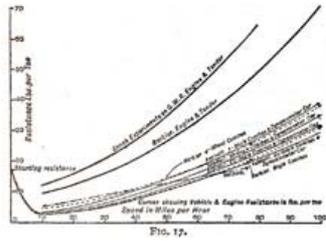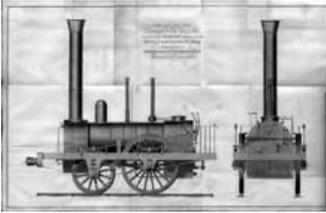# The Brooklyn Historic Railway Association

Why Rail Has 20X Energy Saving Advantage Over Rubber Tire Road Vehicles - The Science of Locomotion

Train Resistance Graph A, Vol. 22, pg 844, Encyclopedia Britannica 1911

Early "Planet" type steam engine.

Early Wood Burning Locomotive Exhaust Partially Covering White Washed Tunnel Roof.

Replica of the "Planet" type steam engine.

"Samson" type steam engine.

Introduction

The study of the old and largely forgotten scientific principals behind what makes trains and railroads work, is an interesting field. For example, one would think that the heavier the train, the more energy per unit weight would be needed to move it. In reality, the reverse is true: as the weight of the rail cars goes up, the energy per ton required to propel the train goes down. It takes much less energy per unit weight (lbs f/Ton) to move a 20 car train, than to move a 5 car train- and still even less energy per ton, than a locomotive running by itself ! (See the graph from the circa 1911 Encyclopedia Britannica). Note: this phenomenon DOES NOT apply to rubber tire vehicles, because of certain factors due to friction, such as "fractional hysteretic energy loss" and "contact modulus [elastic stiffness] ".

The Physics Behind Transportation Energy Efficiency

On the Atlantic Avenue tunnel tour, one of the many things we discuss, is the contemporary soot deposits left on the interior of the tunnel's arch. There is surprisingly little. Why? Low powered steam engines = small soot deposit.

Some of the LIRR's locomotives, such as their "Planet" types (Hicksville, John A. King), produced as little as 30 HP, the same amount of work energy produced by a modern "ride on top" lawn mower. At the time (1844), the LIRR was the fastest railroad in the U.S., operating trains at peak speeds of 50- 60 mph (average speed 38 mph). **How could a fast, heavy train possibly be moved by a force of only 30 HP?**

In the early 19th century, it was discovered by empirical observation, that it only took 8 (eight) pounds of force to move a one- ton weight (or 1/248th part of the whole weight) on a level railroad. (Note: This value was formerly called "Train Resistance". The modern term is "Starting Resistance", which can also apply to highway vehicles). The value cited reflected the primitive friction bearings of the time. It was also discovered, that a force 20 times greater, or 160 pounds (1/12th part of the whole weight) was required to move a one- ton weight on a contemporary [level] common road. Source: American Railroad Journal (ARJ), June 2, 1832, pg 354.

It should be further noted, that "Starting Resistance" is the force required to get an object at a dead stop moving, and is substantially greater than "Rolling Resistance", which is the force required to keep an object already rolling, moving at the same final rate. However, our immediate interest is only in the force required to start a train or truck from a dead stop- simply the "Starting Resistance" aka "Train Resistance". We will take up the topic of the comparative "Rolling Resistance" between steel wheeled railway vehicles, and large rubber tire road vehicles, and its direct effects on energy efficiency (rail is far superior), towards the end of this piece.

First, we're going to perform our calculations in the strictly old school way, only accounting for the factor "Starting Resistance", reflected at different operating speeds. While this original method accounts for the energy required to accelerate from a dead stop to operating speed, in which a modern diesel electric locomotive has about a 10X energy demand advantage over a truck accelerating to 50 mph (a circa 1830's steam locomotive had a 6X advantage over a truck accelerating to 50 mph), it literally only tells half the story. Later, we'll re-calculate using a modern approach, which will reveal the extreme 20X energy efficiency advantage rail has over all types of large rubber tire road vehicles. The advantage in efficiency that railroads have over road transport, is in the rail itself rather than the motive power. There's less friction on account of the relative inelasticity of the wheel and rail.

The key common factor between these physical relationships, is a level surface, which the LIRR has, by way of its natural geology. In general practice, railroad grades are kept as low as possible. This sometimes led to circuitous routes around mountains, or the use of bridges, tunnels, cuttings, embankments or "switchbacks". At the other extreme, some coal railroads in Pennsylvania were powered by gravity.

A look at the specifications and capabilities of some of the very earliest railway locomotives, and comparisons to modern trucks and locomotives:

In the formulas used in this piece, the results are expressed in terms of Power, Speed, Weight and Force. For example, we refer to the formula HP = PLAN / 33,000, which comes into play a little bit later.

To clarify, Work = (force x distance). However, HP and TP (Tractive Power) are measures of Power = (force x distance) / time.

A less descriptive, but simpler and more versatile (steam, diesel or electric) method of determining locomotive HP, other than HP = PLAN/33,000, which only worked for steam locomotives,   is as per the mathematical relationship between HP, TP and Speed "S" (mph), described (in the Brotherhood of Locomotive Fireman's and Enginemen's Magazine, Vol XLVI, Jan- June 1909) by the following formula:

HP =(TP x S) / 375

For a brief, but good, explanation of the inter-relationship between HP, TP, Speed, "Train Resistance", "Speed Resistance" and "Grade Resistance", see the ca 1909 writing cited above, pg 841- 842 here.

It is known*, that the small "Planet" type engines of the period, [at 30 HP power output], produced a Tractive Effort (T.E.) in the range of 1,450 lbs to 1,550 lbs. on level track. Let's do the arithmetic: 1,550 lbs / 8 lbs / Ton = 193.75 Tons total train weight.
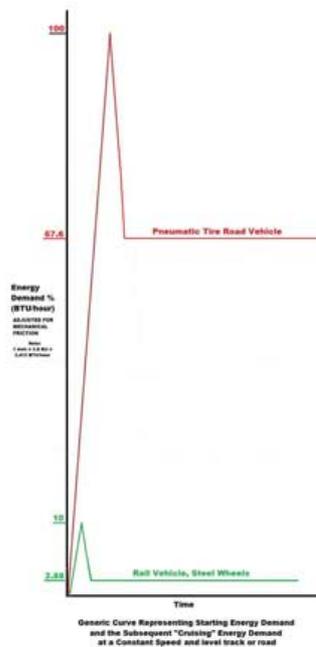
Using the equation**

S = (375 x HP) / T.E. (lbs.)

Where:

S = Speed in mph,
HP = Horsepower,
T.E. (lbs) = (Train Weight (Tons) x 8 lbs/Ton)

And Setting:

HP = 30
T.E. (lbs) = (193.75 Tons x 8 lbs) /Ton = 1,550 lbs.

Generic Curve Representing Starting Energy Demand
and the Subsequent "Cruising" Energy Demand
at a Constant Speed and level track or road

Why Railways Are 20X Energy Superior To Pneumatic Tire Vehicles
"Footprint" Comparison:
The "Contact Print" of a 22.5" x 8.25" Truck Tire (a), Compared to a 27" Bi-
cycle Tire (b), and a Typical 35" Steel Railway Wheel (c).
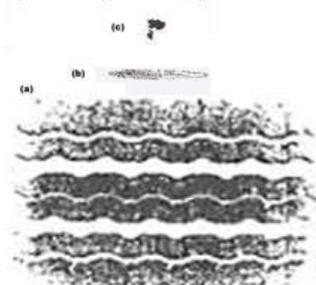
Source (c), (b):
Bicycling Science, by David Wilson, pg 218

Source (a):
Vehicle, Tire, Pavement Interface,
Henry/Wambold ASTM STP 1164,
1992, pg 143

S = 7.2 mph

Let's now speed things up a bit, to 20 mph...and further define Tractive Power (TP):

Tractive Power (TP), also known as Tractive Effort (TE) is only one of the factors used in calculating the relationships between HP, gross train weight and speed. Refer back to the formula HP = (TP (lbs) x S) / 375.

The required TP in lbs, is the (gross train weight in Tons x Train Resistance in lbs/Ton).

On level track, "Train Resistance" was cited as 8 lbs/Ton back in 1832, and was about the same in the ca 1909 writing. The ca 1909 writing cited basic "Train Resistance", (or "Friction Resistance" as they referred to it) as 6 lbs/Ton, but then they added a minimum of an additional 2lbs/Ton for "Speed Resistance", bringing us back to a total "Train Resistance" of 8 lbs/Ton.

By substitution, we get gross train weight

GCW (Tons) = (375 x HP) / (S x 8),

Or,

HP = [GTW (Tons) x 8 lbs/Ton x S] / 375

Tractive Power (TP) of a steam locomotive can also be expressed by the following formula:

Tractive power equals the square of cylin-der diameter, times stroke in inches, times mean effective pressure per square inch [boiler psi x 0.85], divided by the diameter of the driving wheel in inches. Put in the shape of a formula this is :

Tractive power in pounds = (d² x S x P) / D

Where:

d = diameter of cylinder
S = length of stroke in inches,
P = mean effective pressure.
D = diameter of driving wheel.

Source: The Americana Encyclopedia, 1912, Vol 13, pg 51

Now, lets look closer at a key factor in both TP and HP: level track.

As per the the American RR Journal of 1832, once grades are introduced, the railroad starts to lose its efficiency. This is why railroads had to be laid on as level right of way as possible. Otherwise, circuitous routes, tunnels, bridges, cuts, embankments, inclined planes or switchbacks had to be used. This concept is also restated in the ca 1909 writing.

If you incorporate grades (causes power requirement spiking) on your railroad route, the HP required increases drastically, by a factor of [20 lbs for each per cent of grade]. As per the ca 1909 writing, assuming a grade of 3.6%, we then get the following formula:

HP = (70 x 20 x [20 x 3.6]) / 375 = 268.8

Where:

70 = gross train weight in Tons
20 = Speed in mph
[20 x 3.6] = "Grade Resistance" factor

What this means, is if the maximum grade on your railroad is 3.6%, your engine must be able to produce 268.8 HP, but only while its pulling the train over the hill at 20 mph. However, the same engine only needs to produce 30 HP to pull the same 70 Ton train at 20 mph on level track.

Here's an electrical analogy. My High School music teacher had a particular stereo amp that could put out a maximum 200 watts / channel (1 HP = 746 Watts). It had Watt meters on its speaker outputs. At normal volume, the amp never put out more than 3 to 5 watts / channel into the big speakers. However, at the loudest crescendos, it sometimes momentarily spiked up to 100 + watts / channel. They key thing, is the amp had to have enough reserve power to get over the momentarily increased peak power demand requirements, which corresponds to the grades on a railroad.

To improve efficiency in any system, get rid of the "demand peaks", and a lower constant power level will be enough to keep things flowing at a "high" constant rate.

The following calculations were empirically confirmed by runs made in 1830 and 1831 on the Liverpool and Manchester Railway. The original (and most primitive) Planet locomotive (9 Tons) drew a train of 18 "waggons" (four wheel rail cars) weighing some 80 Tons at 14 mph on level track. According to the formula HP = (80 Ton x 8 lbs/Ton x 14 mph) / 375, the Planet engine was exerting 23.8 HP. The Planet had only two driving wheels (2-2-0) wheel arrangement.

The equally primitive engine Samson (10 Tons), drew a train of 30 "waggons" weighing 164.5 Tons, at a speed of 20 mph on level track. According to the same formula, the Samson was exerting 70 HP. The Samson had 4 driving wheels, of smaller diameter than the Planet's, they were of coupled (0-4-0) wheel arrangement, and also had larger cylinder bore (larger engine displacement) than the Planet.

The Samson consumed its coke fuel at a rate of slightly less than 1/3 pound/mile/Ton.

Note, the Samson was the same basic machine as the John Bull rebuild/replica locomotive currently on display at the Smithsonian.

Further, the American Railroad Journal of Aug 1, 1842, pg 90, states a train carrying 1,608 barrels of flour, of 200 Tons weight, was drawn from Albany to Boston.

Let's now calculate the HP output of the Samson locomotive, at 20 mph and a train weight of 164.5 Tons.

Using the formula***

HP = (PLAN) / 33,000, where:

P = 0.85 x Boiler Pressure in psi.
L = 2 times the stroke length in feet
A = area of piston in inches sq
N = rpm = revolutions / minute

Plugging in the data****;

P = 0.85 x 60 psi = 51 psi
L = (2 x 16") / 12" = 2.6 ft
A = 3.14 x [7" squared] = 154 inch sq
N = 123 rpm - how did we get this number? 1 mi/hr = 5,280 ft / 60 min = 88 ft/min; 20 mph = 20 x 88 ft/min = 1,760 ft/min; the driver diameter is 4.5 ft; driver circumference = 3.14 x 4.5 = 14.13ft / 1 revolution; (1,760 ft/min) / 14.31 ft/rev. = 123 rpm.

We get the following results for the Samson engine:

HP = (51 x 2.6 x 154 x 123) / 33,000 = 76 HP. Lets say 70 HP, to agree with formula 1.

Using the same formula, with the Planet engine's empirical and specification data; (same pressure= 51, same stroke= 2.6, 11" diameter piston; radius = diameter/2; A= 3.14 x (5.5 squared)= 95 inch sq; with 5 ft drivers at 14 mph, we have 3.14 x 5 ft/rev= 15.7 ft/rev and 14 x 88 ft/min= 1,232 ft/min, rpm= (1,232ft/min) / (15.7 ft/rev) = 78.5

Therefore, we get 29.96 HP for the Planet type engine. Lets say 30 HP, to agree with the historical information cited above.

As we can see from the formula HP = (TP x S) / 375, circa 1830's locomotives could pull a 70 ton train on level track at 20 mph, with only 29.8 HP.

Let's compare the ratios of horsepower to maximum weight, on level ground, and at 20 mph. Using the same formula above, setting the speed of the Planet type engine to 20 mph, at 30HP we get a maximum train weight of 70.3 Tons.

Therefore, for the circa 1830 Planet type railway steam engine, at 20 mph, the horsepower to weight ratio was: 30 HP/70.3 Ton = 0.4267 HP/Ton. For the circa 1831 Samson type locomotive, the horsepower to weight ratio was 70 HP/164.5 Ton = 0.425 HP/Ton.

Efficiency comparison between Primitive Locomotives and Modern Tractor Trailers (at 20mph Speed)

Compare the above weight ratios to those of a modern highway tractor- trailer. For example, a typical popular make of truck tractor, has a "GVW" (gross vehicle weight) of 39 Tons. Its modern diesel engine produces 440 HP. Its GCW (gross combined weight = tractor + trailer + load) is 70 Tons. This means the modern highway truck tractor can only draw less than 2 times (1.79) its own weight.

Compare the tractor- trailer weight ratio numbers to those of the small, light weight (10 Ton) Samson steam locomotive drawing 16.45 times its own weight, with only 70 HP. In terms of comparative "weight only" ratios, the early 19th century railway steam locomotive was 9.2 times more efficient than today's highway tractor- trailers [16.45 Samson locomotive weight ratio / 1.79 tractor- trailer (Mack "Granite Elite") weight ratio] !

For the modern tractor- trailer the horsepower to weight ratio is 440 HP/70 Ton = 6.285 HP/Ton.

By dividing 6.285 HP/Ton (tractor- trailer) by 0.4267 HP/Ton (Planet type steam engine), we find that at 20 mph, in terms of the comparative horse power to maximum weight ratio, the circa 1830 railway steam engine is 14.7 times more efficient than a modern tractor- trailer !

To restate our data back into the original circa 1832 terms of "force per Ton" required to move 1 ton on a railroad, compared to the "force per ton" currently required to move 1 ton on a highway, we perform the following conversions:

Using James Watt's definition of a horsepower (circa 1783), I derived these conversion factors:

As per Watt, 1 HP = 33,000 (ft x lbsf) / min

Therefore,

In the case of the circa 1830 steam locomotives, plugging in data from above, we have:

0.43 Hp / Ton = (33,000 x [0.43 (ft x lbsf)/min]) / (1 Ton/2,000 lbs) = 7.1 lbs / Ton "Starting Resistance"- not accounting for bearing friction

Assuming bearing friction accounts for an additional 11.25 %, we get 7.1 lbs/ Ton x 1.1125 = 7.9 lbs/ Ton, "Starting Resistance" or 1/253 part of the gross combined train weight (locomotive + cars + payload). Note the ca. 1832 empirical values for "Starting Resistance" (train) as cited above, were 8 lbs/ Ton, and 1/248th of the GCW.

For the modern truck tractor (Mack "Granite Elite"), plugging in data from above, we have:

6.285 HP / Ton = (33,000 x [6.285 (ft x lbsf]) / (1 Ton/2,000 lbs) = 103.7 lbs / Ton "Starting Resistance"- not counting bearing friction:

103.7 lb / Ton x 1.1125 = 115.4 lbs / Ton "Starting Resistance", or 1/17th part of the Gross Combined Weight (GCW)

It appears that at a speed of 20 mph, the efficiency of a standard highway vehicle has not improved much from the cited circa 1832 value of 1/12 part of the GCW !!

Therefore, during the days of primitive steam powered railroads circa 1830's, moving a ton by rail at 20 mph was 14.6 times more efficient than moving a ton at 20 mph by modern truck !!

Efficiency comparison between Primitive Locomotives and Modern Tractor Trailers (at 40mph Speed)

Let's now consider a speed of 40 mph:

Its seems obvious from the formulas, that if you want to double the train speed from 20 mph to 40 mph, you have to double the horsepower, and so forth.

Doubling the speed (and thereby the HP) of the American made "tea kettle"engines of the 1830's, from 20 mph to 40 mph, was easy thanks to Matthias Baldwin and his improved steam fitting joint (ca 1834).

Overnight, boiler pressure in Baldwin's American made locomotives was doubled, from 60 psi to 120 psi, thereby doubling the engine HP- and the possible speed. Source: History of the Baldwin Locomotive Works, 1907, pg 20: . Refer to the formula HP = (PLAN) / 33,000.

Efficiency comparison between Primitive Locomotives and Modern Tractor Trailers (acceleration from 0 to 50 mph Speed)

When moving freight, high speed is not the main priority. Fifty mph is plenty. Some truckers like to use excessive speed, because they want to do the most runs in the least time possible, to satisfy their own personal economic reasons- and they waste lots of fuel and peoples lives doing it.

For empirical data, tests were done on a British railroad (Grand Junction Rwy) during 1839. Due to their notoriously level track, the British commonly achieved both high speed, and a high payload, [30 mph average (includes starting and stopping time at 8 "stoppages"- about 40- 50 mph peak), 82 Ton gross train weight (GCW), over a 190 mile distance) using a common locomotive of the period, exerting 87 HP (using the formula HP = [(GCW (Tons) x 8 lbs/Ton) x S] / 375.

This data yields a steam locomotive power to weight ratio of 87 HP / 82 Ton = 1.06 HP / Ton at 50 mph

Source: Railway Machinery, by Daniel Kinnear Clark, 1855, see pg 11, 17, and the table on pg 20, columns 1 and 7: The LIRR, and later the high speed (for the period) Hudson River RR, were built according to this British design paradigm.

A modern truck will use 440 HP to pull a 70 Ton GCW (6.285 HP/Ton) at about the same speed: **nearly 6 times more horsepower is required per Ton by truck, than the circa 1830's locomotive at 50 mph,** as per the formula 6.285 HP/Ton (truck) / 1.06 HP/Ton (locomotive).

Since 1 HP equals approximately 2,545 BTU/hour, in terms of thermal energy required at 50 mph, the modern tractor- trailer requires 1,119,800 BTU/ hour to draw a GCW of 70 Tons. This corresponds to 6.285 HP / Ton x (2,545 BTU / hour) = (15,995.325 BTU / hour) / Ton (truck).

The circa 1830's steam locomotives required only 189,857 BTU's/hour (16%), to draw the same GCW at the same speed. This corresponds to 1.06 HP / Ton x (2,545 BTU / hour) = (2,697.7 BTU / hour) / Ton (steam locomotive).

In summary, **if you keep your railroad track as close to a zero grade as possible, you never need to produce more than 30 HP to pull your 70 Ton train at up to 20 mph, or 87 HP to pull an 82 Ton GCW train at up to 50 mph (1.06 HP / Ton)**. This corresponds to 74.6 HP required to draw a 70 Ton GCW train at 50 mph, (1.06 HP/Ton) as per HP = [(GCW (70 Tons)) x 8 lbs/Ton x 50 mph] / 375.

Modern diesel electric railroad locomotives have a much greater energy efficiency advantage over diesel trucks.

According to the current AREMA Manual, Volume 1, Chapter 2, pg 55- 57, a typical diesel electric locomotive will produce 3,000 HP, and the "Starting Resistance" (our "Train Resistance" of ca. 1830's) for roller bearing wheels (above 32° F), is cited as 5 lbs/ Ton. Using our simplified HP equation, we get:

TP = (3,000 HP x 375) / 50 mph = 22,500 lbs

Then,

GCW (Tons) = (375 x HP) / (S (mph) x 5 lbs/Ton),

GCW (Tons) = (375 x 3,000) / (50 x 5) = 4,500

Therefore, the power to weight ratio of a modern railroad locomotive at 50 mph, is 3,000 HP / 4,500 Ton = 0.666 Hp /Ton (diesel locomotive).

Since 1 HP equals approximately 2,545 BTU/hour, in terms of (energy consumed per hour) per horsepower, for the modern locomotive, we get:

0.666 HP / Ton x 2,545 BTU / hour = (1,694.97 BTU / hour) / Ton (diesel locomotive), as compared to (15,995.325 BTU / hour) / Ton (diesel truck).

Therefore, in terms of energy demand at starting and acceleration from 0 to 50 mph, as per the formula [(15,995.325 BTU / hour) / Ton (truck)] / [(1,694.97 BTU / hour) / Ton (locomotive)], **the modern diesel electric locomotive is 9.4 (say 10X) times more energy efficient than a diesel truck or bus (upon starting and initial acceleration) !** See: The Next Progressive Era: A Blueprint for Broad Prosperity", by Phillip Longman, pg 151.

Trucks Vs.Trains : Energy required to keep objects moving at a constant speed

So far, all of our calculations have been based strictly on "old school" methods of calculating energy requirements, which do not differentiate between the energy needed to start a train or a truck from a dead stop, and the much lower energy input needed to then keep it moving at a constant speed.

All the foregoing calculations have essentially been functions of "Starting Resistance". Now, let's be more specific, and take a look at the energy required to overcome "Rolling Resistance", and thereby maintain an already moving vehicle at a constant speed:

Rolling Resistance- the force needed to keep a rolling vehicle moving at a constant speed:

Once any vehicle starts moving, it takes a lot less force (energy) to keep it moving at the same rate, than what it required to start it moving in the first place. To keep things simple, by avoiding the use of trigonometric functions, we will again assume a level surface in all instances.

At the same speed, same load (GCW) and on level ground, any steel wheeled railway vehicle is 24.6 times more energy efficient than any large rubber tire road vehicle, regardless of the type of power source.

Let's see why:

We start off with Newton's famous second law :

F = ma

setting a = g = 32 ft/second²

We now have

F = W (weight) = mg

Coulomb's classic model of friction is given as:

$F_f \leq \mu F_n$

 Where F_f is the force exerted by friction (in the case of equality, the maximum possible magnitude of this force), μ is the coefficient of friction, which is an empirical property of the contacting materials, and F_n is the normal force exerted between the surfaces.

Since in our case the track/road is level,

Normal Force = F = W (weight)

And let

μ = Crr

Therefore, the formula for calculating "Rolling Resistance" is given as:

 F_f (lbs) = [W (lbs)] x Crr

Where:
W = weight (lbs) = "GCW" (lbs)
Crr = coefficient of rolling resistance (dimensionless)
F_f = Rolling Resistance

Let's now apply the following data: (for sources see ***** end note)

W = 70 tons (140,000 lbs)
Crr (road truck rubber tires on pavement) = 0.01479
Crr (Railway steel wheels on steel rails) = 0.0006

Therefore, in the case of any large rubber tire road vehicle, no matter what the energy source:

F_f (truck) = 140,000 lbs x 0.01479 Crr (*truck*) = 2,070.6 lbs / 70 Tons = *29.58 lbs/ Ton*, is required to keep any large rubber tire road vehicle moving at a constant speed, no matter what the power source.

In the case of any steel wheel railway vehicle, no matter what the power source:

F_f (Railway) = 140,000 lbs x 0.0006 Crr (*Railway*) = 84 lbs / 70 Tons = *1.2 lbs/Ton*, required to keep any steel wheel railway vehicle moving at a constant speed, no matter what the power source.

Next, we need to derive a multiplying factor:

0.01479 Crr (truck) / 0.0006 Crr (Railway) = 24.65

As we can easily see from the formula HP = (TP x S) / 375, HP is directly proportional to TP. As we already know, as per the formula TP = [GCW x Train Resistance], TP is directly proportional to Train Resistance (TR) when starting/accelerating, and also directly proportional to Rolling Resistance TP = (F_f = GCW x Crr) when already moving at operating speed. As we have seen, Energy Demand (BTU/hour) is also directly proportional to HP (1 HP = 2,545 BTU/hour). *Therefore, if weight (GCW) and speed are held constant, energy demand is directly proportional to Crr.*

Therefore, any steel wheel railway vehicle is 24.65 times more energy efficient than any large rubber tire road vehicle, no matter what the power source is, as long as speed and GCW are held constant.

So, why is rail so much more energy efficient than pneumatic tire road vehicles? Let's refer back to Engineering Tribology, By John Austin Williams, 2005, pg 409, and the equation for μR:

$$\mu_R = \frac{4\alpha}{3\pi}\left\{\frac{W}{\pi RE}\right\}^{1/2},$$

Referencing the formula directly above, "the rolling resistance of a pneumatic tire road wheel is very much greater than that of a steel wheel on a steel rail, because of the very much lower value of the "contact modulus" **E** [elastic stiffness] of a rubber tire on a concrete road, as well as its much greater value of "fractional hysteretic energy loss" α [the energy loss expressed as a fraction of the total input energy], when compared to those of a steel wheel on a steel rail".

Now lets calculate the relative amount of energy required by any steel wheel rail vehicle Vs. any large rubber tire road vehicle, as long as speed and GCW are held constant:

[(1.2 lbs/Ton (rail) / 29.58 lbs/Ton (truck)] x 100 = 4.06%

The steel wheel rail vehicle will require less than 5% (1/20) the energy required by a rubber tire road vehicle, to do the same amount of work.

However, this calculation does not include bearing friction, grade and curve friction, or aerodynamic friction.

If we deduct 1/5, or 20% of our multiplying factor of 24.55 to account for the other forms of mechanical friction, rail still enjoys precisely the same 20X energy advantage over highway vehicles that it had back in 1832 !

CONCLUSION:

At the same constant speed, on level ground, drawing the same load, any steel wheeled railway vehicle already in motion, will use only 5% (1/20) of the energy consumed by any large pneumatic tire road vehicle already in motion. Upon starting and initial acceleration, any steel wheeled railway vehicle will only use 10% (1/10) of the energy demanded by any large pneumatic tire road vehicle. Further, only in the case of railroads, Train Resistance, or Rolling Resistance, is inversely proportional to GCW (train weight). This means, the heavier the train, the more energy efficient it becomes.

As a nod to the Electric Automobile industry, its noteworthy that theoretically, the energy efficiency (range) of any electric automobile on any paved asphalt or concrete road, can be increased up to 2X (doubled), through improved tire design (i.e., by using "special pneumatic" or "special solid" rubber tires, or a hybrid of the two).

For example, a modern light weight automobile with small "footprint" pneumatic tires, has a rolling resistance of about 20 lbsf/ Ton on pavement. Back in 1909, they had the standard rolling resistance of an electric car down to 15 lbsf/ Ton on asphalt. With our modern materials, it could come down still lower.

This information has been publicly available for over a hundred years (since at least 1909). However, historical events in the early 20th century led to an abundant, plentiful and seemingly inexhaustable oil supply. The British, in dire need of an oil supply to fuel their Navy, discovered oil in the Persian Gulf, and by 1911, (then) cheap oil was being pumped out of Iran. After World War I, the Standard Oil Company of California followed suit, and began pumping vast quanities of oil out of the politically unstable countries all around the Persian Gulf. Accordingly, anything electrically powered or "energy efficient" was immediately relegated to the scrap heap of history- along with all the scientific know- how and technology that went with it.

See **Standard Handbook for Electrical Engineers, by Frank F. Fowl, 1916, pg 1,461** (you have to download the entire PDF to view this page). Also see: **Electric Traction, by E.H. Armstrong, 1909, pg 807- 808**: And **Alexander Churchward's original 1909 paper on the Energy Consumption of Commercial Vehicles** (rubber tires: pneumatic, solid and vehicle resistance), presented before the SAE. See Norton's (of B.F. Goodrich Tire Co.) circa 1916 paper on **Tires for Electric Vehicles**, presented before the Electric Light Institute, on pg 96- 113. If you can find it, also see the paper Electric Vehicle Tires, presented before the Electric Vehicle Association of America, by F. E. Whitney, Oct. 27, 1913

* Steam Passenger Locomotives, by Brian Hollingsworth, 1982, pg 20- 22
** Source: Locomotive Fireman and Engineers Magazine, 1909, pg 841.
*** Source: Railway and Locomotive Engineering, Dec. 1907, pg 548.
**** Source: English Mechanic and World of Science, Oct. 18, 1889, pg 158
***** Note: Truck tire Crr is the average of data from SAE Technical Paper 880584, 1988, pg 4, Table 6. The average Railway Crr is from these sources: Engineering Tribology By John Austin Williams, 2005, pg 409- 410, and Bicycling Science By David Gordon Wilson, 2004, pgs 217 & 218, and Tractive Resistance of Rolling- Stock, by J.L. Koffman, British Railways Board, Railway Gazette International, Vol. 120, Nov. 1964, pg 899- 902. .

FIG. 17.

Side and End Views
of a
LOCOMOTIVE ENGINE
Similar to the PLANET employed on the
Liverpool & Manchester Railway.
Manufactured by
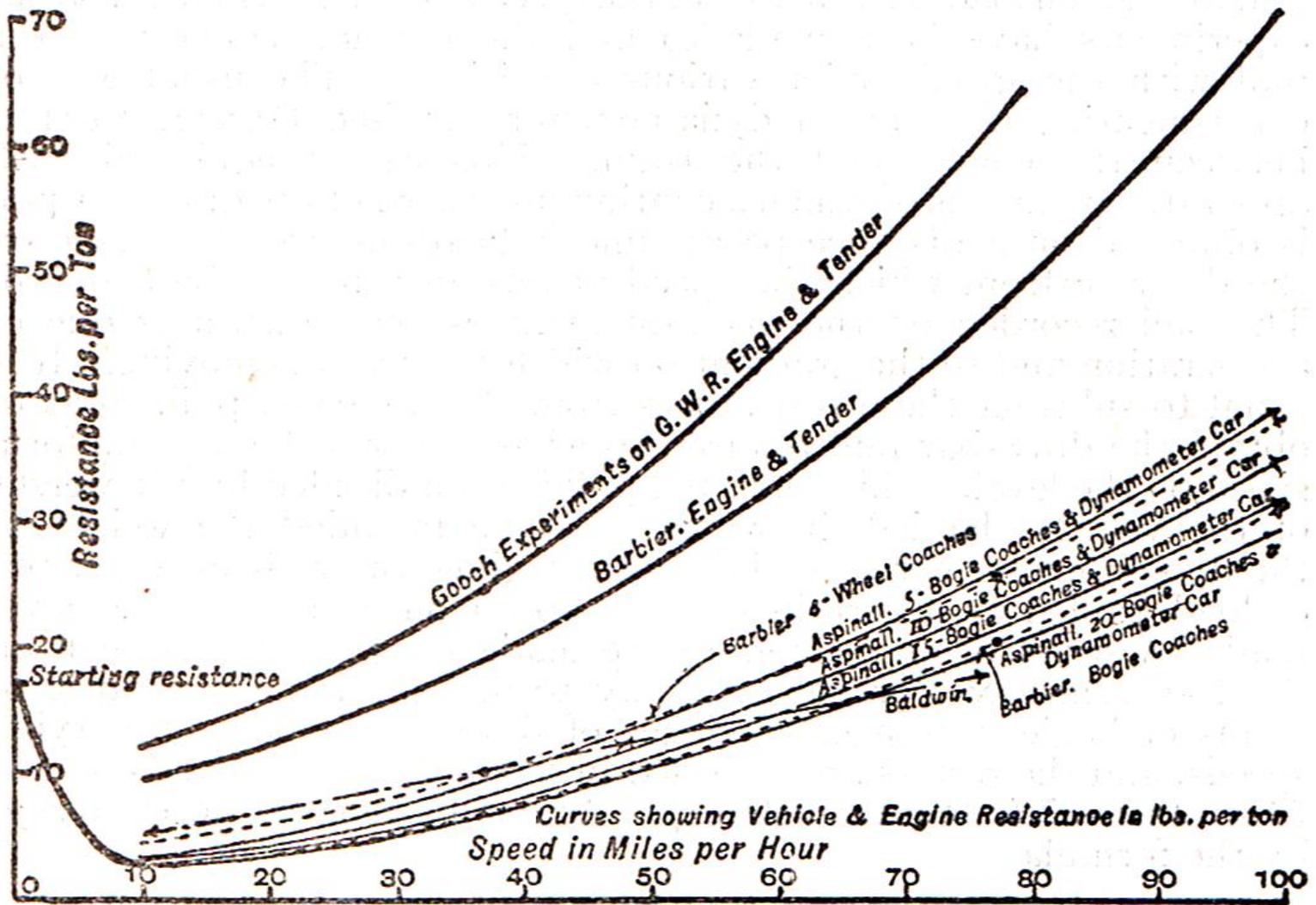MESS?? ROB. STEPHENSON & C?
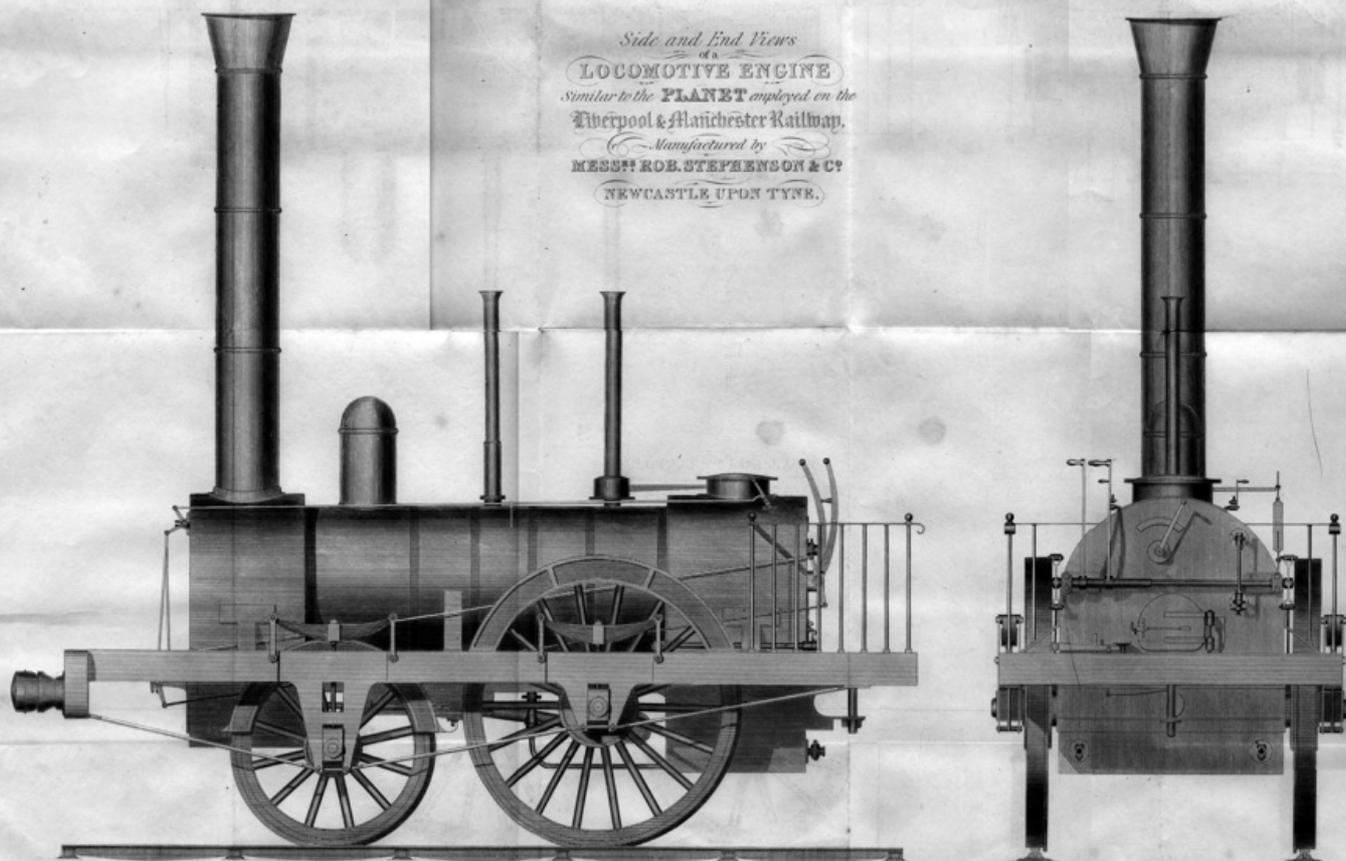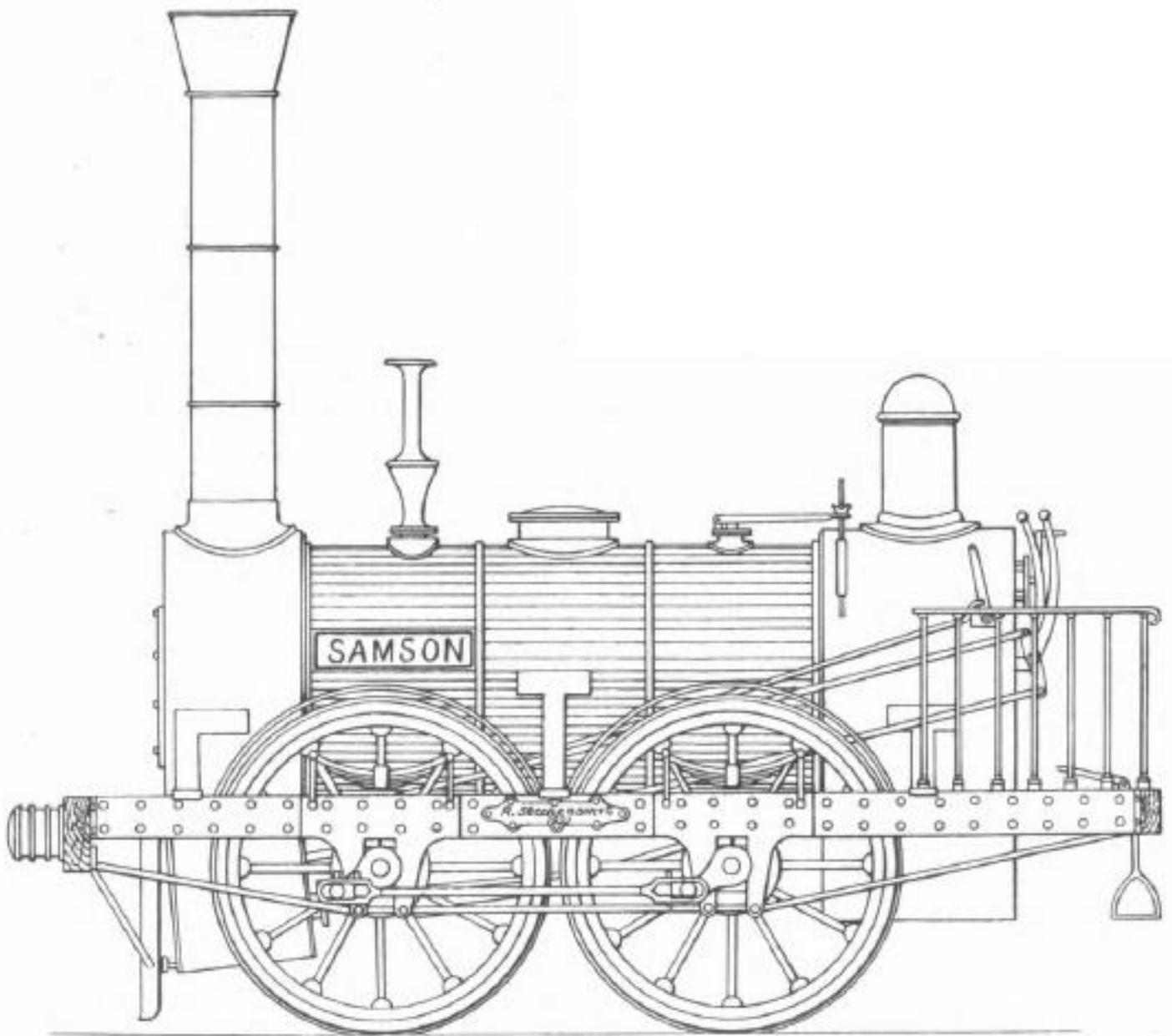NEWCASTLE UPON TYNE.

SAMSON

LOCOMOTIVE FOR THE MANCHESTER & LIVERPOOL RAILWAY.
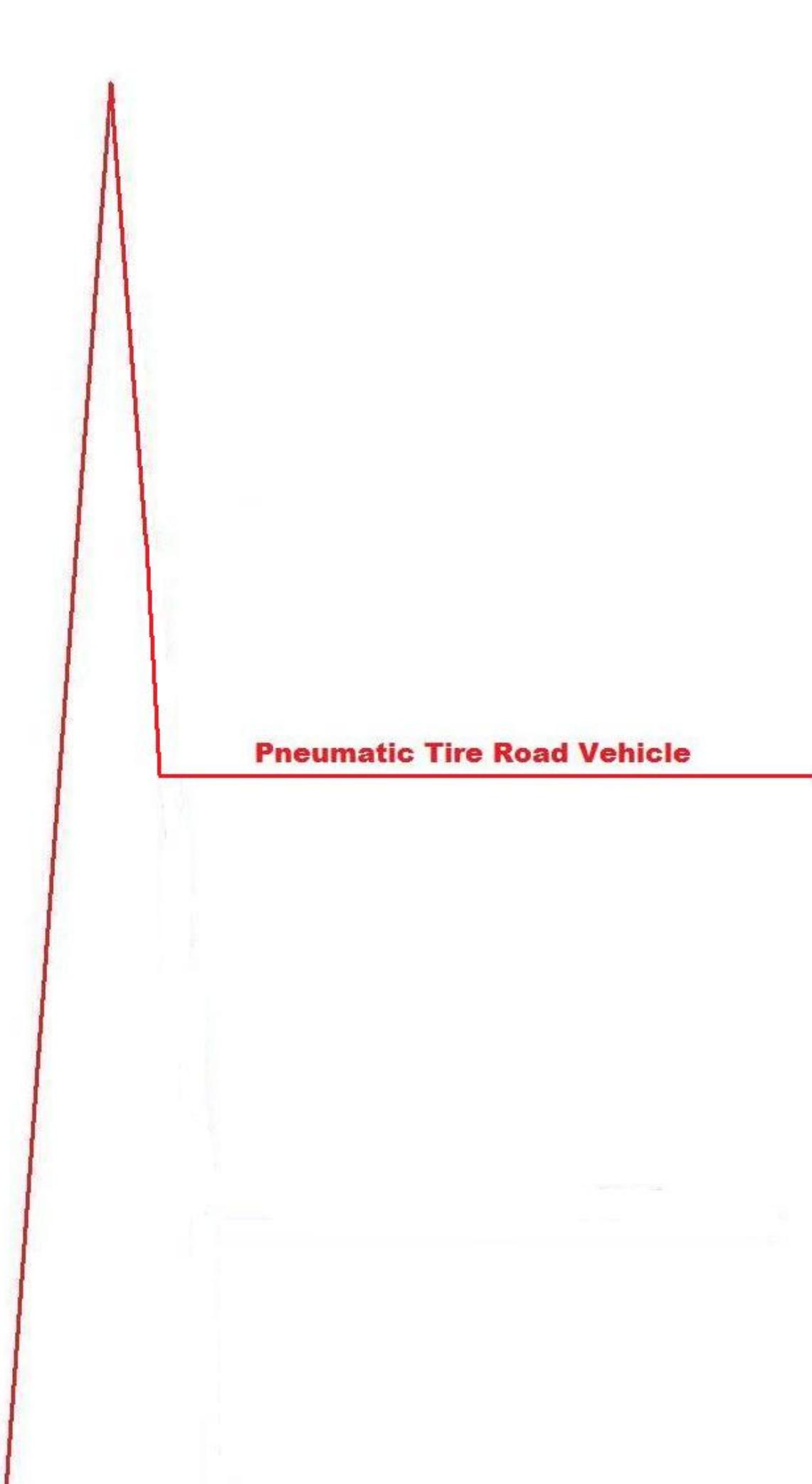BUILT IN 1831 BY R. STEPHENSON & CO., NEWCASTLE-ON-TYNE.
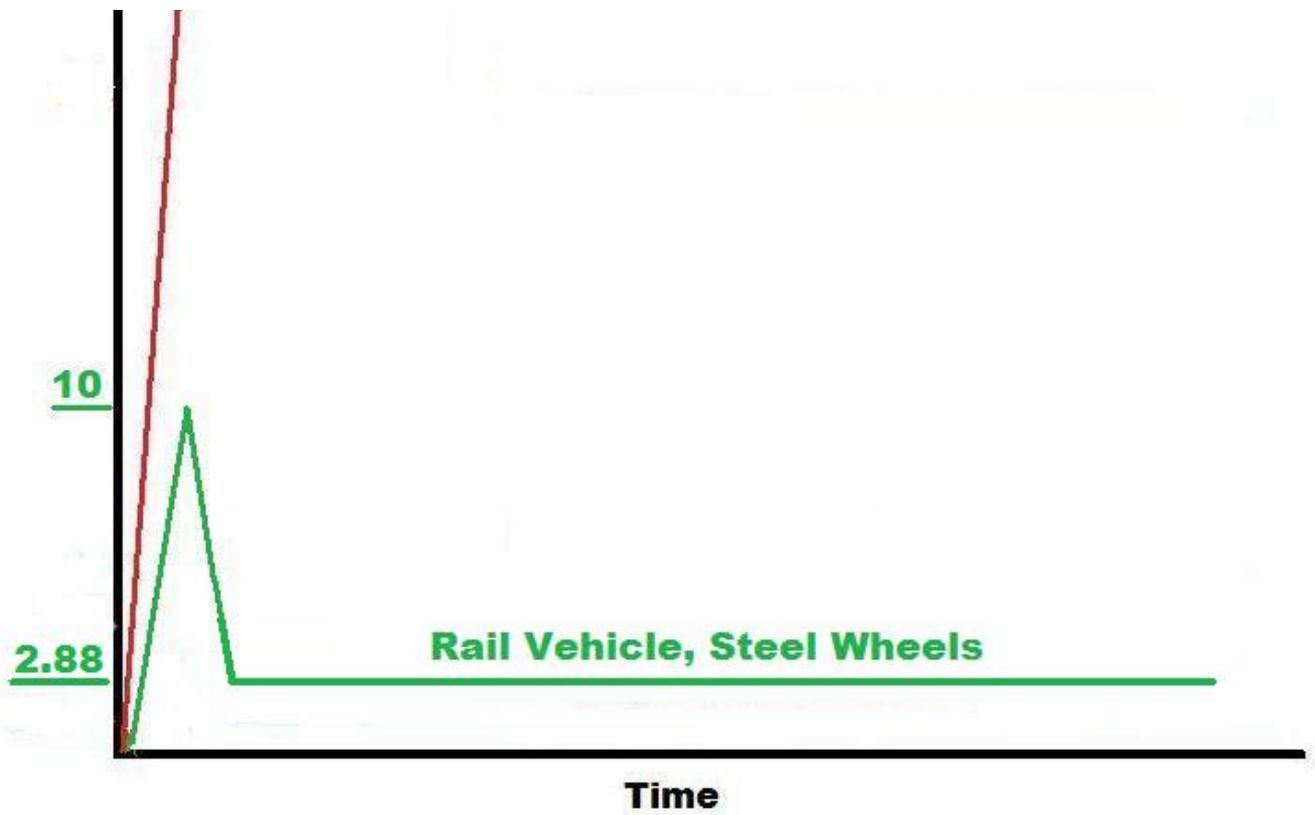
100

57.6

Pneumatic Tire Road Vehicle

**Energy
Demand %
(BTU/hour)**

**ADJUSTED FOR
MECHANICAL
FRICTION**

**Note:
1 kwh = 3.6 MJ =
3,413 BTU/hour**

10
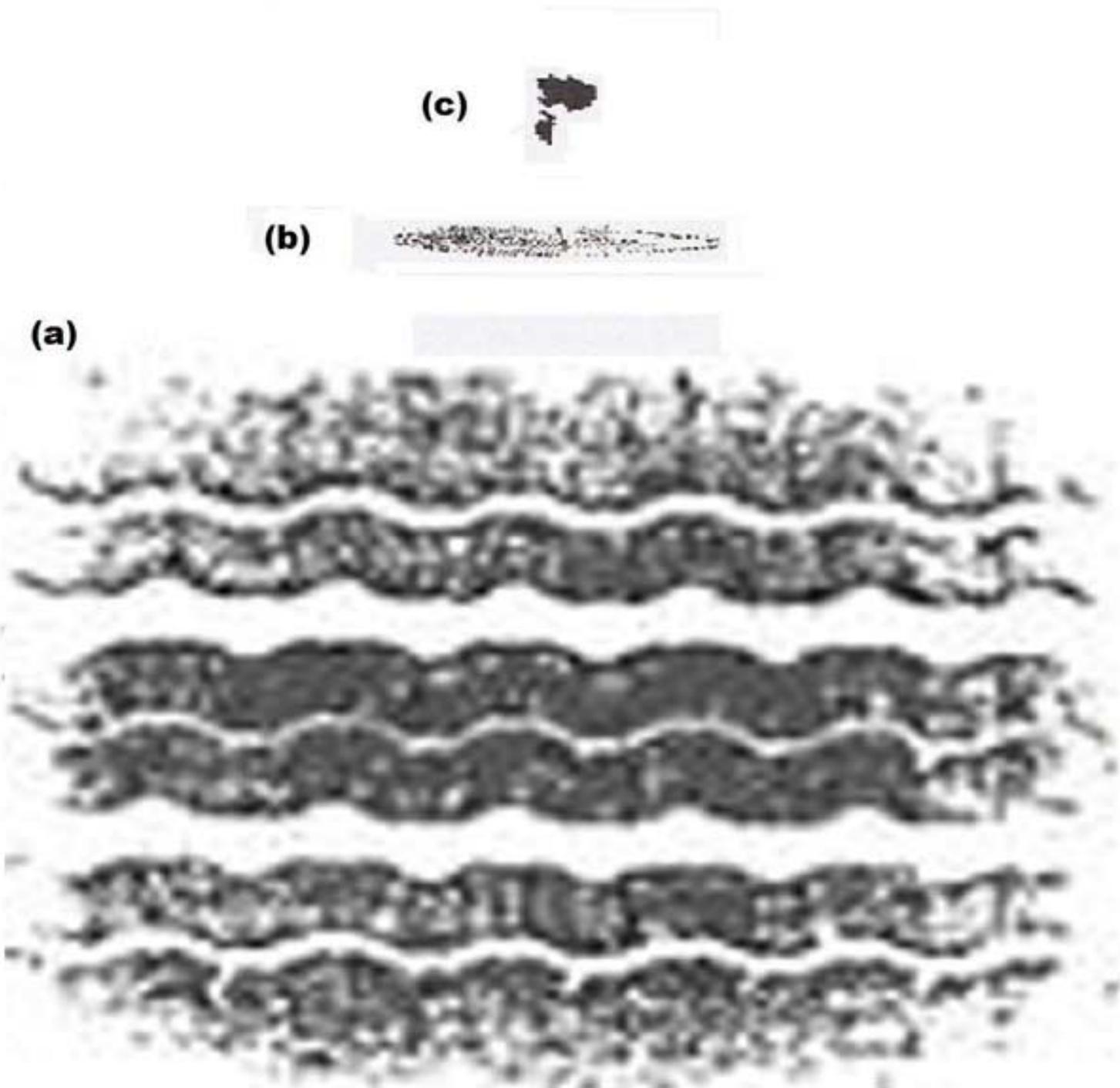
2.88

Rail Vehicle, Steel Wheels

Time

**Generic Curve Representing Starting Energy Demand
and the Subsequent "Cruising" Energy Demand
at a Constant Speed and level track or road**

Why Railways Are 20X Energy Superior To Pneumatic Tire Vehicles

"Footprint" Comparison:

The "Contact Print" of a 22.5" x 8.25" Truck Tire (a), Compared to a 27" Bicycle Tire (b), and a Typical 35" Steel Railway Wheel (c).

Source (c), (b):
Bicycling Science, by David Wilson, pg 218

Source (a):
Vehicle, Tire, Pavement Interface,
Henry/Wambold ASTM STP 1164,
1992, pg 143

1992, pg 143