Dick Scharr 7009.6

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

Single Axle and Articulated-Supporting Truck
Test Results Report

Single Axle
pg 43 didn't get up to critical speeds ie hunting with worn wheels
(max speed 60 MPH)

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

FRA/ORD-81/59

August 1981

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16. Abstract

This report presents the results of a project designed to quantify the service performance characteristics of two types of trucks. The first truck treated is essentially a conventional three-piece freight car truck supporting the articulated connector of a multi-unit prototype intermodal railcar. This truck is referred to as the articulated-supporting truck. The second truck investigated is a single axle truck. This truck, as its designation indicates, is a truck with one axle which is capable of yaw with respect to the carbody independent (within physical limits) of the other truck on the same unit.

The test methodology is presented in detail including discussions of trucks, instrumentation, test zones, and test matrix. The results are presented and discussed in terms of the wheel/rail force vector (lateral-vertical), angle-of-attack, hunting critical speed, and ride quality. From these observations no intrinsic problems were discovered which would preclude these trucks from further consideration as rail service equipment.

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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

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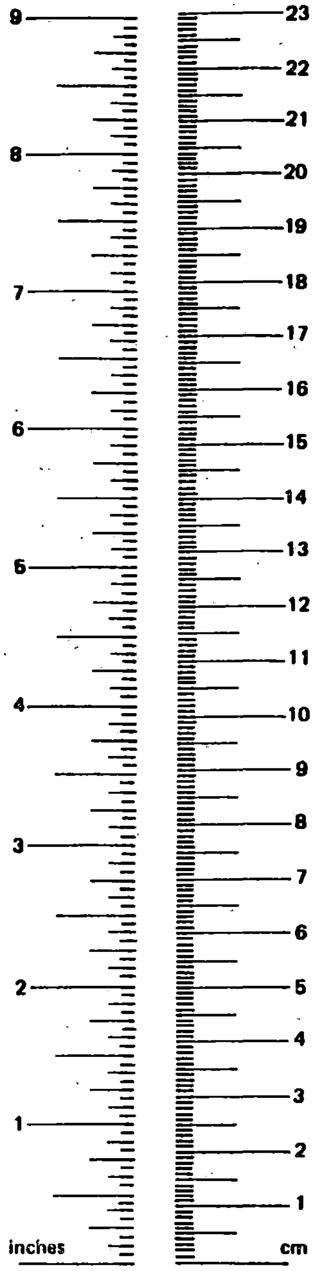
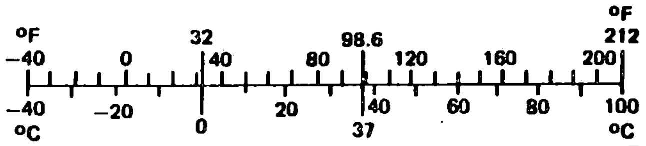
*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



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	36	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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1.0 INTRODUCTION

1.1 BACKGROUND

The Federal Railroad Administration (FRA) Office of Freight Systems has been conducting freight car truck performance research for several years. In Phase I of the Truck Design Optimization Project (TDOP) a study of Type I, General Purpose, three-piece truck was undertaken. Subsequently, in Phase II a performance characterization of the Type I truck was completed and a study of Type II, Special Purpose or Premium truck, was commenced with the objective of developing performance and testing specifications for the Type II truck. Due to the complexity and variety of two-axle trucks meeting the definition of Type II truck, work on single-axle trucks and trucks under an articulated-connector (railcar) was deferred. In addition, equipment in the latter two classes were not readily available at the outset of TDOP Phase II. Recent developments have made available to FRA single-axle and articulated-connector equipment for study on a limited scale. The purpose of this project was to establish such a study as an adjunct to TDOP without encumbering the TDOP Phase II effort itself.

This project was a cooperative effort between the Government and Industry with numerous participants providing the necessary resources to accomplish the project objectives. The Richmond, Fredericksburg and Potomac Railroads made available the trackage for testing and under contract provided the test staging site, equipment and crews necessary to conduct the test program. For the purpose of this project the Budd Company loaned its prototype intermodal car, the Lo-Pac 2000, for testing directed at collecting performance data on trucks under articulated connectors. The Southern Railway leased to the FRA an Autoguard car in order that performance data could be obtained on single axle trucks. The Griffin Wheel Company donated 33-inch wheels with the same modified Heumann profile used in TDOP for the instrumented wheelsets. Axles for the instrumented wheelsets were also donated by Standard Steel. Consultation and engineering drawings on the single axle and articulated suspending trucks were provided by National Castings and American Steel Foundaries (ASF) respectively.

1.2 OBJECTIVE

The overall immediate objective of this project is to provide data which will permit an assessment of the service performance characteristics of a single axle truck and a truck under an articulated connector. Specifically, from the parameters measured flange wear and truck dynamics will be quantitatively evaluated. Truck dynamic evaluation will consist of measurement of hunting, rock and roll and curving performance. The long term objective of this project is to establish an initial base of knowledge of these specific truck configurations which can be incorporated in future research.

2.0 TEST VEHICLES AND TRUCKS

As mentioned in the introduction, two trucks were investigated during this study. Unlike the TDOP tests, during which each truck was tested under the same or identical car, two dissimilar rail cars were used in the present study. This was necessitated by the fact that the trucks studied were integral to a specific car.

In the case of the single axle truck, the Southern Autoguard car was used as the test bed. In the case of the articulated-supporting truck, the Budd LoPac 2000 served as the test vehicle. Each truck/car combination will be treated as a system and is described further in this section.

2.1 ARTICULATED-SUPPORTING TRUCK/LOPAC 2000

The first truck/vehicle system tested was the LoPac 2000 with essentially standard three-piece freight trucks supporting the articulated joints connecting the units which make up the car. For this reason these trucks are referred to in this report as articulated-supporting trucks.

2.1.1 THE ARTICULATED-SUPPORTING TRUCK

The articulated-supporting truck, as previously pointed out, is basically a standard three-piece freight truck placed under an articulated connector. Both the truck and connector are manufactured by American Steel Foundaries. The truck investigated in this program was the ASF 70-ton Ride Control truck shown in Figure 1 supporting two of the articulated units. Each 70-ton Ride Control Truck was equipped with 33-inch wheels and 6 x 11 journal bearings. Figure 2 shows the truck prior to installation with the instrumented wheelsets (See Section 3.2) prior to installation for test.

The only feature of this particular truck which differs from a standard truck are the two structures seen attached to the truck bolster which provide support to the side bearings. This arrangement permits the side bearings to bear outboard loads of two adjacent railcar units while each unit remains free to yaw independent of the other. The side bearings are the constant contact elastomeric type commonly in use today. One other minor difference between these trucks and the majority of 70-ton trucks in use today is the 16 inch center plate employed on the articulated-supporting trucks as compared to the more common 14-inch plate.

The outboard trucks, those at the A and B-end of each articulated car, are actually standard and interchangeable with trucks under 70-ton rolling stock capable of accepting a 16-inch centerplate. These trucks are also equipped with constant contact side bearings. However, since they are under only one unit of the car, they do not require the dual side bearing adaptor shown in Figure 2.

The ASF articulated connector employs the male and female design shown in Figure 3. When mated the truck center pin is accepted through the hole which is perpendicular to the axis of the connector. The assembled connector is shown in Figure 4. Note the center plate at the bottom of the connector in Figure 3b.

2.1.2 LOPAC 2000

The vehicle employing the articulated-supporting truck was the Budd Company's prototype low-profile intermodal vehicle designated the LoPac 2000, shown in Figure 5. The car consists of six units carrying standard 40-foot trailers and not containers as it

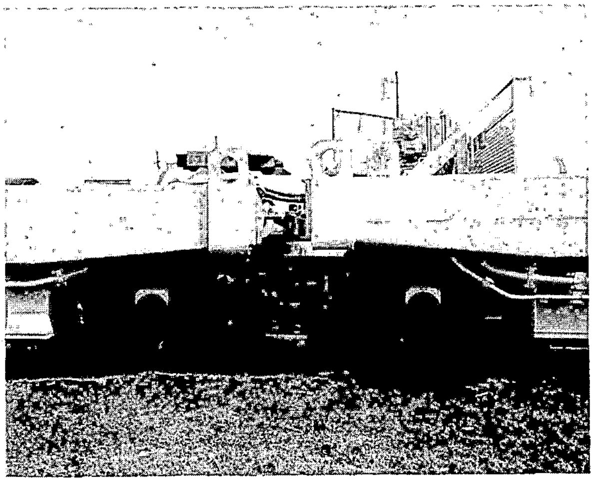


Figure 1. The Articulated-Supporting Truck in Position

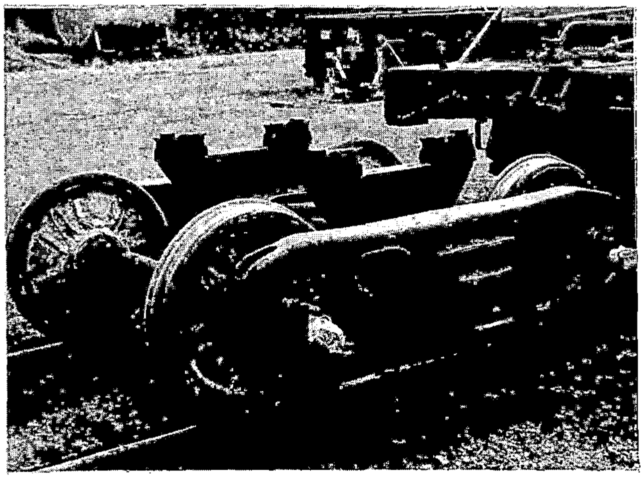
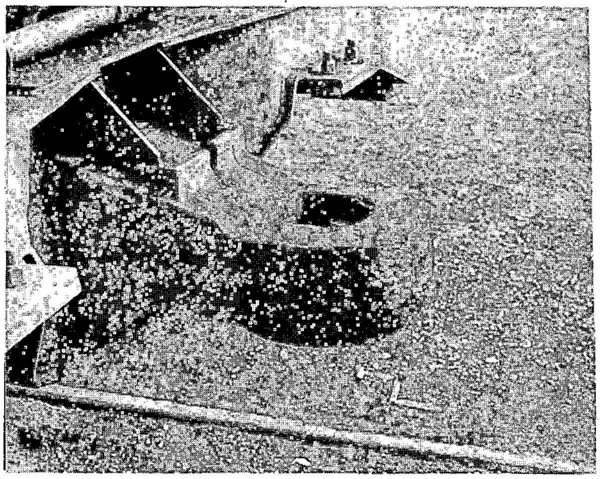


Figure 2. The Articulated-Supporting Truck Prior to Installation



a. Male

b. Female

Figure 3. The Male and Female Articulated Connectors

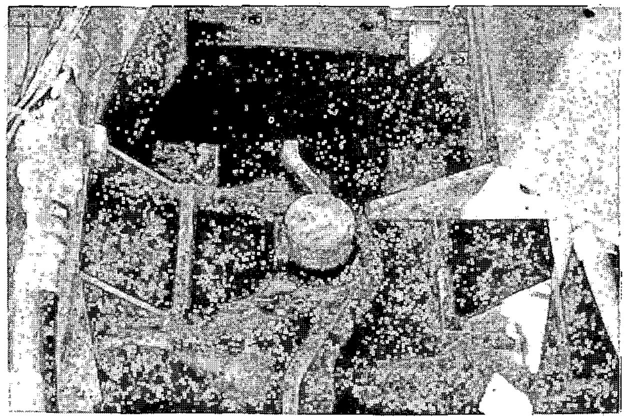


Figure 4. The Assembled Articulated-Connector

may appear. The Lo Pac 2000 design incorporates two full length side sills of rectangular welded steel tubing. This creates the deep well seen in Figure 6 which can accept trailers up to 45 feet in length or standard 40 foot containers. This well accomplishes two ends. First and most obvious is the lowering of the center of gravity and overhead clearance requirement by nearly 2.5 feet. Second the sills act as an aerodynamic skirts which reduces train resistance. Train resistance is further reduced by keeping the gap between trailers small. This is made possible by the use of the articulated connector.

The vehicle employed during this test program consisted of six of these units with a truck center spacing of 50 feet 5 inches and an overall length (over coupler face) of 320 feet. The height of the vehicle above rail was 48 inches (to top of side sill) with a center of gravity 30 inches above the rail. The lightweight of the entire six-unit car was 223,600 pounds with a 65,000 pound capacity (payload) per unit.

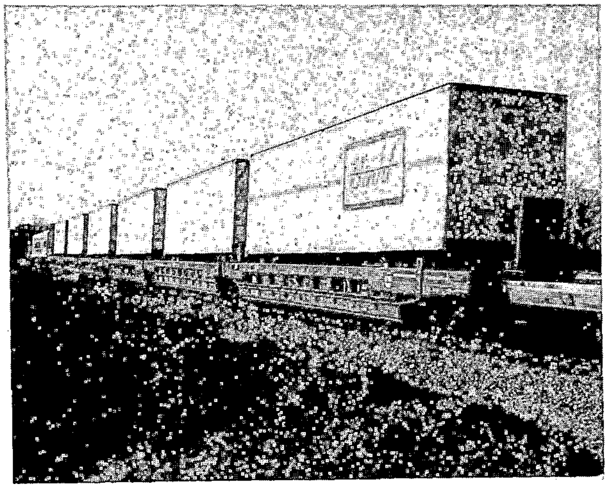


Figure 5. LoPac 2000

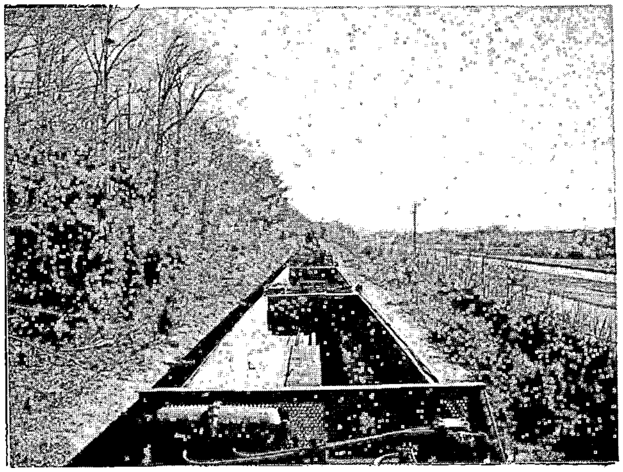


Figure 6. The LoPac 2000 Cargo Well

2.2 SINGLE AXLE TRUCK/AUTOGUARD CAR

The second vehicle/truck system was the Autoguard car equipped with single axle trucks. The term single axle truck, as used here, refers to an axle/suspension system which is independent of any other truck and capable of yaw with respect to the carbody.

2.2.1 THE SINGLE AXLE TRUCK

As mentioned above, a single axle truck is an axle which is independently suspended and capable of yaw with respect to the carbody. The single axle truck used in this investigation was designed and manufactured by the National Castings Division of Midland-Ross.

The truck consists of three primary elements shown in Figure 7. These are the axle, the saddle, and the jaws. As shown, the saddle is hung over the journal bearing with a narrow pedestal adaptor. This particular truck is equipped with 6 1/2 x 12 journal bearings and 33 inch wheels. The saddle in turn fits into the jaws which is bolted to the carbody. The saddle is suspended from the jaws allowing vertical movement within the jaws. In addition, friction wedges placed over the inboard springs allow the axle to displace longitudinally. Note that as the axle moves in the longitudinal direction the wedge forces the springs to compress increasing the longitudinal steering force proportionally. Thus, the single axle truck is able to both roll and yaw independently of any other truck connected to the Autoguard Car.

Figure 8 shows the single axle truck being disassembled. In Figure 8a the saddle is still within the jaws (note: all brake gear has been removed). Figure 8b shows the saddle clear of the jaws. Also seen here are three of the four friction wedges lying on the ground (note: brake gear in place).

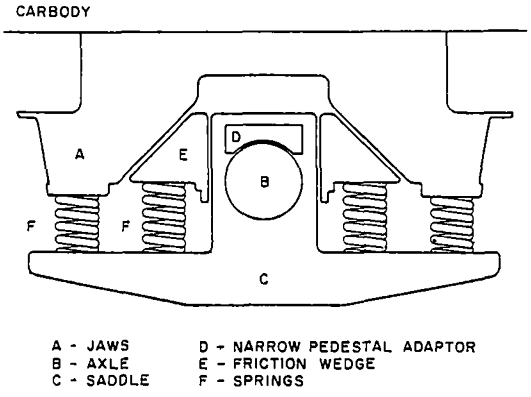
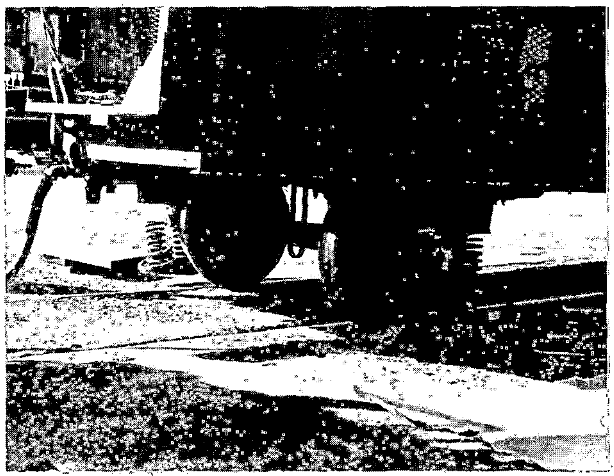
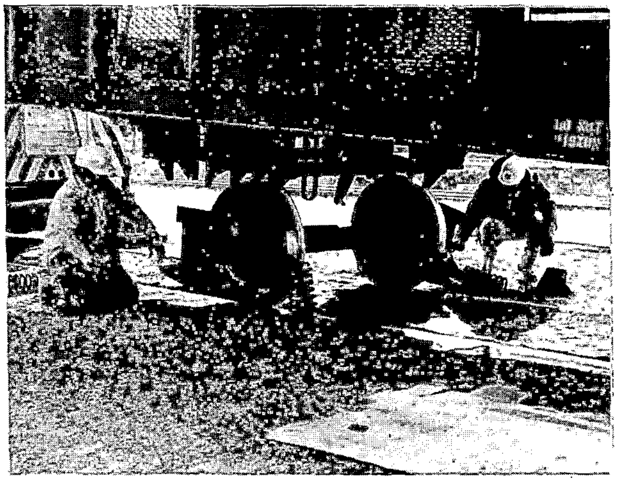


Figure 7. Schematic of the Single Axle Truck



a. Saddle in Jaws



b. Saddle Clear of Jaws

Figure 8. Single Axle Truck Being Removed from Jaws

It should be pointed out here that the instrumented wheelsets, used to measure the vertical and lateral wheel/rail forces (see Section 3.2), were equipped with 6 x 11 journal bearings in the standard 70-ton configuration. Therefore in order to install these wheelsets in the single axle, normally configured with 6-1/2 x 12 journal bearings, it was necessary to use specially modified narrow pedestal adaptors. These adaptors, donated by National Castings, were fabricated from standard 6 x 11 adaptors with a 1/2 inch offset and shimmed crown allowing the installation of the instrumented wheelsets.

2.2.2 THE AUTOGUARD CAR

The Autoguard car, shown in Figure 9, was built by the Greenville Car Company in 1973 and is presently owned by Southern Railway. The car is a tri-level covered auto-rack car with a vertical clearance of 18 feet 7-1/2 inches. The lightweight for the entire three unit car is given as 144,000 pounds with a center of gravity approximately 90 inches above the rail. The Autoguard car is comprised of three units each 40 feet 6 inches long. Each unit is supported by two National Castings single axle trucks at a spacing of 28 feet. Internal connection is provided by a National Castings draw bar and rubber draft gear assembly. Figure 10 shows one end of the draw bar after two units have been separated. The overall length of the car (over pulling face of couplers) is 129 feet.

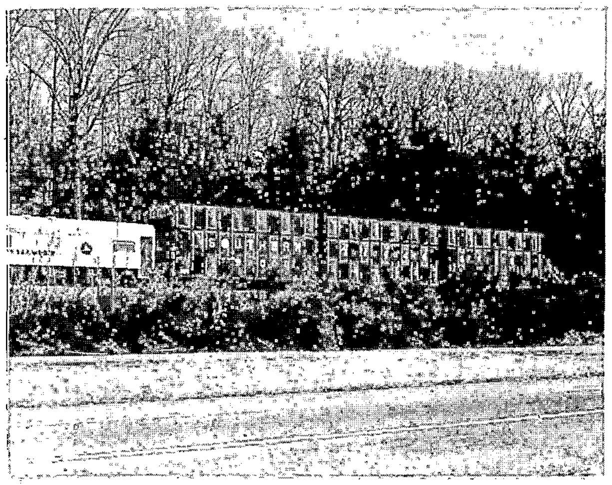


Figure 9. The Autoguard Car

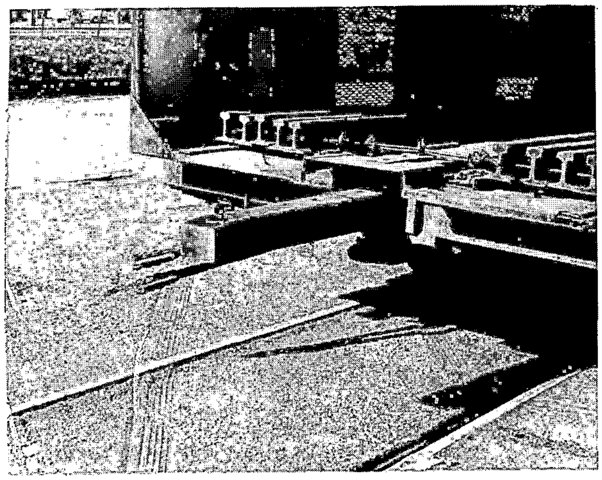


Figure 10. The Autoguard Draw Bar

3.0 DATA ACQUISITION SYSTEM AND INSTRUMENTATION

The Single Axle and Articulated-Supporting Truck test program was supported by the FRA Data Acquisition Vehicle T-5 (DOTX 205). The T-5 vehicle, shown in Figure 11, provided all power, signal conditioning and recording instrumentation as well as providing an observation platform during field tests.

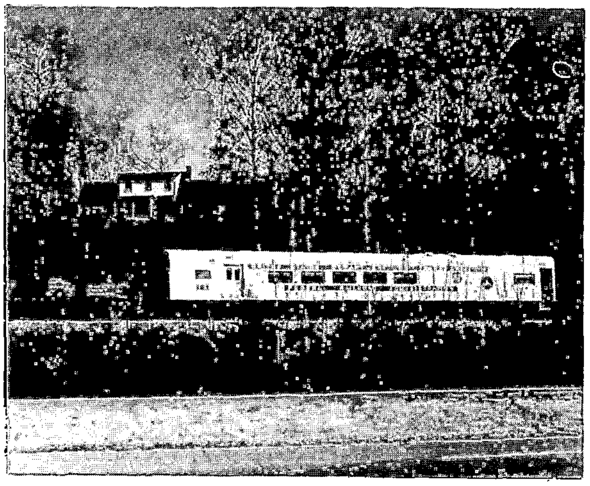


Figure 11. The T-5 Data Acquisition Car

The data collected during the tests can be categorized as follows.

1. Wheel/rail force (strain)
2. Angle of attack (eddy current)
3. Acceleration (inertial)
4. Displacement (potentiometer)
5. Location (capacitive)
6. Speed (tachometer)

3.1 THE DATA ACQUISITION SYSTEM

The T-5 Data Acquisition car is configured to condition and record up to 120 channels of data. Figure 12 shows the system block diagram. Signals are brought into the car via bulkhead connectors which are located at either end of T-5. The pins of each connector are hard wired to a specific point in the onboard patch panel.

Signals are channeled through the required ancillary electronics, e.g. power supplies, amplifiers, etc., via jumper cables. The conditioned signal is filtered to avoid aliasing after digitizing using programmable 4-pole (-24dB/octave) low pass Bessel filters. For the purposes of the present study all signals were anti-alias filtered at 64 Hz (-3dB). Up to six channels can be selected for display on the strip chart recorder for real-time surveillance and analysis.

After the signals are filtered each channel is digitized at 256 samples per second. Note this is four times above the anti-alias filter corner; however, Bessel filters have a relatively slow roll-off over the first octave. Thus, a relatively high sample rate is used to provide reliable digital data.

The data acquisition and reproduction processes are controlled through the on-board minicomputer, a Raytheon 704. Program selection, acquire or reproduce, and parameter entry, channel assignments, digitizing rate, etc. are entered through the teletype. The 704 processor controls the data acquisition through the direct memory access (DMA) as well as formatting and writing the data to tape. Speed is derived from the tachometer pulses received from an optical tachometer (1000 pulses/revolution) located on one of the axles.

3.2 INSTRUMENTED WHEELSETS/REAL TIME PROCESSOR

The primary measurement used in this project was the wheel/rail force vector. That is, the wheelplate was strain gaged in such a manner as to produce continuous analog signals proportional to both the vertical and lateral forces at the wheel/rail interface. These signals were processed in real time to provide a first look and on-board analysis capability as well as quality assurance.

For the purposes of the present investigation two wheelsets, four wheelplates, were instrumented to provide a complete truck force measurement capability. Experience has shown that complete truck measurement is vital to the understanding of truck dynamic behavior.

The wheels which were instrumented for use in these tests were cast by the Griffin Wheel Company. Each wheel was 33 inches in diameter with the same modified Heumann tread profile used in the TDOP. This profile is considered to be a simulated nominally worn profile with a 1 in 20 taper. The actual tread profiles are contained in Appendix A.

After the wheelplates were machined for strain gaging, they were pressed onto standard 70-ton axles (designation E) equipped with 6 x 11 journal bearings. Thus, the instrumented wheelsets were essentially standard 70-ton wheelsets capable of operation under any standard 70-ton car or other cars with axle loadings of 52,500 pounds or less.

The vertical force measuring bridges follow the concept used by ASEA. Each leg of the bridge has one gage on the field side and one gage on the gage side of the wheel. The four legs are evenly spaced 90° apart on the wheel as shown in Figure 13. The strain distribution due to a purely vertical load is highly localized in the wheelplate above the point of rail contact. As the pair of gages in each leg of the bridge consecutively pass

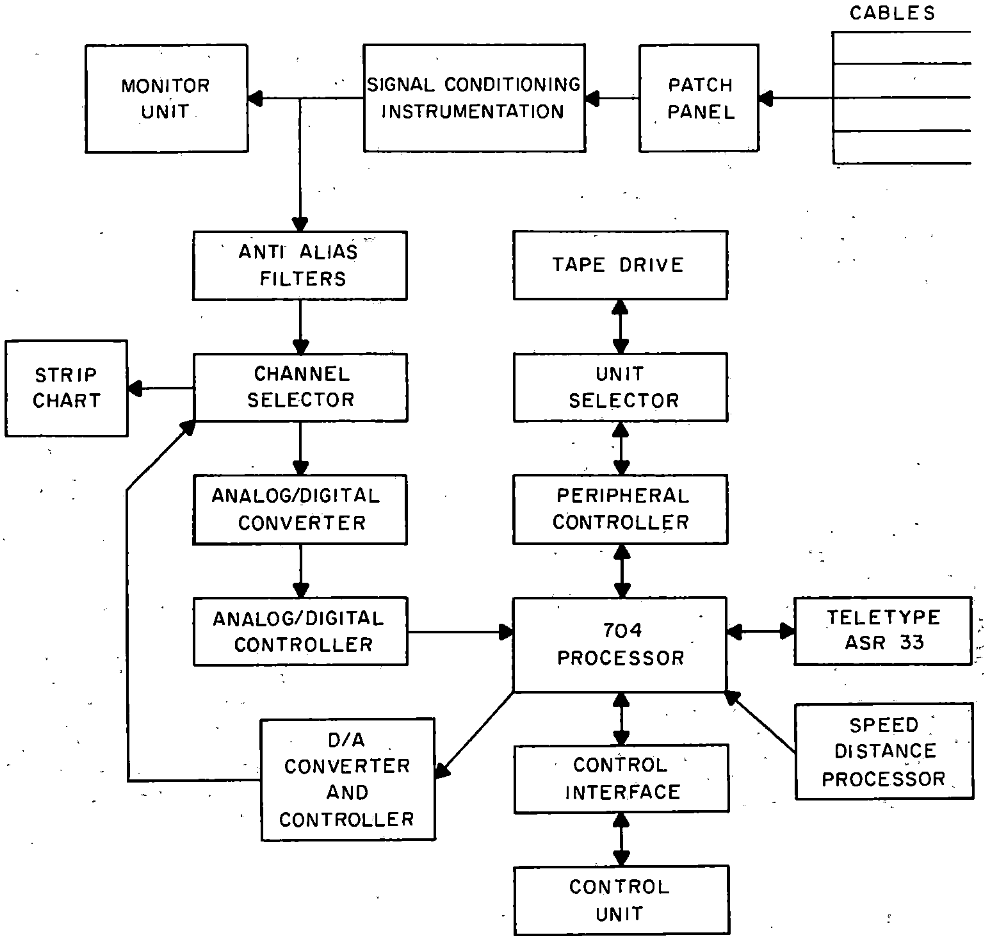


Figure 12. The Data Acquisition Block Diagram

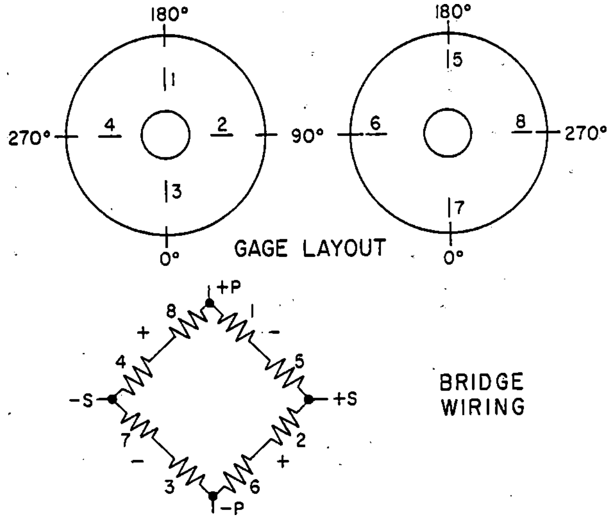


Figure 13. Vertical Force Measurement System

over the rail contact point, two negative and two positive peak bridge outputs occur per revolution. By correctly choosing the radial position of the gages, the bridge output as a function of rotational position of the wheel can be made to resemble a triangular waveform having two cycles per revolution. The purpose of having gages at both sides of the wheelplate in each leg is to cancel the effect of changes in the bending moments in the wheelplate due to lateral force and changes of the tread/rail contact point.

When two triangular waveforms are equal in amplitude, out of phase by one fourth of a wavelength, rectified and added, the sum is a constant equal to the peak amplitude of the individual waveforms. In order to generate a strain signal proportional to vertical force and independent of wheel rotational position, the outputs of two identical vertical bridges 45° out of phase are rectified and summed as shown in Figure 14. Since the bridge outputs do not have the sharp peaks of true triangular waveforms, their sum is lower at the bridge peaks than the ideally constant value between peaks. In order to reduce the ripple or variation in force channel output with wheel rotation, the bridge sum is scaled down between the dips coinciding with the rounded bridge peaks. By taking as the force channel output the greatest of either an individual bridge output or the scaled down sum of both bridges, the scaling down is applied selectively to the part of the force channel output between the dips as shown in Figure 14.

The lateral force measuring bridges illustrated in Figure 15 follow a concept used by Electro-Motive Division of General Motors. Each bridge is composed of eight gages evenly spaced around field side of the wheelplate at the same radius. The first four adjacent gages are placed in legs of the bridge that cause a positive bridge output for tensile strain and the next four gages are placed in legs causing a negative bridge output for tensile strain. The resulting bridge is very sensitive to wheelplate bending stress due to a hub moment caused by lateral force (shown in Figure 16). This is because the tensile strains below the axle and the compressive strains above the axle are fully additive in bridge output twice each revolution (once as a positive peak and once as a negative peak). The bridge is not sensitive to axial loads or to any radially symmetric strain distribution such as thermal or centrifugal induced strain. Radial gage locations were chosen such that the bridge output varies sinusoidally with one cycle per wheel revolution. Two identical bridges, 90° out of phase, are used to obtain a force channel output independent of wheel rotational position as a consequence of the identity:

$$\sqrt{(L\sin\theta)^2 + (L\sin\{\theta + 90^\circ\})^2} = |L| \text{ for any } \theta.$$

Before discussing the processing algorithms it is useful to briefly review the wheelset design criteria and manufacturing process. Prior to the instrumentation process the wheelplate is machined and/or polished to accept bonded foil strain gages. Next the wheels and journal bearings are pressed onto the axles.

Once the machining and assembly are completed a strip of five gages are laid along a radial line approximately one inch center to center. The wheel is placed in a calibration fixture and loaded under prescribed combinations of vertical and lateral loads. Each series of load combinations is carried out at 15 degree intervals for one entire wheel rotation. This constitutes a map of the strain field which is loaded into computer memory.

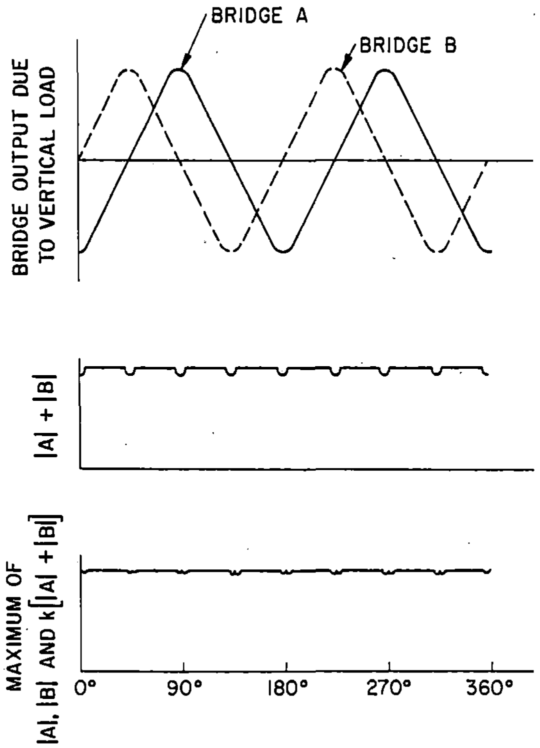


Figure 14. Triangular Output Processing

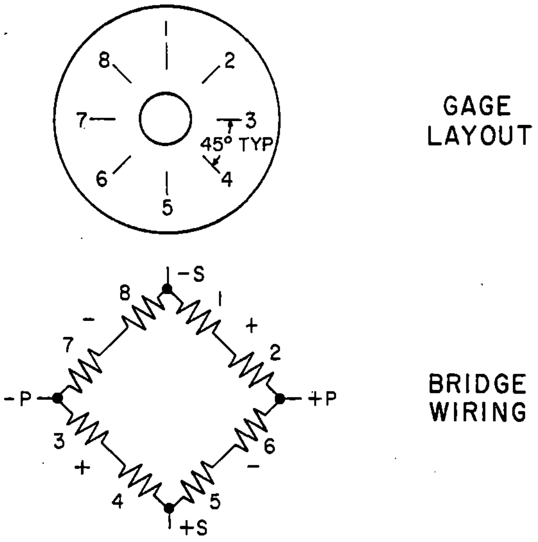


Figure 15. Lateral Force Measurement System

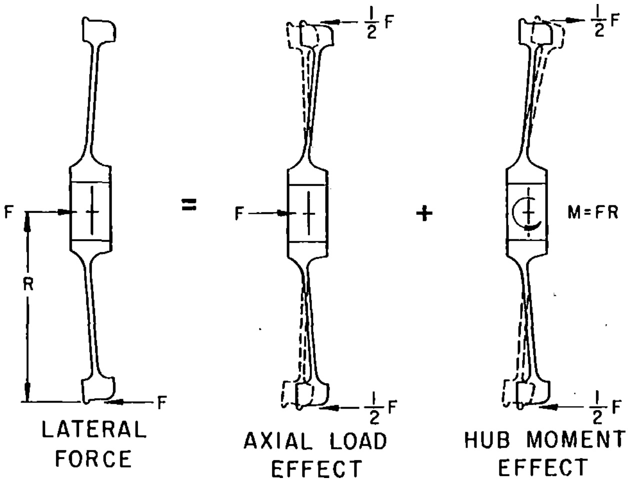


Figure 16. Lateral Force Strain Distribution

The computer is then used to explore specified (see above) bridge designs to seek out an optimum bridge which meets the following criteria:

1. maximum sensitivity (minimum acceptable values: 5με/kip vertical, 10με/kip lateral)
2. minimum ripple (rms error < 8%)
3. minimize crosstalk (5% <)
4. minimize load point sensitivity

It should be pointed out that it is not necessary or desirable to completely eliminate crosstalk, because this source of error is easily removed using a simple algorithm. Furthermore, ripple is only of interest when instantaneous forces (duration of 5 ms to 10 ms) are being considered. Typically impulses of 50 ms or greater are considered for the purposes of analysis reducing considerably the ripple error. When mean values are considered, ripple is virtually of no consequence.

Once a bridge is located which optimizes these criteria, a trial bridge is placed on a wheelplate different from the one used to map the strain field. The trial bridge is then subjected to the same set of loadings and the output is compared with the computer predictions. Minor adjustments, due primarily to gage alignment, are made if necessary. Once adequate agreement is obtained between an actual bridge and the ideal computer bridge, the remaining bridges on plate are installed.

A real-time processor is used to convert the sinusoidal and triangular signals coming from the Wheatstone bridges on the wheelplate to the instantaneous values of lateral and vertical forces. The real-time processor is essentially an analog device with sufficient logic capability to carry out the processing algorithms which include squaring, adding, taking the square root, taking the absolute value, selecting a maximum or minimum value, and applying a crosstalk correction factor. The alorithms implemented by the processor are as follows.

Vertical Channel Processing

$$V = \text{Greatest of} \quad |V_a|,\quad |V_b|,\quad K\,(|V_a|+|V_b|)$$

where

$$K = \frac{(\min |V_a| \text{ or } |V_b|) + (\max |V_a| \text{ or } |V_b|)}{2(\max |V_a| \text{ or } |V_b|)}$$

(NOTE: K is a constant determined during calibration)

Lateral Channel Processing

$$L = \left(L_a^{\,2} + L_b^{\,2}\right)^{1/2} \qquad \text{(Positive Root)}$$

Vertical Force Determination

$$F_v = \left(\frac{1}{G_v}\right) V$$

$$F_v' = \left(\frac{1}{G_v}\right) V - (H_v)\, F_L$$

Lateral Force Determination

$$F_L = \left(\frac{1}{G_L}\right) L$$

$$F_L' = \left(\frac{1}{G_L}\right) L - (H_L)\, F_v$$

Where:

V_a = Vertical bridge A output

V_b = Vertical bridge B output

L_a = Lateral bridge A output

L_b = Lateral bridge B output

K = Scale factor to reduce vertical channel ripple

V = Vertical channel output

L = Lateral channel output

G_v = Average vertical channel (or bridge) sensitivity in με/kip units

G_L = Average lateral channel (or bridge) sensitivity in με/kip units

H_v = Increase in vertical force measurements as a ratio of applied lateral force (positive lat. force crosstalk)

H_L = Increase in lateral force measurements as a ratio of applied vertical force (positive vert. force crosstalk)

F_V = Vertical force indication uncorrected for lateral force crosstalk

F_V' = Vertical force indication corrected for lateral force crosstalk

F_L = Lateral force indication uncorrected for vertical force crosstalk

F_L' = Lateral force indication corrected for vertical force crosstalk

The values of G, H, and K are given in Table 1.

TABLE 1

SCALE FACTORS AND CROSSTALK CORRECTION

	K	G_V με/kip	G_L με/kip	H_V lb/lb	H_L lb/lb
1X	.9114	5.43	16.56	.072	.026
1Y	.9400	5.35	16.42	-.040	.040
2X	.9460	5.47	16.84	-.052	-.049
2Y	.9380	5.52	16.85	-.008	-.011

3.3 ANGLE OF ATTACK MEASUREMENT SYSTEM

The basic angle of attack measurement is accomplished by placing two sensors, for detecting the lateral position of the rail, at a fixed longitudinal distance along the rail. The angle-of-attack is then defined as

$$\alpha = \arcsin \frac{d_1 - d_2}{\ell}$$

where d_1 and d_2 are the two lateral positions and ℓ is the longitudinal distance between the sensors (See Appendix B for error analysis). Since $d_1 - d_2 << \ell$, this can be expressed as

$$\alpha = C \frac{d_1 - d_2}{\ell}$$

where C is a conversion constant from radians to degrees ($180/\pi$).

The relative lateral rail position sensor is an eddy current device. This device sends out a rapidly changing magnetic field and senses the reflected field that is returned by the eddy currents excited in nearby metal objects. Since rapidly changing fields are employed, this type of device is not affected by fields from permanent magnets.

3.3.1 SENSOR SYSTEM

The angle-of-attack sensor is considerably more stable than most eddy current sensors because it separates the excitation coil from the sensing coil and it employs a direct frequency modulation technique. Most eddy current sensors use the same coil to both send the exciting field and receive the reflected field. This has the disadvantage that the exciting current causes a small drift in the coil impedence, due to temperature or humidity changes, and appears the same as a reflected field. Because excitation and sensing is accomplished by different coils with the present system this effect is eliminated, and in addition, the circuit impedence can be chosen to minimize other coil impedence affects.

This angle-of-attack eddy current sensor has the additional advantage of processing no moving parts such as hydraulics to raise and lower the sensor for turnouts and crossings. A typical sensor installation is shown in Figure 17. Here it is seen the sensor is well above the rail head. Because it is suspended from the narrow pedestal adaptor remains fixed at its design height above the rail head.

Amplitude drift and offset voltage severely limits the practical resolutions of most analog detection and data transmission systems. By directly converting the amplitude of the reflected signal to a frequency change, these problems can be avoided by employing digital techniques of data transmission and demodulation. The basic angle-of-attack system signal flow is shown in Figure 18.

3.3.2 SENSOR COILS

The angle-of-attack sensor coils are shunt tuned and connected to low impedence points in the oscillator circuit. This means that the returned signal is always 90° out of phase with the excitation voltage. Since the excitation coils are wound at right angles to the sensor coil, the returned signal may be either leading or lagging, depending on the target location. The coils are phased to null the returned signal when the sensor is centered over the railhead. This allows the sensor to be relatively insensitive to its distance above the railhead (about an optimum height, 2-5/8 inches for the present application, as determined by the coils spacing) and gives an approximately linear response to the lateral position relative to the railhead.

As mentioned earlier the measurement of an angle-of-attack requires a pair of sensors. Thus, each wheel of the LoPac 2000 is bracketed by a pair of sensors as shown in Figure 19. The two sensors located on the side of the axle opposite the spring group are referred to as outboard. Those sensors positioned between the wheel and side frame are called inboard sensors. The angle-of-attack sensor locations for the single axle truck are shown in Figure 21. In the case of the single axle truck there is no inboard/outboard designation.

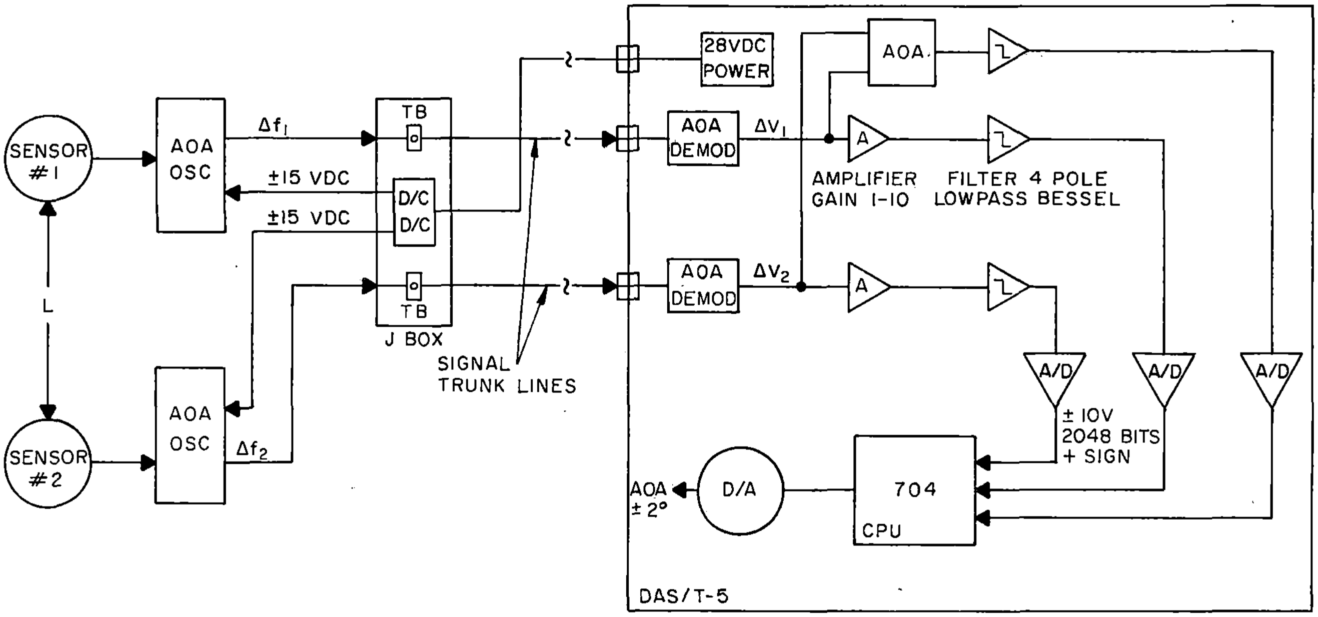


Figure 18. The Angle of Attack Measurement System

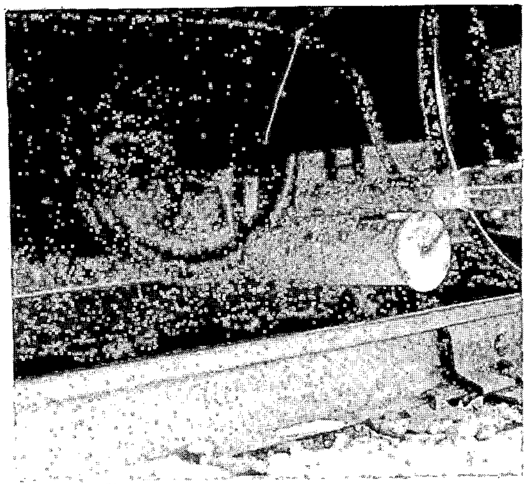


Figure 17. An Angle of Attack Sensor Installation

Since the oscillator circuit demonstrates some sensitivity to the tuning of the receiving coil, a temperature compensating capacitor has been added directly across this coil to stabilize its tuning over a wide temperature range.

The oscillator for the angle-of-attack sensor must be located within a few feet of the sensor. This is because the amplifiers must have very wide response in order to maintain good phase shift stability at the operating frequency. If the sensor wires are to long, they will act as tuned waveguides within the response range of the amplifiers, and spurious oscillations will result.

3.3.3 SENSOR OSCILLATOR

The oscillator consists of three basic sections: the passive tuning network, the summing amplifier and the limiting power amplifier. The overall functions of the oscillators are to produce a frequency that is stable with respect to time, temperature, etc., but is clearly related to the small coupling coefficient induced between the sensor's coils.

3.3.4 THERMAL STABILIZER

The angle-of-attack sensor oscillator is basically very sensitive and stable. However, the signal from the sensor is necessarily feeble in order to fulfill the mechanical requirement of sensor location and cancellation of cross axis inputs. Therefore, the oscillator stability is enhanced by placing it in a thermally stable environment. This is accomplished by mounting the oscillator PC board on an aluminum plate and heating the plate to a controlled temperature.

3.3.5 DISCRIMINATOR

The signal from the oscillator is fed into a digital-type discriminator circuit where it is compared against a crystal controlled clock. The difference counts are then applied to a digital to analog converter. The output signal is then fed through a scaling amplifier and, after filtering, is recorded by the T-5 Data Acquisition System.

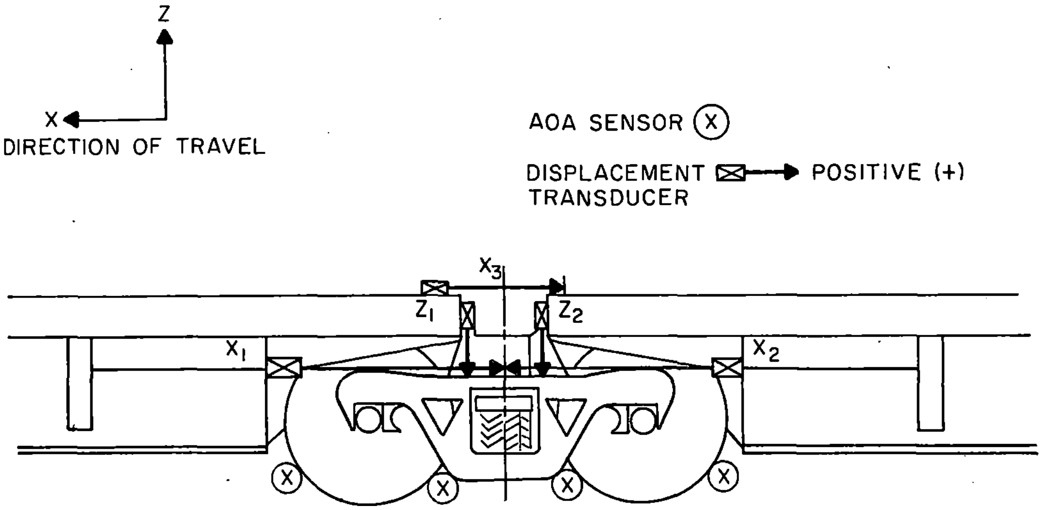


Figure 19. AOA Sensor and Displacement Transducer Location on the LoPac 2000

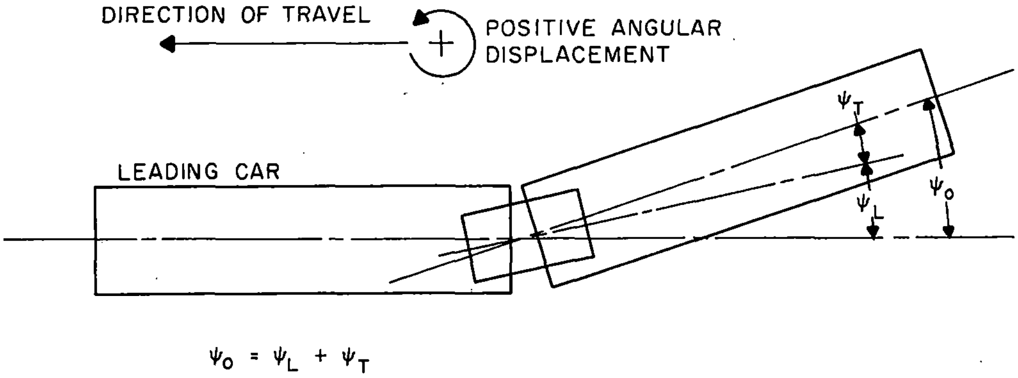


Figure 20. Angular Relations and Sign Conventions

3.4 ACCELEROMETERS

In order to quantify the truck lateral stability and ride quality, servo-accelerometers were mounted on both the unsprung and suspended elements of the truck. In addition, an accelerometer was mounted on the carbody directly above the center pin or as near as possible. Table 2 specifies transducer location and orientation.

TABLE 2

ACCELEROMETER LOCATION AND ORIENTATION

No.	Location	Orientation
1	Narrow pedestal adaptor	Lateral
2	Narrow pedestal adaptor/ unsprung mass	Vertical
3	Carbody above center pin	Vertical

The accelerometers used during this investigation were 5g (Scaevitz model LSBC-5) with a sensitivity of 1 v/g and an overall accuracy of better than 0.1 percent. This type of accelerometer is very sensitive but because of its basic design, a jeweled pivot, is somewhat prone to failure when subjected to environments beyond those it was intended for. For this reason each accelerometer was mounted in a mechanical isolator which attenuates inputs above 150 Hz while passing with unity gain those below 75 Hz. The mechanical isolator is basically a cup-in-cup structure with the inner cup isolated from the outer cup by a firm open cell foam. This design has proven highly successful in allowing the use of these precision servo-accelerometers on the unsprung masses of truck.

3.5 DISPLACEMENT TRANSDUCERS

For the purpose of obtaining data on truck yaw and roll with respect to the carbody, displacement transducers were used. The transducers were spring loaded precision potentiometers manufactured by ENSCO. Each transducer is capable of 10 inches of extension with better than 0.01 inch resolution.

All transducers were mounted on the vehicles rather than the trucks to provide a more hospitable environment. In the case of the LoPac 2000 five transducers were used, three longitudinal and two vertical. These are shown schematically in Figure 19.

All five transducers performed measurements in an approximate vertical plane (x-z) passing through the longitudinal centerline of the truck side frame. The attachment points for the truck roll and yaw transducers to the side frame were directly over the truck bolster. This enhances the algorithm for the calculation of the yaw angle by (1) minimizing crosstalk with roll and (2) minimizing errors due to truck pitch.

The fifth displacement measurement used on the LoPac 2000 provided for the extraction of the angle between adjacent units, denoted ψ. See Figure 20 for sign conventions. This measurement also provided redundancy since

$$\psi_o = \psi_L + \psi_T$$

The Autoguard car was similarly instrumented with four displacement transducers. In this case, no measurement of unit to unit angle was made because of the draw bar design. Furthermore it was necessary to measure the longitudinal and vertical displacements on both sides of a given axle because of the nature of the suspension. That is, because there is no center pin/plate interface to provide the center of rotation the axle is free to rotate about almost any point along its axle. For example, it is possible, at least theoretically, for the spring group at one end to deflect while the other remains uneffected. Thus, the center of rotation would be at the end with no deflection.

Figure 21 shows schematically the transducer locations on the Autoguard car (one side). Figure 22 is a photograph of one side of a typical installation.

Processing algorithms for both cars are given below

LoPac 2000

$$\psi_L = \text{Sin}^{-1} (\Delta X_1/W)$$

$$\psi_T = \text{Sin}^{-1} (\Delta X_2/W)$$

$$\psi_o = \text{Sin}^{-1} (\Delta X_3/W)$$

where $\Delta X_i = (X_i - X_{io})$ $i = 1, 2, 3$

$X_{io} \equiv$ longitudinal static equilibrium extension

$W \equiv$ distance to center of rotation (side frame to center pin)

$$\Theta_{L,T} = \text{Sin} (\Delta Z_{1,2}/W)$$

$$\Delta Z_i = Z_i - Z_{oi}$$

Z_{io} = vertical static equlibrium extension

Autoguard

$$\psi = \text{Sin}^{-1} (X_1 - X_2)/\Delta$$

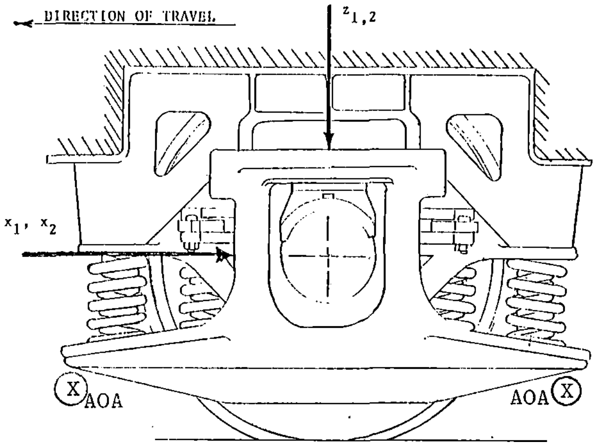


Figure 21. Angle of Attack Sensors and Displacement Transducer Location on the Autoguard Car

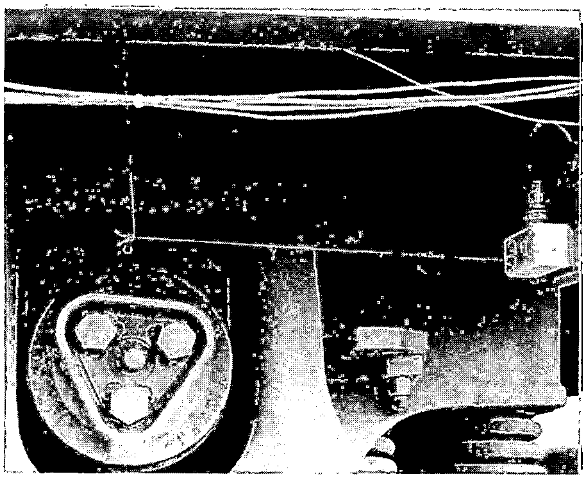


Figure 22. Displacement Transducers Mounted on the Autoguard Car

Δ = distance between transducers X_1 and X_2

$\Theta = \mathrm{Sin}^{-1}\,(Z_1 - Z_2)/\Delta$

The following corrections for crosstalk were applied

$\tilde{\psi} = -Z^2/2X_o$

$\tilde{\Theta} = -X^2/2Z_o$

$\psi = \hat{\psi} + \tilde{\psi}$

$\Theta = \hat{\Theta} + \tilde{\psi}$

where $\wedge$ indicates directly measured value

$\sim$ indicates correction

and no superscript indicates corrected value

3.6 AUTOMATIC LOCATION DETECTOR

During this test program use was made of the Automatic Location Detector (ALD) on board T-5. Basically this system generates a pulse train based on either naturally occuring track features, e.g. turnouts and road crossings or targets expressly situated in the ballast crib. This pulse train is recorded in parallel with the other data streams and thereby uniquely and precisely identifies the exact tape location which holds data of interest. This allows the exact correlation of data obtained from a series of tests performed not only on a given day but for the entire test program. It also assures that the data which is ultimately reduced and analyzed corresponds to the desired track; e.g. data from the body of a curve can be isolated from that of either spiral.

The ALD is a capacitive sensor which, as mentioned above, senses track features as well as artifical targets. For the purposes of this test program, targets were constructed of 7 inch lengths of 4 x 4 stock nailed to the center of a crosstie. To this was nailed a one foot square of 1/16 inch mild steel plate. This system affords several advantageous features. First it is simple and rugged but does not interfere with revenue traffic. When hit by dragging equipment it simply gives and can be easily replaced. Second with no ancillary devices each target produces a single well defined high amplitude (2V) signal. This feature can be used to mark the entry and exit of each test zone with a unique pattern of marked ties (targets) and unmarked ties.

Thus, a pass through a given test zone will produce a unique ALD signature independent of operator control which identifies that test zone. Finally the use of the ALD system provides pin point accuracy in extracting desired data, typically within one foot.

4.0 TEST PROCEDURES

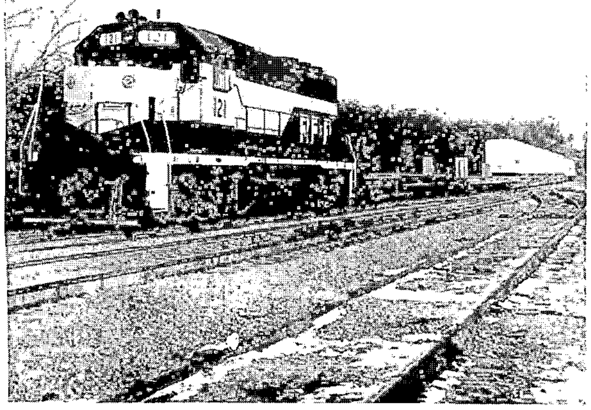
As stated earlier the present test program was designed to obtain performance data on two distinctly different types of trucks which were tested under different types of rail cars. As a consequence the test program was segmented into two portions or phases.

During the first phase of this test program the LoPac 2000 was tested. These tests took place during the month of January 1981. Following this the Autoguard car was tested. This second phase was carried out during February 1981.

Basically each truck was tested using a standard test procedure. This consisted of placing the truck equipped with the instrumented wheelsets at inboard and outboard positions within the car in question. Tests were conducted for all instrumentation configurations under both loaded and empty cars. Each position/load configuration was tested over eight test zones comprising curved, tangent, and rock and roll track. These tests were conducted at specified speed intervals on the mainline (Class 4) test zones between 30 mph and 60 mph and on the branchline (~Class 2) test zones between 15 mph and 25 mph.

4.1 TEST CONSIST

Tests conducted on both types of trucks were based on the same test consist. Basically each consist was made up of a locomotive, two buffer (non-test) flatcars, the vehicle under which the instrumented truck was located, the T-5 data acquisition vehicle, and a caboose. Figure 23 shows two different views of a loaded test consist. Figure 23a shows the head end of the consist powered by a GP-40-2 locomotive. Directly behind the locomotive are two conventional 89 foot flatcars. These flatcars were made part of the test consist to isolate the test vehicle from the influence of the locomotive. Other tests have shown that when the test vehicle is coupled directly to the locomotive certain dynamic parameters can be strongly effected. Immediately behind the second flatcar is seen the LoPac 2000 laded for testing. Figure 23b, an overhead view taken during a test run, shows the data acquisition vehicle behind the test vehicle. The last car in the consist was the caboose.


a) Front


b) Rear

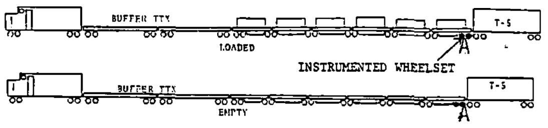
Figure 23. The Test Consist

4.1.1 ARTICULATED SUPPORTING CAR CONSIST

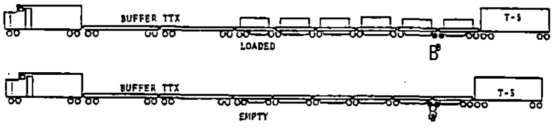
During the tests conducted on the articulated-supporting truck, (see Section 2.1.1) which is a two axle truck, both instrumented wheelsets (See Section 3.2) were installed in one truck. This produced the ability to measure the curving performance in terms of force for an entire truck. This instrumented truck was positioned at three locations under the LoPac 2000, shown in Figure 24. Note the entire test consist, less the caboose, as described above is shown. The articulated-supporting truck, as shown in Figure 24, was tested at three locations, identified as A, B and C. Note also the prefix Roman numeral I designating the first phase of the test program. This convention will be used later in the discussion of results.

Position A is the outboard position which is in effect a conventional truck configuration (Note: the instrumented truck is identified by the solid wheels). Position B locates the instrumented truck at the articulated point such that the truck is supporting the outboard unit and an inboard unit. The outboard unit is coupled by conventional couplers and draft gear at one end while the inboard unit is completely articulated. At position C the instrumented truck is supporting two completely articulated units.

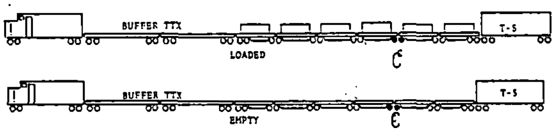
Note also that Figure 24 shows all six instrumentation/load configurations to which the articulated supporting truck was subjected. Each of these six configurations required one full day to complete the series of specified tests discussed in Section 4.2 and 4.3.



TEST CONFIGURATION IA



TEST CONFIGURATION IB



TEST CONFIGURATION IC

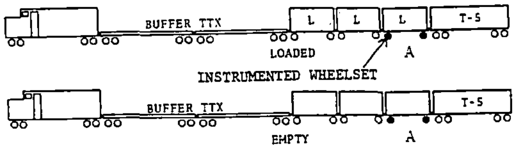
Figure 24. Phase I Test Configuration

4.1.2 SINGLE AXLE TRUCK CONSIST

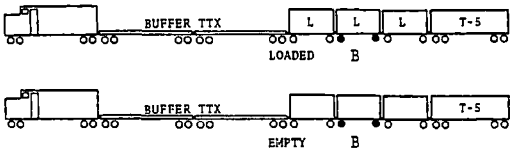
The test consist employed during the single axle truck test phase was very similar to that of the first phase (Section 4.1.1). The major differences were due to the truck vehicle design. That is, with one axle per truck two trucks were instrumented simultaneously. Thus, one entire unit of the three unit car was instrumented for each test day. The second difference was that with the Autoguard car there is only one inboard unit.

Figure 25 delineates the test configurations which made up the second phase of testing (Note the use of the prefix Roman numeral II). As mentioned above the design of the car limited the number of instrumentation locations to two, denoted A and B. As seen in Figure 25 there were a total of four instrumentation/load configurations.

4.2 TEST LOADS



TEST CONFIGURATION IIA



TEST CONFIGURATION IIB

Figure 25. Phase II Test Configuration

Measurements of truck performance were made under vehicles which were both empty and loaded. In the case of the articulated-supporting truck standard forty foot trailers were used which were in turn ballasted. In the case of the single axle truck the Autoguard car was artificially ballasted in an attempt to simulate the inertial inputs that such a truck would experience in typical container-on-flatcar (COFC) operation.

The test loads used to laden the LoPac 2000 were supplied by the Budd Company. In all six 40-foot Z-van trailers ballasted to nominal average gross weight of 44,000 pounds were used during the loaded portion of the articulated-supporting truck test program. Each trailer (lightweight 12,000 pounds) was loaded with 32,000 pounds of steel plates on the trailer foor. The resultant height of center of gravity above rail head for the sprung mass (i.e., load on rail less truck weight) was approximately 53 inches. See Appendix C for details. This would compare to a sprung mass height of center of gravaity of 75 inches for a typical 89-foot flatcar with a similarly ballasted trailer.

Trailers in normal TOFC service typically carry loads which result in significantly higher centers of gravity than those used in these tests. Calculations for a representative trailer indicate the LoPac sprung mass would have had a center of gravity 72 inches above the rail head. This would compare to a conventional flatcar sprung mass center of gravity 96 inches above the rail carrying the same representative trailer.

Ballasting of the Autoguard car for testing of the single axle truck was accomplished using standard lengths (39 feet) of 130 pound rail. Ten rails were placed on the bottom deck of each unit as shown in Figure 26. This 16,900 pounds lowered the center of gravity of the sprung mass to 75 inches above rail. For the purposes of comparison a conventional flatcar laden with containers (COFC) would normally exhibit a sprung mass center of gravity 62 inches above the rail head. See Appendix C for details.

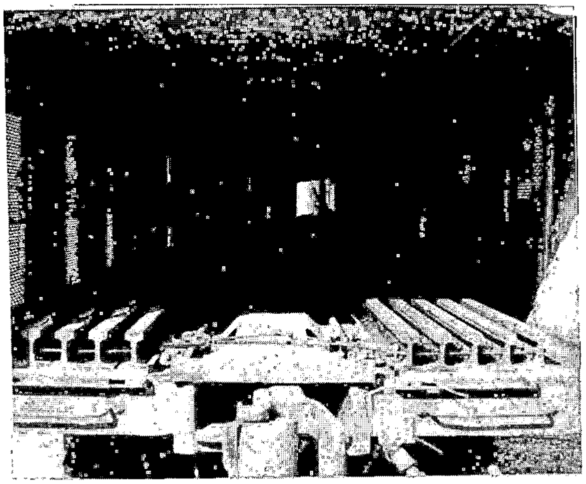


Figure 26. Single Axle Truck Test Load

4.3 TEST ZONES

The test zones were selected to characterize truck performance in three areas.

1. Curving (both high and low speed)
2. Hunting
3. Rock and roll

All test zones were located on the Richmond, Fredericksburg and Potomac Railroad (No. 3 Main Track) between Potomac Yard and Fredericksburg and on the Dahlgren Branch. Test zone locations on the RF&P are shown in Figure 27 while Table 3 summarizes the test zone characteristics.

4.3.1 HIGH SPEED CURVING TEST ZONES (1, 2 AND 4)

There were three high speed curving test zones (see Table 3). Test zones 1 and 2 were selected such that tests over them could be run in tandem, i.e., one pass over both before a reverse move. Test zones 1 and 2 were given the highest test priority. Test zone 4 was selected because it represented the sharpest curve (average measured 2°40') available on the RF&P Railroad mainline. This test zone was given a relatively low test priority because it is only 30' sharper than test zone 2 and required a significant amount of track time (~1 hr) to complete testing.

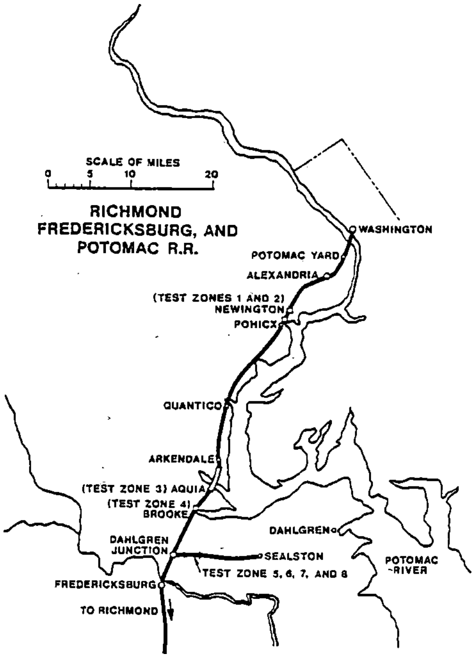


Figure 27. Test Zone Location

4.3.2 HUNTING TEST ZONE (3)

The hunting test zone was selected as the longest interval of uninterrupted tangent track between Alexandria and Fredericksburg. This zone, approximately 2.2 miles in length, was comprised of 140 pound welded rail. This test zone was bounded at the north end by a 1° curve and the south end by a 1°20' curve.

4.3.3 ROCK AND ROLL TEST ZONE (5)

The rock and roll test zone was located on the Dahlgren Branch near test zones 6 through 8. This test zone consisted of 32 rail lengths (approximately 1250 feet) with joints between one half and one inch low.

4.3.4 LOW SPEED CURVING TEST ZONES (6, 7, AND 8)

Test zones 6 through 8 were located on the RF&P Dahlgren Branch line between milepost MP 4 and MP 5.5 (approximate). These test zones were a series of curves, 4°, 3° and 8° respectively. The maximum operating speed is 25 mph consistent with class 2 track. The tests over these zones were conducted in tandem similar to those tests over zones 1 and 2.

4.4 TEST MATRIX

Each load/instrumentation configuration (sections 4.1 and 4.2) for both trucks was subjected to a specified series of tests over each test zone (section 4.3). Tests over the mainline curves were conducted between 30 mph and 60 mph in 10 mph increments. Speeds were held constant through communications with the

TABLE 3

TEST ZONE CHARACTERISTICS

Test Zone Number	Description Purpose	MP	Deg/100 ft	Crosslevel (in)	Balance Speed (mph)	Length (ft)
1	High Speed Mainline 2° Curve	95	2°10'*	5.26	58.9	2550*
2	High Speed Mainline 1° Curve	94	1°10'*	3.31	63.7	2415*
3	Tangent Mainline Hunting	70	0	0	--	11600
4	High Speed Mainline 2°30' Curve	68	2°40'*	6.33	58.2	2275*
5	Low Joint Branchline - Rock & Roll	1	0	0	--	1250
6	Low Speed Branchline - 4° Curve	4	4°**	2	27	850**
7	Low Speed Branchline - 3° Curve	5	3°**	2	31	2554**
8	Low Speed Branchline - 8° Curve	5.5	8°**	3	23	878**

*Average curvature and crosslevel measured December 1979 by T-1/T-3 FRA track inspection vehicle.

** Nominal curvature from surveyor's charts.

engineer. Similarly tests over the branchline curves were conducted at 15 mph, 20 mph and 25 mph. This is summarized in Table 4. Note also in Table 4 that the balance or equilibrium speed coincides or very nearly so with the maximum test speed. Thus, it should be kept in mind that the results to be discussed are all at or below balance speed. In addition to the runs specified in Table 4 repeatibility runs were conducted as time and traffic conditions permitted.

Two tangent test zones were included to provide conditions necessary to measure hunting and rock and roll characteristics of these trucks. Test zone 3 comprised something more than 2 miles of continuously welded tangent rail. Tests were conducted up to 60 mph, the freight speed limit for class 4 track, over this test zone. Tests over the rock and roll test zone were conducted initially in 5 mph increments from 15 mph to the track speed limit, 25 mph. Based on real-time analysis of the data obtained from this coarse mesh survey, additional runs were made in 21 mph to 2.5 mph increments. This find speed control was obtained via constant radio contact with the engineer, advising him of the test car's speed read out, based on a highly accurate optical tachometer. Data reduction has shown that typical speed variations over this test zone were less than 0.3 mph.

4.5 TEST CHRONOLOGY

Tests conducted on the articulated-supporting truck were conducted during January 1981 and those conducted on the single axle truck were conducted during February 1981. Actual dates and test sequence is given in Table 5.

As indicated by the recorded temperatures presented in Table 5, the ballast was frozen during the tests conducted on the articulated-supporting truck. Although the temperature was somewhat milder during the latter portion of the tests conducted on the single axle truck, the ballast remained firm if not frozen. Freezing conditions during this time continued during night, hindering a thaw.

TABLE 4

TEST MATRIX

Test Zone Number	Description/ Purpose	Test Speed (mph)	Balance Speed
1	High Speed Mainline 2° Curve	30, 40, 50, 60	59
2	High Speed Mainline 1° Curve	30, 40, 50, 60	64
3	Tangent Mainline Hunting	To 60	--
4	High Speed Mainline 2°30' Curve	30, 40, 50, 60	58
5	Low Joint Branch-line - Rock & Roll	To 25	--
6	Low Speed Branch-line - 4° Curve	15, 20, 25	27
7	Low Speed Branch-line - 3° Curve	15, 20, 25	31
8	Low Speed Branch-line - 8° Curve	15, 20, 25	23

TABLE 5

TEST CHRONOLOGY

Date	Phase	Primary** Instrumentation Position	Load Configuration	Ambient Temperature	Atmospheric Conditions
1/10/81	I	A	Light	22°F	Dry
1/12/81	I	A	Loaded	23°F	Dry
1/17/81	I	C	Loaded	26°F	Dry
1/19/81	I	C	Light	60°	Dry
1/22/81	I	B	Light	50°F	Dry
1/24/81	I	B	Loaded	50°F	Dry
2/11/81	II	A	Light	65°F	Rain AM Dry PM
2/13/81	II	A	Loaded	70°F	Dry
2/19/81	II	B	Loaded	50°F	
2/21/81	II	B	Light	50°F	

* Phase I - Articulated-Supporting Truck; Phase II - Single Axle Truck

**Primary instrumentation cosnists of instrumented wheelsets and angle of attack measurement system.

5.0 RESULTS AND DISCUSSION

The primary objective of the present investigation was to provide the baseline data necessary to characterize truck performance. The data of greatest interest is the wheel/rail force data and angle of attack. Also of interest are hunting critical speed and ride quality. Each of these areas will be addressed, first for the articulated-supporting truck and then for the single axle truck. (Note: It should be pointed out that for the purposes of analysis the data was filtered off-line using an RC-equilivent recursive 1-pole (-6dB/octave) digital filter. Wheel force data was filtered at 16 Hz, displacements at 8 Hz, accelerations at 32 Hz, and angle-of-attack at 16 Hz.)

5.1 ARTICULATED-SUPPORTING TRUCK TEST RESULTS

The first portion of this test program was concerned with the acquisition of performance data on a truck/suspension configuration referred to in this report as the articulated-supporting truck. This truck is described in detail in Section 2.1.1.

5.1.1 ARTICULATED-SUPPORTING TRUCK WHEEL/RAIL FORCES

The results of the wheel/rail forces experienced by the the articulated-supporting truck are shown in Figures 28 and 29. Complete lateral wheel forces are presented in Tables 6 through 9.

Figures 28 and 29 show that basically there are two parameters which exhibit an influence on the wheel/rail forces generated by this articulated-supporting truck. First, notice that overall the force tends to increase as the degree of curvature. In order to see this more clearly it must be kept in mind that the data presented at speeds less than 30 mph on curves over 3 degrees were obtained on bolted branchline. In contrast the high speed (> 30 mph) low curvature (< 2.5°) data were collected on welded mainline track.

The second parameter seen to influence the wheel/rail force is speed. On the outer wheel there is seen a mild increase in force as speed increases (Figure 28). This, of course, is due to the fact that for the most part this data was taken at speeds less than or equal to balance speed. Thus, as the speed increases the centrifugal force vector causes an increase in force on the outer wheel. The inverse is seen in Figure 29 on the inner wheel. Here the force shows a marked decrease as speed increases. Again, this is as expected since the centrifugal force counteracts the gravitational force caused by crosslevel diminishing the lateral force felt by the inner wheel on the low rail.

Another important point illustrated in Figures 28 and 29 is that there is apparently no strong or noticeable influence of position under the car. In fact, the truck on position A has a significantly smaller load to carry which nominally results in a 9700 pound vertical force per wheel. Recall also that the truck at position A is conventionally connected to the car. The trucks at positions B and C carry a larger lateral load equaling 17,200 pounds per wheel. Thus, the fact that position A exhibits consistently lower lateral force, although not significantly lower, is not surprising and the fact that the forces are comparable for most curves* indicates that the articulated-supporting trucks curve as well as conventionally-supporting trucks (three-piece).

The mean values of L/V are summarized in Tables 10 through 13. Basically, this information shows that overall, the articulated-supporting truck was reasonably well behaved with the mean values all falling below 0.52. In fact, all peak L/V's with a duration of greater than 60 ms fell below 0.75. This is generally accepted as an indication of safe operation. (References 1 through 7.)

Detailed study of these tables show that the leading inner wheel experienced the higher L/V's. This is again attributable to the fact that these tests were conducted below balance speed. Interestingly the leading outer wheel at positions A and C exhibit larger L/V's than does the trailing inner of the same truck. The trailing outer wheel shows by far the lowest values of L/V during curve negotiation.

5.1.2 ARTICULATED-SUPPORTING TRUCK ANGLE OF ATTACK

Because of the proximity and highly dynamic nature of the truck side frame, reliable readings from the inboard (see Figure 19) angle of attack sensors were not possible. However, the out board sensors performed well and can be used to extract an accurate measure of the truck angles of attack and is useful in characterizing truck curving performance.

The results of the articulated-supporting truck angle of attack measurements are summarized in Tables 14 and 15. A cursory study of this information reveals no clear functional dependence on load, position, speed or degree of curvature. It is, however, of interest to note that the average value of angle of attack lies below 0.4 degrees and is generally much less, typically 0.25 degrees. Values of the variation of angle of attack are comparatively small, less than 0.1 degree which indicates these mean values are correct in magnitude. The reason for the apparent large variation in the means within a given test zone and load/instrumentation configuration is connected with the non-linear character of the truck itself. This enters in two forms. First, the truck may indeed negotiate a given curve at widely varying values of angle-of-attack depending on uncontrolled initial conditions. Second, the calculation of offset is done on an adjacent stretch of tangent track and may introduce variance.

There is, however, one very clear feature seen in the measurements of angle-of-attack. That is, the inner side is always positive while the outer side is always negative (values less than 0.05 degrees may be considered

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*The truck at position C exhibited relatively high forces in the 8 degree curve.

TABLE 6

MEAN LATERAL FORCE ON THE ARTICULATED-SUPPORTING TRUCK LEADING OUTER WHEEL (Kips)

DEGREE CURV.	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	0.5	30.9	0.6	28.2	0.8	29.3	0.4	29.0	1.0
	40	43.3	0.4	40.0	0.5	37.9	0.7	39.2	0.7	39.5	0.4	40.4	0.9
	50	52.4	0.4	49.5	0.6	50.0	0.7	48.8	0.8	48.7	0.5	50.7	1.0
	60	63.5	0.4	59.3	0.6	58.0	0.5	58.5	0.9	59.4	0.5	63.2	1.3
2	30	-	-	28.2	0.9	-	-	31.9	1.2	30.2	0.6	31.7	1.3
	40	44.2	0.7	41.4	1.4	40.1	0.6	39.4	1.4	41.8	0.6	42.3	1.2
	50	55.0	0.8	50.9	1.7	53.1	0.6	49.0	1.4	51.3	0.8	50.8	1.5
	60	64.0	0.8	61.1	1.5	60.6	0.7	59.8	1.7	60.3	1.0	60.6	1.8
2.5	40	-	-	-	-	41.2	0.7	39.9	2.4	38.8	0.8	41.3	1.5
	50	56.0	0.8	-	-	51.5	1.0	51.4	2.5	50.6	0.7	50.4	2.3
	60	66.0	0.9	59.6	1.7	57.9	1.9	59.8	2.9	60.1	1.0	64.4	3.0
3	15	14.8	1.2	-	-	15.6	1.4	15.7	3.2	17.4	1.5	14.3	3.6
	20	19.9	1.0	19.8	1.8	21.4	1.5	20.9	3.1	22.3	1.3	19.2	3.3
	25	25.0	1.1	25.2	2.1	26.5	1.6	25.4	3.1	25.8	1.0	24.4	3.2
4	15	13.1	1.0	-	-	13.7	1.7	15.0	2.6	14.4	1.3	13.7	3.4
	20	17.6	1.4	20.2	2.4	20.6	1.8	20.2	2.9	19.7	1.5	18.3	3.6
	25	22.2	1.5	25.2	2.4	24.6	1.1	24.7	3.1	25.0	1.4	22.2	3.4
8	15	17.1	1.8	-	-	14.9	2.3	15.7	2.6	13.7	2.2	14.0	4.7
	20	20.3	2.2	19.7	4.0	18.6	2.0	20.2	3.1	20.6	2.4	19.5	5.1
	25	25.6	2.4	25.4	3.6	26.2	1.3	25.5	3.7	25.8	2.2	25.4	5.0

TABLE 7

MEAN LATERAL FORCE ON THE ARTICULATED-SUPPORTING TRUCK LEADING INNER WHEEL (Kips)

DEGREE CURV.	NOM. SPEED	ACTUAL SPEED	POSITION A EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED	ACTUAL SPEED	POSITION C EMPTY	ACTUAL SPEED	POSITION C LOADED
1	30	-	-	29.4	0.9	30.9	1.2	28.2	1.9	29.3	0.8	29.0	2.3
	40	43.4	0.6	40.0	0.8	37.9	1.1	39.2	1.6	39.5	0.7	40.4	1.7
	50	52.4	0.5	49.5	0.7	50.0	1.0	48.8	1.4	48.7	0.7	50.7	1.5
	60	63.5	0.5	59.3	0.7	58.0	0.6	58.5	1.2	59.4	0.6	63.2	1.5
2	30	-	-	28.2	2.4	-	-	31.9	3.2	30.2	1.7	31.7	3.2
	40	44.2	1.0	41.4	2.6	40.1	1.2	39.4	3.1	41.8	1.4	42.3	2.6
	50	55.0	0.9	50.9	2.3	53.1	0.8	49.0	2.5	51.3	1.1	50.8	2.3
	60	64.0	0.6	61.1	1.6	60.6	0.6	59.8	2.0	60.3	0.9	60.6	1.9
2.5	40	-	-	-	-	41.2	1.4	39.9	4.3	38.8	1.8	41.3	3.5
	50	56.0	0.6	-	-	51.5	1.2	51.4	3.5	50.6	0.9	50.4	3.3
	60	66.0	0.6	59.6	1.6	57.9	1.8	59.8	2.8	60.1	0.4	64.4	2.1
3	15	14.8	1.2	-	-	15.6	1.3	15.7	3.2	17.4	1.5	14.3	3.5
	20	19.9	0.8	19.8	1.8	21.4	1.3	20.9	2.8	22.3	1.2	19.2	3.1
	25	25.0	0.8	25.2	1.8	26.5	1.3	25.4	2.5	25.8	0.8	24.4	2.9
4	15	13.1	1.2	-	-	13.7	2.4	15.0	4.2	14.4	2.2	13.7	3.7
	20	17.6	1.7	20.2	2.8	20.6	2.2	20.2	4.2	19.7	2.2	18.3	4.7
	25	22.2	1.6	22.2	2.7	24.6	1.3	24.7	4.1	25.0	1.9	22.2	4.4
8	15	17.1	2.1	-	-	14.9	3.0	15.7	4.4	13.7	3.2	14.0	6.8
	20	20.3	2.4	19.7	4.5	18.6	2.7	20.2	4.4	20.6	3.0	19.5	6.5
	25	25.6	2.3	25.4	3.6	26.2	1.2	25.5	4.2	25.8	2.4	25.4	5.7

Speed in mph.

TABLE 8

MEAN LATERAL FORCE ON THE ARTICULATED-SUPPORTING TRUCK TRAILING OUTER WHEEL (Kips)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	0.8	30.9	0.7	28.2	1.4	29.3	0.7	29.0	1.5
	40	43.4	0.6	40.0	0.8	37-9	0.7	39.2	1.4	39.5	0.7	40.4	1.5
	50	52.4	0.6	49.5	0.8	50.0	1.3	48.8	1.3	48.7	0.7	50.7	1.4
	60	65.5	0.6	59.3	0.8	58.0	1.0	58.5	1.3	59.4	0.8	63.2	1.4
2	30	-	-	28.2	1.3	-	-	31.9	2.2	30.2	1.0	31.7	2.2
	40	44.2	0.8	41.4	1.2	40.1	0.9	39.4	2.1	41.8	1.0	42.3	2.1
	50	55.0	0.8	50.9	1.2	53.1	0.9	49.0	2.0	51.3	1.0	50.8	1.9
	60	64.0	0.9	61.1	1.3	60.6	1.0	59.8	2.0	60.3	1.1	60.6	2.0
2.5	40	-	-	-	-	41.2	1.0	39.9	2.0	38.8	1.0	41.3	2.0
	50	56.0	0.8	-	-	51.5	0.9	51.4	1.9	50.6	1.0	50.4	1.9
	60	66.0	0.9	59.6	1.3	57.9	1.0	59.8	2.0	60.1	1.0	64.4	2.1
3	15	14.8	0.9	-	-	15.6	0.9	15.7	2.0	17.4	1.0	14.3	2.0
	20	19.9	0.9	19.8	1.3	21.4	1.0	20.9	2.1	22.3	1.0	19.2	2.0
	25	25.0	0.9	25.2	1.3	26.5	1.0	25.4	2.2	25.8	1.0	24.4	2.1
4	15	13.1	0.6	-	-	13.7	0.6	15.0	1.3	14.4	0.7	13.7	1.5
	20	17.6	0.6	20.2	1.4	20.6	0.6	20.2	1.3	19.7	0.7	18.3	1.4
	25	22.2	0.6	22.2	1.4	24.6	0.7	24.7	1.4	25.0	0.7	22.2	1.4
8	15	17.1	0.9	-	-	14.9	0.9	15.7	1.7	13.7	0.9	14.0	1.8
	20	20.3	1.0	19.7	1.4	18.6	0.9	20.2	1.6	20.6	0.9	19.5	1.7
	25	25.6	1.0	25.4	1.4	26.2	0.9	25.5	1.7	25.8	0.9	25.4	1.8

TABLE 9

MEAN LATERAL FORCE ON THE ARTICULATED-SUPPORTING TRUCK TRAILING INNER WHEEL (Kips)

DEGREE CURV.	NOM. SPEED	ACTUAL SPEED	POSITION A EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED	ACTUAL SPEED	POSITION C EMPTY	ACTUAL SPEED	POSITION C LOADED
1	30	-	-	29.4	1.4	30.9	1.2	28.2	2.3	29.3	1.1	29.0	2.5
	40	43.4	0.8	40.0	1.3	37.9	1.1	39.2	2.2	39.5	1.1	40.4	2.3
	50	52.4	0.9	49.5	1.3	58.0	1.1	48.8	2.2	48.7	1.1	50.7	2.2
	60	63.5	0.9	59.3	1.3	58.0	1.0	58.5	2.1	59.4	1.1	63.2	2.2
2	30	-	-	28.2	1.2	-	-	31.9	1.9	30.2	0.8	31.7	1.9
	40	44.2	0.7	41.4	1.0	40.1	0.8	39.4	1.6	41.8	0.7	42.3	1.6
	50	55.0	0.6	50.9	0.9	53.1	0.8	49.0	1.4	51.3	0.8	50.8	1.5
	60	64.0	0.7	61.1	0.9	60.6	1.2	59.8	1.4	60.3	0.8	60.6	1.5
2.5	40	-	-	-	-	41.2	0.8	39.9	1.8	38.8	0.9	41.3	1.6
	50	56.0	0.6	-	-	51.5	0.7	51.4	1.4	50.6	0.8	50.4	1.5
	60	66.0	0.6	59.6	0.8	57.9	0.7	59.8	1.3	60.1	0.8	64.4	1.4
3	15	14.8	0.6	-	-	15.6	0.6	15.7	1.3	17.4	0.7	14.3	1.4
	20	19.9	0.6	19.8	1.7	21.4	0.6	20.9	1.4	22.3	0.7	19.2	1.4
	25	25.0	0.6	25.2	1.8	26.5	0.6	25.4	1.4	25.8	0.7	24.4	1.5
4	15	13.1	1.0	-	-	13.7	1.1	15.0	2.1	14.4	1.0	13.7	2.3
	20	17.6	0.9	20.2	1.4	20.6	1.0	20.2	2.1	19.7	1.0	18.3	2.3
	25	22.2	0.9	22.2	1.3	24.6	1.0	24.7	2.1	25.0	1.0	22.2	2.2
8	15	17.1	1.4	-	-	14.9	1.3	15.7	2.5	13.7	1.4	14.0	2.8
	20	20.3	1.3	19.7	1.9	18.6	1.2	20.2	2.4	20.6	1.2	19.5	2.6
	25	25.6	1.1	25.1	1.5	26.2	1.0	25.5	2.2	25.8	1.1	25.4	2.3

Speed in mph.

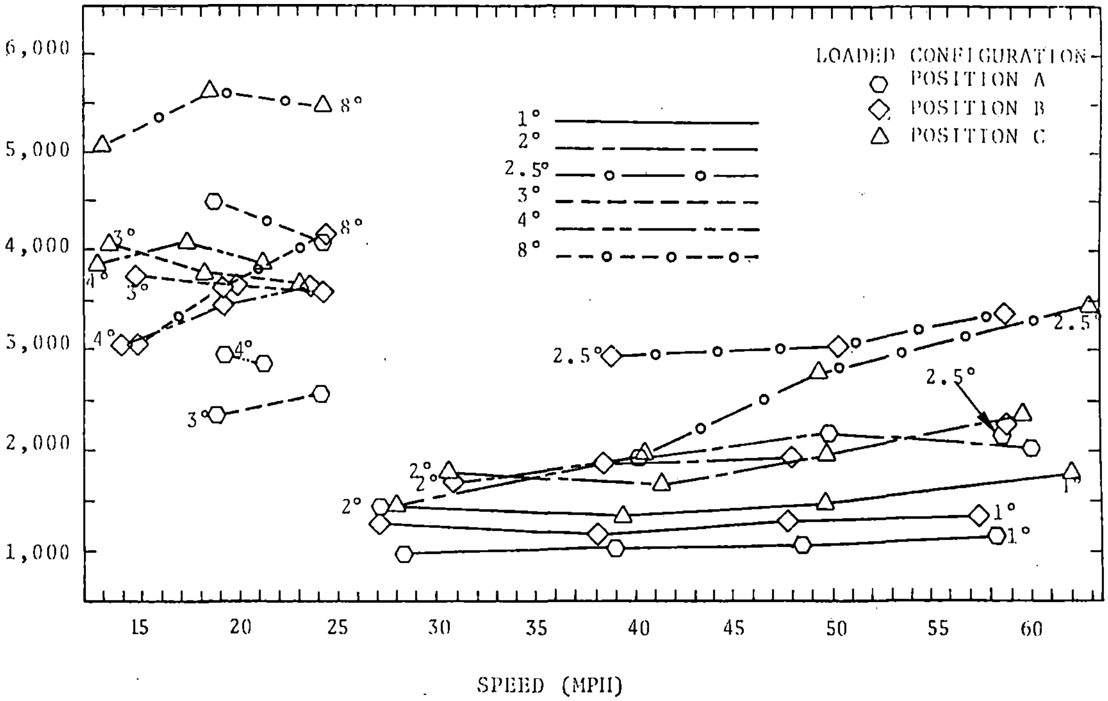


Figure 28. Mean Lateral Force on Leading Outer Wheel of the Articulated-Supporting Truck

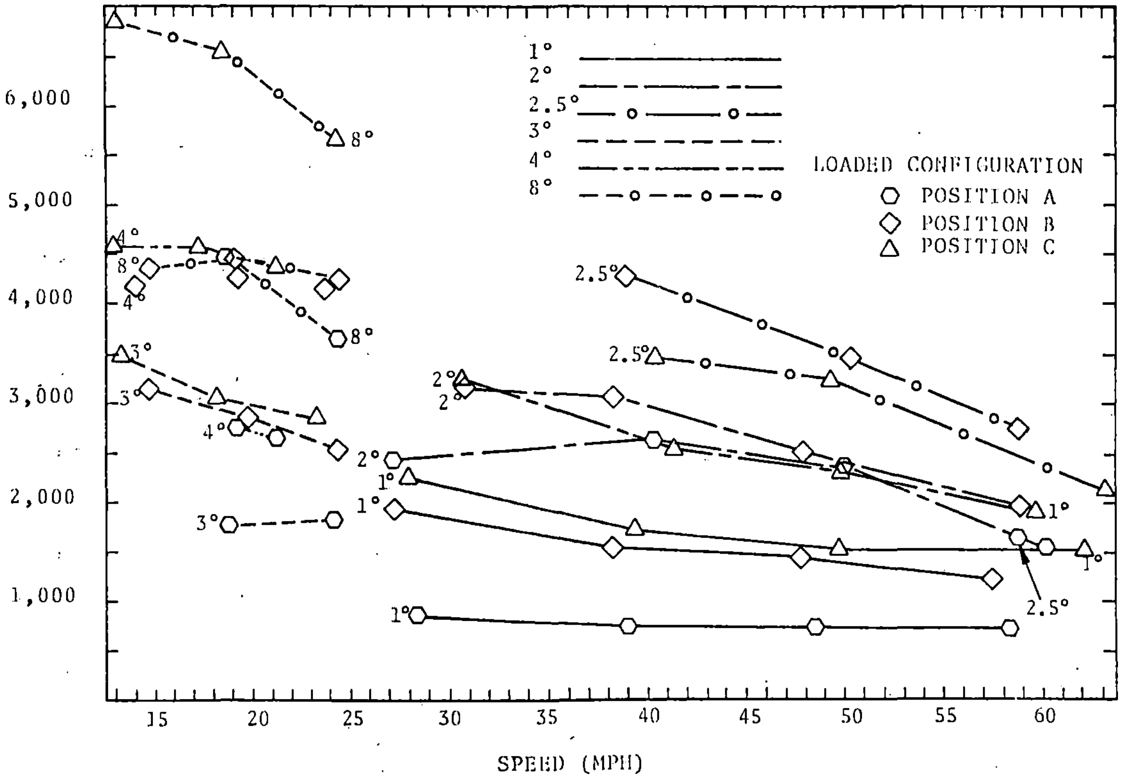


Figure 29. Mean Lateral Force on Leading Inner Wheel of the Articulated-Supporting Truck

TABLE 10

MEAN L/V ON THE ARTICULATED-SUPPORTING TRUCK LEADING OUTER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED	ACTUAL SPEED	POSITION C EMPTY	ACTUAL SPEED	POSITION C LOADED
1	30	-	-	29.4	.05	30.9	.07	28.2	.04	29.3	.05	29.0	.05
	40	43.4	.06	40.0	.06	37.9	.08	39.2	.04	39.5	.05	40.4	.05
	50	52.4	.07	49.5	.06	50.0	.09	48.8	.04	48.7	.06	50.7	.05
	60	63.5	.06	59.3	.06	58.0	.06	58.5	.05	59.4	.06	63.2	.07
2	30	-	-	28.2	.10	-	-	31.9	.07	30.2	.08	31.7	.08
	40	44.2	.10	41.4	.14	40.1	.07	39.4	.08	41.8	.09	42.3	.07
	50	55.0	.12	50.9	.16	53.1	.08	49.0	.08	51.3	.10	50.8	.09
	60	64.0	.12	61.1	.14	60.0	.09	59.8	.09	60.3	.12	60.6	.10
2.5	40	-	-	-	-	41.2	.09	39.9	.14	38.8	.11	41.3	.09
	50	56.0	.11	-	-	51.5	.11	51.4	.14	50.6	.09	50.4	.13
	60	66.0	.13	59.6	.15	57.9	.21	59.8	.15	60.1	.12	64.4	.15
3	15	14.8	.17	-	-	15.6	.16	15.7	.17	17.4	.18	14.3	.19
	20	19.9	.14	19.8	.17	21.4	.17	20.9	.16	22.3	.16	19.2	.18
	25	25.0	.15	25.2	.18	26.5	.18	25.4	.16	25.8	.13	24.4	.17
4	15	13.1	.14	-	-	13.7	.20	15.0	.13	14.4	.15	13.7	.17
	20	17.6	.20	20.2	.22	20.6	.21	20.2	.15	19.7	.16	18.3	.18
	25	22.2	.22	22.2	.21	24.6	.13	24.7	.15	25.0	.15	22.2	.16
8	15	17.1	.29	-	-	14.9	.26	15.7	.13	13.7	.25	14.0	.25
	20	20.3	.33	19.7	.38	18.6	.24	20.2	.16	20.6	.27	19.5	.26
	25	25.6	.35	25.4	.32	26.2	.14	25.5	.17	25.8	.24	25.4	.24

TABLE 11

MEAN L/V ON THE ARTICULATED-SUPPORTING TRUCK LEADING INNER WHEEL

DEGREE CURV.	NOM. SPEED	ACTUAL SPEED	POSITION A EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED	ACTUAL SPEED	POSITION C EMPTY	ACTUAL SPEED	POSITION C LOADED
1	30	-	-	29.4	.09	30.9	.16	28.2	.11	29.3	.11	29.0	.14
	40	43.4	.09	40.0	.08	37.9	.16	39.2	.09	39.5	.10	40.4	.11
	50	52.4	.09	49.5	.08	50.0	.14	48.8	.09	48.7	.10	50.7	.10
	60	63.5	.08	59.3	.07	58.0	.08	58.5	.08	59.4	.09	63.2	.10
2	30	-	-	28.2	.25	-	-	31.9	.18	30.2	.22	31.7	.18
	40	44.2	.18	41.4	.28	40.1	.16	39.4	.18	41.8	.18	42.3	.15
	50	55.0	.15	50.9	.26	53.1	.11	49.0	.15	51.3	.15	50.8	.14
	60	64.0	.12	61.1	.18	60.6	.08	59.8	.13	60.3	.12	60.6	.12
2.5	40	-	-	-	-	41.2	.19	39.9	.25	38.8	.24	41.3	.10
	50	56.0	.11	-	-	51.5	.16	51.4	.21	50.6	.12	50.4	.20
	60	66.0	.10	59.6	.18	57.9	.26	59.8	.18	60.1	.12	64.4	.14
3	15	14.8	.22	-	-	15.6	.19	15.7	.19	17.4	.21	14.3	.21
	20	19.9	.14	19.8	.20	21.4	.18	20.9	.18	22.3	.16	19.2	.19
	25	25.0	.15	25.2	.21	26.5	.18	25.4	.16	25.8	.11	24.4	.17
4	15	13.1	.21	-	-	13.7	.33	15.0	.26	14.4	.34	13.7	.31
	20	17.6	.30	20.2	.31	20.6	.32	20.2	.27	19.7	.34	18.3	.31
	25	22.2	.30	22.2	.30	24.6	.19	24.7	.27	25.0	.29	22.2	.30
8	15	17.1	.40	-	-	14.9	.47	15.7	.29	13.7	.52	14.0	.47
	20	20.3	.47	19.7	.53	18.6	.41	20.2	.30	20.6	.50	19.5	.47
	25	25.6	.46	25.4	.45	26.2	.18	25.5	.30	25.8	.42	25.4	.42

Speed in mph.

TABLE 12

MEAN L/V ON THE ARTICULATED-SUPPORTING TRUCK TRAILING OUTER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	.10	30.9	.09	28.2	.09	29.3	.37	29.0	.09
	40	43.4	.09	40.0	.09	37.9	.09	39.2	.09	39.5	.36	40.4	.09
	50	52.4	.10	49.5	.09	50.0	.18	48.8	.08	48.7	.43	50.7	.08
	60	63.5	.10	59.3	.11	58.0	.15	58.5	.08	59.4	.46	63.2	.08
2	30	-	-	28.2	.15	-	-	31.9	.15	30.2	.13	31.7	.15
	40	-4.2	.14	41.4	.13	40.1	.13	39.4	.15	41.8	.13	42.3	.14
	50	55.0	.13	50.9	.13	53.1	.13	49.0	.13	51.3	.13	50.8	.13
	60	64.0	.14	61.1	.13	60.6	.14	59.8	.12	60.3	.14	60.6	.12
2.5	40	-	-	-	-	41.2	.13	39.9	.14	38.8	.14	41.3	.13
	50	56.0	.13	-	-	51.5	.13	51.4	.12	50.6	.13	50.4	.12
	60	66.0	.14	59.6	.13	57.9	.12	59.8	.12	60.1	.13	64.4	.13
3	15	14.8	.13	-	-	15.6	.12	15.7	.12	17.4	.13	14.3	.12
	20	19.9	.13	19.8	.12	21.4	.12	20.9	.12	22.3	.13	19.2	.12
	25	25.0	.13	25.2	.13	26.5	.13	25.4	.13	25.8	.13	24.4	.12
4	15	13.1	.10	-	-	13.7	.08	15.0	.08	14.4	.09	13.7	.09
	20	17.6	.09	20.2	.14	20.6	.08	20.2	.08	19.7	.09	18.3	.08
	25	22.2	.10	22.2	.14	24.6	.10	24.7	.08	25.0	.09	22.2	.08
8	15	17.1	.14	-	-	14.9	.11	15.7	.10	13.7	.11	14.0	.10
	20	20.3	.13	19.7	.14	18.6	.11	20.2	.09	20.6	.10	19.5	.09
	25	25.6	.14	25.4	.13	26.2	.11	25.5	.09	25.8	.09	25.4	.09

TABLE 13

MEAN L/V ON THE ARTICULATED-SUPPORTING TRUCK TRAILING INNER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	.13	30.9	.15	28.2	.12	29.3	.13	29.0	.13
	40	43.4	.13	40.0	.13	37.9	.13	39.2	.12	39.5	.13	40.4	.12
	50	52.4	.13	49.5	.13	50.0	.13	48.8	.12	48.7	.13	50.7	.12
	60	63.5	.14	59.3	.13	58.0	.13	58.5	.12	59.4	.14	63.2	.12
2	30	-	-	28.2	.12	-	-	31.9	.10	30.2	.50	31.7	.09
	40	44.2	.10	41.4	.09	40.1	.11	39.4	.09	41.8	.44	42.3	.08
	50	55.0	.10	50.9	.09	53.1	.11	49.0	.08	51.3	.45	50.8	.08
	60	64.0	.11	61.1	.11	60.6	.17	59.8	.08	60.3	.45	60.6	.08
2.5	40	-	-	-	-	41.2	.10	39.9	.09	38.8	.10	41.3	.08
	50	56.0	.10	-	-	51.5	.09	51.4	.07	50.6	.09	50.4	.08
	60	66.0	.10	59.6	.08	57.9	.09	59.8	.07	60.1	.09	64.4	.08
3	15	14.8	.09	-	-	15.6	.08	15.7	.08	17.4	.08	14.3	.08
	20	19.9	.09	19.8	.17	21.4	.08	20.9	.08	22.3	.09	19.2	.08
	25	25.0	.09	25.2	.19	26.5	.09	25.4	.08	25.8	.09	24.4	.08
4	15	13.1	.16	-	-	13.7	.14	15.0	.12	14.4	.13	13.7	.13
	20	17.6	.13	20.2	.13	20.6	.13	20.2	.12	19.7	.13	18.3	.13
	25	22.2	.15	22.2	.13	24.6	.14	24.7	.13	25.0	.13	22.2	.13
8	15	17.1	.23	-	-	14.9	.19	15.7	.15	13.7	.18	14.0	.16
	20	20.3	.22	19.7	.19	18.6	.17	20.2	.14	20.6	.17	19.5	.15
	25	25.6	.20	25.4	.16	26.2	.15	25.5	.14	25.8	.15	25.4	.14

Speed in mph.

TABLE 14

ARTICULATED-SUPPORTING TRUCK MEAN ANGLE OF ATTACK INNER SIDE (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30			29.6	.15							29.0	.03
	40	43.4	.15	40.0	.23							40.4	.12
	50	52.4	.08	49.5	.26							50.7	.19
	60	63.5	.06	59.3	.24							63.2	.14
2	30			28.2	.09	-	-	31.9	.37				
	40	44.2	.05	41.4	.18	40.1	.36	39.4	.34				
	50	55.0	.23	50.9	.23	53.1	.27	49.0	.34				
	60	64.0	.20	61.1	.18	60.6	.23	59.8	.10				
2.5	40	-	-	-	-	41.2	.07						
	50	56.0	.11	-	-	51.5	.07						
	60	66.0	.10	59.6	.14	57.9	.14						
3	15	14.8	-.004	-	-	15.6	.16	15.7	.08				
	20	19.9	.06	19.8	.23	21.4	.05	20.9	-.05				
	25	25.0	.05	25.2	.05	26.5	.20	25.4	.16				
4	15	13.1	.13	-	-			15.0				13.7	.17
	20	17.6	.15	20.2	-.02			20.2				18.3	.17
	25	22.2	.14	22.2	.19			24.7				22.2	.06
8	15	17.1	.05	-	-			15.7				14.0	.33
	20	20.3	.07	19.7	-.06			20.2				19.5	.24
	25	25.6	.08	25.4	.16							25.4	.17

NOTE: Blank areas indicate lack of valid data.

TABLE 15

ARTICULATED-SUPPORTING TRUCK MEAN ANGLE OF ATTACK OUTER SIDE (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.6	-.15	30.9	-.14	28.2	-.15				
	40	43.4	-.08	40.0	-.18	37.9	-.02	39.2	-.18				
	50	52.4	-.09	49.5	-.14	50.0	-.11	48.8	-.32				
	60	63.5	-.06	59.3	-.12	58.0	-.14	58.5	-.67				
2	30	-	-	28.2	-.14							31.7	-.41
	40	44.2	.05	41.4	-.16							42.3	-.27
	50	55.0	-.21	50.9	-.18							50.8	-.18
	60	64.0	-.16	61.1	-.24							60.6	-.28
2.5	40	-	-	-	-							41.3	-.23
	50	56.0	-.21	-	-							50.4	-.39
	60	66.0	-.14	59.6	-.37							64.4	-.38
3	15	14.8	.004	-	-							14.3	-.09
	20	19.9	-.01	19.8	-.25							19.2	-.11
	25	25.0	-.002	25.2	-.03							24.4	-.15
4	15	13.1	-.14	-	-	13.7	.01	15.0	-.22				
	20	17.6	-.11	20.2	-.02	20.6	-.10	20.2	-.39				
	25	22.2	-.09	22.2	-.17	24.6	-.04	24.7	-.05				
8	15	17.1	-.11	-	-	14.9	-.05	15.7	-.20				
	20	20.3	-.03	19.7	-.01	18.6	-.14	20.2	-.48				
	25	25.6	-.08	25.4	-.19	26.2	-.05	25.5	-.10				

Speed in mph.

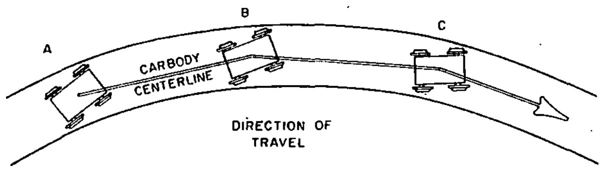


Figure 30. Schematic of the Articulated-Supporting Truck Negotiating A Curve Under Balance Speed

zero and sign has no significance). This is based on the convention that positive rotation of the inner wheel is away from the curve while positive rotation of the outer wheel is into the curve. This convention arose due to instrumentation considerations. Thus, these results show clearly that the truck at all positions studied assumes a particular set with respect to the curve. The truck tends to be rotated slightly, less than 0.25 degree as discussed above, in the opposite direction to the curve. This is shown schematically in Figure 30.

This result is substantiated by the independent measurement of truck yaw with respect to carbody. That is, Figure 30 requires that the angle of yaw of the truck with respect to the leading car unit must be greater than that of the trailing. Referring to Tables 17 and 18 this seems to be the case. Table 16 which contains the data from the outboard truck is included for completeness and offers no additional information on angle of attack.

Note, however, in Table 16, that all values of truck yaw in the 2, 2.5 and 3 degree curves are positive while those in the remaining curves are negative. The former set of curves are all right hand curves while the latter are left hand curves. Thus, from the sign convention the trailing truck curves in a manner similar to those at positions B and C.

Referring to Figure 20, which depicts the situation typical of a right hand curve, the truck orientation may be seen. However, because the trailing yaw angle, ψ_T, is smaller in magnitude than the leading yaw angle, ψ_L, the actual truck attitude with respect to the rail would be as depicted in Figure 30.

Finally, the difference between ψ_L and ψ_T, yields a value equal in magnitude and direction to the angle-of-attack measured. This assumes that each unit of the carbody subtends a chord which is a good approximation over 50 feet knowing the truck center pin is within an inch of the track center.

5.1.3 ARTICULATED-SUPPORTING TRUCK STEADY STATE CURVING PERFORMANCE

Two aspects of a truck's steady state curving peformance which are closely related are curving resistance and wheel/rail wear. Both of these performance areas have been shown analytically by Heumann (reference 8) to be proportional to the product of lateral flange force and the angle of attack at the point of flange contact. This product is essentially the component of the flange force in the direction of travel (small angle approximation) which is intuitively connected with curving resistance and, hence, wheel/rail wear.

The measurement of the flange force, exclusive of creep and gravitational forces, and the angle of attack at the point of flange contact, α_f, are in practice difficult measurements to make. Fortunately, there are measurements which are practical and afford excellent approximations to the desired quantities. First, the net lateral force measured using the instrumented wheelplate is an adequate approximation when lateral creep is sufficiently small.

Second, the measurement of wheelplate angle-of-attack, α_W, affords an excellent approximation to the angle-of-attack at the flange contact point, α_f, as long as the tread contact point and flange contact point are not too far apart. Additionally short wavelength perturbations in alignment must also be small in amplitude.

Recall from the previous section that the angle-of-attack data given for the articulated-supporting truck is truck angle-of-attack, α_T. Truck angle-of-attack will, therefore, be used in conjunction with the measurement of the wheel lateral force to characterize articulted-supporting truck steady state.

Truck side frame angle-of-attack, α_T, is closely related to wheelplate angle-of-attack, α_W, and α_T and α_W are, in fact, equal for a rigid truck and perfectly aligned track. For reasons given earlier angle-of-attack data for the articulated-supporting truck is given in terms of α_T and, therefore, will be used in conjunction with the wheel lateral force to characterize truck steady state curving performance for the purpose of a relative comparison among the three positions tested. Recall that position A was essentially a conventionally configured truck so that comparisons with the results of positions B and C may be useful in characterizing the relative performance of articulate-supporting trucks.

Although the trucks tested were new some parallelogramming may have occurred during the tests. Also the wavelengths equal to truck spacing possess sufficient amplitude to create discernable differences in α_T and α_W. Therefore, the product $L\alpha_T$ is presented here for the purposes of a relative comparison as discussed above. Use of this data for other purposes such as rail life prediction must, therefore, be made with caution.

TABLE 16

OUTBOARD (POSITION A) ARTICULATED-SUPPORTING TRUCK MEAN YAW (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED
1	30	29.3	-.15	29.0	-.10
	40	39.5	-.14	40.4	-.23
	50	48.7	-.72	50.7	.05
	60	59.4	-.29	63.2	-.10
2	30	30.2	.44	31.7	.63
	40	41.8	.26	42.3	.39
	50	51.3	-.32	50.8	.66
	60	60.3	.32	60.6	.57
2.5	40	38.8	.21	41.3	.69
	50	50.6	.40	50.4	.55
	60	60.1	.60	64.4	.52
3	15	17.4	.26	14.3	.61
	20	22.3	.42	19.2	.50
	25	25.8	.58	24.4	.55
4	15	14.4	-.67	13.7	-.86
	20	19.7	-.65	18.3	-.99
	25	25.0	-.55	22.2	-1.06
8	15	13.7	-1.88	14.0	-1.84
	20	20.6	-1.61	19.5	-1.86
	25	25.8	-1.42	25.4	-1.73

TABLE 17

ARTICULATED-SUPPORTING TRUCK MEAN YAW ANGLE WITH RESPECT TO THE LEADING UNIT (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	-.30	30.9	-.41	28.2	-.20
	40	43.4	-.35	40.0	-.29	37.9	-.19	39.2	-.38
	50	52.4	-.32	49.5	-.29	50.0	-.62	48.8	-.31
	60	63.5	-.23	59.3	-.36	58.0	-.40	58.5	-.67
2	30	-	-	28.2	.66	-	-	31.9	.89
	40	44.2	.57	41.4	.70	40.1	.67	39.4	.64
	50	55.0	.47	50.9	.54	53.1	1.12	49.0	.67
	60	64.0	.60	61.1	.47	60.6	.74	59.8	.31
2.5	40	-	-	-	-	41.2	.69	39.9	.95
	50	56.0	.79	-	-	51.5	.98	51.4	.72
	60	66.0	.42	59.6	.73	57.9	1.06	59.8	.73
3	15	14.8	.78	-	-	15.6	.40	15.7	.21
	20	19.9	1.07	19.8	.73	21.4	1.10	20.9	.33
	25	25.0	1.23	25.2	.71	-	-	25.4	.82
4	15	13.1	-1.05	-	-	12.7	-1.32	15.0	-1.82
	20	17.6	-.75	20.2	-1.00	20.6	- .73	20.2	-1.63
	25	22.2	-.60	22.2	-1.05	24.6	-1.13	24.7	-1.27
8	15	17.1	-1.81	-	-	14.9	-2.47	15.7	-3.15
	20	20.3	-1.94	19.7	-2.11	18.6	-1.82	20.2	-2.44
	25	25.6	-1.77	25.4	-2.10	26.2	-2.40	25.5	-2.36

Speed in mph.

TABLE 18

ARTICULATED-SUPPORTING TRUCK MEAN YAW ANGLE WITH RESPECT TO THE TRAILING UNIT (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.4	-.20	30.9	-.18	28.2	-.14
	40	43.4	-.16	40.0	-.27	37.9	-.17	39.2	-.21
	50	52.4	-.19	49.5	-.27	50.0	-.20	48.8	-.19
	60	63.5	-.30	59.3	-.35	58.0	-.13	58.5	-.44
2	30	-	-	28.2	.55	-	-	31.9	.46
	40	44.2	.46	41.4	.76	40.1	.71	39.4	.48
	50	55.0	.57	50.9	.63	53.1	.49	49.0	.49
	60	64.0	.43	61.1	.60	60.6	.69	59.8	.22
2.5	40	-	-	-	-	41.2	.45	39.9	1.80
	50	56.0	.53	-	-	51.5	.53	51.4	.56
	60	66.0	.56	59.6	.58	57.9	.35	59.8	.64
3	15	14.8	.71	-	-	15.6	.73	15.7	.25
	20	19.9	1.08	19.8	.78	21.4	.65	20.9	.35
	25	25.0	1.14	25.2	.72	26.5	.99	25.4	.82
4	15	13.1	-.97	-	-	13.7	-1.12	15.0	-1.25
	20	17.6	-.62	20.2	-1.00	20.6	-1.27	20.2	-1.17
	25	22.2	-.54	22.2	-1.02	24.6	-.92	24.7	-.72
8	15	17.1	-1.47	-	-	14.9	-1.72	15.7	-2.02
	20	20.3	-1.45	19.7	-1.92	18.6	-1.84	20.2	-2.03
	25	25.6	-1.37	25.4	-2.01	26.2	-1.42	25.5	-1.65

NOTE: Blank areas indicate lack of valid data.

TABLE 19

ARTICULATED-SUPPORTING TRUCK MEAN $L\alpha_T$ ON LEADING OUTER WHEEL (Pounds)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	-1.27	30.9	-1.46	28.2	-2.07		
	40	43.4	-.55	40.0	-1.71	37.9	.24	39.2	-2.17		
	50	52.4	-.69	49.5	-1.41	50.0	-1.49	48.8	-4.45		
	60	63.5	-.46	59.3	-1.38	58.0	-1.22	58.5	-10.33		
2	30	-	-	28.2	-2.30					31.7	-9.10
	40	44.2	-2.30	41.4	-3.99					42.3	-5.56
	50	55.0	-3.03	50.9	-5.32					50.8	-4.69
	60	64.0	-2.33	61.1	-6.66					60.6	-8.90
2.5	40	-	-	-	-					41.3	-5.79
	50	56.0	-3.16	-	-					50.4	-15.54
	60	66.0	-3.75	59.6	-10.85					64.4	-19.97
3	15	14.8	.06	-	-					14.3	-5.81
	20	19.9	-.218	19.8	-8.33					19.2	-6.56
	25	25.0	-.18	25.2	-1.14					24.4	-8.48
4	15	13.1	-2.30	-	-	13.7	.35	15.0	-10.17		
	20	17.6	-2.64	20.2	-.61	20.6	-3.19	20.2	-19.88		
	25	22.2	-2.46	22.2	-7.15	24.6	- .86	24.7	-3.31		
8	15	17.1	-4.01	-	-	14.9	-2.18	15.7	-8.87		
	20	20.3	-1.57	19.7	.08	18.6	-5.37	20.2	-27.07		
	25	25.6	-3.58	25.4	-12.31	26.2	-1.31	25.5	-6.57		

Speed in mph.

Tables 19 through 22 summarize the $L\alpha_T$ parameter for all four wheels of each truck. It should be pointed out that in some studies this parameter is reported in units of pound-degrees. In the present study the units are nominally pounds since the angles are small; hence,

$$L\alpha_T \cong L \sin \alpha_T \text{ (for small } \alpha_T)$$

In tables 19 and 20 this parameter is seen to increase from unity to values as large as 30 pounds. There is seen to be some effect of speed on this parameter but for reasons discussed in the previous section (5.1.2) this is not entirely clear. The larger values appear to be associated with the leading axle. This is primarily due to the fact observed earlier that the leading axle experienced larger lateral forces.

5.1.4 ARTICULATED-SUPPORTING TRUCK DYNAMIC PERFORMANCE

In the area of dynamic performance there were two parameters of interest. These were the truck hunting critical speed and carbody vertical acceleration or ride quality.

During the conduct of these tests no hunting was observed either through the use of lateral accelerometers mounted on the journal bearing or from visual observation. It should be kept in mind that these tests were conducted at speeds up to 60 mph and also that the wheel profiles on all but the instrumented trucks were unworn. Recall that the instrumented wheelsets employed the modified Heumann profile which is considered worn. The results of the present tests are also in agreement with tests conducted earlier by CONRAIL employing worn profiles at speeds up to 76 mph (reference 9).

Finally, in order to quantify the truck's ability to isolate the car unit from track inputs, the vertical acceleration on the car near the center pin was used. These results are summarized in Table 23. The values reported here are typical of similar studies. See, for example, reference 10. Basically there is seen to be an increase in acceleration with speed as expected. There is no apparent or strong dependence on truck location.

5.1.5 ARTICULATED-SUPPORTING TRUCK ROCK AND ROLL PERFORMANCE

Tests conducted over the rock and roll test zone (section 4.3.3) revealed no unusual behavior of the LoPac 2000/articulated-supporting truck system. In fact, under the conditions described the carbody roll angle appeared qualitatively to be quite small. The roll angle measured between the truck side frame and carbody during these tests reached peak values of one degree. Similar tests conducted by CONRAIL (reference 9) showed peak carbody roll angles up to two degrees.

5.2 SINGLE AXLE TRUCK RESULTS

The single axle truck was subjected to the identical series of tests to which the articulated-supporting truck was subjected. These results are similarly treated.

5.2.1 SINGLE AXLE TRUCK WHEEL/RAIL FORCES

The results of the wheel/rail force measurements on the leading single axle truck are presented in Figures 31 and 32. Complete data on both the leading and trailing trucks are given in Tables 24 through 27.

The functional dependence of the wheel/rail forces as illustrated in Figures 31 and 32, although not as distinct, does resemble that seen for the articulated-supporting truck. First, increasing of curvature appears to cause an increase in the lateral force, however, with notable exceptions. For example, the leading truck at position B in the 8^o curve experiences the lowest lateral forces on the outer wheel. Secondly, speed has the effect of increasing lateral forces on the outer wheel while decreasing forces on the inner wheel. This is as expected due to the growth of centrifugal force which shifts the load outwards.

Tables 28 through 31 summarize the mean values of L/V measured during the tests conducted on the single axle truck. It is seen that the single axle truck negotiated all test zones with an upper bound for mean L/V of 0.66 which was experienced on the leading inner wheel as should be expected. Peak values associated with this wheel fell below 0.9 with 60 ms duration. These values of L/V are well within the values of L/V considered indicative of safe operation cited in references 2 through 7.

Peak values of L/V (60 msec duration) measured on the outer wheel under extreme circumstances (8 degree curve) approached values of 1.1. Although values of L/V this large are considered by some criteria to be above the critical or safe level, use of Nadal's classic formula for the lower bound of the critical L/V can be made to show that the single axle truck was not tending towards wheel climb. Nadal's formula is given as (reference 1)

$$L/V_{crit} = (\tan\beta - \mu)/(1 + \mu\tan\beta)$$

where β is the flange angle and μ is the coefficient of friction. A nominally worn flange has a flange angle of 70 degrees or more; thus assuming a μ of 0.35 (very high for steel), the critical L/V is 1.22. In fact, the actual flange angle on the wheels tested was nearly 80 degrees so that the critial L/V was 1.8. Gilchrist and Brickle in reference 6 verified Nadal's formula for positive angles-of-attack and zero longitudinal creep as the lower bound of incipient derailment. Negative angle of attack and positive longitudinal creep causes the critical L/V to increase rapidly.

TABLE 20

ARTICULATED-SUPPORTING TRUCK
MEAN $L\alpha_T$ ON LEADING INNER WHEEL (Pounds)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	2.22							29.0	1.18
	40	43.4	1.46	40.0	3.04							40.4	3.53
	50	52.4	.73	49.5	3.34							50.7	5.16
	60	63.5	.45	59.3	2.96							63.2	3.59
2	30	-	-	28.2	3.90	-	-	31.9	20.71				
	40	44.2	3.86	41.4	8.01	40.1	7.36	39.4	18.08				
	50	55.0	3.44	50.9	9.08	53.1	3.58	49.0	14.77				
	60	64.0	2.16	61.1	4.82	60.6	2.27	59.8	3.68				
2.5	40	-	-	-	-	41.2	1.52						
	50	56.0	1.48	-	-	51.5	1.40						
	60	66.0	1.15	59.6	3.97	57.9	4.29						
3	15	14.8	-.10	-	-	15.6	3.87	15.7	4.03				
	20	19.9	.83	19.8	7.03	21.4	1.11	20.9	-1.89				
	25	25.0	.68	25.2	1.43	26.5	4.63	25.4	6.81				
4	15	13.1	2.76	-	-							13.7	14.11
	20	17.6	4.29	20.2	-1.03							18.3	13.69
	25	22.2	3.89	22.2	8.65							22.2	4.58
8	15	17.1	2.18	-	-							14.0	37.66
	20	20.3	3.10	19.7	-4.76							19.5	28.45
	25	25.6	3.38	25.4	10.45							25.4	16.98

NOTE: Blank areas indicate lack of valid data

TABLE 21

ARTICULATED-SUPPORTING TRUCK
MEAN $L\alpha_T$ ON TRAILING OUTER WHEEL (Pounds)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	-2.15	30.9	-1.58	28.2	-3.80				
	40	43.4	-.75	40.0	-2.66	37.9	.28	39.2	-4.23				
	50	52.4	-.91	49.5	-1.96	50.0	-2.48	48.8	-7.36				
	60	63.5	-.62	59.3	-1.67	58.0	-2.54	58.5	-15.58				
2	30	-	-	28.2	-2.89							31.7	-15.81
	40	44.2	-2.68	41.4	-3.31							42.3	-9.55
	50	55.0	-3.00	50.9	-3.76							50.8	-6.19
	60	64.0	-2.42	61.1	-5.50							60.6	-9.81
2.5	40	-	-	-	-							41.3	-7.99
	50	56.0	-2.96	-	-							50.4	-12.97
	60	66.0	-3.27	59.6	-8.09							64.4	-14.27
3	15	14.8	.09	-	-							14.3	-3.17
	20	19.9	-.11	19.8	-5.53							19.2	-3.98
	25	25.0	-.03	25.2	-.62							24.4	-5.60
4	15	13.1	-1.49	-	-	13.7	.14	15.0	-5.04				
	20	17.6	-1.18	20.2	-.20	20.6	-1.11	20.2	-8.99				
	25	22.2	-1.02	22.2	-3.94	24.6	-.46	24.7	-1.28				
8	15	17.1	-1.92	-	-	14.9	-.81	15.7	-5.62				
	20	20.3	-.48	19.7	.66	18.6	-2.15	20.2	-13.90				
	25	25.6	-1.17	25.4	-4.42	26.2	-.68	25.5	-2.32				

Speed in mph.

TABLE 22

ARTICULATED-SUPPORTING TRUCK MEAN
$L\alpha_T$ ON TRAILING INNER WHEEL (Pounds)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED	ACTUAL SPEED	POSITION C - EMPTY	ACTUAL SPEED	POSITION C-LOADED
1	30	-	-	29.4	3.47							29.0	1.46
	40	43.4	2.21	40.4	5.31							40.4	4.87
	50	52.4	1.20	49.5	5.82							50.7	7.38
	60	63.5	.88	59.3	5.45							63.2	5.24
2	30	-	-	28.2	1.82	-	-	31.9	12.23				
	40	44.2	2.49	41.4	3.00	40.1	5.08	39.4	9.53				
	50	55.0	2.50	50.9	3.55	53.1	3.88	49.0	8.18				
	60	64.0	2.27	61.1	2.57	60.6	4.68	59.8	2.43				
2.5	40	-	-	-	-	41.2	.94	39.9	27.05				
	50	56.0	1.22	-	-	51.5	.89	51.4	-4.14				
	60	66.0	1.19	59.6	2.00	57.9	1.66	59.8	1.61				
3	15	14.8	-.03	-	-	15.6	1.79	15.7	1.79				
	20	19.9	.67	19.8	6.59	21.4	.57	20.9	-.95				
	25	25.0	.51	25.2	1.58	26.5	2.32	25.4	4.01				
4	15	13.1	2.08	-	-							13.7	6.98
	20	17.6	2.32	20.2	-.49							18.3	6.59
	25	22.2	2.13	22.2	4.29							22.2	2.30
8	15	17.1	1.33	-	-							14.0	14.05
	20	20.3	1.53	19.7	-2.10							19.5	10.58
	25	25.6	1.65	25.4	4.42							25.4	6.88

NOTE: Blank areas indicate lack of valid data.

TABLE 23

CARBODY VERTICAL RMS ACCELERATION OVER
THE ARTICULATED-SUPPORTING TRUCK (g)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED	ACTUAL SPEED	POSITION C EMPTY	ACTUAL SPEED	POSITION C LOADED
1	30	29.0	.08	29.3	.08	-	-	29.4	.08	28.2	.12	30.9	.10
	40	40.4	.11	39.5	.12	43.4	.11	40.0	.09	39.2	.13	37.9	.11
	50	50.7	.13	48.7	.15	52.4	.15	49.5	.11	48.8	.13	50.0	.14
	60	63.2	.16	59.4	.17	63.5	.17	59.3	.13	58.5	.15	58.0	.16
2	30	31.7	.10	30.2	.11	-	-	28.2	.08	31.9	.12	-	-
	40	42.3	.11	41.8	.12	44.2	.11	41.4	.10	39.4	.13	40.1	.12
	50	50.8	.13	51.3	.15	55.0	.14	50.9	.11	49.0	.13	53.1	.13
	60	60.6	.14	60.3	.16	64.0	.15	61.1	.13	59.8	.15	60.6	.14
2.5	40	41.3	.10	38.8	.10	-	-	-	-	39.9	.13	41.2	.12
	50	50.4	.12	50.6	.14	56.0	.14	-	-	51.4	.13	51.5	.14
	60	64.4	.14	60.1	.15	66.0		59.6	.12	59.8	.14	57.9	.15
3	15	14.3	.05	17.4	.06	14.8	.06	-	-	15.7	.09	15.6	.08
	20	19.2	.06	22.3	.07	19.9	.07	19.8	.07	20.9	.10	21.4	.09
	25	24.4	.08	25.8	.09	25.0	.08	25.2	.08	25.4	.11	26.5	.11
4	15	13.7	.05	14.4	.06	13.1	.06	-	-	15.0	.08	13.7	.08
	20	18.3	.06	19.7	.06	17.6	.07	20.2	.07	20.2	.10	20.6	.10
	25	22.2	.07	25.0	.08	22.2	.07	22.2	.08	24.7	.10	24.6	.10
8	15	14.0	.06	13.7	.06	17.1	.08	-	-	15.7	.09	14.9	.08
	20	19.5	.07	20.6	.07	20.3	.08	19.7	.08	20.2	.10	18.6	.10
	25	25.4	.08	25.8	.08	25.6	.09	25.4	.09	25.5	.11	26.2	.12

Speed in mph.

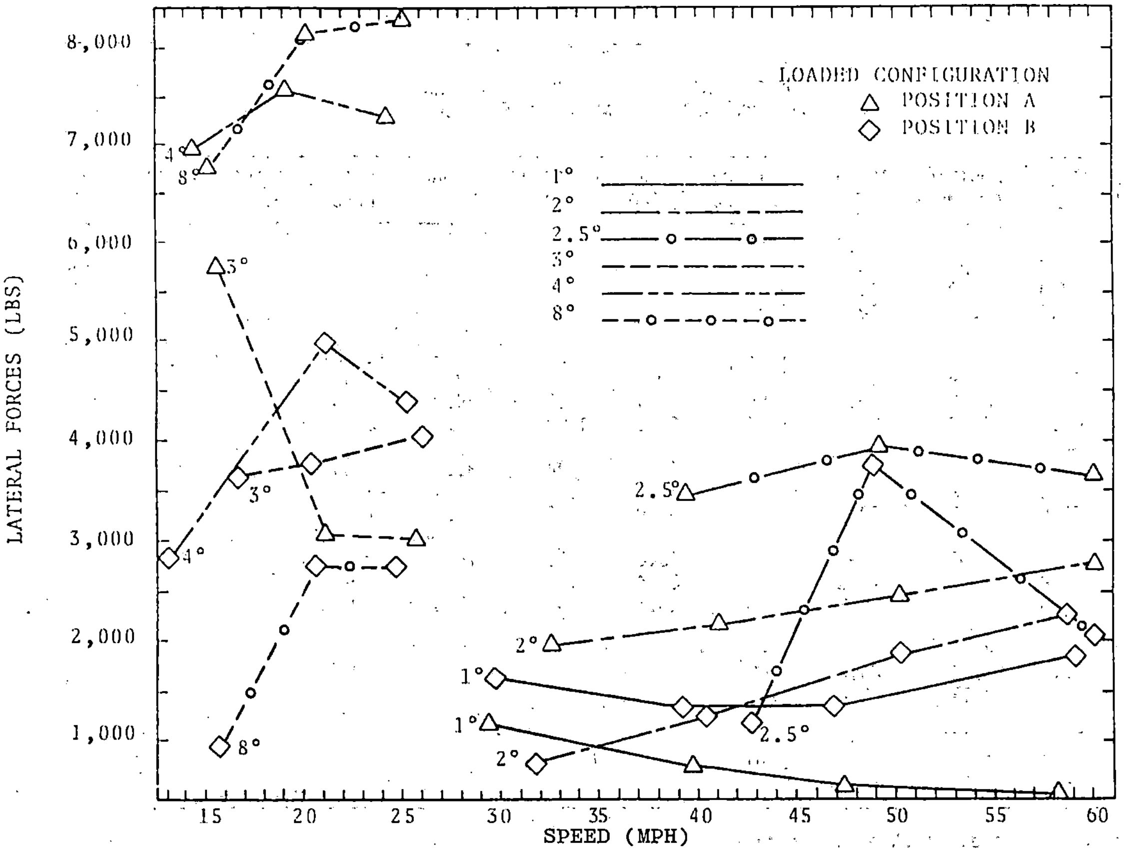


Figure 31. Mean Lateral Force on the Leading Outer Wheel of the Single Axle Truck

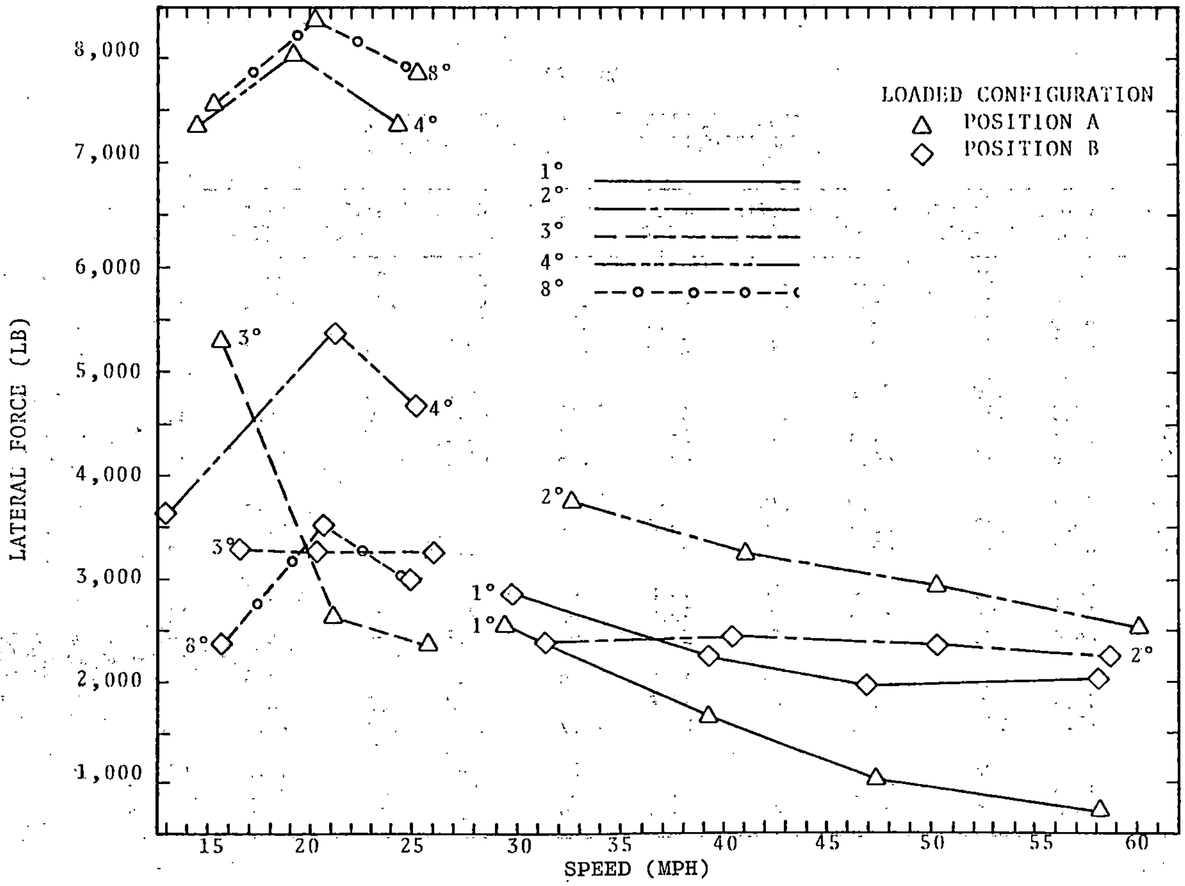


Figure 32. Mean Lateral Force on the Leading Inner Wheel of the Single Axle Truck

TABLE 24

MEAN LATERAL FORCE ON THE LEADING SINGLE AXLE TRUCK OUTER WHEEL (Kips)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	1.2	30.0	0.5	29.8	1.6
	40	39.4	1.3	39.8	0.8	39.9	0.4	39.4	1.4
	50	48.7	1.4	47.5	0.5	48.1	0.3	47.0	1.4
	60	58.4	1.5	58.3	0.4	58.9	0.3	58.1	1.9
2	30	-	-	32.6	2.0	30.5	1.9	31.9	0.8
	40	40.2	1.4	41.1	2.2	40.3	2.0	40.5	1.2
	50	50.6	1.7	50.4	2.5	50.9	2.2	50.4	1.9
	60	60.1	2.0	60.2	2.8	59.8	1.8	58.7	2.3
2.5	40	41.0	1.2	39.5	3.5	-	-	42.8	1.2
	50	50.6	2.0	49.4	3.9	-	-	49.0	3.8
	60	59.6	2.3	60.2	3.7	59.6	2.3	60.2	2.0
3	15	16.2	3.4	15.7	5.7	15.1	3.3	16.7	3.6
	20	21.5	3.5	21.2	3.1	20.5	2.5	20.5	3.8
	25	25.8	3.4	25.9	3.0	25.4	2.6	26.1	4.0
4	15	15.9	4.1	14.5	7.0	14.5	3.6	13.1	2.8
	20	19.9	4.1	19.2	7.5	19.7	1.8	21.1	5.0
	25	24.7	4.7	24.4	7.3	24.1	1.8	25.4	4.4
8	15	16.0	3.2	15.3	6.7	15.2	2.1	15.8	0.9
	20	21.8	4.2	20.3	8.1	20.3	1.2	20.7	2.7
	25	25.7	3.1	25.2	8.3	24.9	1.8	24.8	2.7

TABLE 25

MEAN LATERAL FORCE ON THE LEADING SINGLE AXLE TRUCK INNER WHEEL (Kips)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	2.5	30.0	1.2	29.8	2.9
	40	39.4	1.9	39.8	1.7	39.9	0.9	39.4	2.3
	50	48.7	1.7	47.5	1.0	48.1	0.7	47.0	2.0
	60	58.4	1.6	58.3	0.7	58.9	0.6	58.1	2.0
2	30	-	-	32.6	3.7	30.5	3.5	31.9	2.4
	40	40.2	2.4	41.1	3.2	40.3	3.0	40.5	2.4
	50	50.6	2.1	50.4	2.9	50.9	2.6	50.4	2.4
	60	60.1	1.8	60.2	2.6	59.8	1.8	58.7	2.2
2.5	40	41.0	2.3	39.5	5.0	-	-	42.8	1.3
	50	50.6	2.5	49.4	4.6	-	-	49.0	4.6
	60	59.6	2.0	60.2	3.1	59.6	2.0	60.2	1.8
3	15	16.2	3.0	15.7	5.3	15.1	3.1	16.7	3.3
	20	21.5	2.9	21.2	2.5	20.5	2.2	20.5	3.3
	25	25.8	2.7	25.9	2.4	25.4	2.1	26.1	3.3
4	15	15.9	5.2	14.5	7.3	14.5	4.5	13.1	3.6
	20	19.9	4.4	19.2	8.0	19.7	2.4	21.1	5.4
	25	24.7	4.7	24.4	7.4	24.1	2.2	25.4	4.6
8	15	16.0	3.9	15.3	7.6	15.2	3.6	15.8	2.4
	20	21.8	4.5	20.3	8.3	20.3	2.4	20.7	3.5
	25	25.7	3.2	25.2	7.8	24.9	2.3	24.8	3.0

Speed in mph.

TABLE 26

MEAN LATERAL FORCE ON THE TRAILING SINGLE AXLE TRUCK OUTER WHEEL (Kips)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	1.3	30.0	1.0	29.8	1.2
	40	39.4	0.9	39.8	1.3	39.9	1.0	39.4	1.2
	50	48.7	0.9	47.5	1.3	48.1	1.0	47.0	1.2
	60	58.4	0.9	58.3	1.3	58.9	0.9	58.1	1.4
2	30	-	-	32.6	1.5	30.5	1.1	31.9	1.5
	40	40.2	1.2	41.1	1.6	40.3	1.2	40.5	1.6
	50	50.6	1.3	50.4	1.7	50.9	1.2	50.4	1.6
	60	60.1	1.4	60.2	1.7	59.8	1.2	58.7	1.8
2.5	40	41.0	1.3	39.5	1.7	-	-	42.8	1.6
	50	50.6	1.4	49.4	1.7	-	-	49.0	1.7
	60	59.6	1.4	60.2	1.9	59.6	2.1	60.2	2.3
3	15	16.2	2.0	15.7	2.3	15.1	2.9	16.7	3.9
	20	21.5	1.9	21.2	2.3	20.5	3.2	20.5	3.4
	25	25.8	1.9	25.9	2.4	25.4	3.3	26.1	3.0
4	15	15.9	3.0	14.5	2.2	14.5	1.4	13.1	2.1
	20	19.0	3.1	19.2	1.8	19.7	3.1	21.1	1.6
	25	24.7	3.2	24.4	1.9	24.1	3.5	25.4	1.8
8	15	16.0	4.0	15.3	4.6	15.2	4.1	15.8	4.8
	20	21.8	4.5	20.3	2.9	20.3	4.0	20.7	2.8
	25	25.7	3.0	25.2	2.7	24.9	5.3	24.8	3.2

TABLE 27

MEAN LATERAL FORCE ON THE TRAILING SINGLE AXLE TRUCK INNER WHEEL (Kips)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	2.4	30.0	1.6	29.8	2.3
	40	39.4	2.4	39.8	2.2	39.9	1.5	39.4	2.3
	50	48.7	2.1	47.5	2.1	48.1	1.4	47.0	2.5
	60	58.4	1.7	58.3	1.9	58.9	1.3	58.1	2.3
2	30	-	-	32.6	3.4	30.5	2.0	31.9	3.4
	40	40.2	2.5	41.1	2.2	40.3	1.4	40.5	3.1
	50	50.6	1.9	50.4	1.5	50.9	1.0	50.4	2.4
	60	60.1	1.5	60.2	1.3	59.8	0.9	58.7	1.8
2.5	40	41.0	2.8	39.5	3.6	-	-	42.8	1.5
	50	50.6	2.1	49.4	2.2	-	-	49.0	2.1
	60	59.6	1.0	60.2	1.7	59.6	1.7	60.2	2.0
3	15	16.2	1.6	15.7	1.9	15.1	2.5	16.7	3.7
	20	21.5	1.4	21.2	1.7	20.5	2.7	20.5	3.1
	25	25.8	1.3	25.9	1.7	25.4	2.4	26.1	2.2
4	15	15.9	5.2	14.5	4.8	14.5	2.6	13.1	4.5
	20	19.9	5.0	19.2	3.6	19.7	5.0	21.1	3.2
	25	24.7	4.7	24.4	3.3	24.1	5.1	25.4	2.9
8	15	16.0	7.0	15.3	8.6	15.2	6.8	15.8	7.9
	20	21.8	6.9	20.3	5.7	20.3	6.2	20.7	5.3
	25	25.7	4.3	25.2	4.5	24.9	7.2	24.8	4.8

Speed in mph

TABLE 28

MEAN L/V ON THE LEADING SINGLE AXLE TRUCK OUTER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	.08	30.0	.04	29.8	.11
	40	39.4	.11	39.8	.05	39.9	.03	39.4	.09
	50	48.7	.11	47.5	.03	48.1	.03	47.0	.09
	60	58.4	.12	58.3	.03	58.9	.03	58.1	.11
2	30	-	-	32.6	.13	30.5	.16	31.9	.05
	40	40.2	.12	41.1	.14	40.3	.16	40.5	.08
	50	50.6	.13	50.4	.14	50.9	.16	50.4	.11
	60	60.1	.15	60.2	.15	59.8	.12	58.7	.12
2.5	40	41.0	.10	39.5	.22	-	-	42.8	.07
	50	50.6	.16	49.4	.23	-	-	49.0	.22
	60	59.6	.16	60.2	.19	59.6	.16	60.2	.11
3	15	16.2	.23	15.7	.31	15.1	.22	16.7	.19
	20	21.5	.23	21.2	.16	20.5	.17	20.5	.19
	25	25.8	.23	25.9	.15	25.4	.17	26.1	.20
4	15	15.9	.31	14.5	.41	14.5	.29	13.1	.18
	20	19.9	.31	19.2	.43	19.7	.14	21.1	.29
	25	24.7	.33	24.4	.40	24.1	.14	25.4	.25
8	15	16.0	.26	15.3	.41	15.2	.18	15.8	.06
	20	21.8	.31	20.3	.46	20.3	.10	20.7	.16
	25	25.7	.22	25.2	.43	24.9	.13	24.8	.15

TABLE 29

MEAN L/V ON THE LEADING SINGLE AXLE TRUCK INNER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED
1	30	-	-	29.5	.15	30.0	.09	29.8	.17
	40	39.4	.16	39.8	.10	39.9	.07	39.4	.14
	50	48.7	.15	47.5	.07	48.1	.05	47.0	.13
	60	58.4	.14	58.3	.05	58.9	.05	58.1	.14
2	30	-	-	32.6	.24	30.5	.28	31.9	.15
	40	40.2	.20	41.1	.22	40.3	.26	40.5	.16
	50	50.6	.19	50.4	.21	50.9	.25	50.4	.17
	60	60.1	.18	60.2	.20	59.8	.18	58.7	.17
2.5	40	41.0	.18	39.5	.32	-	-	42.8	.09
	50	50.6	.22	49.4	.32	-	-	49.0	.32
	60	59.6	.20	60.2	.24	59.6	.20	60.2	.14
3	15	16.2	.29	15.7	.40	15.1	.29	16.7	.15
	20	21.5	.29	21.2	.20	20.5	.21	20.5	.15
	25	25.8	.28	25.9	.19	25.4	.21	26.1	.16
4	15	15.9	.40	14.5	.52	14.5	.38	13.1	.23
	20	19.9	.41	19.2	.58	19.7	.21	21.1	.37
	25	24.7	.46	24.4	.56	24.1	.20	25.4	.32
8	15	16.0	.36	15.3	.56	15.2	.30	15.8	.16
	20	21.8	.45	20.3	.66	20.3	.20	20.7	.25
	25	25.7	.33	25.2	.66	24.9	.22	24.8	.22

Speed in mph.

TABLE 30

MEAN L/V ON THE TRAILING SINGLE AXLE TRUCK OUTER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	.09	30.0	.09	29.8	.09
	40	39.4	.08	39.8	.09	39.9	.09	39.4	.09
	50	48.7	.08	47.5	.09	48.1	.08	47.0	.09
	60	58.4	.08	58.3	.08	58.9	.07	58.1	.10
2	30	-	-	32.6	.13	30.5	.16	31.9	.15
	40	40.2	.14	41.1	.13	40.3	.15	40.5	.15
	50	50.6	.13	50.4	.13	50.9	.13	50.4	.15
	60	60.1	.13	60.2	.12	59.8	.12	58.7	.15
2.5	40	41.0	.15	39.5	.14	-	-	42.8	.13
	50	50.6	.14	49.4	.13	-	-	49.0	.14
	60	59.6	.12	60.2	.13	59.6	.22	60.2	.18
3	15	16.2	.17	15.7	.15	15.1	.29	16.7	.29
	20	21.5	.15	21.2	.14	20.5	.31	20.5	.25
	25	25.8	.15	25.9	.15	25.4	.13	26.1	.21
4	15	15.9	.2-	14.5	.16	14.5	.14	13.1	.16
	20	19.9	.29	19.2	.13	19.7	.32	21.1	.12
	25	24.7	.29	24.4	.13	24.1	.35	25.4	.13
8	15	16.0	.45	15.3	.40	15.2	.50	15.8	.45
	20	21.8	.58	20.3	.23	20.3	.47	20.7	.24
	25	25.7	.29	25.2	.20	24.9	.60	24.8	.26

TABLE 31

MEAN L/V ON THE TRAILING SINGLE AXLE TRUCK INNER WHEEL

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	.12	30.0	.12	29.8	.13
	40	39.4	.15	39.8	.12	39.9	.12	39.4	.13
	50	48.7	.14	47.5	.11	48.1	.12	47.0	.14
	60	58.4	.12	58.3	.11	58.9	.12	58.1	.14
2	30	-	-	32.6	.14	30.5	.11	31.9	.15
	40	40.2	.13	41.1	.10	40.3	.09	40.5	.14
	50	50.6	.11	50.4	.08	50.9	.07	50.4	.12
	60	60.1	.09	60.2	.07	59.8	.07	58.7	.10
2.5	40	41.0	.15	39.5	.15	-	-	42.8	.08
	50	50.6	.12	49.4	.10	-	-	49.0	.10
	60	59.6	.07	60.2	.08	59.6	.12	60.2	.11
3	15	16.2	.11	15.7	.10	15.1	.17	16.7	.19
	20	21.5	.10	21.2	.09	20.5	.19	20.5	.17
	25	25.8	.10	25.9	.09	25.4	.17	26.1	.13
4	15	15.9	.31	14.5	.22	14.5	.19	13.1	.23
	20	19.9	.30	19.2	.17	19.7	.34	21.1	.17
	25	24.7	.30	24.4	.16	24.1	.36	25.4	.16
8	15	16.0	.38	15.3	.36	15.2	.43	15.8	.137
	20	21.8	.40	20.3	.26	20.3	.40	20.7	.26
	25	25.7	.27	25.2	.22	24.9	.49	24.8	.25

Speed in mph.

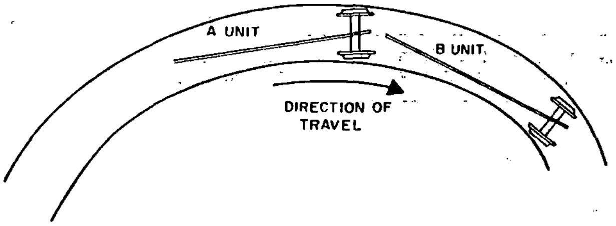


Figure 33. Schematic of the Single Axle Truck Negotiating a Curve

5.2.2 SINGLE AXLE TRUCK ANGLE OF ATTACK

The values of angle of attack measured on the leading truck are presented in Tables 32 and 33. The data contained in these tables represents the measurement of the angle between the individual wheelplate and rail, α_W.

Note that the inner wheel exhibits positive values of angle of attack and the outer wheel negative. The sign convention used for the articulated-supporting truck applies here; thus the leading single axle truck tends to negotiate a curve as shown in Figure 33.

In the case of the single axle truck there is seen to be a trend of increasing angle with increasing curvature for the leading truck of the A unit.

Making use of the fact that the inner and outer angles of attack should be and are, in fact, observed to be equal and opposite in sign, the same trend may be seen for the B unit.

Unfortunately, the geometry and mechanical linkages of the Autoguard car make it impossible to use truck yaw to cross check angle-of-attack. However, the truck yaw summarized in Table 34 does show an interesting feature of the single axle truck. That is, the change in sign of yaw is consistent with the direction of the curve (2°, 2.5°, and 3° are right hand curves - 1°, 4°, 8° are left hand curves). A positive yaw angle indicates a clockwise rotation (looking down). This would seem to indicate steering with the curve. Real-time observations of yaw on the leading axle, in fact, indicated that this truck tended to steer with the curve.

5.2.3 SINGLE AXLE TRUCK STEADY STATE CURVING PERFORMANCE

In contrast to the steady state curving characterization of the articulated-supporting truck which used truck angle-of-attack, the treatment of the single axle truck will use the wheelplate angle-of-attack, α_W. The values of the product of the lateral force and α_W is given for the leading single axle truck in Tables 35 an 36. As explained earlier, the values of $L\alpha_W$ are given in pounds. Also, the nature of α_W should be kept in mind when using this data for purposes other than relative comparisons.

Tables 35 and 36 reveal two interesting points. First there is seen a marked increase in $L\alpha_W$ with curvature. Second, the value of $L\alpha_W$ range upward to just less than 150 pounds. Although this is considerably higher than observed for the articulated-supporting truck, these values cannot be compared. Recall that truck angle was involved in the earlier discussion. Trucks with two axles or more as a consequence of their longer characteristic length filter shorter wavelength perturbations which may exist and cause relatively large instantaneous wheel angles of attack.

5.2.4 SINGLE AXLE TRUCK DYNAMIC PERFORMANCE

The same dynamic parameters discussed for the articulated-suspending truck, were used to characterize the dynamic performance of the single axle truck. These are truck hunting critical speed and carbody root mean square (rms) vertical acceleration or ride quality.

During the conduct of tests on the single axle truck, no hunting was observed. Again these speeds were up to 60 mph. In this case, however, the trucks instrumented with accelerometers for hunting detection had wheels were well worn. The tread was distinctly hollow or concave and the flange was near the condemn limit. There are no other test data available with which to correlate the present results. Thus, the truck hunting critical speed for the single axle truck lies above 60 mph but it is not known from this study.

The results of the ride quality measurements are presented in Table 37. These data show principally that the dynamic environment on the Autoguard car was a function of speed and to a limited extent of position. The effect of position may have been related to the specific truck, however, and should not be interpreted as a characteristic of single axle trucks as a whole. The data contained in Table 37 agree well with the present data base on freight car ride quality (see reference 9).

5.2.5 SINGLE AXLE TRUCK ROCK AND ROLL PERFORMANCE

The tests conducted over the rock and roll test zone described in section 4.3.3 found the Autoguard Car/single axle truck to exhibit no tendency to excessive roll angles. This vehicle/truck system did exhibit the classic resonance phenomenon with a critical speed of approximately 22 mph. The peak roll angle between the carbody and axle at this speed was 2.75 degrees peak to peak.

TABLE 32

LEADING SINGLE AXLE TRUCK MEAN ANGLE OF ATTACK OF OUTER WHEEL (Degrees)

DEGREE CURV	NOM SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	-.03				
	40	39.4	-.57	39.8	-.15				
	50	48.7	-.59	47.5	-.01				
	60	58.4	.08	58.3	-.01				
2	30	-	-	32.6	-.42	30.5	-.33	31.9	-.49
	40	40.2	-.37	41.1	-.43	40.3	-.32	40.5	-.40
	50	50.6	-.32	50.4	-.34	50.9	-.29	50.4	-.45
	60	60.1	-.43	60.2	.13	59.8	-.30	58.7	-.47
2.5	40	41.0	-.46	39.5	-.48				
	50	50.6	.12	49.4	-.34			42.8	-.01
	60	59.6	-.03	60.2	-.38			49.0	-.26
3	15	16.2	-.45	15.7	-.11	15.1	-.26	60.2	-.26
	20	21.5	-.33	21.2	-.25	20.5	-.33	20.5	-.25
	25	25.8	-.35	25.9	-.01	25.4	-.32	26.1	-.15
4	15	15.8	-1.08	14.5	-.68				
	20	19.9	-.29	19.2	-.29				
	25	24.7	-.65	24.4	-.61				
8	15	16.0	-1.17	15.3	.13				
	20	21.8	-.90	20.3	-.84				
	25	25.7	-.78	25.2	-1.01				

NOTE: Blank areas indicate lack of valid data.

TABLE 33

LEADING SINGLE AXLE TRUCK MEAN ANGLE OF ATTACK OF INNER WHEEL (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMTPY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	.04	30.0	.01	29.8	.18
	40	39.4	.34	39.8	.11	39.9	.02	39.4	.27
	50	48.7	.32	47.5	.10	48.1	.05	47.0	.23
	60	58.4	.06	58.3	-.03	58.9	.02	58.1	.24
2	30	-	-	32.6	.53				
	40	40.2	.27	41.1	.39				
	50	50.6	.31	50.4	-.07				
	60	60.1	.64	60.2	.16				
2.5	40	41.0	.32	39.5	1.08				
	50	50.6	.14	49.4	.16				
	60	59.6	.14	60.2	.33				
3	15	16.2	.11	15.7	.24				
	20	21.5	.70	21.2	.42				
	25	25.8	.14	25.9	.07				
4	15	15.9	.36	14.5	.43	14.5	.62	13.1	.49
	20	19.9	.42	19.2	.30	19.7	.54	21.1	.59
	25	24.7	.35	24.4	.53	24.1	.55	25.4	.54
8	15	16.0	.81	15.3	.59	15.2	1.03	15.8	.76
	20	21.8	.75	20.3	.70	20.3	.99	20.7	1.04
	25	25.7	.34	25.2	.95	24.9	.88	24.8	.81

Speed in mph.

TABLE 34

TRAILING SINGLE AXLE TRUCK MEAN YAW (Degrees)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30			29.5	.003	30.0	.08	29.8	.01
	40			39.8	.04	39.9	.13	39.4	-.002
	50			47.5	.09	48.1	.14	47.0	.01
	60			58.3	.14	58.9	.14	58.1	.03
2	30			32.6	.08	30.5	-.02	31.9	.08
	40			41.1	.07	40.3	-.01	40.5	.05
	50			50.4	.04	50.9	-.10	50.4	.05
	60			60.2	-.02	59.8	-.14	58.7	.03
2.5	40			39.5	.03	-	-	42.8	-.08
	50			49.4	-.10	-	-	49.0	-.07
	60			60.2	-.08	59.6	-.17	60.2	-.14
3	15			15.7	-.03	15.1	-.21	16.7	-.16
	20			21.2	-.61	20.5	-.34	20.5	-.47
	25			25.9	-.27	25.4	-.09	26.1	-.47
4	15			14.5	.27	14.5	.60	13.1	.26
	20			19.2	.09	19.7	.02	21.1	.27
	25			24.4	.48	24.1	.37	25.4	.30
8	15			15.3	.18	15.2	.43	15.8	.16
	20			20.3	.59	20.3	-.03	20.7	.07
	25			25.2	.71	24.9	.22	24.8	.36

NOTE: Blank areas indicate lack of data.

TABLE 35

MEAN $L\alpha_W$ OF THE LEADING SINGLE AXLE TRUCK OUTER WHEEL (Pounds)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMTPY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	-1.25				
	40	39.4	-13.2	39.8	-2.58				
	50	48.7	-14.33	47.5	-.43				
	60	58.4	-8.36	58.3	-.28				
2	30	-	-	32.6	-14.63	30.5	-11.28	31.9	-6.71
	40	40.2	-9.49	41.1	-16.63	40.3	-11.35	40.5	-8.57
	50	50.6	-9.80	50.4	-15.03	50.9	-11.87	50.4	-14.99
	60	60.1	-15.97	60.2	-16.90	59.8	-10.70	58.7	-18.92
2.5	40	41.0	-9.8	39.5	-29.21	-	-	42.8	-2.83
	50	50.6	-13.98	49.4	-23.75	-	-	49.0	-1.61
	60	59.6	-3.67	60.2	-24.52	59.6	-10.80	60.2	-9.46
3	15	16.2	-26.90	15.7	-11.69	15.1	-4.07	16.7	-26.75
	20	21.5	-20.36	21.2	-14.83	20.5	-14.63	20.5	-16.76
	25	25.8	-21.51	25.9	-2.19	25.4	-14.69	26.1	-10.99
4	15	15.9	-76.94	14.5	-82.78				
	20	19.9	-20.85	19.2	-38.81				
	25	24.7	-53.89	24.4	-78.62				
8	15	16.0	-69.06	15.3	-110.23				
	20	21.8	-67.17	20.3	-119.20				
	25	25.7	-59.63	25.2	-146.91				

Speed in mph.

TABLE 36

MEAN $L\alpha_W$ OF THE LEADING SINGLE AXLE TRUCK INNER WHEEL (Pounds)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A - EMPTY	ACTUAL SPEED	POSITION A-LOADED	ACTUAL SPEED	POSITION B - EMPTY	ACTUAL SPEED	POSITION B-LOADED
1	30	-	-	29.5	2.01	30.0	.55	29.8	8.60
	40	39.4	11.23	39.8	3.65	39.9	.45	39.4	10.53
	50	48.7	9.80	47.5	1.90	48.1	.57	47.0	8.10
	60	58.4	3.13	58.3	- .30	58.9	.25	58.1	8.30
2	30	-	-	32.6	34.08				
	40	40.2	11.10	41.1	22.11				
	50	50.6	11.41	50.4	-3.50				
	60	60.1	20.32	60.2	11.95				
2.5	40	41.0	12.68	39.5	94.12				
	50	50.6	12.53	49.4	12.29				
	60	59.6	6.98	60.2	17.36				
3	15	16.2	5.71	15.7	22.10				
	20	21.5	35.38	21.2	18.79				
	25	25.8	6.47	25.9	2.82				
4	15	15.9	28.40	14.5	54.46	14.5	49.01	13.1	30.92
	20	19.9	32.61	19.2	41.21	19.7	22.83	21.1	55.36
	25	24.7	29.30	24.4	69.00	24.1	21.34	25.4	43.99
8	15	16.0	55.50	15.3	121.56	15.2	63.84	15.8	31.40
	20	21.8	59.06	20.3	100.25	20.3	39.28	20.7	64.38
	25	25.7	28.91	25.2	129.56	24.9	35.90	24.8	44.92

NOTE: Blank areas indicate lack of valid data.

TABLE 37

CARBODY VERTICAL RMS ACCELERATION OVER THE SINGLE AXLE TRUCK (g)

DEGREE CURV	NOM. SPEED	ACTUAL SPEED	POSITION A EMPTY	ACTUAL SPEED	POSITION A LOADED	ACTUAL SPEED	POSITION B EMPTY	ACTUAL SPEED	POSITION B LOADED
1	30	-	-	29.5	.08	30.0	.08	29.8	.08
	40	39.4	.11	39.8	.10	39.9	.12	39.4	.11
	50	48.7	.12	47.5	.11	48.1	.12	47.0	.11
	60	58.4	.15	58.3	.14	58.9	.13	58.1	.13
2	30	-	-	32.6	.09	30.5	.10	31.9	.08
	40	40.2	.09	41.1	.10	40.3	.12	40.5	.11
	50	50.6	.10	50.4	.12	50.9	.14	50.4	.12
	60	60.1	.11	60.2	.12	59.8	.14	58.7	.13
2.5	40	41.0	.08	39.5	.10	-	-	42.8	.11
	50	50.6	.10	49.4	.12	-	-	49.0	.14
	60	59.6	.11	60.2	.11	59.6	.14	60.2	.13
3	15	16.2	.07	15.7	.08	15.1	.07	16.7	.09
	20	21.5	.13	21.2	.17	20.5	.09	20.5	.10
	25	25.8	.17	25.9	.17	25.4	.11	26.1	.12
4	15	15.9	.06	14.5	.08	14.5	.07	13.1	.06
	20	19.9	.08	19.2	.09	19.7	.07	21.1	.09
	25	24.7	.10	24.4	.10	24.1	.08	25.4	.10
8	15	16.0	.06	15.3	.07	15.2	.08	15.8	.08
	20	21.8	.08	20.3	.09	20.3	.09	20.7	.10
	25	25.7	.10	25.2	.10	24.9	.10	24.8	.11

Speed in mph.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the present study quantify the performance characteristics of an articulated-supporting truck and a single axle truck. The articulated-supporting truck studied was presently deployed under a prototype intermodal railcar which may be categorized as low profile. The single axle truck was deployed under a tri-level auto rack car that had been in service for approximately eight years.

The basic conclusion of this study is that nothing in the data nor were any visual observations made which would indicate intrinsic problems with either truck. Specifically, the lateral forces and ratios of lateral to vertical forces, L/V, fall within the safe regime of most commonly acceptable safety criteria. Maximum mean value of L/V for the articulated-supporting truck were less than 0.6 and less than 0.7 for the single axle truck. The wheel/rail force was observed to be a function of both speed and degree of curvature for both types of trucks tested. The influence of position under the associated car was not entirely clear but for the most part negligible.

The measurement of angle of attack similarly yielded values in a generally acceptable range. The truck angle of attack for the articulated-supporting truck was less than 0.4 degrees while the wheelplate angle-of-attack for the single axle truck attained values slightly greater than one degree in the 8 degree curve. It should be noted that the carbody angle-of-attack in an 8 degree curve with a 28 foot truck spacing would be slightly greater than 2 degrees, which mean that truck yaw was to some extent compensating for curving. The articulated-supporting truck yaw angles did, in fact, substantiate the angle-of-attack measurements.

Under these test conditions, which included speeds of 60 mph, no hunting was detected for either truck. It was, therefore, not possible to determine the truck hunting critical speed. Tests conducted by CONRAIL on the same LoPac 2000 using worn wheels at speeds up to 76 mph yielded identical results, i.e., no hunting was observed. The wheel profiles used on the single axle truck were worn hollow with considerable flange wear.

During tests conducted over the rock and roll test zone neither carbody/truck system exhibited large roll angles. Although no measurements were made of the carbody with respect to the local vertical, measurements of the roll angle between the carbody and truck showed this angle to be one degree or less for the articulated-supporting truck and less than two and three-quarters degree for the single axle truck. It should be kept in mind that the carbodies associated with each of these trucks were radically different from one another.

Measurements of ride quality in terms of the root mean square vertical acceleration of the cars tested were found to be typical of freight service.

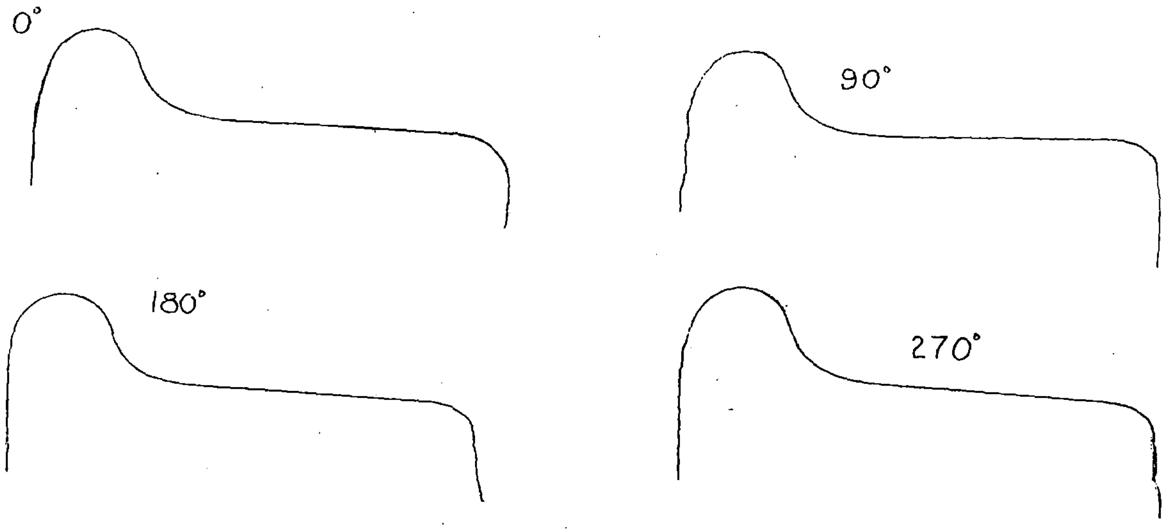
Because it was not possible to determine the truck hunting critical speed for either truck, it is recommended that further tests be conducted which would attain the speeds necessary to initiate truck hunting in order that the critical speed of these two trucks may be quantified.

Further investigation is required in the measurement of angle-of-attack. Although some success was achieved during this study, it was found that the eddy current device used had severe limitations. For example, because of the presence of the side frame, it was not possible to measure wheelplate angle-of-attack on the articulated-supporting truck. In contrast, it was possible to measure and view in real-time angle-ofattack on the single axle truck.

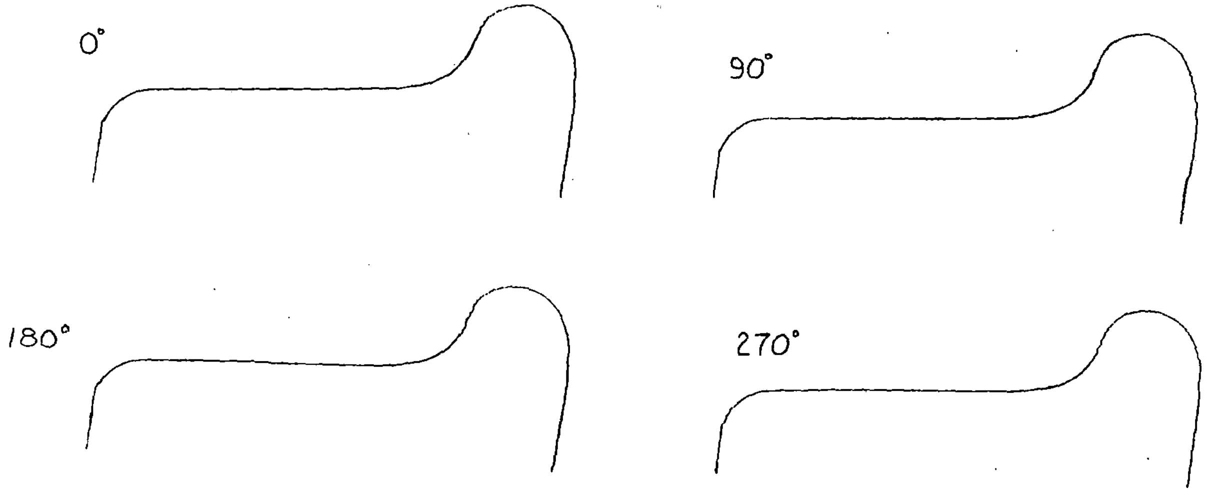
All other instrumentation used during this investigation were found to be fully operational. This is significant in the case of the measurement of the wheel/rail force vector. A particularly advantageous feature of the system employed, was the realtime processor which enabled on-site analysis and evaluation. It is highly recommended that all future work in the area of wheel/rail force measurement incorporate realtime processing to insure maximum advantage of the experiment.

They didn't get up
to critical speed
(ie hunting) in test
with worn wheels
& flange wear
max 66 mph

APPENDIX A
INSTRUMENTED WHEEL TREAD PROFILES

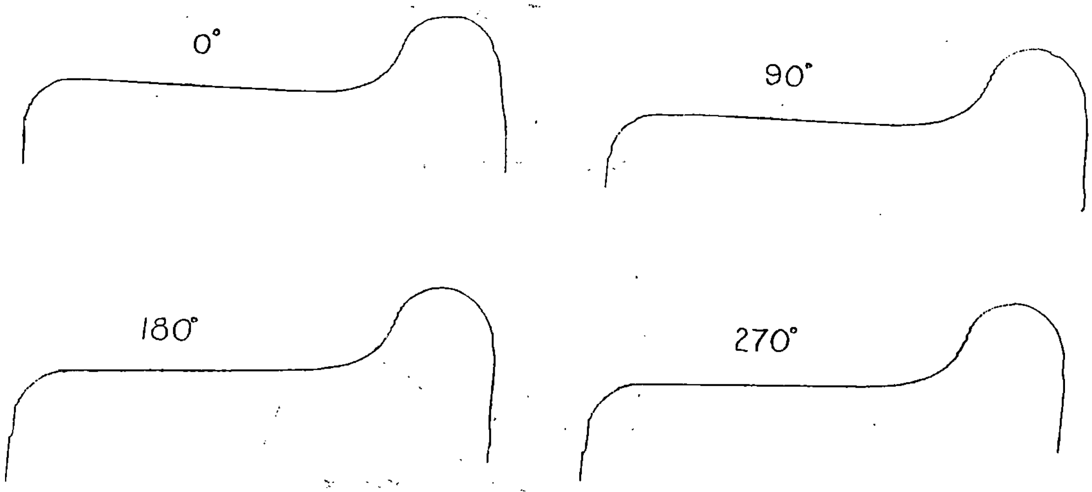


LEADING AXLE - LEFT SIDE

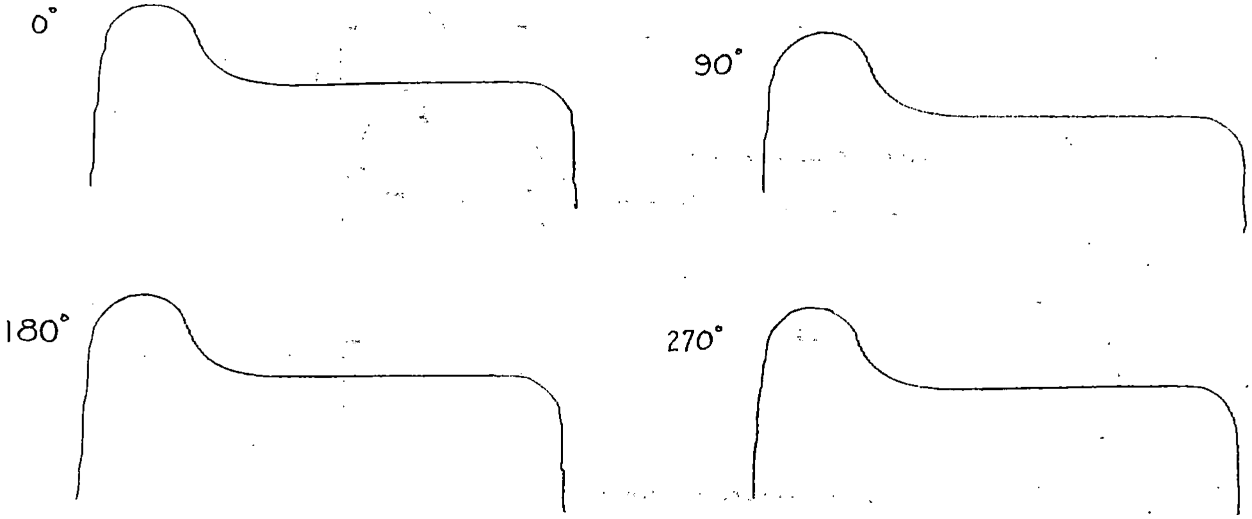


LEADING AXLE - RIGHT SIDE

Figure A-1. Leading Axle Wheel Profiles

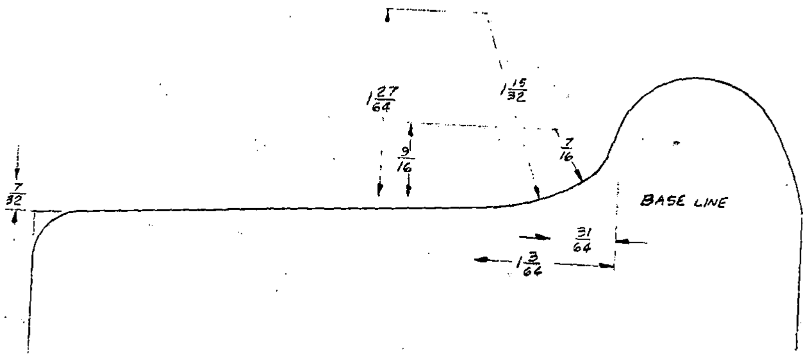


TRAILING AXLE - LEFT SIDE

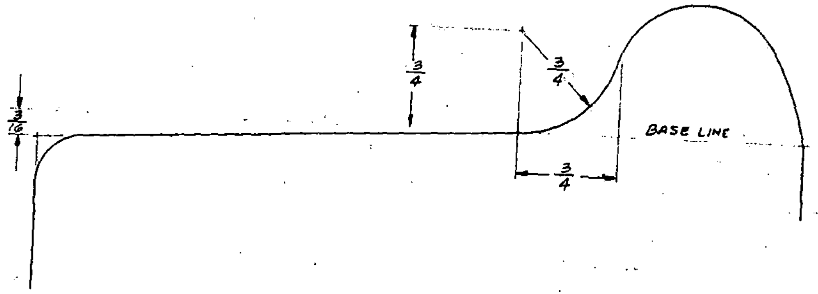


TRAILING AXLE - RIGHT SIDE

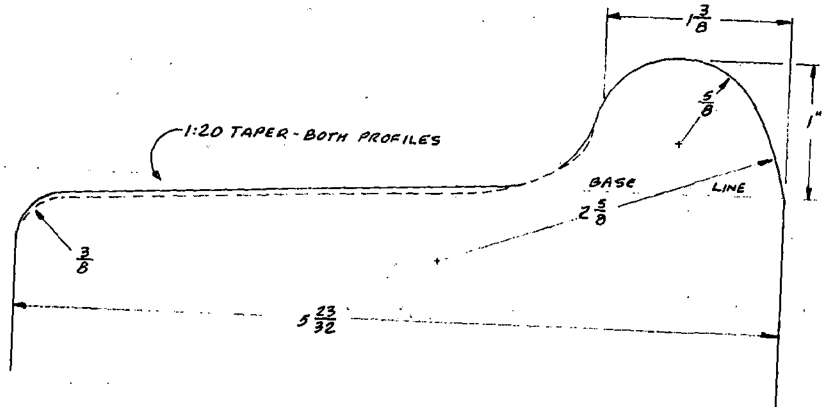
Figure A-2. Trailing Axle Wheel Profiles



a) CN-Modified Heumann Profile



b) AAR Profile



c) Composite of Profiles

Figure A-3. Comparison of the Modified Heumann and AAR Profiles

APPENDIX B

ERROR ANALYSIS OF AOA MEASUREMENT SYSTEMS

The sources of uncertainty in the measurement of the angle of attack using the eddy current device can be placed into two categories. The first category contains those sources of error which can be quantified in laboratory tests using specimens of rail in free space. The second category of error consists of those phenomena arising from deployment which cause unknown distortions in the magnetic field and hence are not amenable to quantification at this time.

Uncertainty of the angle of attack measurement system depends primarily on the ability of the individual sensor to resolve measurement distance. Laboratory calibrations have shown this resolution to be ±0.026 inches square-average for all eight sensors. The maximum error was ±0.041 inches (for one sensor only with the next largest ±0.030 inches) and the minimum error was ±0.016 inches. For the purposes of the present analysis sensor resolution error will be taken to be worst case at ±0.04 inches.

The next source of error is y-z cross talk. That is, the preceived lateral (y) displacement caused by changes in the vertical (z) distance above the rail from the design height. This may be caused by either vertical vibration of the AOA brackets or short wavelength (less than the distance between sensor pairs) profile variations. Calibration of off-design heights have shown that a vertical translation of 0.25 inches creates a signal equivalent to 0.015 inches of lateral displacement. The AOA bracket is extremely rigid and has a natural frequency much higher (> 20 Hz) that those frequencies which are of interest. The distance between sensors is less than three feet. Variations in profile with wavelengths of three feet or less are much smaller than 0.25 inches. The only possible cross talk error would occur at a badly mismatched joint. This would occur only at 39 foot intervals and then infrequently. In order to include worst case situations, a crosstalk error of ±0.015 inches will be considered here.

A third source of error is incurred in determining the system offset. From laboratory calibration the uncertainty in system offset is less than ±0.01 inches. In a field test with periodic updates, the system offset should be accurate to within ±0.01.

A fourth source of error is found in the small single approximation, $\sin \alpha = \alpha$. For a one degree angle the error incurred is less than 2 ppm. This source of error is therefore negligible. Table B-1 summarizes the above discussion.

Because these errors are inherently independent of one another, the overall sensor error may be expressed as

$$\varepsilon_{sensor} = \sqrt{\sum \varepsilon^2} \qquad (1)$$

which leads to the conclusion that the overall sensor capability to measure displacement is something better than ±0.044 inches.

The angle of attack, α, is obtained from the relatively simple trigonometric relation

$$\sin \alpha = (s_2 - s_1)/d \qquad (2)$$

where s_1 and s_2 are sensor outputs or the distance from rail head center and d is the distance between sensors. Making use of the small angle approximation ($d >> s_2 - s_1$),

$$\alpha = 180\ (s_2 - s_1)/\pi d \qquad (3)$$

with α now expressed in degrees.

Each sensor output possesses some uncertainty ε_s previously discussed. Therefore, each sensor output may be expressed as:

$$s_i = \tilde{s}_i \pm \varepsilon_s \quad (i = 1,2) \qquad (4)$$

TABLE B-1

AOA SENSOR ERRORS

i	Source	ε_i (inches)
1	resolution (digitization)	0.04
2	cross talk	0.015
3	off set	0.01
4	small angle approximation	negligible

where $\tilde{s}_i$ is the true displacement. Substituting this into the last expression of α yields:

$$\alpha = 180\ (\tilde{s}_2 - \tilde{s}_1)/\pi d \pm 360\ \varepsilon_s/\pi d \qquad (5)$$

The first term in this expression is, of course, the true angle of attack. The second term is then the uncertainty in the measured angle of attack or error, δ, thus

$$\delta = 360\ \varepsilon_s/\pi d \qquad (6)$$

Note that the sensor errors are taken to be additive in δ which assumes an absolute worst case. Evaluating the above expression with d = 35.5 inches,

$$\delta = 0.14^{\circ} = 8.5' \qquad (7)$$

In addition to the sources of uncertainty discussed above, there are other sources. These include the influence of the truck mass, particularly the side frame which is in close proximity to the inboard sensor, and variation in rail head wear. Of course, track appliances, such as turnouts, switches, and diamonds, completely degrade the system performance. Data obtained in the immediate vicinity (within one or two feet) of such appliances are totally in error and must be discarded.

APPENDIX C - SPRUNG VEHICLE/LOAD HEIGHT OF CENTER OF GRAVITY ABOVE RAIL HEAD CALCULATIONS

	TTX		Lo Pro 2000	
	Weight (lb.)	Height of C.G. Above Rail Head (in.)	Weight (lb.)	Height of C.G. Above Rail Head (in.)
Sprung Carbody	22,800[1]	36[1]	27,350[2]	30[2]
Light Trailer	12,000[3]	97[4]	12,000[3]	68[5]
Test Load	32,000[6]	95[7]	32,000[6]	66[8]
Overall	66,800	75	71,350	53

	TTCX		Autoguard	
	Weight (lb.)	Height of C.G. Above Rail Head (in.)	Weight (lb.)	Height of C.G. Above Rail Head (in.)
Sprung Carbody	22,800[1]	36[1]	40,000[9]	90[9]
Container/ Ballast	40,000[10]	77	16,900[12]	40[13]
	62,800	62	56,900	75

[1] Half Carbody Exclusive of Bolster - Nominal Average Trailer Train Flatcars

[2] Single Unit - Source Budd

[3] Source Budd - Industry Average

[4] 41" to Deck + 56" (Budd) Industry Average

[5] 12" to Deck + 56" (Budd)

[6] 3 Stacks of Steel 12 x 43 x 70

[7] 41" to Deck + 48" to Trailer Floor + 6" to C.G. of 12" Stack

[8] 12" to Deck + 48" to Trailer Floor + 6" to C.G. of 12" Stack

[9] Single Unit - Source National Castings

[10] Most Frequent Gross Weight (Nominal) Encountered (reference 10)

[11] 41" to Deck + 36" to Loaded Container C.G. (Nominal)

	TTX		Lo Pac 2000	
	Weight (lb.)	Height of C.G. Above Rail Head (in.)	Weight (lb.)	Height of C.G. Above Rail Head (in.)
Sprung Carbody	22,800	36	27,350	30
Light Trailer	12,000	97	12,000	68
Typical Load	40,000[14]	129[15]	40,000[14]	100
Overall	74,800	96	79,350	72

[12] 10 lengths (39') of 130 lb rail

[13] 36.5 to deck + 3.5" to rail c.g.

[14] Most Frequent Trailer Gross Weight (52,000 lb Nominal) Encountered in Typical TOFC Service (reference 10)

[15] 41" to Deck + 48" to Floor and 40" to Load C.G.

[16] 12" to Deck + 48" to Floor + 40" to Load C.G.

REFERENCES

1. Dean, F. E. and Ahlbeck, D. E., "Criteria for the Qualification of Rail Vehicles for High-Speed Curving," IPEEP Working Paper, Oct 1977.
2. Yokose, Keiji, "A Theory of the Derailment of Wheelset," JNR Quarter Report, (Special Issue), 1962.
3. Matsudaira, T. M., "Dynamics of High Speed Rolling Stock," JNR Quarterly Report (Special Issue), 1962.
4. Koffman, J. L., "Four-Wheel Wagon Suspensions," Railway Gazette, Nov 7, 1969, pp 823-828.
5. Koffman, J. L., "Limitations of the Three-Piece Bogie," Railway Gazette, May 15, 1970, pp 379-384.
6. Gilchrist, A. O., and Brickle, B. V., "A Re-Examination of the Proneness to Derailment of a Railway Wheel-set," Journal of Mechanical Engineering Science, Vol. 18, No. 3., 1975, pp. 131-141
7. Ahlbeck, D. R., "Safe L/V Ratios to Prevent Wheel-Climb Derailments," unpublished working paper, Battelle Columbus Laboratories, Mar 1977.
8. Heumann, H., Grundzuge der Fuhrung der Schienenfahrzeuge (Principles of Rail Vehicle Guidance), Sonderdruck aus Elecktrishe Bahnen, 1953.
9. Reed, K. D., "BUDX 2000 Test," CONRAIL Memorandum 8521.11.2., Nov 1980.
10. Kenworthy, M. A. and Edelman, J., "Lightweight Intermodal Flatcar Evaluation Program-Volume II: Test Results Report," FRA/ORD-80/07.II, Dec 1979.

Single Axle and Articulated-Supporting
Truck: Test Result Report, 1981
US DOT, FRA, MA Kenworthy