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HISTORY OF WHEELS FOR OFF-ROAD TRANSPORT*

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Fire may have been man's greatest discovery but the wheel must rank as his greatest invention. It is basic to many of the machines conceived by man, but of all its possible applications perhaps the first and most significant is that of transportation. Wheels have played an important role in the spread of civilization, in the rise and fall of nations, and in the development of industry, commerce and agriculture. While there are people in the world today whose daily affairs are little influenced by the presence of wheels for transportation, their status is not envied. It is possible that in the future, as technological developments proceed, the wheel may to some extent be replaced by another land-transport mechanism, but its inherent simplicity and efficiency suggest that it will be useful for a long time to come.

The chronology of the development of off-road wheeled vehicles is outlined in Table 1. The listings are shown under three headings that encompass the principal factors: vehicle mechanics, power source and terrain surface.

To most people the wheel is so commonplace that it is difficult to regard it as an invention. It is simple in appearance and concept and it could be supposed that the wheel should have been discovered independently by many people in many parts of the world. There also is supposition that the wheel was the natural evolution of the practice of placing log rollers under heavy loads to be dragged over land. Neither appears to have been the case, however. The best archaeological evidence indicates that the wheel emerged from the mind of an early genius in essentially wheel-like form.‡ The location was Sumer in ancient Mesopotamia and the time was about 3500 BC. The first wheels of record were solid-disk wheels. Three or four wooden planks were laid edge to edge and held together by transverse battens, and from this was cut the circular disk that formed the wheel. A hole was cut in the center plank to admit the axle (Fig. 1). With the advance of time this particular kind of wheel has been found at increasing distances from Sumer. This occurrence forms the basis for the contention that the wheel was truly a unique invention.

It is of interest to note in this relation that the American Indians (among other primitive cultures far removed from Sumer) never did develop the wheel. They had sleds, travois, bow drills and round balls, but these did not lead to the wheel. It is evident that something more than just the presence of certain circumstances is needed to spark invention.

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‡If there was a roller stage it must of necessity have been brief for the roller is not a very useful device unless there is a very good track for it.

TABLE I. CHRONOLOGY OF THE DEVELOPMENT OF OFF-ROAD WHEELED VEHICLES

Date	Wheel/Vehicle	Power	Terrain/Road
BC 3500	Basic wheel		
3000		Oxen	Cart paths
2500	Metal tires	Onagers	
2000	Spoked wheels	Horses	
1500	Chariots		
1000			Primitive roads
			Stone slab roads
		HORSEMEN	
500	Cargo wagons		
	Wagon steer		
0	Roller bearings		
AD 1450		Concept of powered wheels	
1500			Drainage & surfacing
1600	Spring suspensions		
1700			
	Powered wheels	Steam engine	
1800	Commercial vehicles	Reliable steam engines	Railroad
	Boydell wheel	Gasoline engine	Load limit laws
	Large wheels	Diesel engine	McAdam & Telford
1900	Pneumatic tyres	Electric power	Traction aids
1900	Pneumatic tires	Gasoline engine	Asphalt and PCC roads
	Four wheel drive		Soil measurements
1910			
1920			Road building
	Low pressure tires		Sand mobility tests
1930	Improved suspension	V-8 engines	Theo. analysis of roads
	Very large diam.		Wheeled earthmoves
1940			
	Radial tires		
1950			Terrain measurements
	Very wide tires		
1960	Offroad suspensions	Turbines	
1970			
			Terrain analysis
1980			

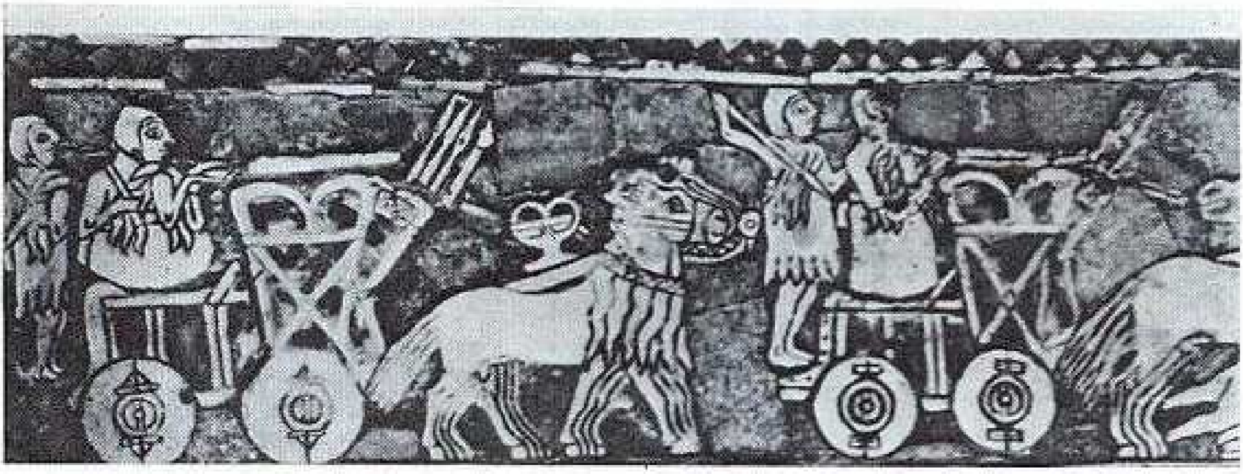

FIG. 1. Early four-wheeled war chariots with solid disc wheels, *ca.* 3000 BC [1].

The most obvious need for wheeled vehicles in early civilization was to carry heavy loads, particularly when the distances involved were taxing of human strength. However, then as now, a fine set of wheels was a status symbol and they were very early associated with royalty. Wheeled vehicles belonging to chiefs and kings were frequently portrayed on early wall paintings and often wagons actually were buried with their royal owners in their tombs. It is chiefly from vehicles thus preserved that knowledge of the very early wheel forms has been obtained. Of the wheeled vehicles used in agriculture and commerce, much less is known, for even when the illustrative arts were well advanced there was not much interest in portraying these prosaic forms.

The earliest wheeled conveyances seem to have been four-wheeled carts. Interestingly, there does not seem to have been any provision for steering. Probably the wheels fitted so loosely on their axles that lateral forces by the animals pulling the cart could cause it to change direction.

The principal impetus to the development of more refined forms of the wheel in ancient times was warfare. Fast-moving and maneuverable chariotry became a potent factor in military campaigns, and if an empire was to prosper it had to be militarily strong. Under the constraints of whatever tactical doctrine was then in vogue, the chariot-makers had to provide wheels and vehicles that were strong enough to carry the requisite men and weapons, durable enough to withstand the punishment of long campaigns over roadless terrains, and light and agile enough to outmaneuver the foe. These requirements still persist today of course, and always will. While there is the belief on the part of many that in the military's efforts to fulfill its requirements adaptation plays a much greater role than innovation, there is no doubt that military incentives have accelerated the rate at which ideas are put into use.

The first source of power for moving wheeled vehicles probably was a pair of oxen. The archaeological evidence indicates that oxen had early been made man's servants and that it soon became customary to use two yoked together to pull plows or drag sledges. It was natural, therefore, that the same motive force should be applied to the first wheeled vehicles.

The pair of oxen probably represented more than adequate power for the uses of the first wagons, and for ordinary transport jobs they have remained adequate in many regions of the world. But man, then as now, wants and strives for a little more speed and is willing to pay for it. The ancient Sumerian chief was no exception. Next to oxen the only animals available to him were the rather small Middle Eastern donkeys called onagers. The onager was significantly more fleet of foot than the ox but possessed only a fraction as much power. The techniques for hitching teams to carts and chariots were satisfactory for the ox but utilized only part of the little power the onager possessed. As early as 3000 BC, Sumerian chariots were propelled by four onagers abreast, evidently the beginning of the horsepower race. However, in addition to increasing the number of animals there was a distinct trend toward lightening the chariot to its bare essentials to minimize the power requirements. Among other things the two-wheeled cart with the pulling animal also providing the fore and aft balance came into use.

Rather suddenly in the records of time, along about 2000 BC, the horse appears, and almost concurrently the spoked wheel (Fig. 2). The one development provided a marked leap forward in power and the other in lightness and efficiency. The result

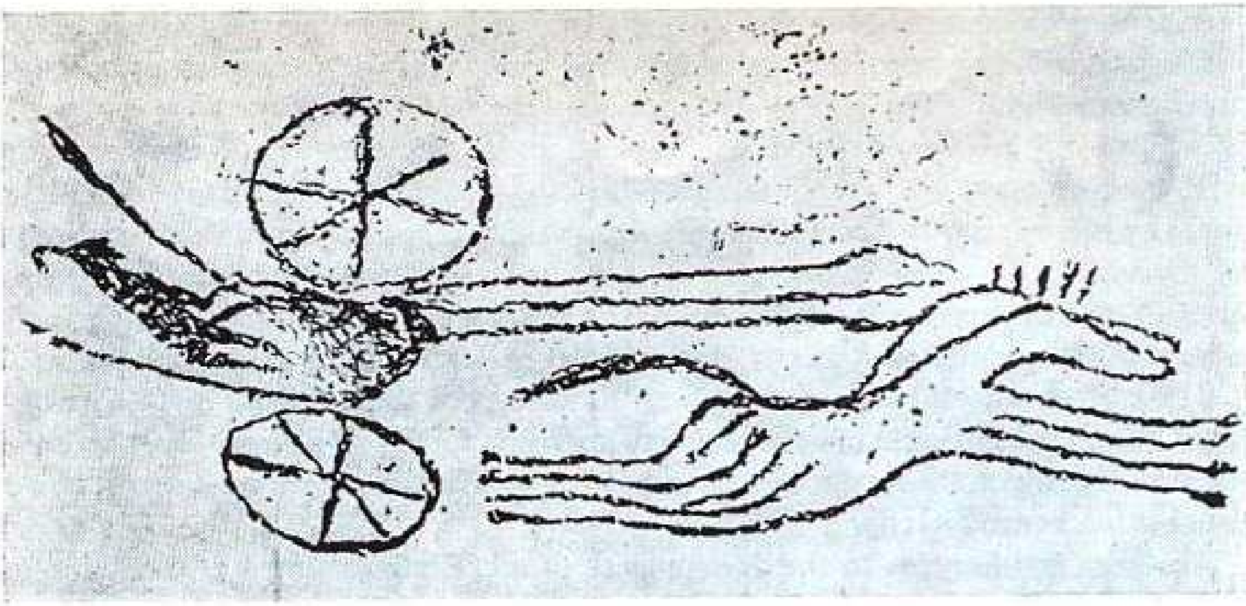

FIG. 2. Cave paintings of horse-drawn chariot with spoked wheels, *ca.* 2000 BC [1].

was speed and maneuverability beyond anything previously available but unfortunately the harnessing technique was still inefficient in that it tended to choke a horse that pulled hard. When more horses were added they were placed alongside each other, another not very efficient arrangement.

One factor above all others has influenced the development and application of wheels for transportation: the surface over which the wheel must move. If the surface is soft and yielding, a relatively great force is required to cause the wheel to roll. Likewise, irregularities in the contour of the surface require greater force to be applied to the wheel, and, in addition, they create a rough and jolting ride. Indeed, surface conditions may well have provided the inspiration that produced the wheel instead of an elegant roller.

At that point the inventor of the wheel may have realized that a roller that was narrow would miss many bumps in its path, and that it could be made to roll on surfaces where wider rollers skidded. This new roller, of course, was the wheel. From this stage the wheel developed through trial and experience, evolving a size, shape, and construction that was narrow enough to avoid the bumps and to have small rolling resistance in soft soils, but not so narrow that it was easily broken or that it cut deeply into the soil. The wheel had to be small enough so it could be constructed from the materials at hand and also large enough to be reasonably efficient in crossing ridges, ditches and soft-soil areas.

The earliest wheels known were 50–100 cm in diameter and perhaps 10–15 cm wide. They were roughly cut from wooden planks and were relatively massive. The spoked wheels developed later were about the same size at first.

Spoked wheels continued to be refined; they became very much lighter in weight than before and apparently were still reasonably strong. Undoubtedly, again the desire to obtain more speed was the motivation. With wheels such as these, chariotry reached a zenith, both in terms of its military effectiveness and in the quality of the product, in the Egyptian and Hittite vehicles of about 1500–1000 BC. Records of a battle in the year 1286 BC between these two peoples state that the Hittites alone had

3500 chariots—and the Egyptians probably had at least that many. The Egyptian chariots of that time were so gracefully light that there must be serious doubt about their durability.

Most of the early wheels were constructed of wood, probably because wood was reasonably strong, light, and could be worked with the tools available in most cultures. Wood has the discouraging characteristic of being easily abraded and worn by passage over sharp stones or even on hard-packed soil, so even the earliest wheels seem to have had some sort of wearing surface (a tire). Copper was the first metal to be used extensively and was a natural for providing protection for the wooden wheel. There is some evidence that copper nails, closely spaced, formed the wearing surface for some wheels. Soon, however, copper bands were fitted to the outer wheel surface to form a true tire. The wheels of the Egyptian chariots were covered with leather tires which had the advantage of light weight, apparently an important consideration in their chariotry, at the expense of some durability.

Besides being much lighter, chariot wheels at this time had assumed a significantly different shape. They were not much, if any, larger in diameter but were relatively very narrow. A copper-covered chariot wheel of Susa that dates back to about 2000 BC is only 3 cm wide but has a diameter of 105 cm. These dimensions yield a diameter to width ratio of 35, which is very high although it is almost exactly matched by the rear wheels of the buggies and light wagons common in the western US as late as the turn of this century. For example a buckboard wagon which was actually measured was found to have a wheel with a diameter of 42 inches (105.7 cm) and a width of $1\frac{1}{8}$ inches (2.86 cm) for a ratio of about 37 : 1.

At this point in history written records begin to add their illumination to this study. Some of these date back to 1000 BC and very clearly show that the major topics of concern for terrain-vehicle systems had already been identified. The mechanics of the vehicle and the terrain condition definitely made some difference.

The influence of the terrain on the effectiveness and usefulness of wheeled vehicles has been recognized in the account of historical military engagements. There is, for example, the cryptic passage in the Bible (Judges I, verse 19, *ca.* 1100 BC) that states the case with magnificent understatement: "And the Lord was with Judah and he drove out the inhabitants of the mountain but could not drive out the inhabitants of the valley because they had chariots of iron". There are many implications in these words. Not only is there the recognition that the chariots were a decisive factor in military success at that time but that the nature of the terrain also was a vital determinant. Judah's men, tactics, and weapons were probably no different on one terrain than another but his results were not the same. On terrain that allowed the chariots to be a mobile striking force he could not prevail, but in the mountains the chariots probably were effectively immobilized and other factors decreed the outcome. O course it was not always rough, rocky, and declivitous terrain that held up the chariots In 401 BC Xenophon, in describing Cyrus's expedition and the defeat of the Greeks often mentioned chariots stuck in the mud, and the Assyrian Tiglath-Pileser I referred to "difficult country where my chariots could not pass".

There is no doubt that a very early realization was that some effort in preparing a way for the wheel was well rewarded in decreased pulling effort and increased smoothness of passage. It is no coincidence that the tread of wheeled vehicles is very close to that of the paths trodden by paired draft animals. The animals' hooves packed the soil to create a firmer surface and tended to smooth some of the irregularities. The passage of the wheels themselves also contributed to the path.

When confronted with the restrictions that the terrain places on the mobility of his vehicles, man has two choices: he can avoid the terrain altogether or he can try to improve his ability to travel. In the latter case he can either create better vehicles or he can change the nature of the terrain. From earliest times the easiest way out and, perhaps, in the minds of the men facing the problem, the only way out, has been to alter the nature of the terrain—to build a road.

Tiglath-Pileser I, writing about a military campaign in about 1100 BC, says: "I took my chariots and my warriors and over the steep mountains and then their wearisome paths I hewed a way with pickaxes of bronze and I made a passable road for my chariots and my troops". Cyrus the Younger, 401 BC, decreed that soldiers not able to fight should be equipped with axes, mattocks and shovels, and should "advance by squads in front of the wagons so that if there be road making to be done you may get to work at once".

In the foregoing passages it is of interest to note that Pileser in 1100 BC refers to his chariots while Cyrus in 400 BC talks about roads for his wagons. A major development occurred that provides the reason. Mounted horsemen began to be used in war during this time and they rendered the chariot obsolete.

The last use of chariots in battle was by the Celts in Britain at about the time of Christ. By 100 AD chariots were effectively gone, even in remote Britain, and the development of wheeled vehicles was given over to agriculture and commerce. Instead of speed being the primary requisite as was the case for military use, there was now the primary need to transport heavy loads, with speed a secondary factor. Gradually, wagon wheels became larger, stronger and heavier, as increasingly heavy loads were transported. Roman wagons were well constructed and had essentially the same form as farm wagons of the 19th C AD. Correspondingly there came greater demand for the usefulness of prepared roadways. The Romans and some others constructed elaborate roads, stabilizing the soil beneath and paving the surface with stones. Road building did not develop much after the Romans faded. Even those roads they built fell into disrepair and some disappeared. During the mid-1500s there was a revival of interest in better road building and new techniques of building the roadway and of draining away water were devised.

It is not an easy thing to provide a good road, and in many respects it is even harder to keep one in good condition. There is a kind of entropy in the interaction of vehicle and surface that causes the surface to degenerate to a state that alternates from rough and uneven to soft and bottomless. The one is uncomfortable and the other exhausting. The 16th C road builder Guido Toglietta aptly referred to the wheel as the destroyer and the road as the resister.

Very little change in either off-road or on-road transportation took place for many years. Even though the Renaissance thinkers recognized that wheels needed some better source of power, their innovations were not successful. They are interesting though. Valturio in 1472 drew a design for a vehicle that was to be powered by the wind (Fig. 3). The rotary power developed by several large windmills was to be transmitted through a primitive set of gears to cause the wheels of the vehicle to turn.

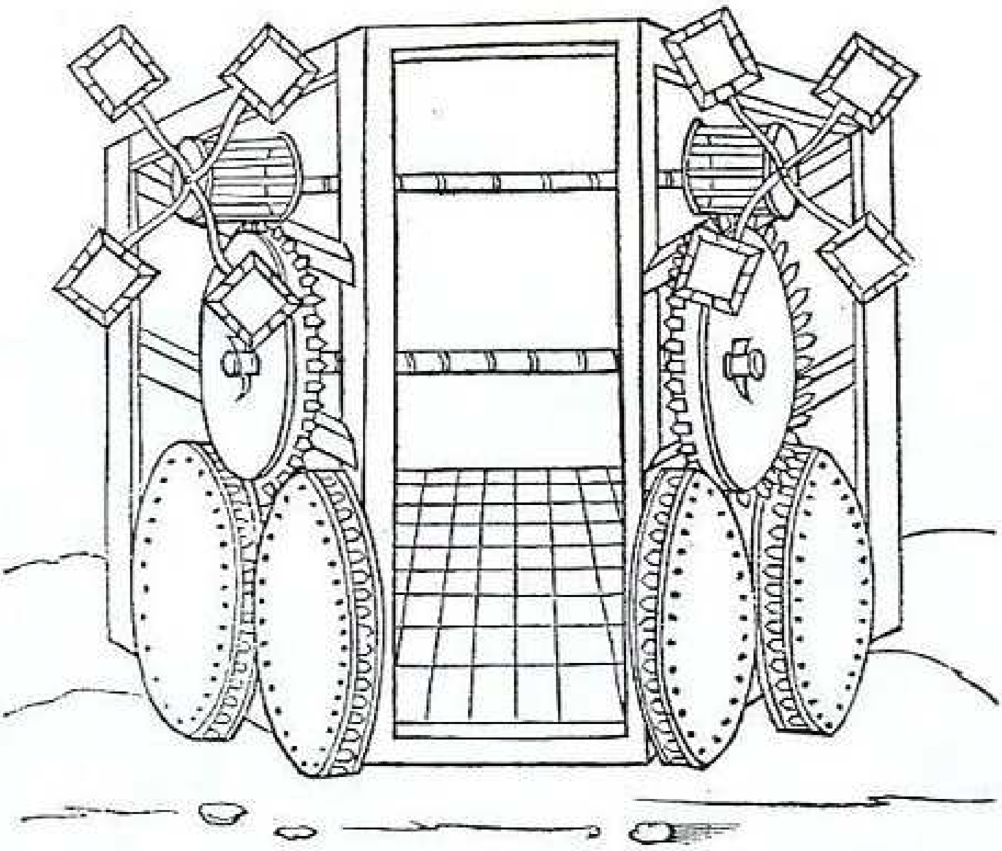

FIG. 3. Valturo's concept of a wind-powered vehicle, 1472 [2].

Ten years later Leonardo da Vinci produced sketches of a covered chariot to be used as an armored vehicle of war. He envisioned a troop of men inside lustily turning hand cranks geared to the wheels to develop propelling power. He also sketched a vehicle powered by a spring. In the late 1500s Simon Stevin tried a different approach to the use of wind for power. He built a four-wheeled wagon rigged with large square sails. It was reported that on hard beach sand with a favorable breeze the vehicle achieved a speed of about 40 mph. Sir Isaac Newton entered the contest by suggesting that steam jets be used as a kind of rocket power. He was really ahead of his time.

There were some developments in the way of suspensions. Rough, bumpy roadways all but precluded the use of wagons for carrying people. Various ways of supporting the passenger box were developed using leather straps and chains. Around the year 1500, simple curved-leaf metal springs were employed. The advantages gained led to further refinements so that, with the concurrent improved roadways, passenger travel became widely accepted.

The next major development was the successful use of the steam engine by a number of inventive people. By the middle 1700s the industrial revolution was underway in England. Newcomen in 1705 used a type of steam power in water pumps. About 60 years later in 1769 James Watt patented an engine with a separate condenser that represented such a major improvement in the use of steam that he is usually credited with being the inventor of steam engines. However, two lesser-knowns deserve mention at this point.

It was in 1769 also that the first actual attempt was made to cause steam to propel a vehicle. In this year a steam-powered wagon was built by Captain N. J. Cugnot, a

French military engineer, who hoped to use it as a prime mover for artillery (Fig. 4). He used two crude single-acting Newcomen-type steam engines as power. This vehicle had a brief but exciting journey on the streets of Paris that ended ignominiously when Cugnot's steering arrangement failed to function to the required degree. He landed in jail and thus chalked up another first. The experience apparently discouraged him for there is no further record of his efforts.

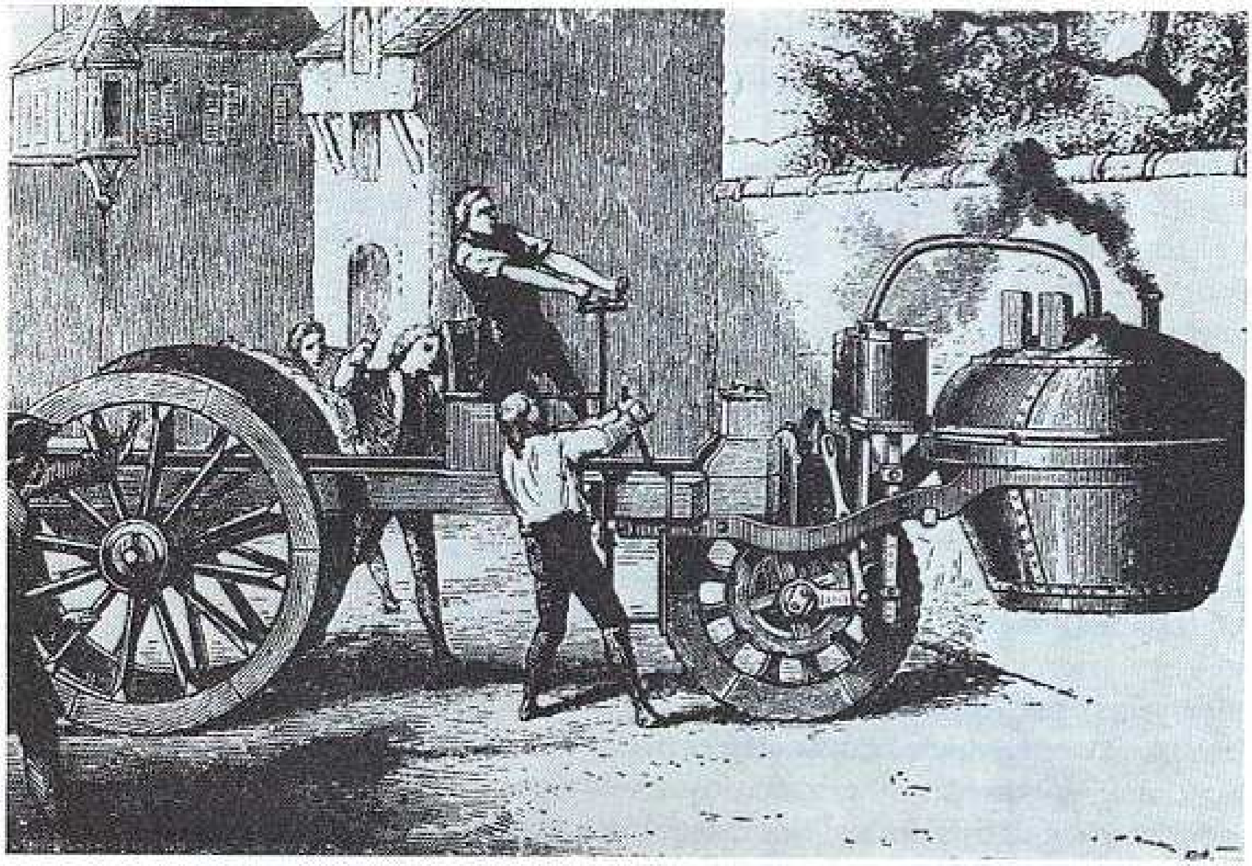

FIG. 4. Cugnot's steam-powered vehicle, 1769.

The next significant improvement came in 1801 when an English coal mine engineer, Richard Trevithick, built and ran a steam carriage for passengers. He made some improvements in a Watt-type steam engine that helped reduce its weight. His first model tipped over and burned but he built another that he operated successfully in London in 1803. His motivation for both seems to have been primarily to provide a horseless carriage. The concept of using the steam engine to pull loads of coal soon attracted him, and since coal wagons rode on rails it was natural that the pulling engine should do so also. From this point on, he and many others in England built better and better locomotives and the steam railroad advanced rapidly.

The development of steam carriages for road travel continued, and by 1813 several enterprising Englishmen were offering regular passenger service between points as much as 10 miles apart at speeds approaching 10 miles per hour. However vested interests taxed these steamers so heavily (road tolls as much as 12 times those for horse-drawn carriages) that progress was slowed. Then in 1865 the Red Flag Act was passed that required steam carriages to have a crew of two, travel at no more than 4 miles per hour, and have a flagman go ahead to give warning. These restrictions in

England, then the world's most industrialized nation, turned most of the innovators of that country toward travel on rails.

One of the factors that weighed against the use of road steam carriages was the tendency for the roads to deteriorate under their great weight. To counter this effect, Boydell in 1846 patented a wheel that placed down large boards for footings under the wheels as they rotated. In one sense it was as much a track device as a wheel. A vehicle with these wheels was built and used primarily as a traction engine. It played a part in the Crimean War in 1856 as a means of pulling supply wagons over difficult terrain. Somewhat similar wheel designs were used in agricultural tractors as late as the early 1900s. However, during this interval the endless track had found favor and Boydell's idea was never used extensively.

The problem of supporting the heavy steam tractors and carriages was also attacked by the road builders. The load-carrying ability and relative permanence of rock and gravel bases were recognized. Engineers, such as Telford and MacAdam, devised ways of constructing more durable roads. MacAdam's approach of compacting a dense layer of graded rock, gravel and sand has survived and, with the addition some years later of asphaltic binders, is well known today.

The laws that held back the development of steam vehicles for road travel were not particularly restrictive insofar as agricultural applications were concerned. The steam engine as a replacement for the horse on the farm presented an attractive potential, and many important and unique developments were begun in the agricultural context. In the late 1800s the opening of the vast prairies of the western United States and Canada to agriculture saw the steam tractor play an important role. Size was not limited by existing roads and the job to be done was great. A whole host of ingenious practical mechanics and tinkerers turned their imagination and initiative to developing even better prime movers for farming. As a consequence some rather startling machines were built around the turn of the century as inventors responded to particular needs. Some steam tractors of the 1880s and 1890s had driving wheels 8, 10 and even 14 feet in diameter. The widths of the wheels appeared to have no restriction other than what the inventor felt was required to do the job. One manufacturer, faced with the need to operate a very heavy steam tractor on the soft peat soils of the Sacramento Valley of California, produced a tractor with two rear driving wheels each 9 feet in diameter and 15 feet wide (Fig. 5). This tractor also had a feature not common even in operations in relatively soft farm soils: the basic steel wheel was fitted with wooden tires. This switch from the usual practice reflected a lack of need for a very durable wearing surface and presumably not too much concern for maximum tractive effort.

Most of the agricultural tractors show that the problem of transmitting power from the drive wheels to the soil arose early. Smooth steel or wooden wheels slipped readily and seriously restricted the work that could be done by a tractor. Simple cross-bar lugs were the first and most common response to the problem of wheel slip. By the 1890s these bar lugs were exhibited in several patterns—straight, diagonal and chevron as they are today. The diagonal and chevron patterns were intended to provide a tendency for the soil to be extruded outward from under the wheels, thereby assuring a good grip on the soil. However, in wet, sticky soil the lugs filled with soil and the wheels became essentially smooth. Pointed chisel-like lugs were used on some wheels. In fact in 1868 Redmon's steam plow boasted of drive wheels fitted with lugs that

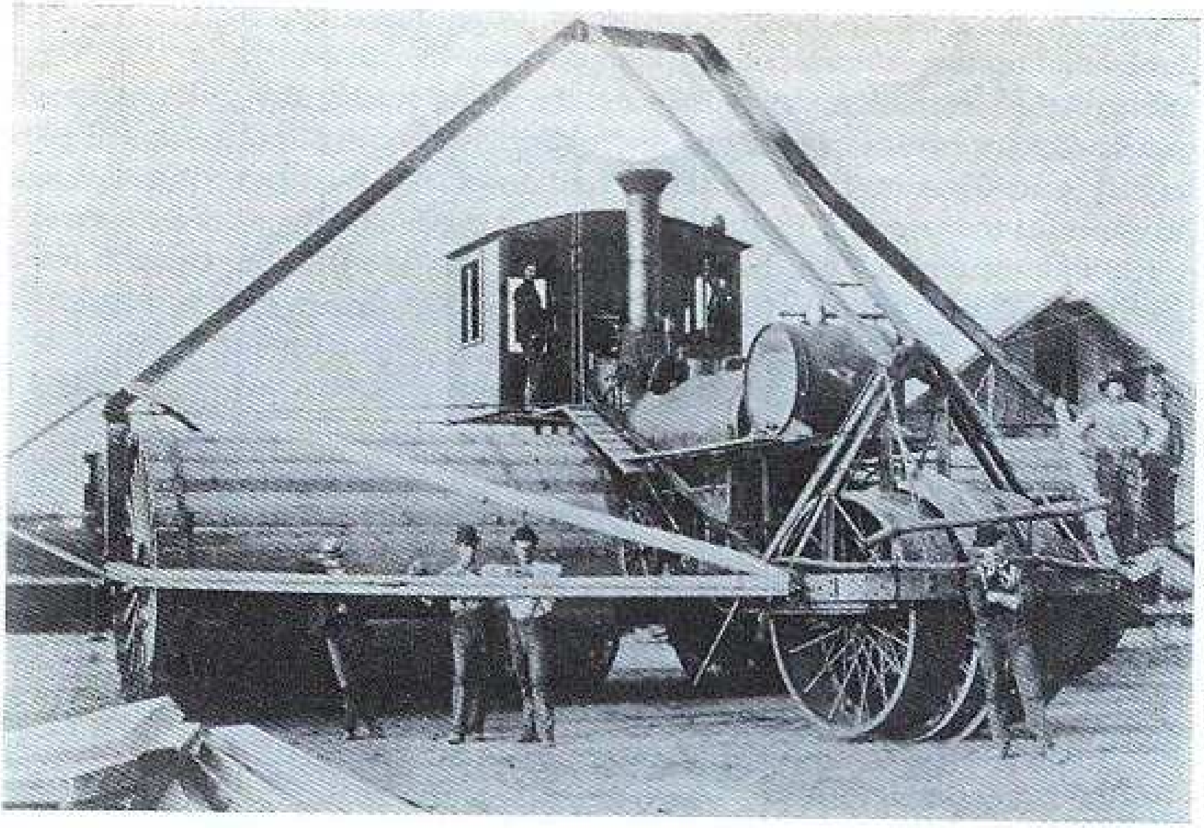

FIG. 5. Best Mfg. Co. adapted a standard design to run on soft soils in 1900 [3].

were forced automatically through openings in the portion of the wheel in contact with the ground and were retracted in the opposite portion of the wheel.

While the agricultural interests were developing and refining steam power, two other important developments were taking place: the internal combustion engine and the pneumatic tire. The idea of controlling an internal explosion to create a power plant had arisen in the minds of several inventors. Various fuels were tried, including gunpowder. Apparently the first successful internal combustion engine was built by a Frenchman, Lenoir, in 1860. He used an illuminating gas for fuel and controlled its flow with an arrangement of sliding valves. There is also some evidence that he used his invention to propel a carriage. In 1864 an Austrian, Siegfried Marcus, also made and ran a self-propelled vehicle with an internal combustion engine.

However, so mamy improvements of the internal combustion engine were made by Nikolaus Otto that he is usually thought of as its primary creator. During the years 1874–1900 he transformed the basic idea into a practical and reasonably reliable bit of machinery. Similarly, two other Germans, Gottfried Daimler and Karl Benz, were pioneers in the application of the internal combustion engine to vehicular use.

The first automobiles looked very much like the horse-drawn vehicles of the day—and they gave about the same rough ride. The great interest in the automobile stimulated the improvement of another contemporary innovation, the pneumatic tire. Again, as is so often the case, the person who first conceived and produced a rudimentary example of an invention is largely forgotten. The second person on the scene frequently seems to reap most of the credit. A Mr. R. W. Thompson obtained British patent No. 10990 in 1845 for an elastic air-filled belt of rubberized fabric and leather to be placed around the wheel. But he was ahead of the state of rubber technology so his product was unreliable. Furthermore, there was no great demand for his invention in 1845. In 1888 Dunlop reinvented the tire, unaware of Thompson's patents. He made major improvements in the tire structure and is usually credited with the invention of pneumatic tires. Thompson was ahead of his time but Dunlop's work coincided with the need to provided a better wheel for the fledgling automobile.

By the turn of this century the final major component of today's land transport systems appeared. Road building for slow-moving wagons and carriages was sometimes a problem but the demands for smoothness and all-weather serviceability were not very great. The automobile changed that, and roads proved to be a major limitation to travel by automobiles. Soon roads were being surfaced with asphalt and portland cement concretes. During the first half of the 20th C the gasoline engine, the pneumatic tire and the all-weather road grew up together. One, by advancing, stimulated developments in the others, so that today there exists a very complex high-speed road transportation network.

Desire for a tactical advantage has often led innovative military men to be in the forefront of the application of new technology to a practical end. This has also been the case in the emergence of mechanized travel. Steam tractors were used in Crimea as prime movers for transport systems and again during the Boer War in the 1890s. Also during the Boer War steam tractors were armored, and it was proposed, although not implemented, that some be fitted with guns to form moving fortresses. In 1899 a Major Davidson of the Illinois National Guard mounted a machine gun on an automobile and thus created the first motorized weapons carrier (Fig. 6). All of these experiments involved adaptation of existing vehicles to a military application. Unfortunately there also are military men—often of high rank—who are unable to accept and support new technologies. None of these early efforts ever resulted in new equipment or new tactics.

An important step was taken by Daimler in 1913 to enhance off-road travel capability. The company built an armored car for combat and equipped it with four-wheel drive. Steel-wheeled farm tractors with all-wheel drive also were developed at about the same time. This set a pattern that has distinguished most off-road vehicles from those intended for on-road use. As with everything there are exceptions, of course; some recent racing cars have had four-wheel drive and many off-road racers have two-wheel drive. In the latter case, however, soft soils are usually not a race factor.

During the early 1900s the initial attempts were made to analyze the interactions of wheels and the media on which they moved. Bernstein was interested in off-road problems, while Goldbeck analyzed the requirements for roads and surfaces and Atterberg sought useful physical soil measurements. The importance of roads to the development of large scale transport helped stimulate further analysis of road and surface mechanics, but not much attention was paid to off-road mechanics until much later in this century.

During World War I wheeled vehicles were used pretty much in their civil form (the Paris taxicabs are famous), and most of the innovations went into the development of the armored tracked vehicle—the tank. World War I off-road wheeled vehicles were simply on-road vehicles used in roles for which they were ill-adapted. They emerged from the War little changed by the experience (Fig. 7).

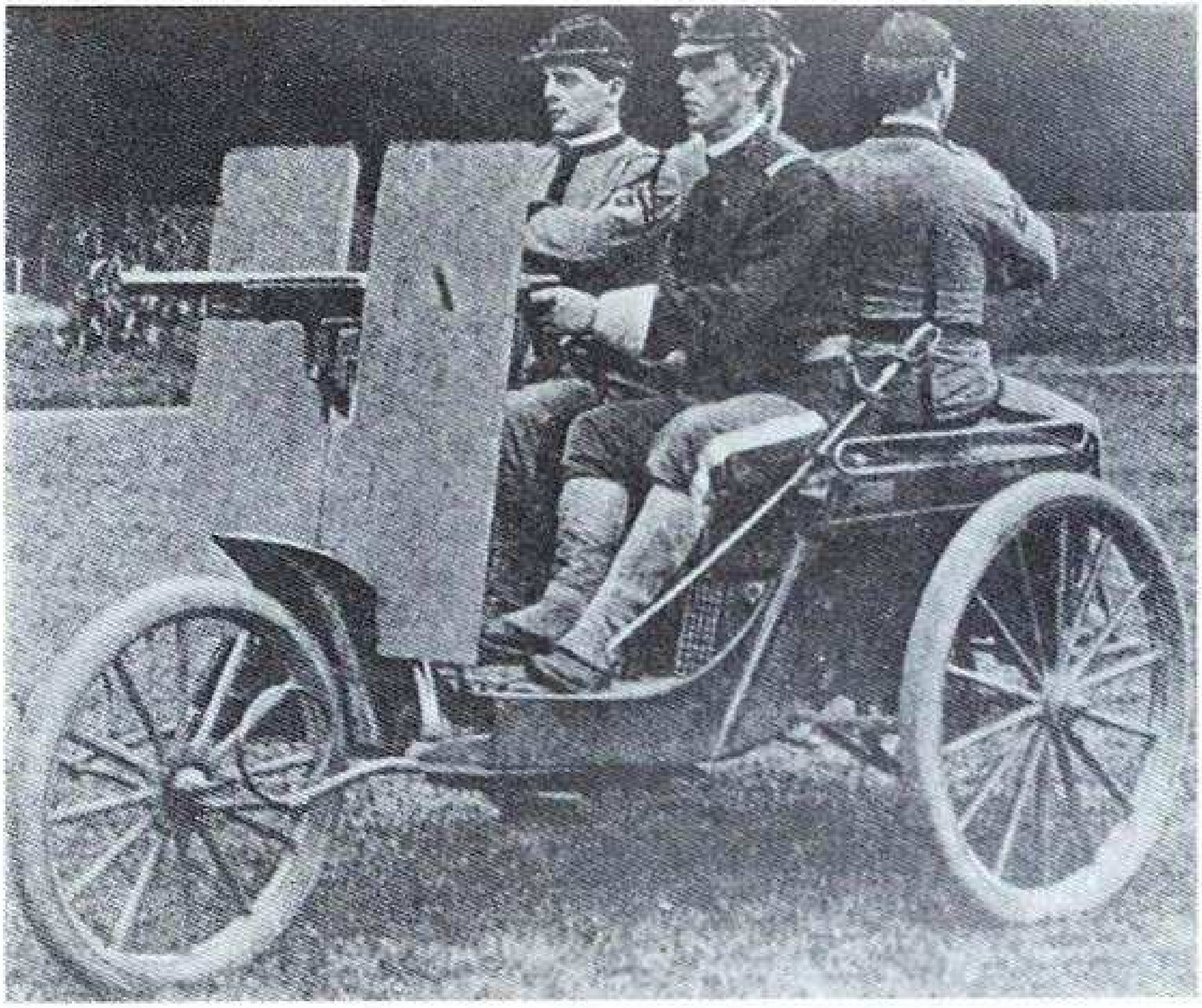

FIG. 6. Major Davidson's Duryea scout car, 1899 [4].

After the Great War, adventurers used the motor car to visit some remote parts of the world. They drove all over the continents and crisscrossed the Sahara, the Gobi and other great deserts of the world. There were no roads so they had to operate vehicles intended for on-road use in whatever conditions they encountered. A major lesson learned was that the tires were a critical factor in the vehicle's ability to travel. This was not only in terms of reliability but in actual go/no-go performance. As early as 1926 it was recognized that travel in sand was improved by lowering inflation pressures and by using larger tires. Much of the improvement in the capabilities of off-road vehicles for a couple of decades was in terms of better tire adaptations.

During the 1930s the tire manufacturers were able to produce larger tires that were also more reliable. The so-called balloon tire, which became widely used on private automobiles, not only required a relatively low inflation pressure but was of a significantly larger cross section than the tires of the early days of the automobile. Some very large tires were made for special purposes—all of them for off-road use. At this time there was serious interest in using rubber tires on farm tractors, and tires about 1.5 m in diameter were required. Whether that was for traction or simply to match the size of the old steel wheels is not clear.

About this same time R. G. Le Tourneau developed his trail-blazing line of wheeled earth-moving equipment. In 1932 he mounted large airplane type tires on wheeled

FIG. 7. World War U.S. Army truck, 1918 (photo courtesy of C. J. Nuttall Jr.).

scrapers. Later, in 1938, he conceived and created the wheeled tractor-scraper combination, the Tournapull (Fig. 8), that made him both famous and rich. Again large-sized tires 1.5–2 m in diameter, this time relatively heavily loaded, were demanded and obtained. Their use in earth-moving operations was a real off-road application and the large tires proved their ability under a variety of difficult conditions. These earth-movers are interesting from several other standpoints as well; they accelerated the rate of construction of roads, and they also set the pattern for the U.S. Army's "GOER" transporter in the 1960s.

Other large tire developments at this time include the building of special tires for the Gulf Oil Company. In the middle 1930s they were interested in oil exploration in the Louisiana marshes. Goodyear developed large tires 3 m in diameter and almost a meter wide for them. Using these tires they translated the need to move about quickly and easily in this terrain into a truly remarkable vehicle—the Gulf Marsh Buggy (Fig. 9). This very light weight vehicle remains one of the most capable wheeled vehicles for very soft soils.

In 1939 Dr. Thomas Poulter, a veteran of Admiral Byrd's 2nd Antarctic Expedition, build a giant wheeled vehicle for the 3rd Antarctic Expedition. This vehicle used four large tires made from the same molds as the Gulf Marsh Buggy tires. He called it the Snow Cruiser. Unfortunately knowledge of wheeled over-snow mobility was inadequate at that time. The Snow Cruiser was many times heavier than the Gulf vehicle and it was not able to operate in the Antarctic snow.

Probably the more far-reaching developments were taking place in Saudi Arabia. R. C. Kerr, working with truck and tire manufacturers, created large vehicles for use by ARAMCO in conducting oil explotation and drilling activity in the Arabian deserts.

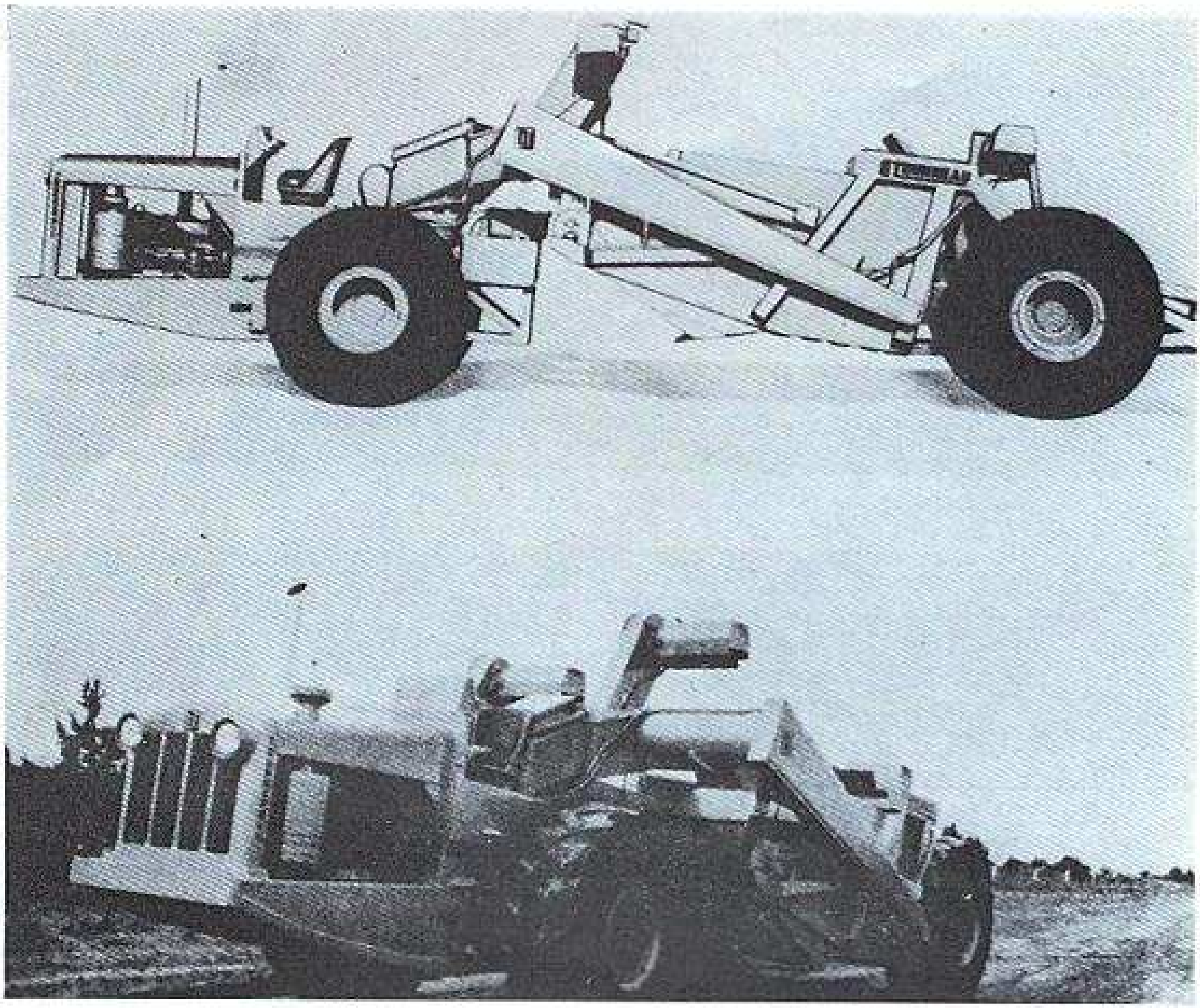

FIG. 8. R. G. LeTourneau's Tournapull, 1938.

This usage was not as spectacular in terms of size as the other large-tire applications but it was more analytical. Careful records were kept of size, load, inflation pressure, tire life and ability to travel. From the analysis the large, very flexible tires known as sand tires were developed. Also, these observations ultimately led to Colonel Karl Eklund's classic 1945 report to the U.S. Army on the "Influence of Load and Inflation on Selection of Pneumatic Tires for Military Vehicles". Unfortunately the U.S. Army did not really use it extensively. Some improvements relative to tire size and loading were made during World War II but soon after the relative tire sizes of the U.S. Army trucks were reduced.

Eklund and many before him, including notably McKibben in the late 1930s, recognized the importance of observations of how well a vehicle performed off-road or in a farm field. Some attempts were made to classify soils or describe them in meaningful ways, and as far back at least as Bernstein in 1913 some force measurements had been made. However, the first large-scale and practical use of measurements of soil conditions to relate to a vehicle's ability to move was made in the late 1940s by Foster, Knight and others as part of the extensive trafficability study conducted by the U.S. Army at the Waterways Experiment Station in Vicksburg, Mississippi. This work, using the cone penetrometer as the measuring device, was pivotal not only

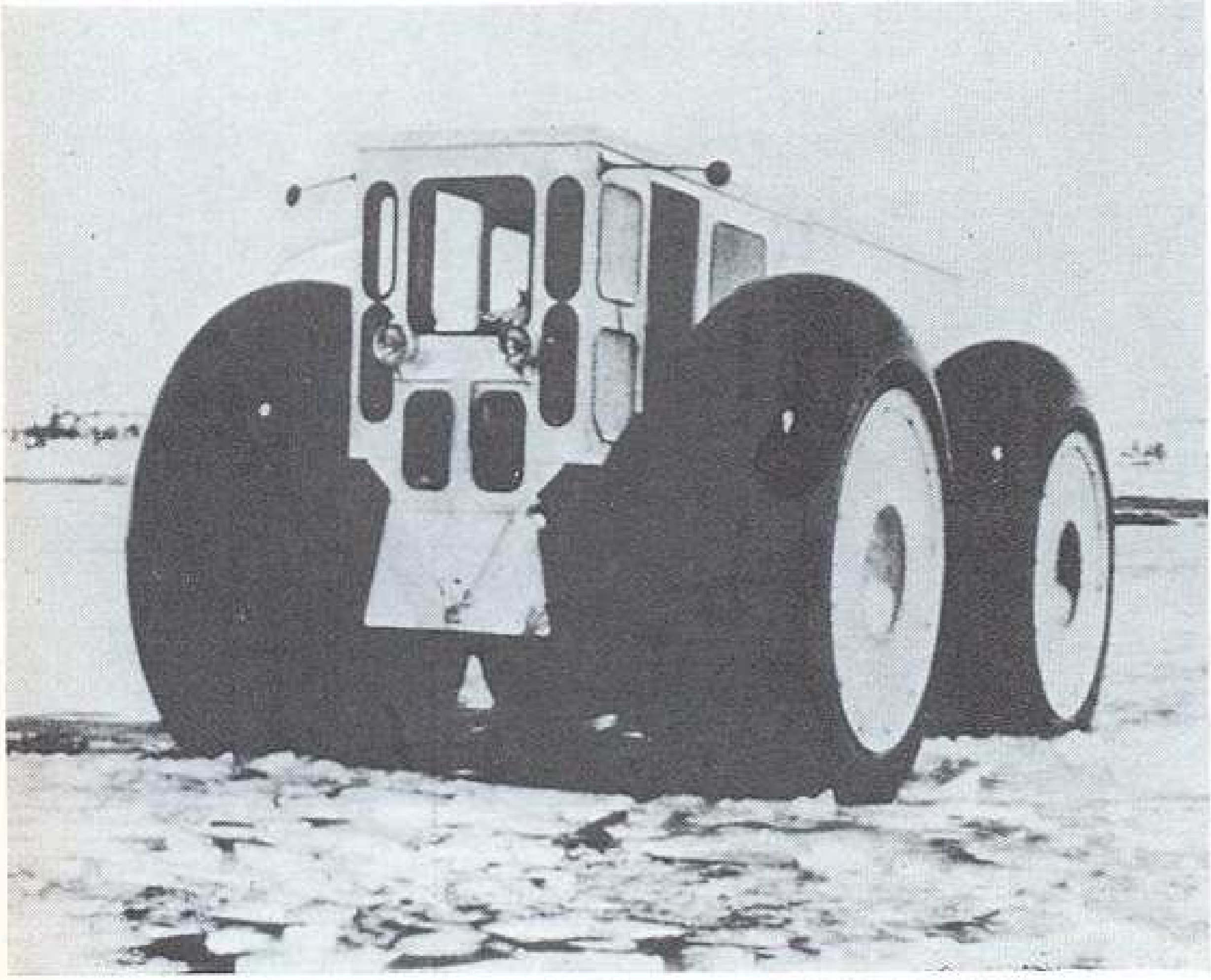

FIG. 9. Gulf Marsh Buggy, 1936 (photo courtesy of C. J. Nuttall Jr.).

in terms of the successes that resulted directly but also because of the related and peripheral studies that were stimulated by it. For the first time the soil-terrain component of the triad was subjected to a quantitative engineered analysis. It was demonstrated that meaningful measurements could be made of so variable a thing as an area of naturally deposited soil. Furthermore, these measurements were related to the relative ability of vehicles to drive over that soil. From this point, ever more sophisticated measurements were sought.

Tire developments took a new turn in the 1950s. It had become apparent that large tires did provide some advantages to off-road vehicles, especially if they were lightly loaded. However, the large diameters that were needed for this were very awkward to arrange a vehicle around. To obtain the advantage of large tires and accompanying low contact pressures, W. H. Albee experimented with very low pressure air bags (Fig. 10). The width of these strange looking tires was significantly greater than their diameter, and they were very flexible. He called vehicles using these devices "Rolligons" and he showed that they had the ability to allow heavy loads to roll easily over very soft ground. A major difficulty in practical application was the transmission of torque for traction through the very flexible side walls. The Goodyear Tire and Rubber Company gave up trying to make a driveable tire of this nature and created their Terra tire which was somewhere between a Rolligon tire and a "conventional" tire. Terra tires usually have diameter to width ratios of between 1 : 1 and 2 : 1.

FIG. 10. Albeé-Bechtel Rolligon, 1974.

Looking back over the years it is found that tire shape evolved in a steady pattern. Figure 11 shows the trends of the diameter to width ratios for the passenger car tire commonly available for representative years. The trend is toward ever-fatter tires that are softer and put more rubber on the road. Tires for special applications such as racing or for off-road work have even lower diameter to width ratios, currently about 2 : 1.

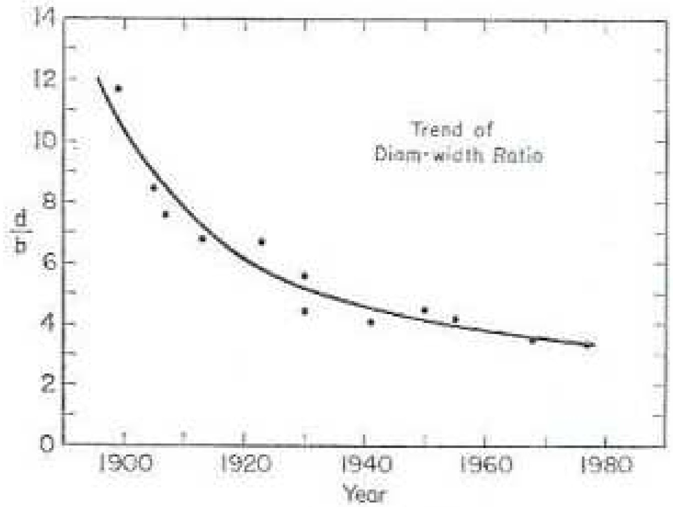

FIG. 11. Evolution of tire shape.

The effectiveness of a tire also depends on the amount of load carried. As there was a definite trend of diameter to width ratios over the years, it is of interest to examine also the chronological trend of load carried relative to the tire size. To do this a load factor determined by dividing the load per wheel by the product of the tire diameter and section width has been employed. This gives a number expressing force per unit area. The number has meaning as it has been shown to be related to vehicle performance on soft soils by a number of investigators. In Fig. 12, a plot of data representative

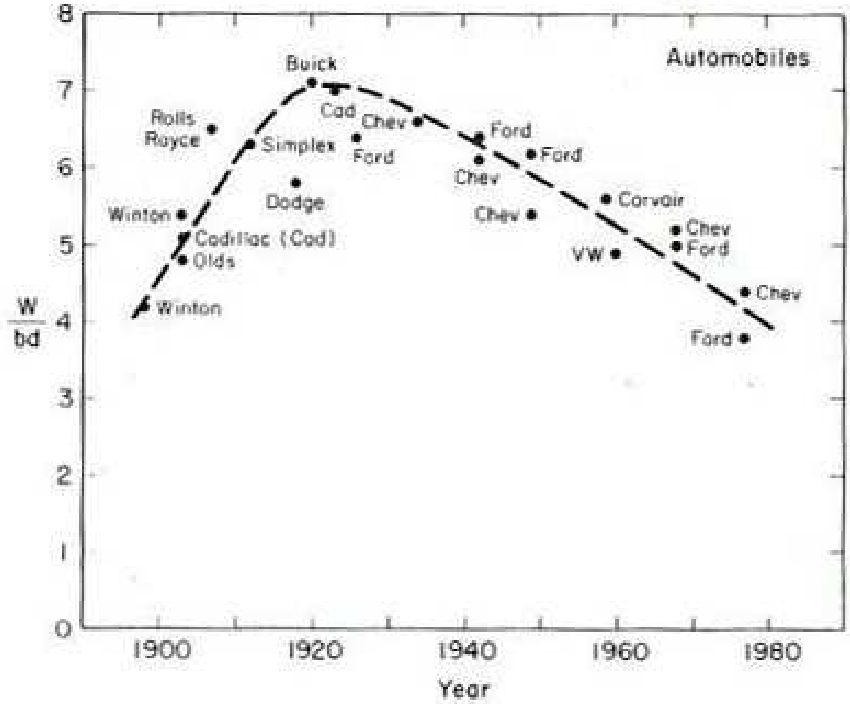

FIG. 12. Trend of load index for automobiles.

of automobiles, the numbers shown have the dimensions of lb/in². Some of the early automobiles were very light. Soon added gadgetry and refinements increased the weight and for a few years the load factors increased. Then tire sizes were increased (or loads were reduced, but usually the former) and load factors diminished again. Figure 13 shows some interesting trends for the Ford Models T and A. Light in

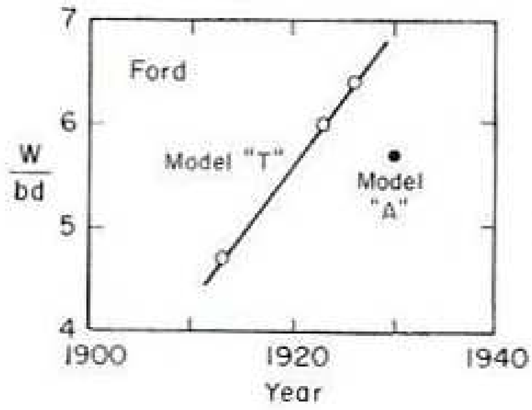

FIG. 13. An example of load index variation with model year and model change.

weight at first, these cars grew heavier over the years, but tire size stayed about the same. The newer Model A shows a significantly lower index. Figure 14 presents data for some racing cars over the same period as for the automobiles in Fig. 12. The data for representative farm tractors, including some of the early steel wheel types, are

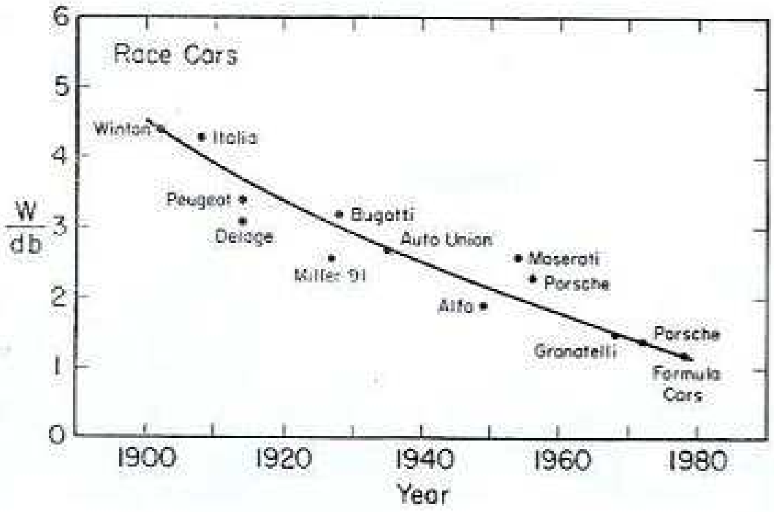

FIG. 14. Trend of load index for racing cars.

shown in Fig. 15. Representative armored cars are shown in Fig. 16 while Fig. 17 contains data for some representative military trucks. The lines of each of the previous graphs are collected in Fig. 18.

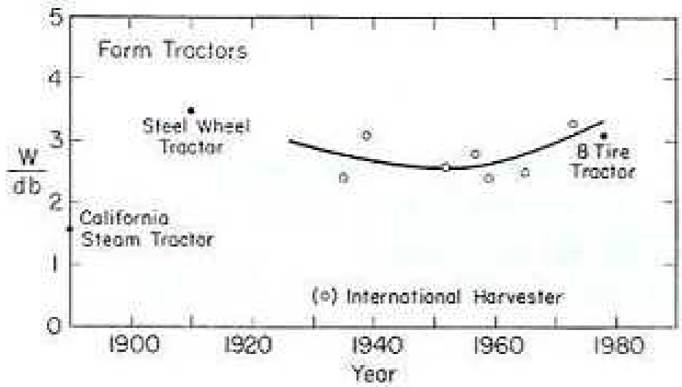

FIG. 15. Trend of load index for farm tractors.

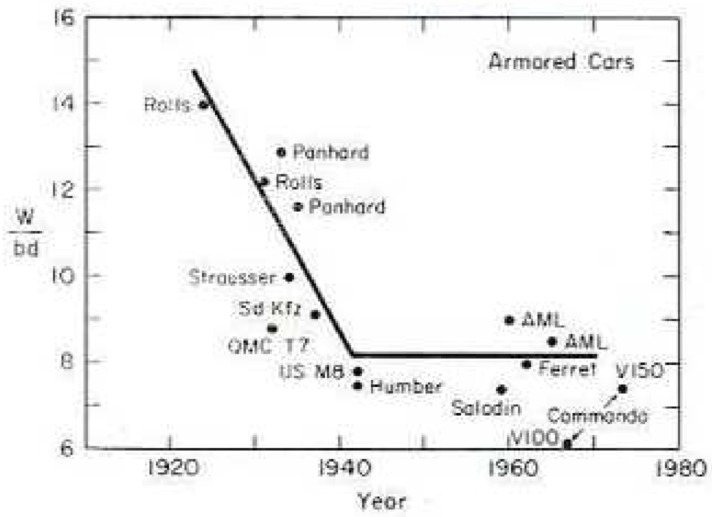

FIG. 16. Trend of load index for armored cars.

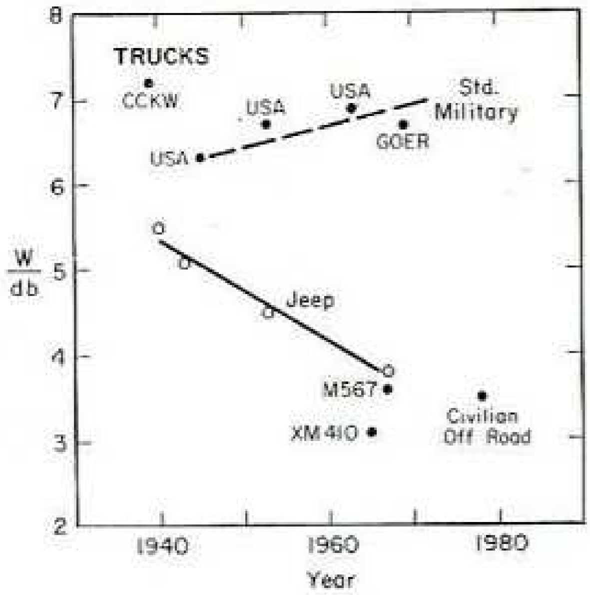

FIG. 17. Trend of load index for trucks.

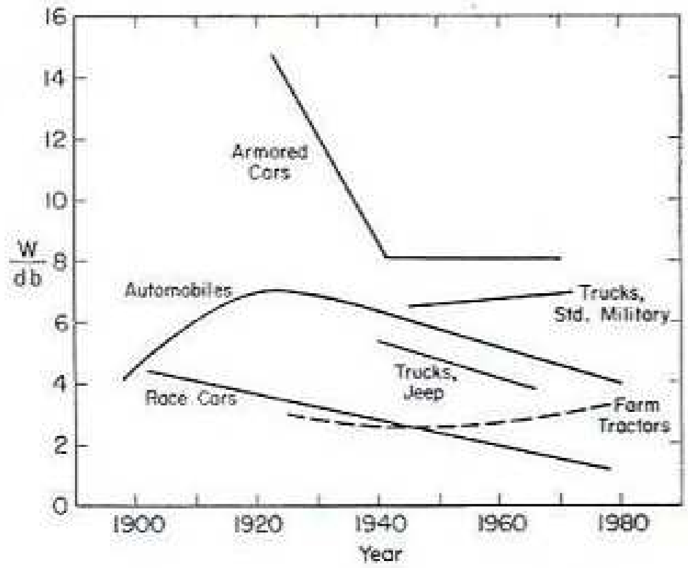

FIG. 18. Composite of load index trends.

The trend toward lighter wheel loads is generally consistent. However, very lightly loaded large wheels were on the agricultural tractor scene very early. A few other exceptional vehicles have since then also had very small load factors. The downward trend in load factors for high speed racing cars is clear and constant. Their greatest spread and most noticeable lack of constancy are shown by the military vehicles. There is a suggestion that during and just after World War II the load factors diminished but soon thereafter either leveled off or even increased. The military vehicles are all relatively heavy, even compared to commercial vehicles intended entirely for on-road service.

Although not a direct wheeled vehicle innovation, the development of the Army Mobility Model could prove to be a major milestone. It represents the summation of