Track Components for 125-Ton Cars

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Each track component is considered in turn and its engineering development is reviewed. Maintenance equipment is similarly reviewed. Ties and fasteners are identified as items to which an engineered approach could produce significant advances in cost-effective track. A detailed description is then given of the dynamic behavior of ties and how it is influenced by impact loading from equipment. Development of tie design from in-track measurements and the benefits of engineered tie pads are also discussed. Finally, suggestions are given for track for 125-ton cars, and the need to control damage caused by defective wheels is identified.

Since the first transcontinental railroad was constructed 120 years ago, developments in mechanical equipment and signaling have been dramatic, and today's equipment would be virtually unrecognizable in scale, power, and complexity to a mechanical engineer of the 1860s. Track, however, although stronger, looks quite similar to that installed by the civil engineer of 120 years ago. Competition is driving railroads to maximize the tonnage carried on each track, and part of the increase in tonnage carried has been achieved by a steady increase in car gross weights. Compared with the 70-ton car, the 100-ton car has been shown to reduce rail life by 40 percent in tangent track (*1*). Now that the 125-ton car with 39-ton axles is becoming a reality, the need for more thoroughly engineered track is greater than ever before.

TRACK MATERIALS

Rail

Modern rail sections have ample strength to span between ties at 19-in. spacing (wood) or 24-in. spacing (concrete), but increasing contact stresses (Table 1) have led to a situation in which railhead fatigue is the factor that controls rail life in heavy-haul tangent track (*2*). Wear and rail stability, however, remain the dominant problems in curved track.

Developments in lubrication, especially on-board lubricators, should reduce side cut in tight curves, but rail will always wear and its rapid change out or transposition, without damage to the ties, is an important requirement that must influence the design and selection of fasteners.

Rail wear and the risk of derailment are influenced by rail stability under dynamic loading, which is dependent on the ties as well as the fasteners.

Understanding of the mechanisms of the development of railhead defects is still inadequate despite major research efforts on this subject. The scale of research on rail defects reflects the place of rail as the most costly track component (Table 2).

TABLE 1 WHEEL-TO-RAIL CONTACT STRESSES (*1*)

Vehicle Type	Wheel Diameter (in.)	Wheel Load (1,000 lb)	Avg Contact Stress (ksi)
125-ton car	38	39	148
90-ton car	36	31.9	140
70-ton car	33	26.3	136
4-axle locomotive	40	32.5	138
6-axle locomotive	40	32.5	138

Progress in reducing the incidence of railhead defects is relatively slow, perhaps because the significant contribution of ballast, ties, and fasteners to rail performance is neglected. Study of the total system can lead to some interesting findings; for example, fully compacted ballast improves the damping of ties and this can significantly reduce railhead contact stresses (*3*).

Ties

Until quite recently, manufactured ties were used only in response to specific problems such as timber shortages (especially in wartime), termite attack, and desiccation in desert conditions. The ties that proved successful in overcoming these problems were, in chronological order, steel, twin-block concrete, and monoblock prestressed concrete. Of these, only monoblock prestressed concrete has a record of successful large-scale use in heavy-haul track.

Monoblock prestressed concrete ties were fully described by White in 1984 (*4*). At that time, the main North American users were Florida East Coast Railway, Amtrak, and Canadian National (CN) Rail. Since then, CN Rail has continued its program and now has more than 2.5 million concrete ties in track. The most recent user is Burlington Northern Railroad who plan to install 3.5 million concrete ties by 1992.

In the last few years there have been major advances in understanding the dynamic behavior of concrete ties. The important attributes of concrete ties in this context must be a record of successful use in arduous conditions and the potential for engineered design. This is considered in more detail in a later section of this paper.

Concrete-slab track received considerable attention in the

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TABLE 2 TYPICAL COSTS FOR TRACK MATERIALS

Item	Concrete-Tie Track	Wood-Tie Track
Rail (132-lb carbon) (%)	42.3	43.4
Fasteners (%)	11.2	16.9
Ties (%)	32.0	25.6
Ballast (%)	14.5	14.1
Total ($000/mi)	247.5	240.9

1970s and now has a limited but important role in specialized applications such as tunnels and elevated high-speed track.

Fasteners

The cut spike helps to destroy wood ties but, despite this, is still the predominant means of securing rails to ties. In the last 150 years the only major development of the cut spike fastener has been the introduction of tie plates.

All of the modern elastic fasteners can be used on tie plates, but they are then only as good as the method of securing the tie plate to the tie (usually cut spikes) and the ability of the tie to resist plate cutting.

With concrete ties, there is an opportunity to match an engineered tie to an engineered fastener with only a tie pad to separate the rail from the tie. Tie pads have a vital role in the satisfactory performance of the system, and this is considered in more detail later.

The favored elastic fasteners for heavy-haul use in North America are shown in Figure 1; they all avoid screwed components, which are labor intensive during installation and maintenance. When used with concrete ties, the clip housing (shoulder) is permanently cast into the tie and must therefore be of a design that has a life expectancy similar to that of the tie. In particular, it must survive dragging equipment and rails dropped onto it during installation.

Fasteners are generally specified by means of static or low-frequency parameters (*5*), which can be readily measured in the laboratory. However, because fasteners have to work in a high-frequency dynamic environment, experience with their performance in use is most important.

Development of design is largely empirical, but the introduction of measuring devices such as the Dichroic Displacement Measuring System (*6*) means that behavior in track can be quantified. Thus laboratory testing can be made to more closely reproduce service conditions; this has already been done with the Battelle impact test rig (*7*), which can be used to measure the relative efficacy of tie pads in attenuating impact loads resulting from wheel defects.

Rail anchors are a fastener component, but they should not be required with proven concrete tie fasteners.

An important consideration in fastener design is machine insertion, and progress is being made with clip insertion. At present, insulator placing remains a hand operation, but initial pad placing can be avoided by having tie pads glued to the ties before delivery, using an adhesive that will permit them to be peeled off later.

The tie pad and insulator are wearing items, but their

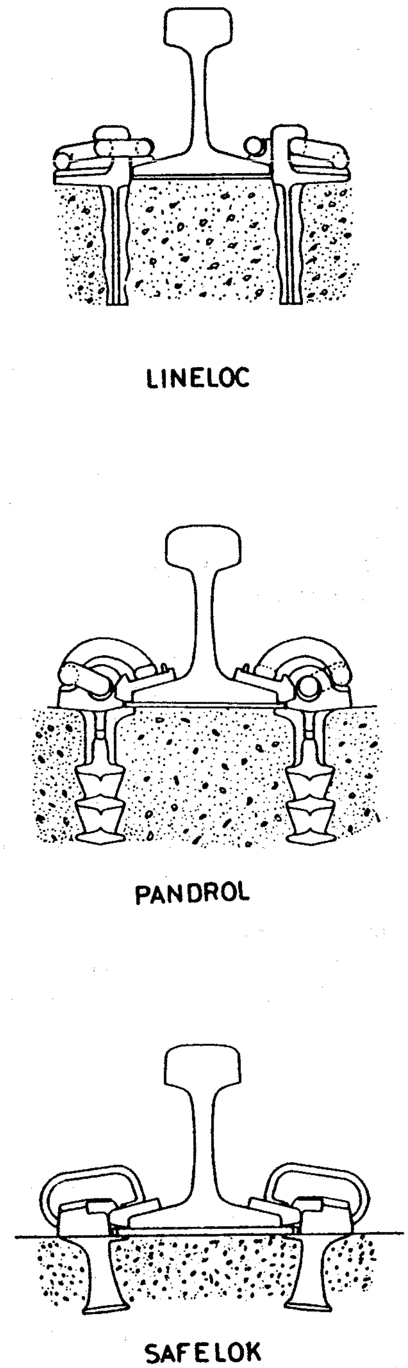

FIGURE 1 Rail fasteners for concrete ties.

integrity should be maintained for one rail life or a whole-number multiple of rail life.

Ballast

The functions of ballast in 125-ton car territory are similar to those in all track. That is, ballast distributes over the subgrade the loads from the ties, especially dynamic loads; holds the ties and prevents lateral, longitudinal, and vertical movement; drains away water; and facilitates lining and leveling of the track.

Only the better types of ballast will continue to perform these functions under the arduous conditions created by intensive high axle-load traffic. Important considerations are particle shape, grading, and individual particle integrity when subject to loading in wet, dry, and freezing conditions.

It is well known that concrete ties impose greater stresses in the ballast. This necessitates particularly careful selection of ballast type and grading for use with concrete ties. Typically, crushed igneous or metamorphic rock such as granite, traprock, and quartzite is suitable.

Subgrade

Two more recent engineering techniques are the use of geotextiles and cement stabilization, which increases the wet and dry strength of the subgrade. These are particularly useful at the surface of clay subgrades where water does not drain readily and mud pumping may develop.

Geotextiles are used over a blanket of free-draining fine material such as sand or selected crusher run fines (*8*). It is important that the profile of the sand blanket permit water to run away and that the sand itself be free draining.

Mud pumping can occur because of breakdown of ballast particles especially when limestone ballast is used, but the more insidious occurrences are due to ties punching into the subgrade. Under these conditions, the best quality ballast can quickly be rendered almost useless. Concrete ties are more likely to give rise to mud pumping than are wood ties. Where the risk is present, insertion of a geotextile and sand blanket can easily be carried out on discrete lengths of track during reasonable work blocks. Cement stabilization is a technique more suited to new construction or reconstruction.

Turnouts

With the advent of continuously welded rail (CWR), the fixed frog is now the major discontinuity in the track. Because of the high impact loading at this discontinuity, the frog itself and the supporting ties and ballast require a disproportionate amount of maintenance.

Swing nose frogs have the potential to greatly reduce this discontinuity. They have been developed in Britain, France, Germany, and Japan in a variety of forms ranging from fully fabricated to fully cast (*9*).

Prestressed concrete switch ties, now widely used in Europe and Australia, are also finding acceptance with installations on CN Rail, Florida East Coast Railway, Amtrak, Burlington Northern Railroad, and Conrail. They offer three basic advantages:

- Reduced rail wear arising from higher track modulus and better fasteners that reduce rail movement;
- Supplied as a kit with fasteners cast in at calculated positions, thus eliminating the need for preassembly; and
- Consistent quality and extended life compared with wood.

Design of switch ties is based on plain line ties with constant cross section. Tests in track by CN Rail have confirmed that in their installation the concrete stresses are within acceptable levels (*10*).

DYNAMIC BEHAVIOR OF CONCRETE TIES

Early work was done by the Talbot Committee (*11*), which studied the behavior of rail, wood ties, ballast, and road bed. A considerable study of in-track loads was also undertaken when prestressed concrete ties were developed in Britain in the 1940s (*12, 13*). The findings were used as a basis for establishing ballast pressure distribution and tie design. Axle loads were complemented by an impact factor to arrive at measured loads.

In the past decade, a greater understanding of the behavior of concrete ties has been achieved. Because loading arises from moving vehicles it is cyclic; even with a perfect wheel on a perfect rail, the duration of load is so short and varies so rapidly that it has a considerable dynamic component. Superimposed on this are the real-life imperfections such as shelled, flat, and out-of-round wheels; rail corrugations; dipped welds; engine burns; and shells. All of these cause dynamic loading of varying frequency and magnitude, which excites the ties at their natural frequencies.

In the first mode, which occurs at about 125 Hz, the ties tend to bounce on the ballast and there is little dynamic bending (*14*). Also, at frequencies below about 200 Hz, well-compacted ballast provides significant attenuation of tie vibration (*3*). The first mode is therefore not particularly significant when the ties are properly supported and there is sufficient quasi-static load to keep the ties in contact with the ballast. In the second mode, the rail seat is close to a node and the dynamic bending is not critical, but in the third mode, which occurs at about 650 Hz, the dynamic bending alternately augments and counteracts the rail seat quasi-static bending (Figure 2). It is this third mode that is generally considered most critical for dynamic strains in the rail seat of ties although significant effects are observed up to 2000 Hz.

When the quasi-static strain is augmented by the dynamic strain, the tie behaves as though the quasi-static load has been increased, hence, the concept of an impact factor applied to the quasi-static load. When the wheel load is relatively small and the speed is high (e.g., empty cars), tie vibration can result in reverse bending that will create a tensile strain in the top of the rail seat of the tie (*15*).

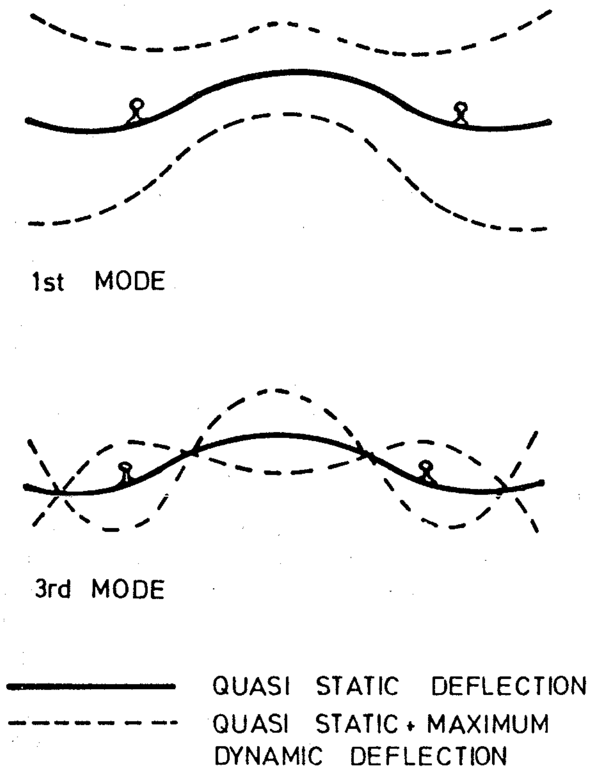

FIGURE 2 Interaction of tie resonance and quasistatic bending (*14*).

The amplitude of vibration will depend on the magnitude of the impact, the decoupling provided by the rail pad, and the damping provided by the ballast. Under a high quasi-static load the tie is more likely to be well damped by the ballast than when lightly loaded. Hence, tie strains are not necessarily related to wheel load, and defective lightly loaded wheels, which tend to travel faster, can be quite damaging.

Although the strain induced in the rail by wheel defects is not directly related to tie strains, some data from rail web strain measurements are shown in Figure 3 to demonstrate the relation between speed and dynamic loading. The speed at which the effect of wheel defects becomes significant is 20 to 30 mph, and it is clear that some wheel defects have an increasing effect with speed whereas others are less speed dependent.

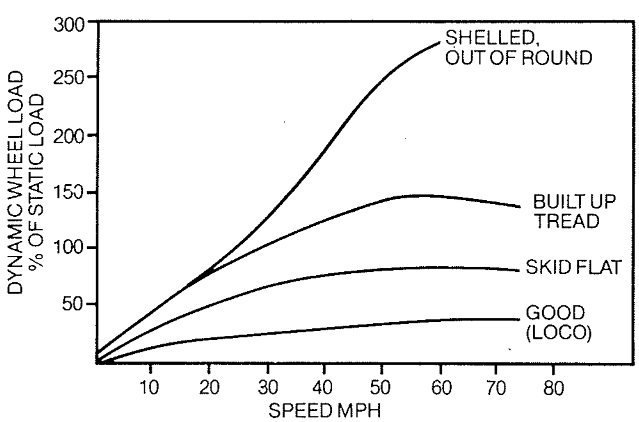

FIGURE 3 Effect of speed on dynamic load from imperfect wheels (*10*).

Resonance of the ties will also have an effect on the positive and negative strain at the tie center. When the tie is first installed with no center support, there is a positive bending moment, but as the tie beds into the ballast, this changes to a center negative moment. However, empirical observation is that distress at the tie center is rare, and, when it does occur, it can invariably be related to ties being center bound at some time.

As discussed previously, well-compacted ballast contributes significantly to tie damping. Tamping is effective in restoring track line and level, but it disturbs the ballast and hence reduces damping. An alternative method of restoring track level by pneumatic stone injection (*16*) is therefore attractive because it causes much less disturbance of the ballast once it has been consolidated.

TIE PADS

Tie pads have the vital role of separating the rail from the concrete tie; apart from its contributions to load distribution and insulation, the pad is vital to the prevention of abrasion of the tie by the rail foot. Tie pads are typically 0.20 in. thick, selected on the basis of their ability to remain in place and not disintegrate or wear out before rail change out, and initial cost.

The importance of tie pads in protecting ties from severe impact loads has been recognized for many years, but consideration of how the contribution of the pad could be assessed was limited to comparison of static spring rates. As part of their investigations of cracked ties in the Northeast Corridor, Dean et al. (*17*) developed the Battelle impact test that has since been refined to incorporate a quasi-static load and more realistic support conditions (*18*). This test is useful in comparing pad attenuation properties, but it must be complemented by other investigations. These include general durability, especially resistance to abrasion; resistance to degradation; and the ability to undergo high-frequency repeated loading without change in elastic properties. It is difficult to measure the dynamic spring rate of pads in the laboratory and, in the absence of suitable tests for the other properties, recourse has to be made to in-track testing.

The effect of temperature on pad performance can be significant because many pad materials are thermoplastic. High-density polyethylene (HDPE) pads, which are satisfactory in South Africa, become brittle under North American winter conditions, but ethyl vinyl acetate (EVA) is satisfactory for North American temperatures.

It is recognized that pads thicker than 0.2 in. made from materials with a low dynamic spring rate, such as natural rubber, are most effective in attenuating impact loads. A profiled surface also contributes significantly to performance (*18*). An optimum thickness of about 3/8 in. has been adopted by Japanese Railways, SNCF (France), and British Rail. This is a compromise among maximum impact attenuation, retention of rail stability, and cost. Not only is the cost increased by the thickness, but the materials are also

inherently more costly than EVA. The increased cost can, however, be justified because EVA does not provide any significant impact attenuation.

HDPE and EVA pads predominate on heavy-haul railways and, in general, their durability is good. They provide good electrical insulation and they prevent the rail from abrading the tie. Consideration has therefore been given to increasing their thickness and using a profiled surface, but, because of the inherently high dynamic stiffness of such materials, there is no benefit.

It is notable that the railroads that use high-attenuation pads tend to be those that operate high-speed passenger networks. This is because impact loading from certain wheel and rail defects is speed dependent rather than proportional to static wheel load. However, there are potential benefits to heavy-haul railroads at speeds in excess of about 30 mph. CN Rail is carrying out tests with high-attenuation pads on tangent track where speeds are fairly high and may increase. As yet, there are no reports on in-track tests of such pads in heavy-haul curved territory.

The use of thicker pads raises the logistical problem of how to ensure that the correct pad thickness is used with each fastener assembly. One approach would be for each railroad to specify only one pad thickness and to vary the material depending on speed, curvature, and type of traffic.

DESIGN AND TESTING OF PRESTRESSED CONCRETE TIES

The AREA specification for concrete ties, which is probably the most comprehensive available worldwide, gives resistance moment requirements and tests to confirm compliance with these requirements. It is based on static calculations augmented by impact and distribution factors. Currently, the impact factor is 150 percent, which is also fairly typical for offshore railroads (*19*).

Specified bending moments have been increased several times as a result of observed in-track performance. More recently, the resistance moments specified for ties at 30-in. spacing have been adopted for ties at 24-in. spacing. The result is that ties designed to these requirements are generally larger in cross section than are ties used anywhere else in the world (Table 3).

The AREA approach to design assumes that the effect of impact loading is proportional to the quasi-static load and hence an impact factor is applied. Although this is conventional and convenient, it does not represent the behavior described in the section on dynamic behavior of concrete ties. Converting the dynamic strain in a tie to an equivalent static load or bending moment does produce figures that the civil engineer can use. However, it does not take into consideration that, within the range of values for stiffness normally encountered, resonance of ties is a strain-inducing phenomenon that is not resisted by increase in the resistance moment of the tie. Tie strain capacity is more important—a point not addressed by the specification except for a requirement for a minimum prestress of 150 psi at any point in the rail seat cross section.

Another assumption that may not be valid is the direct relation between tie spacing and load carried by a single tie. Within the limited range of likely tie spacings, say 20 to 30 in., it is unlikely that direct proportionality applies. Certainly dynamic loading is unlikely to be sensitive to tie spacing.

The present state of the art is that ties somewhat smaller and with lower resistance moments than designs based on the AREA specification are performing well in heavy-haul railroads in Australia, Canada, and South Africa. However, these designs do have a common feature of relatively high extreme fiber prestress at the point of maximum strain (Table 4).

Fatigue of railroad bridges is a well-investigated subject; ties on bridges are probably exposed to an even more demanding fatigue environment but have received less attention. What consideration has been given relates mainly to prestressing tendons for which theoretical studies are well established. In practice, fatigue of tendons is not a problem in countries such as Britain and South Africa with a long experience with pretensioned concrete ties.

Concrete fatigue must be considered because the concrete tie is subject to significant stress changes up to about 2000 Hz. This is much higher than occurs in other prestressed concrete units, and there are no published data on the fatigue behavior of concrete under such conditions. One approach is to design

TABLE 3 COMPARISON OF DIMENSIONS OF TIES DESIGNED TO AREA REQUIREMENTS WITH THOSE USED ELSEWHERE

Tie Type	Length (in.)	Base Width (in.)	Height at Rail Seat (in.)	Approximate Weight (lb)
RT7SS2 (NE Corridor)	102	11	9 1/2	780
CC365 (design to AREA Chapter 10)	102	11	9 3/8	780
CN60B (CN Rail) BN100 (BN Rail)	99	10 3/8	8	630
Hammersley iron	102	10 3/8	8 1/8	650
F27AS (British Rail)	99	10 3/8	8	640
B70 (Deutsche Bundesbahn)	102	11 3/4	8	600

TABLE 4 COMPARISON OF PROPERTIES OF TIES

Tie Type	Prestress at Unloaded Rail Seat (psi)		Resistance Moments (in.-kips)		
			Rail Seat		
	Top	Bottom	Positive	Negative	Center Negative
RT7SS2	550	1,180	310	200	210
CC365	400	1,630	360	170	200
CN60B	630	1,750	260	140	160
Hammersley Iron	130	2,190	320	90	120
F27AS	750	1,760	270	150	170

on the basis that the characteristic loading shall induce no tension in the concrete and that known abnormal loads do not exceed an assumed fatigue limit for tensile stress of, say, 50 percent of ultimate.

The AREA specification includes a rail seat repeated-loading test on ties, but this test requires the tie to first be cracked by a static load so that it is really a check on the fatigue behavior of the prestressing tendons and their bond to the concrete. These properties can be more simply examined in other ways.

Scott (*20*) has applied the test to uncracked ties and obtained useful data on the incidence and propagation of microcracks. The Battelle impact test provides the basis of a test to measure the response of a tie to impact loading. By combining impact and static loading and measuring the strain in the tie, useful data can be obtained.

For design development work, in-track testing, despite the difficulties involved, is really unavoidable. In the past, visual observation of the ability to survive has been the main criterion, but with modern electronic data logging and strain measurement and computer analysis equipment, significant information can be obtained from quite short periods in track.

The prestressed concrete tie is a unique concrete unit in that it has the maximum load applied close to the end. This demands much more rigorous process quality control and finished product testing than are normally applied to pre-tensioned concrete products.

TRACK MAINTENANCE

Improved material components may have higher initial cost, but the cost of materials is typically only about 25 percent of total maintenance costs. There is great potential for using more durable, albeit more expensive, components and installing them more efficiently. Accurate cost data and analysis can help to justify this development (*21*).

Concrete ties will not perform satisfactorily if interspersed in wood-tie track because their higher modulus and more secure fasteners mean that they receive a disproportionate part of the load. Therefore they must be installed out of face.

The modern track renewal machines are an extremely efficient means of tie and rail replacement. When combined with thorough undercutting, the renewed track is much higher quality than can be achieved by traditional spot replacement.

EFFECT OF EQUIPMENT

In previous sections, emphasis has been placed on the damage or, more correctly, rapid wear caused by impact loading from equipment.

Unevenness (wheel burns, shelling, corrugations, etc.) and discontinuities in the railhead will result in accelerated wear. The rail joint, which is fortunately becoming a thing of the past, is the classic example of the wear and tear resulting from impact loading. However, such rail-induced impacts are discrete whereas the impact loading from equipment (e.g., wheel irregularities) is continuous over the track traversed.

Railhead defects are partly induced by high contact stresses as well as wheel irregularities, and the effect of wheel irregularities can be exacerbated by suspension design (*22*). It has been observed that the highest stresses in concrete ties are caused by out-of-round wheels that are not readily detected by conventional inspection of wheels. High tie stresses will also be accompanied by high rail stresses, and there must be a reaction in the equipment wheel bearings. The emphasis that has been placed on impact effects must not completely overshadow the effect of equipment on quasi-static loads. Scott (*23*) found that, in a specific case of rapid track deterioration, locomotive wheel configuration, car wheel bearing design, and wheel profile all had significant effects. There is thus a good case for improvement in equipment design and maintenance for the sake of decreasing wear and tear on the equipment as well as the track.

To find the cars that have a potentially destructive effect on track, a wheel flat detector has been developed (*17*) that measures strain in the web of the rail. Scott (*10*) has estimated that 0.75 to 1.0 percent of wheels have defects potentially damaging to track, so the incidence of this problem is enormous.

CONCLUSIONS

In this selective discussion of track components, those items for which advances in design can readily be made have been identified. A particular case is the use of concrete ties and elastic fasteners to replace the cut spike and rail anchor. Such a change would also require out-of-face track renewal, which would justify the use of more sophisticated and efficient track maintenance equipment.

These potential changes emphasize the need to consider changing from track that has relatively low initial cost and high maintenance to track that has slightly higher initial investment, which pays off in reduced maintenance and less downtime. This change was effectively applied to locomotives 40 years ago, but the equipment designer needs to take more account of the effect of locomotives and cars on track deterioration.

Improved train control methods may well permit more trains on each track with the resulting need for more track maintenance and less time to do it. Better-engineered track is necessary to enable the roadmaster to live with this development.

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