RAILWAY AND CANAL HISTORICAL SOCIETY
EARLY RAILWAY GROUP
Occasional Paper 231

The walking mechanism of William Brunton's mechanical traveller locomotive or steam horse

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SUMMARY

These notes provide a new analysis of the design of Brunton's 'Mechanical Traveller' locomotives with emphasis on the walking mechanism of the two machines that are known to have been built, for Crich and Newbottle, and the possible differences between them.[1] The work includes reference to a physical model built by the author approximating to both Brunton's patent drawings and to the popular image of the locomotive. This model was used to test some of the characteristics of Brunton's mechanism; namely limitations to the direction of travel, its haulage capability and the action of the foot lifting mechanism, the latter detail having been entirely overlooked up to this time. The work also discusses the relative power of Brunton's two locomotives together with a detailed appraisal of the problems associated with the known parameters of the second locomotive constructed. A new hypothesis is presented that attempts to resolve the conundrum of conflicting design parameters for the second locomotive, derived from a satirical print titled 'The Grave Diggers'.

The terms used here to describe the constituent parts of the locomotive are those analogous to the common names of the human leg and used by both Brunton and his obituary writer. Modern nomenclature for robotic walking machines and in biomechanics refer to the 'stride' length and 'step' height but Brunton's uses 'step' to mean the stride length. Brunton's nomenclature is used throughout augmented as 'step length'.

INTRODUCTION

On 28th April 1813, William Brunton wrote '…I have been, as you will easily perceive, in a scheming way lately and invented a horse to go by steam…'[2] Publication of his patent followed less than a month later, and the first working locomotive was completed before the end of the year for Crich limestone quarry. But within a week of Wellington's victory at Waterloo, the experiment was ended by the explosion of Brunton's second locomotive, built for the Newbottle Colliery.

Whilst knowledge of early railways and their locomotives has been significantly advanced since the establishment of the Early Railways conference series, including important work on the history of Brunton's locomotives, in the time since Brunton built his first 'horse to go by steam' only Pendred[3] nearly a century later

[1] The principal references consulted in this work are: details of Brunton's patent GB3700/1813 published in *The Repertory of Arts, Manufactures and Agriculture* Vol. XXIV, no CXL, 2nd series. (1814), 65-75; A Guy, 'North Eastern locomotive pioneers 1801 to 1827', in *Early Railways*, ed by A Guy and J Rees (London, 2001), 125-126; D Hopkins, 'William Brunton's walking engines and the Crich rail-road', in *Early Railways 5*, ed by D Gwyn (Clare, 2014), 221-242; and D Hopkins, *The Butterley Gangroad project* (Derbyshire Archaeological Society, 2015), 50-72.

[2] Reproduction of drawings and a typed copy of a letter to his brother. *The Engineer*. 16 Feb 1912, 164-165. The original letter is in the collection of the Science Museum, acc no 1922-248.

[3] LS Pendred, 'A note on Brunton's steam horse, 1813', *Journal of the Newcomen Society*, vol 2 (1922), 118-120.

has attempted to analyse the mechanical design of the locomotive and little has been added in this direction subsequently. This is in stark contrast to the progress made with respect to other early locomotives, most notably the Chapman-Buddle 'Steam Elephant'.

In the nineteenth and early twentieth century popular railway histories commented with seemingly ever decreasing detail on the mechanics of William Brunton's extraordinary mechanical traveller, seeing it as a mere curiosity and technological dead end. Whilst Nicholas Wood (1825) gives a full account of Brunton's locomotive quoting the patent almost verbatim, Dionysius Lardner (1832) and then Luke Herbert (1836) both simplify their descriptions to a degree. Later, Samuel Smiles (1868 edition), the unreliable Clement E. Stretton (1893) and more recently LTC Rolt (1960) in his biography of the two Stephenson's all dismiss Brunton's locomotive in just a few words.[4] Although the broad context for this progressive diminution of interest in the mechanism of Brunton's locomotives may be largely accurate in terms of the development of mechanised transport during the nineteenth and early twentieth centuries, in the second half of the twentieth century the sciences of biomechanics and robotics have begun to develop an understanding of the mathematics[5] and mechanics required for practical walking machines, which in turn has provided the opportunity to re-evaluate the properties of Brunton's locomotives in a new light.

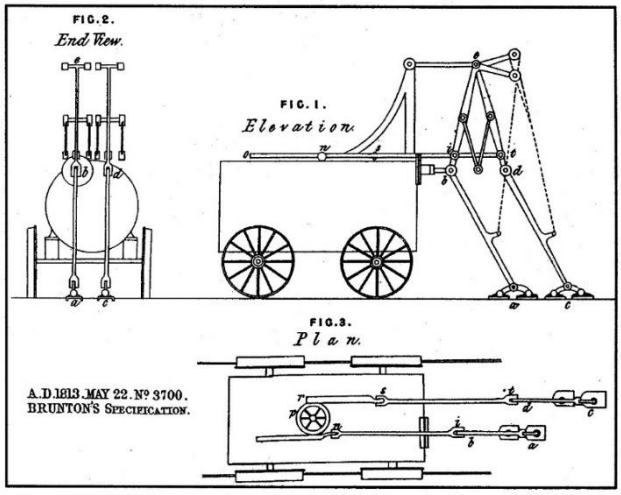


PLATE 1: Brunton's locomotive - Figures 1, 2 and 3 of the patent.

In the notes accompanying his patent publication, Brunton stated that his 'mechanical traveller' locomotive for Crich had been constructed in accordance with patent drawings Figures 1, 2 and 3 (Plate 1) and that the step length was 26 inches. The popular image of the locomotive after Wood is derived from these same drawings. The alternate design of machine shown in Fig. 4 and 6 of the patent (Plate 2) is seldom mentioned but would also have produced a locomotive with a 26 inch step-length. But even before the publication of his patent Brunton had written[6] to his brother in Ireland that he expected his second locomotive (for Newbottle) to have double the step length of the Crich engine and also double the speed. The direct link made by Brunton for a simultaneous increase in both speed and step length is worthy of note. Much later still, Brunton's obituary[7] quotes the step length for the Newbottle engine to be even longer at 6 feet, or nearly three times that shown in the patent and there are serious technical difficulties in reconciling this statement to the patent design that will be explored in more detail.

RELATIVE POWER

A simple comparison of the cubic cylinder capacity provided per unit distance of step length travelled for each of Brunton's two locomotives is illuminating. Since the boiler pressure and mechanical losses can be assumed to have been equal for both machines, the swept volume of the cylinder(s) alone may be taken to be proportional to

[4] N Wood, *A practical treatise on rail-roads* (London, 1825); D Lardner, *Lectures on the steam-engine: in which its construction and operation are familiarly explained* (London, 1832), 153-5; L Hebert, *Engineers' and Mechanics Encyclopaedia* (London, 1836), 398-400; S Smiles, *The life of George Stephenson and his son Robert Stephenson*, (New York, 1868), 83; CE Stretton, *The locomotive engine and its development; a popular treatise on the gradual improvements made in railway engines between 1803 and 1893*, 3rd ed (London, 1893); LTC Rolt, *George and Robert Stephenson: the railway revolution* (London 1960).
[5] JE Shigley, 'Mechanics of Walking Vehicles', *University of Michigan Research Unit*, Report no 2859 (1960).
[6] *The Engineer*, 16 Feb 1912, 164-5; Science Museum inv. no 1922 – 248.
[7] Obituary for William Brunton, in *Proceedings of the Institute of Civil Engineers*, vol 11 (1852) 95-99.

the power available for a given distance travelled independent of the piston stroke rate or speed of travel and without the necessity of using horse power or tractive effort calculations that include mathematical constants with uncertain values.

Whilst the size of the single cylinder for the Crich locomotive is recorded, that of the two cylinders for the Newbottle machine is not. It might seem reasonable to suppose that a common casting pattern would have been desirable for both locomotives and using this as an initial premise enables the likely characteristics of the Newbottle locomotive to be explored and compared with the more extensively documented details of the Crich engine.

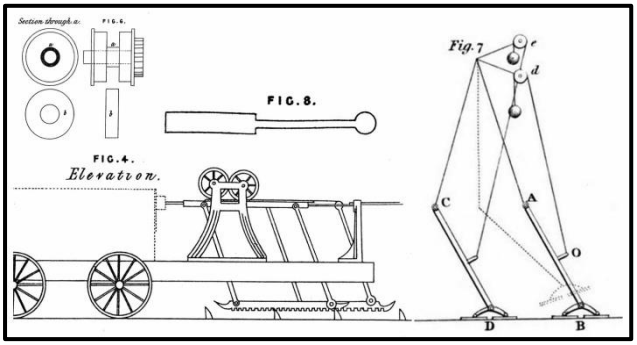


PLATE 2: an assembly of Patent figures 4, 6, 7 and 8

If the Newbottle locomotive had a six-foot step-length compared to the short 26 inch step-length quoted for the diminutive Crich engine, assuming that each of the two cylinders had the same swept volume as the single cylinder provided previously and that the cylinder drive was not geared down, the cylinder volume provided per unit of distance travelled for the Newbottle locomotive would have been only just over 70 per cent[8] of that previously available, representing a considerable reduction in the relative power of this second, larger, locomotive.

The power reduction could have been countered in three ways. Firstly, by a significant increase in boiler pressure, which seems unlikely and will be discounted. Secondly, by an increase in the cylinder swept volume or, thirdly, though provision of gearing such that for each complete double-stride, more than one complete reciprocation of both cylinders took place. In each of these scenarios the steam raising capacity of the first boiler fitted to the Newbottle engine would have needed to be not twice but nearly three times that of the Crich locomotive, but within the constraint of a weight limit only double that permitted for the earlier machine. And these changes would have been required just to match the performance of the Crich locomotive at a given speed, let alone exceed it. Thus, the analysis provides a rationale for the possible inadequacy of the original boiler fitted to Brunton's Newbottle engine in terms of its steam raising capability verses likely steam demand.

The very act of rebuilding the Newbottle locomotive in middle part of 1815 implies that the machine was still a viable technology at this time. What is not apparent is why the boiler was replaced. Was this the result of damage from the riots of the keelmen in the spring of 1815, inadequate steam raising capability (as seems probable), insufficient water capacity, or just due to wear and tear in service? Alternatively, perhaps replacement of the boiler may have been simply due to exposure of latent manufacturing defects? Whilst provision of a larger boiler within a weight limit relaxed from five to six tons should have increased both steam- raising capability and water capacity to help alleviate recorded operational problems, replacement of a serviceable boiler that was less than a year old seems to be unduly profligate. Wrought-iron boiler plate[9] was the most expensive form of the material available at the time and the construction of high pressure boilers using it was at the leading edge of boiler technology. Boiler replacement is unlikely to have been attempted without sound underlying economic reasoning but would performance limitations alone have been sufficient justification for the expense?

As the power and steam raising performance of the Newbottle locomotive as initially constructed can be shown to have been wanting, it is now apparent why the dangerous practice of tying down or increasing the loading of the dead weight safety valve to enable the day's work to be done, as reported in the contemporary press, was a significant contributory factor to the July 1815 Philadelphia boiler explosion. The working conditions and habits of the enginemen William Sharp, were originally born of necessity, but later '*it is supposed, too anxious*

[8] Swept cylinder volume per unit distance travelled: for Crich: 1 x 6 in x 24 in cylinder = 678.6 cubic inches volume with step length of 26 inches per piston stroke = 26.1 cubic inches cylinder volume per inch travelled; for Newbottle: assumed 2 x 6 in x 24 in = 1357 cubic inches volume with step length of 72 inches = 18.8 cubic inches per inch travelled. Ratio Newbottle to Crich = 18.8/26.1 x 100/1 = 72%.

[9] R Hayman, *The Shropshire wrought iron industry c1600-1900: a study of technological change*, University of Birmingham, Ph.D. thesis (2003), 125.

for its success, had overcharged the boiler with steam which caused it to burst with a tremendous explosion',[10] resulting in the unfortunate engineman's untimely demise, along with the loss of life and injury suffered by many of the assembled crowd.

HAULAGE

There is evidence from experimentation with a working scale model to indicate that Brunton's locomotives should be regarded as having been limited in their performance by their axle loading rather than by grip. From the design of the locomotive shown in Figures 1, 2 and 3 of Brunton's patent (**Plate 1**) it can be determined theoretically that if the locomotive stalled and provided that the driving foot did not slip on the ground, the inevitable consequence of a stall would be that the rear wheels would have been lifted from the rails as the piston rod extended and the body of the locomotive rotated around its stationary front axle. This has been confirmed by experiment with the model.

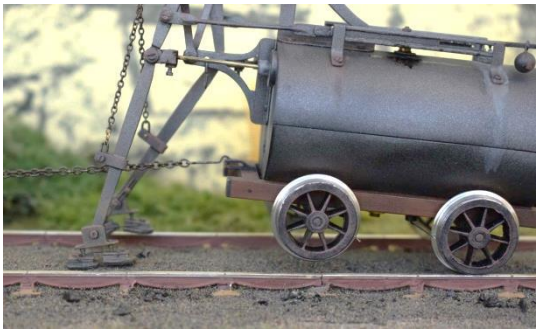


PLATE 3: Stall and foot lift

Under stall conditions, the train load, whether propelled or hauled, would have prevented the frame and wheels of the locomotive moving either forward or back during the piston stroke. The downforce on the rear wheels is therefore the limiting factor governing pull at the drawbar under these conditions, which is exactly analogous to that for any ordinary adhesion locomotive, albeit with a different and potentially dangerous end result. Classification of the locomotive's haulage capability is therefore dependent on whether the foot slipped or the wheels lifted first. And the answer to this question is supplied by reference to Brunton's obituary where the author quotes Brunton as saying of the Newbottle engine that he used an angled chain to provide weight transference from the leading wagon to prevent the wheels being lifted from the rails, i.e., additional adhesive weight was supplied. This explanation also confirms that, at Newbottle at least, the train was hauled behind the locomotive and not pushed in front of it as the weight transference chain could only have functioned if it was under tension and placed between the locomotive and a hauled load.

For a locomotive built in accordance with the popular image with four wheels, only around a half to two thirds of the total locomotive weight could have been placed upon the rear axle and the performance of such a machine would therefore have been likely to emulate that of a similarly sized conventional 2-2-0 single-driver locomotive given a similar weight distribution. Any contemporary locomotive where all the carrying wheels were coupled together either by spur gears, a continuous chain or coupling rods to take advantage of the full weight of the machine for adhesion could not have failed to out-perform a Brunton locomotive of similar weight, power and general dimensions. Comparison of the drawbar pull exerted by the model (**Plate 4**) with that of a simple proprietary toy train locomotive (**Plate 5**) of identical weight and with similar weight distribution has confirmed that the model Brunton locomotive performs remarkably similarly to the toy locomotive after removal of its coupling rods (**Plate 6**).



PLATE 4: The author's 32mm gauge working model Brunton locomotive



PLATE 5: the 16.5mm gauge toy locomotive used for comparative test

[10] The list of known victims of the boiler explosion on 31 Jul 1815 included 'Wm. Sharp, the manager of the engine, who was blown to a considerable distance, and most dreadfully mangled': *Durham Advertiser*, 5.Aug.1815.

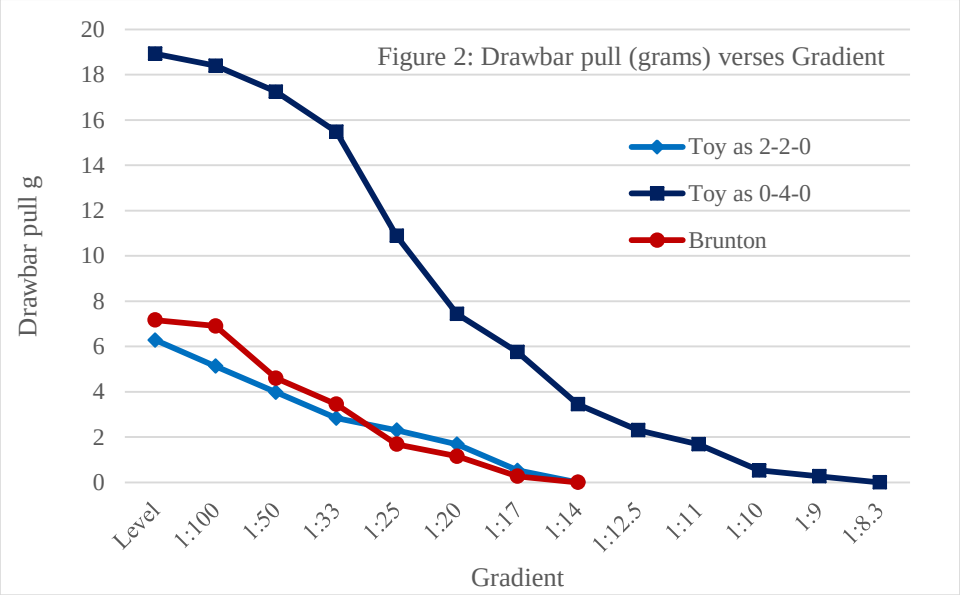


PLATE 6: Graph showing comparative drawbar pull of the model Brunton locomotive and a toy locomotive of identical weight verses increasing gradient.

SHIN ANGLE

Brunton's obituary indicates that latterly he recommended an angle for the shin bone of between 20 to 30 degrees from perpendicular. This represents a slight tightening of the tolerance range compared to his 1813 patent which quotes an angle of between 50 to 70 degrees; unstated but presumed to be measured from the horizontal.

Optimal shin angle would have depended on a number of interdependent factors. If too long a shin was placed at a large angle from the perpendicular, the feet would have slipped easily and load haulage capacity would have been reduced, although wheel lifting would then have been avoided. Conversely, if the shin angle was too small and the shin too close to the perpendicular, the vertical component of the forces generated by each piston stroke would have tended to lift up the wheels at the start of every stroke since the lifting force generated would have exceeded that opposing it due to the mass of the locomotive under the effect of gravity. Minor undulations in the ground surface would have caused only small changes to shin angle and might have been almost entirely avoided if the span of the foot was sufficient. But wear in the horse path, perhaps more pronounced near sharp curves in the railway or on the transition to a gradient, could, over time, have resulted in the shin angle being unintentionally altered. On continuous gradients or inclines there would have been a change in effective shin angle to the true perpendicular which would have been just over two degrees on a 1 in 28 gradient.[11] The resulting effective reduction in shin angle on inclines would have acted to improve traction by virtue of increasing the vertical component of the applied piston force within the constraints of the loading on the rear carrying axle.

The series of triangular bars on the soles of each foot that Brunton described as helping to provide grip in soft ground has perhaps mislead us into categorising the locomotive as an entirely non adhesion type of machine. Other aspects[12] of Brunton's patent do, of course, refer to non-adhesion haulage solutions with spikes like a rack and grip mechanisms for cables being addressed. But the bars on the feet of the locomotive may only have contributed in a minor way to haulage capability and would probably have been much less significant than either the shin angle setting or weight on the trailing axle. Had the horse path been hard packed, cobbled or frozen in winter, the triangular bars would have reduced the effective area of the foot in contact with the ground and

[11] Ruling gradients on both the Crich and Newbottle railways were in the region of 1 in 36.
[12] Figures 4, 5 and 13 of Brunton's patent and associated notes concerning the means to grip spikes in the ground and cables.

therefore reduced available grip rather than increased it. Consider also that one of the few dimensions for these locomotives quoted in Brunton's obituary is that of the shin angle. Why so, unless it was of critical importance?

REVERSING

The popular image of the engine to which design the Crich locomotive appears to have been constructed seems only to have been capable of travelling forwards. Forward travel in this context is when the walking mechanism is pushing or propelling the boiler in front of it. Whilst it does not seem possible for the engine to have reversed its direction of travel as will be shown, the locomotive could, perhaps, have changed from right to left leg lead by changing the sequence of steam admission to the cylinder which in a conventional locomotive would have reversed the direction of travel, although there is no reason why it would need to do so.

The principle evidence concerning the locomotive's inability to travel in reverse is, firstly, the way in which the knee joint was articulated and, secondly, the design of the foot raising mechanism. The shin was articulated so as to rake and hinge backwards behind the locomotive. This confirms the analogy of the engine being like a man pushing a truck in front of him rather than him pushing with his back to the truck,[13] which in the latter case would have required the knee to hinge forwards. Furthermore, by virtue of its length and an inability for the knee to move vertically,[14] the shin could not have been brought into a position with an opposite rake angle so as to have exerted a force in the direction necessary to propel the locomotive backwards. In the second instance, the foot raising mechanism enabled the trailing foot to be lifted at the extremity of the stride for forward motion but did not allow foot lift to initiate from the boiler end of the stride as would have been required for reversing. The friction sheaves used to control foot lift can be seen to have been provided for forward motion only. A single ratchet and pawl per sheave and per leg is shown in Figure 6 of the patent (**Plate 2**) but a switchable duplicate set with reversed ratchets would have been needed to facilitate reverse travel.

The locomotive as popularly envisaged would have needed either a solution to turn it round so it could return to the starting point of its journey under its own power, or a means of supporting the legs clear of the ground to permit an unpowered return by gravity or horse power, perhaps in the manner of later horse Dandy wagons. A long rigid coupling bar would have been required in the latter case to prevent damage to the leg mechanism during compression of the couplings.

The inability to reverse the direction of travel must be regarded as one of the most significant shortcomings of Brunton's design.[15]

THE FOOT-RAISING MECHANISM

It would be inaccurate to regard the means to raise the idle foot as a minor detail of design, as without such a mechanism and the accompanying provision of a knee joint, Brunton's locomotive could not have worked as he described since the engine would have been continuously stubbing its 'toes' on stones, undulations and other obstructions on the walking path of the railway. The trailing foot would have been subject to severe wear whilst being dragged during the return phase of the stride and, perhaps more importantly, the pathway beneath it would also have been damaged. Both the importance of the mechanism and the effectiveness of Brunton's solution to this problem became apparent to the author during construction of the model.

In his patent Brunton described in detail a complex arrangement combining both ratcheted and free-rotating friction-sheaves in a compound grouping, leather straps of two widths and accompanying counter weights that he suggested as a means to control the lift-return-lower (transfer) phases of the foot locus.[16] The complexity of

[13] Guy, 2001, 125.
[14] The knee, piston rod, bottom of the thigh and top of the shin moved in an exact straight line determined by the half beam motion described variously by Oliver Evans, William Freemantle and later by John Scott-Russell, the name by which the motion is commonly known.
[15] The Newbottle waggonway map of 1817 shows turntables only at the staith (see OP 232), although it is possible that others *en route* had been removed since the disaster of 1815.
[16] A Ghassaei, *The Design and Optimization of a Crank-Based Leg Mechanism,* Pomona College Department of Physics and Astronomy, thesis (2011), 6.

the mechanism is perhaps indicative of the attention paid to its design and its importance to the functionality of the locomotive overall. But Brunton in his patent notes says only that '…any contrivance similar in its effects…may be employed…' which shows that he may not have fully realised himself either that the mechanism was critical to walking or that the arrangement described and apparently used on the Crich locomotive was, arguably, both effective and reasonably efficient.

In a 1990 paper discussing passive-dynamic[17] walking machines, McGeer[18] described how in experimental walking machines lacking knee joints, the energy required to lift the foot using a motor-driven telescopic leg was greater than that required for forward movement itself. Inspection of Brunton's system of straps and counter weights shown that these must have utilised energy from forward motion and stored a fraction of this temporarily in the counter weights to facilitate foot-lift during bending of the leg at the knee. This is somewhat analogous to the spring effect of tendons in animals that provides near passive knee lift. Stops to limit the height by which the foot was raised are described in Brunton's patent and these could either have been an adjunct to the strap, perhaps in the form of a pin through the strap to prevent it passing over the friction sheave, or a limit to the freedom of movement at the knee joint. To what extent Brunton would have understood the significance of the knee joint in facilitating foot-raising is questionable as he was probably drawing directly on observation of animal locomotion.

A diagram (**Plate 7**) of the foot locus[19] can be conjectured from Brunton's published description of how the mechanism worked aided through the use of the model[20] and is further illustrated in **Appendix 1**. This diagram requires validation by further experiment or mathematical modelling of Brunton's mechanism as the model lacks the free rotating section of the friction sheaves and the associated narrow part of the straps. The diagram can be usefully compared to a similar plan (**Plate 8**) for the locus of a typical and widely employed modern mechanical walking-machine invented in 1989 by artist Theo Jansen[21] and drawn here after Ghassaei.[22] The modern machine uses a complex linkage comprising of eleven rigid bars with moveable joints based on parallel-motion principles to a design optimised by computer. Whilst there are significant differences between them, the comparative shape of the locus for these disparate machines separated by 176 years in time nonetheless serves to demonstrate the probable effectiveness of Brunton's foot-raising system.

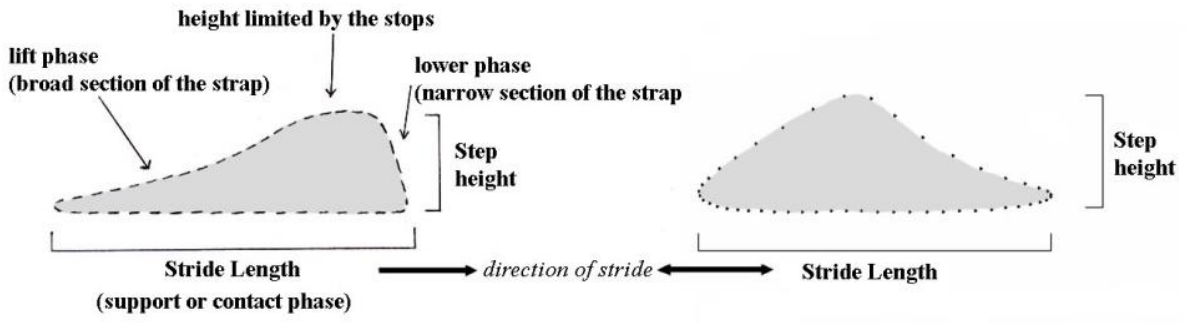


PLATE 7: Brunton (Crich) **PLATE 8: Theo Jansen**

[17] Passive-dynamic: in this context, a machine with legs but no knees incorporating a pendulum motion and capable of walking down a slope with no force input other than that of gravity. Such as machine exhibits dynamic stability but static instability. Human locomotion is also thought to follow this pattern but with the addition of knee joints.
[18] T McGeer, 'Passive Dynamic Walking', *International Journal of Robotics Research*, vol. 9, no 2, (1990), 77.
[19] The locus is the path of the foot seen as if walking on a treadmill from the side view.
[20] The author's small 1/32nd scale electrically-powered model simplifies the friction sheaves eliminating the inner free rotating sheaves and associated narrow straps and the locus of the model is not therefore identical to that of the prototype. The model also has two 'cylinders' and can run without the rack and pionion mechanism.
[21] Theo Jansen, www.strandbeest.com.
[22] Ghassaei, 2011, 32.

Brunton's initial 'lift' phase is perhaps a weakness and could have resulted in toe scuffing until the foot was well into its return cycle and the step height sufficient for safe ground clearance. But the 'lower' phase controlled by the narrow part of the lifting strap and the free rotating central section of the sheave assembly should have given a rapid and precise ground contact or heel strike,[23] perhaps superior to the comparative modern mechanism. The length of the support or contact phase defines the stride length.

The duration of the contact and transfer phases of the locus differ for the two examples shown. Whilst Brunton's machine must exhibit contact and transfer phases of almost exactly equal duration as the legs are phased at 180 degrees, the Theo Jansen device maximises ground contact time and minimises the transfer phase period by varying the angular velocity of the foot as indicated by the density of dots in the diagram.
Brunton's design had the potential for a characteristic not seen in any simple fixed-bar mechanical walking-machine, including that of Theo Jansen. As Brunton used flexible straps rather than fixed bars these permitted, at least in theory, the geometry of the foot lift system to vary. When combined with the motion of the counter-weights the arrangement could have imparted a road speed dependent variation in the relative duration of contact and transfer phases during locomotion; simply put, to a gait transition[24]. It is of course very unlikely that Brunton's machines could have progressed at anything much greater than walking pace so gait transition is unlikely to have occurred in practice even if the stops to control step height did not otherwise prevent it.

A notable feature of Brunton's locomotive is that the foot-lifting straps cross over to the friction sheaves on the opposite thigh. Whilst details of this mechanism are shown in Figures 1, 7 and 8 of Brunton's patent, (**Plates 1 and 2**) in the side view so widely used by later commentators the straps are often shown erroneously connected to the friction sheave of the adjacent rather than the opposing leg. Of the early writers, Nicholas Wood describes the foot- raising mechanism in detail but all the derivative images of Brunton's locomotive fail to show the associated counter-weights at all.

It seems probable that at one point during the stride cycle there may have been contact between the two lifting straps where they crossed and this would have interfered with the precision of the foot raising mechanism by changing the effective length of the strap and thereby altering the height of the foot lift. The provision of stops to control step height suggests that there was excess lift provided so the effect of this interference may have been nullified in practice. The flat leather belts or straps Brunton used would probably have slid over each other without binding or creating excessive wear.

An efficient design of friction sheave requires the angle between the sheave bearing axis and the axis of pull on the rope or strap wrapped over it to be small. A sheave works most efficiently when these axis are parallel to each other. In Brunton's patent drawing Fig. 2 and 3 (**Plate 1**) showing the location of the friction sheaves in plan and end elevations, there is an implicitly large angle between the strap and the sheave axis where the strap crosses from one leg to the other. The issue could have been resolved by angling the sheave assembly on the thigh extensions to align it with the straps. Brunton would have been very familiar with belt-driven machinery so an efficient arrangement should have been provided.

STEP LENGTH: EXPLORING THE IMPLICATIONS OF SIMPLE ENLARGEMENT OF BRUNTON'S MECHANISM

To understand further the design parameters for the leg or propeller mechanism of Brunton's Newbottle locomotive with a 6 feet step-length it is first necessary to explore what a machine would have looked like if the increased step-length had been achieved simply by enlargement of the popular image, or at least an enlargement in isolation of the leg mechanism taken from it.

[23] 'Heel strike' is a term used in biomechanics and robotics. The heel is usually the first part of the foot to contact the ground during locomotion.
[24] 'Gait transition': the change from walking to running in bipeds or walking – trotting – galloping in quadrupeds

Firstly, enlargement would, by simple trigonometry, have required the cylinders to have had a stroke length of no less than 66½ inches as they would have been directly connected to the knee joint and the 6 feet step-length was derived from this via the angled shin of the leg. Retaining a 6 inch diameter cylinder as per the Crich engine would have led to a cylinder with an enormous ratio of stroke to diameter of 12:1, far greater than anything that even Trevithick, who used some notably long cylinder strokes,[25] ever seems to have adopted. Even if the cylinder diameter was enlarged to 8 inches, more typical of contemporary locomotive practice, the ratio would still have been 9:1. With such a long cylinder length it would have been difficult to maintain 50 piston strokes per minute, [26] the rate required for Brunton's stated increase in road speed. Under these conditions, the velocity of the piston in the cylinder would have been necessarily nearly three times higher than for the Crich engine, potentially causing difficulties with cylinder lubrication and excessive wear. This suggests that an alternative piston connection, perhaps using gears, cranks or levers would have been required to derive the stated step-length whilst permitting the use of cylinders with a stroke length similar to that of the Crich locomotive and possibly sharing a common cylinder casting perhaps with it bored out to a greater diameter.

Closely allied with the cylinder stroke and step length is the length of the corresponding racks that transferred power on the return stroke to the opposite leg. Unless the cylinders were connected indirectly to the legs by cranks, then such a mechanism would still have been required to utilise the full power of the double acting cylinders, even on a two cylinder locomotive. For the Crich locomotive, each of the support guides for the racks needed to be just under 4 feet long, i.e., double the piston stroke minus a small allowance for the positioning of the rack connection slightly above the knee. This is feasible as it is less than the known length of the boiler. The same mechanism on a scaled-up engine would have needed to be approximately equal to the double step- length of 12 feet, which even allowing for the effects of leg angle would have meant the rack guides being over 11 feet long. Such long rack guides would almost certainly have been longer than the boiler itself, which does not seem plausible.

Scaling up the patent drawing to the 3 feet 6 inch gauge of the Crich plateway produces a short-step locomotive that is around 9 feet 6 inches tall to the top of the motion standard[27] and therefore within the known loading gauge of the surviving Fritchley tunnel.[28] Conversely, the overall height from rail level of an enlarged leg mechanism with a step length of 6 feet would be approximately 25 feet tall, making it too large to fit within the typical British railway loading gauge or even the modern USA 'double stack' specification[29] with its 20 feet 2 inch clearance. It is clearly too large for use on any early nineteenth century industrial tramway designed for horse operation.[30]

Simple enlargement of the legs on the traditional image of Brunton's locomotive raises the further general objection of weight. For his first engine Brunton can be seen to have been mindful of the limitations of the cast-iron plate-rail technology on the Butterley Gangroad with which he must have been familiar. Chapman's Butterley-built locomotive, probably conceived with just four wheels[31] rather than the six wheels (including a

[25] T Brogden, 'Tom's steam carriages', *The Steam Car*, vol 18, Jan 2003, and http://www.steamcar.net/brogden-1.html, quoting a letter by R Trevithick dated 2 May 1803.
[26] The stroke rate of the Crich locomotive can be calculated from the step length and Brunton's stated speed of 2.5 mph as being 50 strokes per minute.
[27] The 'standard' referred to here is the prominent, tall, approximately triangular bracket on top of the boiler shown in Figure 1 of Brunton's patent to which the hip is connected via radius rods. The chimney height is not known and cannot be used.
[28] B Griffin, D Bunting & B Key, 'The Butterley Gangroad', *Derbyshire Archaeology Journal*, vol 134 (2014), 221-252; and http://www.butterleygangroad.co.uk/bg2a0001%20das%20-0the%20butterley%20gangroad.pdf ; Wessex Archaeology survey of April 2013 for Derbyshire Archaeological Society, report 89010.0, section 4.2.1. Tunnel height of 10 feet (3.05m).
[29] CSX Corporation, *System Clearance map: double stack* (Jacksonville USA, 2015).
[30] The Newbottle waggonway map shows the track running under a road bridge near Sunderland (OP 232), limiting the clearance for a locomotive.
[31] CF Dendy Marshall, *History of the railway locomotive down to the end of the Year 1831* (London, 1953), 69.

bogie) actually adopted, might be seen as evidence that engineers like Brunton needed to be cautious with regard to establishing the true axle-loading of early locomotives. The experience of supervising the building of Chapman's Butterley locomotive could have influenced Brunton's decision making, leading to a very small engine indeed for Crich and perhaps an initially under-sized boiler for the Newbottle locomotive. Allowing for the majority of the locomotive's weight being determined by the wheels, frames, inclusion of two cylinders, a correspondingly enlarged boiler and its increased water content, the projected size increase of the legs would be so significant that even using timber rather than iron to save weight, as in early beam-engine construction, it seems likely that a simple enlarged version of the legs would have adversely compromised the five ton weight of the machine.

As might therefore have been anticipated, it seems appropriate here to draw the conclusion that simply scaling up the leg mechanism of the popular image of Brunton's engine does not offer a design solution compatible with the known parameters of the Newbottle locomotive, although it does provide some useful insights and boundaries to what is plausible.

Any alternative hypothetical solutions to resolve the step-length problem requires the new issues identified above to be addressed: Firstly, some form of gearing, levers or cranks to disconnect the piston from the knee joint and allow the cylinder stroke to remain the same or similar to that of the Crich engine and comparable with other contemporary locomotives. Secondly, but perhaps most importantly, to reduce the physical height of the legs to fit within a reasonable loading gauge for a horse waggonway whilst retaining the essence of the previous design and, thirdly, to keep the weight within the known limit of five tons by making the leg mechanism simple and compact. Whilst it may be observed that there could be myriad permutations of such schemes, in the contemporary image of 'The Grave Diggers' we arguably have a more useful starting point than has been previously recognised.

AN ALTERNATIVE SOLUTION TO THE LEG MECHANISM BASED ON 'THE GRAVE DIGGERS'

If a hypothesis is allowed that the image of 'The Grave Diggers', a satirical print of c1820-30[32] (**Plate 9**), could have been based on the reality of Brunton's engine rather than just a bad interpretation of the patent drawing, this new benchmark could be used to explore hypothetical arrangements to match aspects of the mechanism shown in the cartoon. Within the obvious limitations of the drawing, 'The Grave Diggers' can reasonably be taken to specifically represent the Newbottle engine if the allusion to death is associated with the fatal boiler explosion of 1815. In such a scenario, the fundamental question to consider is how the artist might have obtained the information upon which the sketch was based. Was this first hand as an eye witness to the engine when still complete, of the wreckage after the explosion[33] or perhaps, more likely, only from third party descriptions of it? What is undeniable is that the cartoon differs to such an extent in both substance and detail from either the patent drawing or its later derivations as to suggest an alternative origin for the information upon which it was based, either through an unusually acute imagination or perhaps, quite possibly, from observation of the locomotive itself. This seems to be a compelling argument for a re-evaluation of 'Grave Diggers' as an information source for the Newbottle locomotive.

[32] One of a number of vignettes within a print entitled 'The Progress of Steam' (Beamish Museum, neg no 73843), showing ludicrous (and it would turn out, some not such absurd) uses of the steam engine. Transfer-printed pottery plates with these same scenes are illustrated and described in N Riley, *Gifts for good children: the history of children's china 1790-1890* (Ilminster, 1991), 178-9, plate CXVI.

[33] The 1817 Newbottle waggonway map carefully identifies (twice) a site on the line called 'Steam Horse', presumably the shed for Brunton's locomotive, despite the two years since the locomotive's explosion: OP 232. It is possible that the remains of the engine were kept there and could be viewed.



PLATE 9: The Grave Diggers (courtesy of Beamish Museum, neg no 74719)

In **Plate 10**, the half-beam motion is modified so that the thigh of the classic Brunton engine is folded over on itself at the knee, a change which does not affect the fundamental functionality of the mechanism which can be proved by construction of a simple cardboard model described in **Appendix 2**. Arguably, we then see an engine which has significant correlation to the 'Grave Diggers' drawing, far more so than has the popular image and one that might fit within the loading gauge of a horse waggonway. As with the cartoon, the distinctive tall motion standard to suspend the thigh at the hip joint so prominent in the patent drawings is no longer required.

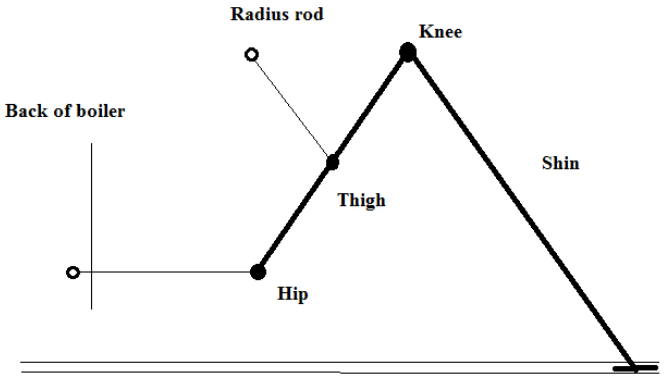


PLATE 10: A conjectural resolution of the step or stride problem with the thigh beam inverted. A single leg in the extended position is shown in side view.

In its place, the cartoon shows some shorter connections along the top of the longitudinal centre line of the engine, perhaps suggestive of the two radius bars and their associated fixings which would still be needed to maintain the axis of travel of the knee and shin. The support for the radius bars must now be carried on a bracket set about three feet out from the back of the boiler to accommodate the desired step length. These two radius bars supporting the piston rods would need to be inverted in the hypothetical arrangement relative to the patent drawing. And these now neatly correlate with the orientation of the uppermost short connections seen in the cartoon. The horizontal links supporting the inverted hip joint previously carried by the tall standard on the boiler top would have to be re-located in an under-slung position and do not seem to have analogous representations on the cartoon. But these could have been converted into a sliding joint as shown in Freemantle's patent[34] rather than the more common arrangement akin to Oliver Evans' version of the 'Grasshopper' motion used by Brunton on the Crich locomotive. Central to the hypothesis is that the inverted thigh beam is strongly reminiscent of the substantial unarticulated diagonal rod shown at the side of the boiler in the satirical print, particularly so when the leg is in the rearward extended position. And almost as importantly, the long shin becomes the dominant visual feature directly mirroring that in the 'Grave Diggers' drawing.

Taken together, the peculiar features which previously might have caused the 'Grave Diggers' drawing to be disregarded because they differed so radically from the patent image begin to resolve themselves into something recognisable in spirit, if not in detail, as the makings of a tangible, functional, walking machine.

[34] William Freemantle's Patent GB2741/1803: *The Repertory of Arts, Manufactures and Agriculture,* vol V, no XXVI (1804), 80-89.

There still remains the problem that the cylinder drive needs to be geared or leveraged to match the stride length whilst the connections to and location of the cylinders is not immediately obvious. Brunton's patent allowed for use of vertical cylinders and cranks to drive the mechanism but 'Grave Diggers' is insufficiently detailed to any give guidance in this respect. Nor is the previous method devised to raise the returning idle foot any longer appropriate without re-design, although Brunton presented other options for foot raising that might have resolved this problem too.

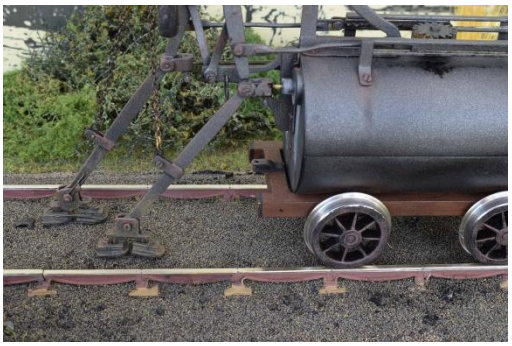
CONCLUSION

Brunton's locomotives can at last be seen to have offered a viable, if marginal, design solution to the problem of locomotion, albeit one with severe limitations which would have rendered the concept obsolete within months even in a counter factual world where the Newbottle explosion did not take place. Neither the limitation to reverse travel nor the poor utilisation of weight that caused issues from wheel lifting could have been easily resolved within the technological constraints of Brunton's day. For the first time the importance and effectiveness of the foot lift mechanism, described and drawn in such detail in the patent, has been demonstrated through the use of an inexpensive model and comparison with comparable modern robotic machines.

Finally, with regards to what may be considered the contentious hypothetical solution offered for the Newbottle locomotive design, it is perhaps worth recounting that, in Brunton's obituary the anonymous author quotes Brunton's description for the Newbottle engine saying that the piston connection is joined to the thigh below the knee. Pendred showed that this could not have been correct as attachment to either a thigh extension or to the shin below the knee would have prevented the piston rod moving in a straight line had the locomotive been constructed in accordance with the patent. The model has supported Pendred's criticism of the published patent drawings confirming that the fixed mounting point and radius bars he suggested were required to complete Brunton's mechanism. The description of the Newbottle engine given in Brunton's obituary does, however, seem to fit perfectly satisfactorily with the hypothesis of an inverted hip design. Readers must draw their own conclusions.

APPENDIX 1

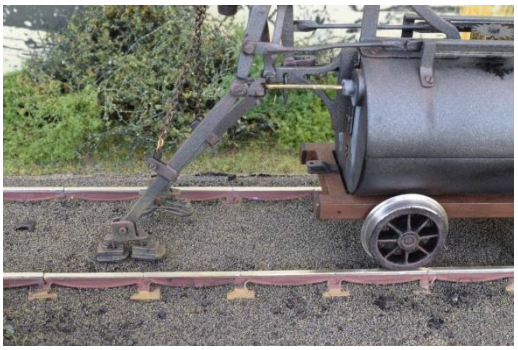
The following series of photographs illustrate the path (locus) of the right foot of the model during walking:



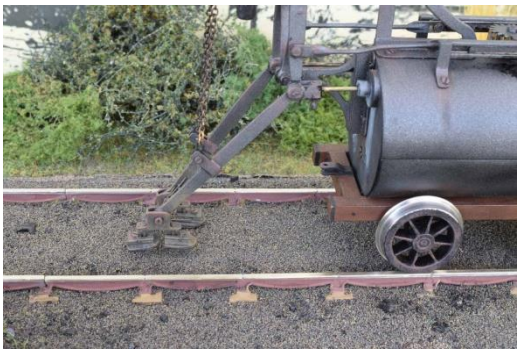
1. Heel strike – start of right foot stride



2. Contact phase – mid stride, driving with the right foot



3. Initiation of lift or transfer phase – right foot returning forward idle



4. Lift phase – midway through the return of the right foot, left foot now driving.

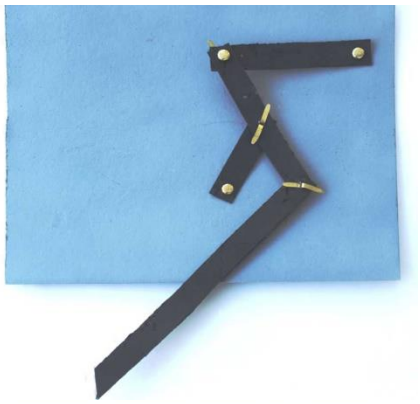
Demonstrations of the working model can currently be seen on YouTube:

https://www.youtube.com/watch?v=Z-GWBdG02Hg
https://www.youtube.com/watch?v=HJgKldFbXSw
https://www.youtube.com/watch?v=jffVbuUhblc
https://www.youtube.com/watch?v=qUeFGhISEwg
https://www.youtube.com/watch?v=6b2a7z2__jk

APPENDIX 2



The statement is easily proved by making a simple two dimensional model of a grasshopper engine fixed to a board using strips of cardboard for the levers and brass paper fasters as joints in the motion.



Firstly, by turning the board through ninety degrees so that the beam is vertical with the 'piston' end facing downwards, the piston rod of the grasshopper engine can be seen to emulate the shin of the Crich engine – a second rod fixed to the same joint would be needed to represent the piston of the Crich engine which had a common joint for both piston and shin.



Secondly, by simultaneously inverting both the board and the shin from the positions described for the Crich locomotive, the model becomes the hypothetical inverted thigh engine. No joints or rods are changed during these transformations so functionality is preserved. A template from which to cut out the parts for this model is available.

[The author is currently preparing an article on the construction of the model for the model railway press]

April 2017