CONCLUSIONS

1. In static triaxial compression tests, ballast breakdown is only slightly affected by cell pressure and is closely related to the factor of safety.

2. In repeated-load triaxial compression tests, the breakdown of ballast is related to the fraction of the failure stress used, rather than to the confining stress. Higher shear strength means less breakdown.

3. Factors one and two may be associated with broader ties and a smaller ratio of tie spacing to tie breadth.

4. Cycling the stress causes ballast to become stiffer, which confirms the practice of using train loads to further compact ballast in track.

5. The extension tests tended to confirm the results of the compression tests; however, failure was observed in the repeated-load extension tests. The number of loadings required to cause failure in the extension tests decreased as the fraction of the deviator stress used increased. The repeated-load failure in the extension tests is important with regard to track stability. There appeared to be a fatigue limit of about one-half the static failure for the dolomite tested.

6. The results of the small-scale model tests reinforce the conclusion that broader ties should perform better than narrow ones in minimizing plastic deformations.

7. The footing rebounds measured suggest that, because of repeated loading, a broader footing should produce a marginally higher foundation stiffness.

8. The plastic deformation of a footing on Ottawa sand subjected to repeated loading has been quantified by using a hyperbolic equation.

9. After parameters for the quantification of plastic deformation of different ballast materials have been obtained, then a design methodology for track maintenance (in terms of plastic deformation) can be formulated.

10. The full-scale model tests indicated that equilibrium in terms of zero plastic strain at the interface of the tie and the ballast is never reached. The displacement is not uniform across the tie. The settlements under the rails are greater than those at the tie centerline. This leads to a center binding phenomenon, the ultimate result of which is fatigue failure of the tie at or near its midpoint. To counteract this phenomenon, tie geometry and dimensions could be changed to encourage a more uniform displacement. The advent of synthetic ties that more readily lend themselves to nonuniform shapes may make such changes practical. Further full-scale testing of ties of various geometries would be a potentially fruitful course of action.

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Track Structure Systems

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The railway track-system concept is a way of looking at things that takes into account secondary and tertiary effects in the totality of cause and effect. A track system is not simply a collection of curves, tangents, switches, frogs, turnouts, crossings, and crossovers, but includes the interrelations among the various components—the rails, ties, ballast, fasteners, and subgrade. One of the earliest railway engineers to employ system thinking was Robert L. Stevens of New Jersey, who in 1830 conceived the flat-bottomed-tee rail and the first cut spikes and joint bars. Later, he evolved the idea of wooden crossties. He single-handedly developed the basic system of mutually complimentary components used in railroad trackage today. The next system thinker to have a profound influence on track technology in North America was Arthur N. Talbot of the University of Illinois, who developed the concept of the modulus of elastic track support, first reported in 1918. This was a quantifiable response to load of ties, ballast, fasteners, and subgrade material that can be used to predict track deformation under vertical load. The Stevens' legacy was a system design of railway track, and Talbot's contribution was a system analysis of track structure. Talbot also left a challenge because, while track performance can be predicted when the modulus is known, how to design to a modulus has not yet been learned. The rate of return on incremental investment in individual track components can be determined only by full-scale experiments. The new full-scale laboratory the Association of American Railroads is building in Chicago should bring about validation of mathematical models of track that are being developed.

This new laboratory will permit applications of calibrated loads to full-scale test sections of track, and the resulting deformations and stresses can be measured. The really important system is not the track system nor the equipment system, but the train-and-track system. An example of train-and-track system thinking occurred in 1934 when the Pennsylvania Railroad chose the GG-1 locomotive over its competitor because of lower wheel and axle loadings. Technical decisions must be influenced by economic and political factors, and track systems are no exception. An example today is the question of proper superelevation on curves, and the answer depends in part on the kind and amount of intercity rail passenger service that will be provided, which is a political question. Even more significant is the question of right-of-way ownership. Would a private company choose a lower axle-load locomotive if it were to be operated over track the company did not own?

The phrase railway track system has a rather nice ring to it and will probably be in use long enough for us to spend a little time discussing it in an attempt to at least avoid semantic confusion.

The simple word system has been part of our language for a long time, but it seems to have come into concentrated use (if not confused overuse and misuse) with the advent of computer technology. It was in the middle 1960s that it became the prefix to all passwords to technical acceptance, and system approach was surely the most popular of these passwords. To gain acceptance, nearly every proposal then, and to some degree today, had to call attention to the system approach used by its proponents.

This apparently new technique represents a very sound and realistic approach to technological problems; however, it is not at all unlike the approach formerly described as the engineering approach. The point I am trying to make here is that, regardless of what we choose to call it, the system approach is simply a concept, a way of looking at things that we hope takes aspects of a situation into account that at first may not be readily apparent, but that are none the less important. Thus, secondary and tertiary effects are to be considered in the totality of causes and effects. The concept is important. The words we use to describe it are much less so. Words are words, concepts are concepts, and the relation between them is not necessarily one-to-one. New words and terms do not, of and by themselves, represent new concepts.

I frequently find myself amused or even annoyed at those who redress good but older ideas in new clothes and present them as progress. But, so be it. If changing the dress code of semantics helps in the understanding and acceptance of useful ideas, then the process is for a good cause, even if it contributes to some confusion.

Thus, we come to the concept of railway track as a system. If you had asked me in 1955 to describe a track system, I would have responded with little hesitation that it was a collection of curves, tangents, switches, frogs, turnouts, crossings, and crossovers making up a network suitable for the conduct of rail transport. Today, while not incorrect, such an answer would be incomplete. That description of a track system is analogous to a plan view; in the language of a draftsman, the side and front elevations are missing. The interrelations among the various components—the rails, ties, ballast, fasteners, and subgrade—are of equal interest.

One of the earliest railway engineers to employ systems thinking in the area of railway track was Robert L. Stevens of New Jersey, the son of Colonel John Stevens. Robert Stevens was the president and builder of the Camden and Amboy Railroad and Transportation Company, which became an important link in the northeast corridor in the 1830s and 1840s. At that time, travel between Washington, New York City, and Boston was largely intermodal (yet another new term for a rather old concept).

The overland portion across New Jersey was slow and burdensome in comparison with travel on the natural waterways of the Chesapeake and Raritan bays, the Delaware River, and Long Island Sound. Many canals were proposed, and many were built to connect natural waterways. But the successes of the Stockton and Darlington Railway of England attracted considerable attention and led to proposals for railroads as alternatives to canals. In particular, the Camden and Amboy was chartered at the same time as the Delaware and Raritan Canal, which had been first proposed in 1804. In 1830, Robert Stevens traveled to England to purchase iron rail and a steam locomotive for use on the Camden and Amboy. During his crossing of the Atlantic, Stevens considered the question of rail and fastenings. While carving out of wood, a section of Birkinshaw rail, such as was popular in England, and which had only a head and a base, he conceived the classic flat-bottomed-tee rail now in general use throughout the world. Had he stopped here, his accomplishment would have been significant, but he did not. Stevens went on to design the first cut or hook spikes and the fishplates or joint bars, as we now know them, to join the rails together. In England, Stevens induced a reluctant supplier to roll his oddly shaped rails and negotiated the purchase of the John Bull locomotive from Robert Stephenson. This locomotive is now in Washington at the Smithsonian Institution. Construction of the Camden and Amboy proceeded; the portion between South Amboy and Bordentown receiving the highest priority because it connected steamer lines operating to and from Philadelphia and New York City. The track construction involved spiking the iron rails to wooden plugs that were driven into holes drilled in large stone blocks. This type of track work was also used on portions of the Baltimore and Ohio Railroad and the level portions of the state of Pennsylvania Public Works rail crossing of the Allegheny Mountains. The stone blocks for use in the Camden and Amboy line were shipped from their source at Sing Sing Prison on the east shore of the Hudson River above New York. It had been hoped to complete the line to Bordentown before work stopped for the winter in 1832, but the slow delivery of the stone blocks was an obstacle to this goal. Stevens then came to the idea of placing logs crosswise to the track and spiking the rails directly onto them. The result was not only efficient and economical of materials, but also a vastly improved track structure. The crossties or sleepers distributed the rail load as did the stone blocks and also maintained the gauge and held the rails in a common plane as the blocks did not. Thus, Stevens single-handedly developed the basic system of mutually complimentary components that with many refinements of materials and detail design makes up the largest part of worldwide railway trackage even today.

The next systems thinker to have a profound influence on track technology in North America did not come along for nearly 100 years. Advances were made in individual components—steel replaced iron for rails, tie plates were introduced, and wood preserving extended crosstie life—and such progress continues today. But it was not until Arthur N. Talbot of the University of Illinois addressed the subject of railway track performance in his report on stresses in track published in 1918 that an understanding of the track response as a system was evolved. Talbot, working with and for the American Society of Civil Engineers and the American Railway Engineering Association, developed the concept of the modulus of elastic track support. This was a single quantifiable term that grouped the response to load of ties, ballast, fastenings, and subgrade material. Together with the geometric and material properties of the rail, it could be used to predict the manner in which a track would deform under vertical loading and what stresses would be developed in resisting the load.

If Stevens' legacy was a systems design of railway track, then Talbot's contribution was to teach us how to perform a system analysis of a track structure. But Talbot left us a challange as well. While we can predict the performance of a track rather well after we have determined its modulus, we have not yet learned how to design to a modulus or to make the economic trade-offs between components that Talbot's analysis makes possible. We know, for example, that larger ties or more ties per length of rail increase track modulus. We also know that increased depth of ballast increases track modulus. By using Talbot's equations, we can compare the effectiveness of any of these increases in track modulus with changes in the moment of inertia of the rail section in reducing track deflection under load, flexure stress in the rail, or rolling resistance to trains. But we cannot yet determine the rate of return on incremental investment in individual track components in a reliable, convenient way, except by full-scale experiments. Nor do we even know what degree of track stiffness is optimal for specified levels of traffic and wheel loadings.

The new full-scale track laboratory the AAR is building in Chicago should enable us to validate the several track models that are being developed. This new facility will permit applications of carefully calibrated loads to full-scale test sections of track and detailed measurements of the resulting deformations and stresses. It is particularly important that the track configuration, rail section, tie spacing, and ballast depth and material can be altered, and the entire structure can be compacted under simulated traffic. The data produced can be used, among other things, to calibrate and validate the new track models, which in turn can suggest detailed track configurations for evaluation amd comparison. At last, we may be able to determine the most economical fashion to achieve a given track modulus.

I would like to turn at this point to some comparatively more recent railway engineering history that would seem, but is not, unrelated to the subject of track systems. That is the development of one of the most successful locomotive designs of all time—the class GG-1 electric of the former Pennsylvania Railroad. This locomotive was developed between 1933 and 1935, and 139 units were built between 1934 and 1943. Of these, about 100 are still in service, long after locomotives 20 years newer have been retired. The single-locomotive unit was measured to have developed 6.95 MW rail power (9300 hp), equivalent to 8.21 MW diesel-electric power (11 000 hp). It accelerated from 0 to 160 km/h (0 to 100 mph) in 64.5 s. In 1942, the GG-1 fleet regularly hauled 416 passenger trains/d. Typically these trains were 18 cars long and covered the distance from New York to Washington [326 km (226 miles)] in 215 min including five station stops.

What does this have to do with track systems? It has to do with the only system that is really important—not the equipment system, not the track system—but the train-and-track system. Historically, track has been the concern of civil engineers, and equipment has been the prerogative of mechanical and electrical engineers. Railroad managements did little to correct the separation begun in universities by grouping the civil engineering track people in engineering departments and the mechanical engineering equipment people in mechanical departments. Fortunately, both groups were responsible to one operating vice president and sometimes the system worked to the common good.

It worked exceedingly well in 1933 on the Pennsylvania Railroad. The GG-1 prototype, locomotive 4900, was one of several designs being considered for the expansion of the electric locomotive fleet. Among its competitors was locomotive 4800, representing class R-1, which was even more powerful. In 1934, both prototypes were taken to Claymont, Delaware, where comparative tests were to be run on a test track that included 300 instrumented steel crossties. The GG-1 design was selected despite its somewhat lower power and anticipated greater maintenance cost (it had 12 motors to the 8 of the R-1 and included an articulated frame). The GG-1 was chosen because it produced lower track stress, especially lateral loads.

In 1934, the Pennsylvania Railroad had the strongest and best track in the world, especially in the territory to be served by the new electric locomotives. The standard track consisted of 45.7 cm (18 in) of crushed granite trap-rock ballast on top of 30.5 cm (12 in) of cinder subballast, 17.8 mm by 2.59 m (7 in by 8.5 ft) crossties laid at 49.5 cm (19.5 in) spacing, and 76-kg/m (152-lb/yd) rail laid in 39.3-cm (15.5-in) tie plates. Thus, it was not the kind of track that might collapse under the loading of the R-1 (the R-1 prototype was renumbered to 4999 and used until 1958 in regular service). The GG-1 was selected over the R-1 because its lower axle loadings and lower dynamic lateral loads would contribute to a lower total cost of the track-and-train system. It was not chosen, as have been some more recent designs, because of high axle and lateral loads that were below some arbitrary standard. It is more than significant that a locomotive chosen for use on the best possible trackage weighed over 220 Mg (200 tons) but had a maximum wheel load of only about 11 300 kg (25 000 lb) and this on 1.42-m (56-in) diameter driving wheels. This is a very favorable ratio of less than 8900-kg/m (500-lb/in) wheel diameter.

Finally, let us spend a few moments to consider how the concept of system engineering as applied to track-structure systems or to track-and-train systems leads us into other areas, particularly those of economic and political concern. Specifically, let us explore the way systems thinking about track and trains should influence our economic and political perspectives on the railroad industry.

Some will say that, as technologists and engineers, we should not be concerned about such things, that we have more than enough to do to keep freight and passenger trains on the rails and on time. I disagree and strongly so. There are important interactions between political, technical, and economic issues. The way technologists react to the political and macroeconomic issues the industry faces will be relevant to whether or not we are able to deal effectively with what may appear to be purely technical problems.

It is the political and economic climate that provides the basis for reference in which technology must guide itself. Technical decisions must frequently be made because of political pressures but, if they are made on a basis of improper or poor appreciation of the political or economic issues at hand, they will be just as wrong as if they were made on a basis of poor technical data.

One small example among the difficult technical track problems we face today relates to the proper superelevation on curves. The answer, however, depends in part on the kind and amount of intercity passenger service the industry is going to provide, and that is a political question. I, for one, do not think that intercity passenger trains will be eliminated, regardless of their economics. But, the answer to this question is one on which track-system people base important technical decisions every day.

Even more significant is the question of right-of-way ownership. Some transportation planners have advocated, as a solution to the problem of nonequal treatment of transportation modes by government, a system in which railroad rights-of-way would be publicly owned, as are highways, but the private sector would own and operate the trains in a manner analogous to the trucking or barge companies. Considered only as a political question, this proposal has some significant appeal. But, when the subject is considered from the systems perspective and the secondary technological effects are evaluated, some rather serious questions arise. For example, Would a private company choose a GG-1 locomotive in preference to an R-1 to operate over trackage it did not own and need not maintain? The private railroads have made errors with respect to track-and-train system compatibility, but these errors have probably not been as numerous or as serious as they would have been without the incentives that common ownership and responsibility provide.

Combinations of public and private ownership and enterprise have considerable appeal today. Their advocates tell us that they combine the private enterprise incentive with public responsibility—but in this case, I am afraid that the limitation to system thinking imposed by the separation of track responsibility from equipment responsibility is too high a price.

Railroads are excellent examples of industrial systems. They include a variety of mutually dependent organizational and technical subgroups that make up a unified whole. In fact, many railroads historically included the word system in their corporate title. Track, the fundamental subgroup of a railroad system, is a system itself. But, systems thinking can lead us into trouble in such a complex environment as railroading by setting the limits of the system under consideration either too narrow to include all the essentials or so broad as to be incomprehensible, and either can lead to disastrous consequences. The really successful system engineer is the one who knows, guesses, intuitively understands, and sets the appropriate limits to the system analysis required by the specific problem. In this respect, track systems are no different from any other kind—they still require qualitative, personal judgment.

Problems and Needs in Tie and Fastener Research

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The advantages of the timber crosstie—relatively low cost; traditional ready availability; toughness, resilience, and strength; allowance for a flexible system of support; relatively long useful life; and availability of a relatively inexpensive fastening system—are compared with its disadvantages—increasing cost; decreasing availability; economic relation to competing demands for timber; suitability for increased train lengths, equipment configurations, and wheel loads; and availability of satisfactory substitutes. Similarly, the advantages of the crosstie fastening system used in North America—relatively low cost, ease of application, satisfactory service for many years, and flexibility of tie loading—are compared with its disadvantages—selective loading of individual ties and mechanical wear in the tie plate and spike holes. Areas for research suggested by the disadvantages are enumerated.

Since the early nineteenth century, after brief experiments with longitudinal support in various forms involving the use of timber, stones, and other materials, American railroads have used the timber crosstie to transmit wheel loads through the rails to the subgrade. At first this was done directly, but then as loads and speeds increased, selected materials were applied as ballast and subballast to assist in maintaining the line and the surface of the track and to facilitate drainage.

During this period, extending for more than 140 years, the solid timber crosstie has served North American railroads well. It represents a considerable improvement over the longitudinal support system used on the earliest roads. The discrete support of the rail and loading of the ballast and subsoil provides a flexible means of load distribution that is highly desirable.

An interesting discussion of the development of stress analysis in rails and ties using this loading system is given by Kerr (1).

As loads have increased, the physical aspects of the crosstie and its use have undergone changes, generally of minor and apparent natures. The length has varied, first with the gauge of the track, and then with the load. Current North American practice uses tie lengths of 2.59 to 2.74 m (8.5 to 9 ft). The size of the tie has been standardized for many years at 17.8 by 22.9 cm (7 by 9 in) for the largest recommended size. Tie spacing, center to center, has varied from about 1.83 m (6 ft) in the earliest practice to the 48.3 to 50.8 cm (19 to 20 in) commonly used in current heavy-duty main tracks.

During this period of time, at least on the North American continent, the timber crosstie has withstood competition from other materials and methods of support. Among its advantages are that

1. It is relatively inexpensive;
2. It was for many years generally in adequate supply, and the raw materials were widely distributed over the continent;
3. It offers excellent physical characteristics of toughness, resilience, and strength in the most favored species;
4. It provides a desirable discretely flexible system of support that allows inexpensive correction of deviations in line and surface;
5. When properly treated with readily available preservatives, it has a relatively long useful life, and
6. The current North American fastening system, involving the cut spike, a steel tie plate, and base anchors is relatively inexpensive and easily applied.

On the other hand, there are new factors that make it desirable to reexamine the function and role of the timber crosstie in terms of changed conditions of service and