made of the small travel by providing a rectangular-shaped hysteresis loop.

The soft and mid settings were used on the shock absorber, the hysteresis loop deviated from the rectangular shape and tended to approach a shape more typical of viscous damping. Although the shock absorber developed high damping forces at these settings, the high forces were not available for the full travel. The absorbers only became effective when relatively large motion was already present and were of little use for small roll angles.

The result is the apparent anomaly that a shock absorber on the soft setting dissipates as much or more energy per cycle as a shock absorber on the hard setting. It must be remembered however, that in the example given, the shock absorber maintained a maximum moment ratio of 0.74 and roll angle of 4 deg on the hard setting and allowed for values of 1.19 and 7 deg, respectively, on the soft setting.

Future Work

It would be desirable if meaningful generalizations could be made regarding the requirements of hydraulic shock absorbers. Much more empirical data is required before this can be attempted, and to this end the Canadian National plans to continue the investigation of hydraulic damping in detail. Specifically, absorbers will be tried across the main springs and between the side frame and car body for trucks with 2 1/2-in. and 3 1/2-in. travel springs.

Test work will be carried out on curved track with superelevation as well as on straight track. In addition, tests will be run to evaluate the influence of promising modifications throughout the full operating speed range.

While test work is time-consuming and expensive, it is desirable that proprietary items be tested and evaluated. Other railroads and agencies are presently cooperating in carrying out experimental work. However, a standardized test procedure should be adopted and results should be analyzed in the same way. The criterion presented here could form the basis of a standardized test which would allow results from different sources to be compared directly.

Conclusions

The main purpose of this paper is to introduce a technique of analyzing the roll motion of heavy cars. The moment ratio is presented as being a realistic yardstick which can easily be calculated from measurements which are reasonably simple to make. The moment ratio, as a criterion, can be used for the following purposes:

1. The highest value of the moment ratio can be used as a basis for ranking the effectiveness of various suspension modifications.
2. The speed range over which wheel lift can occur can be determined by examining the relation between train speed and moment ratio. The critical speed is the range within which the moment ratio is greater than one.
3. The number of consecutive track irregularities needed to cause wheel lift can be found by analyzing the buildup of moment ratio throughout the test track. This can be used as a measure of the likelihood of wheel lift occurring in service.
4. Examination of the composition of the stabilizing and overturning moments used to calculate moment ratio can provide information concerning how an improvement was achieved.

Acknowledgments

The following persons assisted the authors in carrying out this work and their contribution is gratefully acknowledged at this time: C. W. Wagner, Engineer of Tests, Maintenance, Transportation and Maintenance; R. Rotter, Assistant Engineer of Tests, Maintenance, Transportation and Maintenance; A. Chareenko, Engineer, Technical Research Branch, Research and Development; D. Lawless, Engineering Assistant, Technical Research Branch, Research and Development.

DISCUSSION

C. E. Tack

The authors are to be commended for their efforts to find a "figure of merit" to judge the effectiveness of devices offered to control the rocking of freight cars on rough track. We believe a satisfactory method to establish such a figure of merit is sorely needed.

The efforts of American Steel Foundries to define a car rocking problem and develop a cure have led us to measure forces and motions which we believe can be effectively added to the proposals made by the authors. Incidentally, we prefer to use the term "rock" instead of "roll" since roll and rollability have been used to indicate car resistance to longitudinal movement on rail.

Rock angle of car body center of gravity is not significant unless correlating lateral displacement of center of gravity is measured simultaneously. A negative or stabilizing moment results if rotation is not simultaneous with lateral translation of center of gravity to the same side. We would like to point out also that rock angle of car body alone is not significant unless certain other rock angles are measured simultaneously. We believe the rock of the side frames (as a pair) and the rock angle of the truck bolster should be known. It is also necessary to know the difference between static track profile and the dynamic profile—for each run. Track resilience enters the picture.

Table 4 will bring this point into focus.

<table>
<thead>
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<th>Table 4</th>
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<tr>
<td>Difference in cross elevation from horizontal, in.</td>
</tr>
<tr>
<td>0.50</td>
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<tr>
<td>0.75</td>
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<td>1.25</td>
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Since the dynamic track conditions have not been included in any of the test reports which have been available to us, we are unable to compare with any confidence the various tests run to date. Should it be decided to publish this paper, Figs. 15 and 16 are used to illustrate this and other points.

Axial force D or D' can be the result of track irregularity, lateral displacement of sprung and unsprung mass, metal-to-metal gib contact on one side with spring and friction shoe on the other, or spring and shoe on both sides to transfer spring mass loads to frames, or the sum of these factors. Force causing lateral displacement of the axle due to wheel tread conicity must be considered.

If forces are measured at each journal (a) axial force D times wheel radius will be one moment, (b) vertical forces at journal bearing G and G' will produce the other two moments, and forces F and F' (if can be calculated) as F' (or F, depending on portion of rock cycle examined) drops to zero or a negative amount, wheel lifting can be expected. (This method has a basic error since the dynamic effect of wheel and axle mass is ignored.) This approach is less complicated to handle than that used by the authors and should give similar results, obviously a figure of merit could be derived. It should be clear from this discussion that horizontal variations from a true tangent on one or both rails could occur to cause wheel lift despite reduced rocking moments resulting from vertical track roughness.

Most important to the car designer and to the designer of suspension systems is the measurement of peak force at A-A', B-B', and C-C'. Similarly, forces at D-D' and E-E' (at the
spring seat) are of interest to assist in evaluating truck side frame structures.

We believe that moment ratio, while very helpful, should not be used exclusively to establish a figure of merit. Reduction in peak forces in the car and truck components are of equal importance.

The following comments are offered for consideration by the authors:

1. The statement is made in the Introduction that 100 ton hopper cars derail at low speeds due to car rocking and the solution requires rock motion to be controlled. Actually, both car rocking and derailment are due to the forces involved and both are effects rather than one being the cause of the other. It is doubtful that modifications to the suspension alone can be successful in all cases. Further, the authors state that severity of rock motion depends upon speed. This is correct if resonant speed is understood; severity is a function of the car configuration as any car will rock at its resonant speed for that mode. It is true that for a given car configuration the severity will be greatest at the resonant speed. There are probably at least two and possibly three resonant speeds for different car rocking modes.

2. The authors have overlooked the necessity for having the test track modified to produce the same dynamic cross elevation for all tests, if these tests are to be reproducible. Use of only static cross-elevation measurements can be a major cause of the many contradictions mentioned by the authors.

3. The statement is made in the Summary of Observation from the first test program that the results of the test can be used for comparison with other sources. This implies that such a comparison could be universally made, but the comparison would be valid for only cars having the same physical characteristics (wheel base, moment of inertia, etc.).

4. The authors very correctly understand that magnitude of wheel lift by itself does not have much significance. The useful parameter is the amount of net force tangent to the surface of the wheel flange and the direction of force relative to the flange.

5. Figs. 4 and 5 are purported to explain the method of calculating the moment ratio. In general, a better approach would be to include all weights and forces (only two wheels are shown, for example) even though the moment due to these may be zero. It would also be desirable when working with moments of this type to establish a coordinate system and consistent sign convention. Unless this is done the chance of error in calculation is extremely high.

6. In the conclusion the authors discuss the use of value of the moment ratio. By definition, if dynamic effects and all static effects are properly included the wheel will be forced to do the following:

   - If is greater than 1—lift must occur.
   - M is less than 1—lift cannot occur.
   - If is equal to 1—the wheel is in neutral equilibrium and anything can happen with a slight change in the force pattern.

   In any event, this is only part of the story. Consider M being equal to zero for a moment. This says that the wheel will remain exactly where it is in space. As long as the track continues in the same relative position the wheel will stay on the rail. The track can, however, fall away from under the wheel causing an apparent lift, or crowd into the flange forcing the flange up the slope of the railhead and forcing the wheel up and over the rail, under the effects of the unbalanced lateral force. The same condition applies for ratios close to a value of one; a short transient shock, such as a wide gap or an uneven joint, can momentarily change the force balance to unstable even though the steady-state condition is relatively stable. Of course, even without wheel lift there is still the possibility of derailment due to excessive lateral force against the railhead.

7. There is a possibility of improving car stability by improving track surface, or by changing rail length and rail joint stagger. These approaches can help, but cannot completely cure the problem. Obviously, reducing the roughness will reduce the input disturbance and thus help in most cases. Change in stagger or rail length will be helpful only for particular car configurations and could easily tend to make “rockers” out of cars which were previously stable.

8. The phrase “to the frequency at which the car body rolls naturally on its springs” suggests that car can be considered independently as an inverted pendulum resting on the truck bolster. It just happens that these two frequencies usually come close to one another. Rocking energy buildup at critical speed is greatest if the critical rock frequency of the inverted pendulum and the critical rock frequency of the sprung mass are the same and are in phase.

9. In the discussion of Table 3 the authors state that performance, judged by wheel lift alone, would be misleading. Presumably this is based on the fact that both moment ratio and rock angle for both of the runs were approximately the same. This could be due to the neglect of unsprung mass inertial effects and the fact that the same apparent rock angle can be sensed with completely different force relationships. Incidentally, the difference between a ratio of 1.02 and one of 1.03 is probably not sig-
significant either. Experimental error and approximations could cause both of these ratio values to differ by at least several percent.

10 The authors mention a phenomenon in which motion builds up, decays, and builds up again, and ascribes this to a discontinuity in the forcing function when the wheel lifts off the rail. Another likely cause could be a “beating” between the several modes of vibration present at that speed. The amplitude of the rail forcing function, and the energy input, may be changed when the wheel leaves the rail but this would not change the forcing frequency or damp the oscillation. The wheel is not off the rail long enough for this to have any effect. In fact, it might aggravate the situation because of larger wheel motion amplitude.

H. B. Weber

First of all, my congratulations to the authors for the very fine paper, "A Criterion for the Control of 100 Ton Hopper Car Roll Motion."

This paper introduces a method of comparing and evaluating the relative roll performance of a car or cars on which suspension parameters are changed. In other words, it compares and evaluates the effects of changes made to the truck suspensions.

Having lived through the experience of trying to come up with meaningful conclusions from results of several different tests, I am of the opinion that the proposed method is, until now, the best way offered for an objective evaluation. In addition to reducing the amount of subjective interpretation, or should we call it, at times, wishful thinking, the proposed evaluation provides a lot of insight in regard to the dynamics and forces which actually cause the wheel unloading and instability of the car.

I would like to express a difference of opinion in regard to the following statement made by the authors, "The control which is needed to limit the roll motion can be achieved by appropriate modifications to the suspension system." Only tests over level track have been made and evaluated, according to the paper. The detrimental effect of superelevation in regard to reduction of reserve deflection of the load springs on the low side, and the unloading of the wheels on the high rail have to be investigated and analyzed with the same method before such a conclusion can be made.

Otherwise, the conclusions drawn can certainly be accepted without further comments and the anticipated future work is certainly recommendable. This work will result in obtaining a better knowledge and understanding of the complex problem and will help in finding a solution.

It is recommended that this method of analysis be seriously considered in other future car and truck roles, especially in the forthcoming tests where the AAR will evaluate devices for approval in interchange service on the basis of their performance.

Authors' Closure

Many of the observations made by Mr. Tack in his discussion illustrate that in some respects the paper was not sufficiently precise. Mr. Tack has emphasized that the track "dynamic" profile must be maintained to a known cross level. In fact, control was maintained over the "dynamic" profile during all the tests by measuring the track surface while the test train passed over the track at or near the critical speed. It is essential in experimental work of this type to measure and maintain the track profile under load, since this is the profile actually seen by the wheels as a displacement input. Table 2 and Fig. 9 of the paper illustrate the importance of the profile as an input to the system.

We are grateful to Mr. Tack for his comments regarding an alternate analysis which also makes use of the measured forces and moments. As he states, if the wheel load drops to zero or becomes negative, wheel lift will occur and the magnitude of the negative wheel load can be used as a measure of instability. We have analyzed data in this form and have found it to be useful. If a rail-wheel reaction force \( W \) is considered to be acting vertically at the wheel which can lift (see Fig. 4), then it will contribute a moment. Taking moments about the point of rotation and equating the stabilizing moments to the overturning moments, we get:

\[
W = 11L_1 - 11 \times 900 - 21L_4 - 21L_3 - (28 \times 5510) - 36 \times 1300 - 67 \times 900 - 67V_2
\]

Mr. Tack is concerned with lateral motion as well as the roll angle and he makes reference to the idea that lateral forces, due to wheel tread conicity and the effects of horizontal track irregularities, should be considered. We do not believe this has a significant influence at low speeds, as lateral instability due to tread conicity, etc., is a self-excited vibration problem occurring at high speeds.

The rolling or rocking of the car body occurs at a natural frequency when the car is moving at the critical speed. When this occurs, the mode consists of a rotational motion coupled with a lateral motion. There are, therefore, at least two natural frequencies and therefore two critical speeds at which the car can rock, but we believe only one will be in the frequency range capable of being excited violently.

Comment 3 by Mr. Tack is well taken. Comparison of different cars on the basis of roll angle and wheel lift can be misleading. This is discussed under the heading "Summary of Observations from the First Test Program." However, we do not agree with the statements contained in Comment 8. As stated above, the lateral displacement and roll angle comprise a mode and as such, must occur at the same frequency, and are therefore in phase. The phase shift evident in Fig. 2 arises from the fact that the lateral displacement was obtained by a double integration of an acceleration signal. In order to achieve this integration, a filter and "roll-off" had to be employed which caused the apparent phase shift. We must also disagree with the statement contained as Comment 10—the explanation given in the paper is more likely.

Finally, we think Mr. Tack is correct when he implies that the moment ratio must be used with judgment and discretion. It is, as we have said, only a yardstick which can help in achieving an understanding of the mechanics of the vibration. Like all yardsticks, it must be graduated, and in this case the graduations are based on a rail "dynamic" profile of \( \gamma/4 \) in. cross level. If moment ratios are to be compared, it is important that they reflect results obtained with identical rail profiles.

We appreciate the comments of Mr. Weber. He is quite right to point out that additional test work is warranted before definite solutions can be specified. However, we feel that the most realistic approach to the problem is to evaluate the effectiveness of energy-absorbing devices incorporated as part of the suspension system, and we believe that our results to date are encouraging in this regard.