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Rail Rollover—The State of the Art

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ABSTRACT

This report presents a survey and description of work performed in the area of rail overturning. It includes analytical work, as well as test results, both field and laboratory. Comparisons between different tests and their results are made. The various causes and related phenomena are discussed, together with suggested techniques for dealing with this problem.

ACKNOWLEDGEMENT

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INTRODUCTION

The maintenance of the track structure is an area of great concern throughout the railroad industry. Recent data have shown track-related problems make up the greatest percentage of accident causes (35).*

According to a former chief engineer of the Canadian National Railways (17) the interface between the rail and the tie represents the weakest point in conventional track structure. Likewise, accident analysis has shown that problems connected with mainline gage widening, ties, and tie plates consistently rank among the top ten categories of track-related accident causes (35). It thus becomes evident that the problem of holding gage and preventing rail overturning is one of serious magnitude.

The problem of gage widening and rail overturning consists of many interacting causes. Rail roll contributes to the gage-widening problem even in the case where the rail does not overturn. However, much confusion has come about due to interchangeable use of terminology. This leads to a necessary definition of terms. In the following text:

"*Gage Widening*" represents any increase in the standard track gage of 4 ft 8½ in., measured ⅝ in. below the top of the rail head. Wider gages are permitted for curves.

"*Rail Roll*" is defined as any rotation of a rail section from the "original" vertical axis of the rail, or any lateral deflection of the rail head with respect to the rail base.

"*Rail Overturning or Rollover*" is defined to occur when the rail section actually turns over onto its side.

"*Rail Translation*" is defined as any lateral displacement of the base of the rail relative to the tie.

Thus, according to the above definition, rail overturning is a limiting case of rail roll. Furthermore, it can be seen that gage widening may consist of combinations of rail roll together with rail translation.

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* Numbers in parentheses indicate References at end of paper.

Rail roll appears to be due to several distinct causes such as rail twisting, rail rigid body rotation, and in the case of large axial forces, even local buckling of the rail (as opposed to gross track buckling which is an alignment, not a gage-widening problem). Furthermore, rail roll is a cumulative result, whereby initial rail twist gives a greater eccentricity to vertical wheel loads, which when combined with high lateral or combination of high lateral and longitudinal loads, result in spike pullout, tie crushing, rail head bending, and ultimately rail overturning.

It is the purpose of the following sections to present a survey of the analytical, experimental, and field investigations performed in the area of rail roll, in order to establish the state of the art in this problem area. Readers desiring more specific details are referred to the referenced papers.

HISTORICAL BACKGROUND

The historical evolution of the railroad track is well documented (20). During the 19th Century, the cross-tie track gradually came into its own, and with the constantly increasing wheel loads and train speeds the problem of lateral and vertical movement of the rail relative to the tie became important.

In 1875, E. Winkler (46) presented test data on the resistance of spikes, of various shapes and patterns, to pullout. He then postulated a relationship between the pullout force P and the surface area of the spike embedded in the tie, f, as:

$$P = A \cdot f$$

where A is an experimentally determined constant (for oak, $A = 50\ \text{kg/cm}^2$). Winkler also presented results of gage-widening tests conducted on loaded and unloaded track for various spike and plate configurations by M. M. Weber in the mid 19th Century. The displacement measurements, however, were restricted to the gage widening at the rail head.

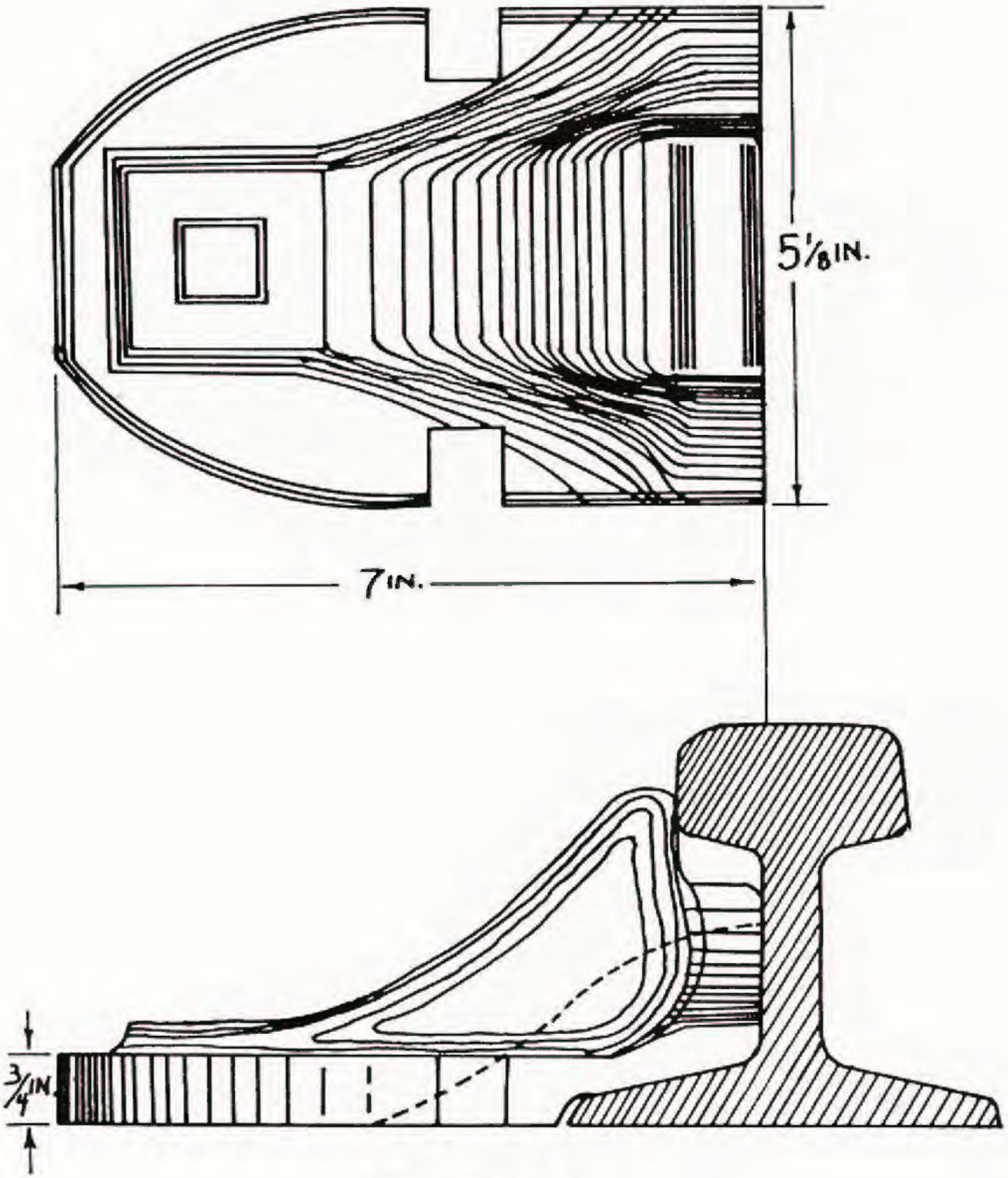
In 1899, A. Wasiutynski (45) pointed out that the lateral deflection of the rail head is due to two independent causes: rail rotation and rail translation. Wasiutynski stated that rail rotation is due to crushing of the tie along the field edge of the tie plate, which results in rigid body rotation of the rail. Lateral displacements at the rail head, of up to 1.5 mm (0.06 in.) were attributed to this rotation.

The equation

$$\delta' \; [''] = \delta \left(1 \pm \frac{6 \; (a \; [\mp] \; h/20)}{b} \right)$$

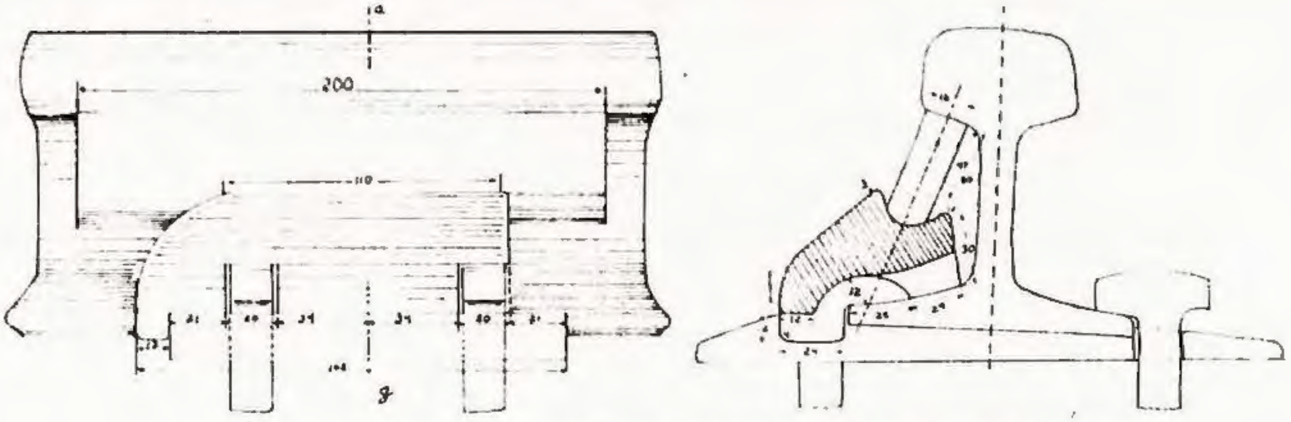
was presented for the determination of the maximum tie plate crushing (δ', δ'') due to a vertical wheel load applied to the field [gage] side of the rail head. δ represents the crushing of the tie due to a uniformly distributed tie plate pressure, b is the width of the tie plate (with 1:20 cant), h is the rail height and a is the distance between the center of the rail and the point of loading. Observations were made on the Warsaw–Vienna Railroad in 1894. Using a location where the rail head wear pattern was well established, so that the load application point on the rail head could be accurately deduced, rotation and lateral rail head displacement measurements were found to be in general agreement with values calculated from the above equations.

The awareness by early railroad engineers of the rail roll problem is confirmed by the Knee Brace, shown in Fig. 1, which, according to an 1886 U.S. track manual (31) should be used for very sharp curves and "all rails which have to resist a

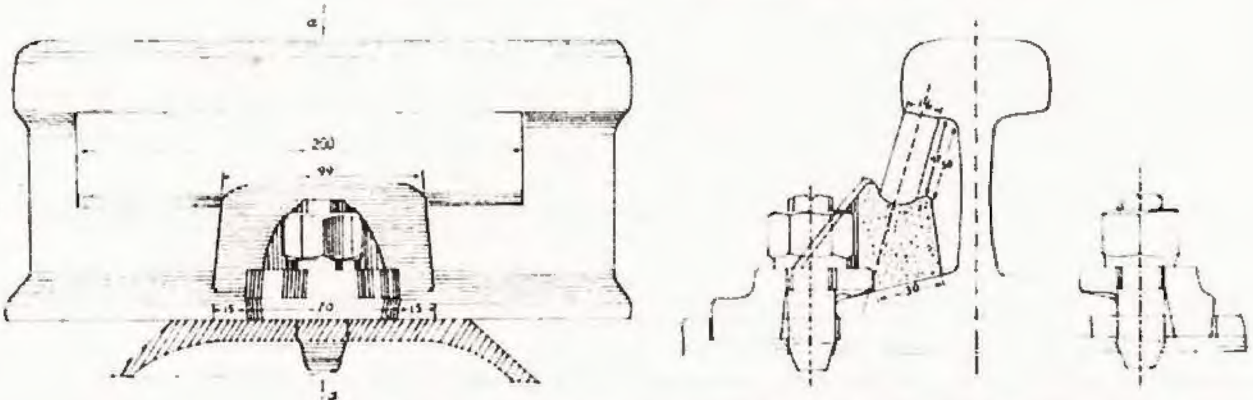


Knee-Brace

FIGURE 1



Pattern of the Aussig-Teplitz Railway Company.



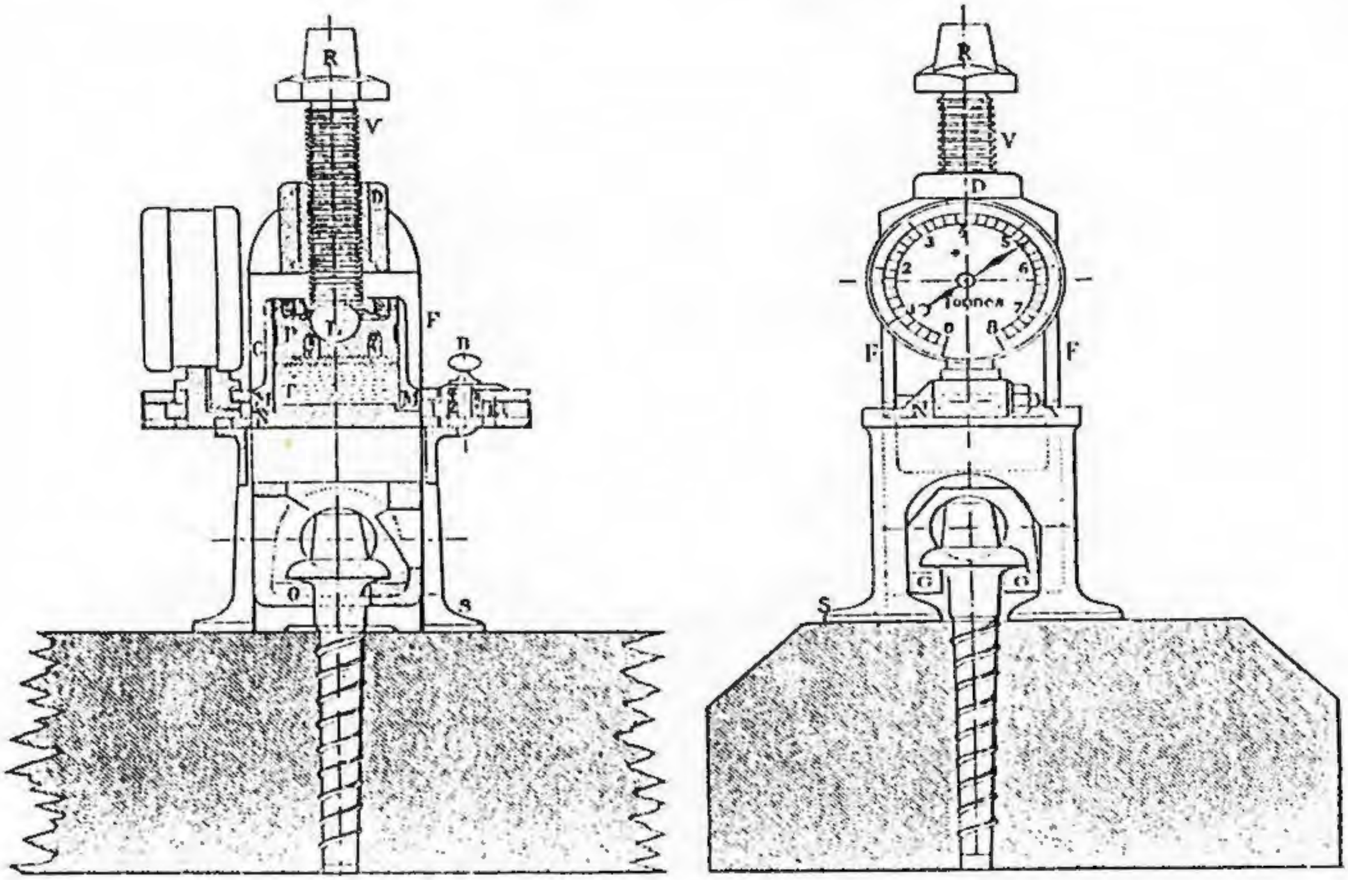
Iron transverse sleeper, Swiss Federal Railway pattern.

Guba Rail Fastener

FIGURE 2

strong side thrust." Another device was the Guba Rail Fastener shown in Fig. 2 which, according to A. Birk (8), makes any spreading of the gage and canting of the rail (rotation) impossible.

Another early investigation of gage widening and rail roll was conducted by G. Cuënot (12) on the Paris, Lyons and Mediterranean Railroad at the turn of the century. From field observations, Cuënot noted that on tangent track, the rails tended to deform inward, while on curved track they tended to deform outward. This he attributed to the corresponding differences in the loads applied by the vehicle to the rail head and to a corresponding bending of the wood cross ties. Tie plate crushing was also observed. Tests were conducted for spike pullout, using the extrahometer (Fig. 3) and for rail roll, using the declimeter (Fig. 4a). The results are presented in Reference 12. It was found that doubling the number of gage side fasteners (to two spikes) resulted in a doubling of the corresponding rail rollover resistance. Additionally, using a tie plate with a reinforced shoulder (Fig. 4b), so that the screw spike (which was the fastener used in these tests) rested completely on the shoulder, resulted in a 20% increase in roll resistance. This was because, with the non-reinforced shoulder the screw head was only partially supported and thus had

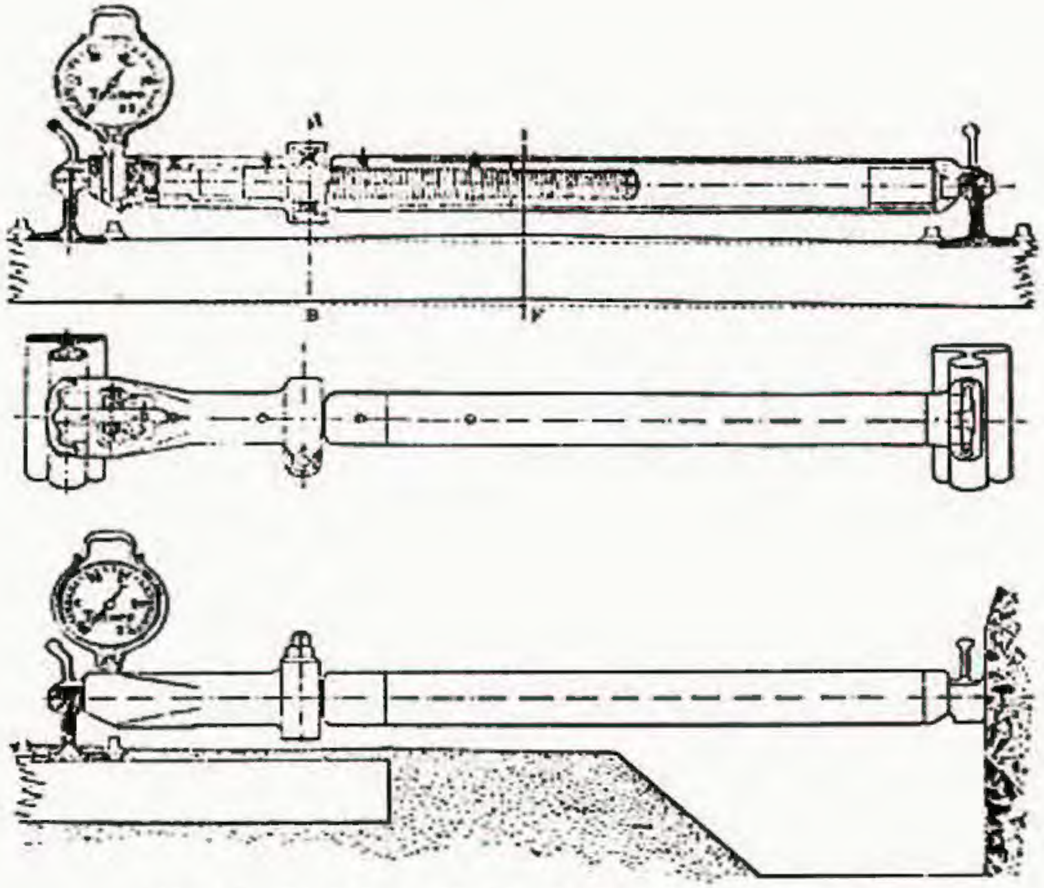


—The Extrahometre, Vertical Section and Front View.

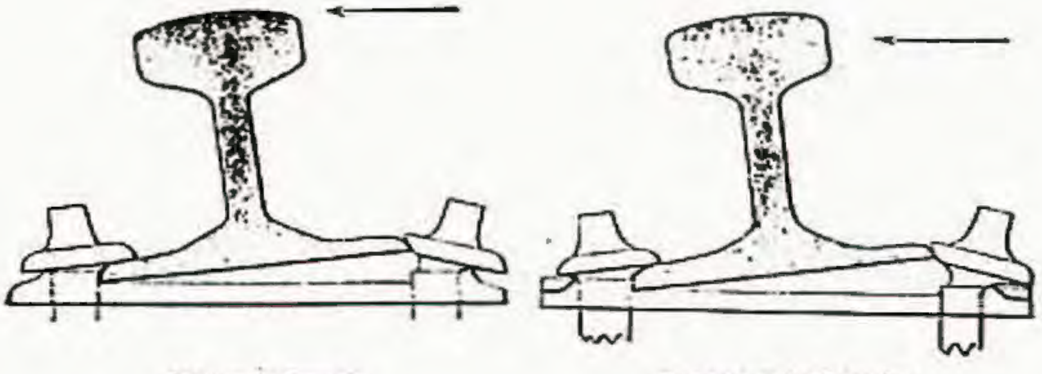
FIGURE 3

a tendency to overturn in the empty space (Fig. 4b) while with the reinforced shoulder supporting the head, this tendency is reduced.

In 1909, E. E. Stetson in an AREA Report (38) presented the concept of an L/V ratio where L is the lateral force and V is the vertical force applied to the rail head. Assuming that the forces are applied as shown in Fig. 5, this concept defines an unstable condition as existing when the (vector) resultant of the lateral and vertical forces falls outside the edge at the rail base. The effect of the rail fasteners and of the rail segment lengths are neglected; however, the effect of the rail cant is included. (The actual purpose of the rail cant, however, is to maintain an improved contact between the wheel tread and the rail head.) As a result of this unstable condition, the question of what prevents the rail from overturning is brought up. Stetson then points out that the long lengths of rail, rigidly connected, and held down by track fasteners along their entire length, together with the vertical loads applied by the train away from the unstable point, are more than sufficient to hold the rail in place. In fact, Stetson states that in order to overturn a rail, it is necessary to fracture the rail in two places and pull out all the spikes on the inner side of the rail between the fractures. Consequently, though he does raise the ques-



(a) —Declimetre; Longitudinal Section, Plan and Elevation.

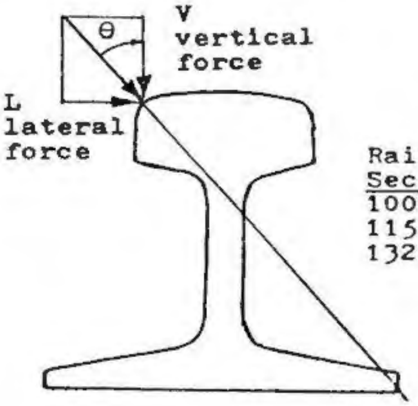


Not reinforced. *Reinforced at ends.*

(b) Edge Reinforced Tie Plate

FIGURE 4

Ratio for resultant rail force to pass through the edge of the rail base.



Rail Section	θ	θ Plus 1 in 40 Cant	Lat./Vert. Ratio
100RE	32°45'	34°10'	0.679
115RE	31°25'	32°50'	0.645
132RE	31°35'	33°0'	0.649

FIGURE 5 L/V Ratio

tion of the instability of the rail subject to certain L/V ratios, he then proceeds to discount the possibility of rail overturning.

In 1918, the Talbot committee of the AREA examined various aspects of track loading and response. Early tests on the Illinois Central Railroad indicated that outward bending of the rail was observed (39). However, the observations were not pursued in these tests. Subsequent tests were carried out on the Lehigh Valley Railroad and others, where the track was loaded by a locomotive and cars travelling at 5 and 40 mph (40). Measurements of the rail tilting (rail roll), lateral rail head deflections, and rail bending stresses were recorded (Fig. 6). Examination of tangent track, both canted (1:20) and vertical, showed a marked increase in average lateral bending stresses for the vertical rail, but little evidence of any significant effect on gage widening. It was noted that the tilting of the rail resulted in lateral deflections at the rail head of up to 0.06 in. (1.5 mm). This was attributed to a larger bearing pressure on one edge of the tie plate than on the other. The use of an unsymmetrical tie plate, having a larger projection on the outside of the rail, was recommended as a corrective measure. Most modern tie plate designs incorporate this feature.

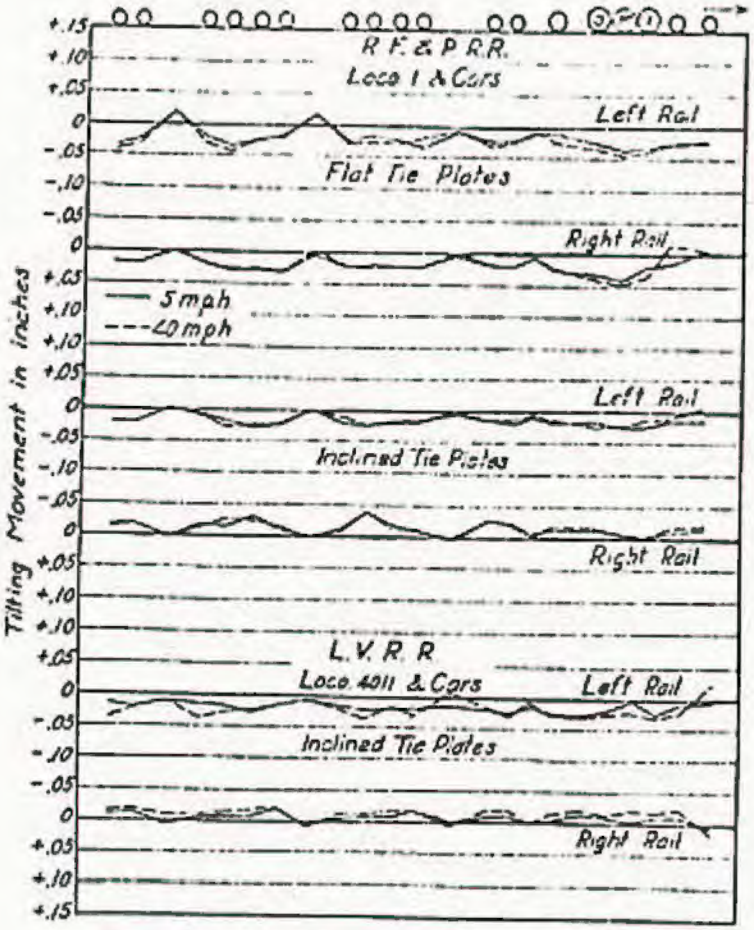
Subsequent investigation into the problem of wear underneath the rail seat, and rail roll, led to the development, by several European railroads, of the hooked or brimmed tie plate (Fig. 7a). This plate, which was described by K. Brauning in 1920 (10) and by A. Bloss in 1927 (9), utilizes the fact that the moment arm, through which the rail fasteners react against lateral or eccentric vertical wheel load, is significantly increased through the use of a hook or brim on the plate which restrains the rail base on the gage side, and a separate tie plate-tie fastener.

The distribution of pressure underneath an eccentric vertical load (Fig. 7a) was given by Brauning as:

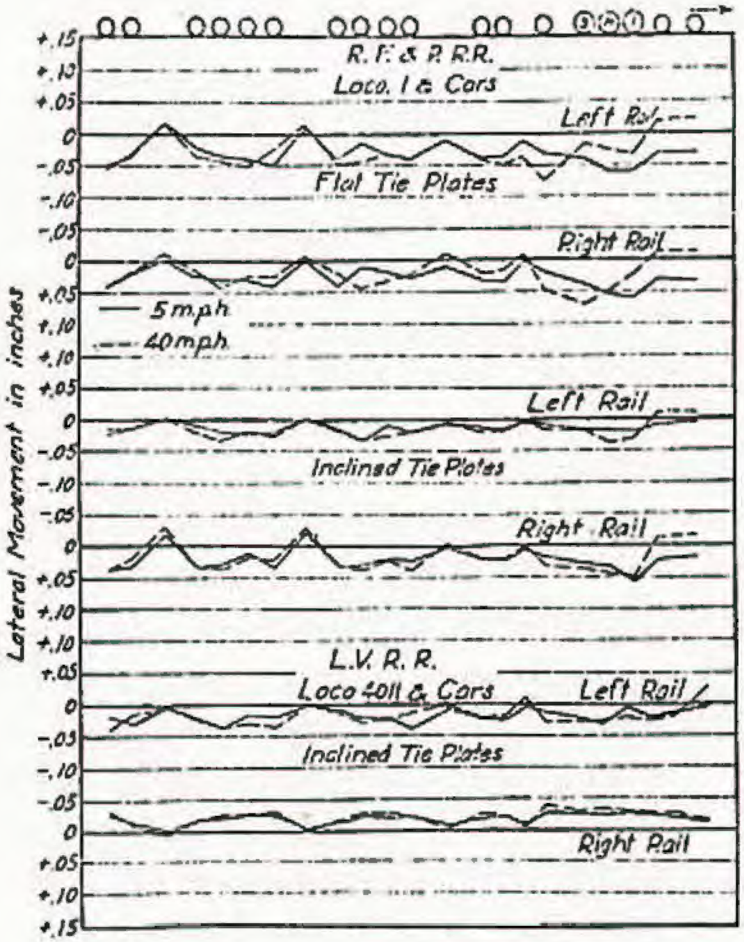
$$\frac{x}{y} = \frac{l + 6e}{l - 6e}$$

where x, y are the end pressures beneath the tie plate, l is the tie plate width, and e is the distance between the plate center and the point of loading. Thus, as the plate width increases, the pressure ratio decreases, providing for a more even distribution of pressure beneath the rail seat and decreasing the amount of rail roll.

In tests using two short pieces of rail fastened to a tie, Bloss notes that a lateral force of 14,300 lb (6,500 kg) was required to fail a hooked tie plate arrangement,

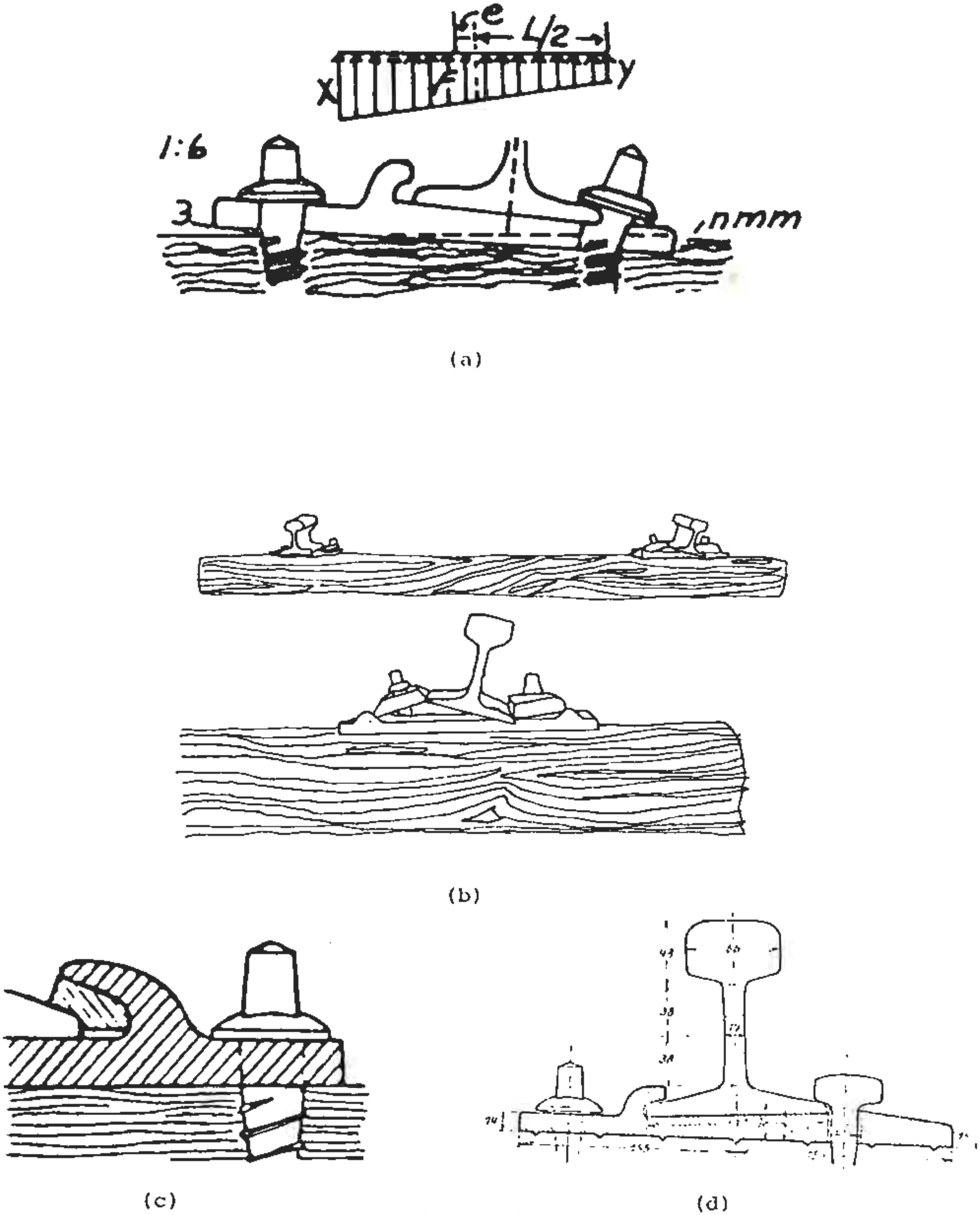


—Tilting Movement of Rail on Straight Track. Pacific Type Locomotive and Cars. R. F. & P. R. R. Santa Fe Type Locomotive and Cars. L. V. R. R.



—Lateral Movement of Head of Rail on Straight Track. Pacific Type Locomotive and Cars. R. F. & P. R. R. Santa Fe Type Locomotive and Cars. L. V. R. R.

FIGURE 6



Hooked Tie Plate

FIGURE 7

while a force of only 7,700 lb (3,500 kg) was needed to fail a clamp-fastener type arrangement (Fig. 7b). Even greater security is provided, according to Bloss, if lateral play is eliminated from the system by means of a wedge inserted between the hook of the plate and the rail base (Fig. 7c). It is noted that by using this hooked plate arrangement, it is sufficient to use cut spike fasteners on the field side of the rail (Fig. 7d). However, Bloss suggests that it may be desirable to separate the rail—tie plate (gage) fasteners and the tie plate—tie (hold down) fasteners altogether, which allows a maintenance crew to remove a rail section without disturbing the tie plates and ties. It is interesting to observe that this feature is present in most of the elastic fastener systems presently being used.

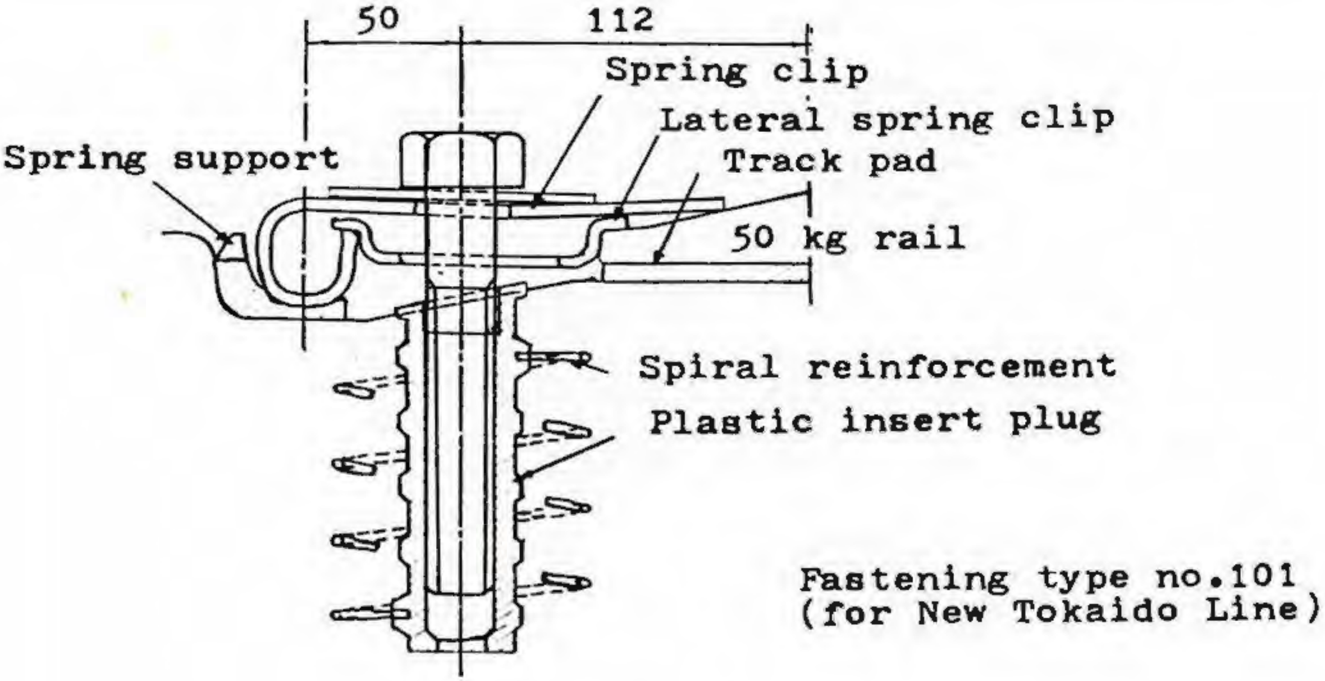
FIELD TESTS

Following these early investigations of rail roll, this problem merged into and became subordinate to the larger problem of gage widening. Field tests and investigations were carried out in the United States by the Association of American Railroads (AAR), in 1951 (5), 1966 (2, 3), and 1975 (1, 44); in France by the French National Railways (SNCF) in 1955 (36); and in Canada by CN Railways in 1972 (25, 34) and CP Rail in 1972 (29, 30). These tests, though aimed primarily at the gage-widening problem, did observe rail roll. A summary of these tests is presented in Appendix A.

In the 1975 AAR Track—Train Dynamics investigation of wide gage (44), the measured data were presented as probability histograms and cumulative probability distribution curves. Additional data on speed dependence and dynamic gage were also presented. It was noted that dynamic rail roll occurred but that no permanent deformation of the track was observed. A similar observation was made on the SNCF test (36), where elastic track fasteners were used. Tests conducted by the Japanese National Railways (JNR) (32) showed that track deformation caused by dynamic lateral load was not as severe as that caused by the identical static load. Consequently, it would appear that dynamic rail roll is not the most severe condition.

Rail roll was also observed during the winter tests conducted by the AAR (44) and by the CN (34). The fact that the winter conditions produced more significant rail roll and gage widening was attributed to larger lateral loads during the winter because of frozen roadbed conditions.

Static gage-widening tests were conducted by the CN in 1972 (25). Using a 50-ton hydraulic cylinder mounted in a special cradle to apply the lateral loads at the rail head, and using freight cars at various gross weight conditions to introduce vertical loads, the lateral deflection of the rail head was recorded for five dissimilar test sections of tangent track. During the course of these tests, it was observed that lateral loading at the gage face caused the rail head to move out more rapidly than the base, forcing the rail to twist. As it twisted and rotated about the outer edge of the rail base, spike pullout occurred at the inner edge. This pullout, it was noted, was continuous in some cases, and in others occurred as a series of "stick-slip" cycles. Crushing of the tie on the field edge of the plate was also observed. However, there was no permanent track damage other than the spike pullout and local tie crushing. After plugging the holes in the tie and respiking to gage, the rail was straight. This indicates that any bending that occurred in the rail was elastic, an observation that is supported by the other field tests as well.



JMR Fastener

FIGURE 8

In tests conducted by the Electro-Motive Division of General Motors Corporation in 1971 (22), large lateral loadings around curves, which resulted in gage-widening and rail-rollover problems, were measured. In these tests when L/V $\geqq$ 0.5*, the resultant load falls outside the rail base, thus making the basic rail unstable and restrained by the fasteners and vertical loads of adjacent wheels. A CP Rail report (29, 30) indicated that this condition occurred with L/V $\geqq$ 0.68 for 115-lb RE and 132-lb RE rail. The remedy suggested by this report was to reduce lateral loading on the track by improving train-handling techniques. This approach, which is suggested by several of these field test reports, would keep the L/V ratio below a critical value necessary for rail rollover.

The other attitude is that of improving the track structure to increase its lateral and torsional resistance. This approach was taken by the Louisville & Nashville Railroad after it had experienced gage-widening and rail rollover problems around curves (13, 24). By installing compression clip anchors on the gage side of the rails, rail overturning was prevented. Use of washer-head screw spikes, where the under side of the washer head is tapered to conform to the slope of the rail base, was also mentioned (13, 24) as a possible remedy to the rail overturning problems. The use of elastic compression clips corresponds to the results of the SNCF tests (36) which showed that elastic fasteners permitted considerable elastic movement of the head of the rail. Thus, the tests show that use of elastic fasteners would reduce the occurrence of spike pullout on the gage side of the rail and consequently rail rollover. Newly designed Japanese National Railways fasteners shown in Fig. 8 provide for both vertical and lateral elasticity, so that several

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* L/V values of approximately 0.5 to 0.55 were given as the values representative of rail commonly used in the United States.

causes of permanent gage widening are eliminated (28). These fasteners are presently being used on the JNR high-speed lines.

In all cases mentioned here the effect of axial forces in the rail, whether due to temperature change (20) or vehicle braking (7), was not directly taken into consideration and consequently no rail axial force measurements were taken.

RAIL ROLL TESTS

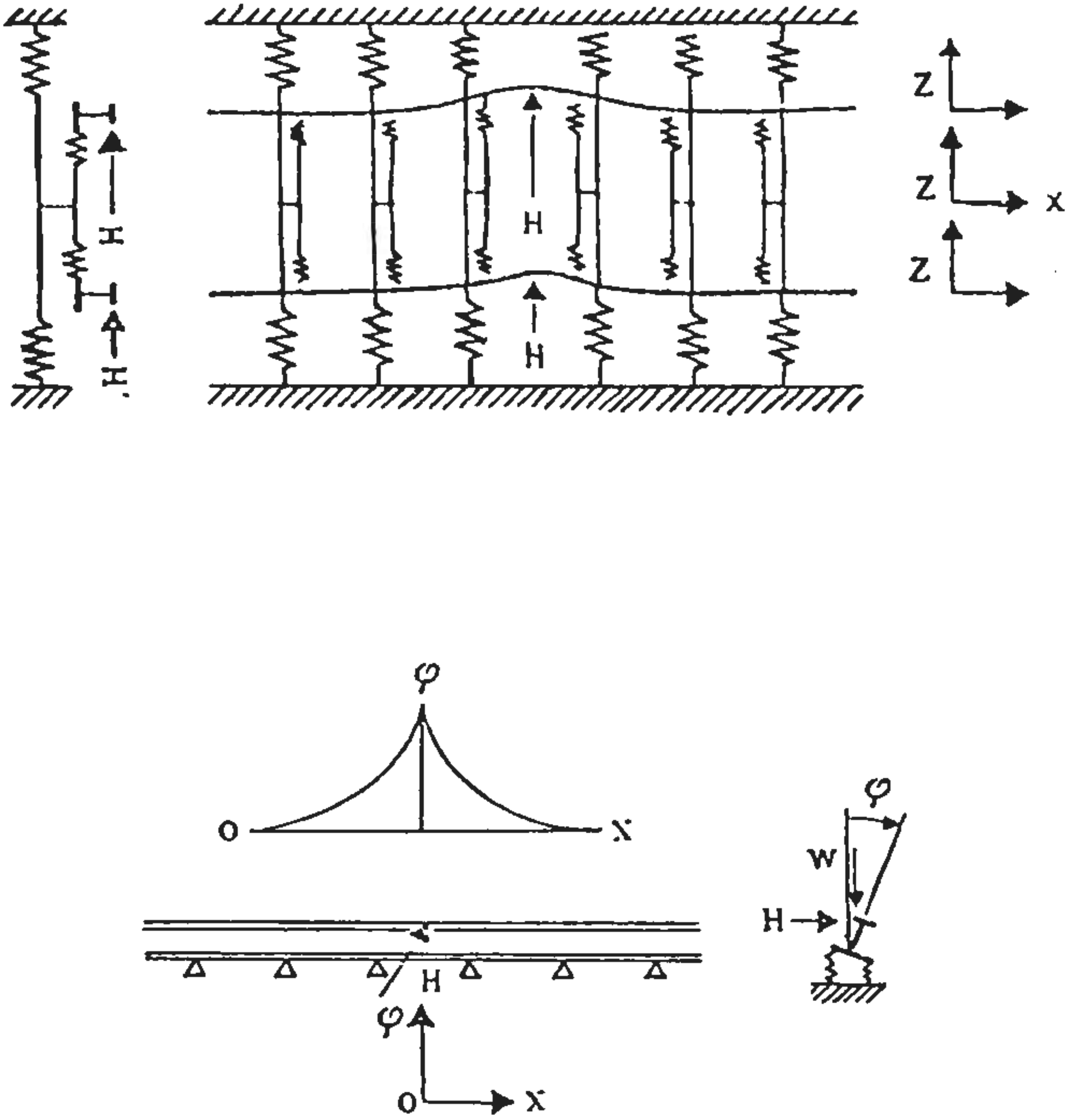
Though the gage-widening tests provided useful information on rail roll and rail overturning, the need for more specific tests was apparent.

In 1961 (32) and 1964 (33), Y. Sato of the JNR conducted a series of tests on the lateral strength of the track. He concluded that the rails in the track structure can be considered to be supported by three distinct springs: a spring representing the transverse displacement of the rail base on the tie, a spring representing the lateral displacement of the tie in the ballast, and a torsional spring representing the reaction of the tie and fasteners to the twisting of the rail. These springs are illustrated in Fig. 9. Corresponding to these springs, three forms of track failure are identified. The failure mode associated with rail roll, pullout of spikes or failure of elastic rail fasteners, was stated to be the one that defines the limit of the lateral pressure that can be applied to the track (33).

A similar approach was used by the AAR in 1967, where static laboratory tests, using a short piece of rail, were conducted to determine the overturning resistance of a rail fastened to a wood or prestressed concrete tie (Fig. 10a). These tests, which were conducted for different L/V ratios, were carried out until failure, which was defined as spike or fastener pullout. The result showed that concrete ties, using bolts and elastic clips, were capable of carrying considerably greater lateral loads than the wood ties with cut spikes (Fig. 10b). Detailed results of the tests, including deflections of the rail head and base, are presented in Reference 4.

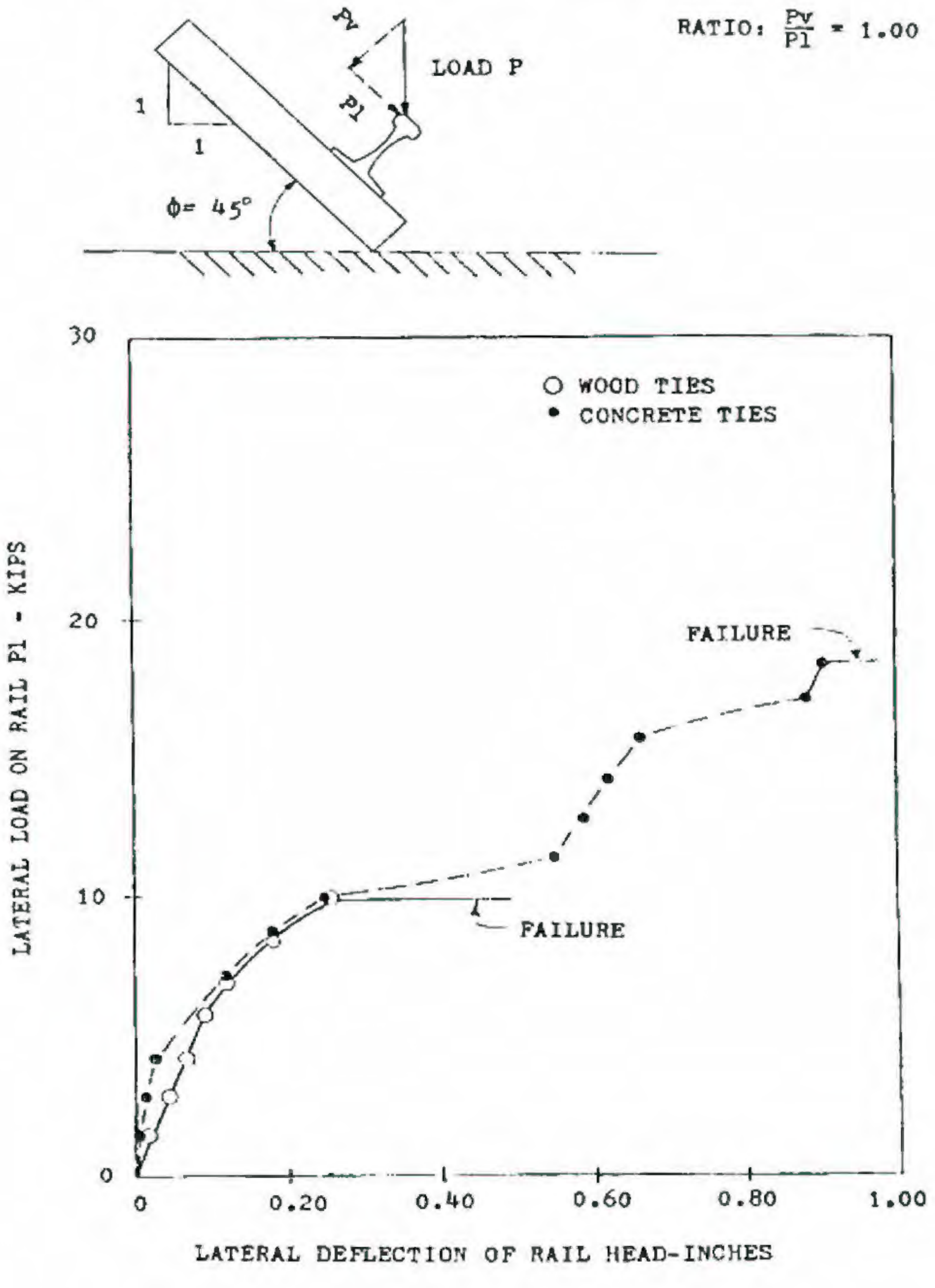
A more recent series of tests, conducted by D. K. Heron and A. Flassig (18, 19), was aimed specifically at the problem of rail roll. In these tests, which were conducted on track in a field environment, vertical and lateral loads of up to 40 kips were applied through hydraulic jacks, and longitudinal compressive loads of up to 200 kips were input with a hydraulic rail puller/expander. Although no actual overturning was observed, gage widening large enough to derail a wheel set was observed. The track structure, except for the pulled out spikes, appeared to behave elastically; however, it was observed at the end of the series that a permanent kink in the rail had developed. This is in contrast to the results of the CN Railways test (25) mentioned previously. The only major difference in the test procedure was the absence of axial forces in the CN tests.

These rail roll tests represent the only major test series to include axial loading or measurement of axial forces (for the field tests). As can be seen in Fig. 11, which is Fig. 7 of the Heron–Flassig report (19), the presence of axial forces on the rail caused significant increases in the magnitude of the gage widening in the track (gage widening here represents both rail roll and rail translation). The question now arises as to the effect of axial loading on rail roll. In the Heron–Flassig tests the axial force appears to be causing an increase in the bending of the rail, working in conjunction with the vertical and lateral forces at the rail head. For very large axial forces, the question of local buckling of the rail (as op-



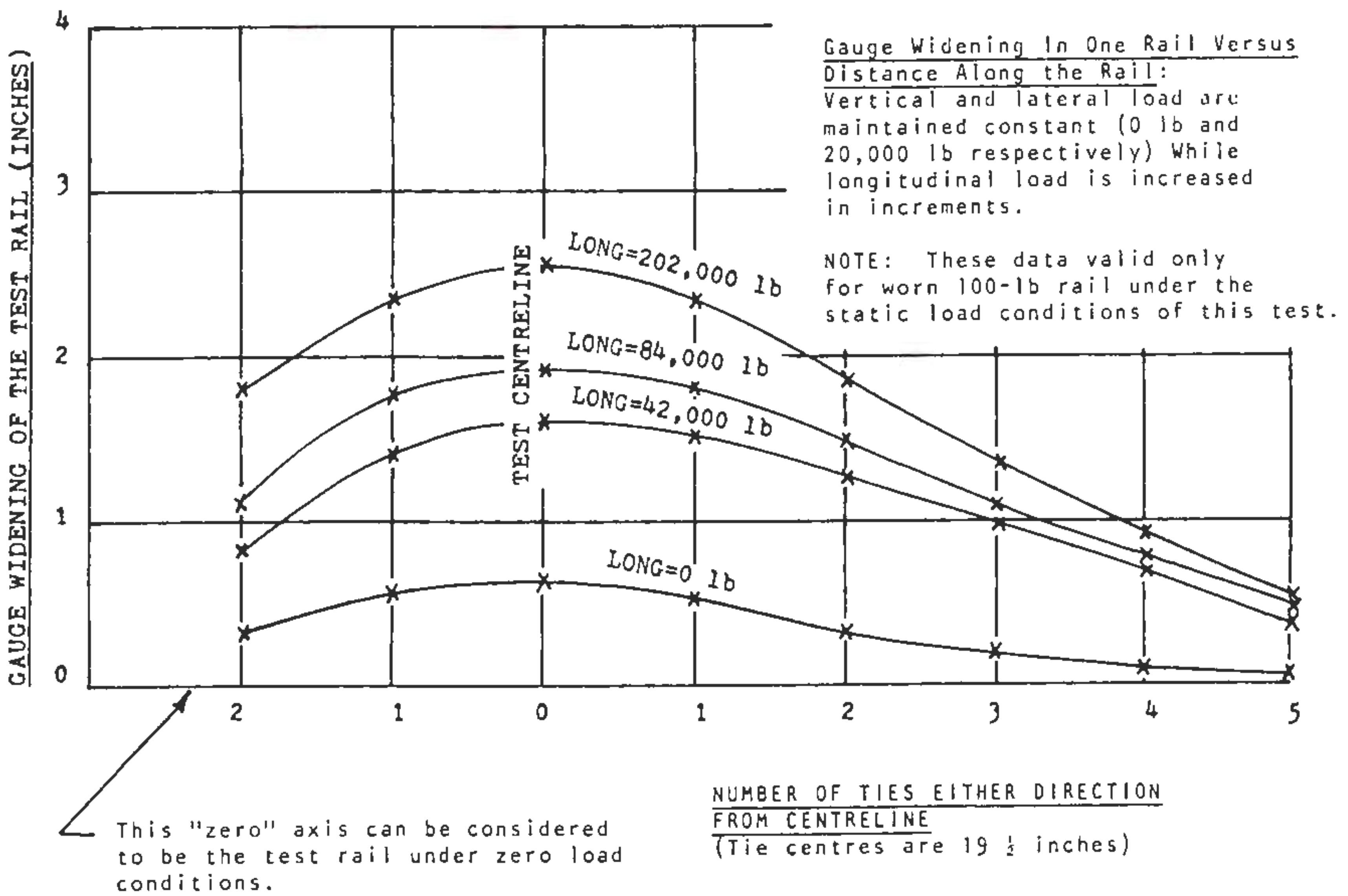
JNR Fastener Spring Model

FIGURE 9



RAIL OVERTURNING INVESTIGATION DEFLECTION OF RAIL HEAD

FIGURE 10



Gauge Widening In One Rail Versus Distance Along the Rail:
Vertical and lateral load are maintained constant (0 lb and 20,000 lb respectively) While longitudinal load is increased in increments.

NOTE: These data valid only for worn 100-lb rail under the static load conditions of this test.

NUMBER OF TIES EITHER DIRECTION FROM CENTRELINE
(Tie centres are 19 ½ inches)

This "zero" axis can be considered to be the test rail under zero load conditions.

Gage Widening Tests(ref.18)

FIGURE 11

posed to track buckling) is now raised. This question will be discussed in more detail in the analytical methods section. However, the fact that large axial forces do appear in the rail suggests that their measurements must be included in any field or laboratory testing program.

Two conclusions were presented in the Heron–Flassig report (19). The first, that a lateral load at a single point would not be likely to overturn a rail, appears to be in disagreement with the results of several field tests, discussed earlier, where it was concluded that derailments due to rail overturning are commonly caused by high lateral loading between the wheels of one truck and the rail (27, 29). The second conclusion is that actual failure—rail overturning—may be due to dynamic gage widening caused by extreme lateral and longitudinal loads, where one or more wheels drop inside the gage, run along the inside of the rail web, and cause the rail to overturn. However, whether this latter explanation suitably accounts for all or even most of the instances of rail overturning is a question that must still be investigated.

A brief summary of the rail roll tests is given in Appendix B.

RAIL TORSIONAL STRESSES

In 1932, Timoshenko and Langer (42) conducted a set of analyses to determine the stress distribution in a rail and to examine the effect of lateral and eccentrically applied vertical loads on the rail. The results showed that the rail responds to these two types of loading in entirely different manners. For lateral loads applied at the rail head, the torsional rigidity of the rail head prevents rotation of the top of the web, so that the rail deforms as in Fig. 12a. For eccentric vertical loading, the deformation of the rail is depicted in Fig. 12b.

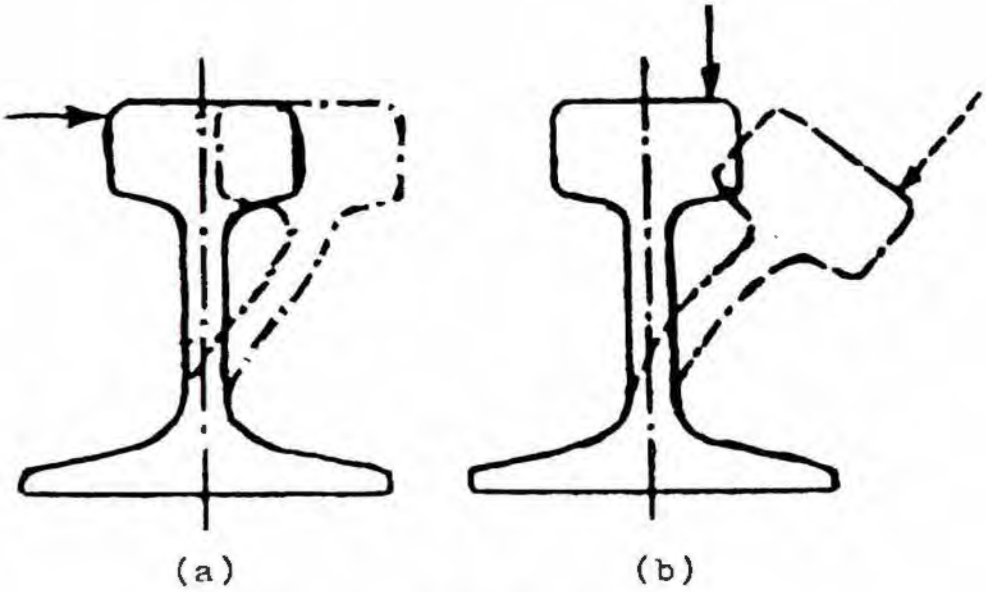


FIGURE 12 Nature of Deflection Produced by (a) Lateral and (b) Eccentric Vertical load

A similar investigation was conducted by G. Maney in 1945 (26). Using both analytical and experimental investigations, Maney concluded that torsion applied to a rail by means of eccentric vertical loading is resisted almost entirely by the head and upper portion of the web, while pure torsion is resisted by the entire rail section.

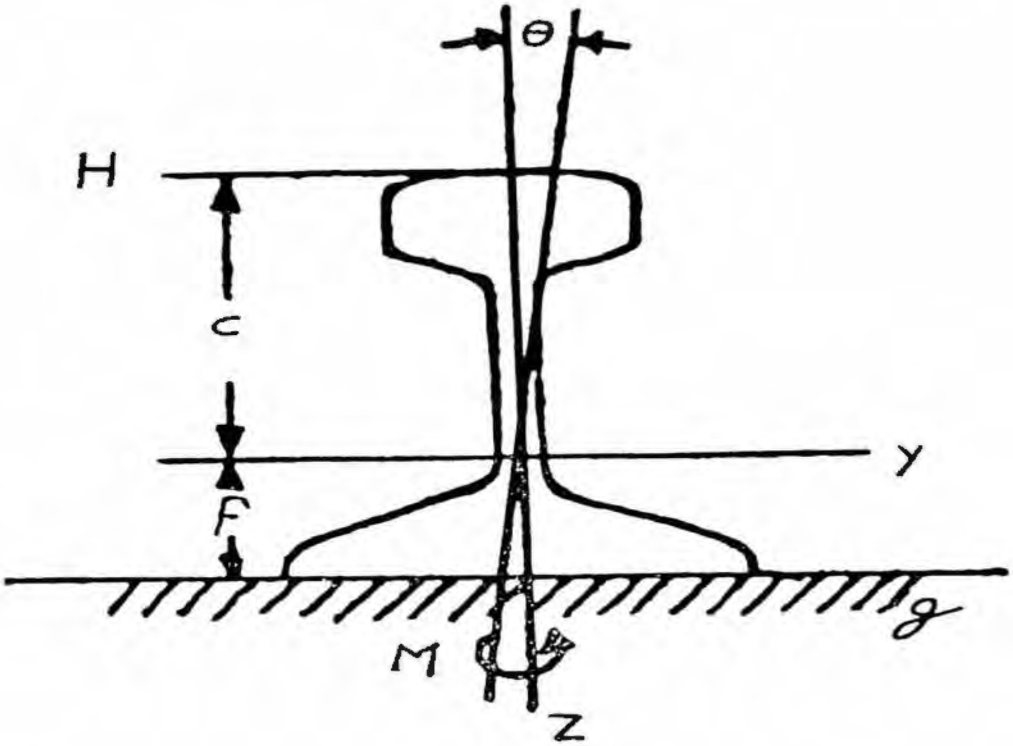
The results of these two investigations suggest that it may not be sufficient to define the rail, analytically, as a single beam, but rather the web and head must be treated as separate, though interacting, entities.

ANALYSIS OF RAIL ROLL

The first attempt to analytically define the problem of rail roll was made by S. Timoshenko in 1926 (41). Treating the rail as a beam subjected to a constant lateral load applied at the rail head (Fig. 13), Timoshenko presents an equation for the combined bending and twisting of a rail:

$$EI \frac{d^4y}{dx^4} = -K_2 \cdot (y - f\theta) \tag{1}$$

$$-C \frac{d^2\theta}{dx^2} + Dh^2 \frac{d^4\theta}{dx^4} = K_2 \cdot (y - f\theta) \cdot f - K_1 \cdot \theta \tag{2}$$



Timoshenko's Rollover Model

FIGURE 13

where

θ is the angle of twist of the rail

y is the lateral deflection of the center of twist of the rail

K_1 is the modulus of foundation with respect to twist (torsional resistance of the rail fastenings and foundation)

K_2 is the modulus of foundation with respect to lateral deflections of the rail (lateral resistance of the rail fastenings and foundation)

An abbreviated version of this derivation is presented in the paper by Timoshenko and Langer (42). Based on his analysis, Timoshenko concluded that the lateral bending and twist of the rail are of localized character, consequently the effect of several lateral forces, such as produced by locomotive wheels, is not substantially greater than that of one of these forces (42).

In response to this paper, R. Eksergian (14) brought up the question of the validity of the continuity assumption for the torsional and lateral supports, K_1 and K_2. In a similar vein, F. M. Graham (15) brought up the fact that, in actuality, both the torsional resistance of the spike fasteners and the lateral resistance of the spike fastener—tie plate—tie system are non-linear and probably inelastic in nature. In answer to these objections, Timoshenko and Langer (43) state that their studies have shown these assumptions to be both reasonable and very useful. R. Grammel (16), in his comments on the paper, discussed the effect of the vertical deflection of the rail and its interrelation with the rail twisting. He proposed that an additional term, K_3z, be added to the right hand side of eq. 2; where z is the vertical deflection of the track obtained from a beam on elastic foundation analysis, and K_3 is a coefficient of "bedding." A more complex interaction between these two modes was also proposed.

In 1964, Y. Sato (33) also suggested that the rail roll problem be analyzed as the torsion of a beam supported by a spring against inclination (rotation), in order to obtain the conditions under which spike pullout occurs. However, no equations were presented.

In 1969, M. Srinivasan (37) examined the problem of eccentric vertical loading of the rail, and the resulting rail twist, and obtained a set of equations which correspond, quite closely, with those of Timoshenko. The differential equation for the rail twist is given by

$$M_t = -C\frac{d\theta}{dx} + Dh^2\frac{d^3\theta}{dx^3} \tag{3}$$

where

$2M_t$ is the torque moment applied to the rail

θ is the angle of twist

It should be observed that in all of the above analyses, the axial force in the rail was neglected. However, Timoshenko's equation can be readily modified to include axial loading by the addition of a $P\frac{d^2y}{dx^2}$ term to the left-hand side of eq. 1. The solution of this problem would then consist of three cases

(a) $P < P_{cr}$

(b) $P = P_{cr}$

(c) $P > P_{cr}$

where P_{cr} represents a critical value of the axial force. For the case $P < P_{cr}$, the rail rollover analysis would be concerned with the bending and twisting of the rail. For the case $P \geqq P_{cr}$, the question of rail buckling arises. Because of the presence of extremely large axial forces in one or both rails, this problem (as opposed to the track buckling problem) should be given additional consideration. Up to the present time, however, this aspect of the problem has not been adequately treated.

In 1974, A. Kish (21) presented a set of non-linear bending torsional equations for a railroad track, subjected to constrained non-uniform thermal expansion. His results, which are in the form of non-linear three-dimensional equations for the track, were not applied to the problem of rail roll.

J. J. Labra (24), in 1974, examined the problem of an axially loaded linear induction motor (LIM) reaction rail (Fig. 14), subjected to a moving lateral load. In doing so, he considered the rail web to be a plate in bending, with the equation

$$D \nabla^4 w + N \frac{\partial^2 w}{\partial y^2} + \rho h \frac{\partial^2 w}{\partial t^2} = P \cdot \delta (y-ct) \cdot \delta (x-a) \tag{4}$$

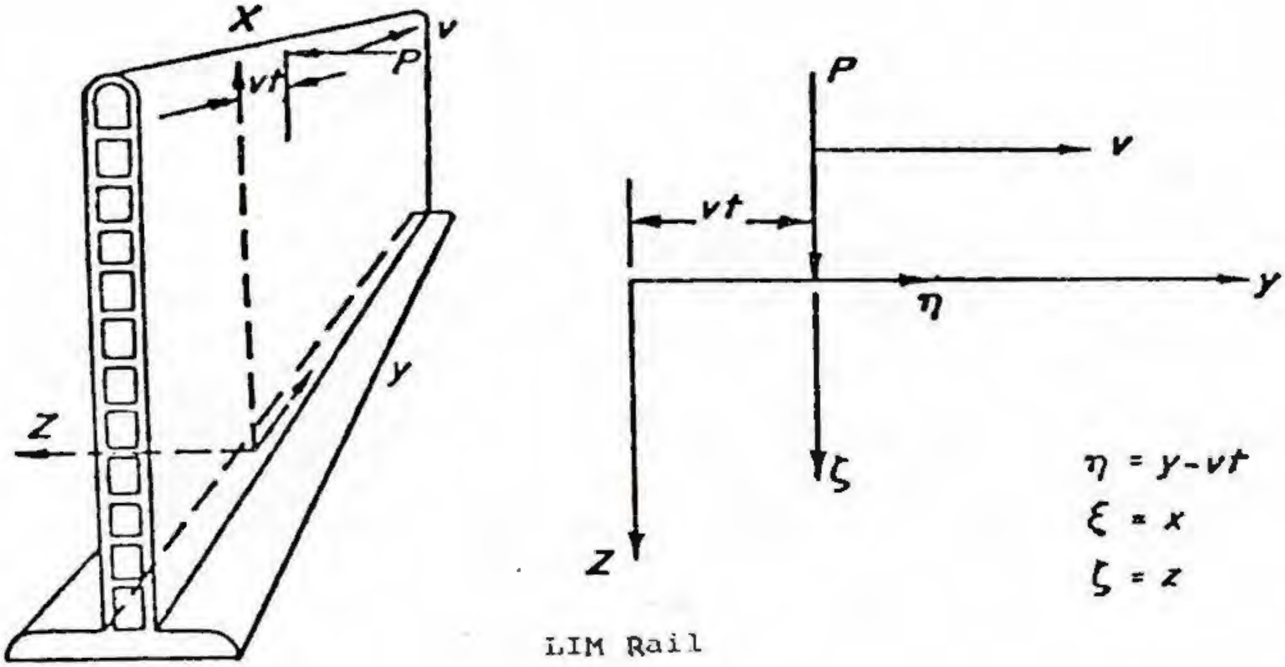
where

w is the lateral deflection of the rail

P is the applied lateral load

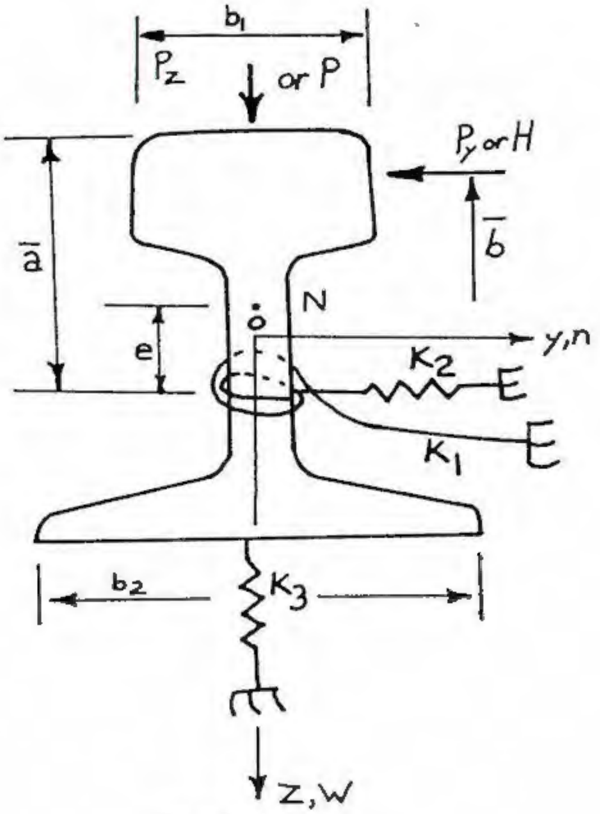
N is the axial load

This analysis does not consider the conventional rail section, and does not take into consideration rigid body rotation or translation of the rail. It does examine, however, the rail bending of the LIM reaction rail. Furthermore, the dynamic effects of a moving load are examined, and it is shown that a critical velocity does exist which is dependent upon the axial loading of the rail.



LIM Rail

FIGURE 14



RAIL MODEL

FIGURE 15

Several recent attempts to solve the problem of rail roll have been made with the use of Finite Element and Finite Difference techniques.

F. Arbabi–Kanjoori (6) used the former technique to investigate the problem. Representing the rail element as a beam restrained by vertical, lateral, and torsional springs (Fig. 15), axial, lateral and vertical loads are introduced into his analysis. The formulation of the problem, and a solved numerical example are presented.

K. H. Chu and Y. S. Wang (11) utilized a Finite Difference solution of Timoshenko's equations, which was modified to include constant axial loading and non-linear effects of interacting moments. The results, which were compared with the test data of Heron and Flassig (18), were in moderate agreement. However, in order to obtain this agreement, Chu and Wang varied the torsional resistance of the fasteners with the different loading conditions in an undefined manner. Furthermore, because of the large computer operation time required for their analysis, Chu and Wang recommended the use of a Finite Element approach for further analysis.

CONCLUSIONS

Though numerous investigations, both test and analytical, have been carried out in order to define and solve the rail roll problems, the basic nature of the problem is still not fully understood. It is known, however, that the mechanics of rail roll includes spike pullout, spike bending, tie crushing beneath the outer edge of the tie plate, and bending of the rail head and web.

Various approaches have been utilized by the railroads in an attempt to contain the rail roll problem. Use of improved train-handling techniques and redesign of locomotive suspensions, to reduce the L/V ratio, has been one approach. Increasing the torsional resistance of the track by means of improved spiking patterns and more efficient elastic fasteners has been another. Use of gage rods, particularly those with gage side clamps, is still another.

However, it is not enough simply to contain the problem. Further study is needed to characterize more fully the nature of the problem and to effect more permanent solutions. It has been the intent of this paper to present the reader with the work that has already been performed and to stimulate further analytical, experimental, and field investigations in this important area.

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Appendix A - Field Tests

Year	Test	Location	Test Procedure	Data Recorded	Best Objectives Results
1931	AAR (5)	Sante Fe Railroad	Locomotives/train driven on instrumented 10° curve/ tangent track sections	Vertical force on rail Lateral force on rail Lateral deflection of rail head Rail bending stresses	Study locomotive design and its effect on curved sections of track, (emphasis on lateral loading)
1955	SNCF (36)	SNCF (French National Railroad)	Special 3 axle track testing vehicle was used on main line track. Middle axle of this vehicle was the track loading device.	Lateral rail head deflection Rail stresses Track lateral "resistance"	Determine reisitance of track to vehicle lateral loading/motion. Various speeds, L/V's and maintenance conditions were examined.
1966	AAR (2)	Delaware & Hudson Rail-Road	Test train was driven on curved (3°), instrumented test section, main line track	Lateral force on rail Vertical force on rail Lateral rail head displacement	Investigate gage widening derailments due to locomotive loadings. Jackknifing and dynamic braking were investigated.
1966	AAR (3)	Southern Pacific Railroad	Instrumented test cars placed in revenue service	Coupler forces Lateral truck forces	Investigate effects of lateral forces generated by dynamic braking on track and equipment. Relate coupler forces, slack action, track curvature.
1972	CN (25)	Canadian National Railways	Static tests. Fixed hydraulic cylinder used to apply lateral loads at rail head. Loaded vehicle provides vertical loading.	Lateral rail head deflection along section of track	Measure static lateral resistance of track, with/ without vertical loading. Examine gage widening under controlled conditions.

Appendix A - Field Tests (Continued)

Year	Test	Location	Test Procedure	Data Recorded	Test Objectives Results
1972	CN (34)	Canadian National Railways	4 and 6 axle locomotives with test train driven on instrumented section of curved (3½°) track. Special instrument tie plates were utilized. Winter/Summer tests	Vertical and Lateral tie plate loading. Lateral rail head displacements Rail wear	Examine the mechanism of lateral track failure. Effect of speed, locomotive type, freight car loadings; seasonal changes.
1972	CP (29,30)	Canadian Pacific Railroad-Pacific Region	3 test trains - with instrumented consist were run on main line track sections.	Braking conditions Coupler forces Wheel loadings on track	Examine the effect of train handling techniques on track. Investigate occurrences of rail overturning, how to prevent it
1974-1975	TTD (44) -Batelle (1)	Union Pacific Railroad	8 sections tangent main line track were instrumented and returned to normal service.	Vertical and Lateral rail displacements. Rail roll Dynamic gage widening Tie plate loading (using special tie plate load cell)	Examine factors contributing to gage widening on tangent track. Long term (cumulative tonnage) and seasonal conditions were included. Various types of tie plates, fastener combinations, and track irregularities were included.

Appendix B - Rail Roll Tests

		Range Of Loading			
Test	Type	Vertical	Lateral	Longitudinal	Observations
AAR (4) 1967	Static Laboratory Test (Using short sections of 136 lb rail) wood/concrete ties	Wood 0-40k concrete 0-80k	Wood 0-13k concrete 0-40k	None Applied	For wood ties. failure (fastener pullout) for L/V = ∞ at L = 6.4 k L/V = 1 at L = 19 k L/V =.5 no failure (max. deflection = .2") Concrete ties failed at greater load levels.
[illegible] (23) 1972	Static Field 5 test sites (85-130 lb rail) wood ties	0-33k	0-100k	None Applied	for 130 lb rail failure (first significant lateral yield) for L/V = ∞ at L = 37k L/V = 2.3 at L = 74k for 100 lb rail L/V = ∞ at L = 22k L/V = 1.9 at L = 51k
[illegible] (18,19) 1976	Static Field (100 lb rail wood ties)	0-40k	0-40k	0-200k	No overturning or fastener failure occured Max. observed deflection = 3.3" Max. observed rotation = 23° for P=0, L/V = 1 L/V = 40k deflection = 2.1" rotation = 15° for P = 0 L/V = ∞ L = 25k deflection = 1.6" rotation = 11°