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ARTICULATED, WHEELED OFF-THE-ROAD VEHICLES

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"The technology of terrain–vehicle relationships—and soft ground performance in particular—has elucidated the fundamental relationships involved, and has clearly demonstrated that major improvements necessarily involve major changes in vehicle form; that there are no cheap answers."

C. J. Nuttall, Jr.

1. INTRODUCTION

During the last 10–15 years the interest in articulated off-the-road vehicles has increased invariably.

Before the mid-fifties the capabilities of the articulated vehicle was not much recognized. Today this type of vehicle is used in all aspects of off-the-road work, as military transportation, earthmoving, construction, mining, farming, logging etc. Even several moon vehicle prototypes are based on the articulation principle.

The reason for this success is, of course, that the articulated vehicle has several definite advantages. These will be discussed later. The subject of articulated *tracked* vehicles has been treated extensively by Bekker [1, 2, 3], Nuttall [4, 5, 6] and Ogorkiewicz [7, 9]. Particularly Nuttall's work gives a very complete picture of the subject. Regarding articulated *wheeled* vehicles the situation is somewhat different. Numerous publications report on one particular vehicle only. Bekker [2, 3], Ogorkiewicz [8, 9] and Nuttall [6] discuss the subject in a wider sense, also describing several vehicles. Another work by Stevens Institute of Technology and Nuttall [10] deals only with trains. A complete and systematic approach to the subject is still lacking, however, at least in published form.

2. DEFINITIONS

According to the dictionary articulated means jointed or segmented. This definition agrees well with the common impression of an articulated vehicle. Such a vehicle consists of two or more body or frame units jointed together. These units or sections should be an integral part of the vehicle. The joints may have one, two or three degrees of freedom (yaw, pitch, roll). All wheels are usually driven during off-the-road operation. It might seem trivial to state this definition, but surprisingly enough, in the literature searched by the author, an accurate definition of an articulated vehicle was nowhere to be found.

Bekker [1] was among the first to recognize the advantages of the train concept for off-the-road use (analytical evaluation and tests with small scale models of train-like vehicles at the Canadian Army Proving Ground, 1949). According to Bekker [2]—"it is based on the use of a single vehicle 'cell' or car with a given constant unit load.

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To increase the cargo capacity of the transporter the 'cell' is not increased as with motor vehicles, but a train is formed by coupling a number of cars so that, irrespective of the total weight and train capacity, the unit pressure under such a vehicle remains constant and equal to that of the single car". Bekker suggests that in an extreme case, the minimum train vehicle would be composed of two units, which could be steered by pivoting around its joint.

A 4×4 articulated vehicle could hardly be considered as a train, even though it consists of two units. The author therefore suggests the following formulation. If the units are able to operate independently of each other, then the minimum train is composed of two units. If the units are not able to operate on their own, then a train would consist of three of more units. The last definition is also valid for a train which is composed of both unit types.

In most cases two units simply make an articulated vehicle. A train is also a vehicle, but an articulated vehicle is not necessarily a train.

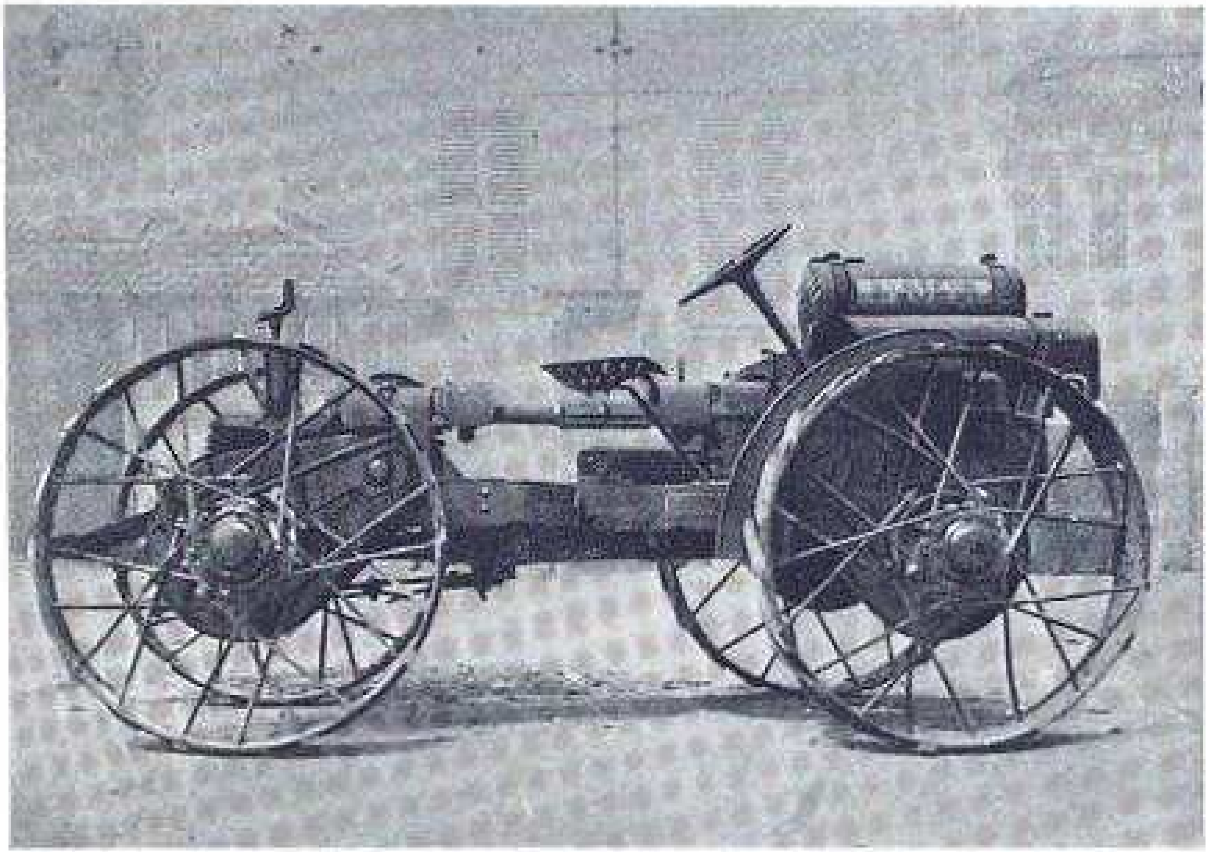

FIG. 1. Pavesi agricultural tractor from 1913 [11].

3. HISTORICAL OUTLINE

The historical review of the *early* development of the articulated wheeled vehicle is compiled partly from Ogorkiewicz [8], Nuttall [5], the Stevens report [10], Bekker [3] and others. The review is kept as brief as possible. It might not be complete.*

*During the study of present literature on the history of articulated, wheeled off-the-road vehicles the author found several omissions and contradictory statements. Lack of time prevented him from checking all such assertions. If any inaccurate statements or omissions are found in this article, please contact the author. Also he will be grateful for additional information that anyone might want to give.

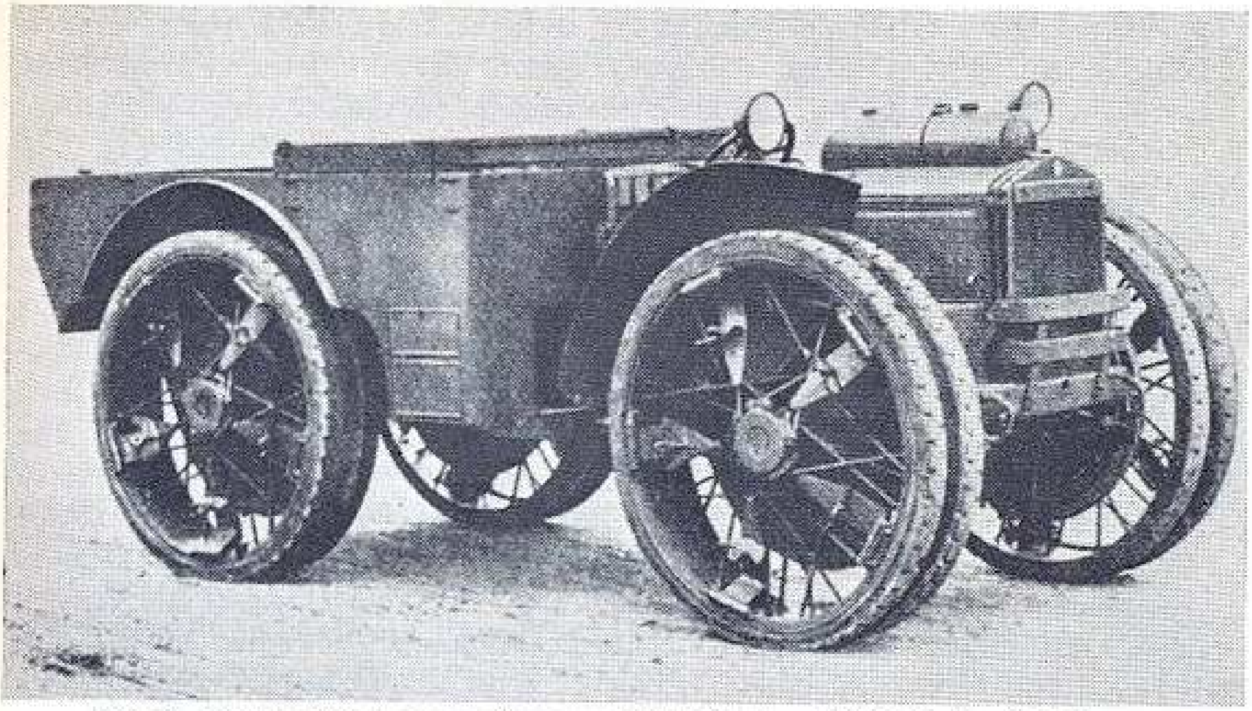

FIG. 2. Pavesi military reconnaissance vehicle [13]. About 1925. Curb weight 3 tons.

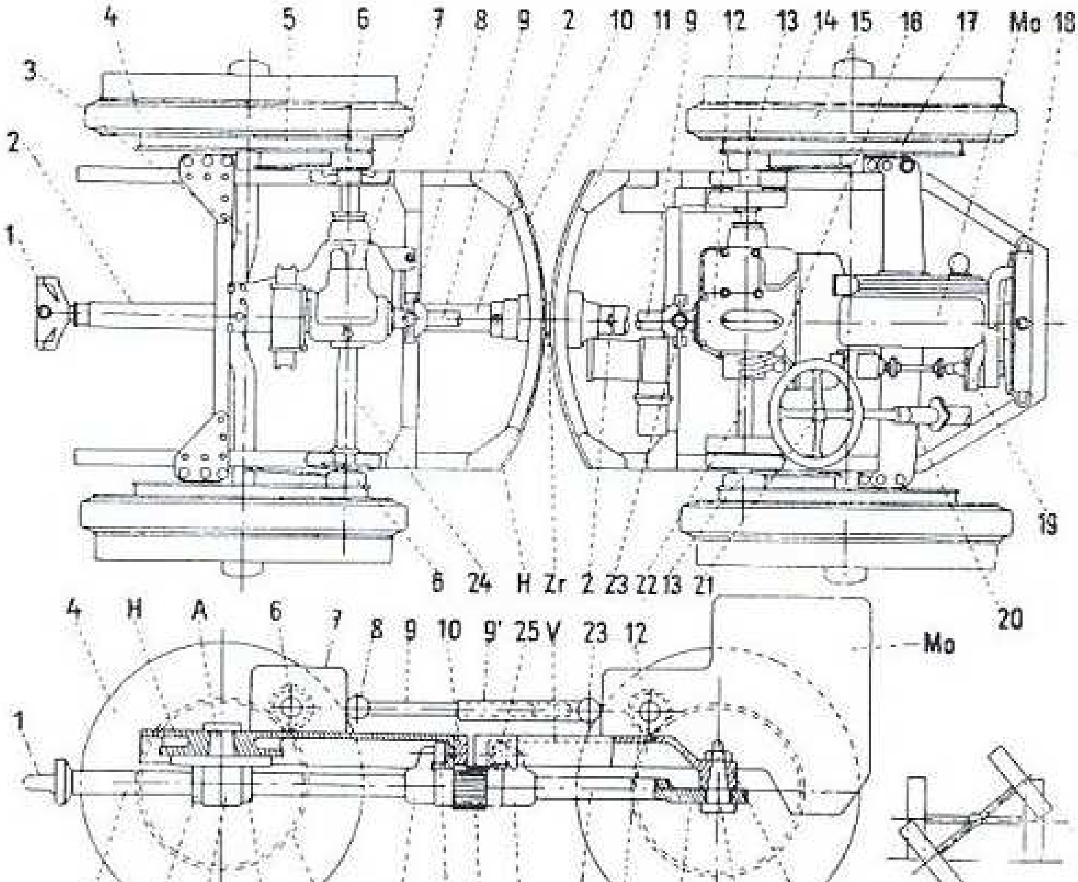

FIG. 3. Design details of the Pavesi vehicles [13]. About 1925. 2: Tubular backbone assembly. 9: Drive shaft. A and B: Pivots.

It is very likely that Diplock was the first to patent and build a joint for use on articulated vehicles, even though Ogorkiewicz asserts that an articulated construction was tried in 1836, also in England, under the name of the Adams equirotal carriage.

Diplock patented a joint for use with either wheels or tracks in 1902 [5]. The joint had two degrees of freedom (yaw and roll). The joint principle was used on a tracked articulated vehicle, the Diplock Pedrail Tractor and Trailer, which he offered on the market in 1913. Diplock did not use the joint in combination with wheeled vehicles.

The first articulated wheeled vehicle was introduced by Pavesi–Tolotti & Co. in Milan, also in 1913 [11]. This vehicle was built as an agricultural tractor, Fig. 1. It had four large diameter steel wheels and was equipped with four-wheel drive. The joint had two degrees of freedom (yaw and roll), and the steering was by articulation.

According to Walters [12] a "hinge steering" vehicle was also made by John Deere & Co. in the U.S.A. This "cultivating" tractor was designed by Theo Brown in 1916.

The Italian Army tested the Pavesi P4 tractor in 1924, and later it was adopted in a modified version with solid rubber tires as the Model 25 artillery tractor [8]. This vehicle was rather successful, and other models, on the same principle were introduced, Fig. 2 and 3 [13]. The tractors were licensed in Sweden and also in England (Armstrong–Siddeley Motors Ltd.).

The British manufacturers fitted experimental models, Fig. 4, with tires, and then extended the original concept to an 8×8 vehicle (Pavesi–Wilson), which had the wheels mounted in pairs on walking beams, Fig. 5 [13]. This vehicle was unique for the time. However, none of these vehicles were equipped with suspension, and especially the 8×8 vehicle must have been hard to steer (scrub), since power assistance was not available. Eventually the production of the Pavesi tractors were stopped, also in Italy, in favour of more conventional vehicles.

Even though it was not meant for off-the-road use, the Porsche "Landwehr Train" [14] should be mentioned here. It was built by Austro-Daimler in 1914 for transport-

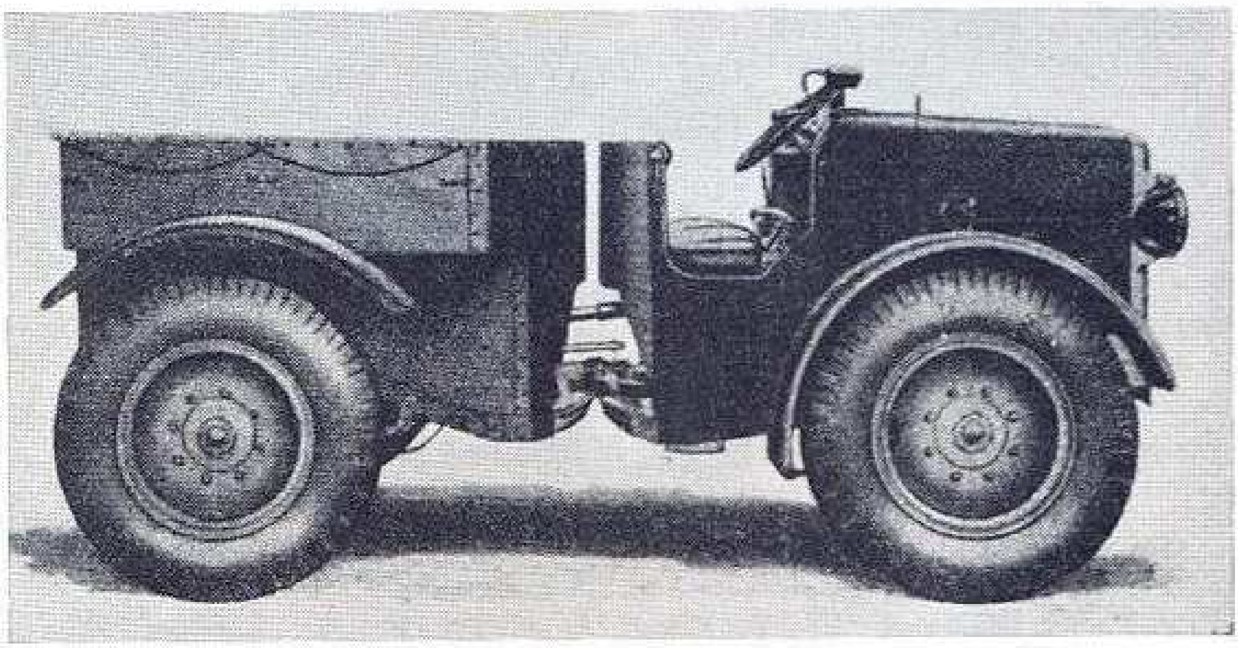

FIG. 4. Armstrong-Siddeley military tractor, Pavesi steering system [13]. About 1930. Payload 1 ton.

ation on road or on rails. Each unit of this articulated vehicle or train was powered and so steered, that all wheels would track. However, Porsche was not the first to build train type vehicles. Diplock proposed a train consisting of single axle units in 1902.

The French Renard Train (1900) had 3-axle units. A mechanical drive-line carried power from the lead unit to the center axle of each car. The American Aldex-Sampson gas-electric road train (1910) also had 3-axle units [10].

Just before the Second World War Kässbohrer (Germany) built a diesel-electric train consisting of six 2-axle units [15]. This 40-ton train was meant for on- as well as off-the-road use. Its maximum speed was about 22 m.p.h. At the end of the Second World War a large articulated vehicle called the "Räumer" [16] was undergoing trials in Germany. This armoured prototype mine-exploder was built by Krupp. The joint was located halfway between the axles, and it was steered hydraulically by articulation. The vehicle was 51 ft long, and its steel wheels were nearly 9 ft in diameter.

Even though our theme is wheeled vehicles it is interesting to note, that between the two world wars hardly any work was done at all on articulated tracked vehicles.

In 1952 Bekker initiated scale-model testing and theoretical work on this subject at Stevens Institute of Technology. A couple of years later articulated tracked vehicles like the Nodwell "North King" and "Scout", the Canadian "Rat" and "Centipede" and the WNRE "Polecat" and "Musk-Ox" pioneered the field.*

As for articulated tracked vehicles, the breakthrough for their wheeled counterparts also took place in the U.S.A. Current interest in articulated wheeled vehicles did not originate from the Pavesi concept, but rather from the successful commercial employment of the articulation principle in the American earthmoving machinery.

R. G. LeTourneau built an articulated type earthmover as early as 1938. This was

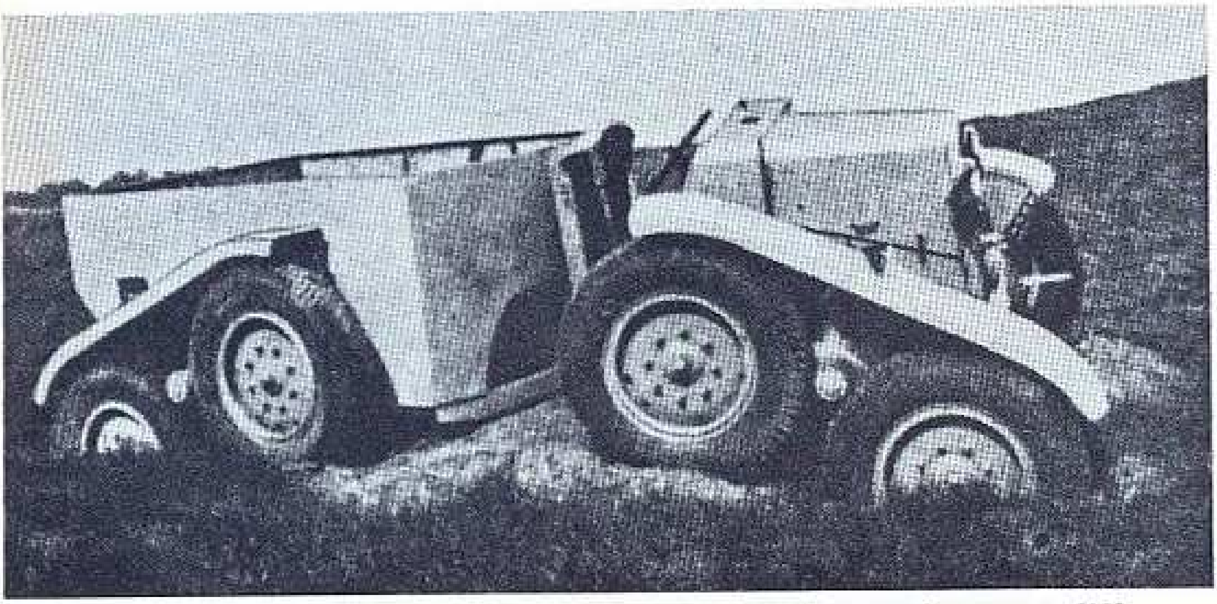

FIG. 5. Armstrong-Siddeley military tractor, Pavesi-Wilson steering system [13]. About 1930. Payload 2 tons.

*The Tucker "Sno-cat" (prototype 1948) is purposely left out, since it is not truly an articulated vehicle.

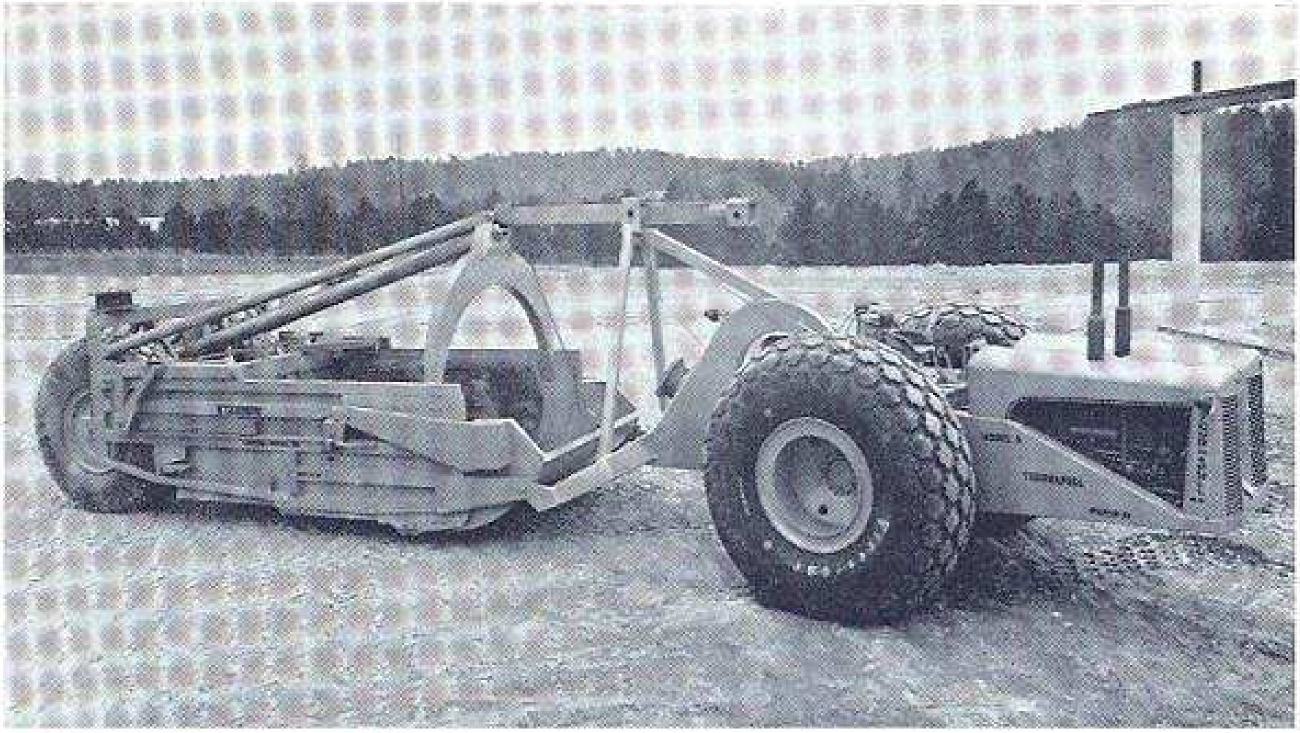

FIG. 6. LeTourneau Model A Tournapull tractor and scraper first introduced in 1938. The picture probably shows a later version. Photograph by R. G. LeTourneau, Inc., Longview, Texas.

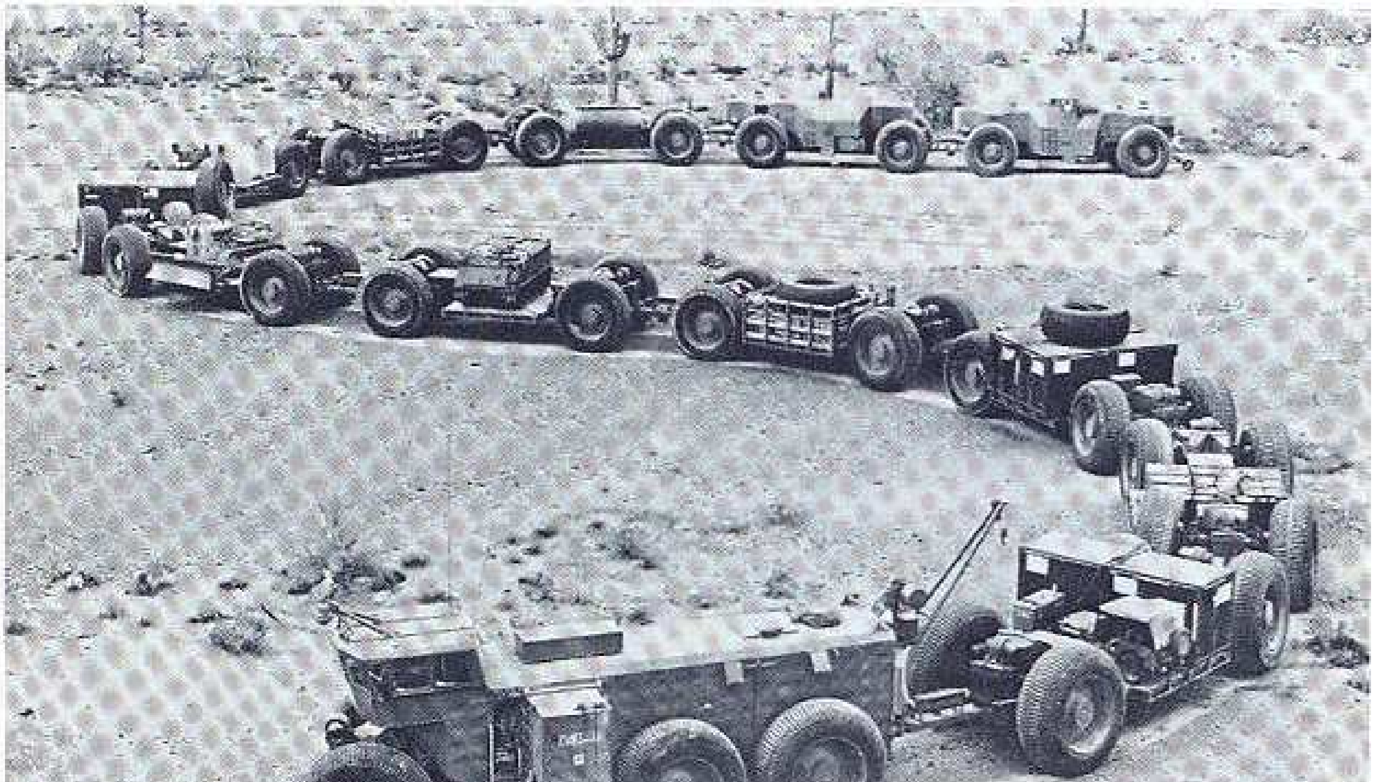

FIG. 7. LeTourneau 13-car Overland Train. Load carrying capacity 150 tons (1962). (U.S. Army photograph.)

the well known Model A Tournapull, Fig. 6. Another articulated vehicle, the "Mountain Mover", was also the work of LeTourneau. However, this electric drive scraper from 1923 had a speed of only 1 m.p.h. The real breakthrough was achieved with the Tournapull model. This four-wheeled vehicle consisted of a two-wheeled tractor with an unpowered scraper. The steering was not by articulation, but according to Hyler [17] by large band brakes and double cone clutches. Nevertheless the vehicle was articulated. This scraper proved successful and was soon followed by the smaller Model C Tournapull and the Super C Model, which saw extensive World War II service. Hyler mentions an all-wheel drive system developed for a military transporter based on the Tournapull. Each wheel in the front and rear section was driven by its own Cadillac automobile engine and hydramatic transmission. Steering was accomplished by controlling the relative speeds of the drive packages.

Positive power steering was introduced on the earthmovers about 1950. Later LeTourneau used electric motors located in the rear section or directly in the hubs of the rear wheels in order to achieve all-wheel drive.

Other companies also active in the field of articulated earthmovers at that time were the Caterpillar Tractor Co. and the Euclid Division of GM.

In the mid-fifties the train concept was reborn in LeTourneau multiple electric scrapers, Le Tourneau Trackless Train (1953), Snow Freighter (1955) and the Snow Train (1956) [10]. The latter was built for USA TRECOM. The culmination of this effort was the Overland Train, also developed by LeTourneau for TRECOM (1962) [10, 18].

The Overland Train, Fig. 7, was built to move supplies over desert or Arctic terrain. It is 572 ft long and consists of 13 units. Each wheel is powered with its own d.c. motor, and the tires are 10 ft in diameter. Three gas turbine engines and generator sets supply electricity to the wheels. The load carrying capacity of the train is 150 tons.

The success of the American industry in the development of articulated earthmovers

FIG. 8. 8-ton GOER XM 520 El, 4×4 cargo truck (1964). (U.S. Army photograph.)

was remarkable. It was only natural to investigate the military applications for such or similar vehicles.

Preliminary studies and tests were carried out by the U.S. Army Armor Board in 1956 [8, 19]. In 1957 the term GOER was born. This type of vehicle is now well known and has been extensively described [8, 9, 19–27]. After proposals had been submitted by several manufacturers of earthmoving equipment a contract was awarded in 1958 to the LeTourneau–Westinghouse Co. for 15-ton test vehicles (the XM 437 Logistical Cargo Truck and the XM 438 Logistical Tanker). These vehicles have powered (electric) wagon steer and auxiliary electric motors to drive the rear wheels. Further their design features integral body-frame construction, freedom in roll, large diameter, low pressure tires and the ability to float in inland waters. However, they are not sprung.

At the same time a contract was awarded to the Clark Equipment Co. for a 5-ton test vehicle, the XM 520 Logistical Cargo Truck. This vehicle is based on the Clark Timber Tractor. It has positive articulated steering and mechanical drive to all four wheels. Tests of these vehicles were conducted by various Army agencies in order to evaluate the GOER concept for military applications. In 1960 initial contracts were awarded to Caterpillar for the development of 8-ton GOER prototypes and to LeTourneau–Westinghouse for the 16-ton versions.

The 8-ton GOER family consists of a cargo carrier (XM 520 E1), Fig. 8 and 9, a fuel transporter (XM 559 E1) and a wrecker (XM 553). Similarly the 16-ton family consists of the XM 437 E1, Fig. 10, the XM 438 E2 and the XM 554. In both families, within their respective weight classes, the GOER front and rear units are interchangeable. Engineering and service tests of these vehicles were initiated in 1961. The performance of the GOERs was rather disappointing in Operation Wheeltrack and Swamp Fox II [24, 28]. However, the 8-ton GOER vehicles proved successful

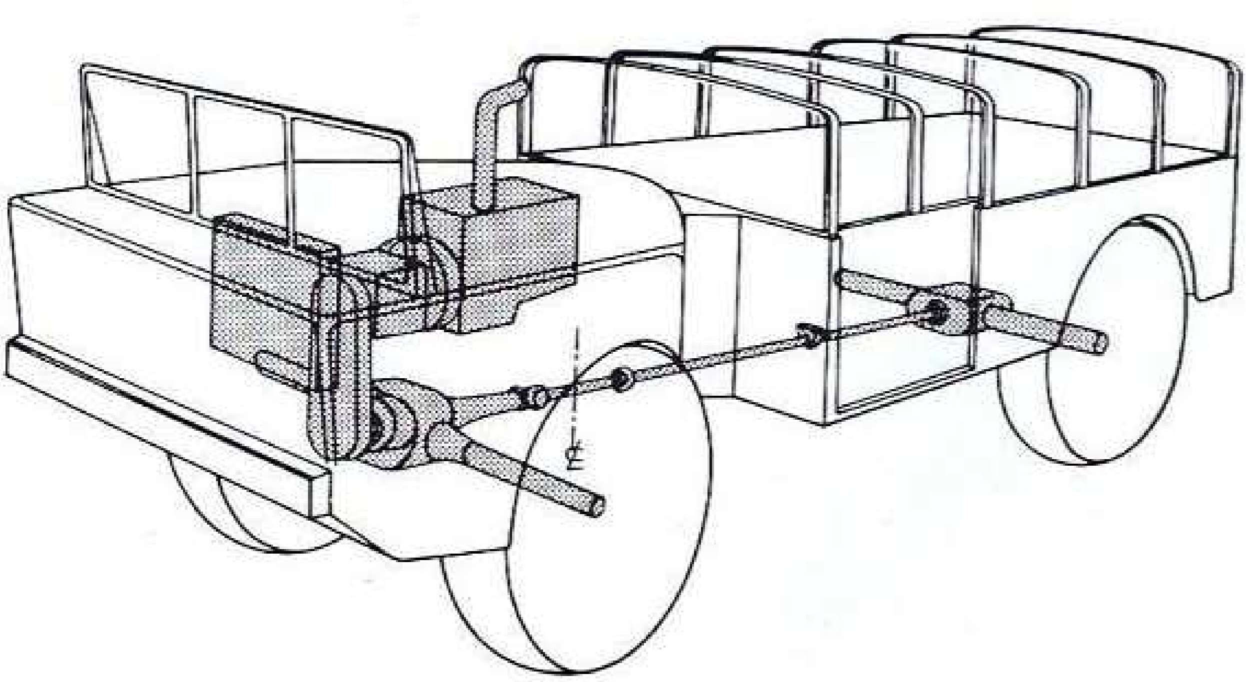

FIG. 9. 8-ton GOER drive system. Center-line shows approximate joint location. (U.S. Army photograph.)

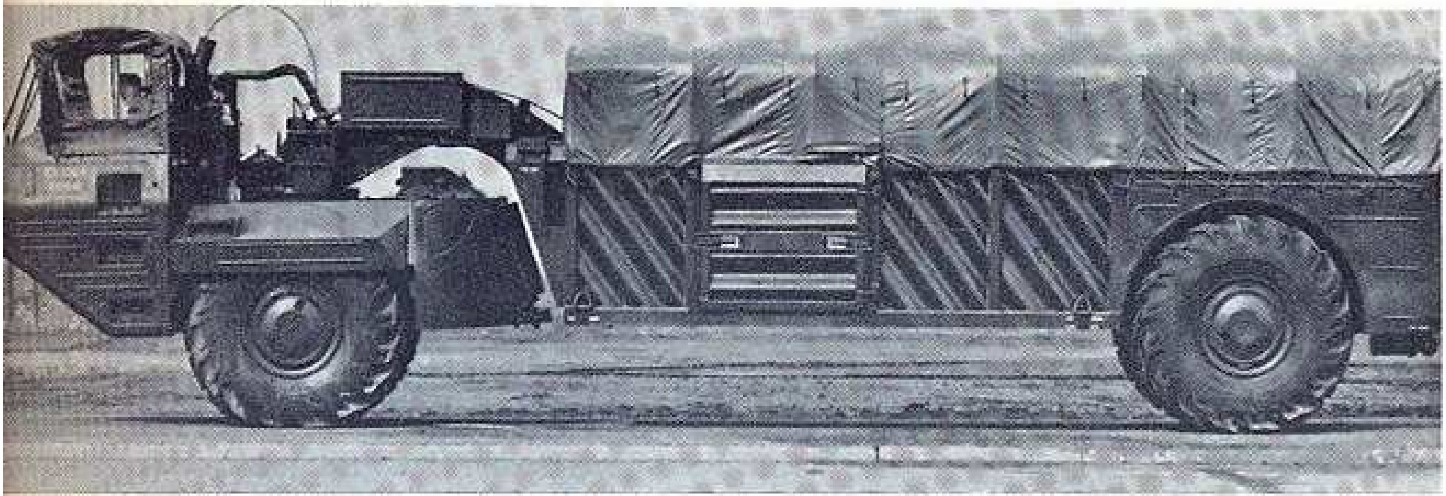

FIG. 10. 16-ton GOER XM 437 E1, 4 × 4 cargo truck (1964). (U.S. Army photograph.)

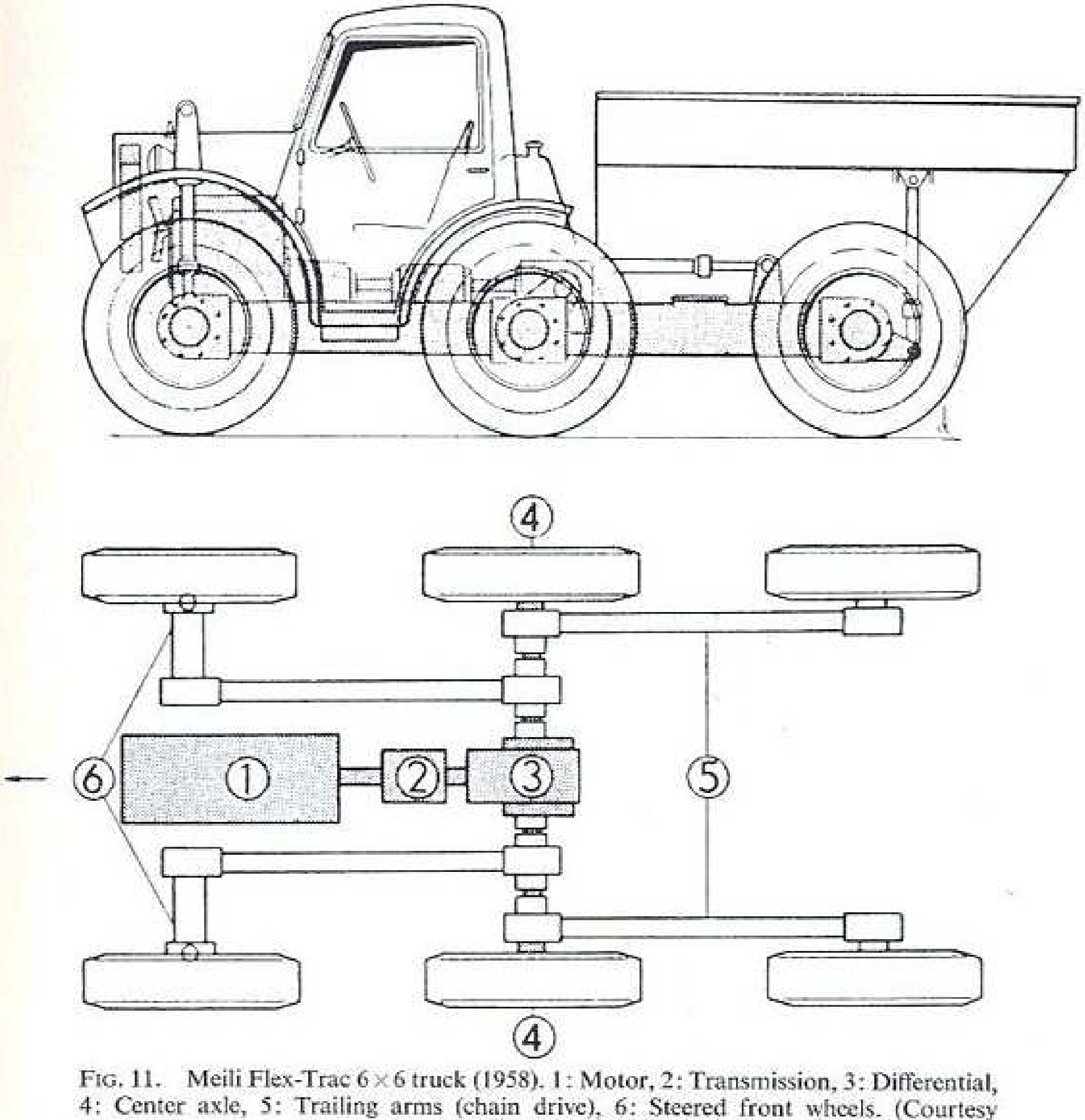

FIG. 11. Meili Flex-Trac 6 × 6 truck (1958). 1: Motor, 2: Transmission, 3: Differential, 4: Center axle, 5: Trailing arms (chain drive), 6: Steered front wheels. (Courtesy *Automobil Revue*.)

during later troop tests in Germany and Vietnam [25, 27]. The 16-ton GOER remained a test item and was not adopted by the army.

In the meantime makers of agricultural tractors rediscovered the articulation principle. In the late fifties FWD Wagner Inc. and John Deere developed articulated four-wheel drive tractors [29, 12]. These tractors are similar to the small GOER in the articulation and drive systems, so they will not be described further here. The main difference is that on the tractors the pivot joint is located half way between the axles, so that the wheels track during turning. In Canada an articulated vehicle, the Bonart Logger, appeared on the scene (1953) a long time before the GOER. This 4×4 vehicle was developed for pulpwood harvesting.

In Europe the ability of the Swiss "Flex-Trac" vehicle, Fig. 11, to climb vertical walls caused some astonishment. This 6×6 vehicle was developed by E. Meili, manufaturers of tractors, and introduced in 1958 [30]. The Flex-Trac has no central joint, and the connection between the two body sections has only one degree of freedom (pitch). Clark Equipment Co. obtained a license for the Flex-Trac in the U.S.A. and built two prototypes, a 1-ton and a 2-ton version [31]. The 2-ton vehicle was tested by the Army [32]. It was not adopted, however, and the vehicles never passed beyond the prototype stage.

The real breakthrough for wheeled articulated vehicles took place in the beginning of the sixties. Articulated vehicles in all sizes and many configurations appeared not only in U.S.A., but also in Europe. Nearly all these vehicles are of the 4×4 configuration with articulated hydraulic steering, usually having freedom in roll, and the joint located behind the front axle at a distance anywhere between 1/3 to 1/2 of the wheel base.

Articulated agricultural tractors, front-end loaders and other construction vehicles, log skidders and mining transporters appeared *en masse* [33, 34]. Also the Russians developed articulated agricultural tractors, first the T-125 and later the K-700.

It would be beyond the scope of this paper to mention and describe all these vehicles. Since they usually are of the standard 4×4 articulation concept with mechanical drive to all four wheels, they bring nothing new. However, they have clearly demonstrated once and for all the feasibility of this concept. The more sophisticated concepts have been reserved for military applications, because of their added complexity and cost.

A very successful vehicle, the Gama Goat, was introduced in 1960. This 6×6 vehicle was conceived by R. L. Gamaunt and built by the Ling-Temco-Vought Corp. It has been described in these pages [35] and in other publicaitons [36–40].

The joint connecting the two body sections features freedom in pitch and roll only. Hence the vehicle is not steered by articulation (yaw), but by Ackermann steering on four wheels (first and last axles). The Gama Goat was tested extensively by the Army. During demonstrations it outperformed other wheeled vehicles. In the meantime a military version was designed by Ling-Temco-Vought in response to the U.S. Army's request for proposal on a new $1\frac{1}{4}$-ton cargo truck. Of this version, the XM 561, Fig. 12, about a dozen prototype vehicles were built in 1963. Several years of engineering design tests followed. The vehicle was finally adopted by the Army and went into production in 1968.

The 5-ton XM 549, Quad Trac test rig, was completed at the Detroit Arsenal in 1961, Fig. 13. This 8×8 articulated vehicle was designed in order to evaluate the

FIG. 12. M 561 Gama Goat, $1\frac{1}{4}$ ton 6×6 cargo truck. (U.S. Army photograph.)

FIG. 13. XM 549 Quad Track, 5 ton 8×8 cargo truck (1963). (U.S. Army photograph.)

effectiveness of a vehicle chassis capable of running on wheels or tracks [22, 23]. A similar concept had already been tried out on the Nodwell North King (1952). Articulation is provided for in yaw, pitch and roll. The traction devices would normally be stored on the vehicle and only be used where maximum mobility was required. However, the vehicle never got beyond the test rig stage.

The UET-RT (Universal Engineer Tractor-Rubber Tired), is a very interesting vehicle. This sectionalized work-horse, designed by Barnes & Reinecke Inc., permits attachment of a wide range of interchangeable center units [41]. The tractor features front and rear powered-axle sections. The U.S. Army tested prototypes equipped with scraper bowl and dozer blade [42]. Renamed the BEST (Ballastable Earthmoving Sectionalized Tractor) it is built for the Army by the Caterpillar Tractor Co. The changing of sections for construction vehicles is, of course, very attractive and is still being pursued [43].

AVRO Aircraft of Canada proposed in 1961 a hybrid GEM-articulated, wheeled vehicle concept, the Gemini [44], as one solution to the problem of transportation over muskeg (a problem already solved by Nuttall [45]). The front unit of the two-section vehicle contains a gas turbine engine driving a fan mounted on the top of the vehicle. The fan supplies air, which is ducted to slots around the base of each unit of the vehicle. Forward propulsion, stability and control are obtained from the four wheels in contact with the ground. The prototype had difficulties in steering, and failed probably also of other reasons [46].

Since the appearance of the LeTourneau Land Train there had been much discussion about the advantages and disadvantages of off-the-road trains for military purposes, the biggest handicap being that because of their size, they are too vulnerable to assault.

The U.S. Army in 1961 gave out a request for proposal on CMD (Coupled Mobility Devices) in different weight classes. The origin of this request was not the Land Train effort, but rather a suggestion by Bekker for a new family of trucks based on the train concept [20]. The request resulted in some very intense work on the subject. At Stevens in New Jersey a rolling road test facility was built in order to study the dynamic stability of train models [10, 47, 48]. A very extensive study on this subject was also performed by Jindra [49, 50].

At Stevens two trains were constructed of 1/4-ton trucks in order to study engine synchronization, brake control, tracking ability and dynamic stability. This work was conducted in cooperation with Wilson, Nuttall, Raimond Engineers, Inc. under U.S. Army sponsorship. The trains finally proposed differs from the Land Train in that each unit can be operated independently and without limitations when desired [10]. To the knowledge of the author the trains were never built.

After several preliminary studies a test rig vehicle was built at GM Defense Research Laboratories (DRL) in order to investigate the feasibility of a train consisting of single axle units. The concept was suggested by Bekker. The author was responsible for the design in cooperation with V. F. Hickey [51, 52, 9, 53]. Named MARV (Multi-element Articulated Research Vehicle) the train turned out to be very promising. After the testing of a three-unit vehicle, Fig. 14, [54, 55] two more units were added, Fig. 15.

The three unit vehicle has an engine and automatic transmission in each unit. Independent suspension and a joint with three degrees of freedom are other features.

FIG. 14. Three-Unit MARV, GM Defense Research Laboratories (1962).

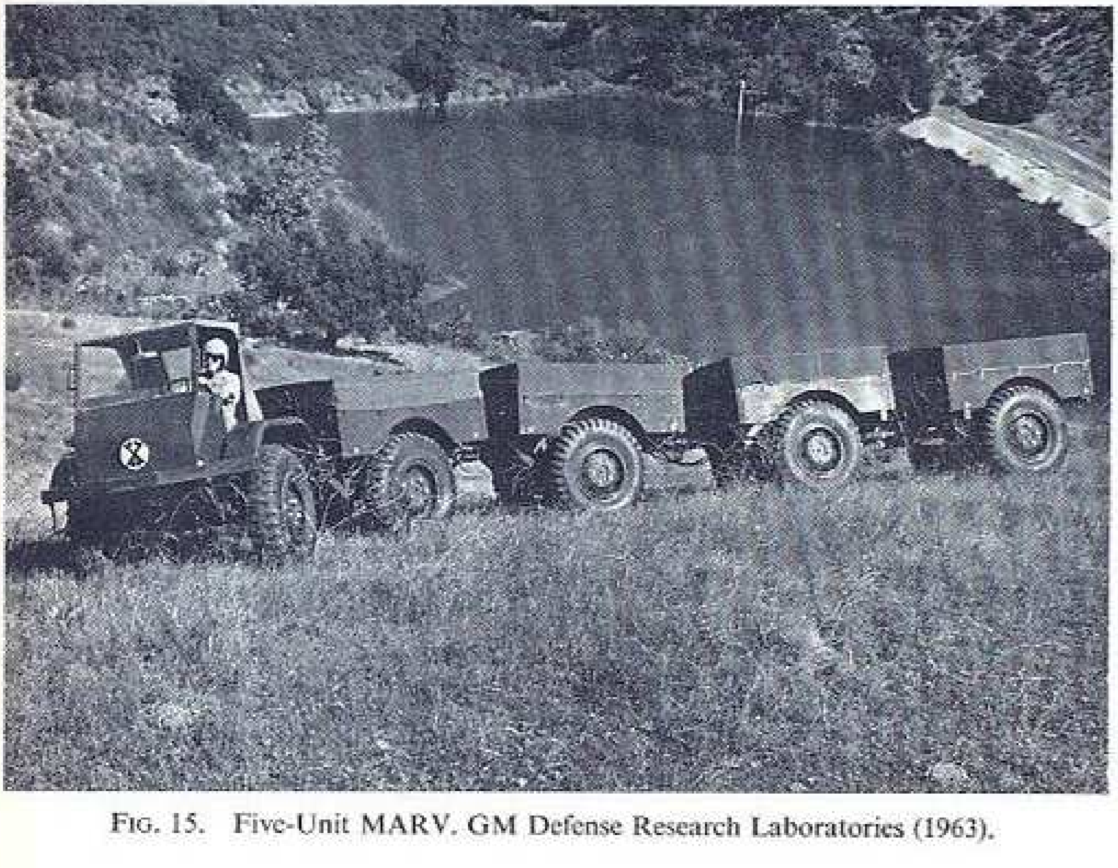

FIG. 15. Five-Unit MARV. GM Defense Research Laboratories (1963).

The articulated steering is actuated hydraulically through a remote servo control valve and hydraulic cylinders. The joint is described in the next chapter. The three-unit MARV vehicle was driven fully loaded at a maximum speed of 48 m.p.h. on dirt roads without stability problems.

At DRL the author proposed an articulated 6×6 vehicle [56], which was never built, but nevertheless deserves some more consideration, Fig. 16. The concept has

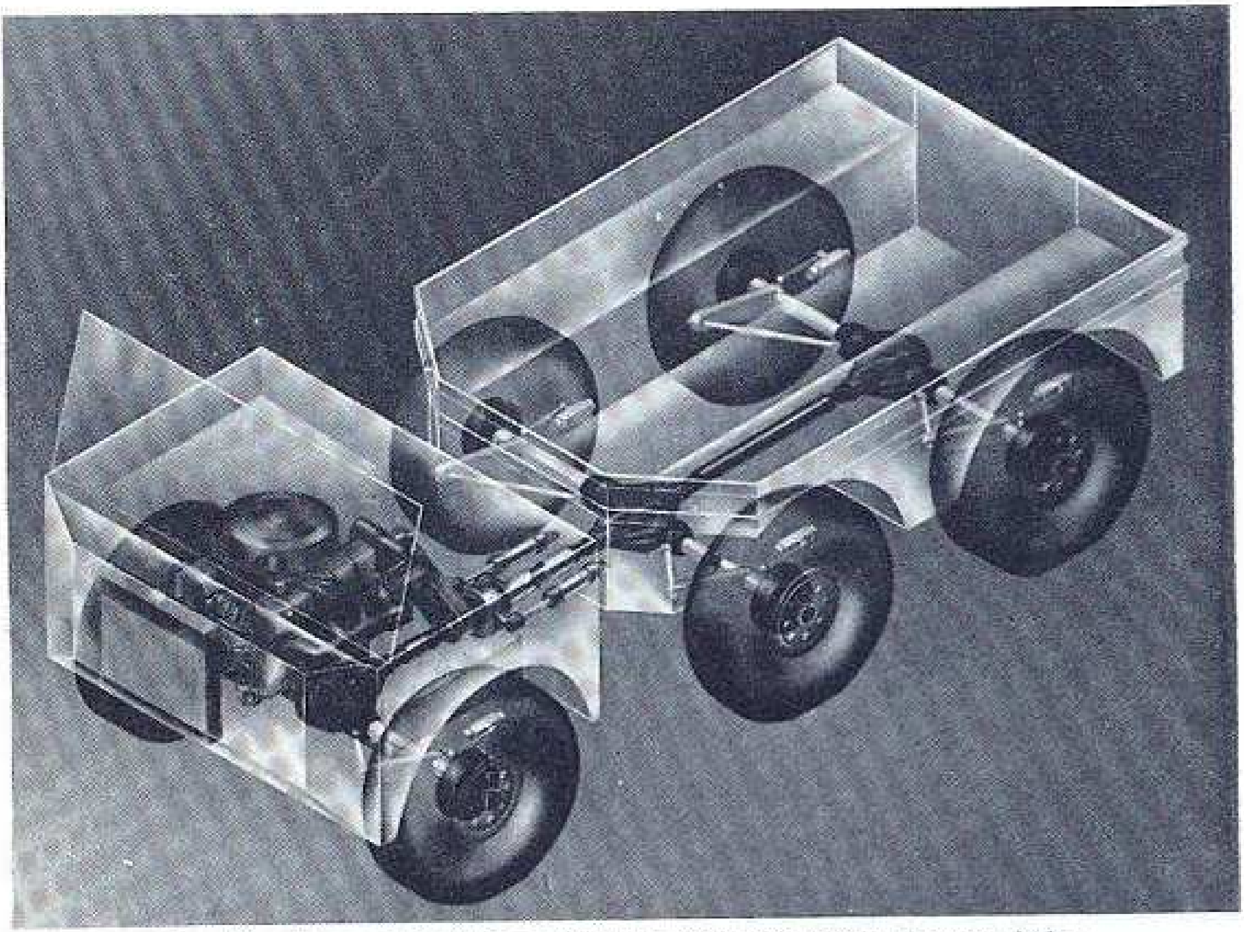

FIG. 16. $1\frac{1}{4}$ ton 6×6 Articulated Truck, GM DRL (1961). Concept design.

several definite advantages over the Gama Goat, namely the articulated steering (about half the turning radius) and a one-piece loading area. Even though the vehicle is shorter, it has more cargo area than the Gama Goat. Hickey conceived another vehicle, the double jointed Sidewinder [57]. The power plant module (middle section) contains power plant and transmission. The whole package can be removed and replaced in the field. The prototype performed very well, and a military version, the TASC (Tactical Articulated Swimmable Carrier), was later developed by Chevrolet [58–60], Fig. 17.

Several aircraft and aerospace companies started to diversify their activities to other areas like off-the-road locomotion and ground vehicles. This trend was, of course, partly due to interest also in lunar surface exploration. Besides new lunar vehicle concepts, several more earthbound prototypes were developed. Lockheed introduced a small 12×12 articulated vehicle [61] consisting of two 3-axle units equipped with Terra Tires. Lockheed also developed another articulated vehicle, the Twister, Fig. 18 and 19. The design and fabrication of this vehicle was completed

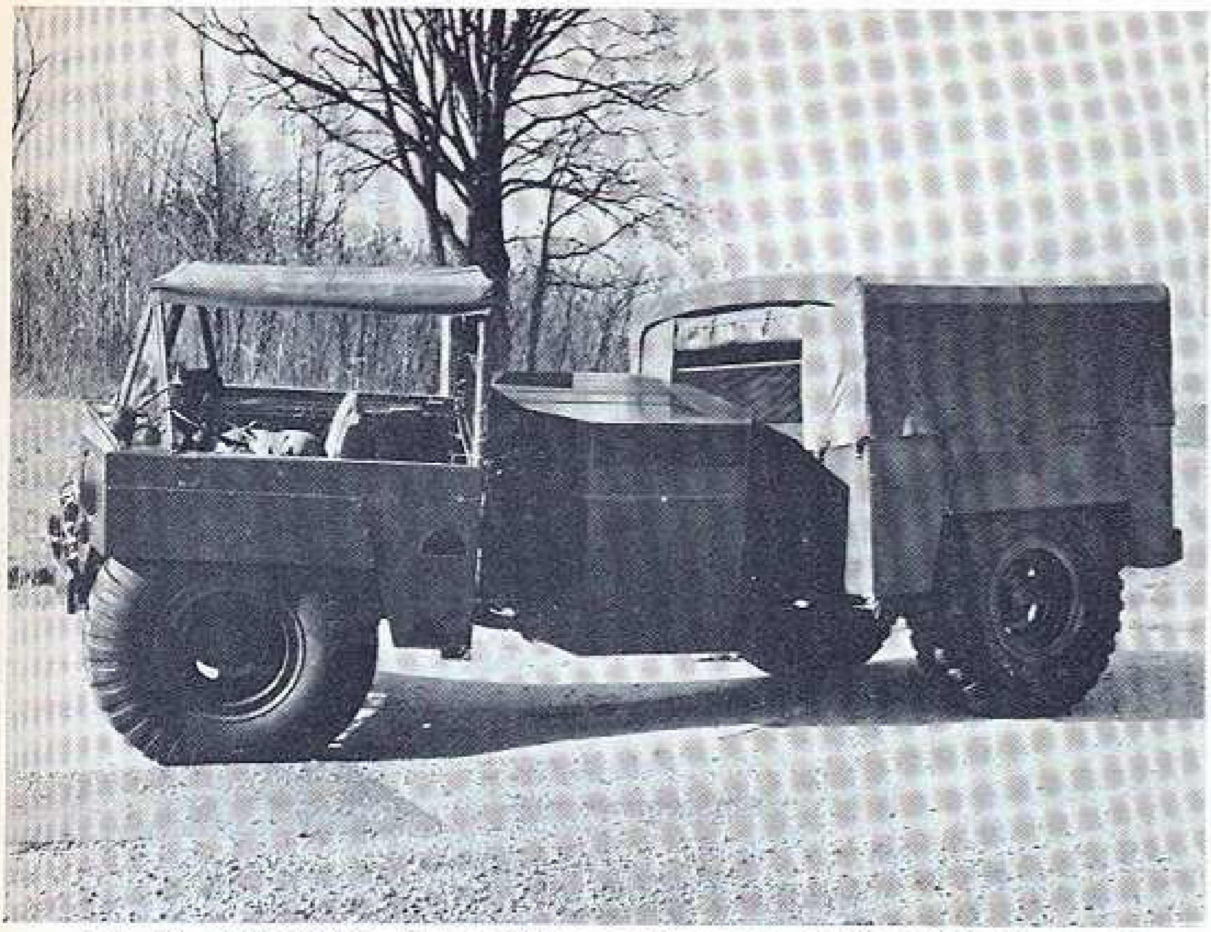

FIG. 17. GM TASC, $1\frac{1}{4}$ ton military multi-purpose vehicle (1966). (Photograph Chevrolet Motor Division.)

FIG. 18. The Twister, high mobility 8×8 vehicle, designed and built by the Lockheed Missiles & Space Co.

FIG. 19. The Twister uses a yoke instead of a central joint.

in 1965 [62]. The Twister concept is in some ways similar to the experimental Pavesi vehicle developed by Armstrong-Siddeley. Both are 8×8 vehicles with articulated steering and freedom in roll. The Twister also has the wheels mounted in pairs on walking beams, but only on the last unit. The main and important concept difference is that the Twister joint allows freedom in pitch, and that the Pavesi tractor had no suspension. The Twister has shown extremely good mobility. Recently a military version has been developed for the U.S. Army.

In September 1964 a "crash" activity—the Vicksburg Mobility Exercise A—was held at the U.S. Army Engineer Waterways Experiment Station. The purpose of this meeting was to discuss and find a solution to different mobility problems and to decide upon vehicle concepts. The vehicles should be capable of operating in remote areas of the world, where extremely soft soil conditions predominate [63, 64].

Participants at this meeting were representatives from the Corps of Engineers (WES), ATAC and Mr. Nuttall from WNRE.

After many ideas and possibilites had been evaluated, it was decided to build three articulated vehicles, two wheeled vehicles with Terra Tires (8×8 and 10×10) and one tracked vehicle with very low ground pressure. The contract to design and fabricate these test beds was later given to Clark Equipment Co. They were delivered in early 1967. During tests the vehicles have shown exceptionally good mobility [65–67]. The joints of these vehicles are described in Section 4. The 8×8 vehicle, Fig. 20, is a rather "way out" solution. The 10×10 vehicle, Fig. 21, has shown some very interesting potential, even though maneuvering in tight spots must be difficult and result in a considerable amount of tire scrub on hard surfaces. The two vehicles are equipped with passive air springs.

In order to make the history of articulated, wheeled off-the-road vehicles complete, several lunar vehicle concepts and prototypes developed during this decade must also be mentioned. The elastic frame concept was developed by Bekker [3, 52, 53, 68–71]. The flexible frame connecting the units consists of springs that allow restricted freedom in pitch and roll. The first models were built at GM DRL in 1961. One

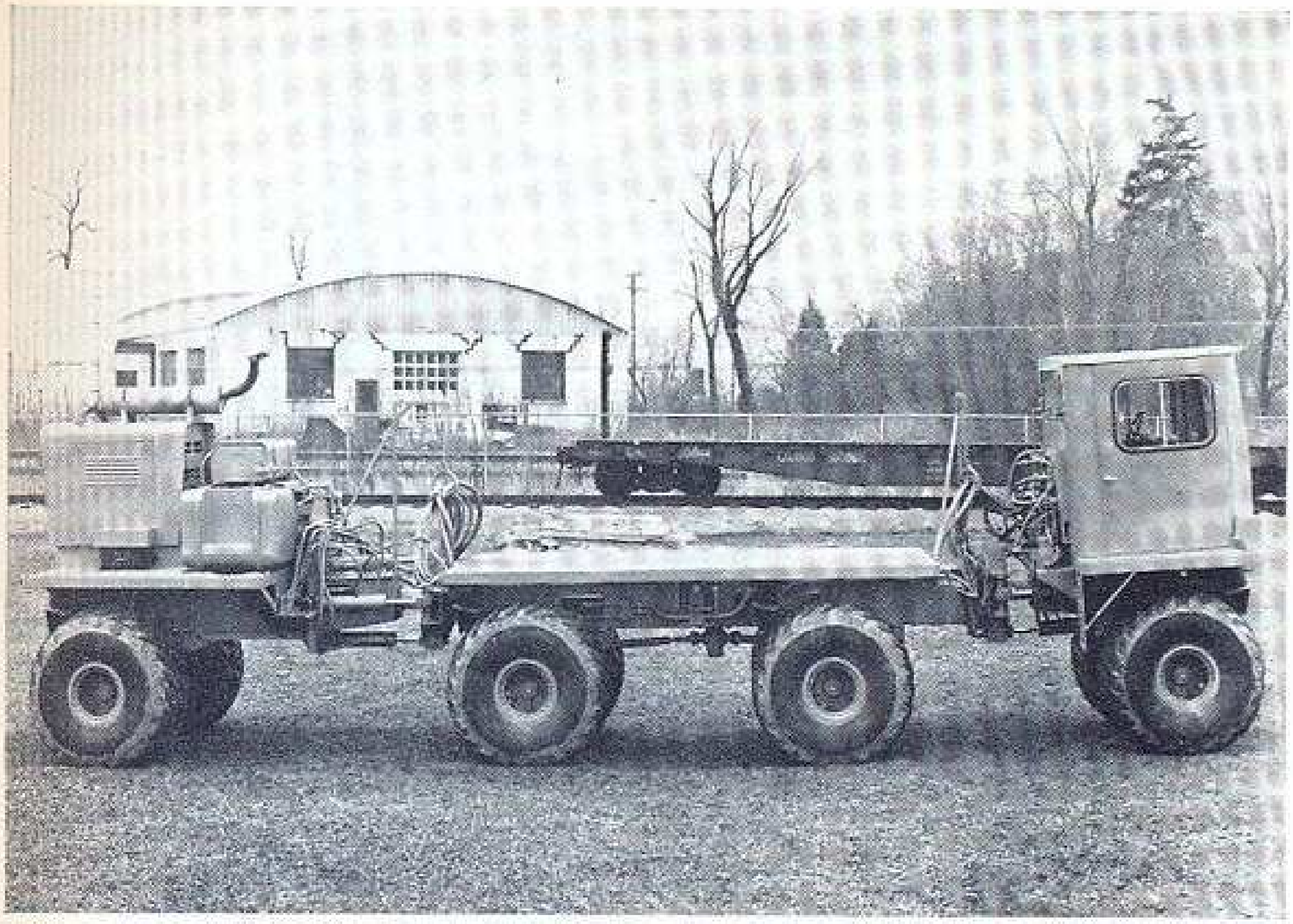

FIG. 20. VEXA 2½ ton 8×8 Mobility Test Rig. (U.S. Army photograph.)

FIG. 21. VEXA 2½ ton 10×10 Mobility Test Rig. (U.S. Army photograph.)

FIG. 22. Flex-Frame Vehicle (ATAC) with double coil spring joint and hydraulic drive to each wheel. (U.S. Army photograph.)

year later a full-size unpowered test bed vehicle was fabricated [3, 71]. Tests were performed with the towed elastic frame vehicle in the field (pitch and lateral stability, obstacle crossing) [72–74].

A similar vehicle, but powered and with a coil spring-joint instead of a rod-joint, was later built at ATAC, Fig. 22. This vehicle is not a lunar model, however, and it differs from Bekker's original concept in that the springs are also replacing the joint. On the Bekker model a joint is needed for articulation in yaw. On the ATAC model the coil springs are mounted so that no restriction is provided for in roll, while the motion in pitch and yaw is restricted. GM DRL designed and built a terresterial lunar training vehicle, the Mobile Geological Laboratory, under contract with NASA. This vehicle is based on the Sidewinder concept [70, 75]. DRL later proposed detailed plans for an Unmanned Lunar Roving Vehicle and a Manned Lunar Vehicle [70, 71]. Analysis had shown that an articulated, six-wheeled vehicle probably was the best answer to the lunar mobility problem. Both vehicles were based on the flex-frame concept,although the manned vehicle had an elastic frame between the second and third axle only. In cooperation with Boeing, GM later bid for the LSSM (Local Scientific Survey Module) contract [76]. Other companies, like the Grumman Aircraft Engineering Corp., were also proposing lunar vehicles based on the articulation principle [77, 78].

Closing up the section on the history of articulated, wheeled off-the-road vehicles it can be mentioned, that elastic metal wheels, so common in lunar vehicle concepts, had already been suggested by Rickett in 1858 [6].

4. JOINTS AND STEERING

It is surprising how many misconceptions exist regarding the steering of articulated vehicles. Some definitions are necessary. The steering of wheeled vehicles fall into the following types (see Fig. 23):

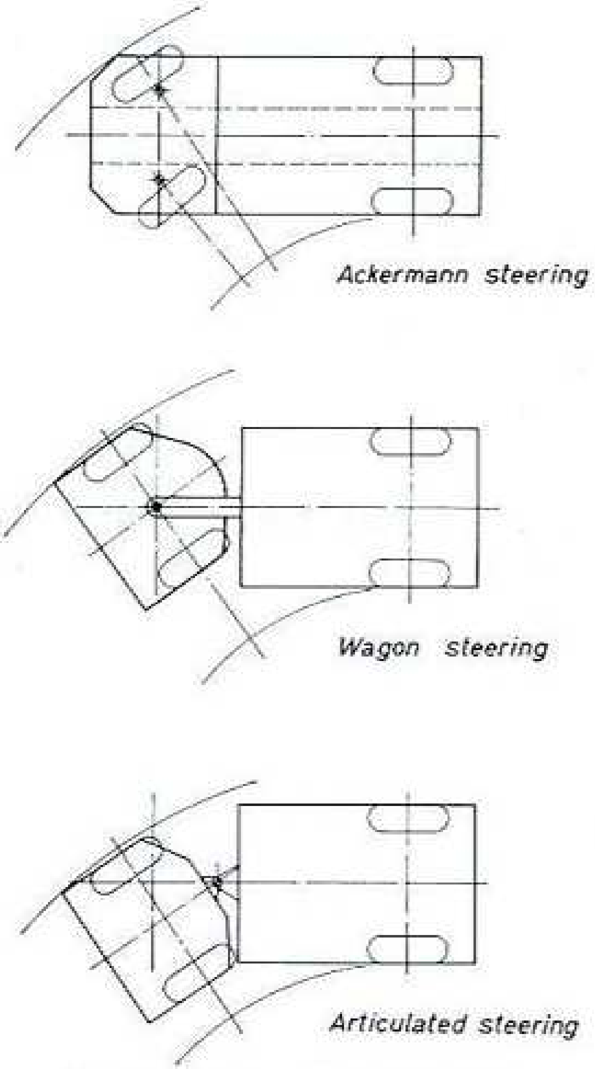

Fig. 23. Steering of wheeled vehicles.

(1) Ackermann steering (conventional).
(2) Wagon steering.
(3) Articulated or frame steering.
(4) Skid steering.
(5) Combinations of the above.

The steering of trains is so specialized, that it will not be treated here (see Jindra [79–81] and Stevens [10]).

The steering of articulated wheeled vehicles can be accomplished by any of the above mentioned methods. Examples are:

(1) Meili Flex-Trac, Gama Goat.
(2) GOER 16-ton.
(3) Deere 8010, MARV, VEXA.
(4) Model A Tournapull.
(5) Twister.

Note that Ackermann steering is only used on articulated vehicles with more than two axles. 4×4 vehicles use wagon steer or articulated steer, since they all have freedom in yaw anyway. No modern articulated vehicle with skid steer is known to the author. It is often believed that an articulated vehicle has to be steered by articulation. This is not so, as shown by the examples. In order to take full advantage of the articulation principle, however, articulated steering should be used.

The reasons for using articulated steering are well known. Schematically they will be repeated. Above a certain ratio of wheel diameter to vehicle width the Ackermann steering results in too much encroachment on the vehicle frame, when at the same time a normal turning radius is wanted. This disadvantage can be avoided by using:

(1) 4-wheel Ackermann steering.
(2) Wagon steering.
(3) Articulated steering.
(4) Skid steering.

Four-wheel steering helps out only to a certain extent. Steering the rear wheels usually wastes cargo space.

Wagon steering is combined with several stability problems.

The disadvantages of skid steering are obvious (tire-wear, only good for relatively low speeds, loss of traction in a turn when needed for propulsion).

Articulated steering is the most attractive solution, particularly because this steering is combined with other advantages (see Section 6).

Often wagon steering is referred to as articulated steering. By definition this is not so, as shown in the "Mobility Studies" [20]:

"Articulated steering is the powered steering of vehicles with a jointed frame by means of a single, vertical pivot system (joint) in which the pivot is located between the axles.

Wagon steering is the powered steering of vehicles (conventional or articulated) by means of a single, vertical pivot system with the pivot joint located over the front axle."*

The difference between a wagon steered articulated and a wagon steered conventional vehicle is obvious. The former has a divided frame and the latter a solid frame. Examples of wagon steered conventional vehicles are (beside the horse carriage) the "Rolligon" and the "Terra-Cruiser" (MM-1 Missile Carrier) [82].

At this stage we unfortunately get into contradictions with common practice in the field of articulated tracked vehicles.

The Tucker Sno-cat is described by several authors as an articulated vehicle. Nuttall [5] carefully avoids doing the same. However, he names the steering of this vehicle "4-wheel" wagon steer or articulated steer. This type of steering can, of course, be called articulated. The vehicle itself is definitely not articulated, since the

*The original text has been slightly changed. The pivot axis is sometimes inclined in order to achieve better stability.

body and frame are not divided. In order not to confuse the issue, it would be better to call the steering of this vehicle double wagon steer.

As mentioned in Section 2, the joint of an articulated vehicle may have one, two or three degrees of freedom. Joints with three degrees of freedom are found only on vehicles with more than two axles. The reason for this is, of course, that there is not much use having pitching capability on a vehicle with two axles. Such vehicles have therefore only two (yaw and roll) or sometimes only one degree of freedom (yaw). Pitching capability on vehicles with more than two axles brings a great advantage, as demonstrated by the Meili Flex-Trac and the Gama Goat. Examples of 6×6 vehicles with one to three degrees of freedom are:

(1) Meili Flex-Trac (pitch only).

(2) Gama Goat (pitch and roll).

(3) $1\frac{1}{4}$ ton 6×6 Truck (yaw, pitch, roll).

The lack of roll capability on the Flex-Trac is partly compensated for by the long trailing arms, which allow extreme wheel travel.

Joint design is very important for the outcome of an articulated vehicle. Joint concepts are so plentiful, that only the main types can be referred to here. An illustration of the Diplock joint mentioned in Section 3, is found in Nuttall's paper [5] on the steering of tracked vehicles by articulation. The Pavesi joint is shown in Fig. 3. A tubular backbone assembly connect the two body sections. This assembly allows freedom in roll and is pivoted about one vertical king pin at each axle. A rather complicated drive mechanism to the rear wheels is located above the joint. The "swan-neck" joint, Fig. 10, introduced on wagon steered earthmovers by LeTourneau has not succeeded on other types of off-the-road vehicles. The electric steering motor is attached to the swan-neck member and rotates the front section of the vehicle in relation to the rear about a vertical king pin. A typical joint with two degrees of freedom for 4×4 vehicles is shown by Walters *et al.* [12]. The Deere joint utilizes a mechanical drive through the joint to the rear wheels. Steering is accomplished by means of a hydraulic cylinder. Today two cylinders are usually employed. This type of joint is also used by the Russians in their T-125 [83].

Other 4×4 vehicles, like front-end loaders, usually have joints with freedom only in yaw (articulated steering). The rolling mode is compensated for by a pivoted rear axle [84]. The steering valve actuates two hydraulic cylinders, one on each side of the joint.

The 8-ton GOER joint isshown in Fig. 24. Between the pivot bearings the left hand hydraulic steering cylinder and the mechanical drive to the rear wheels can be seen. The joint is located underneath the front unit body (left side) rather close to the front axle, Fig. 9. A classic example of joint design is shown in Fig. 25. This joint is designed and patented by Nuttall *et al.* [85]. The drive through joint has three degrees of freedom and is used on a three-unit, articulated tracked vehicle, the WNRE Cobra [5]. The original version did not have pitch control. In ordinary operation, the pitch cylinder floats through chokes to act as a damper, but at driver command it can either be locked or powered to actively control the pitch angle between units. This is very useful for crossing of obstacles. The vehicle and the joint were developed by WNRE under ATAC sponsorship. Positive pitch control has recently been discussed in these pages by Hanamoto [67]. The Nuttall joint shown in Fig. 25 can, of course, also be used on wheeled vehicles. The Gama Goat joint has been described extensively [36–40]. It will not be repeated here.

The MARV joint, Fig. 26, is unique in that a non-active system (coil springs and dampers) are used to control pitching motions. Since the units have only one axle

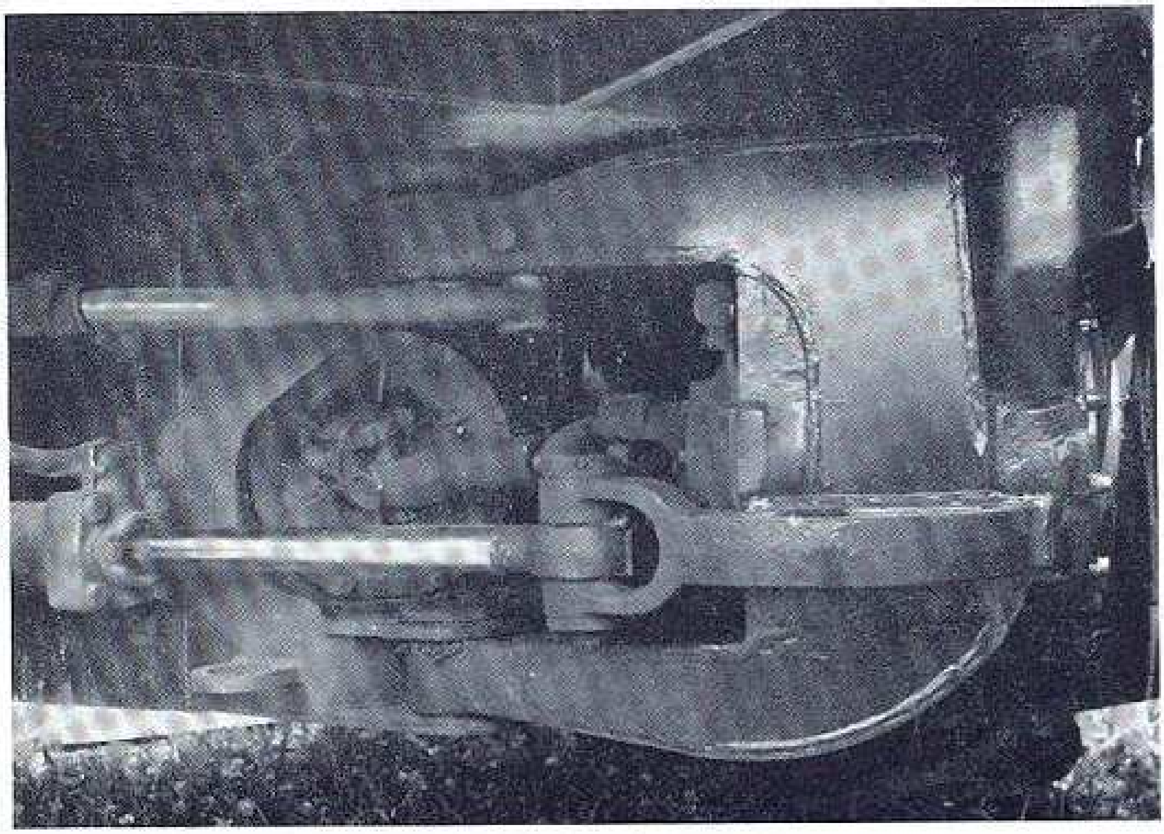

FIG. 24. The 8-ton GOER joint.

each, a pitch control is needed. The joint has three degrees of freedom. The springs were layed out so that the pitch stops are just about reached by maximum acceleration and braking. This way the joints are so flexible, that the units adjust to extreme ground contours, Fig. 14. A drive through joint was not needed, since each unit had its own engine. It should be noted that MARV was not even a prototype vehicle, but was strictly designed as a test bed, meant only to demonstrate a principle. The vehicle was actually designed and built within three months.

On the TASC (Sidewinder) a modular construction principle is used. Three separate units are combined with two steering pivots located at equal distance from front and rear axles. The steering pivots are connected with cross links. They steer simultaneously and in synchronization. The steering is accomplished by hydraulic cylinders located between front and center sections. A pivot joint between center and rear sections allows freedom in roll.

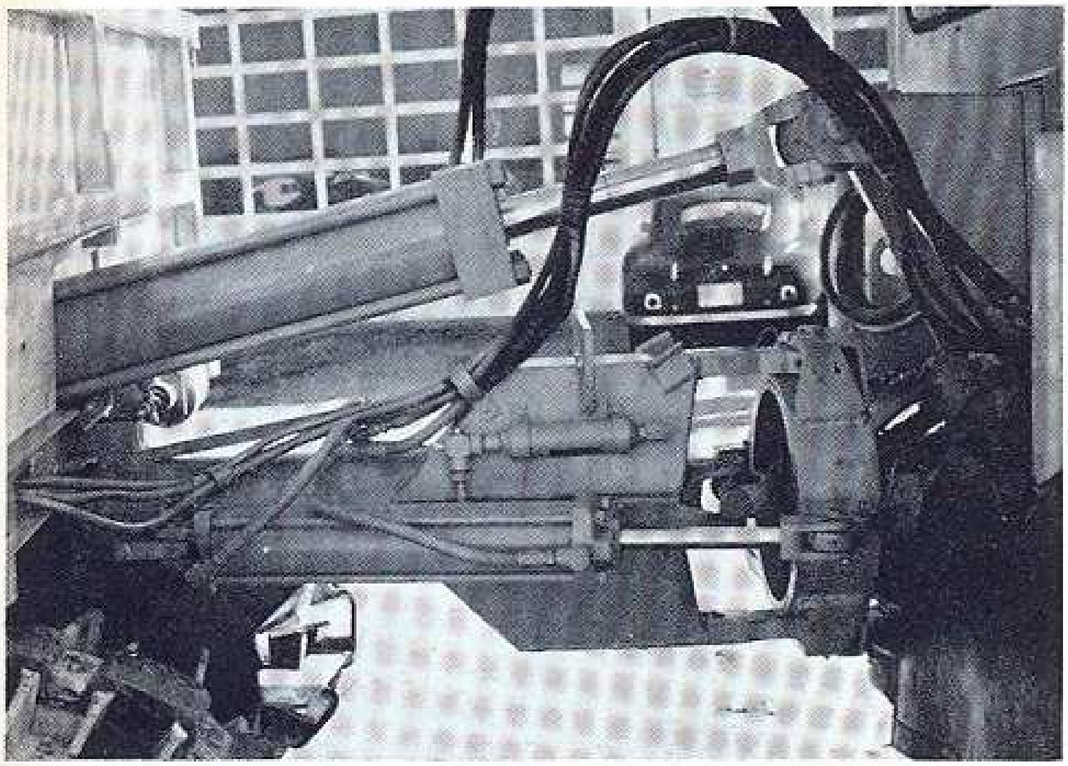

FIG. 25. The Nuttall "train type" joint used on the COBRA (with active pitch control). (Photograph by WNRE, Inc., Chestertown.)

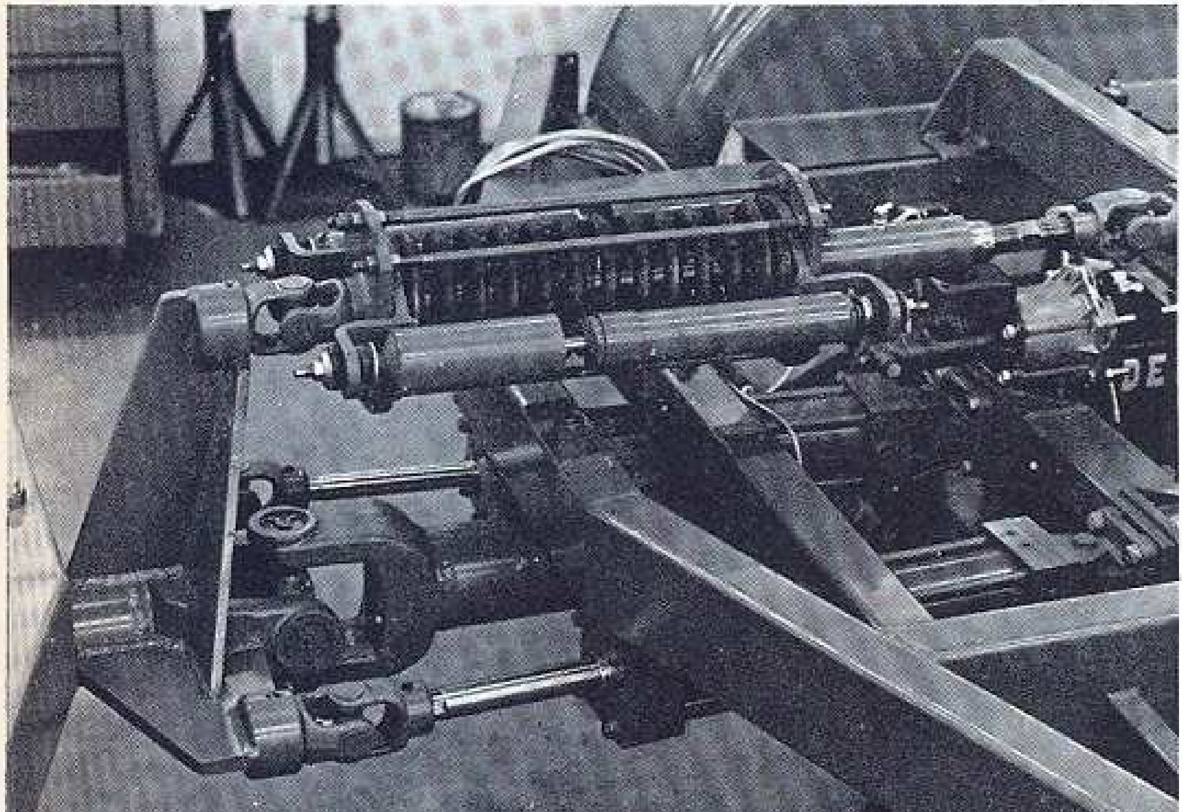

FIG. 26. The MARV joint with non-active pitch control to stabilize units. (GM DRL photograph.)

The Twister utilizes articulated steering in combination with Ackermann steer on the four front section wheels. The pivot yoke linking the front and rear units has three degrees of freedom. The use of a yoke instead of a central joint is rather unusual. Because of the yoke the Twister can hardly carry cargo in the front unit, see Fig. 19. Yaw action is produced by a hydraulic cylinder mounted inside the pivot yoke and connected to the yoke by tension chains.

The positive pitch control of the VEXA (Vicksburg Exercise A) vehicles has been described in [67]. On these vehicles two hydraulic pitch cylinders are used, one at

FIG. 27. The VEXA vehicle joint with active pitch control and inching system. (U.S. Army photograph.)

the top and one at the bottom of the joint, Fig. 27. Another feature of the VEXA joint is the inching capability. The inching system allows one unit to move forward 24 in. while the other unit is standing still. If the vehicle is immobilized, the operator brakes the rear unit and applies power to the front unit. At the same time, power is applied to the inching cylinders between units. After the front unit has moved forward, the action is reversed, and the second unit is pulled and driven up behind the first. However, based on performance in snow, the inching capability appears less useful than originally thought at the design stage [65]. The VEXA joint has, of course, three degrees of freedom, and the articulated steering is actuated with hydraulic cylinders.

The last type of joint discussed in this paper will be the elastic frame. An elastic frame is usually restrained by the springs in pitch and roll (except the ATAC vehicle). A vertical king pin at the axle (wagon steer) or between the axles (articulated steer) give freedom in yaw. The frame may consist of rod springs, Fig. 28, coil springs,

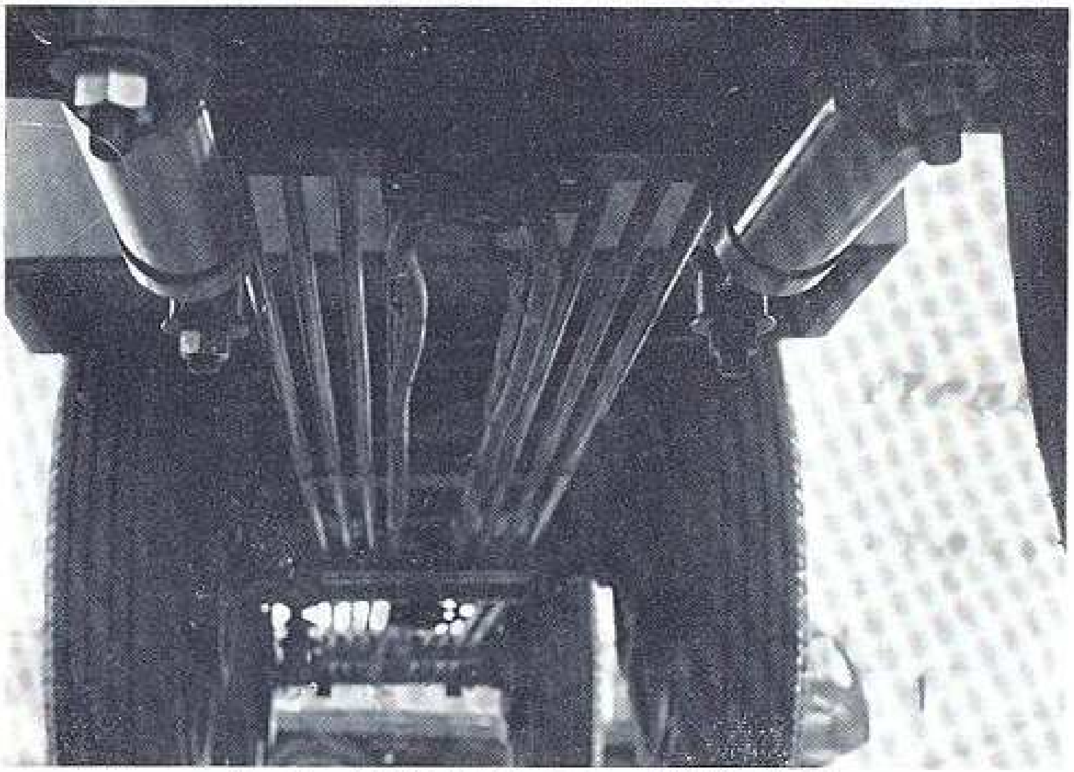

FIG. 28. GM DRL Elastic Frame Vehicle (1962).

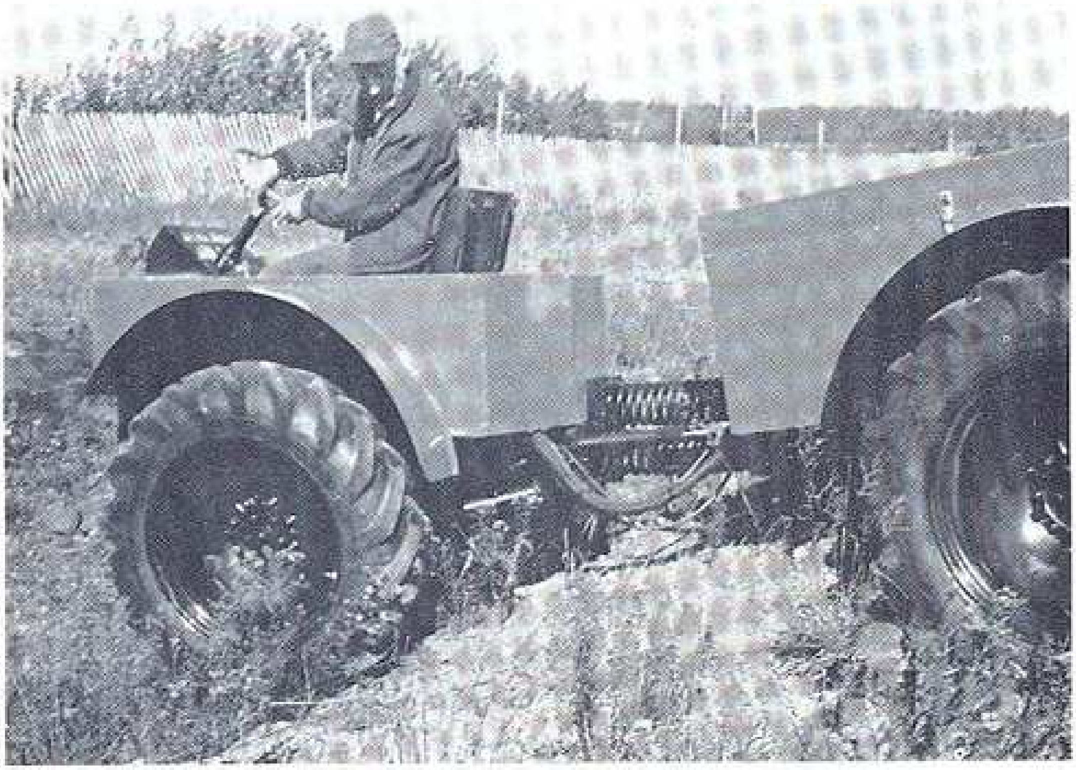

FIG. 29. The Flex-Frame Vehicle joint. (U.S. Army photograph.)

Fig. 29, or leaf springs. It is difficult to combine a flex-frame with a mechanical drive from one unit to the next. Hydraulic or electric drive or one engine in each unit is therefore preferable. Dampers often have to be used in order to control pitch oscillations.

5. CONFIGURATIONS

As seen in the earlier Sections many articulated vehicle concepts have been tried out. It would be interesting to examine what theoretical possibilities exist. In Fig. 30 the possibilities for vehicles with up to five axles are shown. Vehicles with more than one axle difference between units were not considered. A vehicle with, for instance, three axles on one unit and one axle on the other would probably be impossible to steer. Further it does not make sense building vehicles with units of very different mobility characteristics.

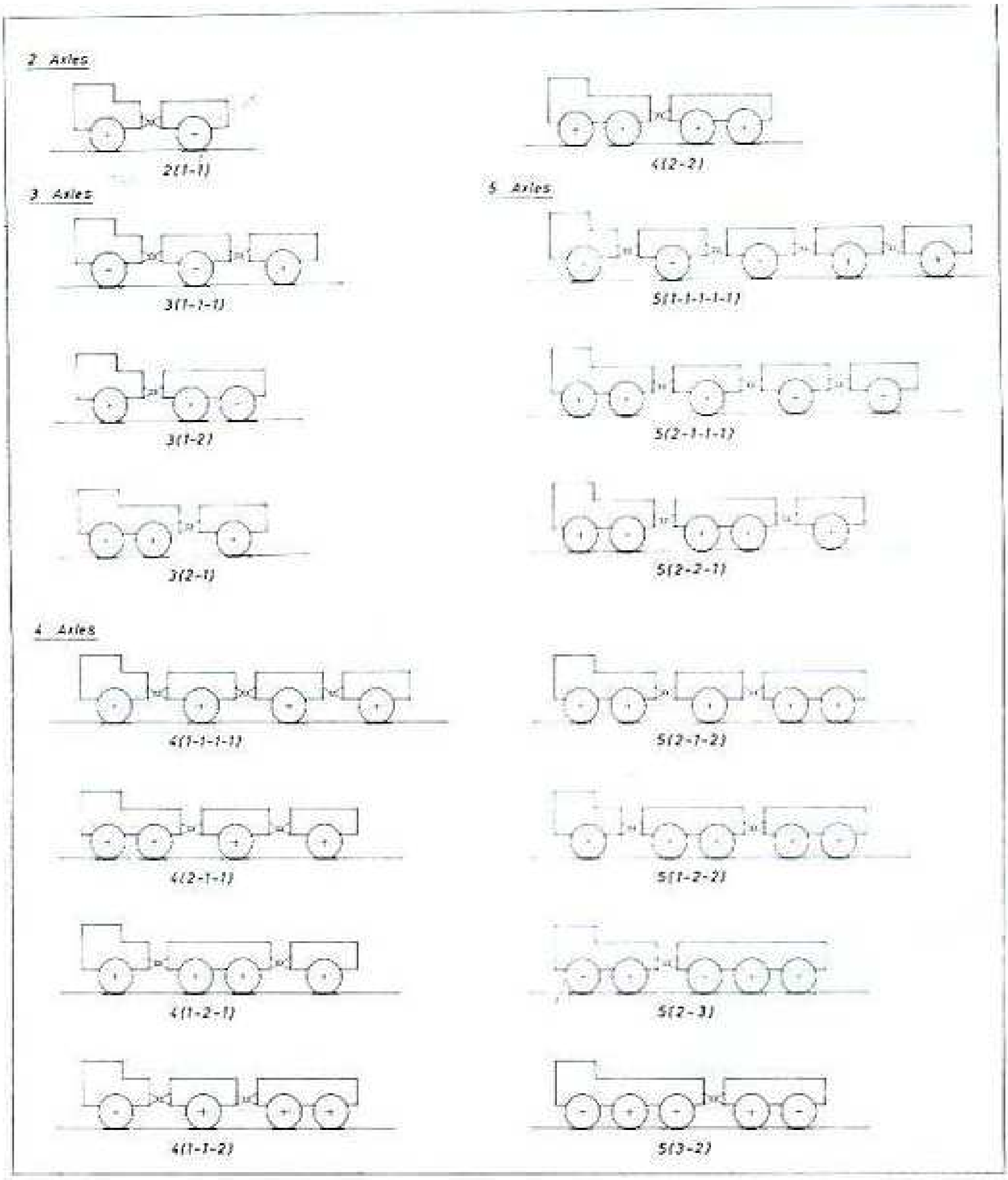

FIG. 30. Concepts of articulated vehicles with up to five axles. The combinations 5 (1–2–1–1), 5 (1–1–2–1) and 5 (1–1–1–2) are not shown.

The following notation is used. The first number gives the total amount of axles on the whole vehicle. The numbers inside the parenthesis give successively the amount of axles on each unit. This way a concept can be pinpointed without long explanations. In Fig. 30 the vehicles 5(1–2–1–1), 5(1–1–2–1) and 5(1–1–1–2) are not shown in order to save space and because they are not important. The range has not been extended to show the possibilities of building 6-axle vehicle concepts, because basically this would add nothing new. The most logical concepts would be:

6(1–1–1–1–1–1)
6(2–1–1–1–1)
6(2–1–2–1)
6(1–2–1–2)
6(2–2–2)
6(3–3)

A train can be formed of like units or unlike units. By like units the presence of a driver cabin with controls is not necessarily considered.

Trains formed of like units

No. of axles Single train unit	Train
1	1 – 1 – 1 – 1 etc.
2	2=2=2=2 etc.
3	3=3=3=3 etc.
4	4=4=4=4 etc.

Single train unit Artic. vehicle	Train
1–1	1–1=1–1 etc.
1–2	1–2=1–2 etc.
2–1	2–1=2–1 etc.
2–2	2–2=2–2 etc.
2–3	2–3=2–3 etc.

Trains formed of unlike units

Primary unit	Secondary unit	Train
1–1	2	1 – 1=2=2 etc.
1–2	1	1 – 2=1=1 etc.
1–2	2	1 – 2=2=2 etc.
2–1	1	2 – 1=1=1 etc.
2	1	2=1=1=1 etc.
3	2	3=2=2=2 etc.

The combinations shown are just examples. Naturally numerous other possibilities exist. (Note: – stands for vehicle articulation joint, = for train joint).

In the "Mobility Studies" [20] a truck family concept that originated in the Land Locomotion Laboratory is suggested (see Section 3). The concept is essentially a train system employing primary and secondary units. The use of three primary units (1, 3 and 5 ton rated capacities) with three powered secondary units (also 1, 3 and 5 ton) permits vehicular combinations covering the entire load spectrum of from 1 to

15 tons. Each of the primary units is capable of completely independent operation as a conventional truck. The concepts suggested are the following:

2 (2)	2 (1–1)
4 (2=2)	4 (1–1=2)
6 (2=2=2)	6 (1–1=2=2)

The modular structure of complete vehicle families was not much appreciated at the time, even though the later work on CMDs probably was a direct result of this study. Bekker would like to see all articulated vehicles as members of a great LLL family of vehicles [3], rather than individual pieces of equipment. They can of course be fitted into a certain scheme as shown classified in Fig. 30. In the "Mobility Studies", however, only the combinations shown above with notations are suggested. For instance three-and five-axle vehicles are not among the concepts.

To the reader not familiar with articulated vehicles, Fig. 30 might look like a lot of impractical theory. It is surprising, however, that half of the concepts shown actually have been built. Examples are:

Pavesi, GOER	2 (1–1)
MARV, Elastic frame vehicle	3 (1–1–1)
Wagner Teletruck	3 (1–2)
Gama Goat	3 (2–1)
VEXA 8×8	4 (1–2–1)
Armstrong-Siddeley, Quad Trac, Twister	4 (2–2)
MARV	5 (1–1–1–1–1)
VEXA 10×10	5 (2–3)

The 3 (1–2) vehicle suggested by the author was not built. However, it has a "big brother" in the Wagner Teletruck MTT-R40 [86]. Apparently Nuttall later suggested the same concept for a 5-ton basic unit or carrier [10]. By adding a trailer (powered from the main unit) a train is formed, 5 (1–2=2).

Several data of typical articulated vehicles are tabulated in Table 1.

The first train consisting of articulated like units able to operate individually was formed with Pavesi tractors [13]. The same 1–1=1–1 etc. concept is suggested by Stevens [10].

Other train concepts, that have been tried out are:

MARV	1 – 1 – 1 etc.
Porsche, Kässbohrer, LeTourneau	2=2=2 etc.
Renard	2=3=3=3
LeTourneau	3=2=2 etc.
Aldex-Sampson	3=3=3

As a curiosity it can be mentioned that off-the-road trains are not only formed of wheeled and tracked vehicles, but also of walking machines (87).

6. ADVANTAGES—DISADVANTAGES—PROBLEM AREAS

Under most off-the-road conditions it is desirable to keep the wheel loads as close to the normal load as possible. Then control is maintained and maximum traction is developed. Whether this goal can be reached depends on vehicle concept and suspension design.

A fairly common picture displayed in vehicle brochures shows a conventional

TABLE 1. EXAMPLES OF DIFFERENT CONFIGURATIONS

	GOER 8 T M 520	TASC	Flex-Trac	Gama Goat M 561	1¼ ton 6×6	MARV	Twister	VEXA 8×8	VEXA 10×10
Configuration	2 (1–1)	2 (1–1)	3 (2–1)	3 (2–1)	3 (1–2)	3 (1–1–1)	4 (2–2)	4 (1–2–1)	5 (2–3)
Payload lb.	16,000	2900	4000	2900	2500	1500/U.	N.A.	5000	5000
Weight, gross lb.	39,900	9300	11,100	10,260	7000	3500/U.	11,400 Curb	19,200	18,000
Engine HP	213	195	95	103	116	80/Unit	140/Unit	214	214
Length o.a. in.	385	202	167	226	197	86/Unit	194	342	292
Width in.	108	85	81	84	80	72	103	108	108
Cargo Area sq. ft.	136	48	N.A.	50	60	30/Unit	N.A. very small	108	108
Wheel base in.	235	135	112	80.7–84.8	74.5–62.5	102	46–60–46	N.A.	N.A.
Tread in.	86.8	69	67	72	68	60	87	N.A.	N.A.
Tires	18.00–33	14.00–20	10.00–20	11.00–18	11.00–20	11.00–20	14.00–18	48×31–16A	42×40–16A
Angle of Appr. + depart.	35–41°	60–50°	90°	62–45°	60°	45°	90°	90°	90°
Turning rad. ft.	27	18	N.A.	29	16.5	16	20	N.A.	N.A.
Steering	Artic.	Artic.	Ackerm. Skid	Ackerm. Fr. + Rear	Artic.	Artic.	Artic. + Ackerm.	Artic.	Artic.
Joint degree of Freedom	2	2	1	2	3	3	3	3	3
Yaw	±60				±35	±40	±22	N.A.	N.A.
Pitch Degrees		N.A.	±30	±40	±30	±25	+35, −27	±30	±30
Roll	±20			±30	±30	±35	±30	Unrestr.	Unrestr.

vehicle standing on uneven ground with all axles inclined in extreme and opposite positions. The purpose of this exhibition is to demonstrate the long wheel travel, or rather how good the vehicle can follow the ground contour. Not a word is said about the fact that the load on the wheels in rebound are extremely low, and the load on the wheels in bounce are extremely high. The type of suspension, of course, plays an important part in this consideration [88]. An articulated vehicle (with freedom in roll) in the same position has the advantage that the wheel loads are closer to normal, since the rolling motion is not restrained by spring action. There is a certain load transfer due to the inclination of the body, but this transfer is not great at 15°, particularly because the center of gravity is usually relatively low on articulated vehicles (the loading area is placed between the wheels, not above them). On conventional vehicles one wheel usually looses ground contact at axle inclinations greater than 15°. The other wheels then have to carry the whole load. On articulated vehicles this does not usually happen, since they have a roll freedom of ± 20–30°.

Freedom in pitch permits the articulated vehicle (with more than two axles) to conform even better to the terrain profile. Hence wheel loads are kept relatively uniform. Because of this, frame stresses are considerably smaller than on conventional solid frame vehicles. Pitch articulation greatly improves vertical obstacle crossing ability, particularly if active pitch control is used. It also simplifies a very difficult task, bank climbing on exiting from the water. Articulated steering makes amphibious vehicles more maneuverable in water. Jindra [89] has published a work on the obstacle performance of articulated wheeled vehicles of the type 3 (2–1). Elastic frame vehicles also conform to the terrain profile. The wheel loading, however, is not as uniform as on normal articulated vehicles, since the movements are restricted by spring action.

As mentioned in Section 4, articulation in yaw permits the use of large tires without the penalty of large cavities in the vehicle envelope. Not only the cavities, but also the universal joints at the steered wheels (all wheel drive) limit the turning radius of conventional vehicles. Articulated steering simplifies the mechanical drive to the wheels. A small turning radius is no problem (except that the joint makes the vehicle longer). Considerably better mobility is achieved if the possibility of using large tires is fully utilized. However, tire scrub, particularly in combination with maneuvering in tight spots on hard surfaces, definitely causes a problem for articulated steered vehicles with more than two axles.

The joint location is important on 4×4 vehicles. With the joint halfway between the axles the wheels track in a turn. For most soils and for maneuvering this is an advantage [90]. On muskeg it is not. A joint located halfway between the axles divides the loading area. This is a definite disadvantage. On cargo carrying 4×4 vehicles the joint is therefore located at or close to the front axle. The turning radius still can be kept small, but the vehicle sweeps a big area when making a sharp turn, see Fig. 23. The swept area is as small as possible when the wheels track. A wagon steered vehicle has stability problems, particularly when the units are standing perpendicular to each other. Even when the joint is located halfway between the axles, certain stability problems arise on a side slope or in turn. Where roll freedom is allowed, each individual unit must have adequate roll stability.

Several studies have been published on the steering and stability of articulated vehicles [83, 91–93], but such papers are rare, and much more work has to be done on this subject. One of these studies is purely theoretical. Apparently the authors are not familiar with a very interesting paper published by Adams [94] in 1958. Unfortunately the latter is not much cited. Besides showing the advantages of articulated steering it clearly shows the great disadvantages of skid steering. An effort was made by Adams to compare the traction and steering characteristics of 4-wheel drive vehicles of various steering and drive systems with conventional 2-wheel drive and crawler vehicles. In order to reduce parameters and variables a research vehicle was built, that could be adjusted or changed in any of at least 17 different combinations of drive, steering and traction. Tests were carried out on pavement, in loose ground and in mud. Low speed traction tests were made to determine the average ground speed, maximum drawbar pull and gross input h.p. while pulling straight ahead, in a moderate turn and in a sharp turn. As would be expected, the performance while pulling straight away was the same for all the wheeled systems (4×4). The effect of a turn on the average speed was approximately the same for the 4-wheel steered and the articulated steered vehicle. In a turn on loose ground the articulated steered vehicle developed more drawbar pull than the 4-wheel steered. Pulling a moderate load in a turn the frame steered vehicle required less gross h.p. On a side slope the articulated vehicle was less stable turning uphill and more stable than the conventional vehicle turing downhill. The frame steered vehicle matched the performance of the crawler vehicle pulling on *turns in mud.* The relatively poor performance of a tracked non-articulated vehicle in a turn has often been referred to by Bekker and Nuttall.

During the above mentioned mud tests, it was observed that the articulated steered vehicle was capable of traversing mud better than either the 4-wheel steered or skid steered versions. The ability to "duck-walk" has been observed on many other articulated vehicles. When the vehicle gets immobilized, the steering is actuated in order to put one or more wheels into new traction spots. The steering is then actuated in the opposite direction while power is applied to the wheels. A theoretical investigation of the problem has not yet been published. Duck-walking can in some ways be compared with the inching described in Section 4 and the "thrust-stride-system" [95]. Similar to the inching and thrust-stride-system some of the wheels should probably be braked when duck-walking. Whether the procedure is successful or not depends largely on the properties of the soil, such as whether it is homogeneous or not and on the depth of the hardpan. Another work [96] on this subject was presented in Essen last summer. Drawbar and self-propelled tests with an articulated forestry vehicle in a wet heavy clay soil were described. The comment to this paper is that duck-walking is a means to free a nearly immobilized vehicle, not to increase traction. It is a question of "go or no-go". By doing so the steering should be actuated carefully in order not to destroy fresh soil structure. It is no use wiggling the vehicle rapidly back and forth. This results only in additional sinkage. It is obvious that drawbar pull under test conditions using straight line pull is superior to that achieved with the use of articulated steering action, since traction is lost due to steering movements. Further the angle of pull results in a smaller drawbar pull value. The same would apply to other steering systems. No comparison is possible, however, since articulated steering was the only system investigated.

A definite disadvantage of articulated vehicles is that for the same load carrying capacity they usually are larger and heavier than conventional vehicles with Ackermann steering. The joint usually makes the vehicle longer if the same cargo area is wanted.

In Fig. 31 the payload in relationship to curb weight of different vehicle concepts is shown. The curve for articulated 4×4 vehicles is nearly identical to the one for 6×6 conventional vehicles of the old World War II concept (M 35, M 54, M 125).

Modern conventional vehicles have a considerably better ratio of payload to curb weight. In the Stevens report [10] a size comparison of different weight classes is given. The difference between articulated and conventional vehicles become more marked as the size increases. One of the reasons for this is that much larger tires are used on the articulated vehicles.

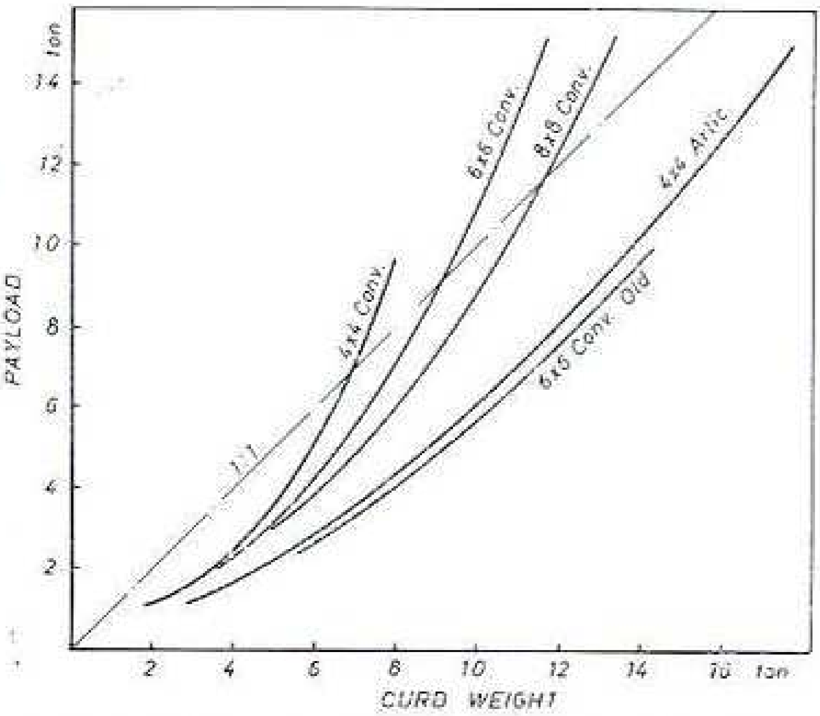

FIG. 31. Payload vs. curb weight of conventional and articulated off-the-road vehicles.

The GOER vehicles have been much criticized. The original concept of the GOERs was that they should be extra high mobility vehicles with performance to match that of tanks. This was to be achieved by the use of a articulated four-wheel layout with large diameter, low pressure tires, all-wheel drive, high power to weight ratio and light-weight design. However, the curb weight went over its design target by more than 50 per cent, so that the axle loading is over the allowable limit. Further, in comparison to the rest of the new U.S. Army truck family, the tires of the 8-ton GOER are somewhat overloaded even in sandy soils [6]. The 16-ton GOER has even higher axle loads, about double the permitted limit. Its weight and excessive width will require special permits for any movement over the road [24]. Even though the ground clearance as such is high, it is not so in relation to the long wheelbase. The large GOER therefore often gets hung up on its belly traversing ridges. The GOERs are not sprung. Due to the lack of a damped suspension system, their ride is poor, even on the road. The bumpy ride limits the speed both on as well as off-the-road. However, there is no reason (except the cost) why an articulated vehicle should not have a suspension.

Only a terrain–vehicle system analysis and evaluation can help decide which vehicle concept is the best for the given conditions. In such an analysis all parameters and variables like mission profile, operational requirements, physical environment, vehicle configuration, vehicle performance parameters and cost effectiveness have to be considered. Such evaluation procedures have been initiated and thoroughly described by Bekker [3, 97].

Trains have their own problem areas. One of the main advantages of the train concept is mentioned in Section 2, namely that the unit pressure under such a vehicle remains constant and equal to that of a single unit, irrespective of the total train capacity. This consideration holds for the case that the train is moving over relatively smooth ground. However, in difficult terrain the middle units have to carry considerably more than their normal share (crossing ridges and gullies). Hence in such a terrain the train length is limited. Another reason to limit train length is stated by Liston [98]. The occurrence of obstacles drastically cuts train speed. In order to negotiate an obstacle it is usually necessary to reduce vehicle speed. If a very long train is moving in difficult terrain, one unit is in contact with an obstacle all the time. Another vehicle could increase speed between obstacles, but the train cannot do so. Liston presents a formula for the average speed of a train. Parameters are the number and length of units, distance between obstacles etc. Further he states: "Experience has shown that an articulated vehicle can operate at a higher speed over rough terrain than can a conventional vehicle. However, as the number of units is increased, the gain is rapidly lost, and a rule of the thumb is that a vehicle having more than four units represents the limit to the usefulness of the articulation principle." This is confirmed by the Stevens report [10] in that all trains suggested have four units. Another factor not mentioned by Liston is that the driver cannot observe the obstacle crossing of the rear units. Hence he has to be careful and cut speed even more. Jack-knifing between units and lateral stability constitutes other problem areas [10]. This does not mean that the train concept is all bad. Long trains can definitely be used for tranportation over relatively smooth ground like deserts, plains etc. They would also fit the requirements of underdeveloped nations with inadequate railroads and poor road networks. For military applications they are too vulnerable. Military type trains would have to be short (4–5 units), and they should be formed of like units able to operate completely on their own.

7. CONCLUSION

An attempt has been made to give a relatively complete picture of the present knowledge on articulated, wheeled off-the-road vehicles. Further an effort has been made to deal with certain misconceptions and prejudices in the area of such vehicles.

To the specialist in the field this paper might seem to contain several trivialities. Detailed definitions of the properties of articulated, wheeled vehicles were needed, however, since they are not common knowledge and often misunderstood.

A few of the authors mentioned in the references are apparently not familiar with previous work done by others. Even though close to a hundred references are given in this paper, other important studies, particularly military reports not known to the author, might have been printed and or published. In this case he asks for indulgence.

The historical review has proven that there has been a continuous development of articulated wheeled vehicles, even though the commercial value of some of them has been rather unimportant. However, there has been no "big sleep" of over 30 years as with the development of articulated tracked vehicles. Where Pavesi left, LeTourneau took over. All aspects of articulated vehicles could not be discussed here. That would be beyond the scope of this paper.

There is no doubt that articulated, wheeled-off-the-road vehicles will be even more important in the future, than they are today. With some exceptions they have demonstrated their capabilites and usefulness. Their advantages as well as their disadvantages have been outlined in this paper. Where high mobility is wanted, the articulation principle has to be taken into serious consideration. Above a certain ratio of wheel diameter to vehicle width this principle represents the only sensible solution. However, a terrain–vehicle analysis is in most cases needed to help decide upon the right concept for a given job.

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