

Spring Equalization for Steam Locomotives

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ABSTRACT AND INTRODUCTION

The axles of steam locomotives are supported by springs, for the obvious reasons and some less obvious. If the axle ends were each independently sprung, owing to the high stiffness (spring rate) the springs must have, even small local undulations in the height of the rail will cause substantial dynamic variation in the distribution of the locomotive's weight over the various wheels, with undesirable effect. To mitigate this problem, locomotive designers soon developed an array of clever mechanisms for equalizing the wheel-to-track force over most of the driving wheels on a given side. Because of the special duties of the first set of driving wheels and the preceding unpowered "leading" wheels, there are different objectives there, fulfilled by a more complex mechanism. This article describes the principles of these equalization mechanisms.

OUR APPROACH

Actual locomotive spring equalizing systems follow a plethora of different and clever designs. Our purpose here is not to catalog these but rather to illuminate their common principles. Thus, we will use certain rather common implementations as the basis of explanation.

The specific proportions and mechanism details used in the illustrations are arbitrarily chosen for clarity of presentation, and actual implementations may depart from them substantially.

OUR FIRST MODEL

To best illustrate the first set of principles of interest, we will base our initial discussions on a locomotive of the 0-6-0 wheel arrangement: three axles of driven wheels ("drivers") and no unpowered leading or trailing wheels. Such locomotives are often used as switchers;¹ as we will learn later, the main purpose of leading wheels (as, for example, in a 2-6-0 arrangement) is to help guide the locomotive around curves at higher speeds, and since switchers do not operate at a substantial speed, the complication of leading wheels can be foregone.

¹ This configuration is widely found in the U.K., both in actual locomotives and fictional ones; Thomas the Tank Engine is an 0-6-0 (actually, 0-6-0T).

Before we enter the fanciful world of hypothetical locomotives, figure 1 gives us a look at an actual locomotive of the 0-6-0 type:²

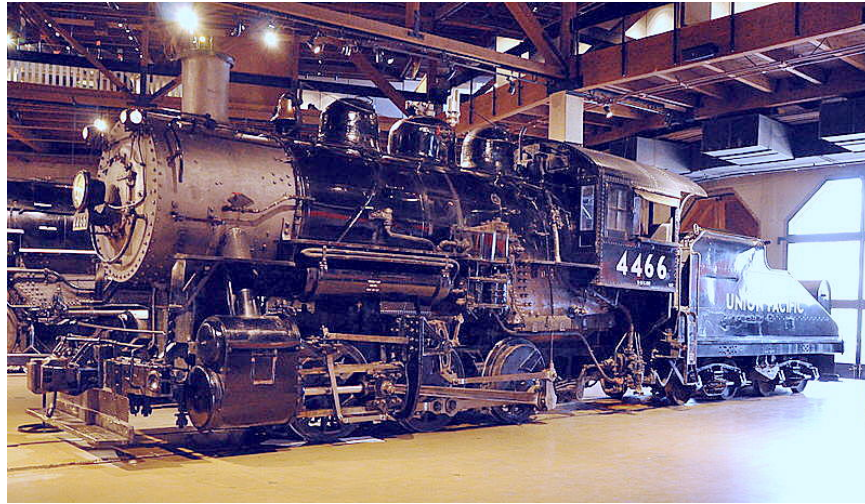


Figure 1. 0-6-0 steam locomotive

THE ROLE OF THE SPRINGS

Since very early in steam locomotive development, in most locomotives the axles carrying the wheels were suspended on springs. These have the three following (and somewhat overlapping) duties:

- Smooth the ride for the crew.
- Reduce the “unsprung mass” and thus reduce the acceleration forces on the wheels and axles caused by rapid undulations in the rail profile.
- Reduce the degree to which undulations of the track profile change the wheel-to-track force, thus dynamically varying the distribution of the locomotive’s total weight over the various wheels.

As we will see shortly, attainment of the third objective cannot readily be done to the degree desirable by simple springing arrangements. It is typically attained through the equalizing arrangements we discuss in this article.

BASIC SPRING EQUALIZATION

Underlying spring arrangement

Figure 2 shows, on our hypothetical 0-6-0 locomotive, the basic (non-equalized) spring arrangement upon which our discussion of

² Union Pacific 4466, 0-6-0 (“Six-wheeler”), built 1920 by Lima Locomotive Works. Seen in the roundhouse, California State Railroad Museum, Sacramento, California.

spring equalization is predicated. It assumes a perfectly flat track. The front of the locomotive is to the right.

The F- designations are forces at various points in the system. At the bottom of this and the following figures, various relationships between the most critical forces are stated. I will not take the reader through the statics algebra that is involved to derive these results.

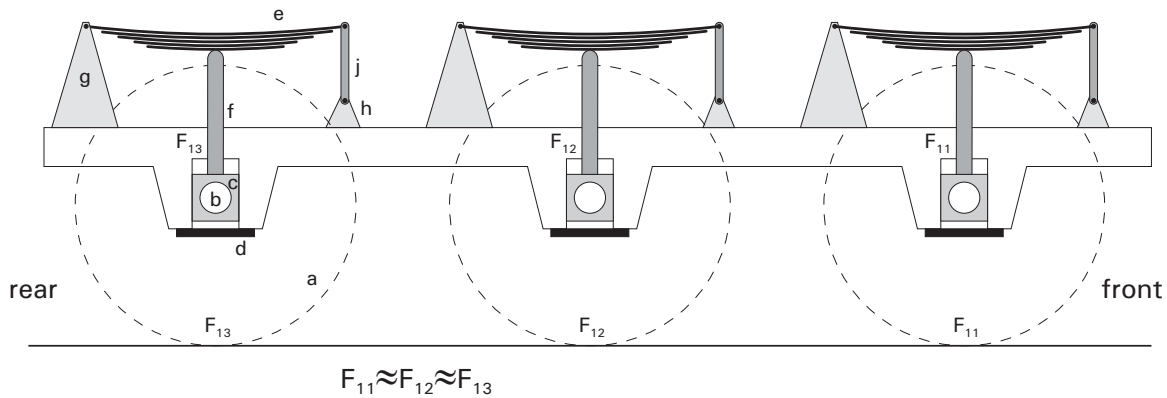


Figure 2. Non-equalized spring arrangement—flat track

The driving wheels themselves are not shown, as they would obscure our views of the spring system. Dotted circles (a), however, show their perimeters (not including the flange). The solid line at the bottom represents the elevation of the top of the rail.

The springs shown are of the multiple leaf type, most commonly (although not universally) used for the purpose. Compared to coil springs, they readily offer a high load capacity and the needed high spring rate, and the sliding friction between the leaves provides valuable “damping” of locomotive motion.

Each pair of drivers is carried on a rigid axle (b). These run at each end in bearings held in what are called *driver boxes* (c). These are held in vertical slots in the frame (or an attached bracket) so that they can move a modest distance vertically.

Each driver box is connected by a spring post (f) to the center of a leaf spring (e). In reality, these spring posts are usually much shorter than suggested by this figure—their length here is to allow space for a clear presentation of the mechanism.

One end of the master leaf of the spring is held on a pivot on a fixed bracket (g). At the other end, the connection is to a spring link (j) leading to another fixed bracket (h). The purpose of the link is to accommodate changes in the horizontal dimension of the spring as it flexes (automotive leaf spring systems have the same arrangement). We assume that the center of the spring can slide slightly across the top of the spring post to make the same accommodation.

Note that it is the brackets **g** and **h** that actually hold the locomotive up!

If all the parts are identical and the dimensional details are “ideal”, the force between the wheel and the track—which is, for all practical purposes identical to the force on the driver box at that end of the axle—will be the same for every wheel. Thus the adhesion of the wheel to the track—the limit of the amount of tractive effort that wheel can impart—will be the same for every wheel.

With an undulating track

In figure 3, we see this same locomotive at a location in which the track has a local undulation, in this case convex upwards. The degree of undulation shown is substantial (actually unrealistic) to make more clear the point to be illustrated.

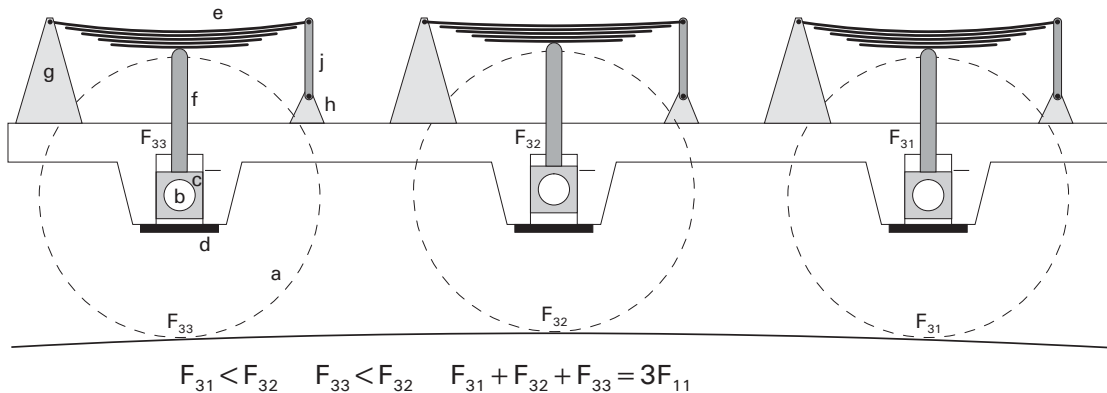


Figure 3. Non-equalized spring arrangement—undulating track

Equilibrium occurs in this situation with the center axle above its “normal” position by a certain amount and the front and rear axles below their normal position by about half that amount. The index marks on the frame adjacent to the driver boxes show their “flat track” equilibrium positions.

The force on the center axle driver box (and thus the wheel-track force) is increased from its “normal” value by a certain amount, and the force on the front and rear wheels is decreased (by about half that amount).

Because the stiffness (“spring rate”) of the springs—the ratio of a change in force to the change in displacement—is quite large, the change in forces is substantial for even a modest height difference.

We may at first be inclined to dismiss the importance of this. After all, the total force on the six wheels remains nearly constant. If the coefficient of friction is constant and uniform, thus the total adhesion will be unchanged.

But, for a number of reasons, including matters of the role the lateral adhesion of the wheels plays in guiding the locomotive laterally along the track, it is very undesirable to have continual substantial change in the distribution of individual wheel forces.

Minimizing this is the objective of *spring equalization* systems, the topic of this article.

A temporary objective

As a premise for our discussion of spring equalization systems, we will at first adopt a simplistic objective. We will later find that it is flawed, in two ways. But following it for now will help us focus on an important basic principle, and to understand the basic equalization mechanism that pursues this objective.

Later, we will refine our objective and cure its flaws. Don't worry—the mechanism we are about to study won't be obsoleted by that insight. We will just find out that it needs some help, given by a second mechanism we will then study.

This interim objective (for a locomotive with drivers only) is:

On either side of the locomotive, at any instant, each driver should have the same wheel-to-track force; that is, all should equally share the weight of "that side of the locomotive".

Basic spring equalization

In figure 4, we see this same locomotive equipped with a common basic spring equalization system (again, the details have been stylized for clarity of presentation), which fulfills our interim objective. It is seen for now on a flat section of track. We also assume for now that the track is not curved; thus, there is no lateral centrifugal force acting on the locomotive.

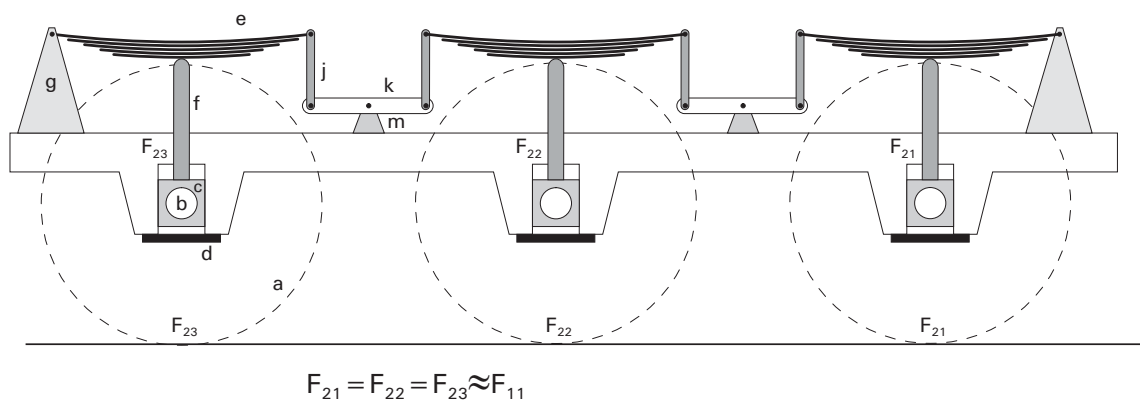


Figure 4. Equalized spring arrangement—flat track

Starting at the leftmost axle, the spring is anchored at its rear as in the non-equalized case. Again, at the front, the spring is connected to a swinging link, but instead of going to a fixed bracket, it goes to one end of an equalizing lever (k). The rear end of the center axle spring goes, via another link, to the opposite end of that equalizing lever. A similar arrangement exists between the center spring and the frontmost one, but its forward end goes to a fixed bracket on the frame.

If we write all the statics equations for this system, we find that in equilibrium the force on each driver box must be the same, and thus the forces on the three wheels are the same. This is the same force as in figure 2.

Note that it is actually the brackets **g** and **m** that hold the locomotive up!

With an undulating track

In figure 5, we see this locomotive on a locally-undulating section of track, with the same profile as seen in figure 3.

As before, we see that the center axle is raised (with respect to the frame) compared to its position on a flat track, and the front and rear axles are lower.

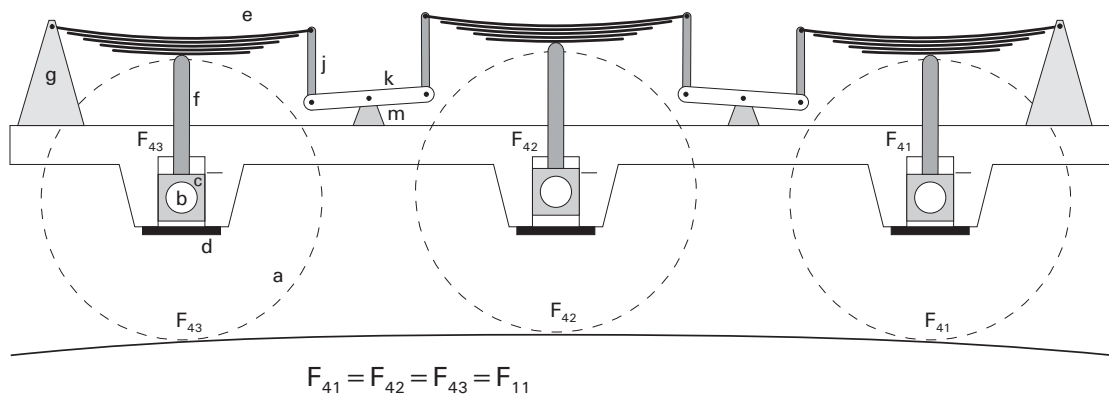


Figure 5. Equalized spring arrangement—undulating track

But the static equations remain the same as in figure 4, and thus there is no choice but for the forces on the three driver boxes (and thus on the three wheels) to be identical—identical, in fact, to the forces in the situation of figure 4. The equalizing levers have shifted their positions to cooperate with this imperative—to allow each of the springs to still be flexed to the same displacement. It turns out that the new positions of the axles are the same as in figure 3 (without equalization); the overall height of the locomotive is the same as in figure 3.

Lateral considerations

What we have seen is the working of the system on the axle ends (and thus wheels) on one side of the locomotive (the right side). Of course, an identical process occurs on the other side, but independently.

Might it not be desirable to equalize the forces right vs. left as well as among the three axles?

Suppose we tried to do that by a system of levers coupling all six springs. That is, the forces all six drivers would always be the same.

Imagine now that pushed down on the left side of the locomotive as far as it would so (the driver boxes on that side all going to the top limit of their travel). The spring system would make the right side go down the same amount, leaving the locomotive with a tilt to the left. If we let go, the upward forces on the two sides of the locomotive would be the same (they are the reactions to the wheel-to-track forces, which the mechanism would assure would be equal).

Thus there would be no unbalance of force to return the locomotive to a level roll attitude. The locomotive in equilibrium could take on any roll attitude. It is not automatically "leveled". In fact, center of gravity considerations would make it prefer to lean "hard over" to one side or the other.

That would hardly be a desirable situation.

So, no, for the general spring equalization system, we want no side-to-side equalization. But the notion will appear in a special way shortly.

RE-EXAMINING OUR OBJECTIVE

I noted at the outset that our interim objective, to have the wheel-to-track forces the same for all drivers on a given side of the locomotive, has two flaws. Let's expose them.

Pitch attitude

If we push down on the front of the locomotive as far as it will go (until the front axle driver box is at the top limit of its travel), the spring system will make the rear rise (probably taking the rear driver box to the bottom limit of its travel). If we then let go, the upward force on the front of the locomotive and the upward force on the rear are identical (they are the reactions to the two wheel-to-track forces, which the mechanism assures will be identical). Thus there is no unbalance of force to return the locomotive to a "level" pitch attitude. In fact, the locomotive in equilibrium can have any pitch attitude over

the range of movement of the front and rear driver boxes. It is not automatically “leveled”.

This hardly seems satisfactory.

The special role of the frontmost drivers

I recently discussed why, in the general scheme of spring equalization we have seen so far, there is not any side-to-side equalization. The reason is that such an arrangement would permit the locomotive to, at will, lean to one side or the other.

Unavoidably, when the locomotive is traversing a curve, centrifugal force will inevitably result in the **total** wheel force on the “inside” wheels to be less than that on the “outside” wheels. We could not avoid that by any overall equalization mechanism—it is an imperative of the dynamic situation of the entire locomotive.

However, let’s consider the implications of this at the front axle, carrying the front two drivers. We rely on these drivers to guide the locomotive around a curve. To make this most effective, it is desirable for the wheel-to-track forces **of these two wheels** to be equal (even though overall lateral equalization of driver force is not desirable).

A single solution for these two shortcomings

Fortunately, these two shortcomings in our objective can be overcome by the addition of a single new mechanism to the overall locomotive suspension system. We’ll see that now.

AT THE FRONT END

The front driver axle

We learned recently of the desirability of the two front drivers always having the same wheel-to-track force, even though that is not desirable all the axles.

To achieve this, often the front axle is completely separated from the overall axle-to-axle (longitudinal) equalization scheme and is given instead a side-to-side (lateral) equalization of force.

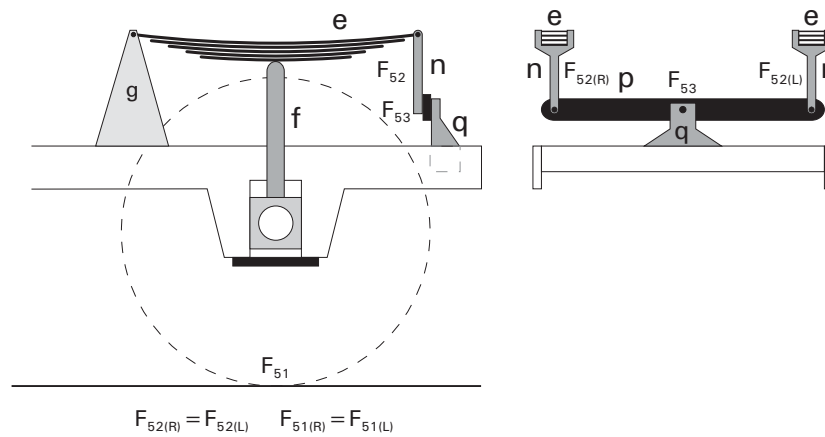


Figure 6. Front driver axle lateral equalization arrangement

A common way to do this in is shown in figure 6 (again highly stylized).

As before, the rear ends of the two springs (we now consider one on each side) are attached to fixed brackets (g), and the front ends are connected through swinging links (n) to the ends of a *transverse equalizing bar* (p), pivoting on a fixed pivot on a bracket (q).

If we consider the statics equations, we find that there is no choice but for the forces on the left and right driver boxes, and thus on the left and right wheels, to be identical.

Will these forces be identical to those of the other wheels on the same side? Clearly in the case of curved travel, no—we know those forces, overall, differ side-to-side because of centrifugal force.

But in the case of this first axle, because of the critical duty of its wheels in guiding the locomotive around a curve, lateral uniformity is far more important than participation in axle-to-axle uniformity.

Influence on the pitch attitude problem

With the front axle taken out of the basic “fore-and-aft” equalization scheme, we have, with regard to pitch attitude, the same situation for a three-axle locomotive as we have on the tractor (“cab”) of an “18-wheeler” truck rig. Like the tractor, the locomotive will now have a preferred pitch attitude (hopefully level).

Two birds with one stone

Thus we see that the separation of the front driver axle, and giving it a lateral equalization system, overcomes both flaws in our simplistic objective and in its fulfillment with the longitudinal equalization mechanism. Now:

- The forces on the two wheels of the front axle are equal, as needed for those wheels to best fulfill their special duty of guiding the locomotive around a curve, and
- The independent springing of (a) the front axle and (b) the remaining axles, as a group, provides a stable pitch attitude for the locomotive.

The leading wheel truck

In fact, locomotive designers soon learned that, even with this nicety, locomotives could not be reliably guided around a curve by the action of the frontmost drivers alone at higher speeds. This was one consideration in the addition of a *leading wheel truck* to the design of locomotives intended for operation at significant speeds. This truck³ carries one or two, and in rare cases three, axles bearing non-driven wheels, generally of substantially smaller diameters than the drivers.

In Figure 7 we see a single-axle leading wheel truck on a 2-6-0 ("Mogul") locomotive.⁴



Figure 7. 2-6-0 steam locomotive

In what follows, we will assume such a single-axle leading wheel arrangement.

³ *Bogie*, in European parlance.

⁴ Strasburg Rail Road 89, 2-6-0 ("Consolidation"), built in 1910 by Canadian Locomotive Works (works number 922) for Grand Trunk Railway (their 1009). It has the "inside" Stephenson valve gear, which is why we do not see much of the valve gear in the photo (*cf.* figure 1, where we see the later Walschaerts valve gear).

The truck can pivot about a point to the rear of the axle, so that the wheels can move from side to side ("steering" at the same time) in order to readily follow a curve. But the truck is urged (by forces from centering springs or otherwise) to take a position aligned with the locomotive axis. These forces actually urge the locomotive overall to follow the lead of the truck on a curve (the nose wags the dog).

As with the front two drivers, it is desirable for the forces on both wheels of the leading wheel truck be equal. This is easily done by having a single spring for the truck, acting on the center of a transverse frame that supports the truck (although allowing it to move laterally).

It is also attractive to assure that the (equal) forces on both leading wheels remain proportional to the (equal) forces on both first drivers, so all four wheels will best contribute to leading the locomotive around a curve.

This is typically accomplished by another ingenious mechanism, seen on figure 8.

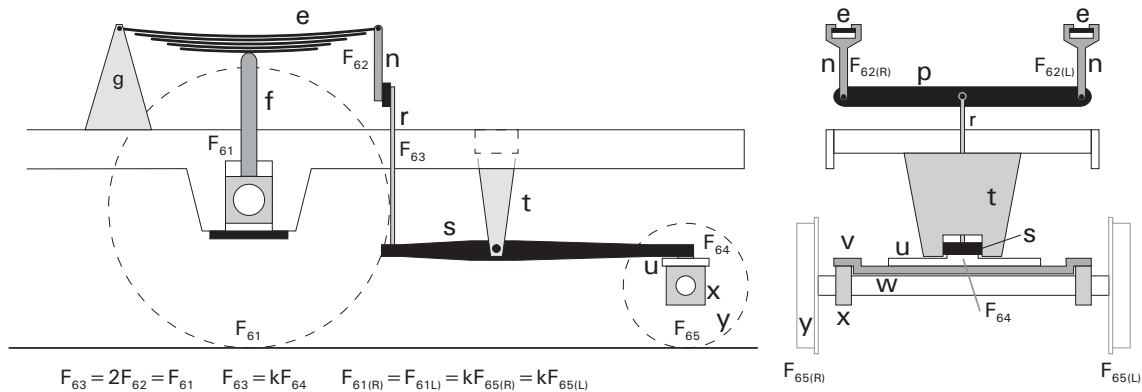


Figure 8. "Three-point" front end equalization arrangement

The scheme begins as in the basic front driver equalization scheme seen in figure 6. Here, however, the transverse equalizing bar does not pivot on a fixed pivot, but rather on the top of a *tension rod* (r).

This leads to the rear end of the leading wheel equalizing lever (s), which pivots on a fixed pivot on a bracket (t) on the frame. The front end of this lever presses down on the center of the leading wheel truck support (u). The leading wheel truck frame proper (v) is supported by this (but can slide from side to side under it, turning slightly in the process, since its pivot on the locomotive frame is to the rear).

The leading wheel driver boxes (x) are held, essentially rigidly, in the truck frame. The leading wheel axle (w) runs in bearings in these

boxes, and the leading wheels themselves (y) are rigidly attached to that axle.

Now, if we write all the statics equations for this complicated linkage, we find that:

- The forces on the two front drivers are equal.
- The forces on the two leading wheels are equal, and have a fixed ratio ($1/k$ in the figure) to the forces on the drivers.

That ratio is generally less than 1, and is determined by the relative lengths of the two ends of the leading wheel equalizer bar (s). (In a 2-8-0 locomotive I recently studied, it appears that $1/k$ is 0.45; that is, the forces on the two leading wheels are 45% of the forces on the two front drivers.

My analysis assumes that, nominally, the forces on the front drivers are the same as on the remaining drivers—I don't know if that is actually the design premise. (In any case, about 12% of the total locomotive weight is said to be on the leading wheels.)

This system is sometimes called a “three-point suspension” arrangement, since in effect the front end of the locomotive is supported, through springs, at three points, the left and right ends of the front driver axle and the center of the leading wheel truck support.

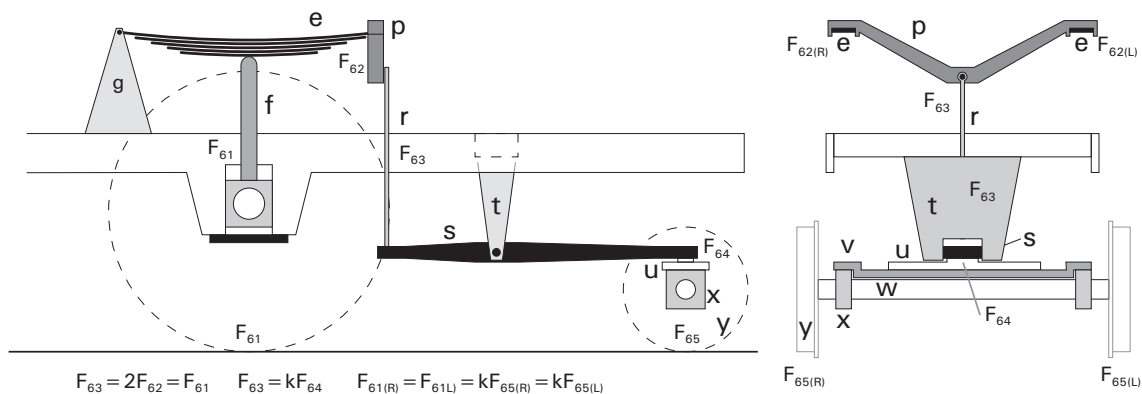


Figure 9. “Three-point” front end equalization arrangement—simplified

Figure 8 above used links (n) to make more clear the evolution of this arrangement from the prior ones. In fact, a somewhat simpler implementation is often used. We see it (again stylized) in figure 9.

Because in this case the transverse equalizing lever “floats” in thin air (it has no fixed pivot), we can eliminate the links (n) and connect the forward ends of the springs directly (more-or-less) to the ends of the transverse equalizing lever (p). As the springs flex or swing, and the front ends move slightly fore or aft, the corresponding end of the lever

just follows to accommodate it. The tension rod (r), itself floating, accommodates the resulting movement of the lever nicely.

In figure 10 we see an actual implementation⁵ following the general concept of figure 9.

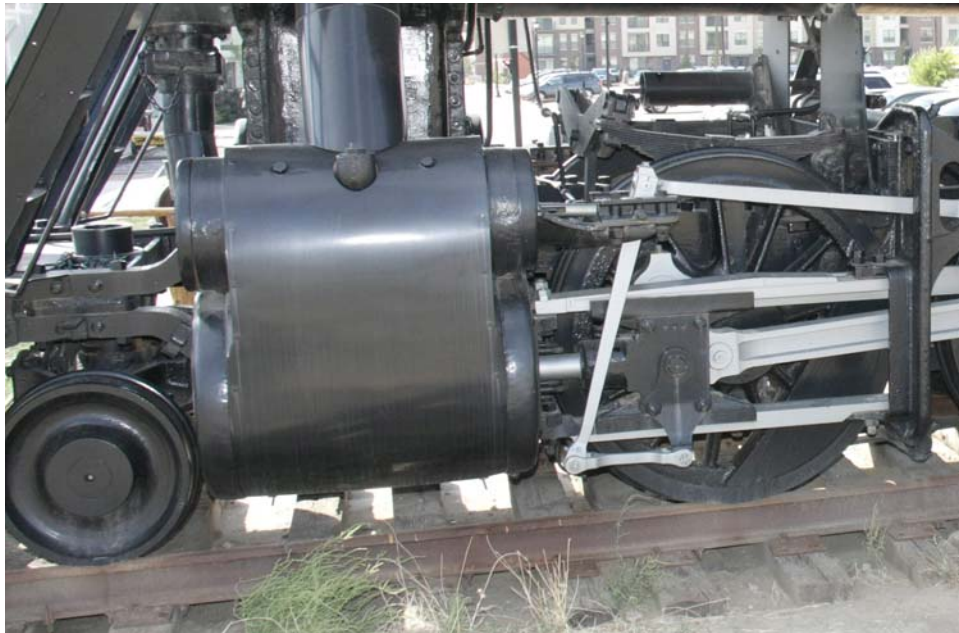


Figure 10. "Three-point" front end equalization arrangement

Note the "vee-shaped" lateral equalizing bar. Sadly, the leading wheel equalizing bar cannot really be seen.

I am uneasy with the observed "cant" of the spring leaves with the locomotive at rest. It is possible that the mechanism is not at present properly assembled. There are other anomalies in the locomotive; for example, the *reach rod* (which operates the reversing/cutoff mechanism in the valve gear from the "Johnson bar" in the cab) is wholly absent. The restoration for its current situation was primarily cosmetic.

The cylindrical "boss" seen at the center of the locomotive above the leading wheels supports a spindle, capable of sliding vertically as well as rotating, which carries the truck support (u). The front of the equalizer bar, which presses down on the top of the truck support, has a fork to straddle that spindle (None of this is suggested in the conceptual figures above.)

⁵ So-called "Frisco 19", a 2-8-0 "Consolidation" on static display at Frisco Heritage Park, Frisco, Texas. It was built in 1916 by Baldwin Locomotive Works (works number 43104) for Lake Superior & Ishpeming Railroad (their 19). It never operated on the Frisco line.

Of course, these are details that vary dramatically between different models and makes of locomotive.

Alternate configurations

Many variations on the basic “longitudinal;” equalization scheme we saw in figure 4 have been employed to meet particular design considerations. Figure 11 shows a variant in which the springs and equalizing levers are beneath the axles. We now realize that this might illustrate an eight-driver locomotive (*e.g.*, 2-8-0); the front two drivers are on a separate lateral equalization mechanism.

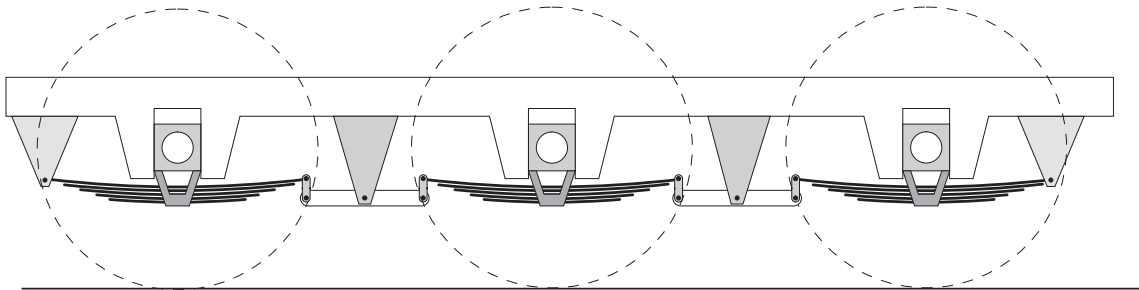


Figure 11. Underhung equalized spring arrangement

The spring centers are supported by hangers connected to the driver boxes. The overall geometrical concept, and the statics equations, are identical to what we saw in figure 4.

This arrangement is attractive when the boiler firebox is located just above the rear driver axle (and in fact may nestle between the wheels). In some cases, the rearmost spring will be underhung as in this figure and the others overhead 4.

In figure 12 we see another variant.

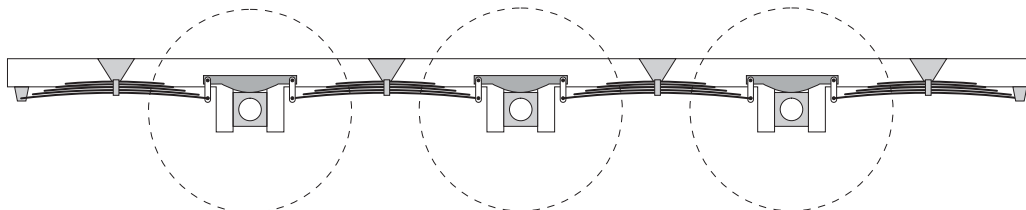


Figure 12. Alternate underhung equalized spring arrangement

Here, the springs are located below, and between, the axles. Their centers bear on brackets mounted on the frame (as do the outermost ends of the outermost springs).

Then, in a tit-for-tat, it is the equalizing levers that are above, and ride on, the driver boxes.

Note that in this implementation, there are four springs for three axles. All the springs (however many there are) all “in series”, and collectively support all the axle loads (however many there are), which are also “in series”. It is like an electrical battery of four cells (in series) lighting a set of three lamps (in series). In fact, it would work with only two springs.

But it is advantageous to take advantage of the opportunity to use more springs, which makes the designs of the springs a bit easier (each has to store less mechanical energy with the whole system at full deflection.)

Two-rate springing

In order that large forces resulting from sudden undulation in the track do not cause the driver boxes to go to the upward limit of their travel, the springs must have a fairly high spring rate (stiffness). This of course means that small undulations cause quite a bit of force on the locomotive. This means a lot of “road noise” to the crew, and the high forces in the suspension system are not desirable from a wear and fatigue standpoint.

To get around this, a “two-rate” springing system is sometimes used. Here, for “small bumps”, the suspension exhibits a modest spring rate, holding down the forces and the resulting vertical motion of the locomotive. But once a certain travel of the spring system has been exhausted, springs with greater spring rate come into control, limiting the chance of exceeding the permissible travel of the driver boxes.

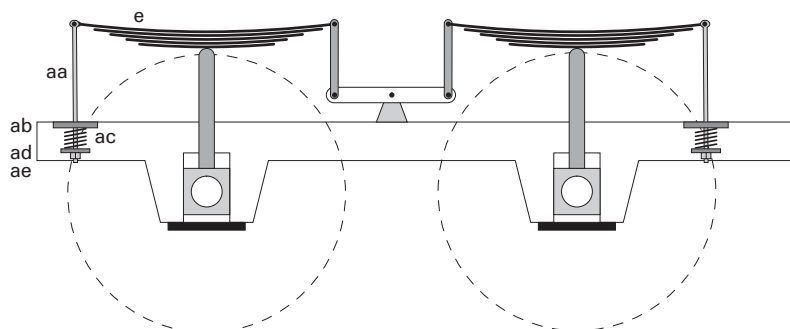


Figure 13. Two-rate equalized spring arrangement

In Figure 13, we see one way this is done, a variant of the familiar configuration of figure 4. However, here I show only a two-axle configuration as a way of dodging some complications.

Here, the “outermost” ends of the spring leaves, rather than being fastened to a fixed bracket on the frame, have tension rods (aa). These pass through brackets (ab) on the frame. Below, they are surrounded by stiff coil springs (ac). Under the springs are circular plates (ad) held by adjusting nuts (ae).

When an upward bump in the rail comes along, and a driver box attempts to move up to accommodate it, this first mainly compresses the coil springs, although the leaf springs flex a little as well. The relatively low spring rate of the coil springs means that a fair amount of movement of the driver box can occur without a lot of force building up. (As with the leaf springs, regardless of which axle encounters the “bump”, both coil springs flex together—they are “in series”.)

But after a certain amount of overall movement, the coil springs “bottom”—they have fully compressed. Further upward movement of the driver box only flexes the leaf springs, with their higher spring rate.

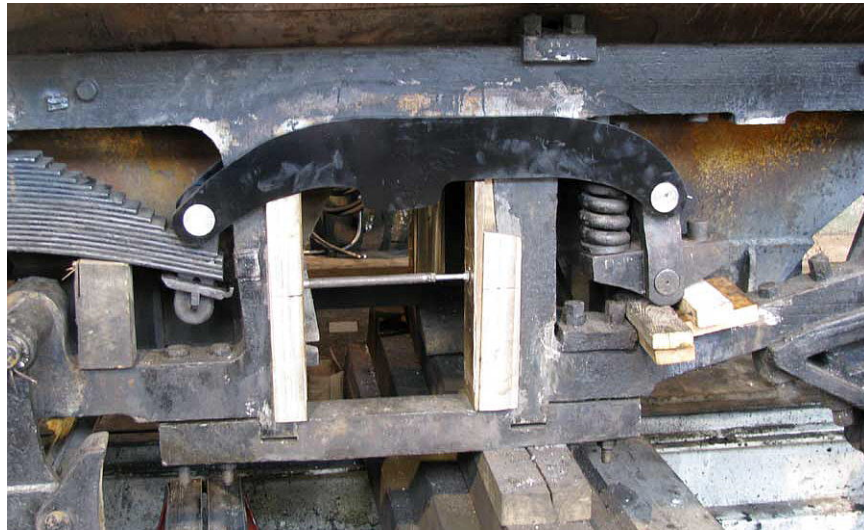


Figure 14. Two-rate equalized spring arrangement

In figure 14, we see the application of the two-rate system as shown in figure 12 on an actual 2-8-0 locomotive under renovation.⁶

As in figure 12, we see the equalizing lever (black) running across the top of the driver box (not present for this picture). The left end of the lever ties to one end of the leaf spring with a hanger on a short link. The right end of the lever goes to a small rocker carrying two coil springs (only one present for this picture)—they are “in parallel”.

The lever has unequal length arms, so the effective spring rate of the two coil springs together (as seen at the driver box) is multiplied with respect to with the effective spring rate of the leaf spring (but is still much less than the effective spring rate of the leaf spring).

I believe that this is the arrangement used for the drivers, other than the front set, of the locomotive seen in figure 10.

⁶ Nevada Northern Railway 93, 2-8-0 (Consolidation), made in 1909 by Baldwin Locomotive Works (Pittsburgh).

REVISITING "FRISCO 19"

Figure 15 is a look at the entire locomotive we saw in figure 10, to put that view into perspective.



Figure 15. Former LS&I 19

A cute little guy, isn't it? Well, figure 16 gives a better visual idea of its scale. The drivers are 57 inches in diameter!



Figure 16. Wedding party in front of former LS&I 19

We see part of a wedding party just about ready to have a group shot taken in front of the machine (the historical park in which it is exhibited is a popular wedding venue).

By the way, the bride is the former wife of my wife's eldest grandson, and a good family friend. Her two daughters from that union are the two girls in the brown bridesmaid's dresses just to our left of the groom (they are, l-to-r, 11 and 13 years old, and beauties already).⁷

At the request of the bride, I was the second photographer at this extensive event (as well as a guest), so you can see why I wasn't able to give a lot of attention to the mechanical details of the locomotive at the time.

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⁷ In this grab shot the bride is explaining, under her breath, wedding photo etiquette to the young man in front of her, who was buzzing around the shot. The actual shot (for the professional photographer) was supposed to be with the female attendants only. But it went down essentially as we see it here!