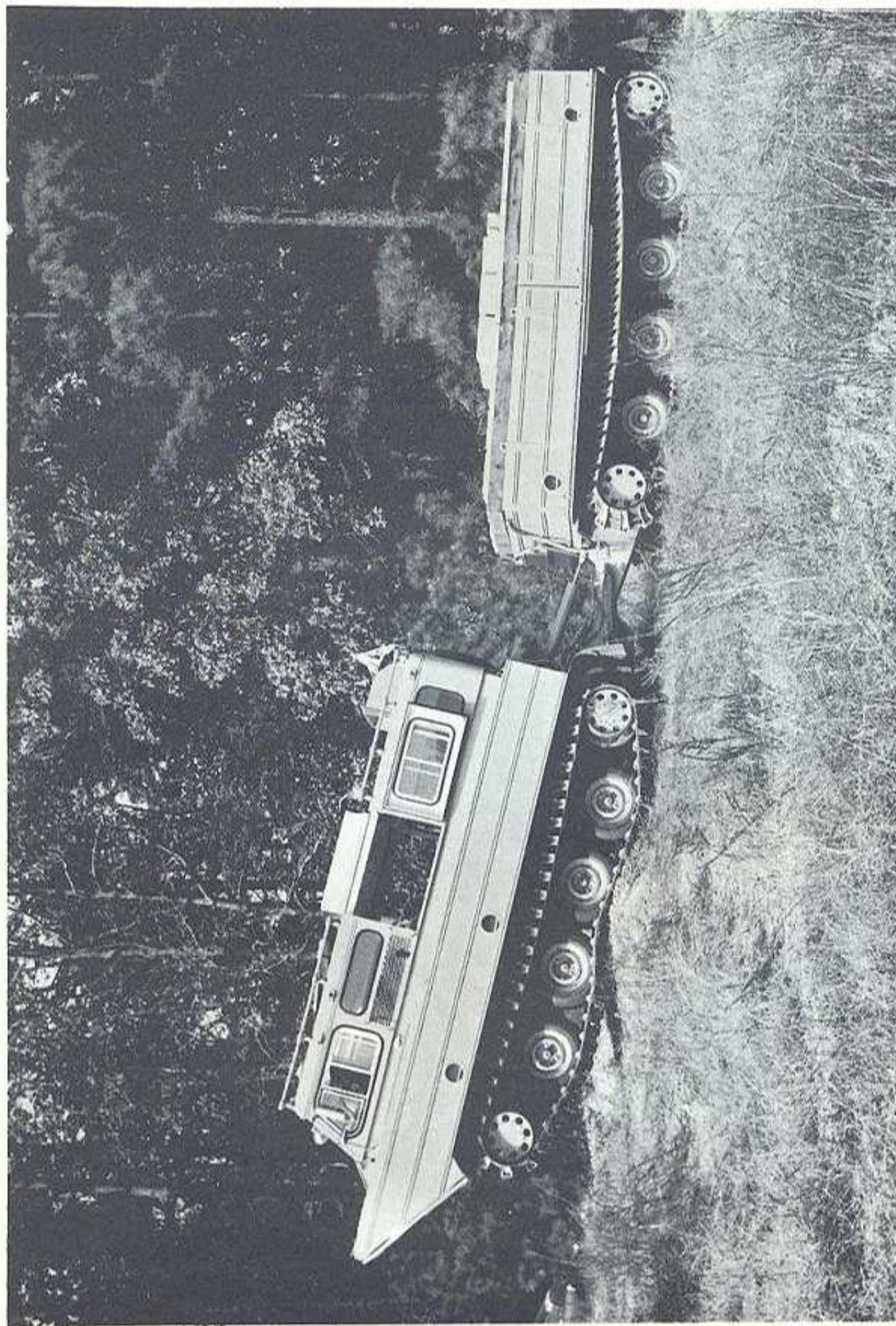


Fig. 28. Amphibious version of the MARK II POLECAT

possible higher loads on the track and suspension than were possible with only two units of the same size. Thus, while track and suspension for a two-unit machine may be designed essentially on the basis of the gross weight of a single unit, the same parts for a three-unit machine must be proportioned for somewhat higher loads in relation to unit weight.

In 1960, WNRE delivered to the U.S. Army the first of its MARK II POLECATS (Figure 28). This two-unit, 12-ton vehicle is amphibious (Figure 29), performs well in such weak materials as snow, marsh, mud, and tidal flats, and is capable of speeds up to 25 miles per hour on the highway. It has soft, high-jounce suspension, giving a good ride on relatively rough terrain. The ride is further improved by the use of a single, large shock-absorber across the joint in the pitching plane (Type IIIA).

The first MARK II was designed to support vehicle mobility research work in all types of difficult terrains, carrying test crews, instruments, recorders, etc. The same chassis, equipped as a 30-passenger bus, entered service in Greenland in 1962, supplementing the smaller, original POLECATS in their icecap operations (Figure 30).

The last WNRE commercial development in the field was the DINAH, introduced in 1961 (Figure 31). This little vehicle (3700 pound curb weight), designed to carry 1000-pound payload and to be a floater, followed previous WNRE practice closely. It was almost immediately overshadowed, however, by the first large-scale effort undertaken by the U.S. Army in the field of articulated vehicles - the design and development of the XM571 in the same general size class (Figure 32).

Work on the XM571 was begun at Canadair Ltd. in 1961. Prototypes were demonstrated and enthusiastically received in the spring of 1963.

The most recent commercial machine of this type appears to be the Swedish BV202, developed jointly by Volvo and the Swedish Army. This vehicle is a floater, of the same general size as the WNRE POLECAT⁽²⁵⁾.

And finally, recent evidence of growing interest in articulated, tracked vehicles is found in the award, by the U.S. Armor Association, of first prize in its 1962 international tank design contest to Robert W. and John P. Forsyth⁽²³⁾. Their winning design is shown in Figures 33 and 34. The distinguished panel of judges who made the final selections was as follows: General Bruce C. Clark (Ret.), President, U.S. Armor Association; Lieutenant General Dwight E. Beach, Chief, Research and Development, Department of the Army; Major General Joseph E. Bastion, Jr., C.G., U.S. Army Armor Center, Fort Knox⁽²⁴⁾.

Brief, overall characteristics of several of the machines mentioned above will be found in Table I. The table is not complete. Interest and activity have expanded rapidly in the past few years, and several

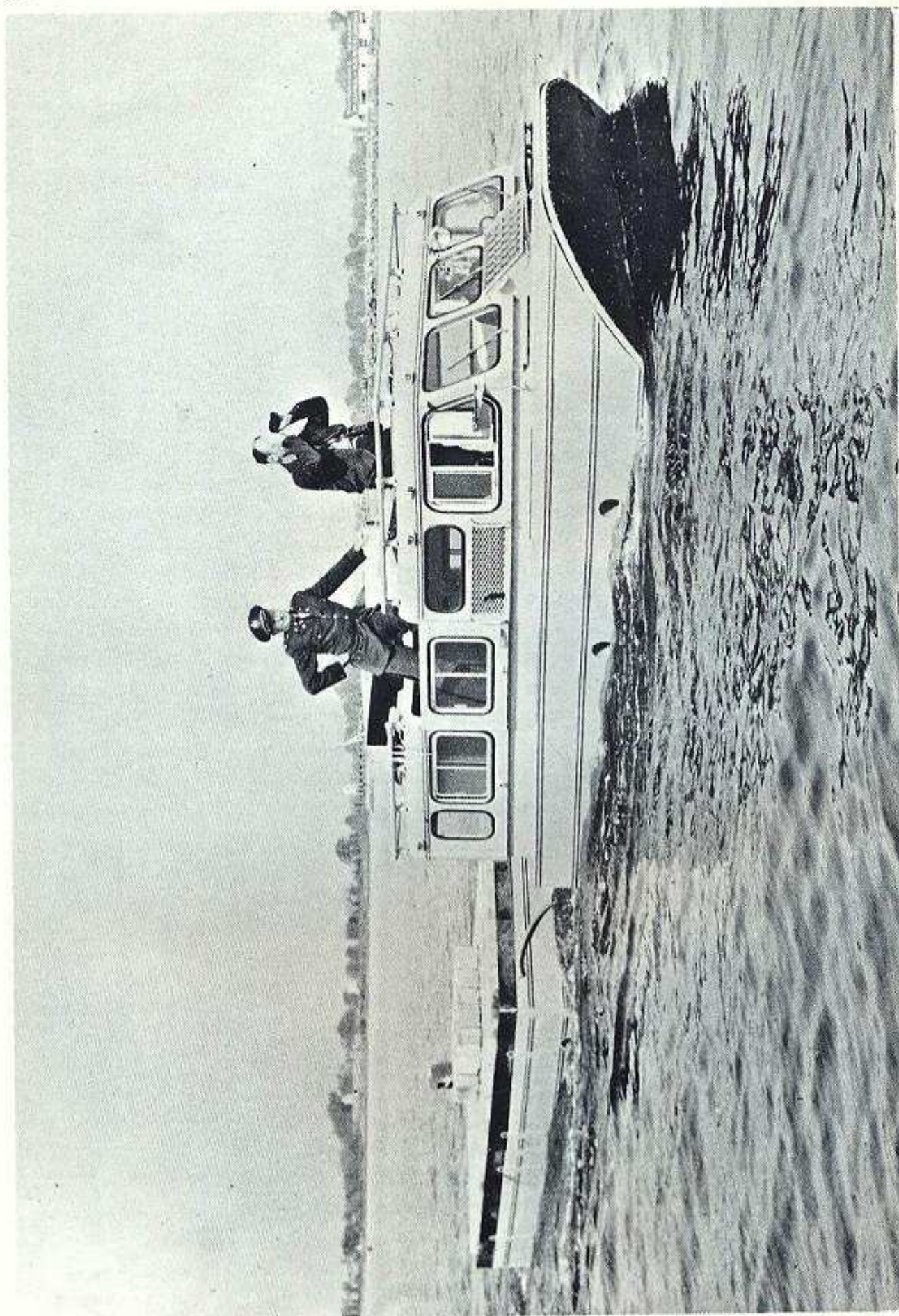


Fig. 29. The Amphibious MARK II afloat

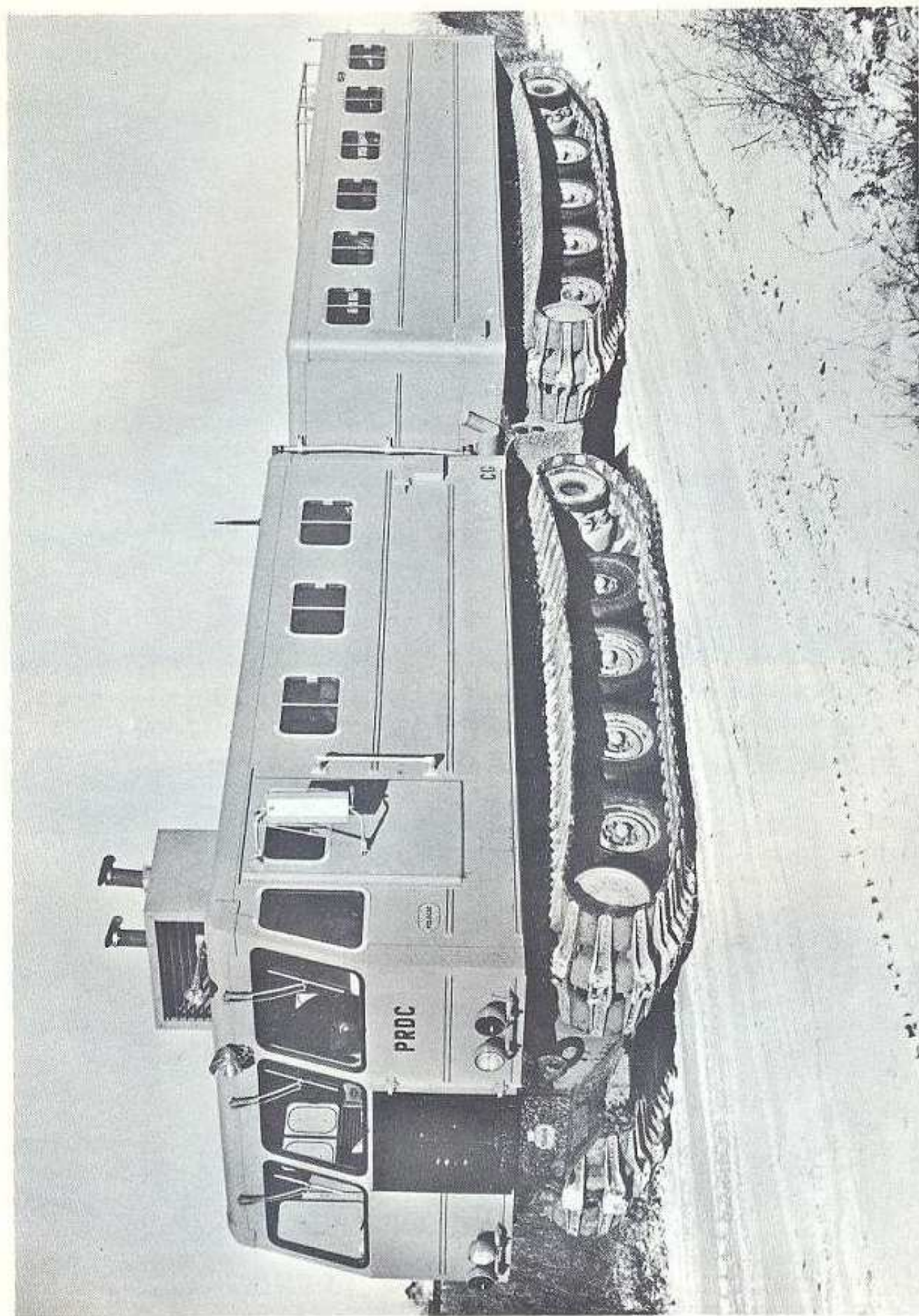


Fig. 30. Greenland 30-passenger MARK II POLECAT, 1962



Fig. 31. WNRE DINAH, 1/2-ton payload, floater, 1961

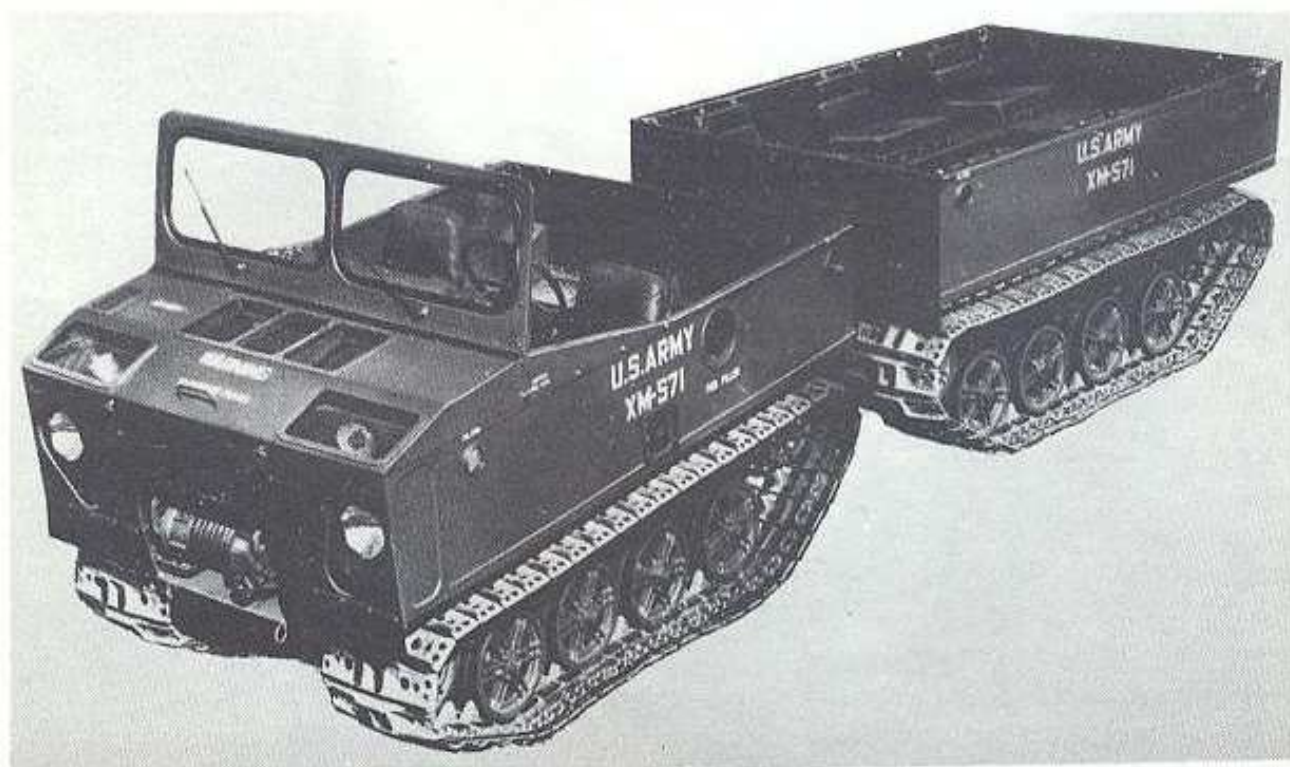


Fig. 32. U.S./Canadian Army XM571, 1963

additional machines have been offered recently, both commercially and in proposals to the military. Except as they testify to the field success of the concept, they contribute little to the art, being mostly close copies of one or another of the vehicles treated herein.

5. ADVANTAGES OF ARTICULATED STEERING

In the opening paragraphs of this review, the advantages of articulated steering, in terms of increased soft-ground crossing and more rational overall form, were mentioned. In this section an attempt is made to illustrate this more completely.

On the basis of the most simplified possible picture of the skid-steering of tracked vehicles, that which considers only a static balance of static, frictional moments, we may write the first order equation for the grade-climbing ability (or drawbar capacity) of a skid-steered vehicle, while executing a turn, as follows:

$$G = f (1 - 1/2 L/T) - (R/W), \quad (1)$$

where G = gradeability of the vehicle;

f = traction coefficient between its tracks and the terrain material;

L/T = its ratio of track length to tread; and

R/W = the external motion resistance encountered by the vehicle, as a ratio to its gross weight.

This simple relationship is graphed in Figure 35. Using this figure, consider three machines operating in level, deep, dry snow (say $f = 0.5$, $R/W = 0.2$). Assume the first machine to be skid-steered with a length-to-tread ratio (L/T) of 1.5, representative of normal military vehicle practice; the second to have an L/T ratio of 1.0, which is typical of commercial tracked tractors. Assume the third steers by articulation.

All three vehicles will develop a drawbar coefficient of 0.3 when running straight. However, if all now make a continuous left-hand turn, the first will become immobilized, while the drawbar capacity of the second will be reduced by 80 per cent. Only the articulated configuration will maintain its full drawbar capacity or (in these grossly simplified terms) its full grade-climbing ability.

It may be noted in passing that when performance during steering is considered, as it must be, skid-steered vehicles having low values of the steering ratio (L/T) will have greater practical soft-ground-crossing ability than otherwise equivalent vehicles having higher L/T ratios. This is borne out by experience with construction tractors, which exhibit good working capacity in poor conditions where a tank, manoeuvring as violently, would surely become immobilized.*

* Other factors such as better ground pressure distribution, higher ground clearance, reduced track lateral aggressiveness also contribute to this result, of course.

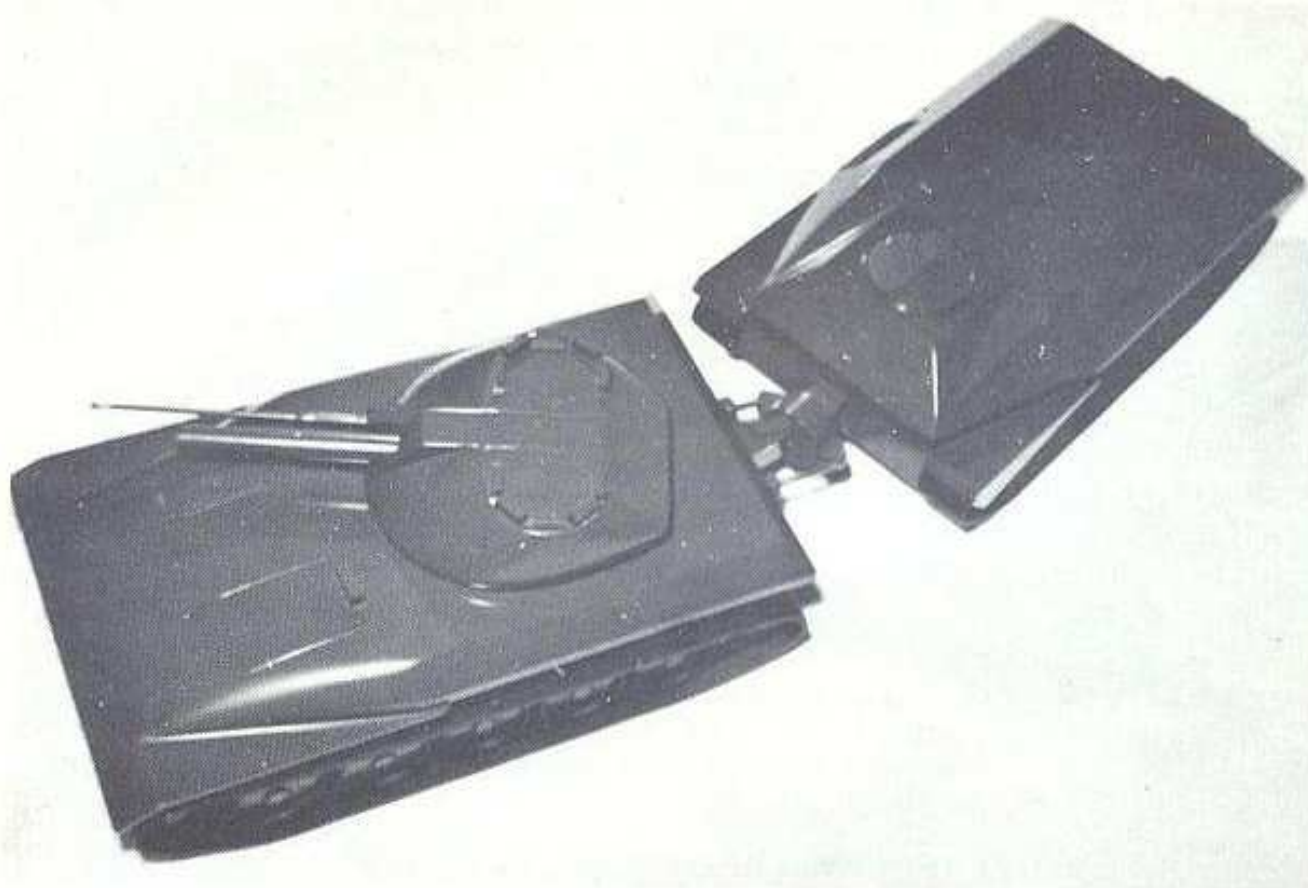


Fig. 33. Forsyth brothers' first-prize-winning articulated design in the U.S. Armor Association international tank design contest

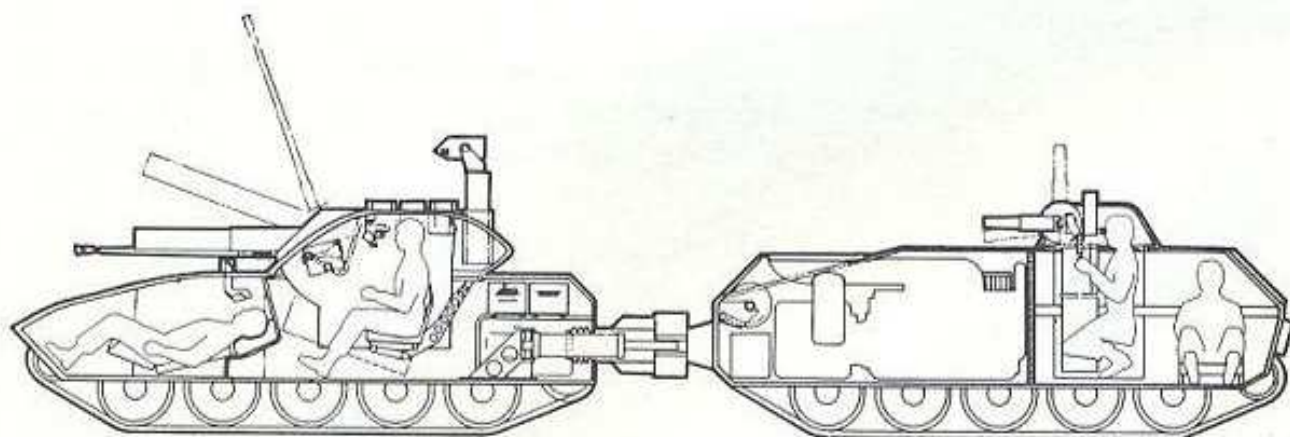


Fig. 34. Layout of Forsyth brothers' tank

Unfortunately, this consideration leads to wide, 'stubby' vehicles, contrary to what is desired for best adaptation of their form to terrain obstacles, for least external motion resistance due to sinkage, for good directional stability when running at reasonable speeds on the road, and for good 'ride' characteristics.

The variation in form of high-mobility vehicles with gross vehicle weight (GVW) for skid-steered and articulated configurations is demonstrated in Figure 36. A nominal unit ground pressure of 3 psi and effectively 'bellyless' construction are assumed for all vehicles. The steering ratio (L/T) is taken at 1.25 for all skid-steered examples. While values up to 1.8 are commonly accepted for military vehicles, it is evident from the discussion just preceding that for good soft-ground performance, the lowest value acceptable from the standpoint of all other considerations is the most appropriate.

Figure 36 clearly shows that while low ground pressure, bellyless, high mobility machines of any reasonable gross tonnage are possible with articulated steering, overall widths of comparable skid-steered vehicles become impractical at a GVW of the order of 20 tons. The form advantages of articulated steering are greatest in high mobility vehicles.

The importance of a rational form for off-road vehicles stems from several considerations. First, a long, narrow vehicle encounters less external motion resistance in soft soils than does a short, wide vehicle with the same track area under it. Straight-ahead drawbar pull tests in snow on the POLECAT, for example, have shown that its drawbar pull is 230 to 240 percent of that of the parent Weasel⁽²⁵⁾. The increase over 200 percent can be traced to, and only to, reduced external motion resistance.

Indicently, during these tests it was interesting to note that the POLECAT sank into the snow evenly from front to rear as slip and drawbar load were increased. It did not assume the characteristic 'tail-down' attitude of conventional tracked machines when undergoing such tests, an attitude also characteristic of them just prior to their bogging down. It is difficult to picture a mechanism whereby a vehicle with Type III articulation could assume this classic attitude.

It is also evident that a rational (i.e. relatively long and narrow, but not 'stiff') form also reduces the 'resistance' arising from obstacles - trees, boulders, etc. - and makes over-the-road transport, whether on a trailer or rail car, or under its own power, easier. Finally, such a form permits the exploitation of 'bellyless' or near 'bellyless' configurations without resort to extremely wide tracks with attendant track and suspension structure and weight problems. The MUSK-OX, for example, has 52-inch-wide tracks, weighing approximately 100 pounds per running foot. The POLECAT MARK II, which uses forged aluminium grouser bars, has a 35-inch-wide track weighing about 25 pounds per running foot.

There are a number of additional advantages demonstrated on the several 'train-joint' (Type III) articulated vehicles discussed previously which are not as easily illustrated. Inasmuch as the author's actual field experience is limited to machines of this configuration, it could be dangerous to assume that they apply equally to all others. In relation to two-unit, train-joint articulated vehicles, then, it may be stated further that:

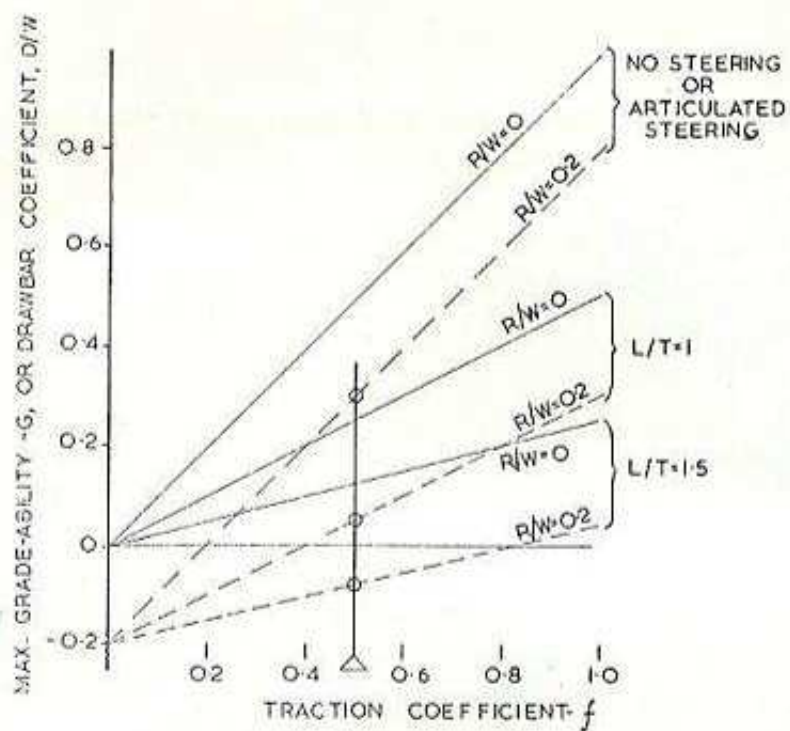


Fig. 35. Gradeability of vehicles while steering

NOMINAL UNIT GROUND PRESSURE 3 PSI
 TRACK WIDTH 0.4 X O.A. WIDTH i.e. BELLYLESS

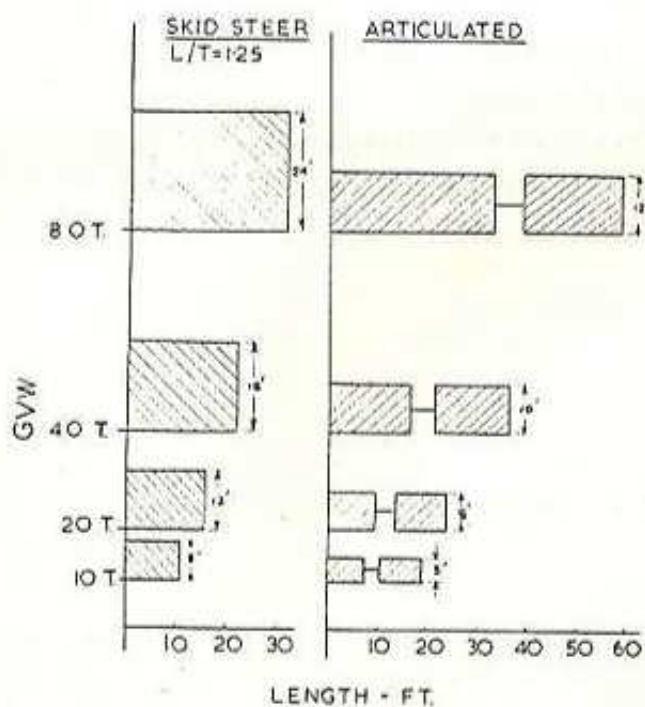


Fig. 36. Comparison of Planforms

- (i) Their 'ride' is significantly better than that of comparable skid-steered machines. Their greater overall length is the principle reason, and is largely effective even though the joint allows complete (but coordinated) pitch freedom to the two units connected. Addition of a large shock absorber across the otherwise free joint still further improves the situation.
- (ii) By and large, the structure of the individual units, and of track and suspension components, need be proportioned to the gross weight of one unit, rather than to that of the entire machine. In fact, U.S. Army experience in Greenland has been that tracks, hulls, and suspensions all 'live' longer on the articulated POLECATS than they do on the parent, single-unit, skid-steered Weasels. This is in spite of a 20 to 25 percent increase in normal weight of the POLECAT units, and of a 40 to 50 percent increase in average trail speeds. One of the reasons for the added track and suspension life must be the elimination of continuous track tension reversals which accompany skid-steering.
 This general easement of structural requirements makes possible the development of vehicles having high mobility, adequate ruggedness, and acceptable payload/gross weight performance. The MUSK-OX, which counts 40 to 50 percent of its gross weight as useful net payload, compares favourably with such relatively simpler vehicles as the U.S. Army's 5-ton, 6x6 truck (M41), whose (off-road) payload-to-gross-weight ratio is only 0.35.
- (iii) Train-joint articulated vehicles require a minimum of specially developed components. Standard commercial, heavy-duty truck parts are used for the entire MUSK-OX drive line, from the radiator cap to the sprockets. Even the steering system for this type of vehicle utilizes no mechanical parts that are not available from commercial stocks. The relatively simple joint-structure only is special.
- (iv) Their performance at all speeds up to relatively high speeds (30 to 40 miles per hour) is in all respects exemplary, so far as steering and control are concerned. This matter has been studied on a theoretical basis, and some problems have been predicted when 'cornering' at somewhat higher speeds⁽²⁶⁾. However, there have been no 'handling' problems with either the POLECAT (which in one version was tested on the road at 45 miles per hour) or the MARK II (at speeds up to 35 miles per hour). One of the most noteworthy features of the MUSK-OX (14 miles per hour governed speed) is its ease of handling, which has resulted in excellent crew acceptance of the vehicle.

Table I OVERALL CHARACTERISTICS OF REPRESENTATIVE CURRENT ARTICULATED TRACKED VEHICLES⁽¹⁾

Vehicle	Mfr.	Date Introduced ⁽²⁾	Articulation Type ⁽³⁾	Curb Wt. lb.	Net Payload lb.	O.A. Length ft.	O.A. Width ft.	O.A. Height ft.	Installed Horsepower	Max. Speed	Nominal Unit Ground Press. psi at GVW	PL/GVW
SNO-CAT 643	Tucker	1949	I	6,400	2,000	20.0	7.8	7.5	140	12	0.9	0.24
RAT	Canadair	1955	III	1,400	600	14.5	3.7	5.0	35	10	0.5	0.30
POLECAT	WNRE	1957	III	8,000	4,000 ⁽⁴⁾	24.4	5.5	6.7	140	27	1.9	0.33
TRANSPORTER RN200	Robin-Nodwell	1958	II	47,500	24,000	41.3	10.3	10.5	260	12	2.6	0.33
MUSK-OX	WNRE	1959	III	50,000	40,000	48.6	10.0	10.2	375	14	3.1	0.44
COBRA	WNRE	1960	III ⁽⁵⁾	19,000	8,000 ⁽⁴⁾	42.7	6.6	7.0	200	20	2.1 ⁽⁶⁾	0.30
POLECAT MK II	WNRE	1960	III-A	20,000	16,000 ⁽⁴⁾	37.0	8.0	8.3	210	15	2.7	0.44
DINAH	WNRE	1961	III-A	3,700	1,000	18.5	5.3	5.5	42	10	1.5	0.21
XM571	Canadair	1963	III-A	5,300	2,400	19.5	5.3	6.0	65	30	2.06	0.31

Notes:

- (1) Specifications of current models
 (2) Date first similar model introduced
 (3) See Figure 2
 (4) All cargo versions
 (5) Three-unit vehicle
 (6) Spaced-link track

6. WHY NOT?

As against all these advantages, there are remarkably few disadvantages. The most obvious, important to bulldozers and to current road-bound armoured vehicles, is that the articulated, tracked vehicle, particularly in configuration III (train-joint) cannot make a pivot-turn. However, the 42-foot turning radius of the nearly 50-foot-long MUSK-OX, and its rapid steering response, make even this large machine extremely agile.

Other disadvantages relate principally to first cost, which, particularly in the smaller sizes of vehicles, is somewhat increased by the necessary replication of suspension parts, sprockets, idlers, etc. This, unfortunately, is not always fully offset by reductions through the use of lighter, simpler, and/or commercially available components. In balance, however, where high mobility is required, a slight increase in cost is acceptable. In practice, increased life and reduced maintenance soon more than offset any increase, but this has not always been considered in making the initial vehicle selection.

7. CONCLUSIONS

The steering of tracked vehicles by articulation has, within the past few years, been successfully demonstrated on high-mobility vehicles from one ton to 45 tons in gross weight. Experience has shown that this configuration is eminently practical. It improves the mobility of tracked vehicles both directly, through the elimination of constant braking while trying to go ahead, and indirectly, by making practical near-bellyless configurations capable of carrying large loads at unusually low nominal unit ground pressures. Vehicles of this configuration are now demonstrating levels of mobility and of reliability not previously thought possible in tracked vehicles.

These demonstrations signal the most important and far-reaching development in off-road vehicles of the past several decades.

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