The Dynamic Effect of Train Loads and its Influence on Railway Permanent Way Design.

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For a number of years experiments and investigations have been conducted by Continental and American engineers to the various railway companies, all tending to ascertain the actual pressures exerted by the wheels of engines and waggons when in motion on the rails and their dynamic effect on the track.

Von Ast, Engineer of Construction and Maintenance on the Austrian State Railway, gives as the result of his studies of experiments carried out in other countries, notably Belgium and France, and also as the result of his own investigations, under ordinary circumstances the dynamic engine wheel pressure on rails at express speeds of 60 miles per hour, is 2.4 times the static wheel pressure—that is to say an engine wheel when in motion may, owing to various causes produce pressures on the rails which are 140 per cent. in excess of the pressure exerted by the same engine when at rest.

The late Dr. Dudley made extensive experiments in the U.S., by means of his "Streemmatograph," to determine the strains in rails under moving loads; they show that the alternate stresses in light rails of compression and tension in the head in reversal are not equal in intensity, those in compression being many times the larger; while in the base of the rail, those of tension are the larger.

He stated that for the American 8-wheel locomotives the tensile strains in the base of the light rails under the wheels are very much greater than the compressive strains of the rail either side of the wheel, and while it is possible to have a tensile stress of 30,000 to 40,000 lbs. under the locomotive driving wheels in the extreme fibres in the base of a light rail of Vignoles section, the maximum compressive stress in the same rail in the base has not been found to exceed 3,000 to 5,000 lbs. per square inch.

The compressive stress is never likely to equal the great intensity of tensile stress in the base of light rails under the wheels.

In the heavier rails the tensile and compressive stresses may become more nearly equal; the maximum fibre stress in either case is very much less than occurs in the lighter rails.

The high tensile and low compressive stresses which are found in the base of light rails do not present as great a variation of stress as the stresses which obtain in rotating steel shafts which endure 5,000,000 to 10,000,000 revolutions, and it is partly for this reason that the rails are capable of withstanding so many repetitions of the tensile stresses.
A range of tensile and compressive stresses in the base of the rails for a 5in. 80lbs. (A.M.S.C.E. section) rail under a 100 ton locomotive has been found at 45 miles per hour as high as 26,000 to 31,000 lbs. tensile fibre stress per square inch, while the compress stress would rarely exceed 6,000 lbs. per square inch—usually only from 2,000 lbs. to 3,000 lbs.—the variation in stress being considerably less than two-thirds the elastic limit of the metal. The time the base of the rail is under the maximum tension per wheel, under fast moving trains is very short; in a train running 60 miles per hour, the duration of greatest intensity of stress per wheel is only 1/500th to 1/300th part of a second, according to the size and stiffness of the rail, spacing of sleepers, and design of fastenings.

The metal in the rails under moving trains is subject not only to large fibre strains and stresses, but under fast trains their reversals are so rapid that they approximate shocks.

It was noteworthy that where a large proportion of the reciprocating parts were balanced in the driving wheels that the stresses showed a greater variation than where only a small proportion of those parts were balanced.

Long, well-fitted fishplates with efficient fastenings, contributed considerably to the transfer of the wave from one rail to the next.

On the 80lb. rails for ordinary traffic after the tires have run 30,000 to 40,000 miles, many instances were found in which the stresses due to generated dynamic effects were double at about 40 to 45 miles per hour, those due to the static wheel loads.

On the 100 lb. rails all the experiments show for the 8-wheel type of engine that the dynamic effects were doubled at about 60 to 65 lbs. per hour.

On the light rails 65 and 70 lbs. per yard, tests have been made up to about 40 miles per hour. At 30 to 35 miles per hour the stresses were more than doubled for the static wheel load while the shocks were severe.

On the 65 lb. rails, even at moderate speeds of 25 to 30 miles per hour, stresses as high as 56,000 to 58,000 lbs. per square inch have been obtained. This confirms the results observed in the American tracks many years ago that the lighter rails were quickly taking a set in the track, the metal in the base having been strained beyond its elastic limits. A number of instances have also been found on 80 lb. rails, the metal having elastic limits of 60,000 lbs. in which they have received permanent sets under high speed trains.

The problem of strengthening the track with a view to increasing the speed of trains differs from that of strengthening solely for the purpose of permitting the use of heavier loading in two ways.
(1) Increased speed means increased impact stresses in addition to any increase in stresses due to the use of heavier locomotives required to develop the increased speed.

(2) As the speed increases, the ill effect of imperfections in track and equipment increases, and a smaller variation from perfect adjustment is allowable.

For a time the increase in the size of the locomotive was checked by the difficulty in securing sufficient heat from the dimensions of the firebox to meet steam generating requirements, the firebox being limited in length by the ability of the fireman to evenly distribute the fuel, and in width by the space between the wheels. This latter limitation was removed by raising the firebox above the wheels, upon which change in design a rapid increase in the size of the locomotive began.

Recently the height and width of the boiler in the American engines have commenced to limit further increase, due to encroachment on the available tunnel and road clearance dimensions.

Again, the more extended use of the Mallet type of locomotive with two independent sets of drivers and cylinders has secured a larger and more powerful locomotive without adding to the existing maximum axle load and consequently without adding to stresses in track and bridge.

INSTABILITY OF RAILWAY TRACK.

While the railway bridge, scientifically designed, represents a stable structure not subject to permanent deformation, the railway track on the other hand is necessarily an unstable structure requiring the more or less constant application of labour to readjust deformation to the part where the deformation remaining is within the allowable limit. The prime cause of this peculiarity of track design is the great cost of construction of a stable structure.

In order to avoid this cost, the sleeper is carried on ballast, the particles of which are somewhat free to move under the rolling load or to be displaced by the action of rain, frost or disintegration. The ballast rests on a formation which for some distance below the plane of contact is also affected by moisture, whereas a bridge abutment or pier foundation is carried deep enough to be beyond the reach of such action, and ample provision is made for efficient drainage. Moreover, in a large percentage of cases, the unit carrying power of the formation is so low that it is often overloaded by the passing train with resultant deformation.

THE TRACK AND ITS LOAD.

Consideration of the application of the driving wheel loads of a locomotive to the road will make plain that the arrangement of ballast, sleeper and rail, which will permit of the max-
imum wheel load being supported by the formation is that in which it is possible to distribute uniformly the load from the centre driver and half the load of each of the end drivers over that portion of the formation covered by the wheel base. In order to accomplish this result, the ballast must uniformly distribute to the formation the pressure from each sleeper an equal portion of the wheel load; this equal distribution of wheel load by the rail can only be accomplished by the various sleepers settling into the ballast a sufficient amount to enable the stiffness of the rail to transmit to the adjoining sleepers their proportion of the total wheel-load, thus producing a rail flexure as shown in Fig.

M.F.C. Schmitz, of the Pennsylvania Co., concludes that with American engines a complete reversal of the elastic line occurs every 56 inches. It is evident that only in the extreme case of the track being loaded to its absolute limit would this perfect distribution of wheel load to sleepers be secured. Generally the sleeper being able to sustain more than its proportionate part of the load, the rail will not be called upon to perform its extreme service, and the closer the sleeper spacing, the less the bending moment to which the rail will be subjected, this varying directly with the sleeper spacing.

Assuming that each sleeper carries an equal load, the maximum deflection is independent of the sleeper spacing, and is dependent on the distance between the axles, the axle load and the stiffness of the rail; consequently the closer spacing of sleepers does not permit of reducing the stiffness of the rail; this closer spacing, however, produces in practice a more uniform distribution over the formation, and consequently increases the total axle load which the formation will carry. The same result is accomplished by increasing the depth of the ballast.

From the various experiments made by Von Ast and Mons. Wasiutynski of the Warsaw and Vienna Railway, the late Mons. Bauchal, then Chief Engineer of the French Western Railways, came to the conclusion "that the maximum pressure of the sleeper on the ballast is equal to 1.2 times the maximum axle load, and according to the experimental and theoretical investigations made on a straight and level road, the rails distribute the static axle loads in such a manner that the most loaded sleeper does not support more than 0.6 times the maximum axle load; on curves, the super-elevation increases the load on the inner side of the curve, but only if the speed is low. The dynamic action of the rolling loads must increase
the static sleeper loads. The increase depends on the method of construction of the track, of the vehicles, and on the state of the maintenance (e.g., the hammering produced by flats on worn tyres).

After taking into consideration the stiffness of the tracks during the past few years, general use of bogies, and the large number of compound cylinder engines running over it, he arrived at the conclusion that at high speeds the dynamic load on the sleeper amounted to 1.2 times the maximum axle load of the locomotive or tender. After all, the distribution of the load on the sleepers varies with the type of the track, and the conclusion enunciated only applies to tracks similar to those which were investigated, viz., tracks of recent construction on main line railways.

According to the experiments of Mons. Alexander Wasiantynski, on rails 76.6 lbs. per yard Vignoles section with sleepers 29 1/2 inches centres, it was found that where 9-13/16in. ballast was under the sleepers, the maximum depression of the part under the sleepers was .0124 in. per ton of locomotive wheel load. It was further found that where the distances between the wheel centres varied from two to three times the sleeper spacing (as is the case of the majority of engines on Victorian Railways) the mean depression of each sleeper would be found to be approximately equal to .0124 in. per ton of loco. wheel load, that the depression commenced and ended three sleeper spacings from the leading and trailing wheels, and that the maximum rail load corresponding to the mean depression is .43 tons per ton of locomotive wheel load, the remainder of the wheel load being distributed by means of the rail on the adjoining sleepers.

In the case of intermediate sleepers, between the wheels, observations appear to show that the upward force exerted by them on the rail is practically unaffected by the dynamic action of the wheel loads.

Further, his experiments on rail tracks with sleepers 8ft. roin. long of oak spaced 29 1/2 in. centres 4ft. 8 1/2 in. gauge, it was found that the mutual proportions between the depressions of the sleeper at its centre (Yo), at the part just under the rail (Yr) and at the ends (Ye) was as follows:

Rail. 76.6 lbs. per yard—Yo : Yr : Ye=74 : 100 : 64
Rail. 63.4 lbs. per yard—Yo : Yr : Ye=91 : 100 : 78

The ballast distributes these pressures in the form of a truncated pyramid. Railroad Director Schubert, of Germany, found "on a well drained formation with 6in. of 2in. ballast under the sleeper, that the maximum unit pressure on the formation was 12 1/2 per cent. of the sleeper pressure, 11 per cent. with 12in. of 2in. ballast, and with 48in. of 2in. ballast the maximum unit pressure was 7 1/2 per cent."
Bauchal states that if the ballast is to act as an elastic support the pressure on its upper surface must not exceed 2 3/4 tons per square foot.

Cholodecki, in Russia, Hautzschel, in Germany, and Coüard, in France, have also independently investigated this problem.

The observations which have been made up to the present do not lead to the conclusion that the dynamic action of the train load tends to any appreciable greater depression of the sleepers in the ballast. According to Hautzschel's and Couard's observations, increase of speed rather reduces than increases the depression of sleepers on a first-class track. On the other hand, according to Couard, the deflection of the rail spans increases in about the same proportion as the speed.

The dynamic effects which are produced when a train moves and which increase the action of the rolling load, may result from the irregular movements of the locomotive and the inertia of the component parts, and also from a defective condition of the track or its irregular resistance.

One of the causes of irregular resistance of the track results from the bending of the rail between the supports.

If, for instance, the excess of rail deflection of the load were the result of centrifugal action, which has sometimes been made, that action would evidently not take place when the load is above the sleeper, but only when on the unsupported part of the rail.

Winkler, in Austria, and, later, Zimmerman, in Germany, investigated the dynamic effect of train loads on rail stresses, and the latter came to the conclusion that where

\[ W = \text{Static wheel load of the locomotive}, \]
\[ L = \text{Distance between centres of sleepers in inches}, \]

the BM on the rail would be

\[ = 0.533 WL \quad \text{for a first-class road, and} \]
\[ = 0.653 WL \quad \text{for a road not so well ballasted or maintained.} \]

MEANS OF STRENGTHENING TRACK.

The relative carrying powers of the ground composing the formation naturally divides into two classes the problem of strengthening the track, viz.:

(1) \textit{Where the carrying power of the formation is at all times sufficient to sustain, direct from the sleeper the moving load.} In this case only such amount of ballast under the sleeper is required as will be sufficient for the correction of the inequalities in the surface of the formation and the direction in which the strengthening of the track must be secured lies in the use of a stronger and stiffer rail, or in the placing of the sleepers closer together, or both.

(2) \textit{Where the carrying power of the formation is small.} In this case, the principal factor in the problem of the
strengthening of the track is how to increase the sta-
bility of the formation.

There are two ways to accomplish this—
(a) By increasing the unit carrying power of the formation.
(b) By reducing the maximum unit pressure on the forma-
tion.

The carrying power of the formation can be increased by
drainage, or by substituting more suitable material, the latter
being usually too costly to be permissible.

Reduction of the maximum unit pressure on the formation
can be accomplished by increasing the uniformity of distribu-
tion of the load, and by increasing the area of the formation
over which this distributed load is applied.

This can be accomplished by
(1) Increasing the depth of the ballast;
(2) Increasing the length, width and number of sleepers;
(3) Increasing the stiffness of the rail; and, of course, in
extreme cases, by combining two or more of these
means.

The effect of strengthening the formation and reducing the
maximum unit pressure thereon is to decrease the rate of de-
formation; the alternative is to increase the amount of labour
applied to correcting the deformation, keeping the track de-
formation at all times within the allowable limit, which de-
creases with the increase in the permissible speed of the train.

Finally, a point is reached where with the present type of track
construction, it will be impossible to keep track deformation
within the limit permissible for very high speeds which may
be desired or to accomplish this at a cost less than that entailed
by the adoption of a stable type of track construction.

In keeping track deformation within the allowable limits as
has already been suggested, the use of a stiffer rail, devices for
overcoming creeping of track, the increase in the size and num-
ber of sleepers, the increase in the depth of the ballast, the
drainage of the formation, the improvement in the quality of
the materials and the application of labour to the correction of
deformation, are means which are to a greater or lesser extent
interchangeable, and where the full use of all these means is
not required in order to secure the results sought, it becomes
a problem in railway economics to determine by which of the
various means the results can most cheaply be secured.

Unfortunately with continuous fluctuations in the labour and
material markets combined with so many indeterminate factors
entering into the problem its exact solution is practically im-
possible, and the most that can be accomplished is to determine
from theoretical discussion and from practical experiments
and observation the general results which may be expected to
follow modifications of existing practice in these various
directions.