Jupiter's finest wheels

Bela I. Sandor

J. H. CROUWEL, *CHARIOTS AND OTHER WHEELED VEHICLES IN ITALY BEFORE THE ROMAN EMPIRE* (Oxbow Books; Oxford 2012). Pp. xv + 234 which includes 171 pls.; figs. 6 (maps). ISBN 978-1-84217-467-8. $80.

The statue of Jupiter seen in fig. 1 is symbolic in many ways, especially in showing the most significant features in the sophisticated design of an ancient wooden wheel, features that are excellent even by modern standards.

J. H. Crouwel's latest book is a valuable addition to a large body of archaeological work on vehicles in Italy, making full reference to influences from other times and places, and including assessments of modern restoration efforts. It will substantially aid researchers engaged in new projects, and this review hopes to help students identify potentially fruitful areas.

A difficult aspect of the study of ancient vehicles is the paucity of surviving hardware. We often have to rely on judgments about works of art, which typically include both essentially realistic but also arbitrarily altered, sometimes even fictional, items. For example, one may notice in Jupiter's wheel (fig. 1) 10 tapered spokes, and that the felloe consists of two layers, which are all realistic; on the other hand, the absence of a linch pin and the surprisingly short nave point to artistic licence. Crouwel has always been keen on making such important distinctions, and his latest work adheres to the same philosophy.

Fig. 1. Jupiter holding a multi-purpose wheel (Musée Calvet, Avignon; inv. G 136^{A}; photo by author).

The structure of this attractive book, which is chiefly concerned with technical matters (xi), is easy to follow, although different arrangements might have appealed to some (e.g., to have placed "I.1. Terrain and roads" in the Appendix, or to have started with solid wheels before turning to spoked wheels). The front matter includes illustrations of major structural elements and harness systems. The book is basically organized around the types of vehicles and bodies, with the main chapters on chariots (II), carts (III) and wagons (IV), all subdivided into 1. Types and body; 2. Axle; 3. Wheels; 4. Traction system; 5. Harnessing; 6. Control; and 7. Use.

Chariots

For chariots, five types (I-V) are given, "chiefly on the basis of differences in the siding of the vehicle body, in conjunction with the shape of the floor plan", but not all the surviving parts or items shown in representations can be easily grouped according to these types. The various chariot types are discussed in great detail and illustrated in many plates, but to grasp the distinctions requires much page-turning (both in the text and among the plates) on the part of the non-specialist reader. It would have been helpful to have been given a schematic sketch of each type, and indeed all 4 or 5 schemas of the different types on the same page for instantaneous comparison. In addition, it would have been helpful if the captions to the plates had given the key technical notation, such as the type number, at least. In the absence of a full schematic presenting all chariot types, it is difficult to see, let alone justify, sufficiently convincing differences between the 5 types based chiefly on sidings and floor plans, as is claimed. It seems that the differences between these types are more in the nature of model differences (to use the parlance of modern automobiles[1]). That said, Crouwel's classification is acceptable for organizing a huge amount of evidence for research purposes and for initiating dialogues.

There are some incomplete or inaccurate statements from an engineering point of view. For example (11): "a mesh flooring … provided a strong and resilient floor in an otherwise springless vehicle". The mesh flooring is indeed resilient, but the chariot is not springless just because it has no steel springs of leaf or coil shape as in modern automobiles. In fact, the opposite can be argued: that any chariot is full of springs, which have a large variety of spring constants, making for springs that range from stiff, such as the axle and the yoke, to softer or more compliant, such as the pole in bending and torsion, or the front floor bar that acts like a bow in bending and warping.[2] Then there is a puzzling statement on the same page (11): "the pole … would represent a weaker construction than that on the Egyptian and other ancient chariots". What makes this construction weak, and, more importantly, would that be a good or a bad thing? Sometimes when an assembly of components appears weak, it might not be fatally so, while perhaps providing a desirable springiness or energy absorption in the structure. More explanation is needed in this case.

Crouwel provides good coverage of the use of bronze and iron in chariots (13), correctly stating that such vehicles were heavy, intended mainly for ceremonial purposes or simply to display wealth and status (note the bronze thrones), and not for racing. However, there was a wide range in the amount of metal used in ancient vehicles — in many cases there were only iron tires and nave hoops — or there was none at all. More work is needed in this area. One way to proceed would be to: (a) estimate the total weight of metal in different classes of chariots; b) estimate the percentages of metal in them; and c) determine the major consequences of having various amounts of metal in terms of cost, the need for skilled labor, horsepower requirement, dynamic performance capabilities (acceleration, top speed, cornering ability), safety, comfort, and durability.

The Type I chariot (the most common type) is identified with the Roman racing car (17), well-represented by the bronze model found in the Tiber and now in the British Museum. Types II-V and a group of uncertain types (17-26) are defined by variations in their sidings, profiles, and floor plans. The discussion also covers special elements, such as spiraliform metal pieces, whose "exact position and function remain uncertain" (23).

Axles and wheels

Some readers may find the discussions on axles and wheels (26-35) particularly useful and thought-provoking. The revolving axle is mentioned briefly in chapt. II as being unsuitable for fast chariots, which had fixed axles everywhere in antiquity as the standard equipment (26). Crouwel mentions here Italian finds where the axle was "attached not directly to the floor but to a separate rectangular frame. This also helped raise the floor over the axle", allowing space for the pole between the axle and the actual floor (27). The additional frame is alright for the spacing of the pole, but it should be noted that this raising of the floor (clearly seen in the book's cover photo) is detrimental in raising the center of mass of the chariot and its occupants, making for a less stable vehicle. In contrast, the pole tails of Egyptian chariots were flat, slightly lowering the center of mass and providing more stability. It is a subtle but significant fact that the S-shaped Egyptian poles lowered the front of the platform and thus further lowered the center of mass of the chariot and its riders. Note that in modern cars and vans the height of the center of mass typically deserves consideration — by designers and users alike — for safety factors. It would be

---

[1] For example, a Buick and a Cadillac seem different in many ways, including shape (fins were used in the 1950s), prestige, engine size and electronics, but they have many basic technical features in common, and they even share specific components. They are different models of comfortable passenger sedans that could be used for business, as limousines, for family camping, or even for stock-car racing. They are, however, clearly different in type from a Tesla electric car or a solar-powered car or a drag racer. Of course, differences in types and models can be blurred, just as a Mercedes convertible roadster is closer to a Buick sedan regarding type than to a Stanley Steamer.

[2] B. I. Sandor, "The genesis and performance characteristics of Roman chariots," *JRA* 25 (2012) 475-85.

worth determining the heights of the centers of gravity of the riders above the ground, and the practical implications of those distances, in a variety of ancient vehicles.

In contrast to the raised platforms seen here (27), there are numerous tantalizing images of Roman chariots with rather low bodies, which would be easy to mount and very stable on account of the low center of mass. Such dropped floors would be readily manufactured by hanging the body from the pole instead of placing it on top of the pole. Studying this possible scheme in depth would be another worthwhile project.

A long axle is rightly said (27) to be desirable for the lateral stability of the chariot, and also for allowing the use of long naves. However, there is little truth in supposing a need for "long naves… to keep these from wobbling on the axle". For well-machined axles and nave holes with tight tolerances, which the ancients could make routinely, there is no need for the enormous nave length of over 40 cm to prevent noticeable wobbling of the wheel. More important reasons for the typically long naves in all chariots are to reduce contact stresses that cause wear, and to reduce the bending stresses at the ends of the naves during cornering at high speed (the bending stresses are causes of nave splitting). The unrealistically short nave of the Jupiter wheel was probably the result of working with a block of stone of limited dimensions.

Central axle locations are stated (27) as typical for the Type I chariot and also for the high-fronted chariot in Greece. This is also found to be "characteristic of most carts, … and is suitable for stable loads or passive … passengers" (78). A central axle position for any two-wheeled vehicle involves an interesting issue of static equilibrium, one illuminated by what happened to an unfortunate donkey and its driver in Cairo not so long ago (fig. 2):

Fig. 2. Photograph taken in Cairo in the year 2000.

All two-wheeled vehicles, carts, chariots and bicycles are inherently unstable. For carts and chariots the axle, whether it is fixed to the body or rotating in fixed bearings, is the fulcrum about which the whole system pivots; the extent of the actual displacement may be invisible, or it may be large (as in fig. 2).

Two special cases should be analyzed, both involving the concepts of stable and unstable equilibrium.[3] Unstable equilibrium may exist when the payload centered over the axle is much larger than the total weight of pole(s) and harness and animal(s), as seen in fig. 2. Here a small additional load on the cart, or a slight backward shift of part of the payload, may trigger the

---

[3] B. I. Sandor, *Engineering mechanics: statics and dynamics* (2nd edn., Englewood Cliffs, NJ 1987) 438.

sudden tipping of the vehicle. Stable equilibrium exists with light chariots and small payloads (at most, 2 or 3 people on board) compared to the weight of the draft animals. In that case, the payload, no matter where it is with respect to the axle, can slightly push down or tug upward on the animals, but it would not lift them off the ground because they are attached to the pole at a relatively long moment arm (length of lever) from the axle (the fulcrum).

The prevalence of fixed axles (as in the multi-purpose Jupiter wheel shown in fig. 1 above) is clear from the book. The above comments regarding the need for long naves to prevent wobbling of the wheel on the axle (27) are applicable here as well. The use of metal nave hoops to prevent the naves from splitting is acknowledged by Crouwel (29).

In connection with the 9-spoked wheels of the chariot from Monteleone di Spoleto, note 126 states that "the choice of an uneven number of spokes is unexplained". The simplest comment to make is that only the relatively rare V-spokes, such as those in the Tutankhamun chariots, require an even number of spokes. Using straight spokes, an even or an uneven number of spokes are all equally acceptable.[4]

The treatment of wheel rims and rawhide and iron tires (30-35) is excellent. Indeed, many different wheel designs are covered. It should be added, however, that an entirely satisfying, ideal wheel can never be obtained because there are numerous conflicting requirements for good wheels.[5] Only a few of the critical issues need be mentioned here:
a) Mass and its topological distribution in order to minimize the linear and rotational inertias;
b) rigidity of the rim to reduce rim bending which causes vertical bouncing of the axle;
c) high strength of the spokes to allow large side loads on the wheels during cornering.

Remarkably, the Jupiter wheel (fig. 1 above) is excellent by any measure of sophisticated design for a wooden structure. From inspection alone, it is seen that this wheel is sturdy with no excessive mass anywhere; thus the total mass (i.e., the linear inertia) is reasonably low for most purposes. That much is obvious; the other fine qualities of this wheel are more subtle. Its creator knew that, especially for racing and in war, the wheel's mass should be minimal at its outer regions in order to minimize its rotational inertia and facilitate high acceleration, while it should also be very rigid to minimize bending of the rim. The relatively large number of spokes also contributes to achieving a rigid rim, at the cost of having extra mass. At the same time, the hub and the spokes at the hub should be relatively massive and strong to resist side loads in cornering, for reasons of safety. In other words, wheel mass should be minimized on the whole, and especially at the outer regions, but not at the hub region. Another subtle aspect of ancient spokes is their slightly elliptical cross-section that is found occasionally, as in the Tutankhamun chariots: in those, the major axis of the ellipse is always perpendicular to the plane of the wheel, which makes it ideal for minimizing weight and maximizing resistance to side loads. The Jupiter wheel's tapered spokes show adherence to these principles (except that elliptical cross-sections of spokes are often impossible to discern in works of art; yet they may be more common than meets the eye, and this point is deserving of further study). The spokes are thicker at the hub than at the rim, appropriate for cantilever beams, which in essence they are. Few extant wheels exhibit so many fine features of design; for example, the chariot from Monteleone di Spoleto (29) has the desirably rigid and strong wheels with much metal, but these come at a high manufacturing cost and with excessive weight and corresponding inertias.

Wheels are among the highest achievements of humans and their complexities are evident throughout Crouwel's book, but more research on ancient wheels is needed in order to develop a better understanding of the subtler issues. For example, there are innumerable ways to stiffen a wheel rim while trying to minimize its weight. An interesting one is using "wooden wedges

---

[4] There is one puzzling reference, without any bibliographic citation, to "two- or four-spoked wheels found in Italy" (29). This must be an error, since a wheel with only two slender spokes of wood is impractical, and in antiquity highly unlikely.

[5] B. I. Sandor, "Chariots' inner dynamics: springs and rotational inertias," First International Chariot Conference, Cairo 2012, proceedings forthcoming, PalArch's Journal of Archaeology of Egypt/Egyptology [www.palarch.nl].

… on either side of the spokes… to distribute the pressure more evenly over the felloe" (30). Another approach is seen in the Jupiter wheel (fig. 1 above) and other layered felloes (31). The many methods found for stiffening rims should be classified, clarified, and ranked according to their efficacy — a project that is far from trivial, as well as being difficult to accomplish.

Traction system and harnessing

Crouwel provides a good discussion of the pole, pole bindings, yokes and harnessing (35-43). A minor issue which deserves further discussion is whether a pole running "all the way under the floor … made for a stronger pole, less apt to break during turns" (35), while "the pole ending at the central axle… would have been much weaker" (36). Was it really much weaker? How much, and why? These imprecise opinions are not justified on technical grounds. Certainly more research is needed to clarify the significance of such common and apparently minor design differences.

The matters of "a pole support or breastwork brace" or "a thong running out horizontally from the top of the front rail to the forward end of the pole" are briefly mentioned (37). These apparently minor structural details (not shown in all the pertinent works of art) are mainly for the purposes of the structural integrity of the vehicle during dynamic events, such as the driver grabbing the front rail during acceleration or cornering. These elements and the yoke braces (40) are rather flexible parts of the complex spring and shock-absorbing system, and they deserve further study.

Control

Crouwel provides good coverage of bridle bits and reins (43-52). The most intriguing issue is that of handling — or not handling — reins (50):

> Two methods of handling the reins are in evidence ... [In one] The driver holds the reins in both hands … The other… involves the reins passing through one of the driver's hands before being tied in a knot behind his waist or back… The same practice is documented in Egypt and the Near East in much earlier times, and it continued into the Roman Imperial period.

Actually, there are three methods that can be identified here, with the Roman method being a variation of the earlier Egyptian technique. It all sounds complicated, and it is. The technique needs to be clearly understood, and practiced, before one attempts to drive in the advanced modes, where only one hand is on the reins — or no hands, as seen in many Egyptian representations. The latter, being the most complex, should be analyzed first.

It has been long believed that hunting or fighting in battle while driving with no hands on the reins was just artists pandering to kings, and that such driving was possible only in slow parades or prepared hunts (battues), but in fact it was possible for experienced drivers, and certainly for the extremely athletic warrior-pharaohs. The key to understanding this comes from an unlikely place, the world of advanced stunt-kite flying, best illustrated by R. Bethell of Vancouver.[6] Bethell is a Multiple Kite World Champion: he can fly many stunt kites at once, with each kite independently doing complex manœuvers for hours on end, even from a moving convertible car (which is analogous to a chariot). He invented the technique for this kind of spectacular performance (fig. 3 illustrates this with three kites, but he can do many more than three at once). Each kite has two thin control lines sometimes at very different angles for the three. Each hand controls one kite, while the third kite is managed by his waist clips on his left and right sides. He can simultaneously control additional kites by his head, shoulders, and knees.

The waist clips are the most relevant to controlling horses from a chariot, assuming the lines are wrapped around the waist, the left reins coming around the left side, the right reins from the right side, and preferably passing completely around before being tied together at the back. A simple forward leaning of the driver's torso relaxes both lines equally, letting the horses accelerate (probably with spoken stimulation from the charioteer too). The driver leaning slightly back will tighten both reins equally, slowing the horses. A slight twisting of the driver's torso

---

[6] www.raybethell.com. Ray Bethell kindly told me he agrees with the following thoughts on controlling kites and horses.

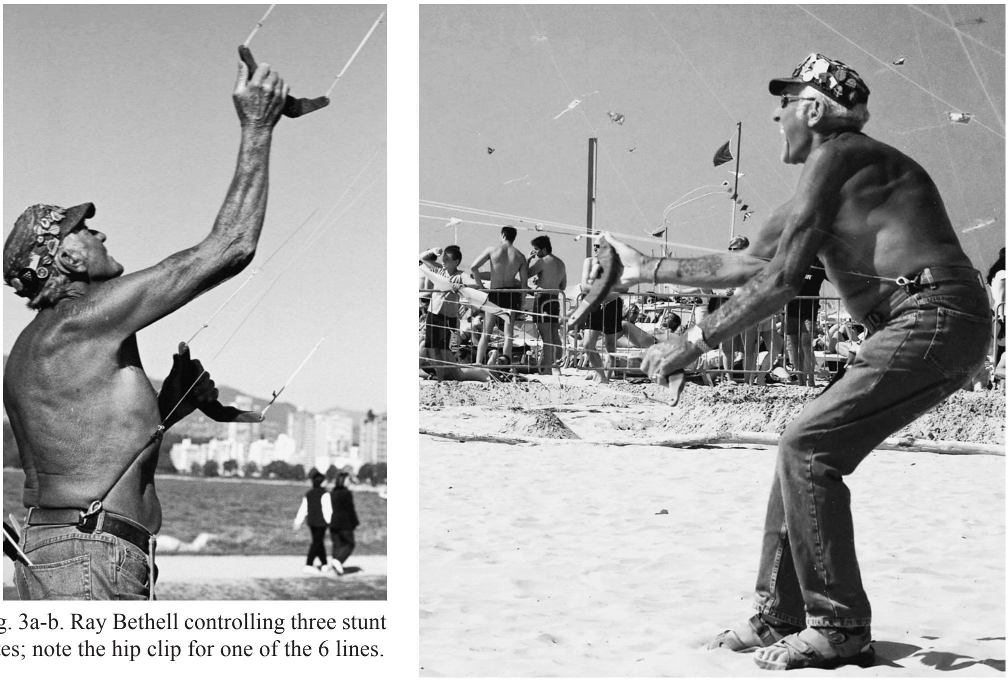

Fig. 3a-b. Ray Bethell controlling three stunt kites; note the hip clip for one of the 6 lines.

will tighten one rein and loosen the other, causing the horses to turn. An expert driver could combine such manœuvers — say, to turn left while accelerating. Simple experiments using two humans, one playing a horse, the other the driver, confirm the validity of the concept. In any event, driving a chariot in this manner is actually simpler, being a two-dimensional activity, than controlling several kites at once in three dimensions. This idea is supported by Bethell's 5-min. DVD, *Romancing the Wind*, where he flies three kites in a spectacular aerial ballet; a fast hip movement can be seen at 3:56 in the DVD.

The Roman technique is a variation of this Egyptian method, especially if the reins are knotted in front of the driver. In that case only the forward/backward movements of the torso have an effect, for speeding up or slowing down (67); control by the waist is not possible to effect a turn. For both the Egyptian and Roman driving techniques, it should be noted that in suspension systems and control systems small changes in forces and displacements of structural and control elements (such as Bethell's hands and hips) may be significant. More experimental work needs to be done to understand fully the possibilities and limitations of the "hands-free" and "one-handed" driving techniques.

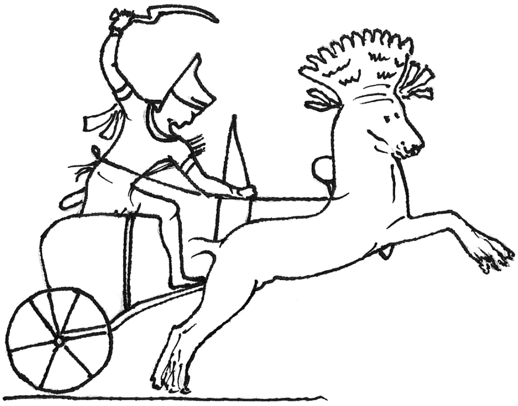

Fig. 4. Ritualistic high-speed war games, the ultimate test of a warrior-driver's complex skills (adapted from an image of Ramses II in Cottrell 1968 [n.7] 121, fig. 22). Focus on the reins on the hips and the foot on the pole.

The advanced "hands-free" driving technique of the warrior pharaohs[7] needs to be investigated in detail. Consider for example a representative warrior pharaoh (fig. 4). The image should be thought of as part of a public demonstration of exceptional athletic skills. Prior to the stance shown, the driver probably fired 2-3 arrows during his rapid approach to a copper-ingot target; probably the hits were counted and the arrow penetrations measured and graded. Continuously during the approach the driver will have had one foot firmly planted on the pole at the junction of

---

[7] L. Cottrell, *The warrior Pharaohs* (London 1968).

the acceleration braces (possibly with his foot nested between the braces or with two big toes gripping an acceleration brace, though this is not shown in art), while his hands were free to handle weapons. This is certainly realistic as there are several good reasons even in battle for driving this way, quite apart from showing off at a royal festival: he can squeeze the front railing between his thighs for stability; he can lean out sideways farther to fight, and better protect the vulnerable horses at the same time. Note that the driver's weight is shifted forward significantly on the pole. No one could invent this scene without having seen it or heard about it. There is no illustration of this difficult technique in Roman art, but the question should be: Why not? We need experimental work with good chariot replicas.

Use

Crouwel's section on chariot usage is extensive and excellent (52-69). It is good to learn, and important to remember, that the military use of chariots in Italy and Greece was much more limited than most people think, and that they were never used for warriors fighting from them (59). The references to frequent accidents in chariot racing point to an intriguing question and opportunities for further work. Were most crashes caused by collisions or by structural failure? The answer is probably mostly by collisions in the chaos of the race, but mechanical failure was also common. Which components failed and why? Sorting these out remains a challenge.

Carts

In the relatively short chapt. III (70-88) two types of carts are identified; Type I, the Y-poled cart (73), and Type II, the central-poled cart (75). Some further carts are difficult to classify.

Axles

"A central axle is … characteristic of most carts … and is suitable for stable loads" (78). This issue was discussed above in connection with fig. 2. The commonly-found revolving axles with wheels fixed on them (78) are deemed to be "suitable for relatively slow transport". Some readers may deduce from this statement that rotating axles are perhaps ideal for carts, if not for chariots, but the opposite is true: rotating axles are a bad idea for most vehicles that have to turn even a little and just occasionally.[8] The reason is that curved tracks require a differential rate of rotation of the wheels to avoid them scraping the ground. Any scraping or sliding at the contact patch between a wheel and the ground entails much extra work by the draft animals. This may be tolerable in the case of a slow cart that travels mostly on straight paths, but at high speeds and with more turning the rate of work increases, to the point where the available horsepower simply cannot move the vehicle very far.

Wheels

Three kinds of cart wheels are discussed: disk, cross-bar and spoked (80-84). A most unusual spoke design is seen in the large (diam. 1.14 m) Populonia cart wheels (83), dating to the 7th c. They are bronze-sheathed and exceptionally elegant, even by the standards of fancy modern automobile wheels; such a wheel, obviously not belonging to a peasant's cart, is truly deserving of admiration (fig. 5). The Populonia wheels should provoke thought because of their unique geometric pattern: "two four-spoked wheels, one within the other; the respective spokes are staggered". Aside from their beauty, these wheels imply a great effort made to increase the stiffness of the rim, which is more difficult to achieve on account of the large diameter. The bronze sheathing helps, as do the flared outer ends of the spokes; the staggered intermediate set of short spokes is possibly also in order to get a more rigid rim, which is indeed obtained, but at the cost of adding the extra weight of the inner rim, by comparison with creating just 8 straight spokes. The Populonia wheel (pl. 86) and several other elegant and efficient rim-stiffening spoke systems (cf. pls. 103-4) deserve full technical analyses. Note that some approaches to stiffening the rim accomplish that task, but they appear nearly as solid wheels (e.g., pls. 42 and 138).

---

[8] Railroad cars are an exception: http://boingboing.net/2013/04/10/why-do-trains-stay-on-the-trac.html

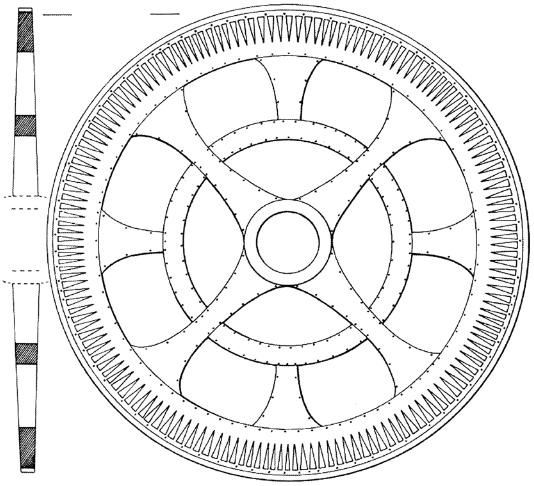

Fig. 5a. Populonia cart wheel with bronze sheathing (Crouwel pl. 86); elegant and technically sophisticated design: spokes tapered in width and thickness, and flared near hub (for bending resistance) and at rim (for rim stiffness).

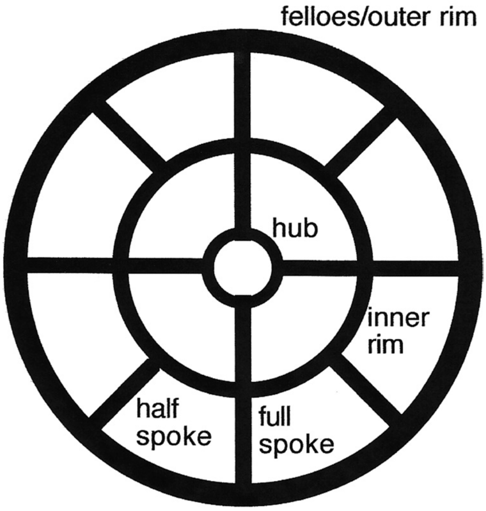

Fig. 5b. Schematic of Populonia cart wheel.

Wagons

The short chapt. IV has the same structure as the previous ones, covering the essential features of 4-wheeled vehicles (89-96) in an adequate manner. Interesting differences from the technical aspects of 2-wheeled vehicles include the necessary structural arrangements to allow the use of a kingpin and an articulated front axle, which facilitates the turning of wagons (91). Finds include both fixed and revolving axles (93), but their pros and cons for wagons are not discussed. A special item of interest is an extremely thick (2.4 cm) iron tyre (94), which raises various issues demanding further research.

Much can be learned from Crouwel's latest book. This valuable work can provide an excellent, broad foundation for further investigations, often in interesting new directions. I am delighted to have it in my hands as I savour the cover photo of J. Spruytte's magnificent chariot model and all that it implies and represents.[9]

sandor@engr.wisc.edu Dept. of Engineering Physics, University of Wisconsin–Madison

---

[9] A few typographical errors were noted. Note 22 (p. 10) gives F. Müller (1995, 272-4), note 26 (p. 112) gives Müller, F. 1995, while the Bibliography gives Müller, F. 1975. Note 73 (p. 106) correctly cites Raulwing and Clutton-Brock 2009, but the Bibliography gives Rauwling. Page 21 "these objects would been"; p. 23 "on on"; p. 61 "and and" .... "interprete"; p. 104 "well well-known". On p. 112, Wentwang should be Wetwang.