



COALITION for  
SUSTAINABLE RAIL

# Steam Locomotive Rail Wheel Dynamics Part 2: Mechanical Balancing of Steam Locomotives

Ing. Wolf Fengler, Ing. Hugh Odom, P.E. and John Rhodes

Edited Ing. G.R. Mangels, Jr., Ing. S.T. McMahon, D.A. Ward

## About the Coalition for Sustainable Rail

The Coalition for Sustainable Rail (CSR) is dedicated to advancement of modern steam technologies, research and development of biofuels, and educational outreach. CSR is a 501c(3) nonprofit working in collaboration with the University of Minnesota to advance the state of the art in these areas. A scientific and educational organization, CSR's mission is to advance biofuel research and production; to research and develop sustainable railroad locomotives; to promulgate associated sustainable technologies; and to support and conduct non-partisan educational and informational activities to increase awareness of its mission.

## About CSR's White Paper Program

Working in conjunction with the University of Minnesota (U of M), the Porta Family Foundation, and other not-for-profit rail and biomass research organizations, CSR's White Paper Program is bringing works pertinent to biofuel, modern steam locomotive and transportation research into the public discourse.

**Cover Photo** - Condensation drips off of the siderods of former Nickel Plate Road 2-8-4 number 765, currently owned, operated, and maintained by the Fort Wayne Railroad Historical Society. - Kelly Lynch Photo

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## Foreword

Dear Reader:

Dynamic augment. Hammer blow. These ominous sounding synonyms are often bandied about as one of the primary reasons why direct drive steam locomotives will be forever relegated to the realm of history. And for good reason – failure to control these forces can cause a locomotive to shake itself apart and warp the very rails that support it. This very possibility is why CSR is investing considerable research into this subject; it affects all aspects of our development programs.

In part one of this series, CSR reviewed empirical evidence providing real world examples of the high speed capabilities of state-of-the-art steam circa 1944. Analyzing old test reports is one thing, but this paper delves into the underlying physics that must be understood and properly applied to achieve such a goal.

While our technical staff is made up of engineers, this paper attempts to distill important concepts into more understandable verbiage. Beginning with defining key terms, we will present equations relevant to the rail wheel dynamics of steam locomotives, take a closer look at the techniques and technology introduced to facilitate high speed operation and conclude with a discussion of how advances in materials science, physics, computing, and machine design over the last 50 years provide additional tools for the modern locomotive design engineer – tools which may just help CSR relegate dynamic augment to the history books.

We hope that you enjoy this peek into the world that our engineering team inhabits. It is a place where we are taking a fresh look at the strengths and weaknesses of direct drive steam locomotives, applying sound analysis principles, and leveraging modern technology to alleviate the problems.

Please note: this revised version of the White Paper is released with modifications provided by two outside reviewers who, at their own initiative, reached out to CSR to provide feedback. If you read one of our papers and see something you have a question about, or think should be reconsidered, please reach out. We are always available at: [info@csrail.org](mailto:info@csrail.org).

As always, these papers are provided as an educational service. If reading so inspires you, please consider a tax-deductible donation to CSR to help us continue this important research.

Yours truly,



**Ing. Wolf Fengler, MSME**  
*Senior Mechanical Engineer*

# 1. Back to Basics

The fundamental concepts of balancing are fairly simple to understand, even if the details are more difficult to grasp. Picture an old fashioned teeter totter, something akin to a lever system, one of the six simple machines that are the building blocks of classical engineered systems. If the pivot is in the middle and the two children on it weigh the same (and are sitting still!), the teeter totter will not move because it is balanced.

Replace one child with a heavier adult and the adult will quickly find themselves on the ground. With a heavy enough adult sitting down fast enough, the child can be launched into the air. Now if the pivot point is shifted toward the adult just the right amount, the weight of the child will balance the weight of the adult.

Another example of balancing may be more applicable to our discussion: a front loading clothes washing machine. Imagine standing in front of a front loading washer as the washer goes into the spin dry cycle. If the clothes aren't evenly distributed, the drum will be unbalanced and the washer will jump around, the effect getting worse as the drum spins faster. This is corrected by stopping the washer and distributing the clothes evenly (some washers redistribute the clothes automatically). The moving parts of a steam locomotive behave in a similar fashion to the washer and this will be discussed later in this paper.

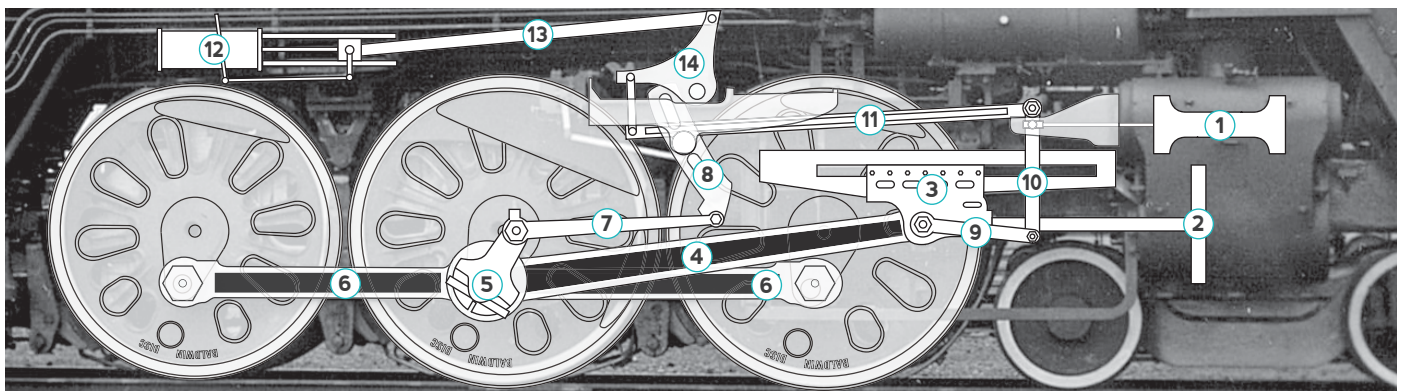
On a conventional steam locomotive a number of components are used to regulate the flow of steam into

and out of the cylinder, thus turning the driving wheels as illustrated BELOW.

The majority of steam locomotives in North America followed the pattern illustrated BELOW. The key component here is the main rod (4). The so-called "small end" of the main rod (4) moves with the linear motion of the piston (2) and crosshead (3). The opposite portion of the rod, the "big end" connects to the crank pin on the main driver (5) and follows a circular path. As the crank pin is offset from the center of the axle by a certain distance, the piston force transmitted through the main rod thus imparts a torque to the wheel. This arrangement is known as a crank-slider.

When the piston is fully forward or backward, the crank pin, piston rod, and main rod are all in a straight line with the center of the axle. With no offset distance from the axle pivot point, no torque can be produced to turn the wheels. To solve the threat of "locking up" the locomotive, mechanical engineers quickly learned to offset one cylinder from another so that one piston would always be in a position to impart torque upon the wheelset. This value is typically set at 90 degrees which puts one piston at mid-stroke while the other is either fully forward or backward (in contrast, bicycle cranks are set 180 degrees apart). More on that value later.

Internal combustion engines get around this problem by always maintaining a minimum rotational speed (IDLE) and using additional equipment, such as a



**COMPONENTS OF WALSCHAERTS VALVE GEAR**

1	PISTON VALVE	6	CONNECTING RODS	10	COMBINATION LEVER
2	PISTON	7	ECCENTRIC ROD	11	RADIUS BAR
3	CROSSHEAD	8	LINK	12	POWER REVERSE
4	MAIN ROD	9	UNION LINK	13	REACH ROD
5	MAIN PIN / ECCENTRIC CRANK			14	LIFTING/REVERSING ARM

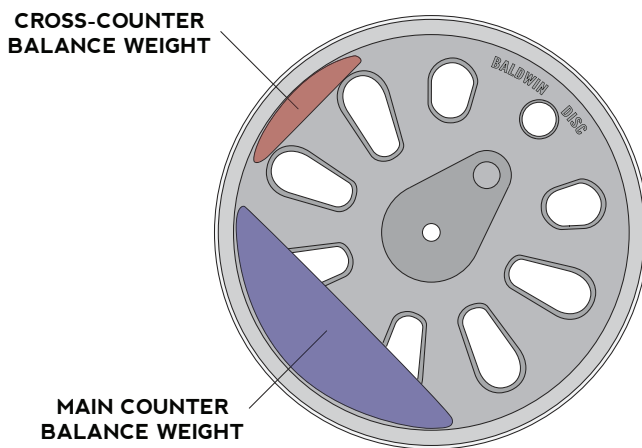
generator and electric motors, to give the operator control over motion. This minimum speed is needed to support the combustion process and make sure that there is enough momentum in the rotating parts to carry the pistons past the point of lockup. That additional equipment comes at the cost of increased complexity and a higher price tag.

To distribute the weight of the steam locomotive so as to not damage track or bridges and increase tractive force, additional drive wheels are used. The side rods transmit the torque imparted to the main driving wheel to the other driving wheels so the weight they carry can be put to good use producing drawbar pull. The coupling action of the side rods provides an additional benefit. If one wheel were to encounter a spot of oil on the track and start to slip, the connected other wheels and their better grip on the rails act to counter the slip.

The side rods are considered a rotating mass as they are confined to circular motion. The other rotating masses on a steam locomotive include wheels, axles, eccentric crank, crank pins, and the big end of the main rod. All of this machinery has mass, and with only the weight of the side rods on them, the drive wheels would not be balanced.

Much like an unbalanced load in a front loading washer, the wheel would bounce with each rotation with the effect worsening with increased speed without counter balancing. However, since the weights of the side rods and other rotating weights can be determined, a counterweight can be added to the side of the wheel opposite the side rod to counterbalance the weight of the rotating masses (this is the visible portion of the driving wheel without “spokes” - ABOVE RIGHT).

While determining the rotational masses was straight forward, balancing the main rod requires additional calculations. This is because its motion transitions from linear at one end to circular at the other. A portion of the main rod’s mass is effectively rotating, while the remaining portion is effectively in linear motion (reciprocating). Determining these proportions requires the main rod to be suspended from one end and swung like a pendulum. The number of swings in a given time is recorded, and calculations are performed to determine the main rod’s “center of percussion”. From this, the proportions of rotating and reciprocating mass can be determined.



The main challenge with steam locomotive balancing concerns the reciprocating mass – those components confined to essentially a back-and-forth, straight line motion coupled to the pistons. On a steam locomotive this includes the piston assembly (2), piston rod, crosshead (3), union link (9), the lower part of combination lever (10) and the small end of the main rod (4). With the 90 degree offset between the piston motions from one side of the locomotive to the other, there is no force to directly oppose the momentum of the piston. This momentum can impart a side-to-side (LATERAL) motion to the locomotive known as “nosing” and a fore-and-aft (LONGITUDINAL) motion termed “surging.” To help offset these effects, steam locomotive designers resorted to “overbalancing,” adding mass to the counterweights in the wheels greater than that needed to simply balance the aforementioned rotational masses. As in most areas of engineering, this led to a compromise. A larger amount of overbalance would help reduce nosing and surging, but the extra weight would itself introduce an additional vertical unbalanced force which came to be known as “dynamic augment.”

As locomotive power and speed increased, another issue became readily problematic. Increasing locomotive size, speed and power meant more force was imparted upon the engine, and the size of the bearings on the crank pins needed to increase as did the size of the main and side rods. To bear the weight of larger locomotives and add more tractive force, more driving wheels became standard. Additional coupled axles meant more side rods to connect between crank pins. This in turn resulted in greater weight hanging farther away from the axle support bearing (SEE DIAGRAM ON PAGE 6). The increased running gear weights on both sides of the locomotive imposed yet additional forces on the axle which needed to be balanced.

## Enter: Cross Counterbalancing.

Another factor became more of a concern as locomotive sizes increased. Due to the fact that the rotating parts of the locomotive are not in the same vertical plane as the driving wheels, where the counterweights were located (SEE DIAGRAM BELOW), an additional imbalance was introduced by the counterbalancing material. Also known as “dynamic balancing” in the US, cross counterbalancing was developed to mitigate these forces. This required an additional small counterbalance weight to be placed in the opposite wheel to balance the near wheel on each wheelset. In practice, it usually meant additional weights were placed on the wheel roughly halfway between the crank pin and the counterweight, a location that is ultimately determined by calculation (SEE TOP OF PRECEDING PAGE). In some engines, the cross counterbalance weight was combined with the main counterbalance weight, the total weight and location being determined by calculation.

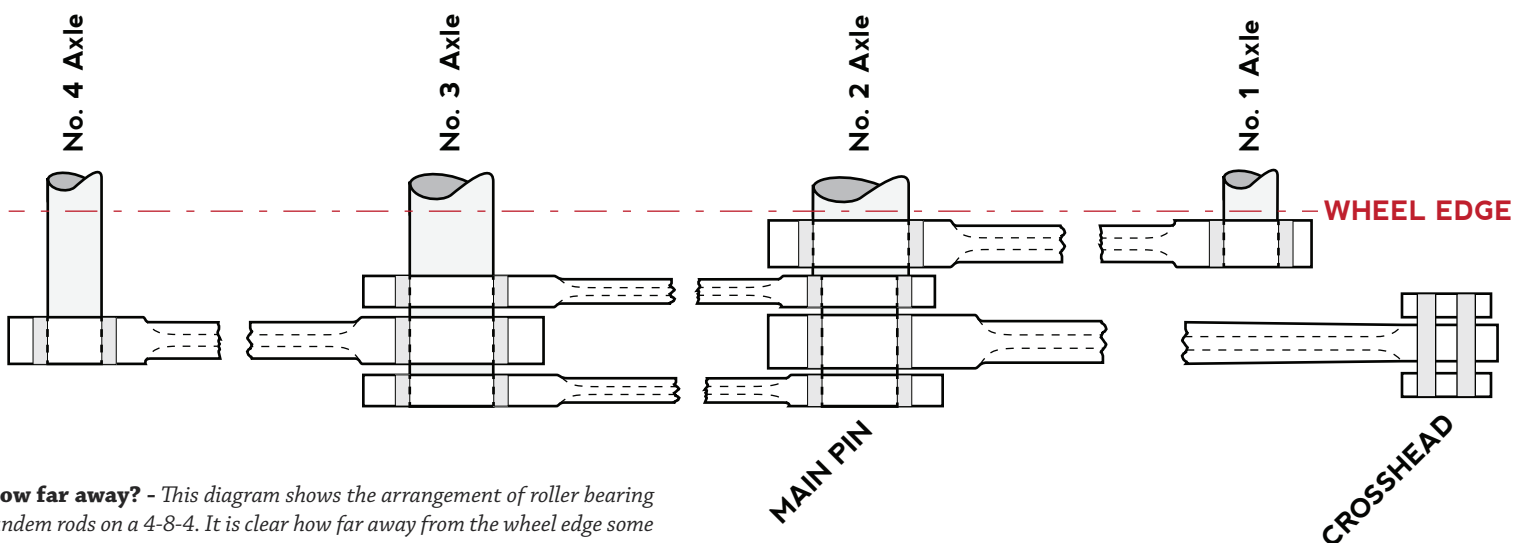
The increased power of locomotives and consequently larger side rods and crank pins began to take their toll on traditional steam locomotive wheel centers. Cast, spoked driving wheel centers tended to crack under extreme use and fatigue quickly so, around the time cast bed frames came into the norm, a new type of wheel was invented. The BOXPOK or DISC driving wheel center thus became another useful tool in the locomotive designer’s toolbox. As it turns out, these new wheel designs not only manage stresses within the wheel better than traditional spoked drivers, but their hollow interior box section provided increased room at more optimal locations to apply counterweights.

One area often neglected in the consideration of locomotive balancing is the valve gear. While poor weight management in this mechanism is not likely to cause track damage, poor attention to detail would introduce excessive vibrations that would fatigue and cause premature failure of components.

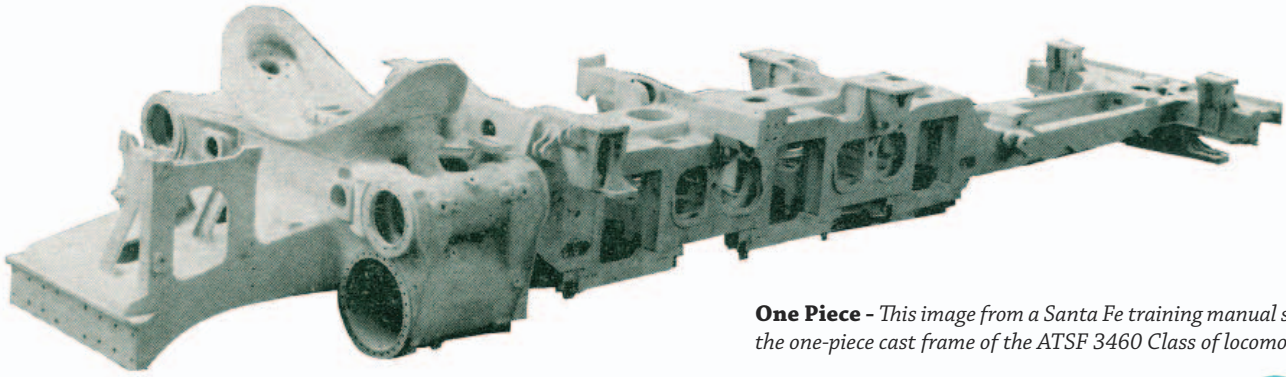
It is important to note that while the weights and their placements could be calculated, the design engineers of the day could not always accurately predict the performance of the locomotive’s running gear. Several locomotive classes designed in the 1930’s in accordance with accepted engineering guidance developed unforeseen problems, such as driving wheels leaving the rails at far lower speeds than calculations predicted, resulting in extensive track damage.

Calculating the dynamic interaction between the locomotive at speed and the track and supporting bed was beyond the capabilities of engineering calculations at the time. Over time, engineers developed guidelines based on real world performance locomotives, but those were still limited in many respects by only educated guesses. Engineers also realized that overbalance sometimes created more of a problem than it solved and developed other techniques to counter nosing and surging.

The outstanding high speed performance of the N&W J class discussed in part one of this two part White Paper is largely due to careful design and extensive utilization of these new techniques.



**How far away?** - This diagram shows the arrangement of roller bearing tandem rods on a 4-8-4. It is clear how far away from the wheel edge some of the connecting rods hang, placing strain on the steel crank pins.



**One Piece** - This image from a Santa Fe training manual shows the one-piece cast frame of the ATSF 3460 Class of locomotives.

## 2. State of the Art in 1950

The first part of this two part White Paper series on steam locomotive rail wheel dynamics focused greatly on the story of the Norfolk and Western Class J, one of the most modern traditional steam locomotives produced in the United States. Built in 1944/1950, this class of locomotive featured the most modern techniques for mitigating rail forces including: 1) a one-piece cast steel frame; 2) FRANKLIN Automatic Wedges; 3) FRANKLIN radial buffer; 4) roller bearing side rods; and 5) limited lateral motion. These five traits created a rigid, low maintenance and low force engine mechanism allowing the Class J to excel as a leader in traditional locomotive design.

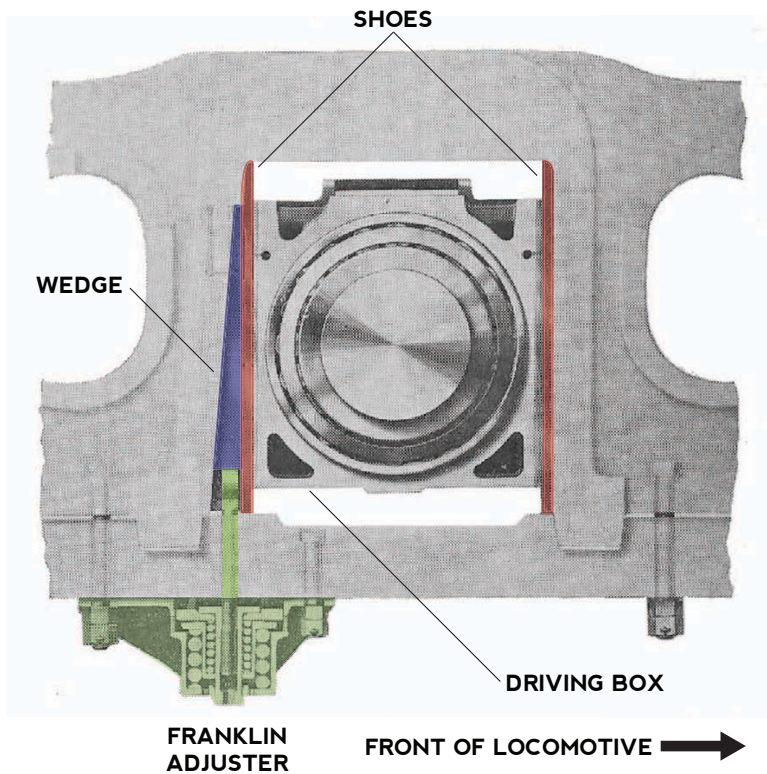
The foundation of any modern steam locomotive is a rigid frame, and the solution devised in the early 1930's was the one-piece cast steel locomotive frame. In this arrangement, coupler pockets, cylinders, frame openings, mountings for appliances and supports for the boiler are formed in one massive casting. This design reduced overall maintenance on the frame (traditionally built-up of multiple pieces of steel bar) and increased rigidity across the locomotive. The additional rigidity translated into greater mechanical accuracy, facilitating the addition of more precise mechanisms (e.g. roller bearings in place of traditional solid bronze bearings). In modern practice, welding technology would facilitate manufacture of a locomotive frame without needing one solid casting, but the concept is the same: a rigid frame means the possibility of a more precise engine.

Partnered with the more rigid frame was the ability to pair roller bearing axles with driving wheel boxes and employ an "automatic" wedge system to keep driving wheels in "tram," or accurate mechanical adjustment, with each other and the pistons on the locomotive. Each driving wheel axle sits in a driving box that fits into the jaws of the locomotive frame. The front part

of this box (toward the pistons) is machined perfectly vertically and at a perpendicular angle to the piston stroke. It is against this surface that the axle box rides on a machined, wearable surface known as a "shoe." This provides a square surface for the axle box to push against. Remember, even though the train rides on track, the axle boxes need to slide up and down over rail joints and as the engine rocks on its suspension. These up-and-down motions, however, need to be in tram with the pistons.

To keep the driving boxes pushed flush against the shoes, the back of the frame jaw opening is tapered upward (meaning the bottom of the opening is larger than the top). A wedge is placed between the tapered opening of the frame and another wearable shoe in which the rear half of the driving box rides. This wedge was traditionally held in place by hand-tightened bolts that provided adequate upward force (translated into forward tension) of the box against the wedge. As the solid axle bearings heated up, that bolt could become too tight and result in misalignment of the pieces or binding of the axle boxes, both of which are big problems and a traditional source of repair issues for steam locomotive maintenance crews.

To solve this, the FRANKLIN RAILWAY EQUIPMENT SUPPLY COMPANY (FRANKLIN) invented a device known as the "Automatic Compensator and Snubber," or simply the Franklin Automatic Wedge (TOP OF FOLLOWING PAGE). Through use of a spring actuated pall of set tension, it provides a spring-loaded upward force against the wedge that is consistent even as the axle boxes heat and expand under operation. This alleviated much of the risk of failure associated with traditional axle box design and greatly reduced overall maintenance cost. It also allowed the boxes to compensate for additional shocks and forces incurred during operation that traditionally might not have been possible.



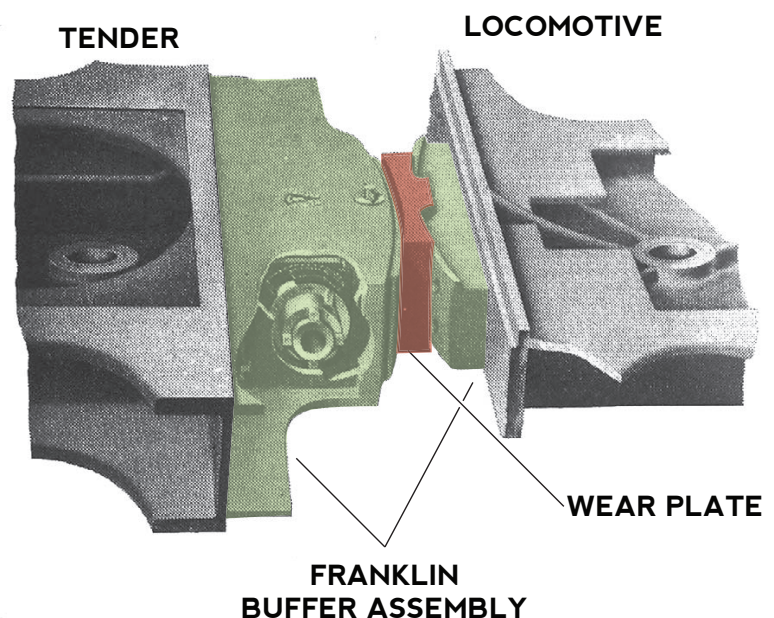
traditional steam locomotives in the U.S., including the N&W Class J. The alloy steel rods used on the J were paired with roller bearings which, in contrast to the traditional bronze bearings used on steam locomotives that needed servicing every few hundred miles, could go nearly a thousand miles between servicing and greatly reduced mechanical resistance. Further, the rods on the Class J locomotive were originally installed as TANDEM RODS, meaning the force from the main piston rod is transmitted to two driving wheels, not one, further reducing track forces and increasing power transmission efficiency. The theory was that if the piston forces were transmitted between two driving axles, the main force of that rod would be effectively centered in the middle of the side rod and not directly against a crankpin, reducing internal forces and the risk of possible crankpin failure while increasing efficiency. In practice, however, this led to failure at crankpins and of the rods and, at least on N&W, TANDEM RODS were later removed from the Class J locomotives.

Further innovation from FRANKLIN was its radial tender buffer. This connection was employed on locomotives beginning in the 1930's and its purpose is to maintain constant connection between the locomotive and tender while allowing for adequate motion of the tender in all directions (RADIAL MOTION). The elastic connection between the two devices allows the further dissipation of vibrations caused by the running gear and essentially ensures that the tender mass is also part of the locomotive mass. This is very important in deadening unbalanced horizontal inertial forces of the pistons and rods within the locomotive and tender which would otherwise be transmitted to the rails or through the train. The use of the buffer also enables designers to minimize or completely remove overbalance (SEE NEXT SECTION), dissipating track pounding forces.

As discussed above, the side rods on a steam locomotive are responsible for transmitting tractive force from the pistons to the wheels, thus their mechanical efficiency is crucial to increasing the efficiency of the locomotive as a whole. TIMKEN and SKE, the two leading bearing manufacturers from the time and to-date, each had designs for low friction side rods, the former using tapered roller bearings and the latter spherical roller bearings.

Timken, also a specialist in high strength alloy steel, created roller bearing side rods for many advanced

With the implementation of cast frames, FRANKLIN adjusters and more advanced roller bearing rods, the need to keep steam locomotive running gear in perfect alignment became even easier to accomplish. The last white paper in this series discussed the 70" drivered Class J hitting 111 miles per hour. One of the reasons this was achievable is the tightening of lateral motion in the frame. The locomotive itself lacks significant lateral motion in the drivers and a tightened lead and trailing truck, serving to deaden lateral forces in the locomotive. By deadening forces otherwise counteracted via overbalance, it allowed a much better balanced locomotive and one that could operate smoothly to high rotational speed.





### 3. Dynamic Augment Explained

As explained previously, DYNAMIC AUGMENT is the force acting upward and downward on the driving wheels due to the “extra” balancing weight added to the counterweight to compensate for the reciprocating mass of the piston, piston rod, crosshead, and a portion of the main rod. The basic equation to calculate this force is:

$$F = \frac{WV^2}{gR}$$

- F = centrifugal force
- W = weight of body in pounds
- V = linear velocity of the center of gravity of the body in feet per second
- g = force of gravity; 32.174 feet per second per second
- R = radius of path in feet

For the case of a steam locomotive, the formula is:

$$\text{Force} = \frac{1.6047 \times \text{stroke} \times \text{unbalanced force} \times (\text{speed})^2}{(\text{Diameter})^2}$$

- Stroke = piston stroke in inches
- Unbalanced force = weight of OVERBALANCE or UNDERBALANCE on driving wheel
- Speed = miles per hour
- Diameter = diameter of driving wheel in inches

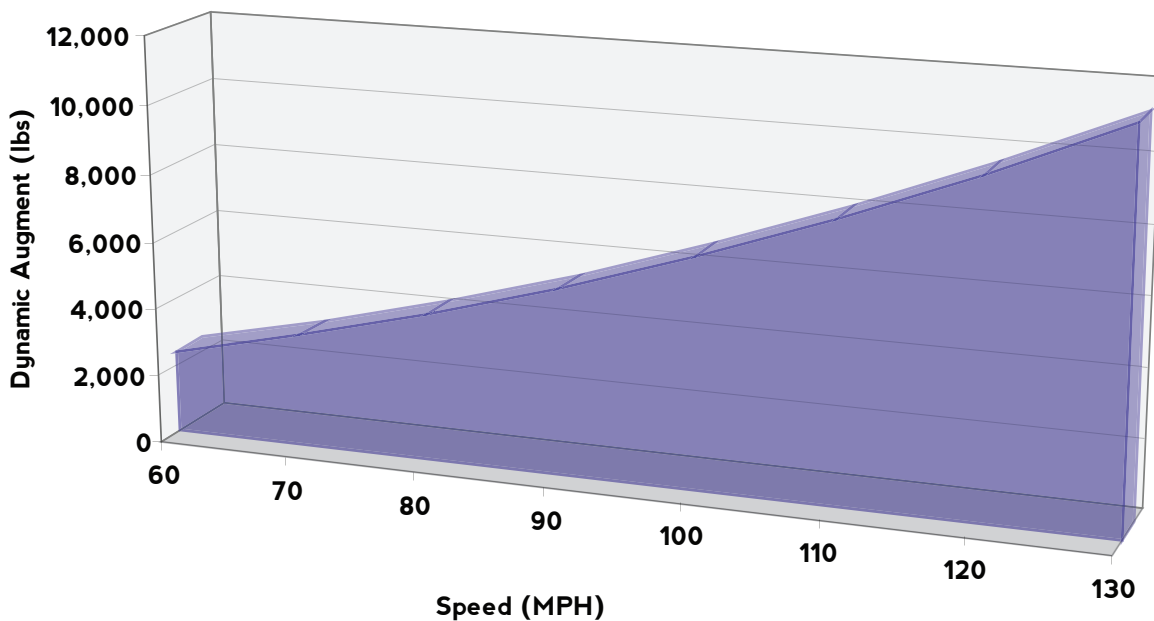
This formula shows that DYNAMIC AUGMENT (force) is dependent on the amount of overbalance (the

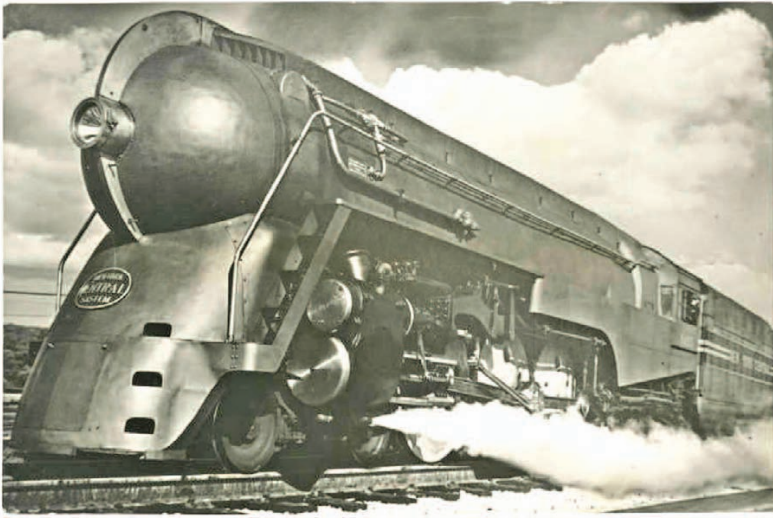
unbalanced force), the length of the piston stroke, the speed of the locomotive, and the diameter of the driving wheels.

Using this formula, we can calculate the THEORETICAL DYNAMIC AUGMENT that occurs with the driving wheels of a locomotive similar to 3463. By the 1940’s, Baldwin, the builders of no. 3463, recommended that no more than 100 pounds of overbalance be added to the main drivers of a “modern” steam locomotive. While CSR intends to minimize overbalance (thus DYNAMIC AUGMENT), if we assume hypothetically that 100 pounds of overbalance has been added to the main drivers, the dynamic augment would be as follows:

Speed, MPH	60	70	80	90	100	110	120	130
Dynamic augment, lbs	2,415	3,287	4,294	5,434	6,709	8,118	9,661	11,338

As you can see, the DYNAMIC AUGMENT rises rapidly with speed. At 130 MPH, with only 100 pounds of overbalance, over 11,000 pounds of DYNAMIC AUGMENT would occur in the main driving wheels. This sounds like a huge figure, but remember that the drivers already carry a great deal of weight. In this example, when standing still, each driver supports approximately 35,600 pounds. At speed, as each driver rotates, the DYNAMIC AUGMENT adds to this load for a portion of the revolution (DOWNWARD ROTATION) and subtracts from this load (UPWARD ROTATION) for a portion of the revolution. This means that at 130 MPH, the actual force of each of the two main drivers pressing on the rail would vary from a minimum of about 22,400





**Running in place** - The New York Central tested its J3a Hudson class locomotive on greased rails to a rotational speed of nearly 700 RPM, or 164.5 miles per hour. It caused no damage to rail or locomotive. ROBERT YARNALL RICHIE PHOTO, Southern Methodist University, Central University Libraries, DeGolyer Library.

pounds to a maximum of about 46,900 pounds. That said, according to the Passenger Rail Investment and Improvement Act (PRIIA) Section 305 Next Generation Corridor Equipment Pool Committee, the maximum P2 force, the total vertical force generated at the interface between rail and wheel including static loading and inertial forces associated with dynamic response of unsprung masses to variation in the vertical alignment of the rail, of an Amtrak P42 DC operating at 110 mph generates a P2 force of 43,231 lbs on each wheel.

This level of dynamic augment could cause either or both of two problems. When acting downward, the force generated increases the weight on rail, but it would not be enough to damage modern track infrastructure. When acting upward, the reduced axle load could cause the driving wheels to slip, which could lead to even higher rotational speeds, causing higher dynamic augment and even failure of mechanical parts. Fortunately, the torque on the driving wheels decreases with speed which offsets the effect of dynamic augment increasing the likelihood of slipping.

The upward force associated with dynamic augment was sometimes associated with being able to lift the locomotive off of the rails at very high speeds (meaning the upward forces of the rods on one side of the engine outweighed the downward force (WEIGHT) of the locomotive. Though this could happen on the largest, most ungainly of locomotives, the New York Central railroad undertook tests in 1938 on one of its 4-6-4 type locomotives where it greased the rail and ran the locomotive to a top slipping speed of roughly 700 RPM. Very little wheel lift occurred at those speeds, and there

was no damage to the engine or rails resulting from the test, indicating a well-balanced locomotive. Note: at 700 RPM, the locomotive tested would have been spinning its 79 inch diameter driving wheels at 164.5 mph.

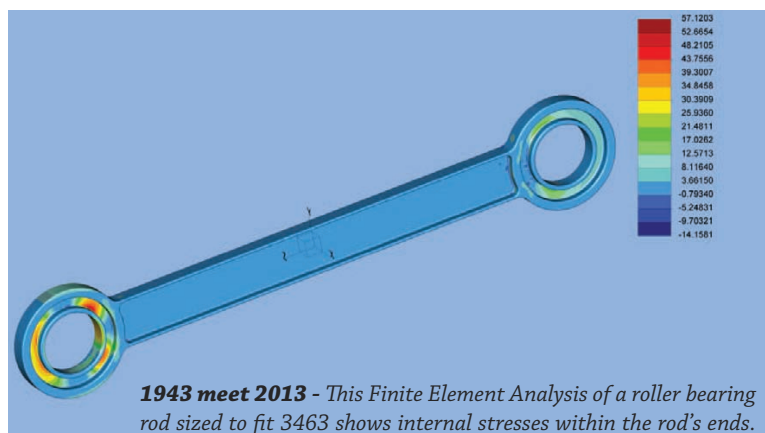
## 4. To Infinity and Beyond

With the notable exceptions of the work done by Andre Chapelon, Livio Dante Porta, David Wardale, Nigel Day, CSR's own Shaun McMahon, and a few others, steam locomotive development essentially came to a halt in the 1950s. However, the ensuing decades have seen tremendous advances in technology which have yet to be truly employed to maximize the potential inherent in direct drive steam locomotion.

Innovation starts with an idea which must be evaluated to determine its effectiveness. During the steam era and even to some extent in the later work of Porta and others, most new concepts had to be built first and tested empirically. This is an expensive and time consuming prospect which is one reason why the introduction of improvements was, and is, a slow process. Furthermore, while much of the underlying physics was understood, the equations were often too difficult to solve with hand calculations. As noted above, the more complicated mathematics was often simplified by developing approximations based on test data (i.e. add 100 lbs as a "rule of thumb"). While useful for designing a locomotive similar to what was tested, the equations begin to fail the farther afield a design gets from the original.

### Enter the Computer.

As computer technology matured, techniques were developed allowing previously impossible-to-solve equations to be calculated with amazing accuracy as verified by actual hardware tests. This means that the CSR engineering team can now create three-



dimensional models of the running gear components on 3463 and test them in the computer before the locomotive even turns a wheel. New designs for side rods and other components can be evaluated for stress and inertia forces in days, not months. While these techniques do not totally eliminate risk, they certainly go a long way to improve the process and reduce development costs. Computer and sensor technology also allows the static and dynamic balance of rotary equipment, such as wheel sets, to be more accurately checked than was possible with the equipment available during the steam era.

Even the availability of sensors used by the railroads themselves have important impacts on the research CSR is pursuing. In Great Britain, certain railroads employ a system known as WHEELCHEX to measure wheel rail forces as trains pass over. This system recently picked up the forces of a streamlined A4-class steam locomotive (same model as that which set the world speed record in 1938) passing over a sensor going 81 mph / 130 kmh (BELOW). The data is interesting in that it shows precisely how much force at that instant is being imparted on the rail.

According to the data at hand, the locomotive's lead driving wheel is generating about 100 kN (22,480 lbs) of downward force and a P2 force of 155 kN (33,800 lbs) downward on the rail on the right side of the locomotive. The locomotive has a static main driving wheel loading of 114 kN (25,800 lbs). Subtracting this force from that recorded indicates an instantaneous dynamic augment of roughly 14 kN (3,147 lbs) in an upward direction. It is important to note, however, that the dynamic augment could be greater depending on where the wheels were on their rotation while traveling over this sensor and that the locomotive has three pistons, not two, leading to a slightly different rail force pattern.

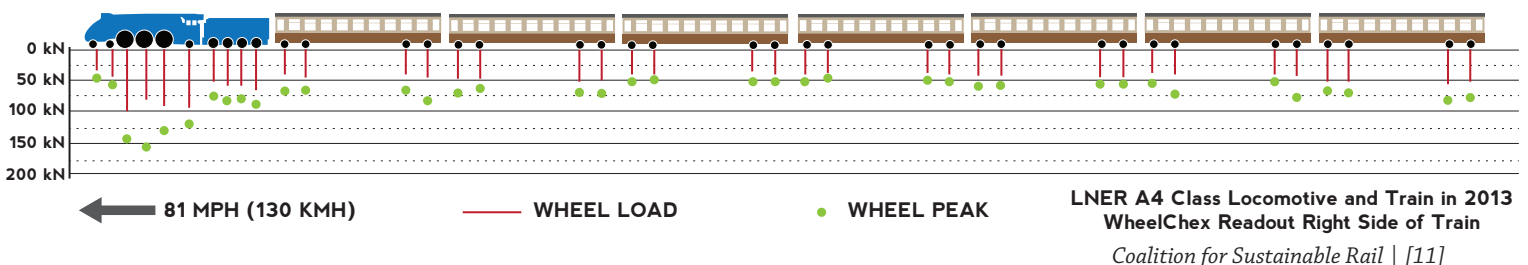
A key component of being able to predict performance using computer programs accurately is having reasonable values to use as inputs. Herein is one reason why the rebuild program with 3463 is so important. CSR can make good estimates for many of those inputs,

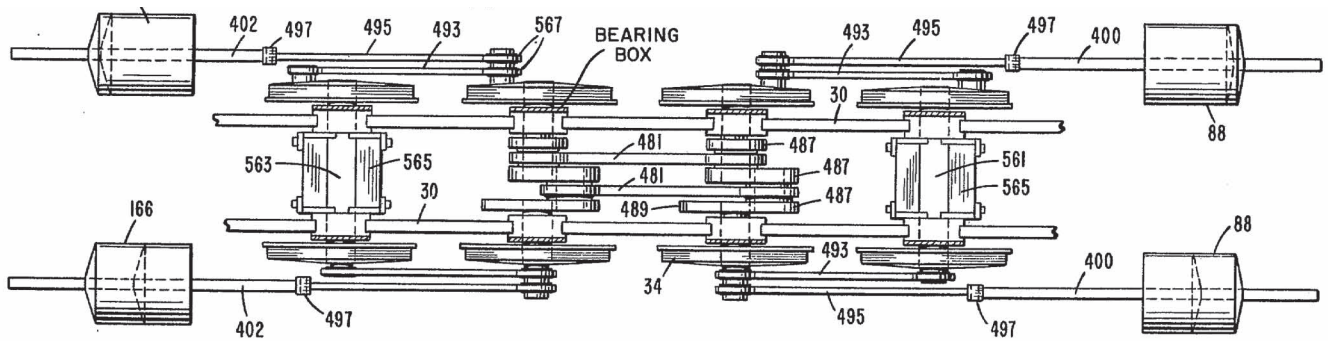
but we need a solid baseline from which to start. Hence CSR's data gathering will start with 3463 in essentially un-modified form.

As the astute reader will have noted in previous sections, reducing weight in the wheels and running gear is important to allowing a locomotive to reach high speeds. Prior to World War II, materials like plastics as well as aluminum, titanium, magnesium, and other light weight metal alloys were in limited use. Carbon fiber composites were decades off from being invented although fiberglass was seeing its first applications in the aircraft industry.

While the rapid growth of air travel following the war nearly killed off intercity passenger rail in North America, it spurred the tremendous development of strong, light materials so critical to flight. The availability of these higher performance materials provide design options only dreamed about by the engineers at ALCO, BALDWIN and LIMA. Here again, design software allows the material properties for specific alloys to be programmed. Everything from tensile strength and density to thermal expansion ratio can be utilized to weigh the performance of a given material arranged in a particular geometric configuration in concert with the rest of the running gear components. Material cost is also a factor, with the higher performance materials naturally coming with a higher price.

It should be noted that carbon fiber and similar materials have optimal strength when the fibers are in tension and practically no strength in direct compression. Most structural elements will see both tension and compression, so any components designed using these materials must be fabricated to anticipate those loads with the fibers oriented accordingly. The properties of metals are essentially the same in any direction and thus metals are in many ways easier to design with. Special software is typically used to create a fiber pattern so that the strength of the part is more or less uniform in most directions with special attention paid to the critical load paths.





**A Balanced Approach** - The drawing above illustrates the running gear arrangement on the aborted ACE 3000 project. Known as the WITHUHN COUPLED DRIVE, reciprocating and rotational masses were laterally and vertically balanced by the four piston arrangement.

So far CSR's study of future possibilities point us toward being able to more accurately predict where and how much weight to use to balance the inertial forces in the running gear, use modern instrumentation to be sure those weights were in fact accurately placed, and use advanced materials to reduce the amount of component weight we need to balance in the first place.

Two questions must thus be asked: 1) are there additional ways to improve the traditional locomotive running gear; and 2) is the traditional running gear layout really the best we can do in a direct drive arrangement or is it just that – traditional?

The answer to question one is most certainly yes. Thanks to TIMKEN, SKF, and MCGILL, rolling contact bearings found their way into side rods and valve gear components in the later decades of steam development in North America. Crosshead designs were little changed, however. In recent decades the linear ball bearing has been developed which may prove a good answer to reducing friction and maintenance for the purely reciprocating parts of the running gear. There are a number of other opportunities as well.

The answer to question two is also a resounding "affirmative." The fundamentals of a traditional direct drive steam locomotive include double-acting cylinders and a ninety degree offset between the right and left side wheel sets as noted previously. It is indeed, however, traditional and not necessarily the best way to smoothly apply power to the rails. One option would be to use three cylinders each set at 120 degree increments. This arrangement would still provide the anti-lockup ability of a traditional locomotive, but geometrical studies point to smaller torque fluctuations and thus a reduced tendency to slip. Another possibility was proposed by CSR advisor Bill Withuhn for the ACE 3000 project in the 1980s. While similar to the design of the Pennsylvania Railroad T-1 class 4-4-4-4 locomotives, it features two important differences as shown ABOVE. First, the front and back pistons on

one side are arranged to be 180 degrees out of phase with each other and ninety degrees out of phase with the other side. This cancels out the forces which lead to nosing, surging, and dynamic augment without sacrificing the anti-lockup geometry. Second, the inside connecting rods increase the number of coupled axles, which leads to a lower risk of slipping. Other variations may be possible, and the CSR engineering team is taking a close look at this fundamental design element.

## 5. Conclusion

The reader should now have a sense that CSR is serious in its intent to leverage the best of traditional steam locomotion with the innovations of Livio Dante Porta and modern technology to create a new locomotive design that truly is cleaner, quicker, and cheaper. Indeed, to gain acceptance a new steam locomotive would have to excel in all three of those areas to be viable. To ensure success, CSR has gone back to basics in evaluating critical locomotive subsystems as illustrated in this white paper series on steam locomotive speed and rail dynamics.

One aspect CSR has yet to touch on is the fact that track infrastructure is in much better shape in the modern era thanks to innovations such as welded rail and improved understanding of rail – tie – ballast interactions. This helps our position as roadbed so constructed to support heavy diesel-hauled trains is also well suited for steam hauled trains.

It should also be apparent that CSR is evaluating a number of promising approaches to minimizing or eliminating dynamic augment, one of the key stumbling blocks to the acceptance of direct drive steam locomotives. The baseline data derived from high speed operation of a restored 3463 will play a key role in proving out those approaches. A future white paper will provide more details once the engineering team is further along in its efforts.

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