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AERODYNAMIC FORCES ON FREIGHT TRAINS
VOLUME II
CORRELATION REPORT
FULL SCALE TESTS OF TRAILERS ON FLATCARS AND COMPARISON WITH WIND TUNNEL RESULTS

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FINAL REPORT

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16. Abstract

Full scale measurements of the aerodynamic forces of trailers on flatcars have been performed at the Transportation Test Center in Pueblo, Colorado. These measurements were performed by mounting the trailers on the flatcar through force balances. In the two configurations that were tested the flatcar in front of the test car was loaded and unloaded. The tests were quite successful and resulted in consistant reproducable results. In addition to the full scale tests, wind tunnel tests were performed at Reynolds numbers up to 20% of full scale values for the same configurations. These wind tunnel tests supplemented previous wind tunnel tests similar to those previously reported in Volume I of this series. Reasonable agreement, to about 20%, was found between the wind tunnel and full scale tests. This agreement was about as good as between the wind tunnel tests themselves.

Rolling resistance was also determined from the full scale tests as the difference between total and aerodynamic resistance. The results were degraded by hysteresis in the coupler force measurement but show good agreement with the Davis relation.

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PREFACE

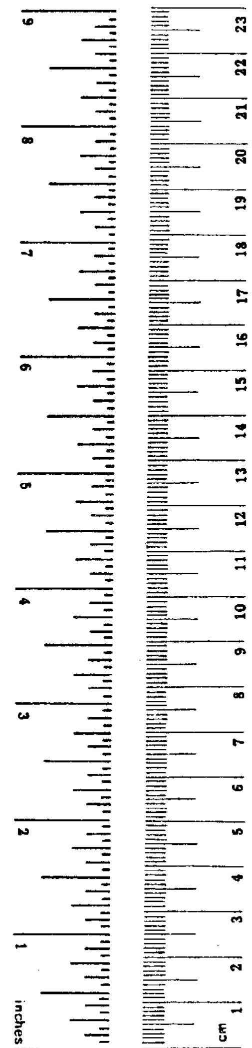
The research reported in this document was sponsored under the Improved Freight Service Program of the Office of Research and Development, FRA. This report is the third volume of a four volume series on the aerodynamics of freight trains. Volumes I and II reported on the initial scale model wind tunnel tests on Trailer-on-Flatcar (TOFC) equipment and full-scale validation tests, respectively. This volume discusses the correlation of the full scale measurements with the wind tunnel results. The fourth volume will provide wind tunnel data on other types of freight cars.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

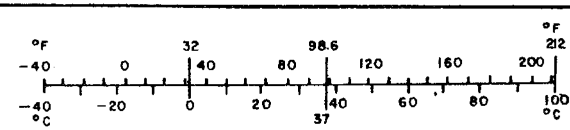
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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NOMENCLATURE

a	Speed of sound.
$C_D A$	Drag area. Along direction of track.
$C_Y A$	Side force area. Perpendicular to direction of track.
l	Length
M	Mach number.
n	Number of axles on car.
R	Resistance force and Correlation Coefficient.
Re	Reynolds number.
v,V	Velocity.
W	Weight per axle in tons.
ρ	Density of air.
μ	Viscosity.
ϕ	Angle of yaw.

EXECUTIVE SUMMARY

This report is the third in a series on the aerodynamic forces on trailer on flatcar and container on flatcar configurations, TOFC/COFC. Volume I gave the results of wind tunnel tests on a variety of actual and modified configurations. Volume II presented the results of full scale tests. This volume presents the results of additional wind tunnel tests using the same configuration as the full scale tests and correlates the wind tunnel and full scale results.

Full scale tests were run by mounting the trailers on a system of flexures and load cells so that the forces applied to the trailers could be measured. These forces consist of aerodynamic and body forces. The body forces are of two types, gravity and acceleration. These forces were principly determined by measuring the velocity of the train into and out of the test zone and by determining the grade, super elevation, and curvature of the track through the test zone. The aerodynamic forces can then be determined by subtracting the gravity and acceleration forces from the total forces on the trailers. It was also necessary to know the relative wind speed and direction. This was determined by an on-board anemometer located in front of the locomotive and a set of two anemometers located at a wayside ground station along the test zone. The relative wind could be predicted by the vector addition of the ground wind and the velocity of the train and compared with the wind measured by the on-board sensor. These two results were in reasonable but not exact agreement.

In the series of wind tunnel tests reported in Volume I, but omited from the report, measurements were made of the forces on the trailers alone when mounted on the TTX car in anticipation of the full scale tests. However, the configuration tested turned out to be not identical to the full scale tests. For this reason, and also to obtain tests at a Reynolds number closer to the full scale value, a set of wind tunnel tests was made at the Calspan pressurized trans-sonic wind tunnel facility. The same models were used as in the original set of tests but they were run at higher velocity and density. It must be understood that Reynolds number is the proper aerodynamic scaling parameter and not the actual size of the model. Since Reynolds number involves a combination of size, velocity, and density, high Reynolds numbers can be obtained by proper combinations of all these parameters. Results obtained at these different velocities and densities can then be compared if the actual forces are divided by dynamic pressure.

The full scale and wind tunnel results obtained from these tests were then compared. The agreement between these sets of data is reasonable, within about 20%. The sets of wind tunnel data bracket the full scale results. The agreement between the wind tunnel results themselves is not as good as anticipated.

Experience with these test methods has demonstrated that the wind tunnel is a very cost effective way of obtaining aerodynamic data as compared with full scale tests. Full scale tests are much more expensive and would be even more so for configurations other than those for which full scale hardware is in existance. The wind tunnel tests give proper trends and reasonably exact values. The accuracy and repeatability of the full scale tests are difficult to evaluate for different sets of tests until more experience with these techniques is gained.

A secondary objective of the full scale tests was to obtain a measurement of the rolling resistance. These measurements were made over very good track, using cylindrical wheel contours with the result that no truck hunting occurred. In these respects, they may not be representative of revenue train operation. The technique used was to subtract the measured aerodynamic forces from the total resistance obtained from measurement of the coupler forces. Difficulty was encountered by relatively large hysteresis in the measurement of the coupler forces. This difficulty led to the need to place relatively large error bars on the data. However, within this uncertainty, the data is consistant and in reasonably good agreement with the predictions of the Davis formula. The technique appears to be sound but a better coupler force measurement technique is needed.

1. INTRODUCTION

The measurement of the resistance of railroad trains has been a subject of interest for more than 100 years. Notwithstanding this long history, engineering data is not yet available for making accurate predictions of such resistance. The rolling resistance is hard to measure and the parameters which effect it are hard to control. The wind tunnel is a good way of measuring aerodynamic forces but has not yet become a thoroughly reliable and trusted means of measuring aerodynamic forces for railroad trains operating on the ground. The principle reasons for this are the lack of proper ground plane simulation and the old classic problem of Reynolds number extrapolation. In full scale tests of total resistance, it is difficult to separate aerodynamic from rolling resistance.

Not surprisingly, the aerodynamics of trains seems to have been the area in which aerodynamic resistance first was recognized as being of practical importance. Full scale and wind tunnel measurements were both used in studying this problem. Until the early 1900's trains were the only means of conveyance that could reach high enough speeds so that wind resistance became important. Wind tunnels were first utilized for testing railroad trains by W. F. M. Gross at Purdue University in 1896, Reference 1. This seems to be one of the first recorded uses of wind tunnels in the United States and took place before the advent of the airplane. Full scale testing also took place at quite an early date and was of two forms. The overall resistance of trains was measured and the aerodynamic resistance of a car body itself. In 1910, Professor Schmidt at the University of Illinois, Reference 2, made measurements of the resistance of freight trains starting a line of research which continued at the University of Illinois up to the present time. An interesting early attempt to measure the aerodynamic resistance of a street car body was carried out by the Electric Railway Commission in 1906, Reference 3, by measuring the aerodynamic resistance on a street car body mounted on a railroad flat car.

Many of the early reports on the overall resistance of trains have been compiled by W. J. Davis, Jr. in his 1926 paper, Reference 4. He attempts to break the resistance up into various components by a functional relation. The resistance term that varies as the square of the speed is considered to be the air resistance. This same method has been used by most of the investigators who have attempted to separate air resistance from other overall resistance measurements.

The use of wind tunnels to determine the aerodynamic resistance was not exploited until the 1930's. By this time the technique had been developed in connection with the aircraft industry and the importance of air resistance was better appreciated. Streamlining of trains was also being considered and a variety of wind tunnel tests were run to determine the characteristics of trains in general and streamlined trains in particular. The work of O. G. Tietjens and K. C. Ripley at Westinghouse, Reference 5, A. Klemin at New York University, Reference 6, and F. J. Johansen at London, Midland and Scottish Railway, Reference 7, are all examples of wind tunnel aerodynamic testing to determine and improve the aerodynamic resistance of passenger trains.

Since World War II, interest in the aerodynamics of passenger railroad trains has been minimal in this country. Considerable work has taken place in England, France, Germany, and Japan. The actual operation of high speed rail lines in Japan over the past several years has been an important stimulus to such investigations. The French have built a special wind tunnel for the testing of railroad trains at Saint Cyr L'Ecole, Reference 8. This tunnel provides a longer test section than that ususally found in other wind tunnels and is more appropriate for testing of railroad trains. A boundary layer control system is provided to make this long test section usable.

In recent years, the interest in the aerodynamics of freight trains has increased in this country. This interest was generated by the problems of special cars which had particularly high aerodynamic resistances. Practical experience on the railroads has shown that the power to pull rack cars and trailers on flatcars is higher than for the usual type of car. Wind tunnel tests were made by J. T. Matthews and W. F. Barnett in 1968, Reference 9, on automobile rack car configurations. These tests confirmed the high aerodynamic resistance of rack cars and showed ways in which it could be reduced. R. W. Luebke, Reference 10, compared the wind tunnel results with full scale data on the overall resistance of rack car trains and showed a reasonable agreement between the two. Full scale tests of trailers on flatcar configurations have demonstrated their high drag. Such tests were run by the Erie Lackawanna, Reference 11, the Santa Fe, Reference 12, the New York Central, Reference 10, and the Chesapeake and Ohio, Reference 10, and have all shown the increased resistance of this configuration.

All of the full scale tests which have been mentioned use measurements of overall resistance and attempt to determine the aerodynamic resistance from this measurement. The one full scale attempt to determine aerodynamic resistance directly was that briefly mentioned previously by the Electric Railroad Commission, Reference 3, in connection with the centennial celebration of the Louisiana Purchase in 1906. In this case, a street car body was mounted on top of a self propelled flat car. The street car body was attached to the flat car by a balance system that allowed the forces on the street car body to be measured, Figure 1. For a car run at a constant speed in a straight and level direction, the body forces were zero and the only forces on the body were aerodynamic forces. This is the only method that has been used for the direct measurement of aerodynamic forces on a rail vehicle and seems particularly appropriate to the problem to be considered in this report.

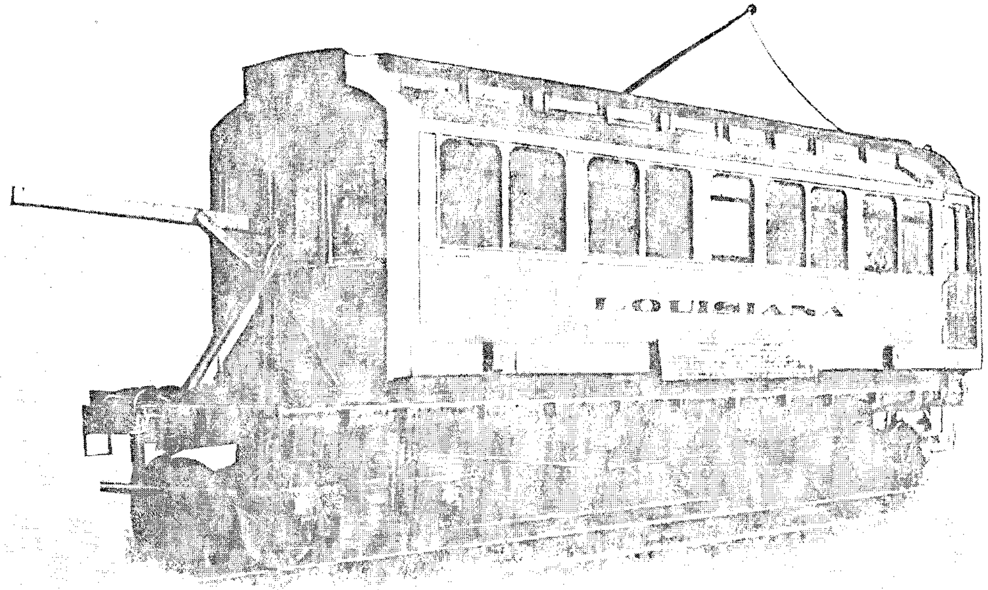


Figure 1. "Louisiana", Test Car Run for Louisiana Purchase Exposition in 1906 to Measure Aerodynamic Drag. Trolley Car is Attached to Flat Car by Balance so that Aerodynamic Forces can be Measured. Car is Shown with Flat Vestibule in Front and Lever Mechanism Designed to Statically Calibrate Balance.

The program to be discussed in this report investigated the aerodynamic characteristics of trailer on flatcar configurations using both wind tunnel and full scale tests. The wind tunnel tests were used to study a variety of configurations. Models of actual TTX cars loaded with various trailers and containers were used with a variety of loading configurations. In addition to these standard configurations, a variety of modified flatcar and trailer designs were tested to evaluate the benefits which might be achieved.

Full scale tests were then run using only the standard configurations in order to evaluate how accurately the wind tunnel predicted actual conditions. These full scale tests were run by a technique similar to that pioneered by the Electric Railway Commission in 1906 , Reference 3. The aerodynamic forces were measured on the trailers themselves, exclusive of the flatcar, in both the full scale tests and the particular wind tunnel tests performed for direct comparison with them. In this way a direct comparison between the wind tunnel and full scale was obtained by direct measurement. It is believed that this is the first time such a direct comparison has been made.

This program has consisted of two sets of wind tunnel tests and two sets of full scale tests. The original wind tunnel tests were carried out at the California Institute of Technology's GALCIT 10 foot wind tunnel facility in December, 1975. These tests were on a wide variety of different configurations and have been reported in Reference 13. During the accomplishment of these tests, the concept for the full scale experiments was developed, References 14, 15 and 16. In order to prepare for the comparison with the full scale tests, a few runs were made in the CIT tunnel with the trailers only mounted on the balance.

The next step was a series of full scale tests run at the Transportation Test Center at Pueblo, Colorado. ENSCO Incorporated designed and constructed the instrumentation and was responsible for carrying out the tests following the principles developed in References 15 and 16. The initial tests were unsuccessful in producing reliable and repeatable results, References 17 and 18. The instrumentation was apparently not capable of performing adequately under the rather hostile environment to which it was subject. After a thorough evaluation, it was decided that the concepts were sound and that the difficulties could be overcome by more careful execution. It was decided to proceed with another set of full scale tests and an additional set of wind tunnel tests at a higher Reynolds number, one more nearly matching full scale than the one achieved in the original tests, and using the same configurations as those to be tested full scale. These additional wind tunnel tests were carried out at the pressurized wind tunnel facility at Calspan. The data from these tests is reported in Reference 19 and analysed in Reference 20. The data for the full scale tests is reported in Reference 21.

The present report will not cover the original series of wind tunnel tests conducted at the CIT facility since they have been adequately reported in Reference 13. It will cover the wind tunnel tests performed at both CIT and Calspan (in which the forces on the trailers alone were measured for direct comparison with the full scale results), analysis of the full scale results, and correlation between the two.

2. FULL SCALE TESTS

2.1 Methods for Measuring Aerodynamic Effects

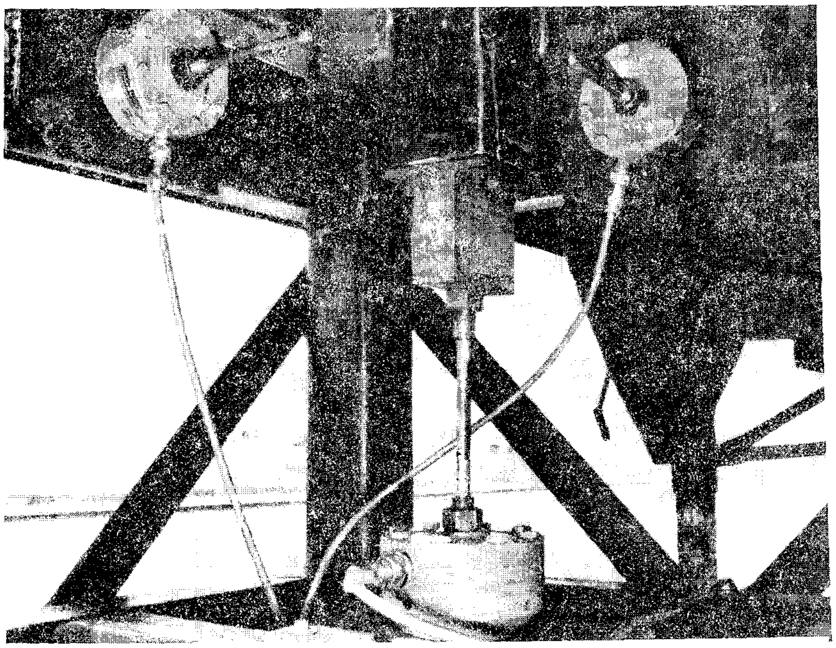
The measurement of the aerodynamic forces on railroad cars is not a simple matter. The main difficulty is that the aerodynamic forces are relatively small compared with possible inertia and gravity forces and that it is also difficult to isolate them from the wheel forces. The longitudinal force is the aerodynamic force of most interest. It is necessary to measure the aerodynamic forces on a particular car or on a group of cars while coupled into a consist of other cars since the force on an isolated car is not of particular interest. Measurements in the past have been confined to measuring the longitudinal force by obtaining the total resistance of an entire train and then separating the aerodynamic part of this total either by subtracting off the rolling resistance as obtained from some other source or by fitting a polynomial to the resistance as a function of velocity curve and assuming that the part which is proportional to the velocity squared is the aerodynamic longitudinal force. If the resistance of an individual car located in a consist of several cars is required, the problem is more difficult since the difference between the coupling forces at each end of the car must be obtained. However, both of these techniques for obtaining the aerodynamic part of the entire resistance term leave much to be desired.

For the present program, a direct measurement of the aerodynamic resistance seemed to be the best method. The direct method is particularly appropriate to the case of trailers on flatcars since the principle aerodynamic forces are applied to the trailers which are attached to the flatcars at only a few points. It is relatively simple to mount the trailers on flexures and load cells and thereby determine the forces applied to the trailers. The aerodynamic forces applied to the flatcar are not measured but these are only the smaller part of the total. However, the real purpose of these experiments is to compare wind tunnel and full scale measurements. If the forces on the trailers alone are also measured in the wind tunnel, the results should be directly comparable with the full scale measurements. This technique is particularly appropriate because of the special nature of the trailer on flatcar configuration and would not be as easily accomplished or convenient for other configurations.

The difficulties of making such measurements are caused by the relatively small size of the aerodynamic forces relative to the weight of the trailers and the relatively large accelerations and oscillations to which railroad equipment is subject in normal operation. The short time oscillations caused by the track roughnesses, truck hunting, and other ride quality effects can be eliminated by averaging over many oscillations. The longer time accelerations such as longitudinal acceleration and track curvature can be controlled, their magnitude measured, and corrections made. Along with accelerations, the component of the gravity vector in directions other than that perpendicular to the deck of the flatcar can also be important. These effects can be reduced by using a good quality section of track, improving the ride qualities of the flatcars, and correcting for the changes of speed and elevation over the length of the run and the average super elevation between the rails.

2.1.1 Forces

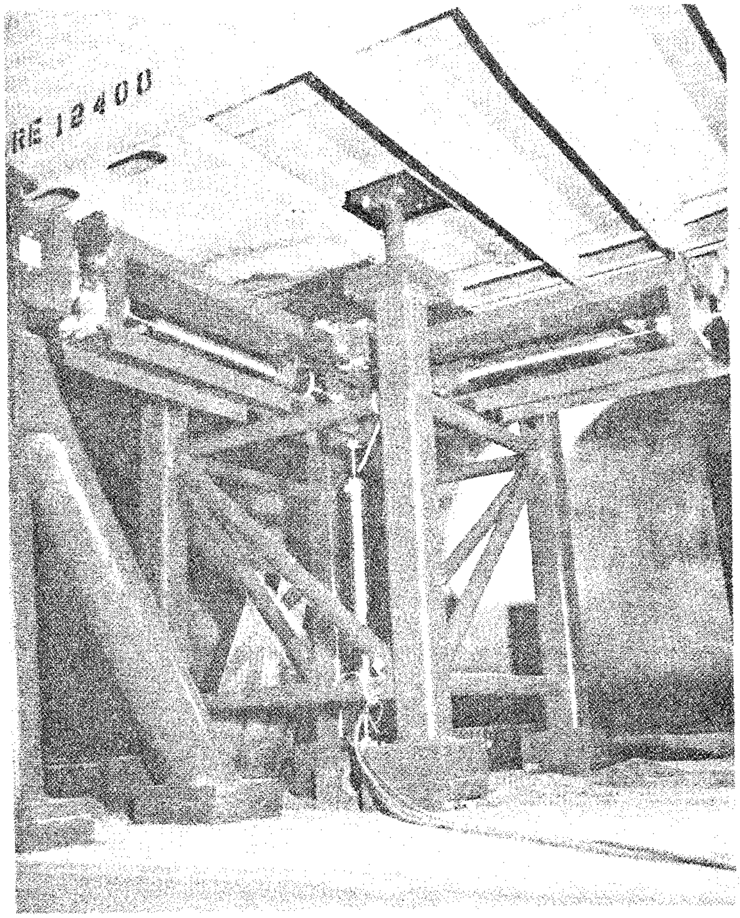
The basic techniques used in both Phase 1 and Phase 2 of these experiments were the same. The main difference was the care with which these techniques were carried out. The need for greater care and precision was demonstrated during Phase 1 and the success of Phase 2 showed the benefits learned from these lessons. The measurement of the forces applied to the trailers was achieved in both instances by supporting the trailers on flexures and measuring the forces by load cells. The flexure/load cell system used in both cases is shown in Figures 2 and 3. The trailers were supported at the forward ends at their kingpins in the vertical, longitudinal, and lateral direction by flexures and load cells. At the rear, the trailer was supported by two vertical flexures and load cells on each side, which also prevented rolling, and one lateral flexure and load cell. This system of six flexures and load cells allowed the six force and moment components to be determined. After experience with the Phase 1 balance assembly, it was judged that the support structures were too flexible and the flexures too rigid. These difficiencies were corrected in Phase 2 by using more massive support structures, longer flexures, and flexure pivots. Mechanical stops were also incorporated in the Phase 2 balance to prevent the load cells from being overloaded during train handling operations. Con-



Forward Support Under King Pin

Support Under Rear Axle

Figure 2. Force Balance System Used in Phase 1.



Forward Support Under King Pin

Rear Support at Back of Van

Figure 3. Force Balance System Used in Phase 2.

siderable more care was exercised in lining up and calibrating the Phase 2 balance with the result that "cross talk" between the various load cells was virtually eliminated.

In the Phase 1 balance assembly, the strain gauge amplifiers were located on the deck of the TTX car to make the unit more self contained and reduce the amount of support equipment needed to check out the systems. In the post Phase 1 evaluation it was judged that locating these electronic assemblies in an unprotected location could have been responsible for some of the zero shift problems which were encountered in the Phase 1 testing. In the Phase 2 tests all of these assemblies were moved inside of the supporting DOT/FRA (T-5) instrumentation car where the temperature was better controlled and the vibration level was reduced.

2.1.2 Wind Velocity

Another important measurement is the velocity of the wind relative to the train. In both phases of the experiment a relative wind measuring instrument was mounted on the train and another along the wayside. The instruments used in both experiments were the same. A Propvane Model 8002 was used on the train and two Climatronics Mark 3, located 8 feet and 20 feet above track level, were used for the wayside station which was located about the middle of the test section and 100 feet from the track in both Phase 1 and 2, Figure 4. In Phase 1 the instrument on the train was mounted on a mast 11 feet above the forward end of the T-5 car, Figure 5. In

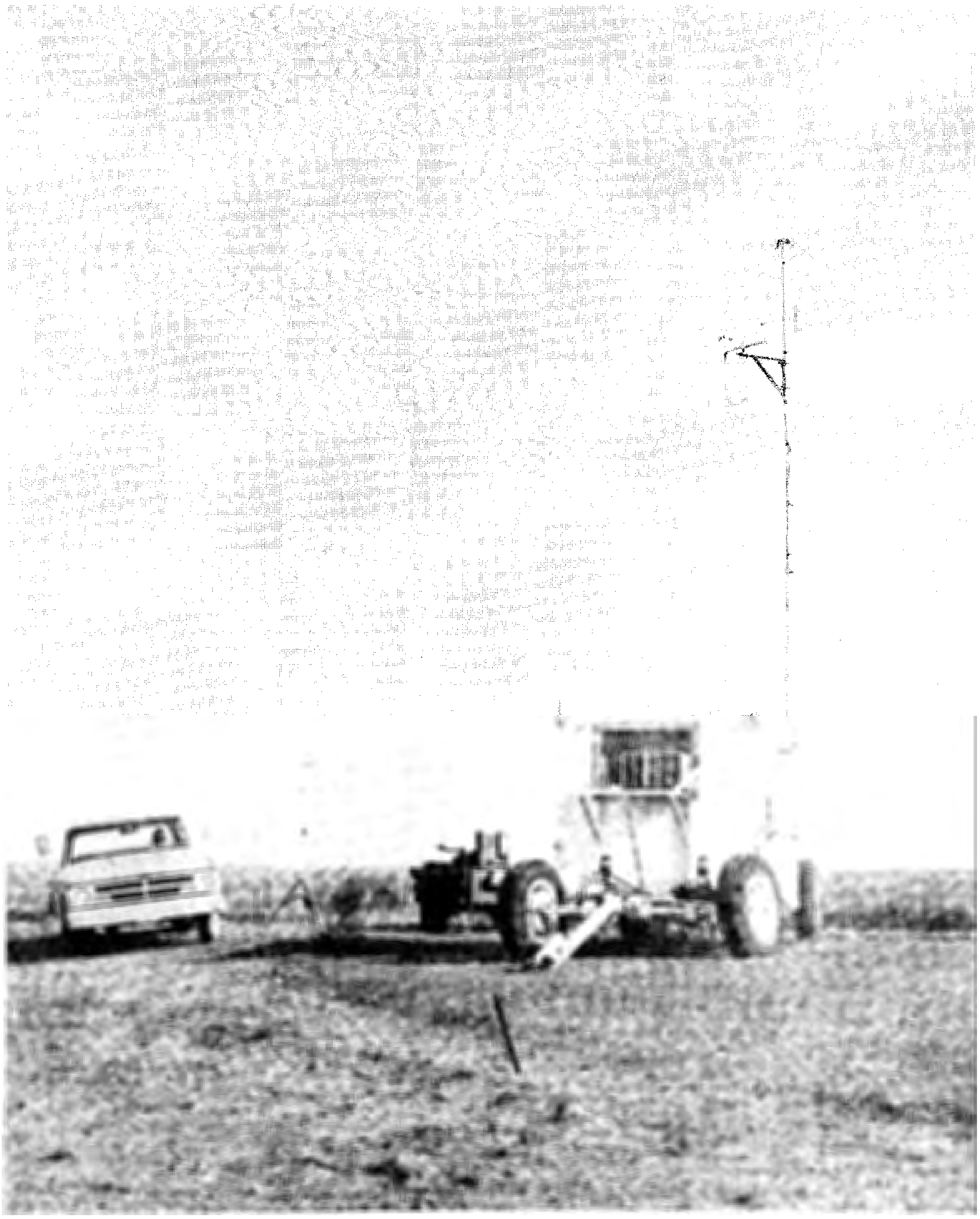


Figure 4. Wayside Weather Station Showing Anemometer on Side of Van 8 feet Above Rail and on Mast 20 feet Above Rail.

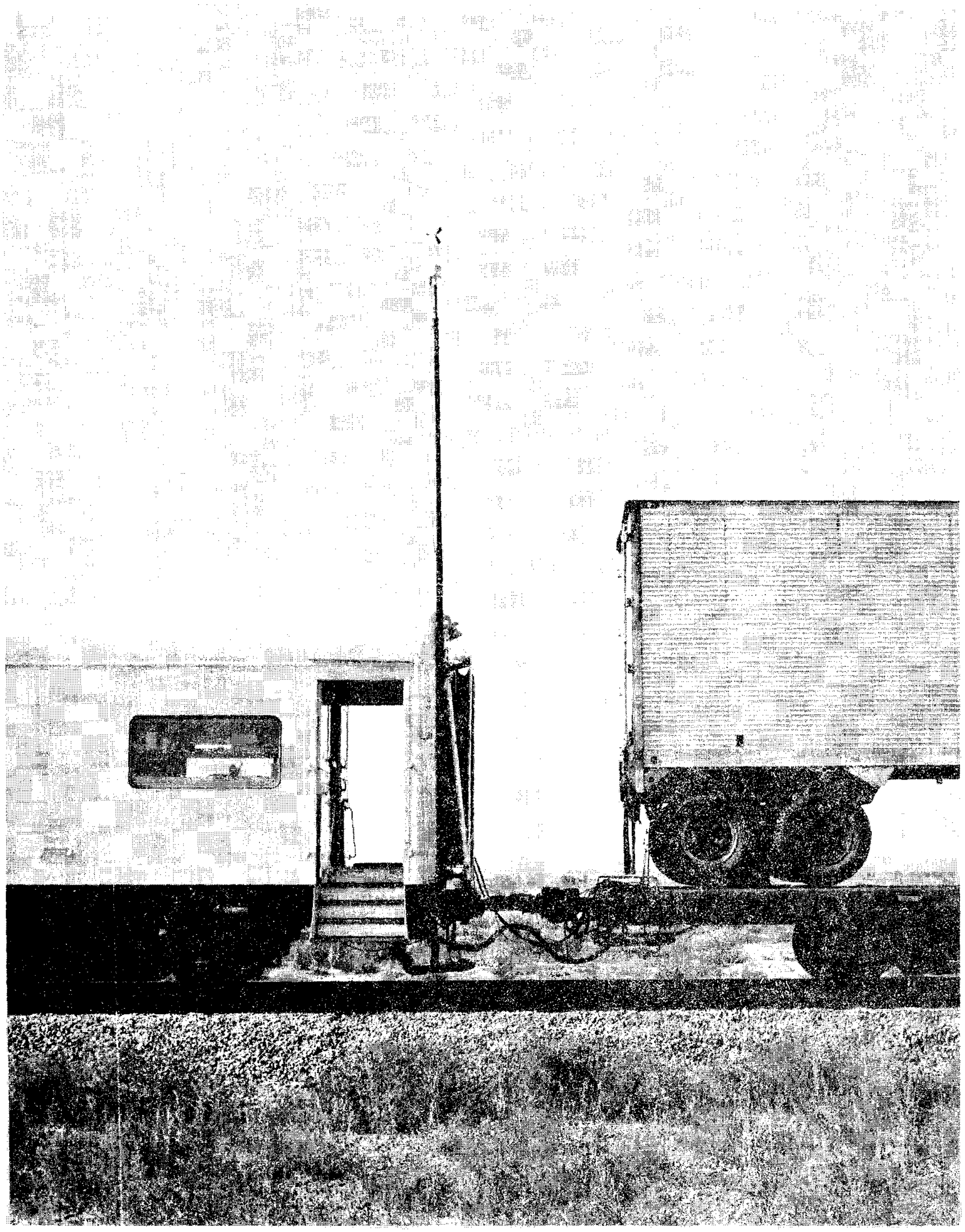


Figure 5. Phase 1 Test: On-board Anemometer Located on Mast 11 feet Above T-5 Instrumentation Car.

the Phase 2 tests it was located 19 1/2 feet above the rail and in front of the locomotive, Figure 6. The mast used for Phase 1 proved to be too flexible so the boom used in Phase 2 was built considerably stiffer.

2.1.3 Accelerations

It is important to know the accelerations to which the trailers are subjected in order to subtract the body forces from the measured forces. These accelerations were determined in two ways. The system recommended in Reference 15 was to determine the longitudinal accelerations from the change in velocity through the test section and lateral and vertical accelerations from curvatures obtained from track survey data. It was possible to obtain a section of track for which the curvatures were small enough so that they could be neglected. For Phase 1 it proved impractical to use the wheel count speed measuring device as originally planned to obtain the change of speed through the test zone and it was necessary to use the time between the first and last set of ALD markers to do so. In Phase 2, the wheel count device was used although unexplained difficulties did occur on a few runs. The component of the gravity vector in the longitudinal and lateral directions also caused a body force for which corrections had to be made. In order to do this, the orientation of the deck of the TTX car had to be known with considerable accuracy. The track grade and super elevation was determined from track survey data. In Phase 2 an additional step

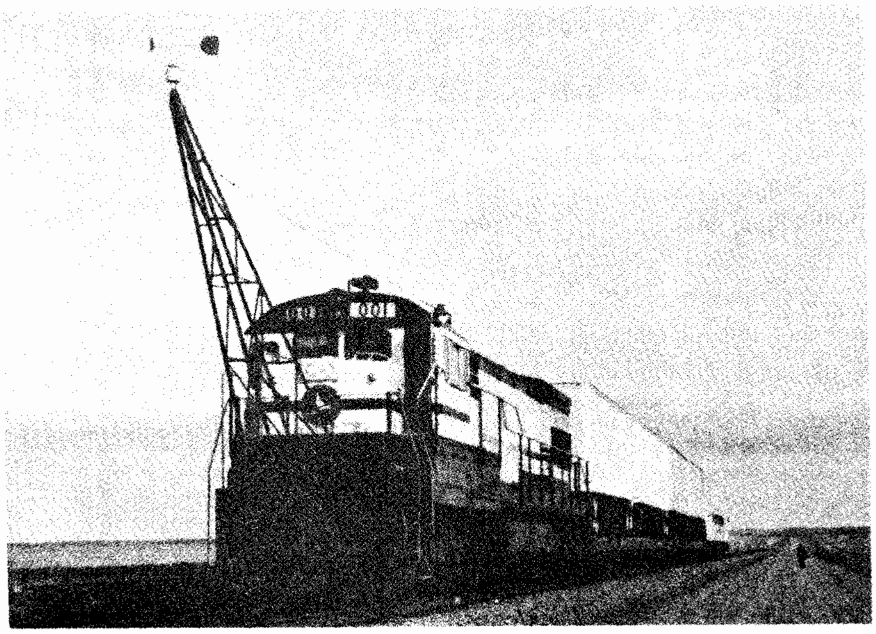


Figure 6. Phase 2 Test: On-board Anemometer Located 19.5 feet Above Rail in Front of DOT 1 Locomotive.

was taken to relate track conditions to the TTX car deck. Linear transducers were mounted across the truck spring groups to measure any changes in length which might take place during operation. An additional acceleration measurement was obtained by mounting several 3-component accelerometer packages on the TTX car and trailers. Since it was desirable to know accelerations to .001 g, it was anticipated that these accelerometers might prove inadequate and they were not considered as the primary source of acceleration data.

2.1.4 Position

Position along the track was measured by automatic location detector (ALD) markers. For the Phase 2 tests these were spaced at 800 foot intervals along the 4,000 foot test zone. These markers were detected by the DOT T-5 instrumentation car to determine the beginning and end of the test zone as well as progress along the zone.

2.2 Data Recording and Processing

The data was digitized at the rate of 256 samples per second and recorded on tape in the T-5 car. In the Phase 1 experiments the wayside weather station data was recorded on a strip chart in the weather station. This system was improved for Phase 2 so that the data was telemetered to the T-5 car and recorded along with the other data. The data was then time averaged over the entire length of the run by the computer on the T-5 car and printed out. Data could be read out after the completion of each run but it was usually found to be more practical to complete several runs and process in larger batches. The data was available quickly enough so that decisions on how the tests were to be carried out could be made based on this information. A careful analysis of the various source of errors has been made and presented in Reference 20. This analysis proved useful in the design of the experiment and the identification and improvement of the major sources of error. Various averaging techniques were considered and are described, but, considering the practical restraints that existed, it was concluded that simple time averaging of the different quantities as had been done in Phase 1 was as good as could be done for at least the initial onboard data reduction.

2.3 Method for Conducting Tests

The test program was run at the Transportation Test Center in Pueblo, Colorado. For the Phase 1 tests the west tangent of the Railroad Test Track was employed. This provided a 3,520 foot length of straight bolted track with a 0.62% upgrade when running in the northerly direction, Figure 7. For Phase 2 the test track was the east tangent of the Railroad Test Track. The test section provided a 4,000 foot stretch on straight 136 lb. welded rail track with a uniform downgrade of 0.275% when running in the southerly direction. The test section was maintained to meet FRA Track Classification 6.

The test consist was made up of the DOT 1 locomotive, two TTX cars, and the T-5 car, Figures 8a and b. The second TTX car was the instrumented one. The forward TTX car was termed

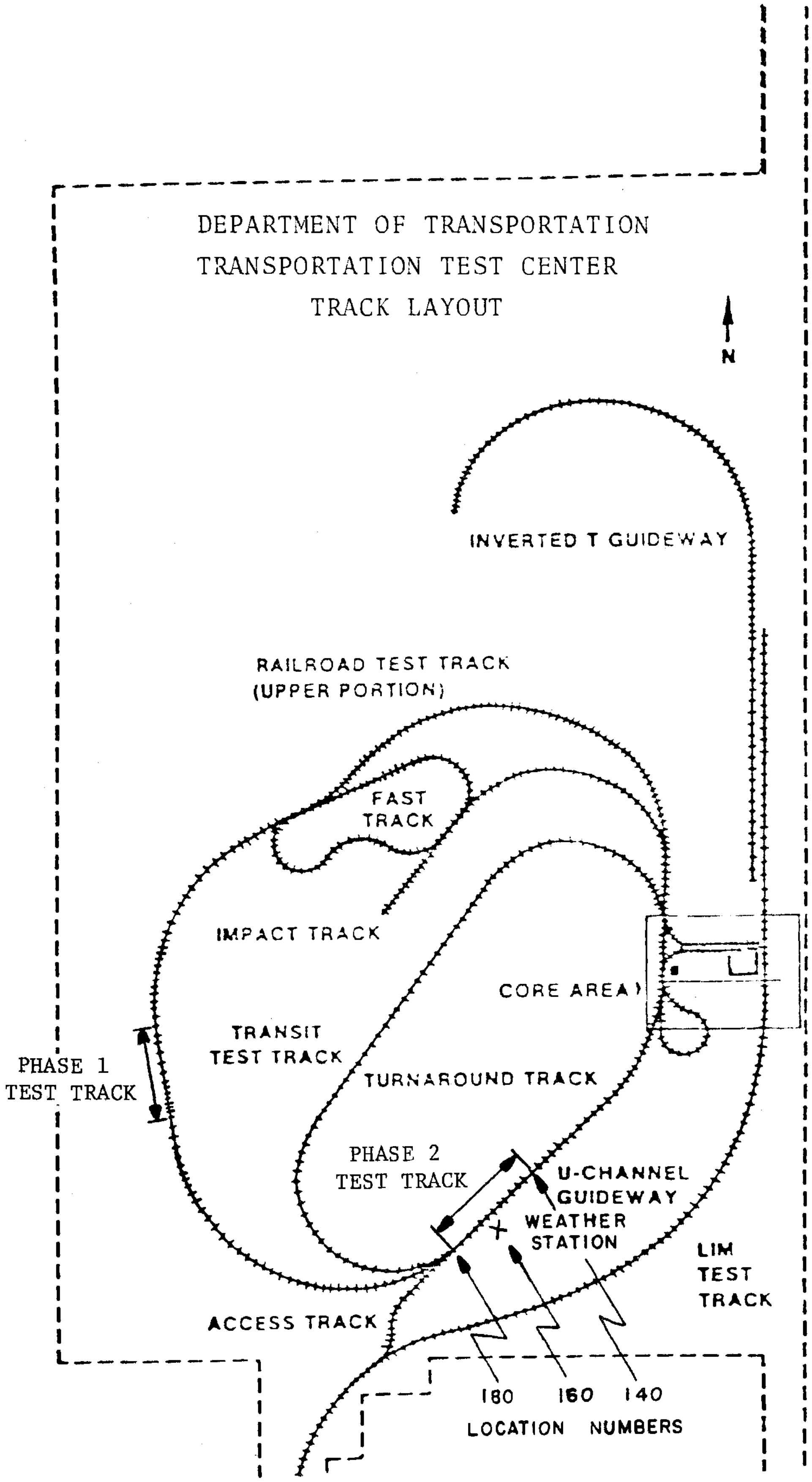


Figure 7. Transportation Test Center Railroad Test Tracks Showing Location of Phase 1 and 2 Test Zones.

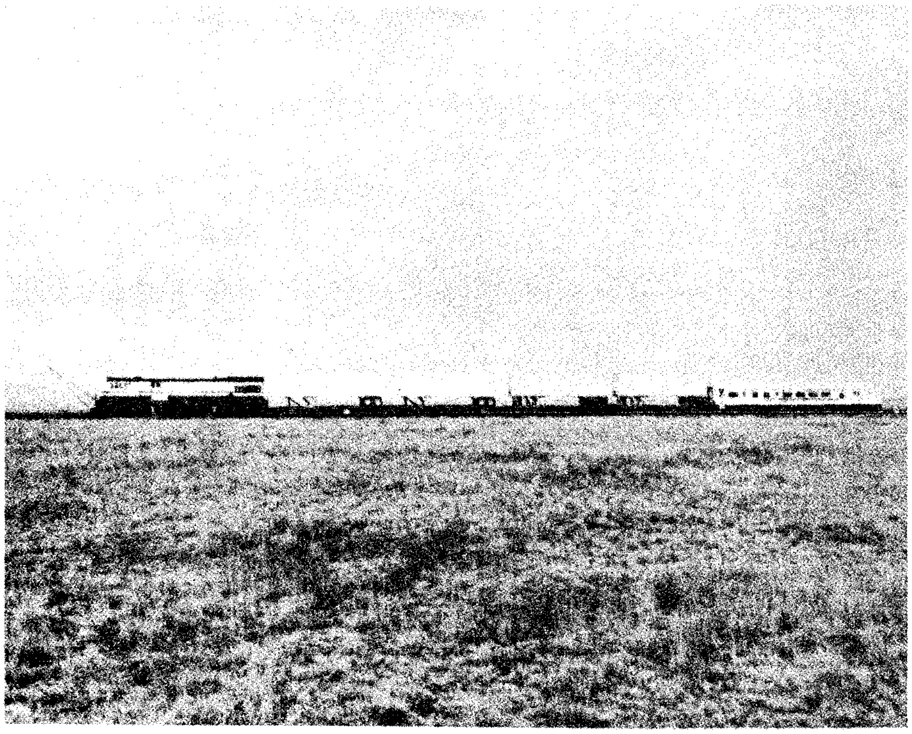


Figure 8a. Test Consist - Configuration 1

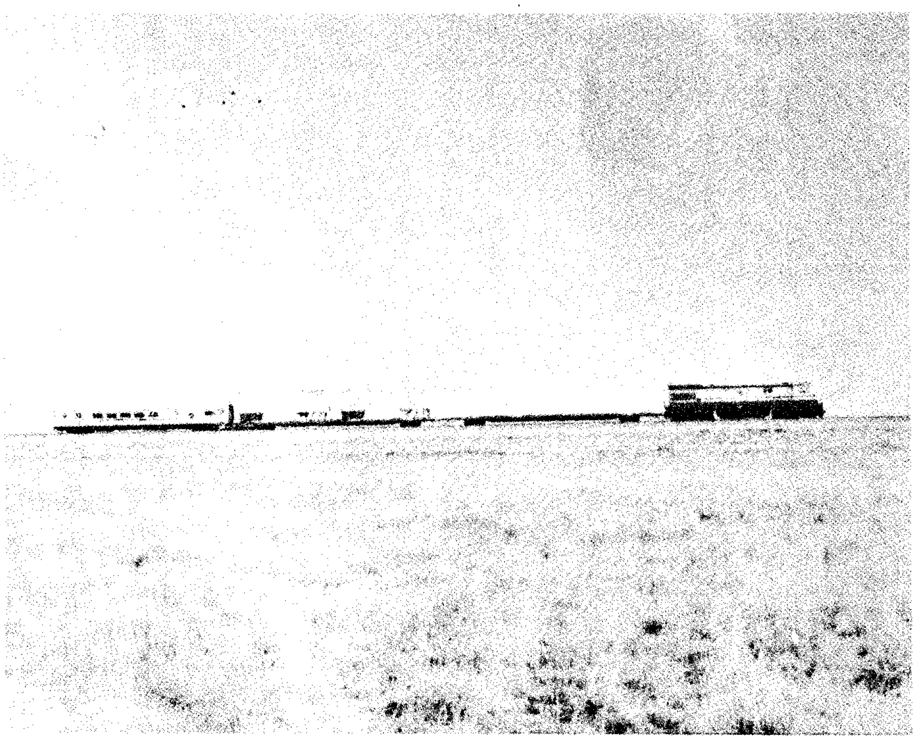


Figure 8b. Test Consist - Configuration 2

the buffer car and was run in both the loaded condition for Configuration 1 and the unloaded condition for Configuration 2. In the Phase 2 testing the TTX car was specially modified to minimize truck hunting and to provide a stable platform for the measurements. Truck hunting had been encountered during the Phase 1 testing and the rough environment to which the instrumentation had been subjected during these tests was blamed for some of the difficulties encountered. For the Phase 2 tests special modifications were made to provide a better ride. The wheels were turned to a cylindrical profile and softer spring groups were used in primary suspension. In neither phase of testing could the consist be run completely around the track. The anemometer boom would not pass through an obstruction located on another section of the track. The test procedure was to start the train from a location far enough in front of the test zone to accelerate to the desired speed, reach the desired speed before entering the test zone and set the throttle to maintain this speed, keep the throttle at a constant setting through the test zone even if this resulted in a small change in speed, and then decelerate after leaving the test zone. To achieve the proper speed and throttle setting at the beginning of the test zone required some skill and experience on the part of the engineer. During the Phase 2 testing, the engineers became quite skilled at doing so and this was an important contribution to the success of the tests.

The wind conditions could not be controlled by the experimenters but some flexibility existed in the selection of the time for the test runs. It proved easier to obtain runs under conditions of low winds than strong winds. An attempt was made to schedule tests when strong winds were predicted and some runs were obtained at reasonably large angles of yaw but the wind did not always live up to the predictions. During the Phase 1 testing, the instrumentation was found to undergo considerable zero shifts. The procedure that was adopted was to stop the train at the middle of the test zone and record the zero readings. Unfortunately, the shifts between the beginning and end of a run were sufficiently large such that the run results were questionable. Also, this zero checking procedure was not considered completely reliable. There was some question whether the TTX car was at the same point on the track and at the same grade and whether the winds were causing an important effect. The Phase 2 testing was planned to provide reliable zero checks before and after each day's testing and checks of the static calibrations during the testing period. The TTX car was returned to the same point in the TTC Central Services Building where the zeros could be checked and the orientation of the deck of the TTX car measured optically. The details of this procedure are described in some detail in Reference 21. During Phase 2, the instrumentation proved very reliable. The zero readings and the static calibration held very well during the entire run series.

The major problems that had existed in the Phase 1 testing seemed to be overcome in the Phase 2 testing. However, some problems did exist in Phase 2. An unreliability was found in the wheel count speed measuring systems. The system had originally been set up so that the counts were dropped over a small part of the recording cycle. This dropping of counts had negligible effect over the longer averaging periods for which the system had been originally designed. However, when the time over which the counts were obtained was shortened to obtain an accurate reading of the initial and final velocities, an important error was introduced when counts were dropped during the period of making this initial and final measurement. This difficulty was recognized early in the program and corrected. However, this did not overcome the entire difficulty with this system. For each run the total number of counts obtained was recorded and this number was compared with the length of the test zone. In some instances spurious results were obtained. This only occurred on a few runs and the test series is not seriously degraded by leaving out these runs. Another difficulty encountered was obtaining correlation between the ground station wind readings and the on-board wind readings. Since the velocity of the train causes the principle component of relative wind and this velocity is measured accurately, the true relative wind can be determined from this velocity and a small correction for the actual ground wind. In this way the relative wind can be obtained more accurately than the measurement of the ground wind. The on-board wind measurement has the advantage that it was actually on the train and close to the location at which the actual measurements were being made. It has the disadvantage that it was on the train where it was more likely to be influenced by the disturbance caused by the train. As will be discussed later, it is difficult to determine how exact an agreement should be expected and which means of obtaining the relative wind is the more appropriate for correlating the aerodynamic data.

2.4 Test Program

The Phase 1 test program is described in References 17 and 18. Since worthwhile results were not obtained from this phase of the testing, a further discussion of these tests is not warrented.

A total of 108 test runs were made over a period of 25 days during the Phase 2 test series and reported in Reference 21. Tests were run at nominal speeds of 50, 70, and 90 mph. The first 23 of these runs were considered check out runs and no data was reduced. A few additional difficulties were found during the next few runs which invalidated some of the runs and could be considered part of the check out process. Of the 85 runs made after the check out phase, some problems occurred on 31 which made them not fully satisfactory. However, 54 runs were obtained on which there did not appear to be any problems.

2.5 Data Reduction

The data obtained from the Phase 1 tests contained too much scatter to be definitive as discussed in Reference 18. The Phase 2 tests were conducted with considerably better results. For this reason the data presented will be that obtained in Phase 2.

2.6 Test Results

The data reduction process is described in some detail in Reference 21. In general, the data was averaged over the full length of the run giving only one data point per run. An initial step is to compare the relative wind velocity and direction obtained both from the on-board instrument and calculated from the wayside readings and the train velocity. There were two wayside anemometers located 8 and 20 feet above the rail. The average results are available only for the one located 20 feet above the rail. A plot of the difference between the on-board and calculated results is shown in Figures 9a and b for both direction and speed. The on-board anemometer was calibrated after the completion of the runs in the wind tunnel at the Virginia Polytechnic Institute and State University. This calibration showed an error of 1° at 50 and 90 mph and no error at 70 mph. The details of this calibration are discussed in Reference 21. The results shown in Figures 9a and b are based on the corrected value of the anemometer. The figures show a scatter with a standard deviation of 2.3° about an average difference of 1.3° and a standard deviation of 5.8 mph about an average difference of 0.5 mph. While this is a relatively small difference, it appears to be an important contribution to the scatter in the force vs angle of yaw data. It would be desirable if a better resolution of the merits of these two methods of determining wind direction could be obtained. If the wind were steady, it would appear that the relative wind calculated from the ground station measurements and the train speed would be the most reliable. This is because any

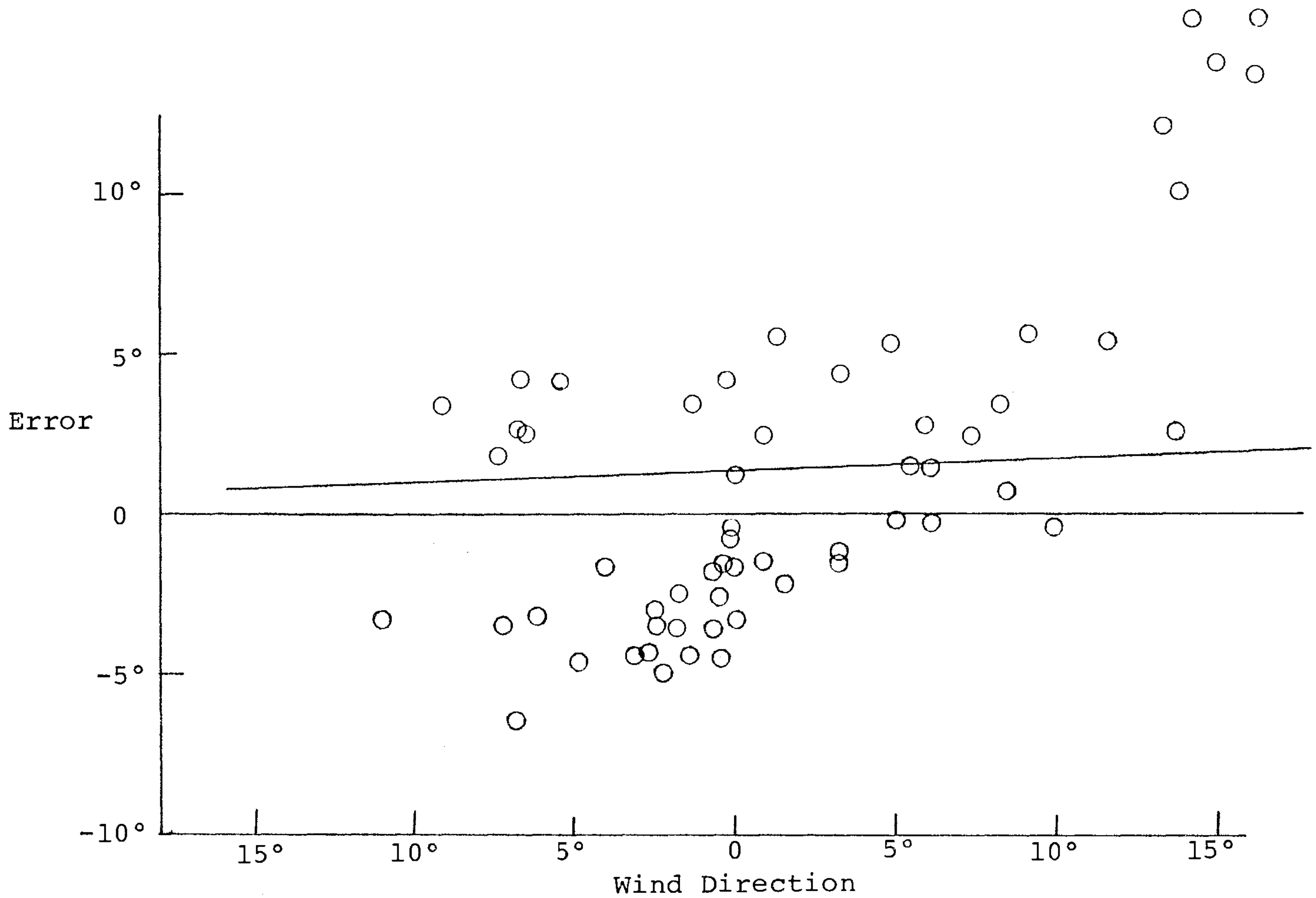


Figure 9a. Difference in Direction Between Relative Wind Measured with On-board Anemometer and Calculated From Train Velocity and Ground Wind as a Function of Yaw Angle.

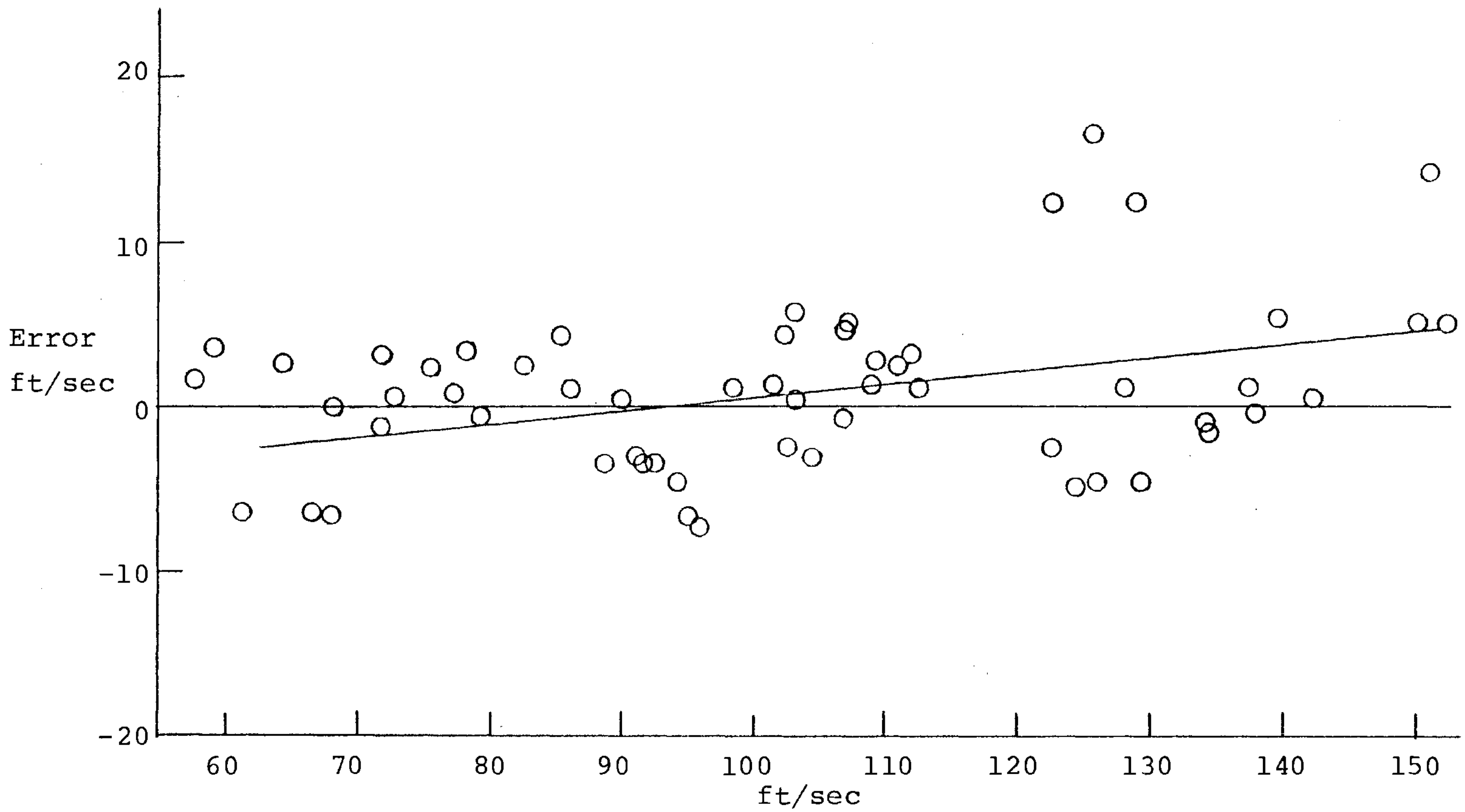


Figure 9b. Difference in Speed Between Relative Wind Measured by On-board Anemometer and Calculated From Train Speed and Ground Wind as a Function of Relative Wind Speed.

error made in the wayside wind measurement results in a considerably smaller error in the calculation of the relative wind. Also, the train speed measurement is one which is made with considerable accuracy. However, the question of variation of the wind both with respect to time and space cannot be ignored. Observations of the on-board and wayside wind vane show that there is considerable variation, especially when there is an ambient wind. If it is considered that the variations or turbulance of the ambient wind are carried with the speed of the wind, the train, moving at a much higher speed than the true wind, will encounter many more gusts in the time needed to traverse the test zone than will the stationary wayside wind station. Another possible source of inaccuracies is the interference caused by the train on the on-board anemometer and on the wayside station at the time of passage of the train. Some resolution of the question might be possible if the data averaged between ALD markers was available for a substantial number of runs. If this data were available, one could attempt to examine whether there was a systematic variation of the wayside readings when the train was passing the station and whether the differences between the on-board and wayside results were more pronounced when the train was distant from the wayside station than when it was passing the station.

The forces on the trailers were determined by the load cells of the balance. The static calibration showed that the longitudinal force could be determined directly from the longitudinal load cell and the lateral force directly from the two lateral load cells. There was no need to use a calibration matrix involving other load cells. To obtain the longitudinal aerodynamic force in the initial data reduction, the measured longitudinal force was corrected by gravity effect, a grade of 11 feet in 4,000 feet, and by the longitudinal acceleration. This acceleration was obtained from the differences of the velocities of the T-5 car at the beginning and end of the test zone. The force areas were then obtained by dividing the total force by the dynamic pressure of the relative wind obtained from the on-board anemometer. In the latter phase of data reduction, secondary effects were also considered. Velocity differences between the T-5 car and the TTX car were determined from the linear transducers located between the cars to measure the change of length of the coupler. The changes in slope of the deck of the TTX car with respect to the rails was also measured by linear transducers around the spring groups on the trucks. Examination of these measurements showed that neither had a noticable effect on the longitudinal force data. Therefore, there was no modification of the longitudinal force data caused by the final data reduction.

The lateral forces on each trailer were determined as the sum of the two lateral force load cells. No lateral accelerations or gravity effects were included in the initial data reductions. The final data reduction included an examination of lateral accelerations caused by track curvature and gravity effects caused by super elevation and changes in the slope of the deck of the TTX car with respect to the rails. An examination of track survey data showed that the track was straight with a slight super elevation amounting to an average of 0.1

inches, giving a net side force per trailer of 17.6 lbs. An examination of the linear transducers on the trucks showed no additional lateral tilt of the deck of the TTX car.

In this experiment the forces were measured on each trailer. On the other hand, in the wind tunnel tests, measurements were made only of the combined forces on both trailers. Therefore, for comparison with the wind tunnel tests, while it is necessary to consider only the combined forces, it is still useful and informative to consider the forces on each trailer. In the presentation of these forces, it is necessary to select one set of relative wind results to serve as a basis for presentation. In Reference 20 both sets of wind data were used in performing the data reduction. The use of the on-board results seemed to give the smaller degree of scatter although a greater degree of symmetry about the zero yaw angle axis was achieved by using the wayside results. Because of these findings and because it seems to be a result which should be more consistantly and uniformly related to the conditions on the train, the on-board wind measurements are used.

The runs for which the data meets the various criteria are listed in Table 1 by yaw angles. For some angles, there are several runs and for other angles only one or no runs at all. When repeat runs are available at the same angle, the repeatability of the data can be judged. In this respect it is unfortunate that data averaged over shorter sections of the run are not also available. These would give more data points and a better evaluation of repeatability and spread of the data. Some measure of the fluxuation of the data can be

TABLE 1

LIST OF RUNS AT DIFFERENT YAW ANGLES
FOR FULL SCALE TESTS

Yaw Angle	Runs: Configuration 1	Runs: Configuration 2
-11°		42
-7°	73	23, 24, 25, 30, 41
-5°	72	26
-4°	52	
-3°	69, 71	
-2°	54, 55, 60	49
-1°	56, 74	37
0°	57, 58, 59, 75, 76, 86	32, 36, 39, 48
1°	68	33, 38
2°	70, 88	
3°	78, 80, 81	45
5°	82	
6°		105, 106
7°	67	
8°	66	107
9°	79	108
10°	65	
11°	99	
13°	63, 95, 97	
15°	96, 98	
17°	100	

obtained by the standard deviation of the difference between the average value and the individual run value at those angles for which more than one run is available. The results shown in Table 2 are obtained in this way showing a standard deviation for runs with repeat data of 2.7 lbs. for longitudinal forces and 4.68 lbs for lateral forces. The repeatability shown by these runs is quite good.

The longitudinal and lateral forces on each of the trailers for the two configurations is shown in Figures 10 through 13 presented as a force area. The force area is obtained by dividing the force by the dynamic pressure.

$$C_D A = \frac{R}{\frac{1}{2}\rho v^2}$$

The advantage of using the force area is that it is the same for all velocities so need not be presented as a function of velocity. A further discussion of the reasons for using force area is given in Reference 13, page 9. The longitudinal force on the rear trailer seems to be about the same for the two configurations at low yaw angles. The curve for Configuration 1 shows an increase in longitudinal force near zero yaw. How seriously the detailed shape should be taken is not clear although some similarities were observed in the wind tunnel tests. Configuration 2 seems to give noticably higher longitudinal forces at the larger yaw angles. It is not clear why this should be so. The longitudinal force on the front trailer is only marginally higher than on the rear trailer for Configuration 1, with some overlapping of the points at low angles of yaw. For Configuration 2, the longitudinal force on the front

TABLE 2

REPEATABILITY OF REPEAT RUNS
FOR FULL SCALE TESTS

Case	Number of Repeat Runs	Standard Deviation
Longitudinal force		
Configuration 1	23	2.49 lbs.
Configuration 2	13	3.19
Configuration 1 and 2	36	2.72
Lateral force		
Configuration 1	23	4.23
Configuration 2	13	5.59
Configuration 1 and 2	36	4.68

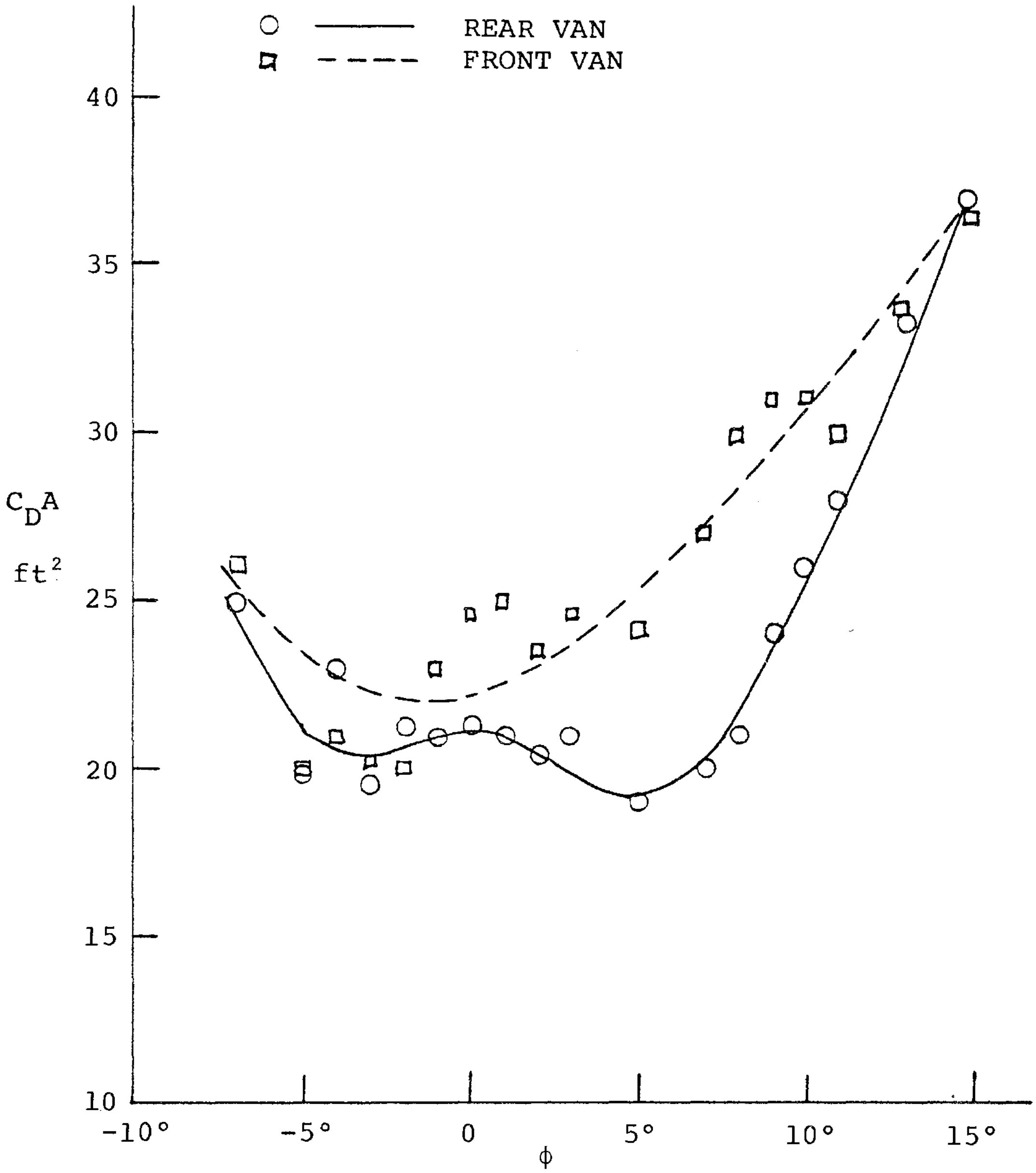


Figure 10. Longitudinal Force Area Versus Yaw Angle for Front and Rear Vans, Configuration 1.

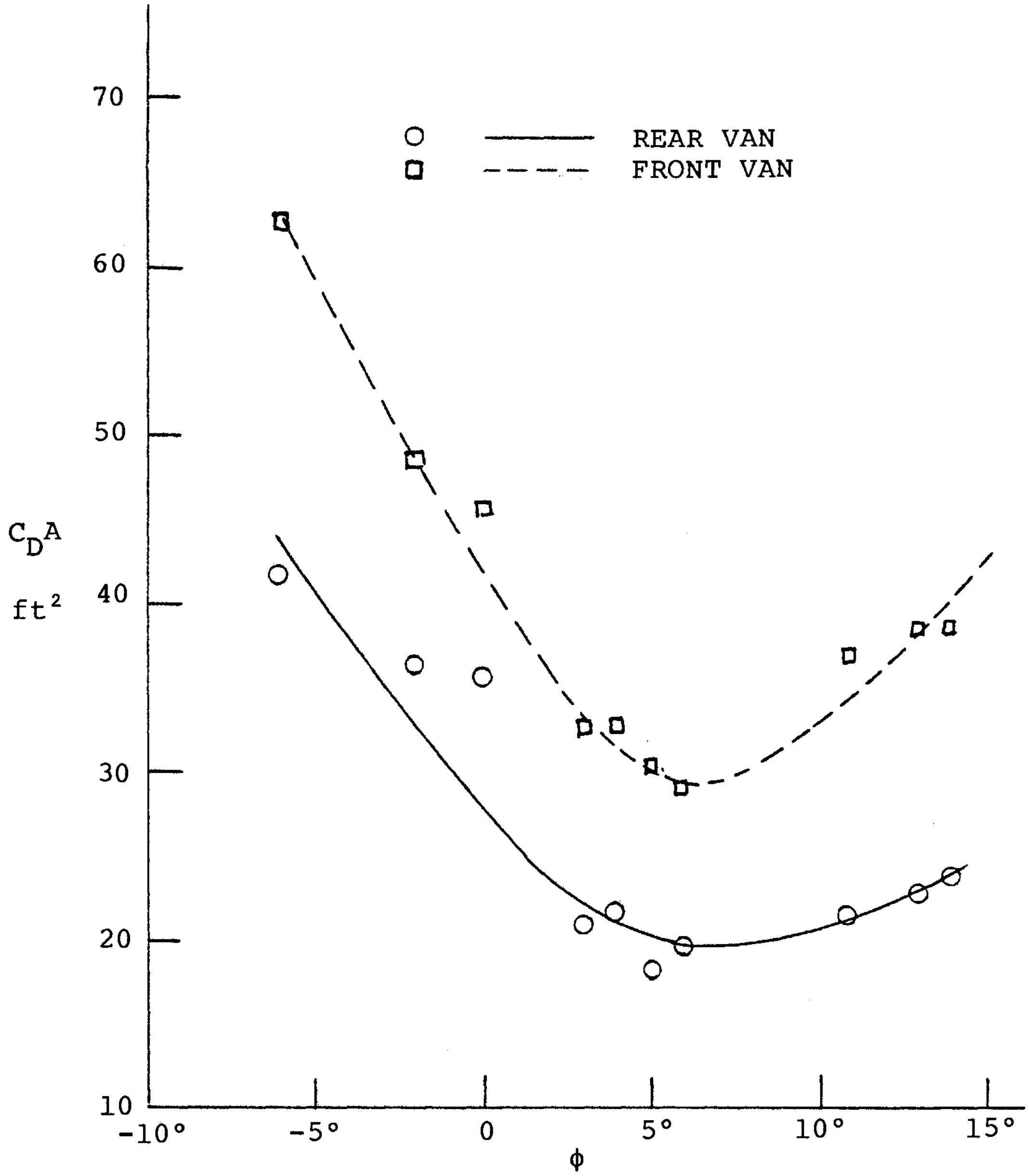


Figure 11. Longitudinal Force Area Versus Yaw Angle for Front and Rear Vans, Configuration 2.

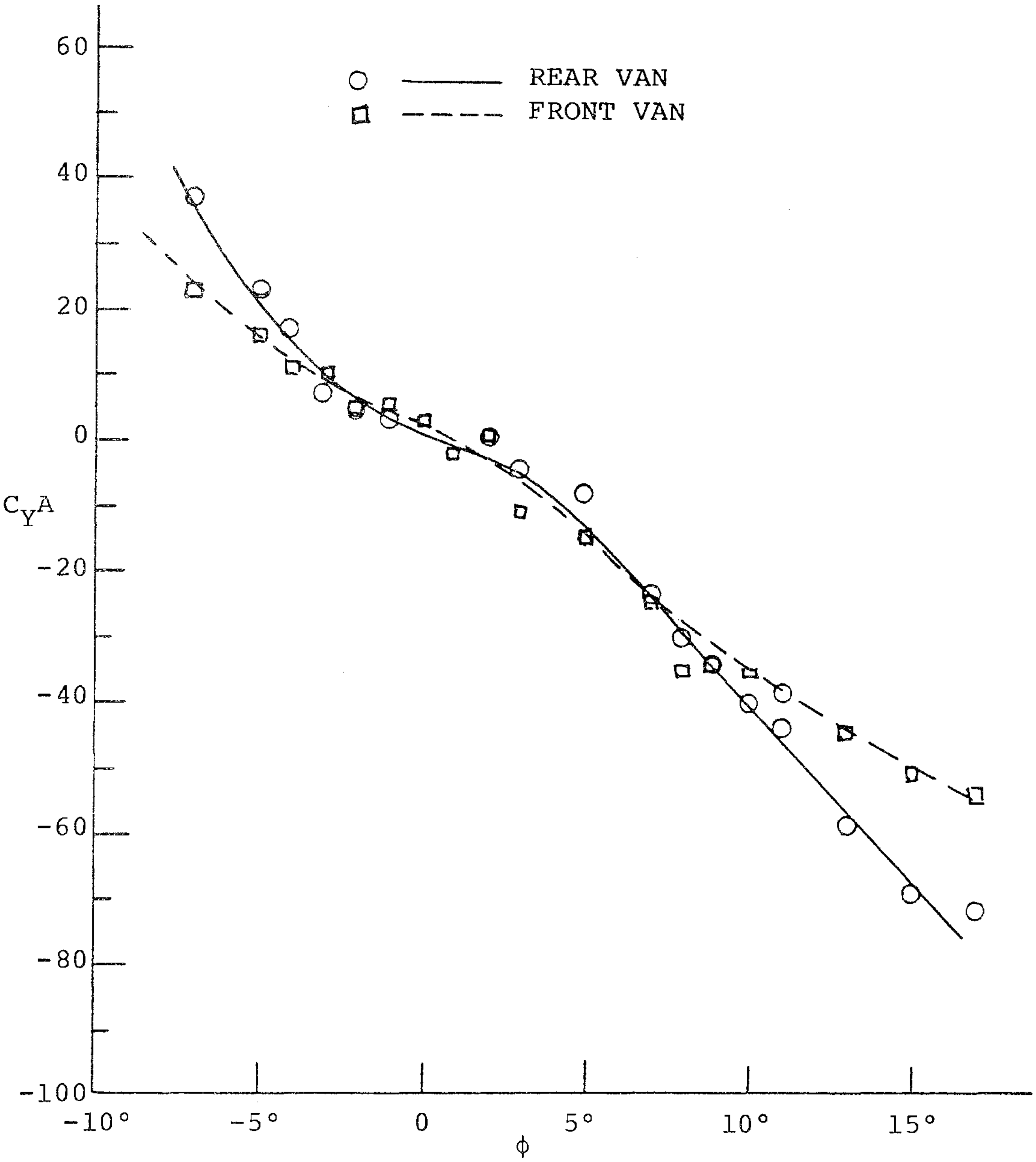


Figure 12. Lateral Force Area Versus Yaw Angle for Front and Rear Vans, Configuration 1.

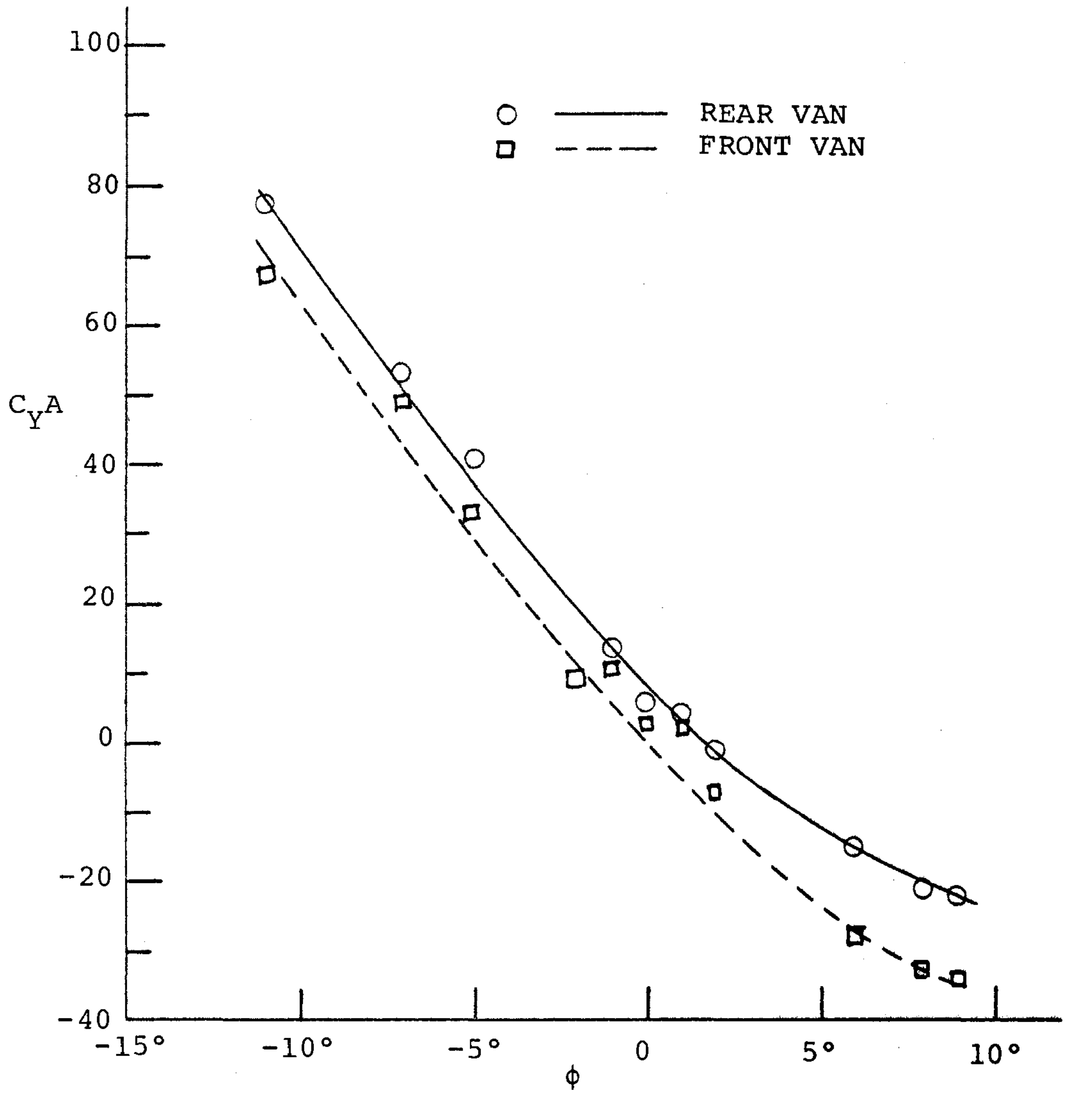


Figure 13. Lateral Force Area Versus Yaw Angle for Front and Rear Vans, Configuration 2.

trailer is definitely higher than on the rear trailer as expected. These results can be compared with those found for the effect of changes in gap size between blocks in the basic block tests and those found for changing the coupling distance between cars as reported in Reference 13. The basic block tests show no change in drag as the gap spacing increases from about 0.4 times the width of the blocks to 1.0 times the width. The rail car tests show that, when the normal coupler spacing is reduced from the condition where the distance between the trailers is .96 to .5 times the trailer width, there is no effective change in longitudinal force. Therefore, one would conclude that the gap in front of the forward trailer in Configuration 1 is not sufficiently large to have a major effect on longitudinal force but when the buffer car is unloaded, the gap is large enough to do so.

The lateral forces on the trailers are shown in Figures 12 and 13. The forces on both the forward and rear trailers are about the same for both configurations and there is little difference between the two. Judging from the basic block tests one would not have expected much difference between the two trailers in Configuration 1. The basic block tests show little change with changes in gap spacings up to a gap spacing of two block widths, especially for the case of sharp edged blocks. However, the basic block tests would predict a larger lateral force on the leading trailer for Configuration 2. The reason this does not occur is not clear.

3. WIND TUNNEL TESTS

A set of wind tunnel tests of the trailer on flat car (TOFC) and container on flat car (COFC) configurations was carried out using the GALCIT wind tunnel at the California Institute of Technology (CIT), Reference 15. In conjunction with these tests, a few additional tests were run measuring only the forces on the vans. This was done in anticipation of the full scale tests. These tests were also carried out on relatively small 1/43 scale models. In order to provide a more valid comparison between the wind tunnel model and the full scale tests, additional wind tunnel tests were carried out using the transonic wind tunnel at Calspan at conditions more nearly resembling those of full scale.

3.1 Wind Tunnel Facilities

The aerodynamic scale of a configuration is more correctly determined by the Reynolds number than by the actual physical scale. The Reynolds number is given by the relation

$$Re = \frac{\rho v l}{\mu}$$

In addition to the scale, modifications of the density and velocity can be used to effect the Reynolds number and modify the aerodynamic scale independently from the actual physical scale. Another aerodynamic parameter which is effected by velocity is the Mach number.

$$M = \frac{v}{a}$$

At low Mach numbers, the changes in pressure which can occur as air flows over a particular object are so small that the density remains approximately constant. Under these conditions, the air may be considered incompressible and for this condition aerodynamic theory shows that changes in Mach number are unimportant as long as the Mach number remains small. If the flow can be considered incompressible, all pressures and forces scale directly as the dynamic pressure, $\frac{1}{2}\rho v^2$. If coefficients are derived by dividing the forces by the dynamic pressure, measurements taken at different densities and velocities will yield coefficients that do not depend on the density and velocity at which the experiment was run.

The Reynolds number of the full scale TOFC configuration at a velocity of 75 mph, using the length of a 40 foot van as the reference length, is $26(10^6)$. The CIT wind tunnel tests were carried out using 1/43 scale models and velocities up to 150 mph. These conditions result in a Reynolds number, based on the length of a scaled van, of $1.20(10^6)$, 1/20 of full scale Reynolds number.

It was desired to obtain higher Reynolds numbers more closely matching full scale. This can be done by using larger models in larger wind tunnels or by increasing the density and speed of the tests. However, there are limitations on both of these parameters. The CIT tests were run at a Mach number of about 0.2. In order to insure that the flow remained incompressible, it was decided that the test Mach number should be limited to 0.3. Density limitations are set only by the capability of the wind tunnel and the strength of the models. After an investigation of pressurized wind tunnel facilities, the only one found suitable for these tests was the facility at Calspan. This facility has an 8 foot diameter test section, a pressure capability of 0.1 to 3.25 atmospheres, and a Mach number range of 0 to 1.3.

Of the two possible approaches for achieving high Reynolds number tests considered, the use of the same 1/43 scale models in the Calspan pressurized wind tunnel was selected. The cost of these tests was less because the cost of modifying the existing models to be suitable to the pressurized conditions in the Calspan tunnel was considerably less than the cost of constructing new larger models. Using the pressurized facility a higher Reynolds number could be achieved and tests could be run from essentially the same conditions as the CIT tests up to the highest Reynolds number obtainable.

Four test conditions were selected.

	Pressure	Mach Number	Reynolds number scaled 40 ft van
1	1 atm	0.2	$1.2(10^6)$
2	3.25	0.2	$3.8(10^6)$
3	1	0.3	$1.8(10^6)$
4	3.25	0.3	$5.6(10^6)$

3.2 Test Configurations

3.2.1 CIT Tests

The CIT tests used the models and support hardware described in Reference 13. The configurations tested are shown in Table 3. These tests were run before the full scale tests at TTC were fully planned so did not exactly match the TTC configuration also shown in Table 3. The support and connections to the balance mechanism are shown in Figure 14. This mechanism was a simple modification of the model support

TABLE 3

TEST CONFIGURATIONS

			Metric Car		
CIT Wind Tunnel Test Configurations: Re = $1.2(10^6)$					
1)	Locomotive	Loaded TTX	Loaded TTX	Loaded TTX	Box
2)	Locomotive	Unloaded TTX	Loaded TTX	Unloaded TTX	Box
Calspan Wind Tunnel Test Configurations: Re = $1.2(10^6)$ to $5.6(10^6)$					
1)	Locomotive	Loaded TTX	Loaded TTX	Box	
2)	Locomotive	Unloaded TTX	Loaded TTX	Box	
TTC Full Scale Test Configurations: Re = $26(10^6)$					
1)	Locomotive	Loaded TTX	Loaded TTX	T-5 Instrumentation Car	
2)	Locomotive	Unloaded TTX	Loaded TTX	T-5 Instrumentation Car	

Re based on the length of a van.

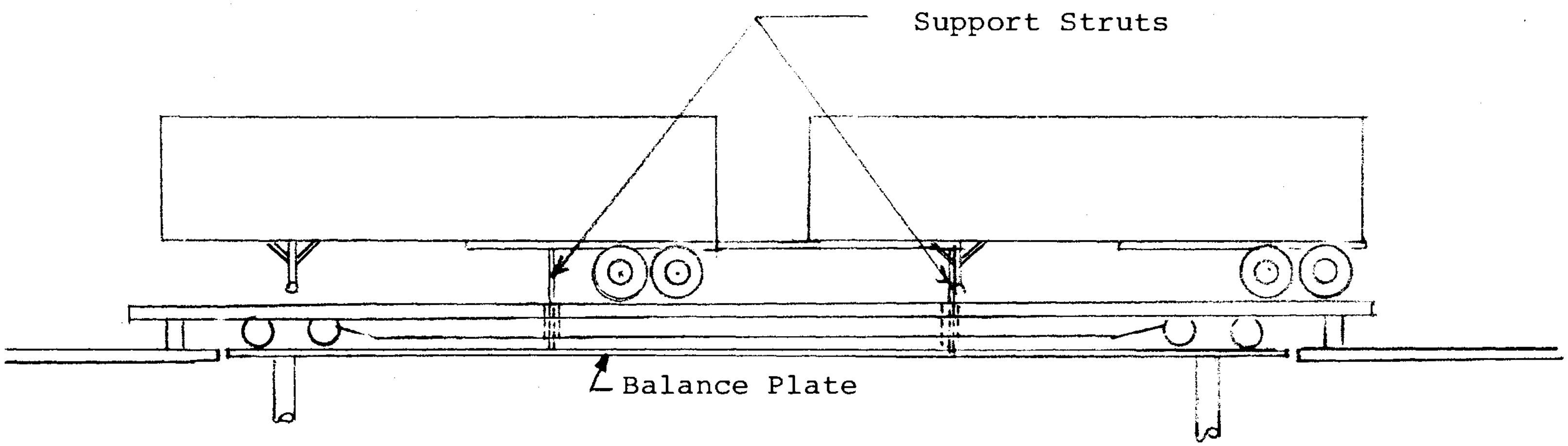


Figure 14. CIT Test Arrangement Showing Vans Only Mounted on Balance.

arrangement used in the other CIT wind tunnel tests. The balance support struts were carried up through holes in the TTX car deck to support the vans only and the vans were connected together by a metal bar. The forces that were measured were those on the vans and the unshielded support struts. A photograph of the model in the CIT wind tunnel is shown in Figure 15.

3.2.2 Calspan Tests

For the Calspan tests it was desired to use the same models as for the CIT tests. However, the configurations were to be the same as for the full scale TTC tests. Because of the higher pressure and velocity, the dynamic pressure in the Calspan tests was a factor of eight higher than in the CIT tests. For this reason, the strength of the models and support system also had to be increased. Some other modifications were also appropriate because of the differences between the Calspan and CIT balance and ground plane systems. The models were modified as shown in Figure 16 and a photograph in the Calspan tunnel is shown in Figure 17. The principle external changes were the increase in the number of support struts to four (two per van) and the increase in their diameter to 5/8 inches. A one inch outside diameter shield was also provided about these struts to shield them from aerodynamic loads. Even though the trailers were supported independently, only the forces on the combined vans could be measured since only one balance was available.

3.3 Calspan Test Results

A detailed reporting of the Calspan wind tunnel tests results is given in Reference 19. A listing of the valid runs is shown in Table 4.

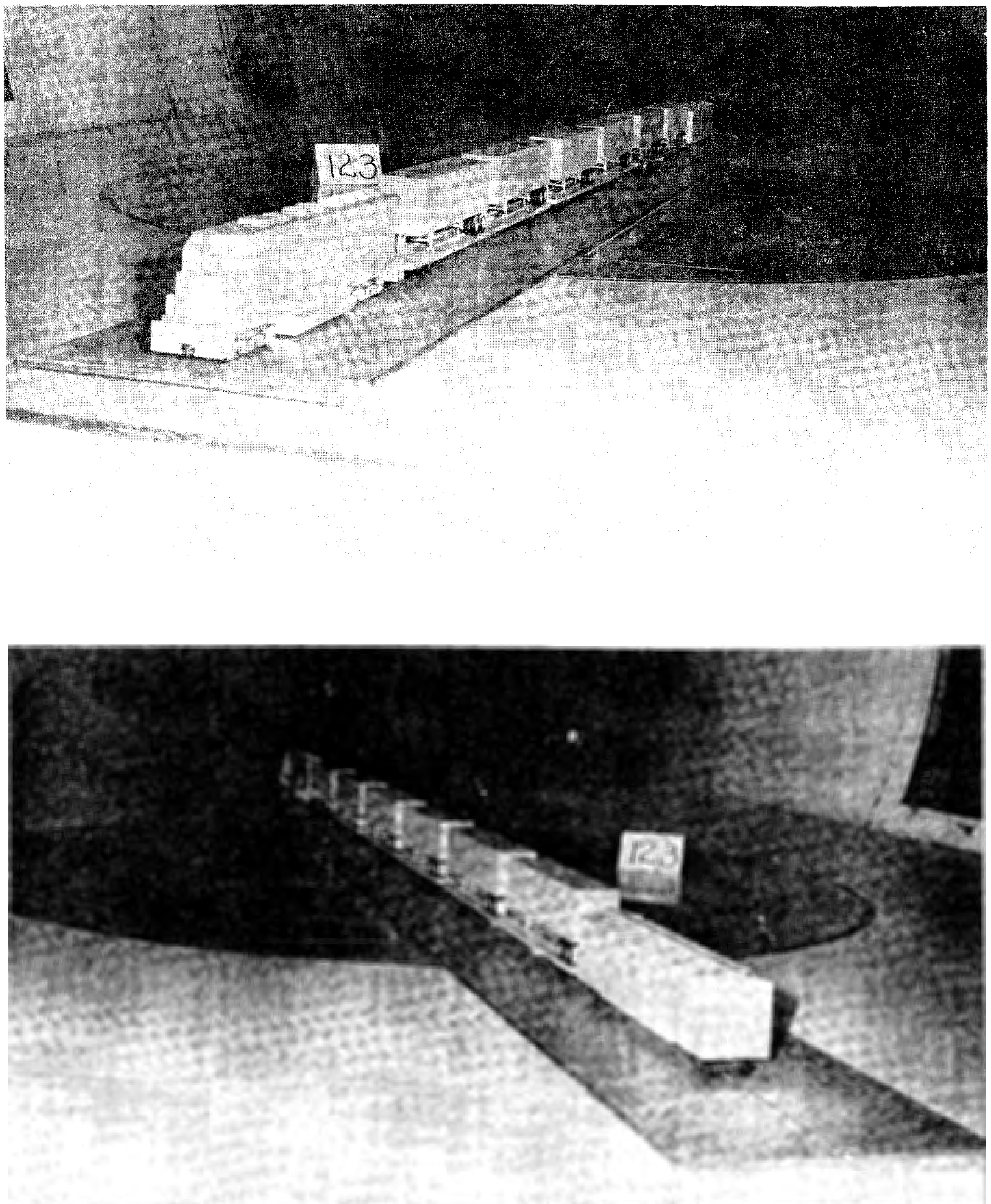


Figure 15. Model for Configuration 1 in CIT Wind Tunnel.

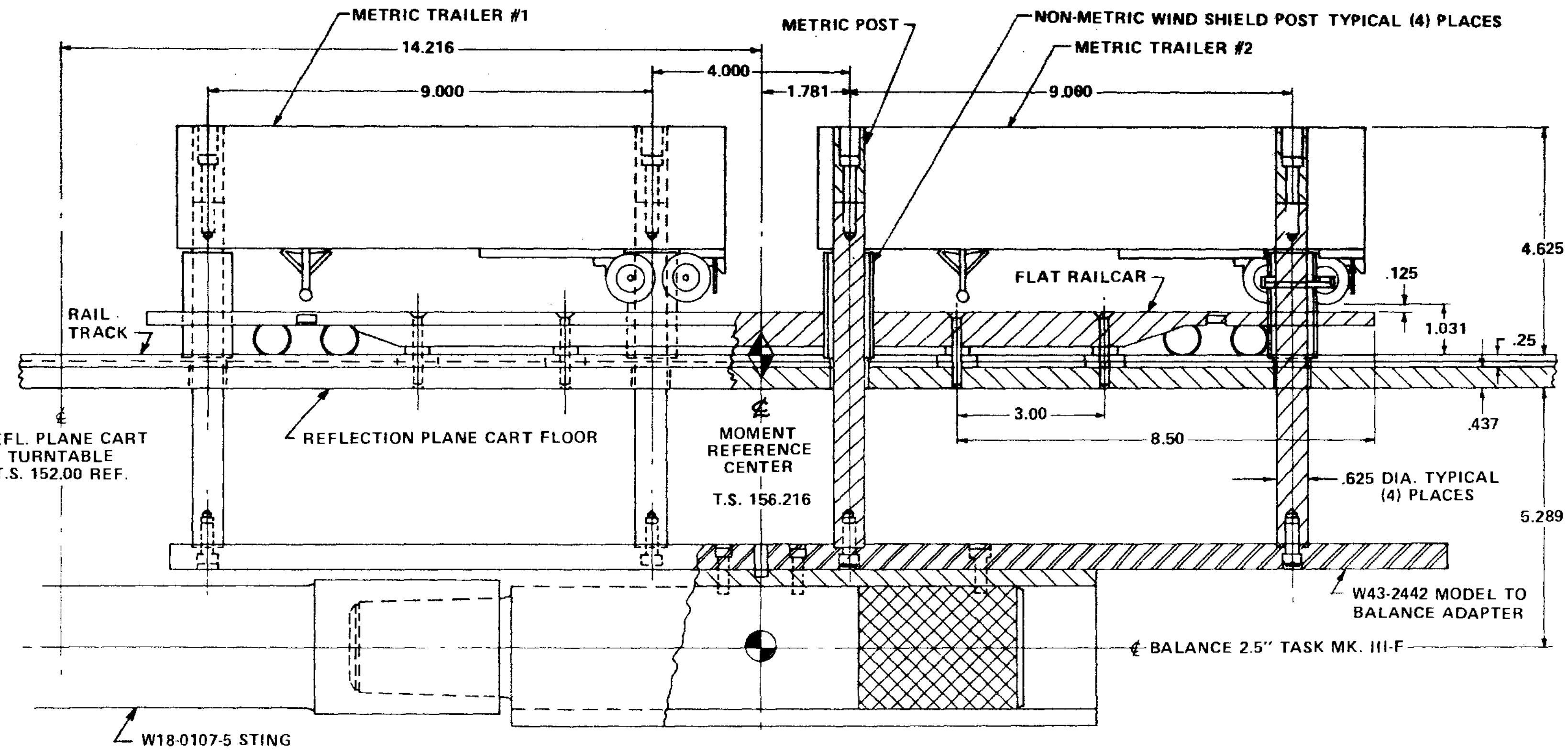


Figure 16. Calspan Test Arrangement Showing Vans Only Mounted on Balance.

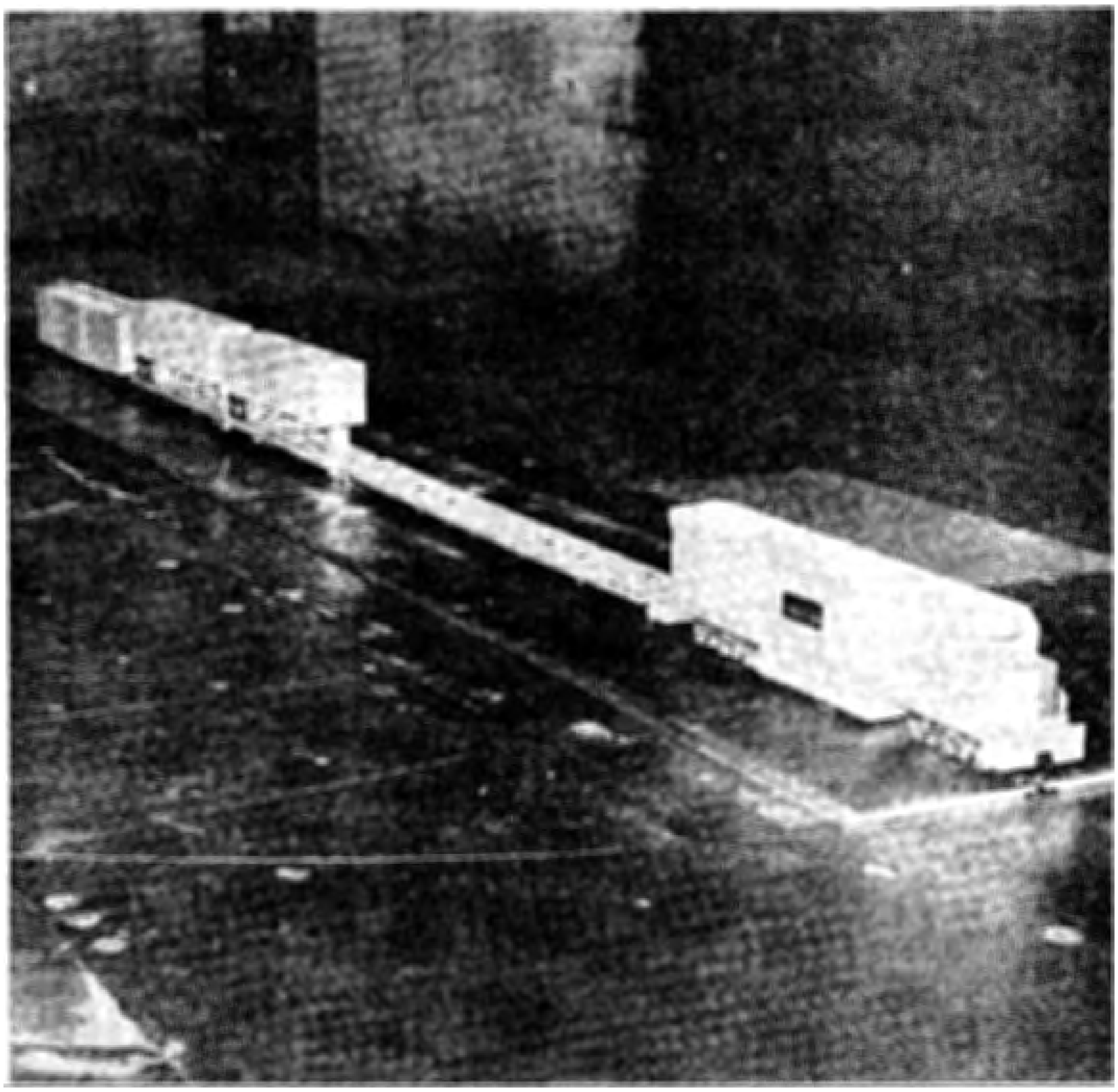


Figure 17. Model for Configuration 2 in Calspan Wind Tunnel.

TABLE 4

CALSPAN TEST RUNS

Run	Configuration	Mach Number	Pressure atms	Reynolds Number	Remarks
7	No. 1	.2	1.0	$1.2(10^6)$	
9	"	.3	"	$1.8(10^6)$	
10	No. 2	.2	"	$1.2(10^6)$	
12	"	.3	"	$1.8(10^6)$	
17	No. 1	.3	3.25	$5.6(10^6)$	
18	"	.2	"	$3.8(10^6)$	Intermittant model ground at ϕ=25°. No. 2 metric van aft wheel loose. Repaired after run.
19	No. 2	.2	"	$3.8(10^6)$	
20	"	.3	"	$5.6(10^6)$	
21	"	.2	"	$3.8(10^6)$	Repeat of run 19.
22	"	.2	1.0	$1.2(10^6)$	Repeat of run 10.
23	"	.3	"	$1.8(10^6)$	Repeat of run 11.

Runs 5, 6, 8, 11, 13-16 void due to excessive balance zero shifts.

Nominal Yaw Angle Range

ψ = -5, -3, 0, 3, 5, 9, 12, 16, 20, 25, 30 and zero degrees repeat.

3.3.1 Repeatability of the Data

The repeatability of the data can be determined by examining the results found for different conditions. Enough repeat runs are not available to do a good job of determining the repeatability, but the data available has been examined. The longitudinal force data for Configuration 2 will be considered first since the only repeat runs available, see Table 4, are for this configuration. First, examine the repeatability of repeat points taken within the same run. The only points actually repeated were points at zero yaw angle. There are two zero yaw angle readings in each run. In order to calculate a standard deviation representative of all zero points for this configuration, the average value for each run at zero yaw angle was determined, this value was subtracted from the actual reading and the difference divided by the average value. The standard deviation of all these normalized differences can then be obtained. The results are shown in Table 5. The normalized standard deviation was less than 2% for all zero points. During each run, the longitudinal force was measured at ± 3° and ± 4.8° angle of yaw. If ± values of the same yaw angle are considered duplicate points, then more data is available for this consideration. Using the same method of calculating differences from the mean (the mean being calculated for each run at each yaw angle), the standard deviations were obtained and are shown in Table 5. The normalized standard deviation had now increased to almost 5%. The repeatability between runs can now be examined by considering the runs for the same Reynolds numbers. Table 4 shows that two

TABLE 5

COMPARISON OF REPEATED MEASUREMENTS
FOR CALSPAN TESTS

Repeated measurements within a run for Configuration 2.

Standard deviation of repeat 0° yaw angle data divided by mean.	.0183
Standard deviation of all repeat yaw angles data divided by mean. For this purpose runs at + of - the same yaw angle are considered repeats. Data for 0°, ±3°, ±4.8° yaw angle.	.0476

Repeated measurements including duplicate runs.

Standard deviation for all runs at the same Reynolds number. Differences from mean at all yaw angles divided by mean values. (6 runs at 3 Re available)	.1288
Standard deviation for all runs without separation by Reynolds number. Differences from mean divided by mean value.	
6 repeat runs	.1332
all 7 runs	.1282

runs were made at three of the four Reynolds numbers used for Configuration 2. The mean was now determined for all of the points at each yaw angle in the two runs at the same Reynolds numbers. In the two runs there were four points at zero yaw, four points each at 3° and 4.8° yaw (taking the ± together), and two points at each of the other yaw angles. The difference from the mean at any given yaw angle should be a quantity which is independent of yaw angle and whose standard deviation considered over all yaw angles is a meaningful evaluation of the data scatter. For each pair of duplicate runs there are now twenty-four differences to be considered which is a large enough number to have statistical meaning. The result for the normalized standard deviation shown in Table 5 is about 13%. Of the various repeat runs, 19 and 21 repeat quite well but 10 and 22, and 12 and 23 show considerable difference. These two, of the three repeat runs which show poor repeatability, are responsible for the large standard deviation of the results.

3.3.2 Reynolds Number Effect

The next object is to see if a Reynolds number effect can be reliably detected within this data. One means of doing this is to determine if the data has appreciably more scatter when the Reynolds number differences between runs are not considered in grouping the data compared to when they are considered. The last standard deviation presented was for the runs grouped by Reynolds number. If all of the runs for Configuration 2 are considered as one group, and the same method used to calculate a normalized standard deviation, the result, shown in Table 5, also gives a 13% scatter standard deviation. For this calculation, the average value was determined for all runs of the same configuration at a given yaw angle but without regard for Reynolds number, the differences determined, and the standard deviation calculated. The calculation was performed using only the six runs at the three Reynolds numbers previously considered and again using the seventh run at a different Reynolds number. Leaving out the run at the fourth Reynolds number gives a slightly lower standard deviation than including it. Since ignoring the grouping by Reynolds number has no appreciable effect on the standard deviation, the conclusion is that there is no detectable Reynolds number effect.

Another analysis was also performed to examine for Reynolds number effect. Using this same data, the normalized difference calculated, using an average value determined at each yaw angle over all Reynolds numbers, was assumed to be a function of Reynolds number and a straight line curve fitted by a linear regression analysis. Figures 18a and b show this line and the average normalized difference for each run plotted at the appropriate Reynolds number. A bar is also drawn to show the standard deviation about this average. The correlation coefficient of this straight line fit to the data was determined to be .1409. This low correlation coefficient is simply a statement of the fact that the line is not a good fit to the data which is also easily seen from the figure. Figure 18a again shows that it is the inconsistancy between the two repeat runs at Reynolds numbers of $1.2(10^6)$ and $1.8(10^6)$

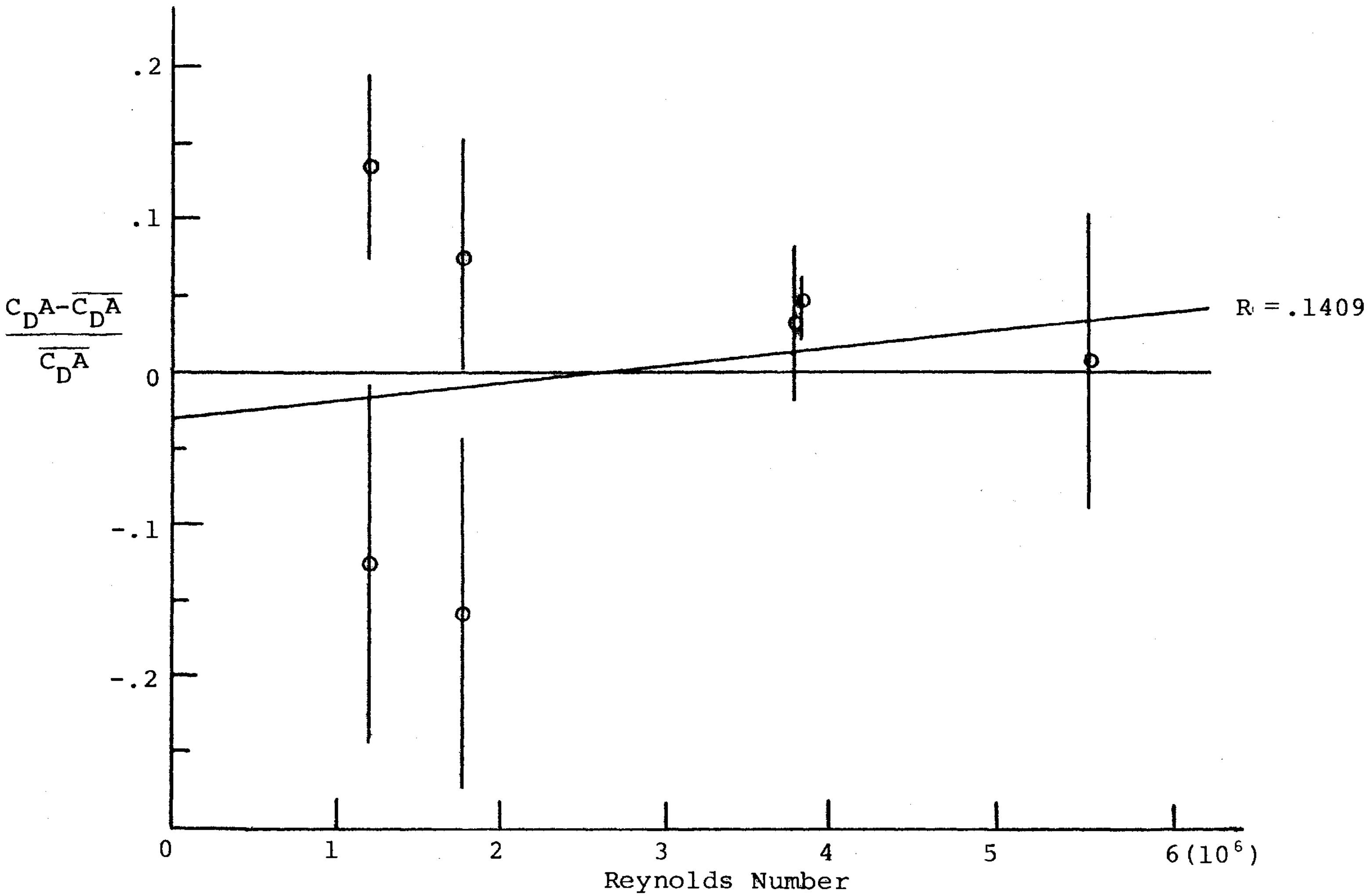


Figure 18a. Longitudinal Force Area Normalized Differences From Mean as a Function of Reynolds Number Including Linear Regression Straight Line Fit for Configuration 2.

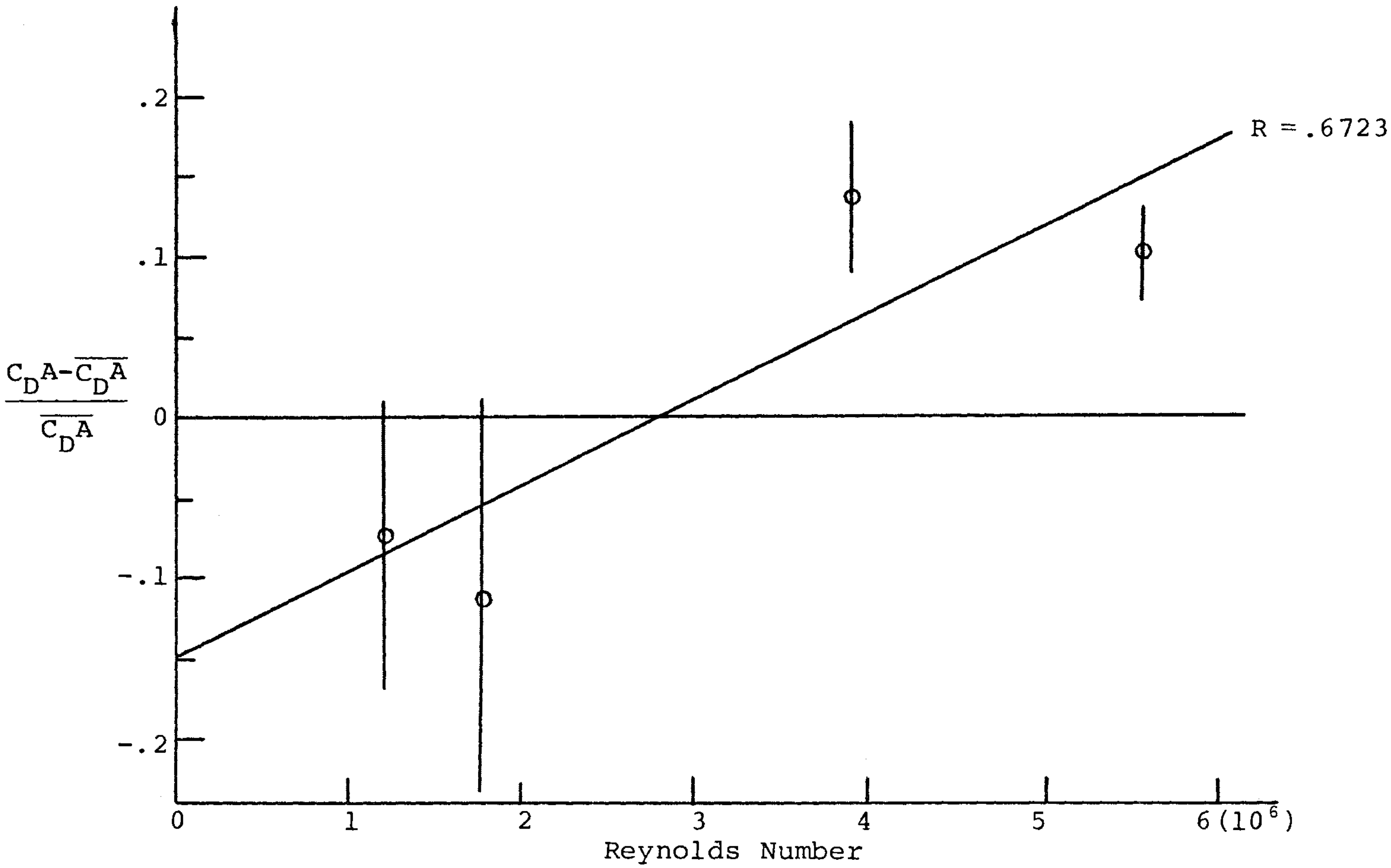


Figure 18b. Longitudinal Force Area Normalized Differences From Mean as a Function of Reynolds Number Including Linear Regression Straight Line Fit for Configuration 1.

that confuses the predictions of a Reynolds number trend. If only one run had been made at each of these conditions, the conclusions would be considerably different. The size of the error bars also shows the size of scatter relative to any existing trend. This latter technique for analysing the data seems to be the more informative one so it will be used for the analysis of the remaining data.

The results for Configuration 1 found by this last method for the longitudinal force area are shown in Figure 18b. These results are somewhat different than those found for Configuration 2. The Reynolds number trend line has a very definite slope. The total change with Reynolds number over the Reynolds number range considered is about the same as the maximum standard deviation at one Reynolds number. The fact that there are no repeat points makes it more difficult to judge the possible errors in the individual Reynolds number values. Comparing with the results for Configuration 2, one might conclude that the two results would look very similar if the two upper points at low Reynolds numbers were missing from the Configuration 2 results. It does not seem reasonable to conclude that the Reynolds number trend shown by the linear regression fit is significant.

The results for the lateral force have been treated in the same way as the longitudinal force results and are shown in Figures 19a and b. The linear regression fit to the data shows almost no slope with Reynolds number, certainly much less than the size of the standard deviation bars and than the

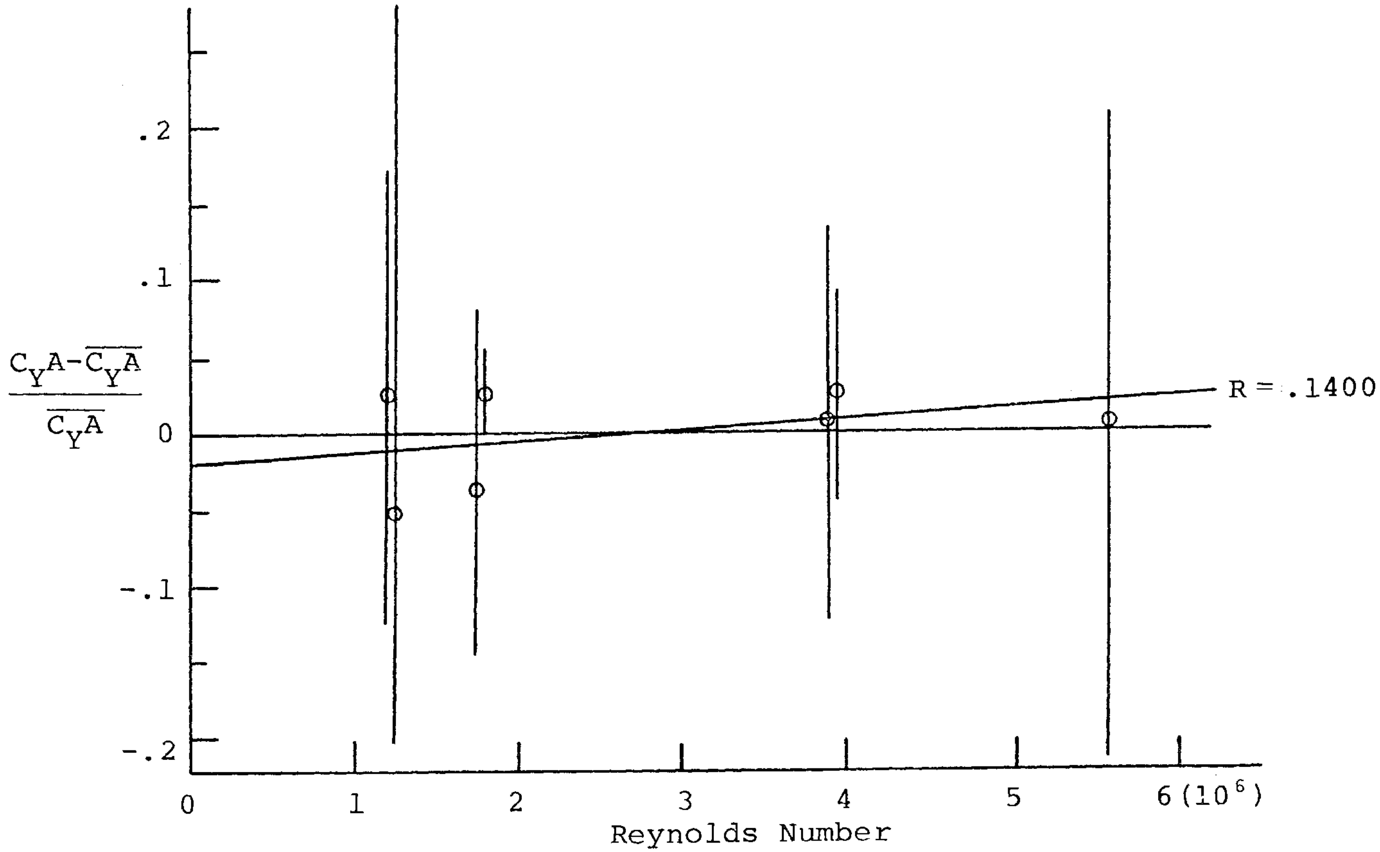


Figure 19a. Lateral Force Area Normalized Differences From Mean as a Function of Reynolds Number Including Linear Regression Straight Line Fit for Configuration 2.

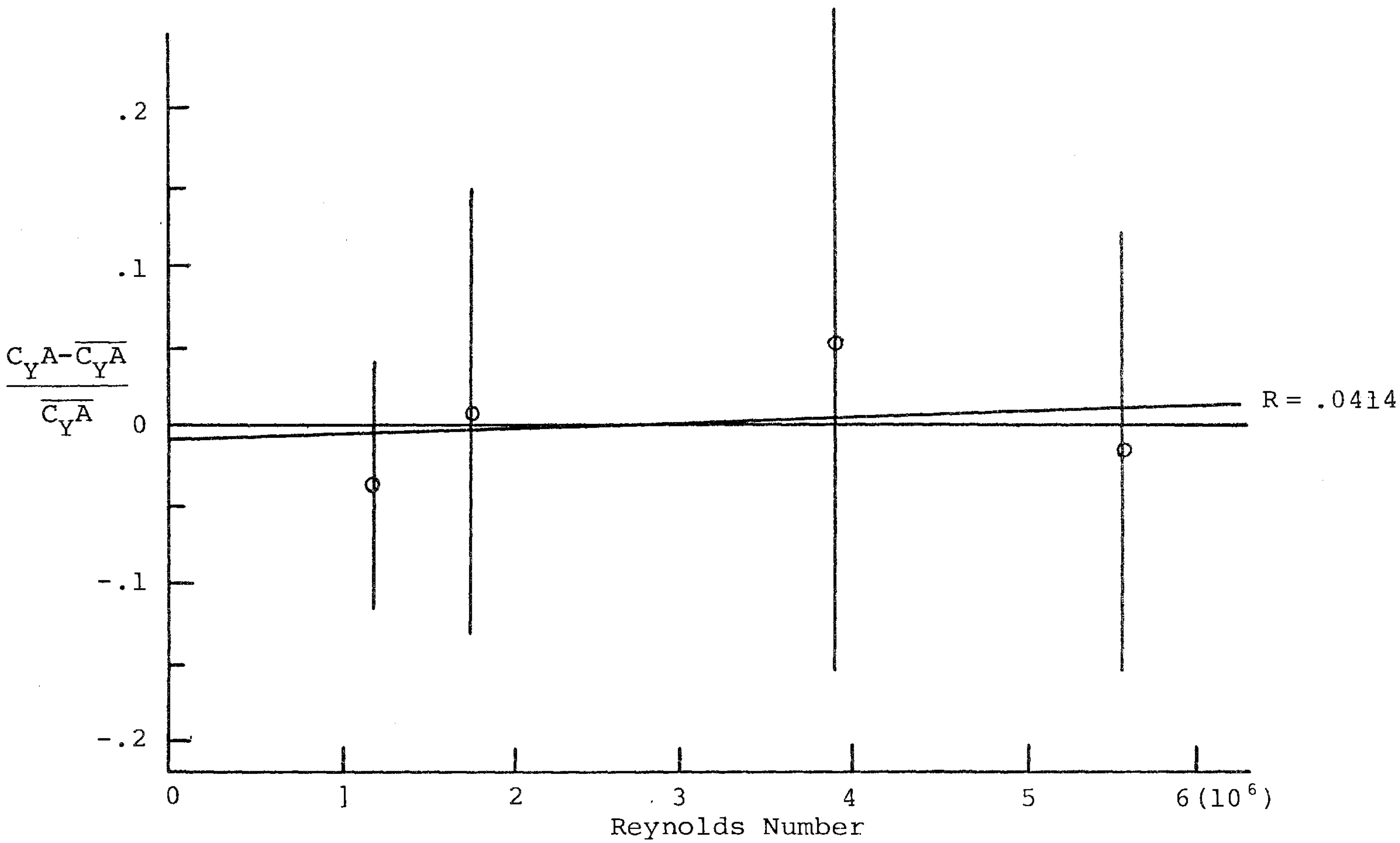


Figure 19b. Lateral Force Area Normalized Differences From Mean as a Function of Reynolds Number Including Linear Regression Straight Line Fit for Configuration 1.

repeatability of the repeat runs for Configuration 2. This data shows no Reynolds number effect. The standard deviation bars for the three pairs of repeat runs overlap each other.

3.3.3 Longitudinal and Lateral Force

Based on the conclusion that there is no detectable Reynolds number effect in either the longitudinal or lateral force data, the resulting forces as a function of yaw angle can be determined. Figures 20 and 21 show the longitudinal and lateral force results as a function of yaw angles based on an average of all runs. The average value is shown by the point and the standard deviation at that yaw angle by the bar. For the longitudinal force data on both configurations, the standard deviation bar is larger than is expected for wind tunnel tests. For the lateral force data, the standard deviation bar is considerably smaller lending a higher degree of confidence in this data.

3.4 California Institute of Technology (CIT) Results

The results for the CIT tests are also shown on these same figures. The CIT results give larger longitudinal and lateral forces than the Calspan results. The reasons for this difference are not obvious, but there are several small changes between the two sets of tests which at least partially explain the differences. As has been pointed out, the overall configuration is different. For Configuration 1 the difference is very slight. In the Calspan tests a box car is the only car behind the metric car while in the CIT tests there is

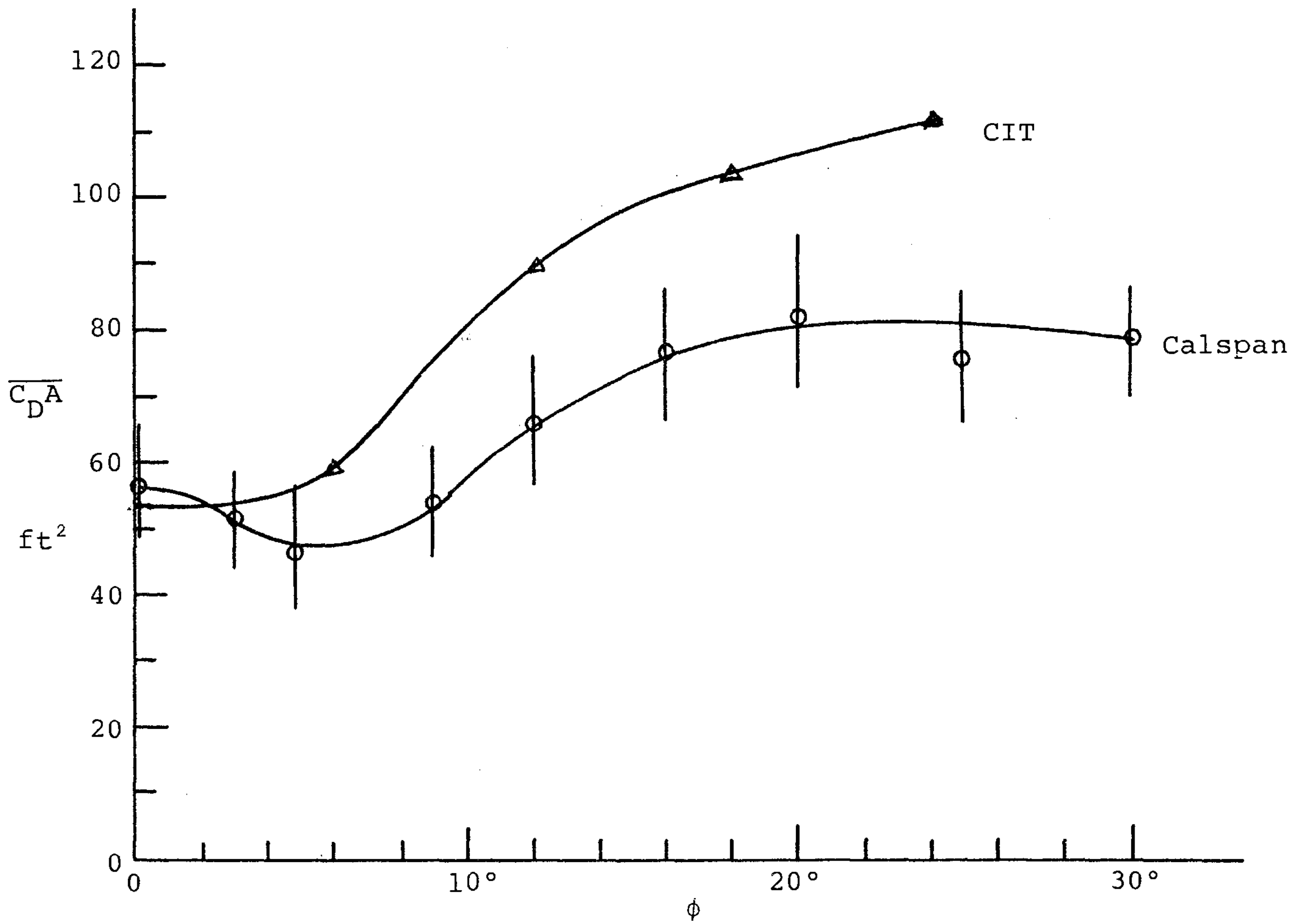


Figure 20a. Mean Longitudinal Force Area as a Function of Yaw Angle. Configuration 1.

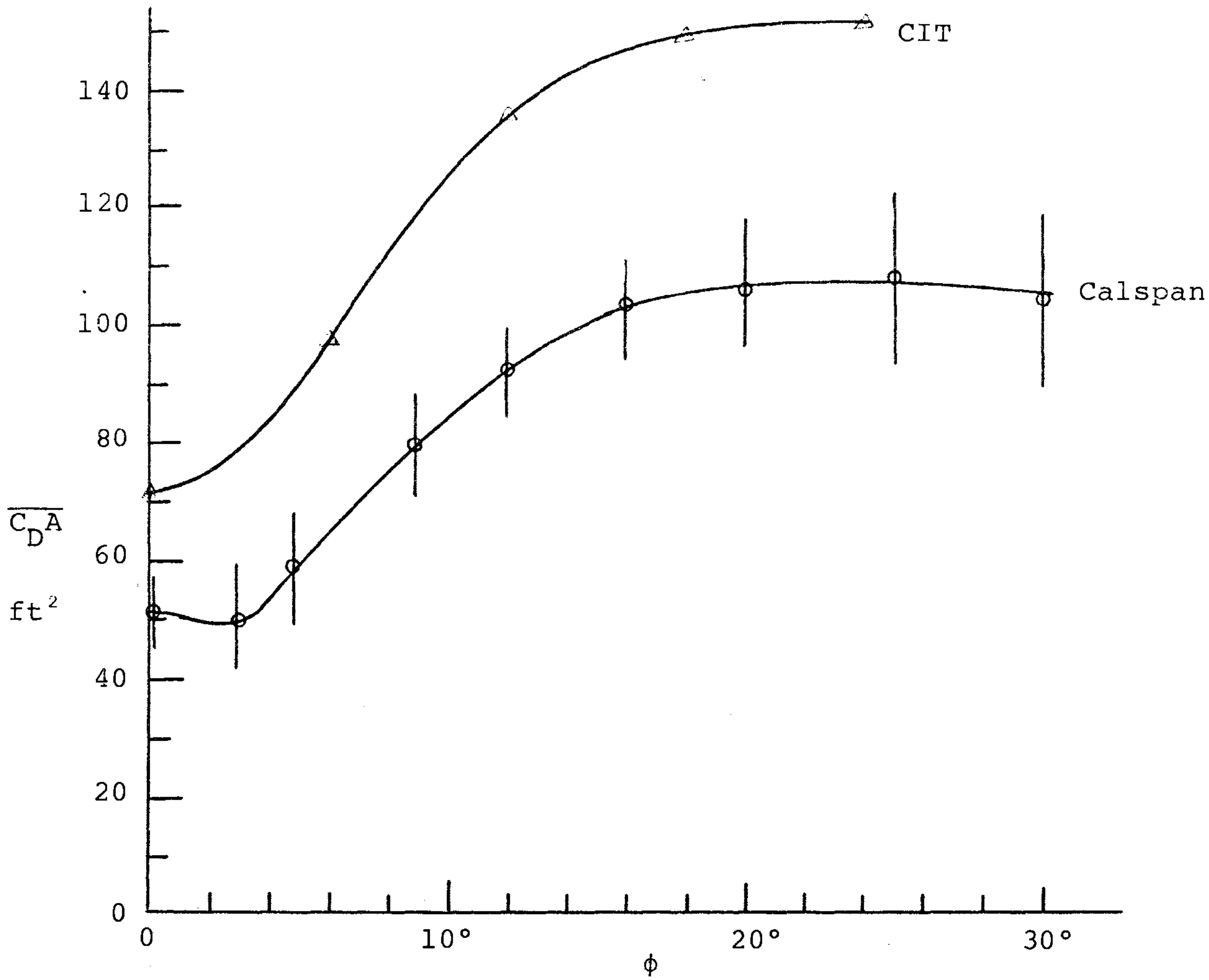


Figure 20b. Mean Longitudinal Force Area as a Function of Yaw Angle. Configuration 2.

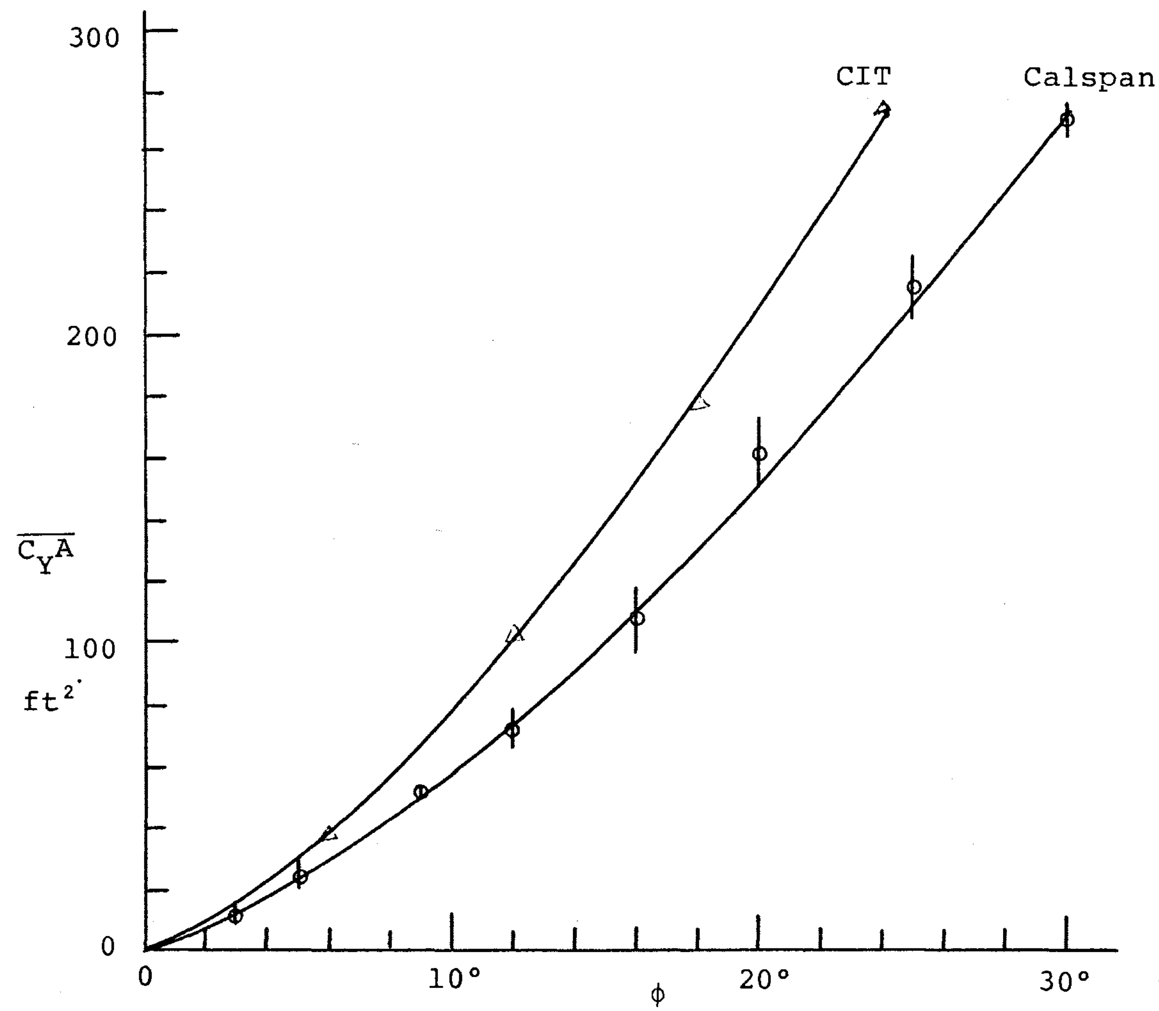


Figure 21a. Mean Lateral Side Force Area as a Function of Yaw Angle. Configuration 1.

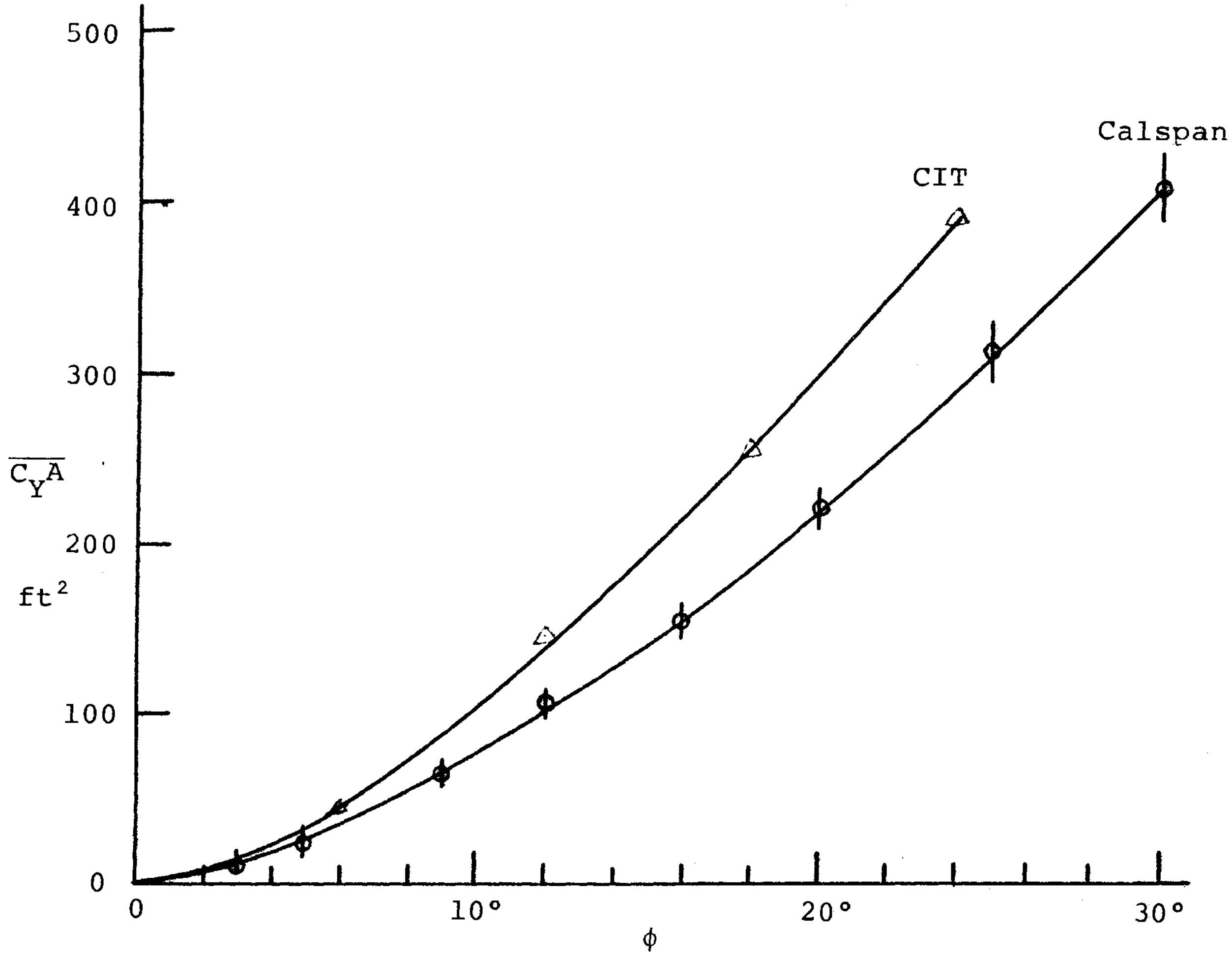


Figure 21b. Mean Lateral Side Force Area as a Function of Yaw Angle. Configuration 2.

a loaded TTX car followed by a box car. Since a trailing car has only a minimal effect on the preceding car, as shown by the other CIT wind tunnel tests, this difference should be slight. For Configuration 2 the difference is larger. In the Calspan tests the box car still directly follows the metric car, but in the CIT tests, the metric car is followed by an unloaded TTX car and then the box car. The effect of a loaded or unloaded trailing TTX car was examined in the CIT tests for the case in which the forces on the entire TTX car were measured and not just the forces on the vans. There is a small but measurable difference between the two. Judging from this data one would expect the CIT results of Configuration 2 to be high by about 10%. In the CIT tests the rods that supported the vans were about 0.2 inches in diameter and were unprotected from the airflow. In full scale these rods would have a frontal area of about 10 ft^2. It seems unlikely that their contribution of force area would be more than a small part of this frontal area considering their location. In the Calspan tests larger support rods were used and they were shielded by tubes with an outside diameter of 1 inch. Since the 1 inch diameter of this tube is almost half the width of the scaled van, it caused a restriction of the air flow between the TTX car and the van and reduced the force applied to the underside of the van. For these reasons, the forces measured in the Calspan tests should be on the low side and the forces in the CIT tests on the high side.

The CIT tests were done as part of the larger series of tests. During these tests, repeat runs were made on several configurations and confidence was established that the test results were repeatable. However, the runs in which only the vans were metric were not repeated so no statistical analysis of the results can be presented as has been done for the Calspan tests. One somewhat disturbing feature of the CIT tests is the comparison between the longitudinal force on the TTX car plus vans and the vans alone. At zero yaw angle there appears to be no difference. However, at high yaw angles, the TTX car plus vans gives the larger force, but, at the low yaw angles, the CIT and Calspan results are in quite good agreement.

4. COMPARISON BETWEEN FULL SCALE AND WIND TUNNEL TESTS

Since only the forces on the combination of both trailers were measured in the wind tunnel, the comparison can only be made with the full scale tests on that same basis. The longitudinal and yaw forces measured in the full scale tests have been shown as a function of yaw on each of the trailers in Figures 10 through 13. Figures 22 through 25 show the sum of the longitudinal and lateral forces on the two trailers for each configuration. The results for the two sets of wind tunnel tests are also shown on these figures. The agreement obtained is probably as good as can be expected from experiments of such different types. The full scale longitudinal force areas agree with the Calspan test results within the error bars of the Calspan data for all cases except at negative yaw angles for Configuration 2. The CIT data lies somewhat higher. All the longitudinal force area curves show a bump near zero yaw

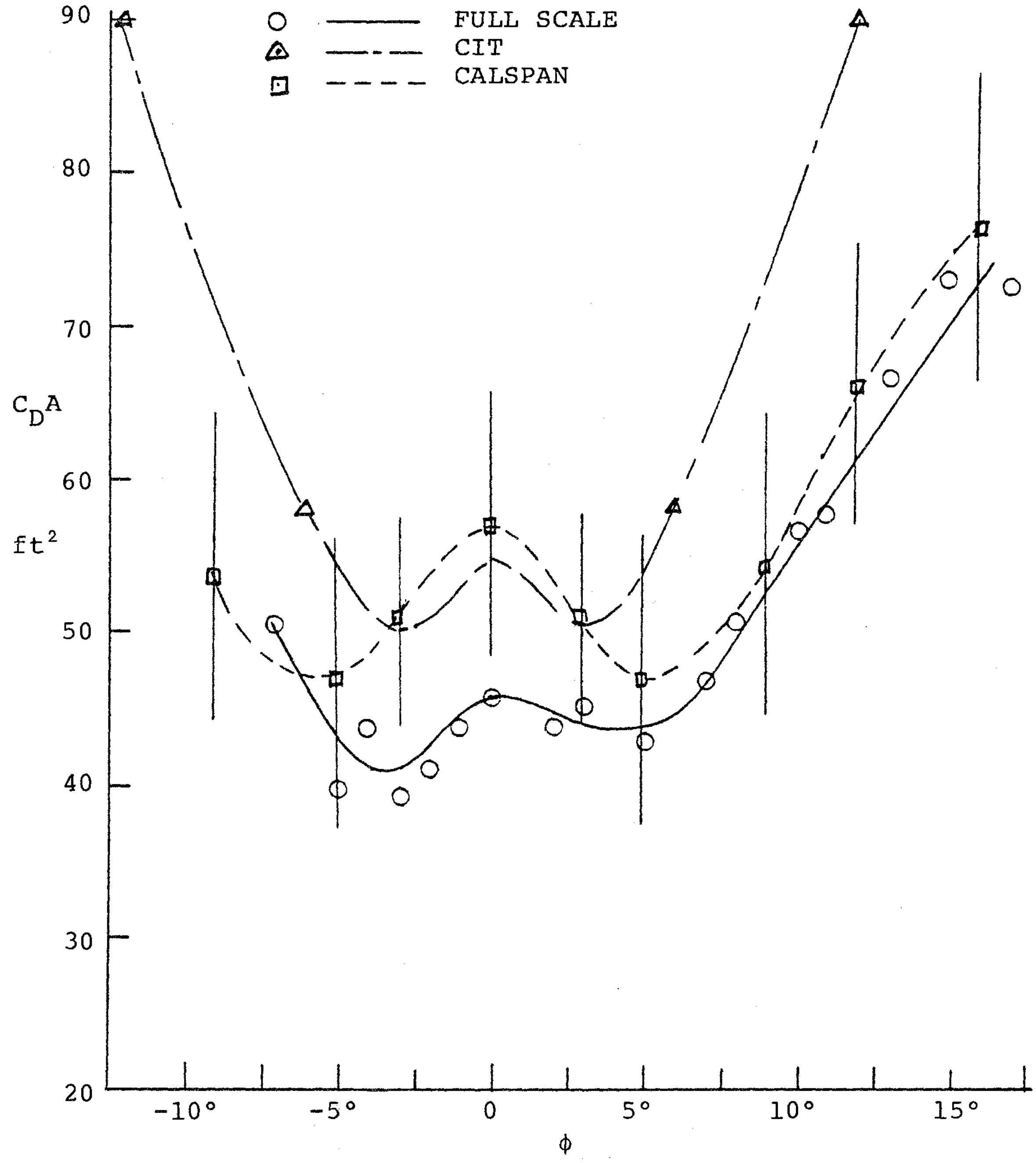


Figure 22. Longitudinal Force Area Versus Yaw Angle for Configuration 1. Comparison Between Wind Tunnel and Full Scale Results.

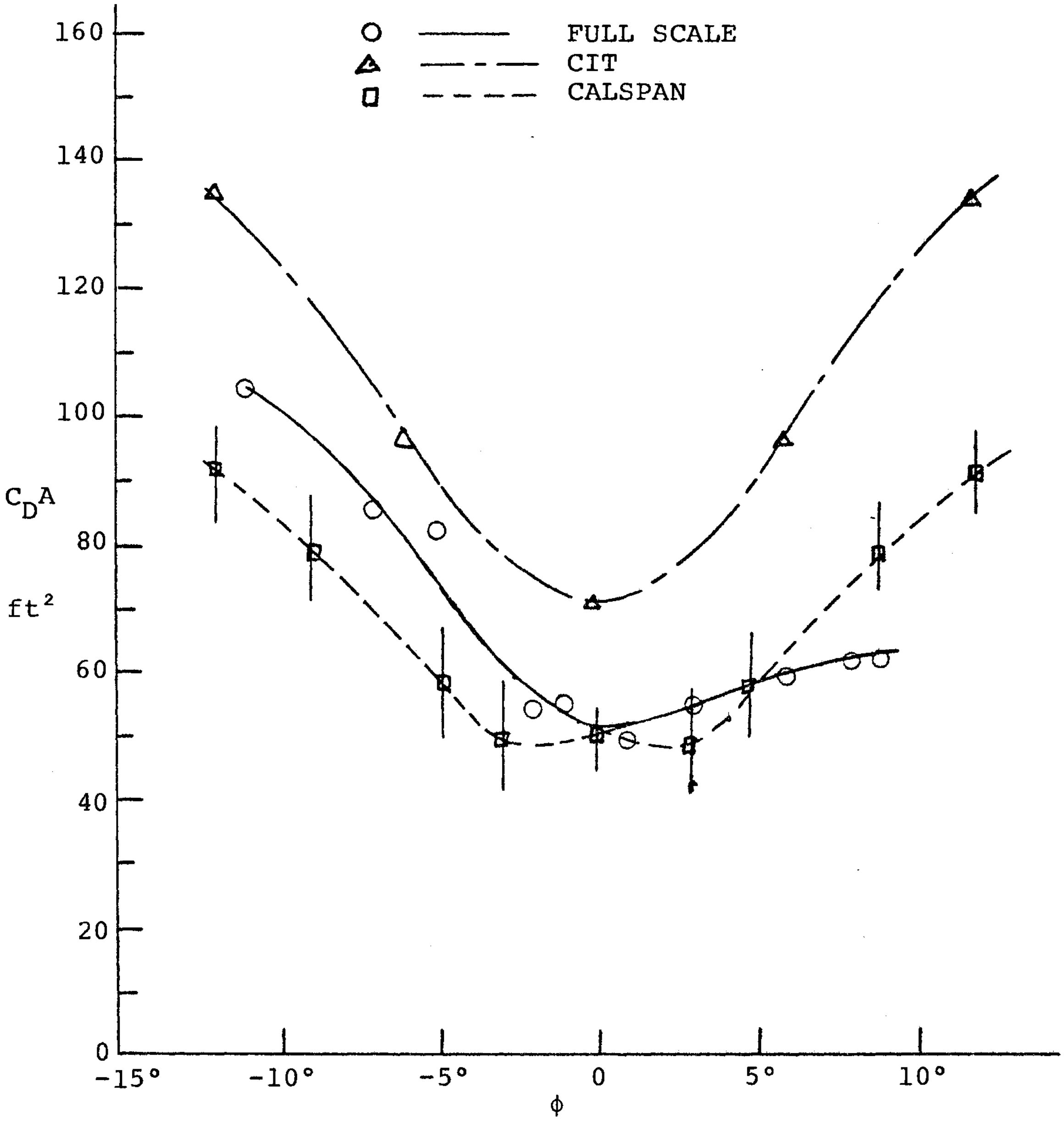


Figure 23. Longitudinal Force Area Versus Yaw Angle for Configuration 2. Comparison Between Wind Tunnel and Full Scale Results.

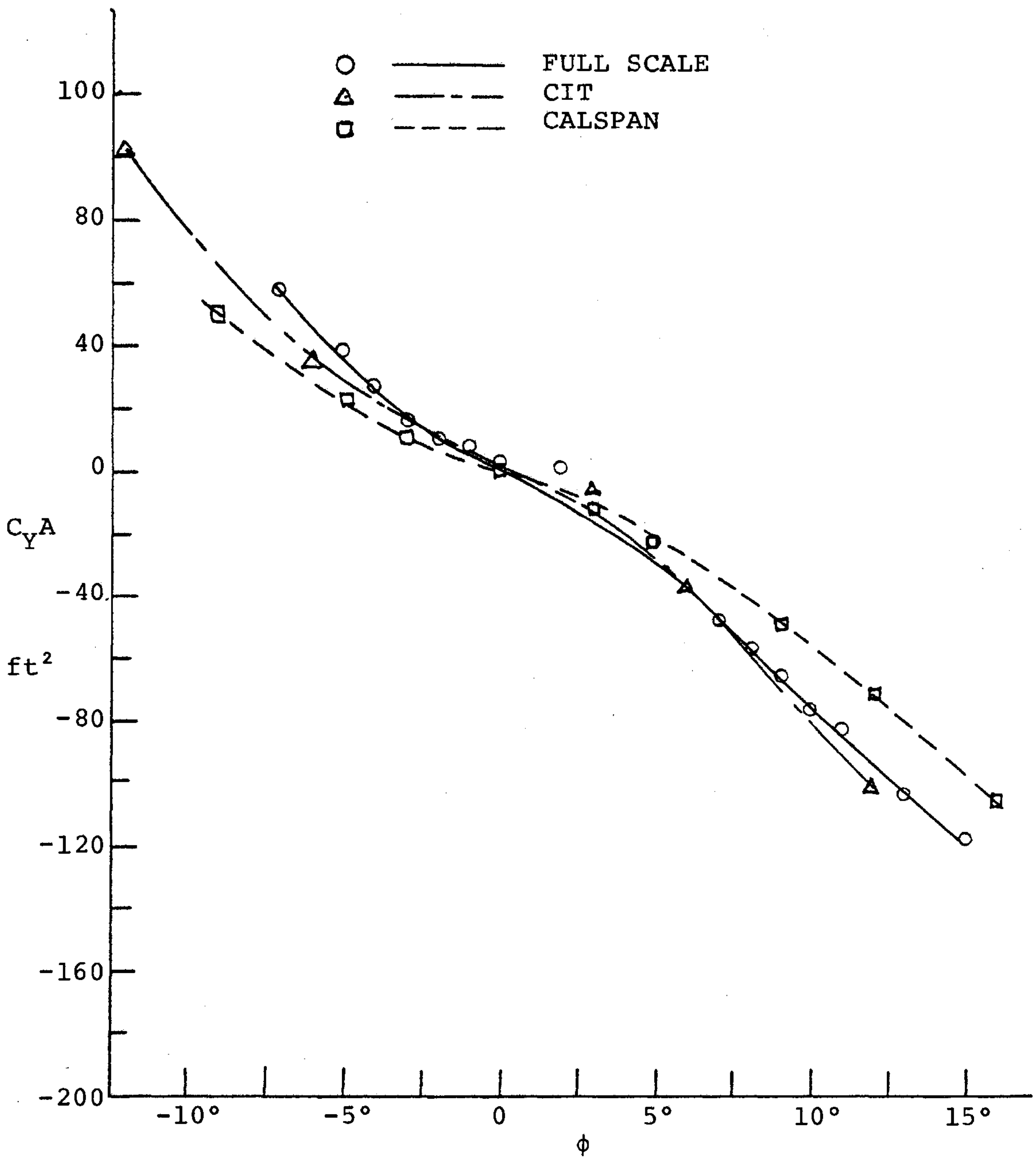


Figure 24. Lateral Force Area Versus Yaw Angle for Configuration 1. Comparison Between Wind Tunnel and Full Scale Results.

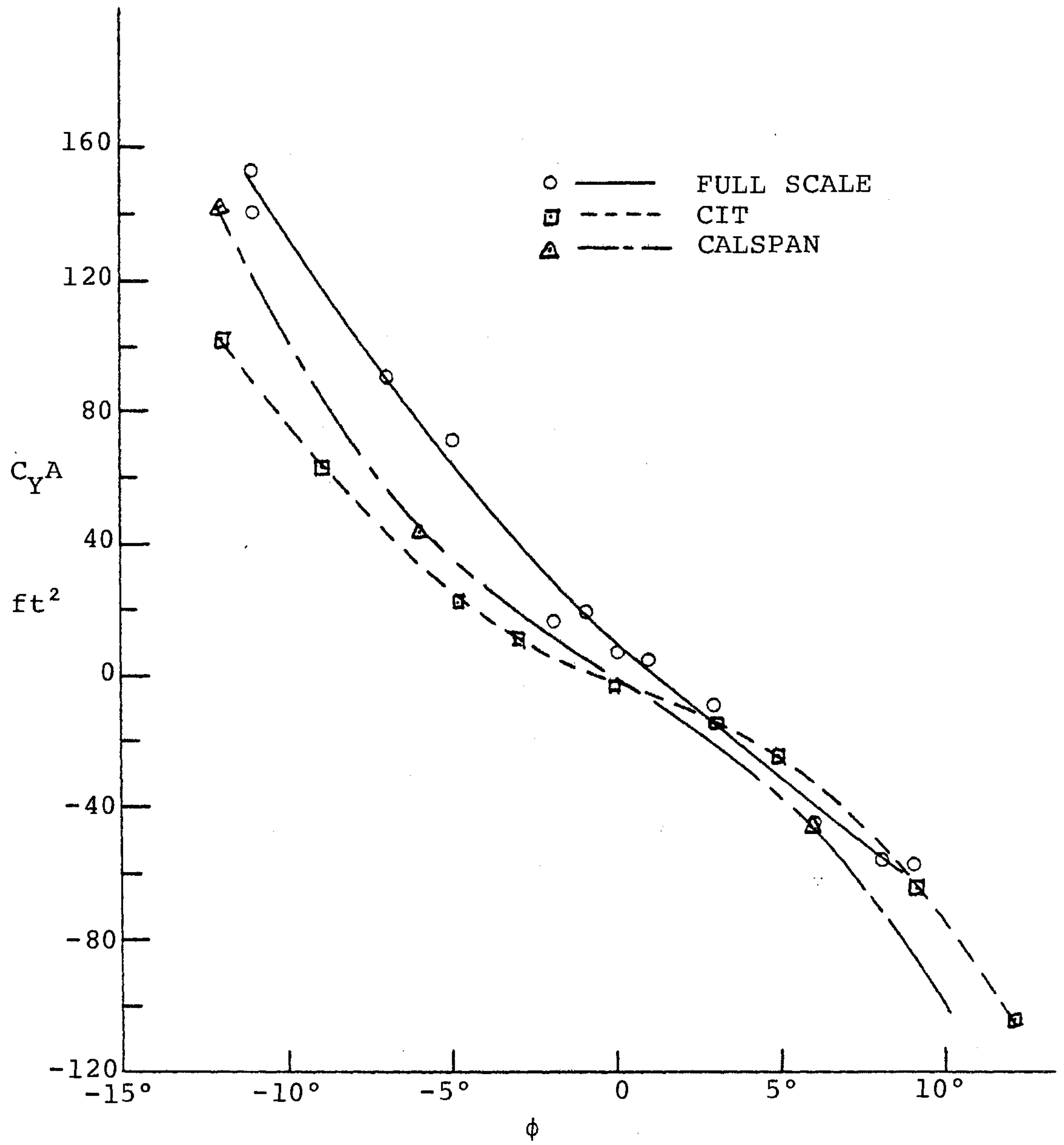


Figure 25. Lateral Force Area Versus Yaw Angle for Configuration 2. Comparison Between Wind Tunnel and Full Scale Results.

angle for Configuration 1. The lateral force data shows better agreement with the CIT data than with the Calspan data. For Configuration 2 at negative yaw angles, the full scale lateral force areas are somewhat above the CIT results.

It should be noted that there is no significance, other than an indication that there is some asymmetry in the full scale results, in the difference in the comparison between plus and minus yaw angles with the wind tunnel results. Most of the wind tunnel measurements were made in only one direction of yaw and the wind tunnel results have been assumed to be symmetric in drawing these curves.

The principle parameter difference between the different wind tunnel tests and full scale is the Reynolds number. The Reynolds numbers for the different tests are shown in Table 3. The Calspan wind tunnel tests were particularly designed to determine if there were an important Reynolds number effect on these measurements and no effect could be detected. The full scale results are a further check in this same process. The fact that the longitudinal force areas agree more closely with the Calspan tests and the lateral force areas with the CIT tests does not show any reliable change with Reynolds number. The principle other difference between the wind tunnel and full scale tests is the relative velocity between the train and the ground plane or between the air flow and the ground plane. This effect should be minimized by the nature of these tests. The ground plane effect should be more important for the TTX car itself than for the trailers. The fact that the trailers are on the deck of the TTX car which is moving at the same velocity as the trailers in both the full scale and wind tunnel tests makes the difference in the ground plane less important.

The general conclusion is that the differences between wind tunnels seems to be about the same as the differences between wind tunnel and full scale tests. Each of the tests gives better repeatability with itself than with the tests in the other facilities but there does not appear to be variation caused by any known or controlled parameter.

5. ASSESSMENT OF AERODYNAMIC TESTING METHODS

This work has shown that aerodynamic measurements on railroad rolling stock can be made using wind tunnels and by full scale testing. The wind tunnel provides the easiest and cheapest way of making aerodynamic measurements. There are many well developed wind tunnel facilities in the country manned by experienced and competant experimenters. The wind tunnel facility is usually well developed and instrumentation, which has been proved in the wind tunnel environment, is available. Models for wind tunnels are relatively inexpensive since they are usually passive. Different configurations can be tested easily and many tests run in a short time. The cost of models and wind tunnel time depends on the size of the facility.

There are many possible methods of making full scale aerodynamic measurements in addition to the one used in this work. All full scale testing is difficult and expensive. It requires large equipment and the experiments must usually be set up in the field in an environment which is more hostile than that found in the laboratory. It is usually necessary to develop special instrumentation and to prove the instrumentation in the course of the test being run and it is difficult and expensive to try new configurations.

The prime objective of this set of experiments was to compare the results found by wind tunnel and full scale testing. These experiments have established that the wind tunnel results are similar to the full scale results. The experiments give accurate full scale results. The inconsistancies between the results of the two wind tunnel tests and even between the different Calspan tests is disappointing. These discrepencies could probably be better understood or resolved by additional testing. The present tests have demonstrated an agreement to about 20% between the two wind tunnels and the full scale results and similar trends with changing parameters.

The wind tunnel is the only cost effective means of making aerodynamic measurements on railroad rolling stock. The experiments presented here have shown that it gives results representative of full scale results but the differences are larger than desired.

6. ROLLING RESISTANCE

A measurement of the rolling resistance of the TTX car was a secondary objective of these experiments. Since the aerodynamic resistance of the vans was being measured directly, the rolling resistance could be determined by measuring the total resistance and subtracting off the aerodynamic resistance. The coupler forces both ahead of and behind the TTX car were measured to obtain the total resistance. Since there was only the T-5 car behind the TTX car the forces on the two couplers were substantially different. The subtraction of the rear force from the front force did not involve the subtraction of two numbers of about the same size.

A set of instrumented couplers for this application was designed and fabricated at the TTC instrumentation laboratory, Figure 26. The coupler force was measured on a load cell as shown. The assembly used two concentric cylinders which were designed to slip one inside the other to insure that a large lateral load or bending moment could not be transmitted to the load cell. A set of Belleville spring washers were inserted in the load path to increase the flexibility enough so that the inner cylinder would contact the end stops provided before an excessive load was applied to the load cell. A grease fitting was provided on the outer cylinder to lubricate the space between the cylinders to reduce friction. Unfortunately, this measure did not prove to be completely effective and a hysteresis of about 250 lbs. developed in the coupler as reported in Reference 20, Appendix B. While this is only 5% of the full scale value of 5,000 lbs it is a much larger part of the actual values measured which in most cases were below 1,000 lbs.

The resistance force of the TTX car itself has been obtained by subtracting the longitudinal forces measured on the vans, inertia force, and gravity force from the net forces applied by the couplers. While the major aerodynamic effect

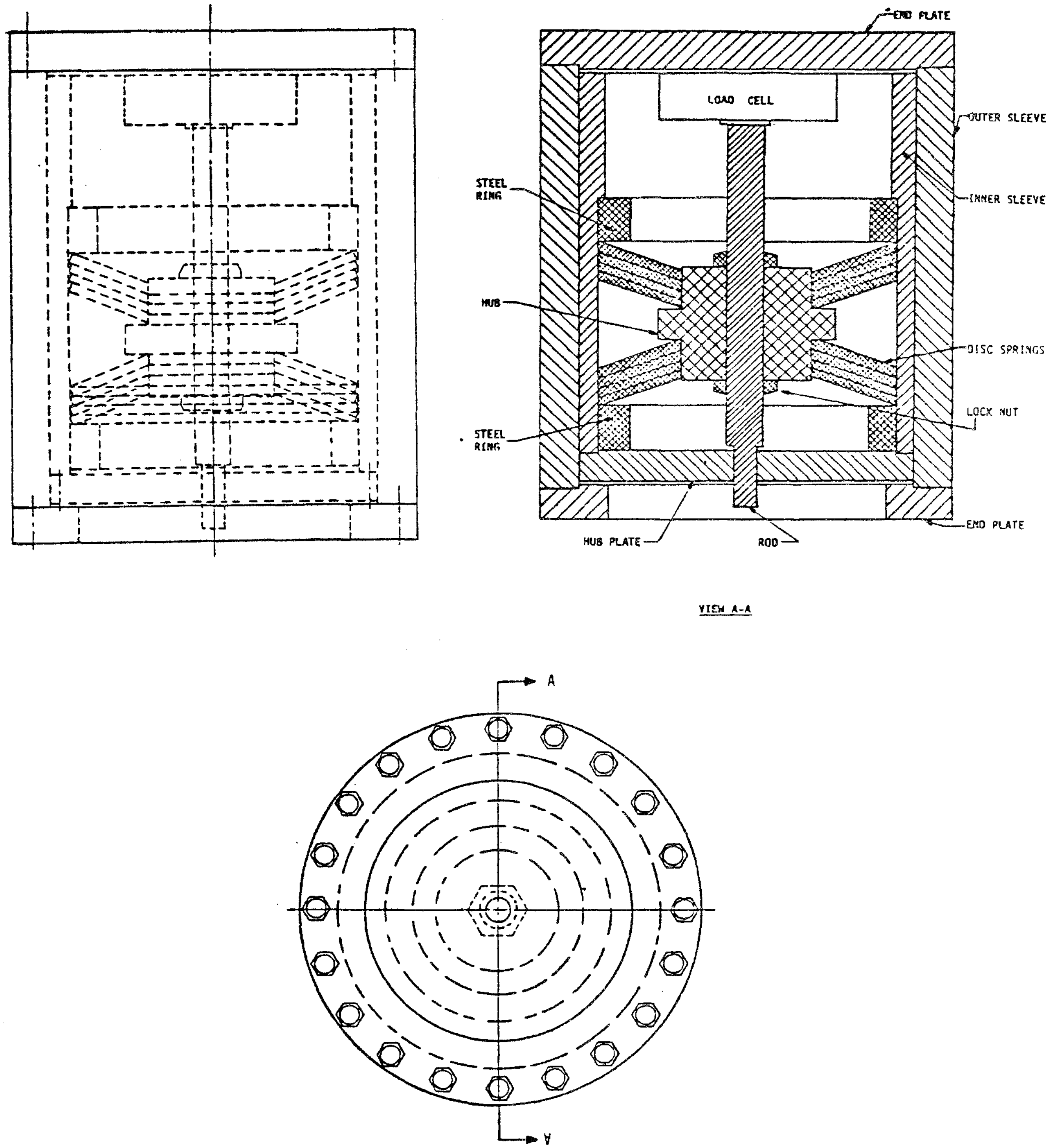


Figure 26. Instrumented Coupler Used to Measure Coupler Forces.

was removed by subtracting out the force on the vans, there still was an aerodynamic force on the TTX car itself. An estimate of the magnitude of this aerodynamic force can be obtained from the wind tunnel tests reported in Reference 13. The aerodynamic forces on an unloaded TTX car were measured both with a loaded and an unloaded TTX car in front of it. Lacking any better information, these results were used as the aerodynamic longitudinal force on the TTX car itself for Configurations 1 and 2 respectively. The rolling resistance was then obtained by subtracting the aerodynamic resistance evaluated from this data at the appropriate value of relative wind velocity and yaw angle. Almost all of the runs were made at nominal speeds of 50, 70, and 90 mph. The rolling resistance at each of these speeds for each configuration has been grouped together and examined to see if there were any trend with yaw angle. The conclusion was that the effect of yaw angle, which was apparant in data before the aerodynamic resistance had been subtracted, had now been removed. It was concluded that the spread in the data at each speed was random scatter such as that caused by hysteresis in the coupler and the results were averaged. The averaged results are shown in Figure 27 as a function of train speed together with an error bar to represent the size of the standard deviation. In all cases, the standard deviation is less than the 250 lb. hysteresis found in the calibration. The results for the two configurations agree surprisingly well considering the size of standard deviations. The rolling resistances as calculated by the Davis formula and the Modified Davis formula, Reference 13,

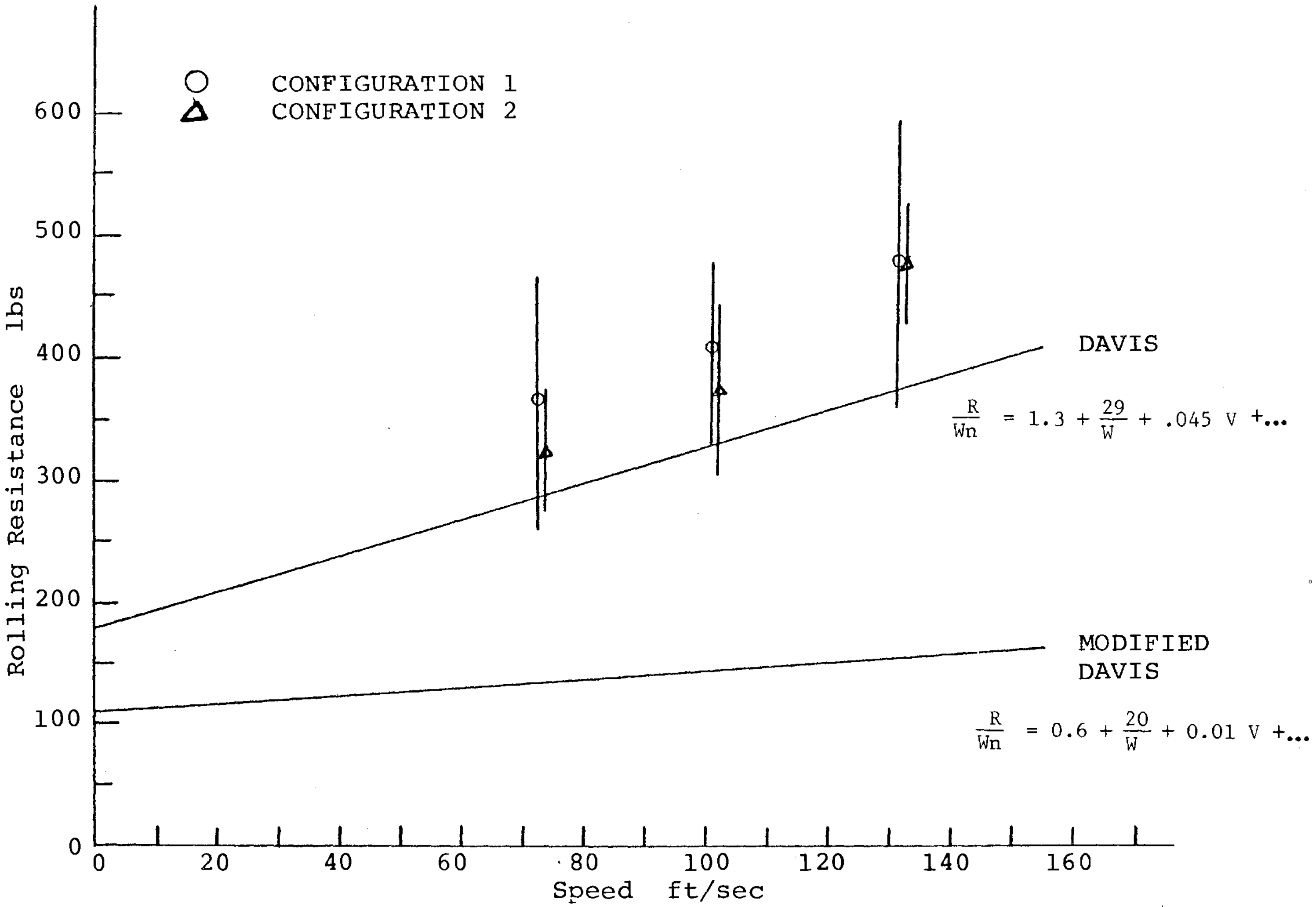


Figure 27. Rolling Resistance as a Function of Speed Compared with the Original Davis and the Modified Davis Formula. (V in Davis Formula is in mph.)

are also shown on the figure. The measured results lie above, but agree surprisingly well with, the Davis formula.

In evaluating these results for rolling resistance, it should be remembered that the wheels of the TTX car had been turned to a cylindrical profile and the car rode very smoothly over very good track with no signs of truck hunting. This car is probably not typical of actual revenue service equipment. These results suggest that this is a good technique for measuring rolling resistance and only requires the development of a more reliable means of measuring coupler force.

7. RECOMMENDATIONS AND/OR CONCLUSIONS

Both the wind tunnel and full scale direct force measurement techniques have been demonstrated to be effective means of measuring aerodynamic forces on TOFC/COFC railroad cars.

Reasonable agreement has been obtained between the different wind tunnel and full scale measurements but not as good as should be possible.

Full scale testing is considerably more difficult and expensive than wind tunnel testing. This difference would be even larger if tests on different configurations are to be considered.

Aerodynamic characteristics of the existing TOFC/COFC railroad car configurations are now available. Testing of other railroad cars is needed.