PB85 173706 AAS

May 1984
Final Report

DOT/FRA/ORD-84/10

OR+D FILE 7007

U.S. Department
of Transportation
**Federal Railroad
Administration**

Assessment of Radial Truck Safety Performance Data

Office of Research
and Development
Washington, D.C. 20590

S. Shladover
Systems Control Technology, Inc.
1801 Page Mill Road
Palo Alto, California 94303

12 - Safety

Technical Report Documentation Page

1. Report No. FRA/OR&D-84/10	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Assessment of Radial Truck Safety Performance Data

5. Report Date
May 1984

6. Performing Organization Code
5381-A00

7. Author(s)
Steven E. Shladover

8. Performing Organization Report No.

9. Performing Organization Name and Address
Systems Control Technology, Inc.
1801 Page Mill Road
Palo Alto, CA 94304

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT-FR-9050

12. Sponsoring Agency Name and Address
Federal Railroad Administration
Office of Research and Development
400 Seventh Street, S.W.
Washington, DC 20590

13. Type of Report and Period Covered
Final
May 1983 - May 1984

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The available test data collected on radial freight trucks has been reviewed and evaluated for possible future use in establishing the safety performance characteristics of these trucks. Documentation of tests conducted by the railroads, equipment suppliers, FRA and AAR is reviewed to determine what safety related issues involving radial trucks can be addressed using the test results. These are then compared with the full spectrum of data which would be needed to provide a comprehensive evaluation of radial truck safety. The gaps in the available data are identified and used as the basis for defining additional testing needs. Recommendations are presented for a new truck safety performance evaluation program, which would include extensive testing on radial trucks of diverse design. The basic outlines of that test program are suggested, including the selection of trucks for testing, the operating conditions to be included and the instrumentation required.

17. Key Words
Freight car trucks
Radial trucks
Rail vehicle testing

18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 53	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

CHAPTER I - INTRODUCTION

In recent years, considerable effort has been expended within the railroad and railroad equipment supply industries on the development of new truck designs. This effort has been motivated by the need to improve on a variety of aspects of truck performance, including reduction of wear of both wheels and rail, especially on curves, the reduction of rolling resistance to improve fuel economy, enhancement of stability for use at higher speeds and elimination of behavior which could lead to derailments. Increased use of unit trains for specialized movements of certain commodities has also motivated the development of some more specialized truck designs. These include the extra heavy duty 100-ton trucks for bulk commodity trains (especially coal) which operate on captive routings with considerable track curvature and both single-axle trucks and conventional trucks with articulation joints for use with the new generation of intermodal cars having single and multiple platforms respectively. The rapid changes which have been occurring within the railroad industry during the past few years increase the probability that more and more of the new truck types will be entering the active fleet in the coming years.

Considerable testing has been conducted on innovative trucks in recent years. Some of this testing has been performed overseas and some in the United States, by railroads, equipment suppliers and by universities and private research organizations with the support of the FRA and AAR. These tests have been conducted on many different truck types, under different test conditions, with the recording of different measurements and all for different purposes. This diversity of testing makes it difficult to compare results or to use them in conjunction with each other. Each test program has in its own way enhanced understanding of the characteristics of unconventional trucks, but there does not appear to be much synergism among these diverse test programs. In other words, there may not be a great deal to be gained by attempting to combine the results of several test programs, beyond the simple summation of the results of those programs. The whole may not be greater than the sum of its parts.

One of the principal goals of the present investigation has been to seek ways in which the existing sets of radial truck test data can be combined to form a common data base upon which future testing efforts can be built. The results of those prior tests will be discussed in Chapter 2. Important results have been gained from those tests, which have increased knowledge in certain specific areas. However, substantial gaps remain in our understanding of aspects of radial truck performance which were not treated by the earlier test programs because they were not relevant to the purposes of those tests or were too difficult to treat adequately. Those gaps which need to be filled by further work under the FRA Truck Safety Performance Evaluation Program will be discussed in Chapter 3.

1.1 GENERAL GOALS

A new truck test program must be directed at answering the questions which have not already been answered by other test programs in order to make most efficient use of the available resources. The mandate of the FRA to focus on safety-related issues helps to further define the scope of the new test program. Within these general constraints, however, there are still many possible directions in which a test program could proceed. The planning for such a test program must be based upon a clear statement of goals, or a definition of the purposes which the tests are intended to serve. A portion of the present work has been devoted to considering what goals should be addressed by a new test program in order to make the most valuable contribution to improving the safety of radial and other new-generation trucks.

The best starting point appears to be identifying the differences in safety performance between the conventional and the innovative truck designs (radials and others). This may include both advantages and disadvantages of the new trucks, because there is evidence that both could be found. Such differences, once defined, could indicate the need for adjustments to some of the FRA safety regulations. Depending upon the differences which are found, this could lead to recommendations for either the loosening or the tightening of some regulations.

Because radial trucks contain special components which are not found on conventional trucks, it is important that the loads imposed on these components be thoroughly understood. The existing body of test data includes virtually no information about the loads which these special structural members (steering arms, cross links, etc.) experience. The designers of new trucks need this information in order to ensure that their trucks can survive all anticipated operating conditions without suffering structural failures. It is particularly important that the low-cycle and high-cycle fatigue environments of special truck components be understood so that the manufacturers can ensure long and safe operating lives.

Although truck components have traditionally been very robust and rarely prone to catastrophic structural failure, that was because the design philosophy did not include minimization of weight as a goal. This has changed dramatically with the rise in fuel prices and the eagerness of the railroads to maximize the weight of payload which they can carry in each car. There is great pressure on the truck suppliers to minimize weight now, particularly for radial trucks with their extra components. This means that truck designs will now have to be less generous in their use of metal than ever before. That places the burden on the designer to reduce the safety margins in the design, which in turn means that he must have a much more accurate knowledge of the loads which his equipment will experience.

An overriding principle which should be applied to the new truck test program is the development of generic results which can be applied to many truck designs, and not only to the specific trucks which were tested. This is not easy to accomplish because it requires very careful control of experimental conditions, very precise measurements and a large number of test cases. The existing sets of truck test data collected by the railroads and equipment suppliers have been very specific investigations of the performance of individual trucks and have not been directed at revealing the underlying physics which make the trucks perform as they do. The government-supported tests have on the other hand attempted to develop results which could be generalized to other cases, although not always successfully. A commitment to the collection of comprehensive test data which can be applied beyond the limited set of trucks tested is essential to ensure that the test results will continue to be of use to the railroad industry over a reasonable period of years. This principle is developed at greater length in Chapter 4, which contains recommended requirements for a new truck test program.

CHAPTER II - REVIEW OF EXISTING RADIAL TRUCK TEST DATA

In the years since 1976, there has been considerable testing of radial freight trucks conducted under a variety of auspices. Each test program has had its own goals and emphases, and there has been little if any attempt to coordinate these test programs. The available published references on this testing have been reviewed and further information has been sought from the organizations which have performed the tests in order to fill gaps in the published documentation. This has included telephone discussions with cognizant personnel and acquisition of additional unpublished documentation. This review is believed to have covered all of the radial truck test programs which could possibly contribute to a common data base on radial truck performance.

The truck test programs have by and large been designed to serve some very specific purposes, which means that they have produced results which are focused on answering some very limited questions about specific trucks rather than leading to enlightenment about broader questions of the performance under diverse operating conditions of trucks of different designs. This is an important issue which must be kept in mind when designing a new truck test program and it bears some additional explanation before reviewing the existing test data.

2.1 PURPOSES OF TESTING

Each test program has its purpose, and the range of test conditions and instrumentation must be chosen so as to satisfy that purpose. Because of the cost of testing, it is rare for test results to be found applicable to purposes broader than or different from those which were originally defined. As the breadth of test purpose increases, the cost of the testing typically increases dramatically. A typical hierarchy of test purposes, ranging from the narrowest to the broadest, can be defined as follows:

(Testing applicable only to the specific equipment tested):

1. A/B comparisons of two trucks under comparable conditions
2. Acceptance tests to ensure adequate performance under well defined operating conditions
3. Testing to diagnose a possible problem
4. Exploration of envelope of acceptable performance

(Testing which produces results that can be generalized to new equipment without additional testing):

5. Definition of operating environment in which it must work
6. Development of rules of thumb or design guidelines for new equipment
7. Definition of underlying physical relationships which govern performance for well-defined conditions
8. Validation of mathematical models which predict performance over a broad range of conditions

The first two categories of testing can be conducted under one or a few specific operating conditions, not requiring a large number of test runs. Only a few measurements may be needed (such as wheel wear measurements) to answer the questions of interest. The third category of test is likely to require more test conditions and measurements in order to test uncertain hypotheses about what is causing the problem of interest. The instrumentation requirements are likely to be more stringent, since considerable accuracy and resolution may be needed to identify the source of the problem. The fourth category of test purpose will require that tests be performed under many different combinations of operating conditions, with a substantial number of measurements for each. These are needed to thoroughly define the limits of the operating conditions for which performance is acceptable, and to measure all of the physical quantities which determine acceptability of performance (forces, displacements, accelerations, etc. in various locations).

The second group of four test purposes represents much more ambitious goals, which are more difficult to achieve. The experimental conditions need to be more carefully controlled, a larger number of cases must be tested and the measurements must generally be more precise. These tests also require considerably more advance planning in order to be successful at producing results which are broadly applicable. Each of these factors increases in significance as the test purpose advances from (5) to (8). This means that the test programs become increasingly costly and difficult to accomplish, while their results become increasingly valuable. If the "ultimate" testing goal of producing validated mathematical models can be successfully achieved, the validated models could be used extensively in the design and evaluation of future equipment without requiring substantial additional testing.

The goals of a broad-based Truck Safety Performance Evaluation Program would appear to be such as to require test results from programs designed with purposes in the categories from (5) to (8). A program which produced results that could only be applied to the specific trucks which were tested would be of very limited long-term value. Rather, the test data which will be of interest are those which can be generalized to a range of truck designs.

2.2 AVAILABLE RADIAL TRUCK TEST RESULTS

The data which have been collected during previous radial truck test programs have been investigated. These test results are summarized on separate pages in the Appendix, where citations to the data sources are called out by reference numbers. The test programs which were reviewed have been organized into separate categories based on their sponsorship. The first group, as described in References [1-12], was sponsored by the Federal Railroad Administration in the TDOP and FAST programs. Another group of test programs was sponsored and conducted by many of the major North American railroads (References [13-21,23,24]), mainly directed at evaluating the wheel and rail wear impacts of the different trucks. There have been a few test programs conducted by the truck manufacturers [25-27] as well as some outside North America [22]. The emphasis in this review has been on tests of trucks which are or may be used on freight railroads within the United States, rather than on those used only overseas. Therefore, the tests by British Rail and the South African Railways on trucks which differ substantially from those used in North America have not been included here. This review has also been directed at radial trucks rather than some of the other unconventional trucks which have been tested in recent years (single axle trucks tested by Trailer Train [28] and separately under FRA sponsorship).

The Canadian National Railroad has conducted extensive testing of the DR-1 radial truck, playing an integral role in the development of that truck [13-17]. Their testing has covered a variety of dynamic response conditions, mainly aimed at purposes in categories (1)-(4). Because of the near-term goals of their test program and their interest in relatively qualitative measures of performance, the dynamic response data were recorded by oscillograph rather than magnetic tape, making it very difficult for others to analyze the data quantitatively. The angle of attack and wheel/rail force measurements were only taken at fixed wayside locations in curves, providing only a partial picture of these measures of truck performance. The CN has also been gathering extensive data on wheel wear with the DR-1 in a unit train service.

The Canadian Pacific Railroad conducted a comparative performance test of four different radial trucks in 1978 under carefully controlled conditions [18,19]. The wheel/rail force and angle of attack measurements in curves, which are the principal dynamic response variables of interest, were recorded at fixed wayside locations rather than being recorded continuously on the vehicle. Comparable tests were performed in 1980 on the RDI split friction wedge truck [20]. More recently, the CP has been measuring wheel wear on the DR-2 and Barber-Scheffel trucks in revenue service on a unit coal train.

In the United States, the Southern Railway [23,24] and the Burlington-Northern have been measuring wheel wear on radial trucks used in revenue service. In Australia, the Mt. Newman Mining Company Railroad tested three radial trucks in a two degree curve in 1977-8, but the results of those tests have not been very thoroughly documented [22]. Among the truck manufacturers, ASF has reported on the outcome of a program of tests on a radial truck based on British Rail technology [26], but the test results themselves are regarded as proprietary. UTDC has reported some tests of their "frame braced" retrofit truck in curving and in revenue service in a coal train [25].

All of the privately supported tests described here were designed to address some specific and limited questions, rather than to explore the fundamental characteristics of the radial trucks. Their results are therefore of very limited applicability for any wider purposes. The only test programs which were designed to produce results of broader applicability to radial trucks in general were the two sets of tests sponsored by the FRA, in TDOP and FAST. The remaining attention will therefore be focused on these two sets of test data, which were the most thoroughly instrumented and documented of any of the radial truck tests.

2.3 TRUCK DESIGN OPTIMIZATION PROGRAM TESTS (TDOP)

The TDOP program was carried out in two phases during the period between 1976 and 1981, with two separate contractors, Southern Pacific and Wyle Laboratories. The second phase concentrated on the "Type II" unconventional trucks, including radials and rigid-frame trucks. Seven different Type II trucks were tested under a wide range of conditions, including: tangent track at high speed (lateral stability); curves of 1.2 to 6.3 degrees at, above and below balance speed; severe crosslevel disturbances at 4-30 mph speeds (harmonic roll and bounce); and through a 12 degree yard curve at 10 mph (load equalization). Under all of these test conditions, extensive dynamic response measurements were recorded (96 channels of digital tape at 200 samples per second).

The TDOP tests were designed to aid the railroads in evaluating the potential advantages of the new-generation trucks over conventional three-piece trucks. These included differences in lateral stability at high speeds, differences in rolling resistance, especially in curves, differences in wheel/rail forces with possible implications for wear of both wheels and rails and differences in the potential for derailments via different mechanisms and under different operating conditions. Obviously, most of these purposes are not directly related to safety issues, but are more oriented towards an economic evaluation of the trucks. The sheer volume of the TDOP test data poses a challenge to any potential user of even a small portion of these test results. The extensive documentation produced by Wyle Laboratories [1-5] helps considerably, but any attempt to extract information from the test data tapes must be expected to take substantial time and effort [6,7].

The time and effort required to analyze existing test data are generally much less than what would be required to perform a new set of tests, so there should be a strong motivation to make the best possible use of the TDOP data base. An independent evaluation of the TDOP data [7] has demonstrated the difficulties involved in doing this. In particular, this evaluation raised doubts about the value of the wheel/rail force and angle of attack measurements from the TDOP tests. A separate study by Canadian Pacific [29] has raised further questions about the angle of attack measurements. Unfortunately, it is these measurements (wheel/rail forces and displacements) which would be of greatest potential interest for the development of a data base on radial truck dynamic response. The TDOP measurements in which greater confidence can probably be placed (carbody accelerations and suspension vertical and lateral displacements) are much less revealing of the potential safety differences among the different truck types. Rather surprisingly, the TDOP tests included almost no measurements of forces in the special truck components which make the Type II trucks different from conventional trucks. Therefore, the results of those tests cannot be used to answer many of the questions about potential safety issues associated with the introduction of these new trucks.

2.4 "MINI-TEST" AT FACILITY FOR ACCELERATED SERVICE TESTING (FAST)

The second major FRA-sponsored program to have produced dynamic response data on radial trucks is the "mini test" which was conducted on the FAST track at the Transportation Test Center in 1982 [10-12]. This test program was designed to reveal the steady-state curving performance and energy consumption (resistance) of three radial trucks of two basic design types (DR-1, DR-2 and Barber-Scheffel). These trucks were tested, along with control trucks of conventional design, over a wide range of speeds, principally on the curved tracks available at TTC (curvatures ranging from 1.5 to 7.5 degrees). The tests included both lubricated and unlubricated rail, and radial trucks operated with and without their steering connections in place. The test cases for the DR-1 and Barber-Scheffel without their cross-links are of particular interest for the light they may be able to shed on the operation of radial trucks when their steering devices fail. The testing of the Barber-Scheffel using both its own recommended wheel profile and the standard AAR 1:20 wheel profile also helps to reveal the influence of wheel profile on truck performance, in contrast to the TDOP and other tests which have not used multiple wheel profiles.

Although the instrumentation for the FAST "mini test" did not include as many data channels as the TDOP program and the documentation of the test program was not as extensive, there appears to be more useful data available here. The data are available on digital tapes, at sample rates ranging from 200 to 1000 Hertz, depending on the train speed for each test. The wheel/rail vertical and lateral forces were measured using an IITRI instrumented wheelset, which produced much more accurate results than the technique used in TDOP. Although the British Rail angle-of-attack measurement system used at FAST had some problems, particularly in establishing a constant datum reference, it appeared to produce much more credible results than the TDOP system. Other truck measurements included axle alignment and longitudinal displacement and truck swivel. An instrumented coupler and longitudinal accelerometer were used to estimate curving resistance and the wheel and rail profiles were measured separately to establish the wear characteristics of each.

The FAST radial truck "mini test" has demonstrated some of the performance characteristics of two types of radial trucks under some very specific operating conditions. Only three cars were equipped with each type of truck for the curving resistance test, and only one car with each truck was completely instrumented for the remaining test cases. This provides a limited sample, perhaps not enough to draw broad conclusions about truck performance. All the trucks tested were new, so no information was obtained about changes in truck safety performance as the truck components wear. All the tests were run for fully-loaded vehicles, so there was no indication of the sensitivity of performance to changes in vehicle loading. The curving results were found useful in the steady state, but not necessarily for evaluating curve entry and exit performance. The test program included very careful characterizations of the trucks' static characteristics prior to the initiation of the dynamic tests. The dynamic test results were also found to be useful for defining the relative importance of spring and damping characteristics in maintaining truck geometry.

These FAST tests have produced some results which are likely to be useful for incorporation into a radial truck data base, and their existence may make it possible to effect some savings in the design of a new program of radial truck testing. However, these results are only applicable to the two types of radial trucks tested, for the limited sets of conditions under which they were tested. A more thorough discussion of the applicability of these test data relative to the radial truck safety performance information needed is contained in Chapter III.

CHAPTER III - EVALUATION OF EXISTING DATA RELATIVE TO THE NEEDS FOR RADIAL TRUCK SAFETY INFORMATION

Because the emphasis in the previous test programs on radial trucks has not been explicitly on safety issues, the existing test data sets have not been designed to answer the important safety-related questions. In preparation for any new radial truck testing, it is important to first consider what questions need to be answered and then determine which of those questions can be answered using existing test data. That is the subject of this chapter. In the next chapter, the shortfalls evident in the existing data will be used as the basis for formulating recommendations about the shape of a future test program.

3.1 RADIAL TRUCK SAFETY INFORMATION NEEDS

The first step in this process is to identify the safety concerns which need to be addressed. In order to determine what the potential safety issues are relative to the introduction of radial trucks, the reports and papers in the Reference list were studied for potential safety concerns and the authors of most of them were contacted by telephone to discuss what they thought would be the important safety problems. They were also asked to suggest what types of tests or what specific test conditions they would like to see in a new test program.

The safety concerns expressed by these leading industry representatives (mostly from the research or mechanical departments of the railroads or from the equipment supply companies) were:

- Failures of special truck components at locations of stress concentration. Do these failures degrade truck performance only slightly or do they lead to unsafe conditions?

- If the radial trucks are designed to operate with special profiled wheels, do they become unsafe when inadvertently equipped with standard wheels?
- What will the fatigue life be of the new trucks and their components under a realistic load environment? What, precisely, will that load environment be as a function of different operating conditions?
- Radial truck components have been known to fail because of unanticipated high forces. How can these forces be determined in advance so that the designs can be modified before the trucks fail in service?
- There is evidence that radial truck steering arms experience very large forces, and possibly severe vibration during hard braking. Is this in fact true, and if so, how can it best be eliminated or accommodated?
- Some radial truck users have noticed accelerated wear on individual wheels, leading to some surprisingly early wheel failures. Is this only because these wheels are receiving closer scrutiny than the wheels on the much larger fleet of conventional trucks, or is there something about the radial trucks which may under certain conditions lead to aggravated wheel wear?
- There is evidence that radial trucks are more sensitive to component mismatches and require closer tolerances on parts. How close must these tolerances be to obtain the desired truck performance, and what are the consequences of accidental substitution of the wrong parts (parts with poorer tolerances or even of the wrong nominal tolerance)?
- How does the performance of radial trucks change as their components wear and tolerances change? Which wear phenomena are the most important in terms of changes in performance? Which aspects of truck

performance change, and do those changes lead to possible safety problems?

In addition to the concerns listed here specifically for radial trucks, there have also been concerns raised about the single-axle suspensions being introduced on some of the new intermodal cars. These concerns have related specifically to the possibility of increasing the propensity to derail because of the long effective wheelbase on these cars. Although that question does not relate directly to radial trucks, it could serve as the subject of an independent safety-related test program.

When the railroad industry people were asked to suggest tests which could be included in a new radial truck safety test program, not all of the suggestions turned out to be applicable to safety issues. At least as much interest was expressed in the economic aspects of the new trucks, specifically in wear and fuel consumption. The suggested tests included the following:

- Direct measurement of rail wear under controlled conditions.
- Measurement of fuel consumption on both tangent and curved track.
- Controlled experiment to show all the effects of changes in wheel profile.
- Investigation of how the wheelsets align and what conditions produce oversteer and understeer.
- Measurement of lateral and vertical wheel/rail forces in transition spirals as well as fully-developed curves.
- Investigation of the effect of lubrication on the high rail gauge face on wheel/rail lateral force and angle of attack.

It is apparent from the lists of safety concerns and suggested tests which have been enumerated here that the implications of increased use of radial trucks could be very broad. The challenge is to distill these concerns and desires into a coherent truck safety research program which can be conducted within reasonable budget and schedule constraints. The issues raised by the railroad industry people can be grouped into several general categories, which can serve as the basis for defining research needs. Perhaps the most revealing way of doing this is to formulate a basic set of questions which need to be answered. On the basis of the review of radial truck testing needs which has been conducted here, the basic questions appear to be the following:

(1) How does the performance of radial trucks (stability, ride quality, curving resistance, wheel/rail forces) change as the trucks wear?

(2) How sensitive are radial trucks to component tolerances ? How tight must these tolerances be, and is that significantly tighter than the tolerances for conventional trucks?

(3) What is the load environment imposed on radial trucks as a function of their operating conditions? How does this translate into stresses in the vital truck components, and what implications does that have for possible component failures?

(4) What are the principal failure modes of radial trucks and what are the consequences of each? In particular, are any of the failure modes specific to radial trucks likely to lead to unsafe conditions which would not be experienced with conventional trucks?

(5) Are there substantial differences between radial and conventional trucks in their propensity to produce derailments by the mechanisms of wheelclimb, rail rollover or gauge widening?

(6) What are the stability limits of radial trucks in terms of a transition into hunting at higher speeds or dynamic roll at low speeds on track having crosslevel disturbances?

In order to answer these questions thoroughly it is necessary to develop a comprehensive understanding of the fundamental dynamics of rail vehicles. This includes the derivation of quantitative descriptions of the dependence of performance on a multitude of inputs. The development and validation of such comprehensive mathematical models requires extensive testing, which must be conducted according to a carefully developed advance plan. In the absence of testing which is both comprehensive and carefully planned, it will not be possible to answer the six questions which have been posed.

3.2 POTENTIAL FOR USING EXISTING TEST DATA

The test data which have already been gathered and the operating experience of railroads which are already using radial trucks can be used to answer some parts of some of the six basic questions which have just been posed. By building on this heritage, it should be possible to save some of the effort which would otherwise be needed to develop a comprehensive radial truck safety data base from scratch. By identifying the subject areas in which there is already some substantial knowledge, future efforts can be focused on addressing the remaining unknowns.

Basic Question #1 is one which does not appear to have been addressed by any of the existing test programs. The formal tests have all been performed on new trucks and have not involved extensive enough usage to generate much wear. The FAST "mini-test" included curving resistance tests of the Barber-Scheffel truck using the Scheffel profiled wheel and the standard AAR 1:20 wheel and Scheffel reported that his testing of his truck with the incorrect wheel profile (1:20) led to some loss of wheelset steering, but with performance still competitive with a forced-steer truck and better than a rigid-frame truck [33]. These appear to be the sole examples of a radial truck being tested with different wheel profiles and in neither case have quantitative test results been published (although the FAST data would probably be available for inspection). The TDOP Phase II program was designed to include the collection of wear data on the test trucks following the main set of dynamic response tests. Consideration was given to performing a comprehensive set of dynamic tests on the worn trucks at the end of the wear data collection period, but this has not yet occurred. Such testing, if carefully designed, could be extremely valuable in developing some of the answers to Question #1.

Several sources have cited the heightened sensitivity of radial trucks to component selection and tolerances, but there is as yet no quantitative data available to answer Basic Question #2. In fact, this issue of sensitivity to tolerances does not even seem to have appeared in print yet, although it was mentioned in conference sessions by three different speakers, from three separate organizations, at the October 1983 conference, "The Economics and Performance of Freight Car Trucks" in Montreal. There has certainly been extensive discussion in print about the effects of different wheel profiles on vehicle dynamic response, regardless of whether radial trucks are used. Even the FAST tests of the Barber-Scheffel truck with two different wheel profiles are not suitable for answering this question because those tests only considered differences in curving resistance, rather than addressing any other questions of vehicle dynamic performance.

There is very little data available which could help to answer Basic Question #3. The load environment experienced by railroad equipment does not appear to have been characterized in a systematic, quantitative way for general use. The Canadian National has performed road tests on the DR-1 radial truck with a strain-gauged steering casting to define the load spectrum expected in operations on both tangent and curved track with empty and fully loaded cars [16]. This appears to be the only reported test data which could be applied to answering Basic

Question #3, and it only represents results from two track sections and one radial truck.

There is an important difficulty associated with defining what represent "typical" operating conditions of different types. The dimensions needed to define these conditions are considerable: speed, rate of acceleration or braking, grade, track curvature, coefficient of friction (lubrication), and five types of track geometry perturbations (surface roughness, alignment, gauge, crosslevel and profile) which can have different amplitudes, wavelengths and phase relationships. Even the tests which have been performed on track segments that do not pretend to being "typical" have not generally produced load or stress measurements. There were a few very limited attempts to measure loads in radial truck steering arms and cross-links in the TDOP program, but these were not successful for a variety of reasons. The net results is that the truck manufacturers may have measured some of these loads in their own proprietary tests under a few specific conditions, but there does not appear to be any wider knowledge of the magnitudes of the loads seen by radial trucks.

There does not appear to have been enough operational experience with high-mileage radial trucks to yet identify their most important failure modes (Basic Question #4). Some of the developmental testing has identified failures in steering arms and their attachment points, which have led to design changes [23]. There has also been some testing on radial trucks with the steering arms or linkages removed to simulate some of the effects of failures of these components. These tests have shown that the radial trucks tend to revert to performing more like conventional trucks without their steering devices, representing a "soft" rather than a catastrophic type of failure. It has also been shown that the lateral wheel/rail forces produced by a radial truck with and without its steering connections were virtually identical in a five degree curve [12]. These observations should not be taken to mean that the failure of a steering connection is totally benign. Reversion of a radial truck to conventional non-steering performance because of a failure during high-speed operation could lead to the sudden initiation of hunting because of the sudden decrease in the critical speed of the truck. Also, the fractured remains of a broken steering connection could become fouled with other truck components or could drop to the track, leading to derailment or other damage. None of these possible consequences has been tested, and there appear to have been no tests directed at failure modes other than the elimination of the steering connections.

Investigations of derailment mechanisms are probably the most difficult of all rail vehicle dynamics experiments, making Basic Question #5 the most difficult of all to answer. The derailment mechanisms are highly nonlinear and transient, which means that they cannot be easily analyzed or tested. Full-scale derailment tests are impractical because of the obvious safety hazards and costs they would generate. Some full-scale derailment tests of single wheelsets have been performed by British Rail [30], and 1/5 scale model derailment tests have been conducted at Princeton University [31]. Although these tests have revealed much about the physics of the derailment of individual wheelsets, the direct extension to derailment predictions for radial trucks is not apparent. In particular, additional work will be needed to be able to identify the differences in the propensity to derail of radial and conventional trucks. None of the radial truck test programs which have been identified attempted to define derailment mechanics of these trucks.

There is probably more information available to answer Basic Question #6 than any of the others, at least for the part relating to lateral stability (hunting). Several test programs have compared the stability of radial and conventional trucks in high speed operation, including TDOP [1-6], Canadian National

[13-15], Canadian Pacific [18-20] and ASF [26]. Although there may be some disagreements about how to interpret hunting test data and how to define what constitutes the onset of hunting, these test programs have at least been fairly consistent in showing the radial trucks to remain stable at higher speeds than the conventional trucks. However, additional fundamental research and testing are likely to be necessary to enable the critical speed for hunting to be predicted reliably for new and untested truck designs. Therefore, the requirement for high-speed stability tests of new radial trucks cannot yet be bypassed because of the satisfactory testing of previous radial truck designs.

Low-speed dynamic roll testing of radial trucks has only been performed as part of the TDOP program, and the results of those tests have only been reported in the most general and qualitative terms [32]. The conclusion reported from TDOP was that the harmonic roll response of all of the trucks tested was sufficiently low that no problems were anticipated. This of course does not provide any assurance that future radial trucks of different design would not suffer harmonic roll problems.

3.3 CONCLUSIONS REGARDING USE OF EXISTING DATA OR PERFORMING NEW TESTS

As the preceding discussion indicates, there is a limited potential for using some of the existing radial truck test data to characterize the safety performance of radial trucks in general. This potential should be exploited to a reasonable extent, but there should be no illusions about the limitations of the existing data. These data sets were collected to meet the specific needs of prior programs, and therefore are often not suitable for answering new questions. Because the earlier test programs were not as concerned about answering safety-related questions, they did not include all of the test conditions and measurements which are important to safety. There have been significant problems with the instrumentation on prior test programs, particularly for measuring wheel/rail forces and displacements (especially angle of attack). Since these measurements are vital to the development of a fundamental understanding of the dynamics of freight trucks, data sets which are deficient in these measurements are of severely limited utility.

Perhaps the most important limitation to the existing radial truck test data is that almost all of it was collected on trucks of relatively old design (the "pioneering" radial trucks). The designs of radial trucks have continued to evolve, and should change more rapidly than ever before with the increased recent emphasis on weight reduction. Test data for older, heavier trucks of different construction are not likely to shed great light on the performance of more modern trucks, especially for investigations of stresses and possible structural failures. The prior test programs were not designed to produce data which could be broadly generalized to trucks of significantly different character, so it will be necessary to perform new tests to establish virtually any of the characteristics of substantially new truck designs.

A new test program can be expected to require the expenditure of considerable time and money. However, because of the limitations of the existing data it would appear to be necessary in order to learn anything substantial about the safety performance of new radial trucks. The new test program can be carefully planned and specifically tailored to answer the safety questions which are of concern today. It can also be conducted on the most recent truck designs, to ensure that the results can continue to be of use for the longest time. Suggestions for the type of testing such a program should contain are offered in the next chapter.

CHAPTER IV - RECOMMENDATIONS FOR TESTING IN THE TRUCK SAFETY PERFORMANCE EVALUATION PROGRAM

It should be clear from the review of the existing radial truck test data that a new test program will be needed to produce safety performance information which can be applied to the full range of radial truck designs. In order for the new test program to produce results of maximal value, these results must be appropriate for making generalizations to truck types and operating conditions other than those which were tested. Such a test program must therefore be designed to develop a fundamental understanding of the physical processes which govern truck performance. That requires that a thorough and scientific approach be applied from the start, beginning with the design of and planning for the test program.

The test program should be designed so that its end product will be a set of validated mathematical models which can then be used to predict performance of diverse trucks (trucks having widely varying parameter values) under different operating conditions (performance regimes including more conditions than the specific ones which were tested). Those mathematical models, if properly formulated, should embody the current state of knowledge of freight truck dynamics and safety issues. They can then be used to develop the answers to the six basic questions which were defined in Section 3.1, as well as possibly other questions not included in that list.

In order to meet these requirements, the truck tests will need to be very comprehensive and carefully executed. The number of cases to be tested will have to be extensive, as will the instrumentation. Significant effort will need to be devoted to the planning of the specific test cases and to the development of the models to be validated long before the tests are initiated. Such a detailed test plan is substantially beyond the scope of the present task, but the general dimensions of the test program can be outlined now. The test program is defined here in terms of three basic attributes: the trucks to be tested, the operating conditions and the instrumentation.

4.1 SELECTION OF TRUCKS FOR TESTING

The new truck test program must include a diverse mix of trucks, representing the full range of truck designs of interest. There is little to be gained by testing several very similar truck designs because that would not reveal much about the design features which influence truck performance. Rather, the trucks to be tested should be chosen to be as different from each other as possible in dimensions, geometry, weight and steering mechanism. In addition, there should be a "standard" truck included to serve as a baseline case for all tests so that the performance of the new trucks can always be referred back to a well-known and common departure point.

Each truck design chosen for testing needs to be represented in the test program by several individual trucks so that peculiarities in the condition of one sample truck do not misrepresent the characteristics of the entire truck design. Furthermore, it is important that each truck be tested in both new and worn conditions and with more than one wheel profile. These requirements are much more important for answering the safety-related questions of interest for this test program than they would have been for prior test programs. The worn representatives of each test truck should if possible be service-worn so that they represent the kinds of wear which would be experienced in revenue service. The dimensions of the service-worn trucks must be taken carefully so that the differences (especially in clearances) relative to new trucks are clearly understood. If performance of the worn trucks is found to differ markedly from the performance of the new trucks, the test plan should include provisions for retrofitting individual worn components into the new trucks to aid in identifying the source(s) of the differences.

Wheel profile is known to have a significant influence on truck performance, and if it is not controlled carefully in a test program its influences can mask the effects of other test variables, leading to misleading results. Each truck should be tested with the profile suggested by its manufacturer, both new and in worn condition. In addition, those trucks which were not designed for use with the standard AAR 1:20 taper wheels should be tested with those wheels to ensure that if they were mistakenly installed for revenue service they would not lead to unsafe conditions. The testing of these trucks with the different wheel profiles also helps to explicitly define the effects of the changes in wheel profile on truck performance.

4.2 OPERATING CONDITIONS TO BE TESTED

The test program must include a sufficient range of operating conditions to enable the prediction of truck performance under all reasonable combinations of conditions. The operating conditions can be defined in terms of the vehicle which is mounted on the truck, the speed of operation, acceleration or braking, and the track characteristics.

The most important vehicle characteristic to vary in the test program is the loading, because truck performance can vary significantly depending on whether the vehicle is full or empty. Both full and empty vehicle loads should be included for most of the test conditions. Although the type of vehicle body may influence overall vehicle performance (truck center spacing, bending and torsional stiffness), it does not appear to have different effects on different trucks. This makes it a less important factor to incorporate in the plans for a truck test program.

The selection of vehicle speeds and acceleration and braking conditions to include in the test program must be combined with the selection of track conditions because of their combined effects on truck performance. Particular emphasis must be placed on tests of braking, at both service and emergency rates, because of evidence that this may have adverse effects on radial truck performance. The track conditions to be included in the testing cannot be characterized simply, making it more manageable to define the operating conditions in terms of the aspects of truck performance which are to be investigated. These include lateral stability (propensity for hunting), ride quality (absorbing vibrations), steady and dynamic curving and dynamic roll. Truck performance in each of these regimes will be affected by track geometry, track surface condition (roughness and lubrication), operating speed and, to some extent, by acceleration or braking.

As discussed in Chapter 3, there is probably more test data available about truck lateral stability than about the other dynamic response issues. Hunting is a nonlinear dynamic response phenomenon which is particularly associated with higher operating speeds, and therefore must be tested at higher speeds. Because of the initial condition dependency of hunting responses, the lateral stability tests must be done for both increasing and decreasing speeds. An example of such a test pattern would be operating the truck at 45 mph and then at constant speeds of 50, 55,.... mph increasing in 5 mph increments until hunting was fully developed, continuing for an extended period of time. The fraction of the time that the truck hunted at each speed would be recorded, along with the severity of the hunting. After the speed of fully developed hunting was established and maintained for a while, the speed would be reduced in 5 mph increments and observations of the severity and the fraction of time hunting would be continued until there were no longer any instances of hunting. Tests of this nature need to be continued for substantial periods of time and should be repeated more than once because of the random processes which cause the initiation and the quenching of hunting. Sufficient test data must be obtained to produce statistically valid results.

The lateral stability tests require tangent track or the use of a special test installation such as the Roll Dynamics Unit (RDU) at the Transportation Test Center. The track geometry perturbations and surface roughness should be representative of what the trucks would see in revenue service, neither rougher nor smoother. These tests should not be performed on extraordinarily smooth track, because there is evidence that the apparently random causes of hunting initiation and quenching are related to track perturbations. The need to continue the hunting tests for substantial periods of time in order to obtain statistically valid results tends to imply the use of a very long test track, which could be difficult to obtain and even more difficult to maintain in consistent condition for a full test program. The alternative to this is use of the controlled conditions provided by the RDU. Because the RDU is designed to represent very smooth track conditions, it would be necessary to use its supplementary actuators to impose random forces corresponding to those which would be produced by track perturbations in a field test. The close control of experimental conditions which this permits may enable the effects of these perturbations on hunting initiation and quenching to be proven.

Ride quality tests demonstrate the truck's ability to isolate the carbody from vibrations while also characterizing the loads experienced by the truck components. Pending the development of a definitive characterization of track perturbations found in each of the six classes of track across the country, it will probably be necessary to perform the ride quality tests on "typical" sections of revenue track of each Class, at speeds up to the maximum allowed on that Class. As in the case of the lateral stability tests, considerable lengths of track will be needed to ensure statistically valid results.

Eventually, this type of testing could be performed on the Vibration Test Unit (VTU) at the Transportation Test Center if definitive input data for the VTU were available. In some sense, this type of testing would be an extension of the fatigue load characterization tests which the Canadian National performed on the DR-1 trucks [16], but in this case including more kinds of track and many more truck measurements.

The testing on "typical" track or using the VTU to represent "typical" track would establish a fatigue load distribution for the truck and its components. In other words, this testing would reveal what portion of the operating time each instrumented component would experience loads of each amplitude (i.e., probability density functions of individual loads or the joint probability density functions of multiple loads). These statistics derived from limited VTU or track tests of complete trucks should then be used to define the loads to be applied in extended fatigue tests on the key individual truck components. The fatigue tests can be accomplished more quickly and economically in a laboratory environment using conventional fatigue testing devices to apply millions of cycles of the appropriate controlled loads to the individual truck components. This testing procedure is also inherently safer than attempting to fatigue test an entire truck in VTU or track tests because it avoids the possibility of damage to other components or vehicles when a fatigue failure occurs.

Characterizing "typical" track for these ride quality and fatigue load tests is extremely difficult because of the number of variables needed to characterize any track. These include the surface roughness (short wavelength perturbations) as well as all of the large amplitude, long wavelength disturbances. These track geometry variations are typically classified as alignment, gauge, crosslevel and profile. These separate components can be present at different amplitudes and in different phase relationships with each other, producing a great diversity of possible combinations. In addition, the rail head profile, or the cross-sectional shape of the rail, can have a very significant effect on the details of the wheel-rail interaction. This input is very difficult to measure and control for any testing on typical revenue service track. If it is not adequately considered in the development of the test program, variations in the rail head profile can introduce extra factors into the test results, obscuring the effects which the tests are intended to reveal.

Tests of curving performance are the most difficult to perform, but also the most important for defining potential problems with truck performance. There are no laboratory installations such as the RDU or VTU which could be used for these tests, so they must be performed on curved sections of track. Some diverse track curves are available at the Transportation Test Center, and were used in the FAST "mini-test", although none of these are reversing curves (S-curves), which could be of considerable interest. Most of the prior tests of curving, including the FAST "mini-test", concentrated on steady curving, at constant speed and constant curve radius. However, it is also necessary to perform dynamic curving tests involving curve entry and exit spirals and acceleration and braking and buff and draft forces in curves.

The steady curving tests should be performed through curves of several different radii, at speeds above, below and at the balance speed. The curves must be traversed in both directions (left-hand and right-hand) in order to isolate any asymmetrical effects in the trucks or instrumentation. The effects of different lubrication conditions on the track gauge faces (inner and/or outer) and upper surfaces must be tested so that the effects of deliberate lubrication and unintentional lubrication (i.e., rain) are understood. Some of these steady curving conditions were covered for the DR-1 and Barber-Scheffel trucks in the FAST "mini-test", but these tests did not include other types of radial trucks and there were some difficulties with the angle of attack measurements, so there could be some value in duplicating portions of those tests.

The dynamic curving tests are considerably more complicated to specify because of their many dimensions. Curve entries and exits should be performed at several different speeds and curve transition rates, requiring the availability of several different sections of track. Within the constant-radius curves, tests need to be performed at several different acceleration and braking rates, with several different levels of buff and draft force. It is particularly important to obtain substantial test data for hard braking in curves because there is some evidence that this may have adverse consequences for some radial trucks, including possible loss of steering action and high loads on special truck components.

Dynamic roll is the final operating regime to consider for truck testing, and is probably the least important for identifying safety differences between radial and conventional trucks. Tests to investigate this performance regime need to be conducted on track having substantial crosslevel perturbations, preferably at the maximum amplitudes allowable within the respective FRA track classes. The operating speeds must be relatively low, and need to be varied slowly over the expected range of roll resonance of the truck/vehicle combination. The loaded test conditions for these tests should be conducted with high-center-of-gravity carbodies, loaded with the density of lading which will produce the highest possible center of gravity.

4.3 INSTRUMENTATION REQUIRED

The usefulness of the results from a test program is every bit as dependent on the quantity and quality of the instrumentation as on the selection of the test cases. Some of the most extensive rail vehicle test programs in the past have produced results of only limited usefulness because of the limitations of their instrumentation. There are certain basic issues which should be common to all rail vehicle test programs, while others may be specific to only certain programs.

The general principles applicable to all test programs include the use of proper signal conditioning and the recording of the data in a form suitable for quantitative analysis. Dynamic response data must be sampled frequently enough to capture changes which may occur rapidly, and they must be filtered before sampling at the appropriate frequency to avoid aliasing. The instruments must be accurate enough to produce results which can answer the questions of interest with sufficient confidence, and they must be calibrated for use at the signal levels which will be encountered in the test program. Finally, the data must be recorded on a medium which can be accessed for accurate post-test processing, which normally means recording on digital tape or FM analog tape with post-test digitization. If substantial numbers of test samples are to be obtained, other methods of data recording are too cumbersome to work with.

Rail truck test programs should begin with careful and precise static measurements of the truck characteristics. These include dimensions of parts and spacings between parts, masses, stiffnesses and surface friction (viscous or dry). These characteristics must be used in the mathematical models which will predict truck performance, and it is essential that they be determined accurately. This has not often been the case in previous test programs, although the FAST "mini test" was conspicuously careful about this.

In order to be able to evaluate the effects of wheel/rail interactions on truck performance, the measurements should ideally include the wheel profile, the complete track geometry and the rail head profile. Although track geometry has been measured in conjunction with other vehicle dynamic test programs, the rail head profile has only been measured infrequently because of the difficulty of measuring it at many locations along the track. If the track is relatively unworn or is consistently worn through the test section, a limited number of rail head profile measurements should be able to characterize the rail head without excessive effort. These measurements are particularly important for curving experiments, in which there is a possibility of two-point contact between the wheels and rails.

Dynamic measurements of truck response are often quite difficult to make, particularly the most important of these measurements, which are the wheel/rail forces and displacements. It appears that instrumented wheelsets are virtually essential for obtaining continuous and accurate measurements of wheel/rail forces. Typically they are used for lateral and vertical forces, and in the near future an attempt will be made to use one for measuring longitudinal forces as well at TTC. That is hoped to eliminate the need to measure wheel/rail angle of attack, which is the most difficult of all to measure, based on the experience of previous test programs. Since the success of the attempt to measure longitudinal wheel/rail force directly is at present uncertain, the planning for future testing should still include consideration of measuring angle of attack. It is also important to measure the lateral displacement of the wheelset relative to the track centerline (or a reference rail).

The other dynamic response measurements which should be made on the truck or vehicle do not pose comparable difficulties. These include general suspension and truck/carbody interaction measurements and special measurements associated with radial truck components. The types of measurements which should be common to most trucks include the rotation of the truck bolster relative to the carbody, parallelogramming of the truck frame (rotation of bolster relative to side frames), vertical suspension deflections at each corner of the truck, and lateral and longitudinal displacements of bolster relative to each sideframe. For radial trucks in particular, the wheelset yaw should be measured, perhaps in terms of the longitudinal displacements of the bearing adapters. The forces and/or torques in the special truck components (steering arms or crosslinks or struts, connections to bearing adapters, shear pads, etc) should be measured. Similarly, the displacements of the special truck components (such as the bearing adapter housings on the Barber-Scheffel truck) should be measured. The precise measurements which should be made on each truck cannot be specified completely in advance, prior to a careful study of the construction of each truck, its design philosophy and its operational experience. Obviously, if problems are suspected with certain features of a particular truck the instrumentation to be applied should be selected so as to identify those problems directly.

Development of comprehensive and accurate instrumentation for a test program is costly and time-consuming but it is a necessary investment if the tests are to produce results of maximum utility. The results of multimillion-dollar test programs have been undermined by failures to spend several thousand additional dollars for the appropriate instrumentation in the past. This type of false economy is to be avoided.

REFERENCES

1. Gibson, David, "Truck Design Optimization Project (TDOP) Phase II: Type I Truck Test Plan," Wyle Laboratories Report No. C-901-0004-A, Revised - April 1980.

2. Gibson, David, "Truck Design Optimization Project (TDOP) Phase II: Type I Truck Test Results Report," Wyle Laboratories Report No. C-901-0013-A, September 1980, FRA/ORD-81/77.

3. Gibson, David, "Truck Design Optimization Project (TDOP) Phase II: Type II Truck Test Plan," Wyle Laboratories Report No. C-901-0007-A, Revised - April 1980.

4. Peacock, Richard A., "Truck Design Optimization Project (TDOP) Phase II: Type II Truck Test Results Report," Wyle Laboratories Report No. C-901-0012-A, April 1981.

5. Gibson, David, "Truck Design Optimization Project (TDOP) Phase II: Type II Truck Test Events Report - Series 1 through 4," Wyle Laboratories Reports No. C-901-0011-A (August 1980), C-901-0014-A (October 1980), C-901-0015-A (December 1980), and C-901-0016-A (December 1980).

6. Telecons with Gordon Bakken, Robert Glaser, David Gibson, Richard Peacock, Arnold Gilchrist and Charles Bush (conducted as part of work under Task 9 of Contract DOT-FR-9050).

7. Shladover, Steven, "Evaluation of Selected TDOP Phase II Test Data," Systems Control Technology, Inc. Report to Federal Railroad Administration, FRA/ORD-83/02, December 1982.

8. Roy A. Allen and John F. Leary, "Radial Truck Wheel Wear," Proceedings of 1981 FAST Engineering Conference, Denver, CO, Report No. FRA/TTC-82/01, pp 205-216.

9. "Axle Alignment Measurements: Radial Truck Experiment," FAST Technical Note FAST/TTC/TN-81/04.

10. Roy A. Allen and James P. Jollay, "Radial Truck Curving Performance Evaluation," Proceedings of 1981 FAST Engineering Conference, Denver, CO, Report No. FRA/TTC-82/01, pp 247-250.

11. FAST Experiment Plan - Radial Truck Mini-Test, FAST Document Number ME-4.4, November 30, 1981.

12. Elkins, J.A.; J.P. Jollay, J.F. Leary, K.C. Rownd, "A Generalized Truck Wheel Wear Predictor - Extensions from FAST", in The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

13. E. C. Bailey, W. N. Caldwell and P. Marcotte, "The DR-1 Radial Truck, A Significant Advance in Freight Car Truck Technology," Proceedings of 14th Annual Railroad Engineering Conference, 1977, Pueblo, CO, pp 289-297.

14. P. Marcotte, W. N. Caldwell and H. A. List, "Performance Analysis and Testing of a Conventional Three-Piece Freight Car Truck Retrofitted to Provide Axle Steering," CN Rail Research Internal Report No. 154, Nov. 1978 (also presented at 1978 ASME Winter Annual Meeting, San Francisco).

15. P. Marcotte, W. N. Caldwell and H. A. List, "Performance Analysis and Testing of a Conventional Three-Piece Freight Car Truck Retrofitted to Provide Axle Steering," Journal of Dynamic Systems, Measurements and Control, Vol. 104, No. 1, March 1982, pp 93-99.

16. Caldwell, W. N. and D. W. Dibble, "Development and Testing of DR-1 Self-Steering Freight Car Truck," Proceedings of Fifth Symposium on Engineering Applications of Mechanics, University of Ottawa, June 1980.

17. Caldwell, W.N. and R.W. Radford, "The Evaluation of Self-Steering Trucks in Revenue Service Operation: CN Experience", in The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

18. H. Ghonem and R. Gonsalves, "Comparative Performance of Type II Trucks," Canadian Pacific Ltd. Report No. S576-78, November 1978.

19. H. Ghonem, R. Gonsalves and G. W. Bartley, "Comparative Performance of Type II and Premium Trucks," ASME Paper 80-RT-8, 1980.

20. Gonsalves, R., et al, "Railroad Dynamics Incorporated (RDI) Truck Evaluation Test," Canadian Pacific Ltd. report for Transport Canada, Number TP 2970, March 1981.

21. Khatchadourian, V., "Comparative Performance of New Generation Freight Car Trucks", The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

22. P. H. Townend, C. J. Epp and P. J. Clark, "Bogie Curving Trials, Rail Profiling and Theoretical Modelling to Reduce Rail Deterioration and Wheel Wear on Curves," Proceedings of 1978 Heavy-Haul Railways Conference, Perth, Western Australia.

23. Reynolds, David J., "The Barber-Scheffel Truck on Southern Railway," ASME Paper 83-WA/RT-18.

24. Reynolds, David J., "Radial Trucks on the Southern Railway System", in The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

25. Smith, R.E., "The Theory and Performance of Frame - Braced Freight Trucks" in The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

26. H. W. Mulcahy and R. J. Weeks, "Development of a Cross-Braced Truck," ASME Paper 81-WA/RT-1, 1981 (Journal of Engineering for Industry).

27. Bullock, R.L., "The Development and Service Results of a Cross Braced Radial Freight Car Truck" in The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

28. Wolf, E.J. and F.F. Stec, "Single Axle Suspensions for Intermodal Cars" in The Economics and Performance of Freight Car Trucks, Pre-Conference Proceedings, October 1983, Montreal, Canada.

29. Ghonem, H., "Comparison of Wyle and CP Angle-of-Attack Data," Canadian Pacific Research Department Report No. S693-81, August 1981 (Transport Canada Report No. TP3032).

30. Pocklington, A. Ronald, "The British Rail Load Measuring Wheel" in Proceedings of International Conference on Wheel/Rail Load and Displacement Measurement Techniques, Cambridge, MA, January 1981.

31. Sweet, L.M. and A. Karmel, "Evaluation of Time-Duration Dependent Wheel Load Criteria for Wheelclimb Derailment," Journal of Dynamic Systems, Measurement and Control, September 1981, pp 219-227.

32. Ramachandran, P.V. and M.M. El Madany, "Truck Design Optimization Project (TDOP) Phase II Performance Specification for Type II Freight Car Trucks," Report FRA/ORD-81/36-I, August 1981.

33. Scheffel, H., "Experience Gained by South African Railways with Diagonally Stabilized (Cross-Anchor) Bogies Having Self-Steering Wheelsets," Proceedings of Heavy-Haul Railways Conference, Perth, Western Australia, September 1978.

APPENDIX

SUMMARIES OF RADIAL TRUCK TESTING

RADIAL TRUCK TESTING SUMMARY

TEST PROGRAM:	Truck Design Optimization Project, Phase II
PERFORMING ORGANIZATION:	Federal Railroad Administration and Wyle Laboratories
DATE(S) OF TESTING:	April 19 - December 9, 1980
SOURCE OF INFORMATION:	References 1-7
TRUCK(S) TESTED:	DR-1, Barber Scheffel, Devine-Scales, Maxiride 100, ACF Fabricated, Alusuisse, National Swing Motion
OPERATING CONDITIONS:	Tangent track, high speed (lateral stability) Curves of 1.2° - 6.3° at above and below balance speed Loaded and empty Harmonic roll and bounce (4-30 mph speeds) Load equalization (10 mph, 12° curve in yard)
MEASUREMENTS:	Wheel/rail lateral and vertical forces (instrumented bearing adapters and axle bending) Wheel/rail angle of attack and lateral displacement Coupler forces, speed, suspension vertical and lateral displacements, truck yaw, carbody accelerations, axle longitudinal displacements, axle accelerations
RECORDING MEDIUM:	Digital tape, 200 Hz samples

RADIAL TRUCK TESTING SUMMARY

TEST PROGRAM:	FAST Radial Truck Wear Tests
PERFORMING ORGANIZATION:	Transportation Test Center (FRA and AAR)
DATE(S) OF TESTING:	May 1980 - April 1981
SOURCE OF INFORMATION:	References 8, 9
TRUCK(S) TESTED:	DR-1, Barber Scheffel, Devine-Scales
OPERATING CONDITIONS:	FAST track, curves of 3°, 4°, 5°
MEASUREMENTS:	Wheel wear (flange height and thickness, rim thickness) Static axle alignment Vertical and lateral loads Angle of attack
RECORDING MEDIUM:	Writing (manual)

RADIAL TRUCK TESTING SUMMARY

TEST PROGRAM: FAST Radial Truck "Mini Test"

PERFORMING ORGANIZATION: Transportation Test Center (FRA and AAR)

DATE(S) OF TESTING: March 2 - August 2, 1982

SOURCE OF INFORMATION:
References 10-12
Telecons with John Elkins, TTC, 12/20/83, 1/31/84
Telecon with Jim Jollay, TTC, 2/1/84
Letter from John Elkins, 2/10/84
Radial truck mini-test log

TRUCK(S) TESTED: DR-1, DR-2, Barber-Scheffel

OPERATING CONDITIONS:
FAST track, curves of 3°, 4°, 5° at speeds of 10, 20, 30, 40, 45 mph
TTC balloon track (7.5°) at 10, 17, 25, 32, 40 mph
Train Dynamics Track (1.5°) at 25, 35, 45, 55, 65 mph
Railroad Test Track at 25, 35, 45, 55, 65 mph
Lubricated and unlubricated
Radial trucks with and without steering connections

MEASUREMENTS:
Curving resistance (instrumented coupler and longitudinal acceleration)
Wheel/rail vertical and lateral forces and angles of attack
Axle alignment and truck parameters
Wheel and rail profiles and wear
Axle longitudinal displacement
Truck swivel

RECORDING MEDIUM: Digital tapes, 200-1000 hz, depending on speed

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Canadian National Railroad

DATE(S) OF TESTING: 1976-1978

SOURCE OF INFORMATION: References 13-16

TRUCK(S) TESTED: DR-1

OPERATING CONDITIONS:
Mainline track to 60 mph (extended fatigue test)
Curved track (0-10°)
High speed stability test
Curved track (5° and 12°)
Four wheel profiles

MEASUREMENTS:
Interaxle lateral force (steering frames)
Truck stiffness (static)
Angle of attack and wheel/rail forces (wayside)
Carbody lateral acceleration
Bearing adapter longitudinal displacements

RECORDING MEDIUM:
Oscillograph (steering frame forces and axle displacements)
Digital data logger (fatigue test)

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Canadian National Railroad

DATE(S) OF TESTING: From November 1978 on

SOURCE OF INFORMATION: References 16, 17

TRUCK(S) TESTED: DR-1

OPERATING CONDITIONS: Unit train service

MEASUREMENTS: Wheel profile section (wear)

RECORDING MEDIUM: Digital tape

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION:	Canadian Pacific Railroad
DATE(S) OF TESTING:	June 1978
SOURCE OF INFORMATION:	References 18, 19 Telecon with R. Gonsalves 7/83 Telecon with H. Ghonem 7/83
TRUCK(S) TESTED:	DR-1, Barber-Scheffel, Devine-Scales, Swing Motion
OPERATING CONDITIONS:	5° mainline curve, at above and below balance speed High-speed tangent track stability test (45-75 mph)
MEASUREMENTS:	Vertical and lateral track forces in curve Angle-of-attack in curve (fixed wayside locations) Axle accelerometers (stability test)
RECORDING MEDIUM:	FM magnetic tape (analog)

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION:	Canadian Pacific Railroad
DATE(S) OF TESTING:	September 2-14, 1980
SOURCE OF INFORMATION:	Reference 20
TRUCK(S) TESTED:	RDI split friction wedge truck (new wedges only)
OPERATING CONDITIONS:	5° mainline curve, at 25, 37, and 45 mph High-speed tangent track stability tests (40-75 mph by 5 mph) New Heumann and service-worn wheels
MEASUREMENTS:	Axle accelerometers (stability tests) Wayside wheel/rail force and angle-of-attack measurements
RECORDING MEDIUM:	FM magnetic tape (analog)

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Canadian Pacific Railroad

DATE(S) OF TESTING: January 1982 and on

SOURCE OF INFORMATION: Reference 21

TRUCK(S) TESTED: DR-2, Barber-Scheffel

OPERATING CONDITIONS: Revenue service in unit coal train, route with 40% curvature

MEASUREMENTS: Wheel profiles at 70,000 mile intervals

RECORDING MEDIUM: Digital recording on magnetic tape

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Mt. Newman Mining Co. Railroad (Australia)

DATE(S) OF TESTING: 1977-8(?)

SOURCE OF INFORMATION: Reference 22

TRUCK(S) TESTED: Scales, Scheffel, National Swing Motion

OPERATING CONDITIONS: Curve, 2°

MEASUREMENTS:
Axle longitudinal displacement
Truck rotation and lozenging
Intercar longitudinal displacement

RECORDING MEDIUM: FM analog tape (90 channels)

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Southern Railway

DATE(S) OF TESTING: From 1979 on

SOURCE OF INFORMATION: References 23, 24
Telecon with David Reynolds, 6/14/83

TRUCK(S) TESTED: Barber-Scheffel, DR-1

OPERATING CONDITIONS: Revenue service on route with 30% curvature, 55 mph max. speed
S-curves of 6° and 8°, low speed (steering test)

MEASUREMENTS: Wheel wear
Condition inspections
Drawbar pull (instrumented couplers)
Truck rotation and relative axle movement (steering test)

RECORDING MEDIUM: Writing (manual)

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Urban Transportation Development Corporation

DATE(S) OF TESTING: 1982-3(?)

SOURCE OF INFORMATION: Reference 25

TRUCK(S) TESTED: UTDC "frame braced" retrofit

OPERATING CONDITIONS: 19° curve, empty and loaded
Revenue service in ore train

MEASUREMENTS: Angle of attack (from wayside)
Loads in frame bracing rods
Side-frame loads
Tread wear

RECORDING MEDIUM: Desk-top computer

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Burlington-Northern Railroad

DATE(S) OF TESTING: From February 1983 on

SOURCE OF INFORMATION: Telecon with Ron Newman of B-N, 7/26/83
Results confidential

TRUCK(S) TESTED: DR-1, RDI (split friction wedges)

OPERATING CONDITIONS: Two trains in regular unit coal train service, with many curves up to 3°

MEASUREMENTS: Wheel wear
Flange thickness
Condition inspections plus tear-down at end

RECORDING MEDIUM: Writing (manual)

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: American Steel Foundries

DATE(S) OF TESTING: ?

SOURCE OF INFORMATION: Reference 26
Telecon with Harry W. Mulcahy, 6/16/83
(Proprietary tests)

TRUCK(S) TESTED: Proprietary ASF design, based on British Rail "cross-braced" truck

OPERATING CONDITIONS: Lateral stability (hunting) up to 102 mph on smooth track
Curving at 1.5°, 3°, 4°, 5°, 7.5°

MEASUREMENTS: Vertical and lateral wheel/rail forces
primary suspension lateral and longitudinal motions
Secondary suspension vertical and lateral displacements
Bolster swivel angles
Carbody accelerations
Cross-brace forces

RECORDING MEDIUM: Analog magnetic tape

RADIAL TRUCK TESTING SUMMARY

PERFORMING ORGANIZATION: Standard Car Truck Company

DATE(S) OF TESTING: 1979 -

SOURCE OF INFORMATION: Reference 27

TRUCK(S) TESTED: Barber - Scheffel (329 car sets)

OPERATING CONDITIONS: Unit train revenue service

MEASUREMENTS: Wheel flange height and thickness (wear)

RECORDING MEDIUM: Manual

Assessment of Radial Truck Safety Performance
Data, US DOT, FRA, S Shladover, 1984 -12-Safety