MECHANICAL EFFICIENCY OF RECIPROCATING STEAM LOCOMOTIVE ENGINES

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Overview

1. Introduction, relative importance of the (not very popular) subject
2. What is it: not clear
3. Measurement methods, from stationary test plants to road testing
4. Causes, comparison with (other) torque transmitting engines
5. Agenda: possible improvements

(May not be a most exclusive contribution, at least not so in its lack of practical relevance—let me still try to guide you through the subject with as little friction as possible)

1. Introduction

Importance of heat → mechanical power output efficiency self-evident: micro-mechanical movement to be optimally transformed to macro-mechanical movement, within $(T_1 - T_2) / T_1 = (Q_1 - Q_2) / Q_1$ (the theoretical Carnot / Rankine limit) of course:

Reality still far away from it: thermal efficiency not very good, mechanical losses → micromechanical movement back to useless micromechanical movement or simply heat again …

1. Introduction

Even today: total energy input / effective traction work done is not good at all (transmission, stand-still etc. losses even in state of the art electric locomotives & trainsets)

Thus regarded steam traction is not totally behind other traction beforehand

(DR calculations in the fifties of the last century → (steam : electric) = (1:1,5) → second generation steam may approach 1:1, apart from ± constant stand-still losses)

1. Introduction

Discussion of steam traction efficiency almost exclusively focused on thermal efficiency, incl. all kinds of suggestions for improvement

Without much further complication 10+% total efficiency at full load is ± the limit

(Boiler though rather smaller and lighter than the optimum is not the main problem, at 80-90%, but very low reciprocating steam engine efficiency is, though even pre-WW2 loco engines reached 94% of the theoretical ihp efficiency maximum: 240P)

1. Introduction

But then ihp is not dbhp, the one & only interesting factor on the road (apart from reduction of startup + standstill losses etc.)

+ just because thermal efficiency is bad mechanical efficiency is important, standing in between ihp & dbhp

What is & remains standing in between? (Stiction &) **friction**, or transformation of mechanical power back to waste heat

In cylinders, steam distribution, sliding bar surfaces, bearings, wheel-rail slip, other track resistance, wind resistance, …

1. Introduction

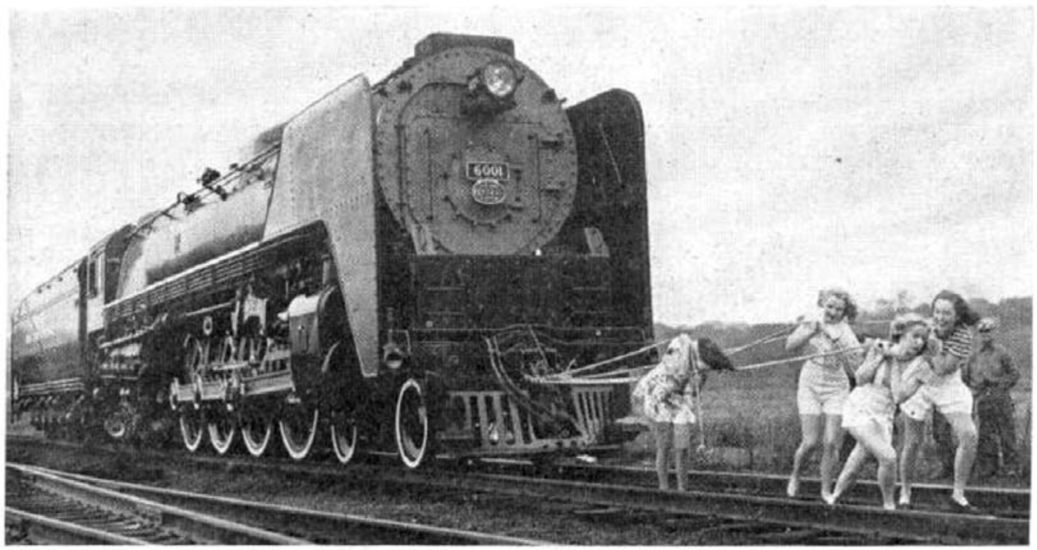
Main subject here is **internal engine resistance & what to do about it** (though this is not easily separable from track resistance)

Less fuel fired for given locomotion duty environmentally ever more important

Engine mechanical losses ought to be sizeable in order to be interesting at all of course … However:

1. Introduction

6001 In Service, 24 Others on the Way



The second Niagara type locomotive, similar in f_damental design to the original experimental Niagara, which was delivered tc the Central last March, was receivec .ast month and will be quickly followed by two dozen others of the same series. On October 16, this 6000 horsepower locomotive, which weighs 448 tons loaded and is 115 feet long, was pulled by four New York models at Harmon, N. Y. This demonstration was made to illustrate the effect of the use of Timken roller bearings on this locomotive and will be used in a film to be shown in 11,000 theaters under the sponsorship of the roller bearing industry. Pathe Newsreel also filmed the scene.

1. Introduction

Indeed Meineke & Röhrs (leading steam loco engineers in post WW2 Germany):

Steam loco mechanical resistance "*uninteresting problem for loco engineering, covered by standard engine resistance formulas like Sanzin's & next to be left alone*"

1. Introduction

But then other data, like recorded of King class locomotive on GWR stationary test plant:

the Institution of Locomotive Engineers in November 1953 by Mr. Ell, and some of the more spectacular results are tabulated herewith. Working at a constant steam rate of 33,600 lb. per hour, with a coal consumption of 5465 lb. per hour the following results were obtained.

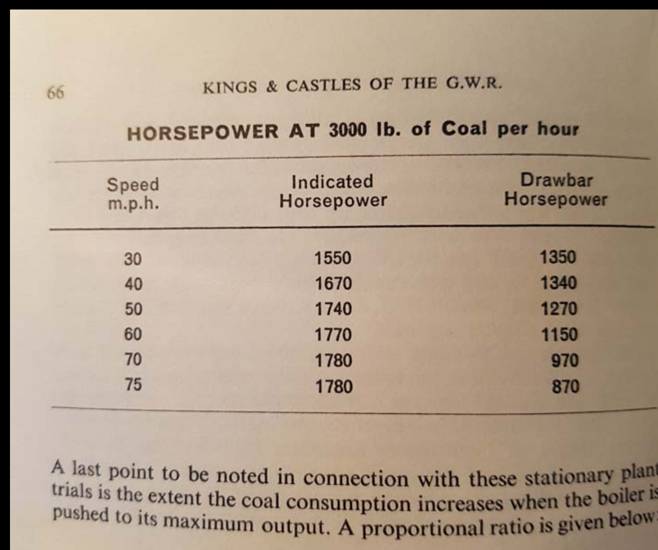
Road speed m.p.h.	Cut-off %	Indicated Horsepower	Drawbar Horsepower
30	55	2050	1810
40	40	2150	1800
50	35	2160	1680
60	31	2160	1515
70	28	2150	1310
75	27	2140	1200

These figures show clearly how the internal resistances of the locomotive mount up with increased speed, so that whereas all but 240 horsepower of the 2050 developed in the cylinders is available for traction at 30 m.p.h. no less than 940 h.p. is absorbed internally in the locomotive at 75 m.p.h.

The maximum coal consumption that a single fireman could manage continuously was agreed at 3000 lb. per hour, and this provided the following power outputs at speeds between 30 and 75 m.p.h.

1. Introduction

→ more than 50% difference between test plant ihp & dbhp, unhindered by track & wind resistance … ? Quite a contrast with the Niagara girls (or were they equipped with superhuman strength?)



66 KINGS & CASTLES OF THE G.W.R.

HORSEPOWER AT 3000 lb. of Coal per hour

Speed m.p.h.	Indicated Horsepower	Drawbar Horsepower
30	1550	1350
40	1670	1340
50	1740	1270
60	1770	1150
70	1780	970
75	1780	870

A last point to be noted in connection with these stationary plant trials is the extent the coal consumption increases when the boiler is pushed to its maximum output. A proportional ratio is given below:

1. Introduction

These are just two examples of (not so numerous & systematically collected) rather different data concerning steam locomotive mechanical resistance

First hint concerning explanation of the "Niagara-King difference":

Passive loco engine resistance ≠ active loco engine resistance

2. Engine resistance = ?

Basically simple: friction generating heat → loss of mechanical energy from piston thrust to wheelrim ($\pm$)

Simple in principle with torque transmitting engine, like car ic engine: mech eff = shp / ihp

But locomotive engine mech eff is not equal to dbhp / ihp:

losses also caused by running resistance: track & air, including (other) carrying axles + tender

2. Engine resistance = ?

Not identical to stationary test plant mech eff (which indeed is dbhp / ihp) *as well*: no influence of different driving and coupled wheel diameters, no influence of engine induced sway etc. on track resistance, … (+ more stationary ihp ← less cylinder air cooling, + less bearing cooling on the other hand)

Further complications: what is engine resistance / mech losses & what is track resistance / track mech losses? Slipping as a consequence of axle torsion, different driving wheel diameters &c. is engine inefficiency, but what about loss of mech eff due to driving & coupling rod misalignment caused by track irregularities? Etc.

2. Engine resistance = ?

Simplifying suggestion / working definition:

mech eff = (dbhp + mhp) / ihp

mhp = power output needed to overcome (idling / driven engine, track & air) motion resistance*

(* complex notion in itself, given factors like pumping losses not present in engine under load)

2. Engine resistance = ?

Main definitional issue indeed: no strict mechanical separation between working engine proper & the whole of the locomotive moving on track, producing dbhp (again: the one & only factor of real importance, indeed partly determined by mech eff)

3. Measurement

Signs of mechanical inefficiency?

Fitted against oil splashing due to chronic overheating

3. Measurement

Measurement of excess heat indeed the theoretically best determination of mechanical i.e. friction losses

Not very practical, still apart from isolating the influence of fluid (steam & water) heat, air cooling, …

Reliable formulas or better models would be too complex as well: even highly complex varieties would require too many input factors, … (though models based on empirically reliable test results may be more or less sensible? Pure theory for now)

(Classic & simple standard formulas like Sanzin's empirically refuted)

3. Measurement

Or direct torsion measurement (in driving & coupled axles or in SAB-like driving & coupled wheels)? Not that practical either + presupposes establishment of ihp, like the standard formula:

So back again to ***mech eff = (dbhp + mhp) / ihp***

Indeed presupposes determination of ihp in the first place: not always reliably done, due to condensation in apparatus, (long) piping, etc. (electronic devices plagued by condensation issues as well) but then given suitable precautions repeated tests may well lead to realistic results

3. Measurement

Ihp may also be determined independently from any indicator diagrams, as expressed by

$\mathbf{E_i = (P + M) / g) \times (d^2x / dt^2)}$

P = locomotive weight, M = weight of the train hauled, g = gravity constant, $d^2x) / dt^2$ = acceleration and E_i is indicated tractive effort (ihp = $[E_i \times V_{kph}] / 270$)

Application of the formula is done by closing the regulator at once: ensuing slowing down is in exact accordance with the tractive effort just stopped, multiplied by the total train mass

3. Measurement

d^2x / dt^2 (acceleration) is measured by **pendulum deviation** (due to acceleration relative to the track and gravity due to inclination) probably older than direct tractive effort measurement (by spring, hydraulic, semiconductor etc.)

(Pendulum method reputedly already used by Robert Stephenson)

Not just ihp thus established but mhp as well: **hp related to this total tractive effort may be substracted from dbhp (established by spring loaded dynamometer car): = locomotive & tender motion hp = mhp**

Again: *mech eff = (dbhp + mhp) / ihp*: now all three variables measurable

3. Measurement

A bit complicated right? Still it has been done (France, Belgium, in even more sophisticated setups), with generally rather more favorable track results than the stationary GWR Kings

Results in France (before WW2): mech eff 70-95% (! Quite different from GWR King results)

With vehicle motion resistance of (plain bearing) 240P more or less equal to coach resistance (! No fixed wheelbase etc.)

3. Measurement

Maybe simpler just to pull or push a locomotive (+ tender) by itself in order to determine m(otion) hp?

But push is no pull (concerning track resistance), + air resistance influenced by accompanying vehicles → no clear results to be expected

4. Causes

Back to torque transmitting engine:

Mech eff = *shp* / *ihp* (again, full stop)

Caused by internal friction turning mechanical energy back into heat, due to effects on parts moving "against" each other stemming from

1. **compression, driving forces**, (some) pumping, valve actuating, auxiliaries like oil pumps, cooling pumps, …

2. **centrifugal & reciprocating forces**

(Relatively shorter stroke → higher bearing forces ← higher piston thrust, etc. etc.)

4. Causes

2. (mostly) reciprocating forces) sooner or later stronger than 1. (energy forces etc.):

(Max reciprocating forces ±: $\mathbf{Gn^2S / 1800}$: G = weight of reciprocating parts, n = rpm, S = stroke)

(+ centrifugal force = $\mathbf{mv^2 / r}$: less important but more so in loco driving mechanisms than in torque transmitting engines)

4. Causes

Low to medium speed diesel engines:

mech eff more or less unrelated to load & rpm

(apart from increasing piston ring friction due to [much] higher driving pressures + some pumping losses)

→

1. Mech eff = shp / ihp = mhp / ihp (?)
2. **Decrease of mech eff at lower loads** from up to 95% down to ± 70% at half load to 0% at idling

4. Causes

Like factors in steam locomotive engines, from compression* to driving forces (less / nil pumping losses under load) to reciprocating forces

*This may explain part of the King loco performance: test plant dbhp less than 50% of ihp (higher in test plant than on the road):

* "… Certainly the Kings were quite well known for rattling their compression relief valves when running fast well notched up. …"

4. Causes

Steam loco's different (apart from coupled axles in most cases, may still be no major factor):

A. *Out of line in principle* (due to engine movement relative to frame, including suspension play + lateral play) → in practice more play in engine parts as well

B. *Not (just) torque transmitting*

C. Torque transmission creates torsion

D. Play in engine mechanism

E. …

4. Causes

A. Suspension + lateral play → more friction due to “out of line” forces in mechanism:

Driving axle movement “taking along” driving rod (up & down + sideways)

Coupling rod horizontal & vertical misalignment

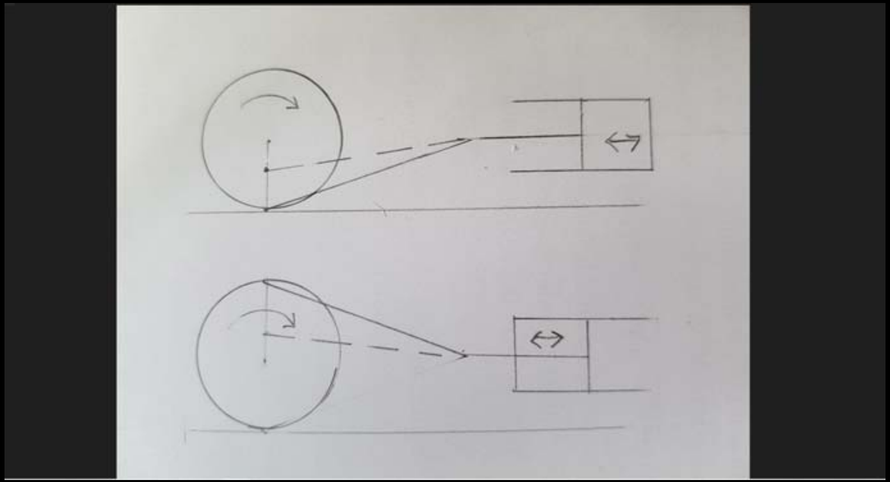
All leading to more “out of line” bearing friction

Sway and other locomotive movement relative to the track, caused by many factors including reciprocating forces + driving (/ compression) forces:

4. Causes

B. Locomotive engine is *not* a (purely) torque transmitting engine

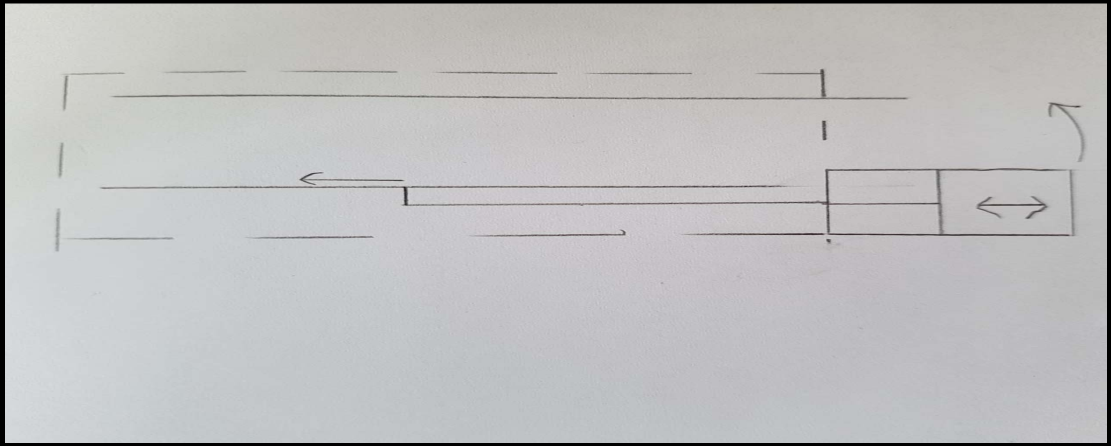
→ fluid (steam pressure) forces *not* contained within engine as with torque tranmitting engine:



4. Causes

Thus driving (+ compression) forces add to sway (strongest in 2 cyl locomotives), reducing mech eff

(Sway resistance is not purely vehicle-track induced but partly effect of working engine and thus reducing mech eff)



4. Causes

C. Torque transmission from driven side to “undriven” opposite wheel presupposes axle torsion

→ continuous intermittent slipping, reducing mech eff

Britannias renowned for high speed slipping, fitted with hollow axles (for better heat treatment) but with less torsion stiffness

(+ slipping caused by coupling rod tension ← non 90^0 crank angles)

4. Causes

D. Bearing + axlebox play → intermittent slipping as well, again reducing mech eff: "jerk effects"

Stronger with concentrated (single axle) drive and more or less proportional to number of coupled axles (though not always so in practice)

(E. Several other factors like higher rpm → lower mech eff, small driving wheels worse than large driving wheels, …, vibration, …)

4. Causes

+ higher loco weight → more motion resistance → lower mech eff

So thermal efficiency is good for mechanical efficiency as well …

Related: *partial load reduces mech eff* (see above): "heavier loco" delivering power output identical to full power output of lighter locomotive

5. Remedies

Recycling heat otherwise lost?

What next to do with it: train heating?

Slightly theoretical …

5. Remedies

Negative differences with purely torque transmitting engines may be *partly* (given remaining engine induced sway etc.) done away with by

Eliminating suspension play (indeed destroying drive geometries)

Presupposes perfect track, no high speed joints, …

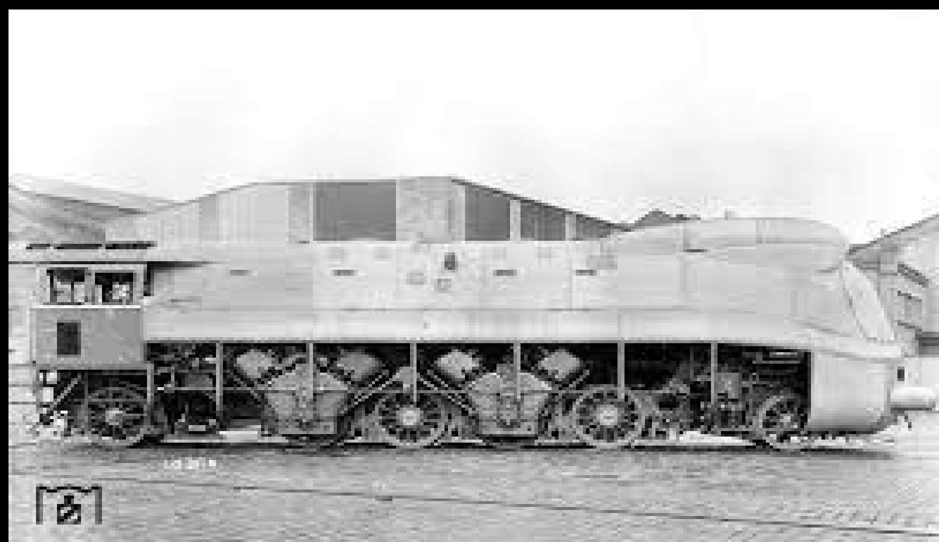
Effect may not be worth it?

(Drivers' Unions may disagree as well?)

(Still: stiffer suspension → less engine misalignment)

5. Remedies

Or go for pure torque transmission (no more external fluid forces indeed, given pure torque transmission) like in the DR 19^{1001}:



5. Remedies

Or central axle drive only: DR designs for 1 (!) & 2 cyl single crankaxle drives

→

No driving force induced sway (causing track resistance) +

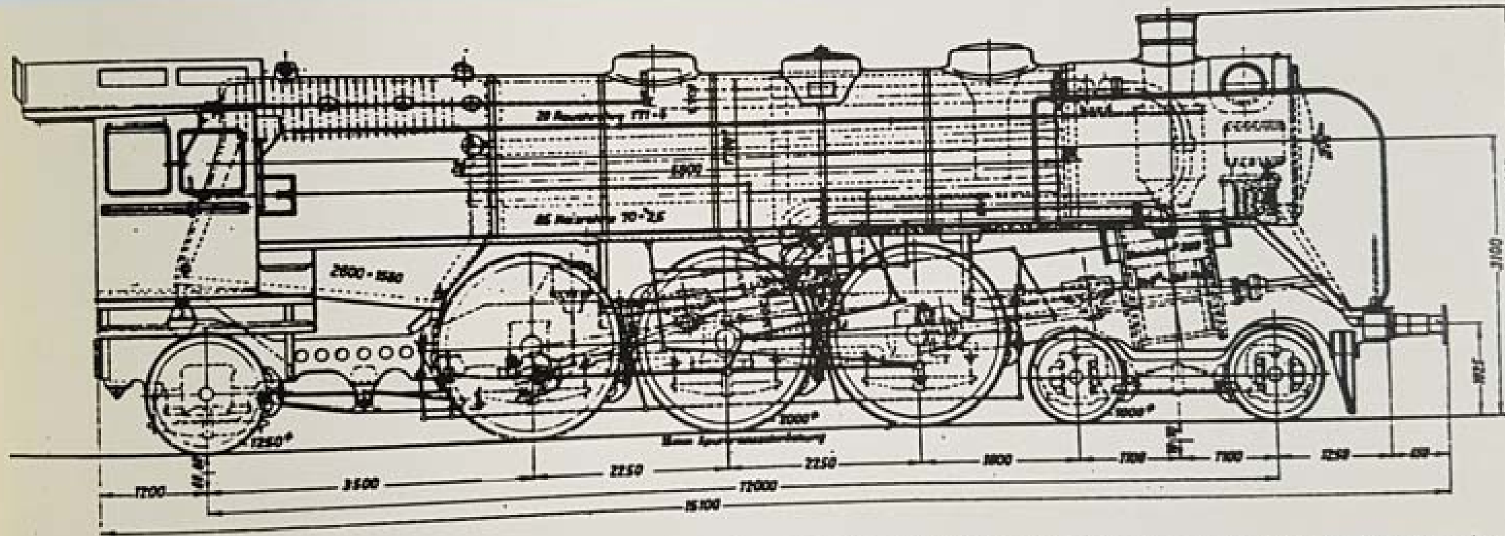
No “one sided” torsion causing microslip (not good for mech eff either) +

Lower asymmetric frame forces +

Longer frame etc. life

(Worth the hassle?)

5. Remedies



Eine bislang kaum bekannte Projektstudie beinhaltete eine 03-Variante, die als Mittenzylinder-Verbundlokomotive unter dem Arbeitstitel „Baureihe 03.20“ geführt wurde. Im Gegensatz zu den Baureihen 03 und 03.10 sollte sich diese Type vor allem durch einen geringen Dampfverbrauch sowie ei ruhigeres Laufverhalten wegen der wegfallenden Schlingerbewegunge auszeichnen. Durch den zweiten Weltkrieg kam es nicht zu einer Ausführun

5. Remedies

More cylinders better (6 cyls minimum for internal balancing):

4 cyl engine rather less "peaky" than 2 and 3 cyl (not necessarily better than 2 cyl in this respect)

(Though more cylinders → more internal friction + less thermal efficiency in single expansion engines …)

Divided drive better than concentrated axle drive

Compound better than single

Low rpm / big driving & coupled wheels (not good for thermal eff), …

All a bit theoretical nowadays as well?

5. Remedies

Riding qualities (partly determined by engine influences) important for total mech eff as well,

←

Wheel taper, unsprung weight, suspension qualities, (though too much suspension play is undesirable indeed) bogie and other lateral axle control, number & position of cylinders, compression "accommodating" reciprocating forces, …

5. Remedies

Stiffest possible frames

Optimal alignments

Pistons, piston rods, steam distribution, driving & coupling rods *as light & stiff as possible*

Tandem coupling rods

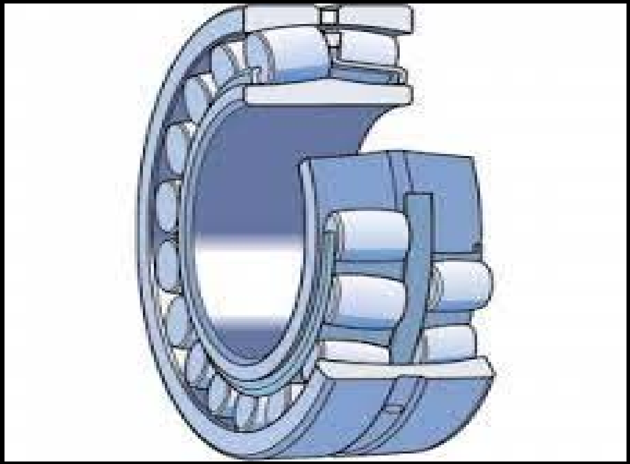
Minimal (bearing / axlebox) play

Low rpm / big wheels (though not good for thermal efficiency)

Sliding urface polishing & hardening, …

5. Remedies

Spherical / swivel joint roller bearings accomodating inevitable torsion (“bending”) (of crankpins etc.) wherever feasible (apart from crosshead + 1 non-swiveling bearing in coupling rod assembly):



5. Remedies

(Vertical) axle guidance / suspension in such a fashion that driving rod geometries are respected as much as possible

Jamie Keyte's suspension superior in this respect as well?

5. Remedies

Everyday practice:

Keep alignment in good order

Best possible lubrication

(Again) valve events to be set to “compression compromise”

Longer cutoff with lower steam chest pressure (!)

Full load whenever feasible

(Track maintenance, …)

5. Remedies

Better mech eff → lower maintenance costs as well:

Less wear + less breakdown

+ heated debate? *Friction please*!

Thank you very much.