The genesis and performance characteristics of Roman chariots

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There is a general misunderstanding of the design of Roman chariots, due in part to the influence of the motion-picture films *Ben Hur* (1924 and 1959), the latter of which created very heavy welded-steel chariots with huge ornate wooden wheels, and due in part to the paucity of ancient chariots displayed in museums and indeed the paucity of surviving pieces of hardware. The present paper aims to elucidate the essential structures and internal dynamic characteristics of Roman chariots by trying to understand the thinking of their designers who were trying to achieve good compromises to satisfy the conflicting requirements of safety, comfort, prestige, durability and, especially, winning performance.[1]

The Roman chariot wheel built upon knowledge gained by earlier wheelwrights in Europe and elsewhere to create multi-spoked, relatively simple and economical wooden wheels with or without iron tires. To understand the design, construction and physical characteristics of a chariot it is necessary to consider two classes of structural elements: the wheels, and the suspension system. For each element or subassembly there are many possible good design choices. The major issues, in order of significance, are: safety, comfort, performance as measured by acceleration capability, and the economic constraints of structural methods and horsepower availability. Specifically, any wheel must be rigid yet light in weight, and not just light but topology-optimized for minimal rotational inertia as well as for resistance to bending loads which are encountered when turning and on sloping ground. The flexibility requirements of a suspension system are the opposite to those of the wheel, with the general need for springiness, not rigidity. The best tools for dealing with these complex issues belong to the mechanical sciences of statics, dynamics, and the mechanics of materials;[2] an experience in engineering design and failure analysis is also useful. Another useful method for investigating chariots involves the creation of small flexible models — which the ancients must have used too; in these models, the flexibilities of some components must be exaggerated to demonstrate instantly the numerous specific aspects of a chariot's inner dynamics and to answer questions about the suspensions.

For present purposes, our chariot may be defined as a light, fast and manoeuvrable vehicle with two spoked wheels, on which the driver stands.[3] The fundamental advantage of a spoked wheel was the greatly reduced mass and corresponding linear inertia, and the reduced rotational inertia. Minimizing rotational inertia is crucial for racing wheels, though not for other vehicles such as carts or stage coaches: for an infinitesimal mass element, its rotational inertia with respect to the axis of rotation is defined as the mass times the square of its distance to that axis. For a rigid body, its rotational inertia is the summation of all of its elemental inertias. Remarkably, some ancient engineers understood,[4]

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1 For issues of harnessing, see the publications by J. Spruytte (e.g., *Early harnass systems*, transl. M. Littauer; London 1983). For recent reconstructions, see R. Hurford's www.chariotmaker.com.

2 Cf. B. I. Sandor, "Mechanics of solids," in D. Y. Goswami (ed.), *The CRC handbook of mechanical engineering* (2nd edn., Boca Raton, FL 2004) 1-1 through 1-130.

3 See S. Piggott, *The earliest wheeled transport* (Ithaca, NY 1983) 95; M. A. Littauer and J. H. Crouwel, *Wheeled vehicles and ridden animals in the ancient Near East* (Leiden 1979) 4.

4 Through simple experiments. For example, a chunk of metal attached to a spoke at various