Side Friction for Superelevation on Horizontal Curves

Appendices A - G
Volume III

C. C. MacAdam
P. S. Fancher
L. Segel

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16. Abstract

The basic objective of this study has been to address the issue of how adequate point-mass representations are in predicting friction requirements for actual vehicles operating along superelevated curves. The project focused on this and related questions by combining computer analysis and full-scale vehicle testing. Simple-to-use models for predicting the friction factor requirements at individual wheel locations were first developed and applied to the steady-turning condition. An existing comprehensive computer model used for predicting transient or nonsteady maneuvering situations was also employed to analyze friction demand while maneuvering along superelevated curves. Highway tests were then performed for two passenger cars and a five-axle tractor-semitrailer to collect representative test data and assist in validing the predictions of the computer models. Finally, a sensitivity analysis was performed to illustrate the relative importance and interactions of various vehicle parameters and highway geometrics in influencing side friction requirements.

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Appendix A

STEADY TURNING MODEL EQUATIONS: TWO-AXLE VEHICLE

The equations presented here represent the steady turning motion of a two-axle vehicle moving along a circular path while resting upon a road surface which contains both superelevation and grade. The two-axle vehicle model is described by four degrees of freedom for the sprung mass element (vehicle body): roll, pitch, yaw, and bounce. Front and rear unsprung mass elements (suspension masses) are also represented but are located at a fixed height above the road plane (no vertical tire compliance). Solution of the model equations produces the steady state values for vehicle sideslip velocity, roll angle, pitch angle, vertical bounce, front wheel steer angle, and tire drive thrust required for traversing a curve of specified geometry at a given speed. The six equations describing the model are three force equilibrium equations and three moment equilibrium equations applied to the vehicle with respect to a body axis system whose origin is located along the vehicle centerline at a distance d_f aft of the front axle. All rotations and displacements of the sprung mass are with respect to a static reference condition defined by the vehicle at rest on a horizontal plane which is normal to the gravity vector. Normal SAE sign conventions apply [7].

The next section of this appendix contains a list of definitions for symbols appearing in the equations which are then presented in the final section. The equations are in the form $\mathbf{A}\,\mathbf{x} = \mathbf{b}$, where $\mathbf{A}$ is a 6 by 6 matrix, and $\mathbf{b}$ is a 6 by 1 vector. Each of these two arrays contains various vehicle and highway geometric parameters. The 6 by 1 solution vector, $\mathbf{x}$, is obtained by computing the matrix inverse of $\mathbf{A}$ and multiplying it by the $\mathbf{b}$ vector:

$$\mathbf{x} = \mathbf{A}^{-1}\,\mathbf{b}$$

A two- or three-stage iterative solution is required since a few terms in the $\mathbf{A}$ and $\mathbf{b}$ arrays contain components of $\mathbf{x}$ as weak nonconstant influences. The

six elements of **x** are the solution quantities noted above and are also defined in the following nomenclature listing. The first three model equations represent force equilibrium conditions acting in the longitudinal, lateral, and vertical directions. The last three model equations represent moment equilibrium conditions about the roll, pitch, and yaw axes.

Lastly, equations defining the lateral and vertical tire forces, suspension forces, and friction factors at each wheel location are included.

Nomenclature

C_{af}	front tire cornering stiffness (<0)
C_{ar}	rear " (<0)
C_D	aerodynamic drag coefficient
C_{L0}	" lift coefficient at trim pitch angle ($p = p_r$)
C_r	rolling resistance percentage / 100
d_f	distance from front axle to vehicle body-axis origin (arbitrary)
d_r	" rear " " ($L - d_f$)
e	highway superelevation
F_{XTf}	front tire traction force, **x**(6)
F_{XTr}	rear tire traction force
g	acceleration of gravity
h	height above ground of sprung mass c.g.
h_A	height above ground of the aerodynamic center of pressure
h_r	arbitrary height above ground of reference axis system origin
K_f	front suspension stiffness
K_r	rear "
L	vehicle wheelbase
m_s	mass of sprung weight (body)
m_{uf}	front unsprung mass
m_{ur}	rear "

N_{sf} front static axle load

N_{sr} rear "

p vehicle sprung mass pitch angle relative to the horizontal plane normal to the gravity vector, $\mathbf{x}(4)$

p_r highway grade

q aerodynamic force = [(density of air)(reference area) U^2 / 2]

R highway curve radius

s_L slope of aerodynamic lift coefficient with respect to pitch

s_Y slope of aerodynamic side force with respect to sideslip angle

T_F front suspension spread

T_R rear "

TT_f front tire track

TT_r rear "

U vehicle speed

v vehicle sideslip velocity at the body-axis origin, $\mathbf{x}(1)$

W_T total vehicle weight

x_A distance of aerodynamic center of pressure ahead of body-axis origin

x_c distance of sprung mass center ahead of body-axis origin

z vehicle sprung mass displacement normal to the road surface (relative to the static reference condition), $\mathbf{x}(2)$

z_f height above ground of front suspension roll center

z_r " rear "

∂_{FW} vehicle front wheel steer angle, $\mathbf{x}(5)$

ϕ vehicle sprung mass roll angle relative to the horizontal plane normal to the gravity vector, $\mathbf{x}(3)$

Two-Axle Model Equations: $\mathbf{A\,x = b}$

$$
\mathbf{A} = \begin{bmatrix}
U W_T / (R\,g) & 0 & 0 & 0 & 0 & 2 \\
\left[2\,(C_{af} + C_{ar}) - q\,S_Y\right] / U & 0 & 0 & 0 & -2\,C_{af} & 2\,\partial_{FW} \\
0 & -2\,(K_f + K_r) & \begin{array}{l} 2(C_{ar}\,d_r - C_{af}\,d_f)/R \\ +\,U^2\,W_T / (R\,g) \\ -2(C_{af}+C_{ar})V/U \\ +2C_{af}\partial_{FW} \end{array} & \begin{array}{l} 2\,(d_f\,K_f \\ -\,d_r\,K_r) \\ +\,qs_L \end{array} & 0 & 0 \\
\begin{array}{l} 2[C_{ar}\,(z_r - h_r) \\ +\,C_{af}\,(z_f - h_r)]/U \\ -\,(h_A - h_r)s_Y/U \end{array} & 0 & \begin{array}{l} m_s g(h-hr)+m_{ur}g(z_r-h_r) \\ +m_{uf}g(z_f-h_r)-T_f{}^2K_f/2 \\ -T_R{}^2K_R/2-N_{sr}(z_r-h_r) \\ -N_{sf}(z_f-h_r) \end{array} & 0 & -2C_{af}(z_f-h_r) & 2\partial_{FW}(z_f-h_r) \\
\begin{array}{l} U[m_s(h_r-h) \\ +m_{uf}(h_r-z_f) \\ +m_{ur}(h_r-z_r)]/R \end{array} & 2(K_f d_f - K_r d_r) & \begin{array}{l} 2[C_{ar}d_r{}^2-C_{af}d_f{}^2]/R \\ -\,U^2[d_f m_{uf} + x_c m_s \\ -\,d_r m_{ur}]/R \\ +2(C_{af}d_f+C_{ar}d_r)V/U \\ -2C_{af}d_f\partial_{FW} \end{array} & \begin{array}{l} m_s g(h-h_r)+m_{ur}g(z_r-h_r) \\ +m_{uf}g(z_f-h_r)-2d_f{}^2K_f \\ -2d_r{}^2K_r-N_{sr}(z_r-h_r) \\ -N_{sf}(z_f-h_r) + x_A qs_L \end{array} & 0 & -2(z_f-h_r) \\
\begin{array}{l} 2(C_{af}d_f - C_{ar}d_r)/U \\ -x_A s_Y/U \end{array} & 2\partial_{FW} & 0 & 2\partial_{FW}(z_f-z_r) & -2C_{af}d_f & 2d_f\partial_{FW}
\end{bmatrix}
$$

$$
\mathbf{x} = [\ v,\ z,\ \theta,\ p,\ \partial_{FW},\ F_{xT}\ ]^T
$$

$$\mathbf{b} = \begin{bmatrix} qC_D - 2F_{xTr} + W_T C_r + W_T p_r \\ \\ 2C_{ar}d_r/R - W_T e + U^2 W_T/(Rg) - 2C_{af}d_f/R \\ \\ 2(C_{ar}d_r - C_{af}d_f)\,e/R + 2(d_f K_f - d_r K_r)\,p_r + q(C_{L0} - s_L p_r) - 2(C_{af} + C_{ar})e\mathbf{v}/U + 2C_{af}e\,\boldsymbol{\partial}_{\mathbf{FW}} \\ \\ 2C_{ar}d_r(z_r - h_r)/R + m_s U^2(h - h_r)/R - m_{uf}U^2(h_r - z_f)/R - m_{ur}U^2(h_r - z_r)/R \\ -T_F^2 K_f\, e/2 - T_R^2 K_r\, e/2 - N_{sr}(z_r - h_r)\,e - N_{sf}(z_f - h_r)\,e - 2C_{af}(z_f - h_r)d_f/R \\ \\ 2C_{ar}d_r^2 e/R + m_{uf}g d_f + m_s g x_c - m_{ur}g d_r - qC_D(h_A - h_r) - 2d_f^2 K_f p_r - d_f N_{sf} + d_r N_{sr} - x_A q(C_{L0} - s_L p_r) \\ -2d_r^2 K_r p_r + 2F_{xTr}(z_r - h_r) - N_{sr}(z_r - h_r)p_r - N_{sf}(z_f - h_r)p_r - 2C_{af}d_f^2 e/R \\ +2(C_{af}d_f + C_{ar}d_r)e\mathbf{v}/U - 2C_{af}d_f e\boldsymbol{\partial}_{\mathbf{FW}} \\ \\ -2C_{ar}d_r^2/R - d_f N_{sf} e + d_r N_{sr} e + U^2(d_f m_{uf} + x_c m_s - d_r m_{ur})/R - 2C_{af}d_f^2/R \end{bmatrix}$$

The boldface terms, $\mathbf{v}$ and $\boldsymbol{\partial}_{\mathbf{FW}}$, appearing in the **A** and **b** arrays represent the **x** components contributing to weak nonlinear terms.

Lateral Tire Forces

Front Tires: $F_{yf} = C_{af}\,(alf)$
$= C_{af}\,(v/U + d_f/R - \partial_{FW})$

Rear Tires: $F_{yr} = C_{ar}\,(alf)$
$= C_{ar}\,(v/U - d_r/R)$

Front Suspension Forces

Left Side: $F_{sfL} = [-T_F(\phi - e)/2 - d_f(p - p_r) + z]\,K_f$

Right Side: $F_{sfR} = [T_F(\phi - e)/2 - d_f(p - p_r) + z]\,K_f$

Rear Suspension Forces

Left Side: $F_{srL} = [-T_R(\phi - e)/2 + d_r(p - p_r) + z]\,K_r$

Right Side: $F_{srR} = [T_R(\phi - e)/2 + d_r(p - p_r) + z]\,K_r$

Front Vertical Tire Forces

Left Side: $F_{zfL} = N_{sf}/2 + (F_{sfL} + F_{sfR})/2 - T_F(F_{sfR} - F_{sfL})/(2TT_f)$
$+ F_{yf}\,z_f / TT_f$

Right Side: $F_{zfR} = N_{sf}/2 + (F_{sfL} + F_{sfR})/2 + T_F(F_{sfR} - F_{sfL})/(2TT_f)$
$- F_{yf}\,z_f / TT_f$

Rear Vertical Tire Forces

Left Side: $F_{zrL} = N_{sr}/2 + (F_{srL} + F_{srR})/2 - T_R(F_{srR} - F_{srL})/(2TT_r)$
$+ F_{yr}z_r / TT_r$

Right Side: $F_{zrR} = N_{sr}/2 + (F_{srL} + F_{srR})/2 + T_R(F_{srR} - F_{srL})/(2TT_r)$
$- F_{yr}\,z_r / TT_r$

Friction Factors

Front Left Side: $ff_1 = F_{yfL} / F_{zfL}$

Front Right Side: $ff_2 = F_{yfR} / F_{zfR}$

Rear Left Side: $ff_3 = F_{yrL} / F_{zrL}$

Rear Right Side: $ff_4 = F_{yrR} / F_{zrR}$

Appendix B

STEADY TURNING MODEL EQUATIONS: TRACTOR-SEMITRAILER

The equations presented in this appendix represent the steady turning motion of a multiple axle tractor-semitrailer moving along a circular path while resting upon a road surface which contains both superelevation and grade. In this model, the semitrailer and rear end of the tractor are treated as a single unit (full-trailer) with articulation acting as the "steer" angle for the full-trailer. Following solution of the full-trailer steady turning equations, the front wheel steer angle of the tractor is solved with the requirement that the tractor front axle tire forces support and counterbalance its share of the centripetal force deriving from the tractor sprung and unsprung masses during steady turning motion. The vehicle model is described by four degrees of freedom for the sprung mass element (semitrailer body): roll, pitch, yaw, and bounce. Tractor and semitrailer unsprung mass elements (suspension masses) are also represented but are located at a fixed height above the road plane (no vertical tire compliance). Solution of the model equations produces the steady state values for semitrailer sideslip velocity, roll angle, pitch angle, vertical bounce, articulation angle, and tractor tire drive thrust required for traversing a curve of specified geometry at a given speed. The six equations describing the model are three force equilibrium equations and three moment equilibrium equations applied to the vehicle with respect to a body axis system whose origin is located along the trailer centerline at a distance d_f aft of the tractor rear suspension centerline. All rotations and displacements of the trailer sprung mass are with respect to a static reference condition defined by the vehicle at rest on a horizontal plane which is normal to the gravity vector. Normal SAE sign conventions apply [7].

The tractor front axle lateral tire forces, steer angle, and sideslip angle are obtained from the required yaw moment equilibrium condition about the kingpin, the calculated articulation angle, and the specified turning conditions. The tractor sprung mass is assumed constrained to the semitrailer for roll motions. The tractor pitch angle is calculated as equal to the semitrailer pitch angle, modified by pitch moment effects deriving from centripetal forces during

turning. The tractor sprung mass vertical position is the vertical displacement of the tractor spung mass c.g. relative to the kinpin and due only to tractor pitch angle.

The next section contains a list of definitions for symbols appearing in the equations which are then presented in the final section. The equations are in the form **A x = b**, where **A** is a 6 by 6 matrix, and **b** is a 6 by 1 vector. Each of these two arrays contains various vehicle and highway geometric parameters. The 6 by 1 solution vector, **x**, is obtained by computing the matrix inverse of **A** and multiplying it by the **b** vector:

$$\mathbf{x} = \mathbf{A}^{-1}\,\mathbf{b}$$

A two- or three-stage iterative solution is required since a few terms in the **A** and **b** arrays contain components of **x** as weak non-constant influences. The six elements of **x** are the solution quantities noted above and are also defined in the following nomenclature listing. The first three model equations represent force equilibrium conditions acting in the longitudinal, lateral, and vertical directions of the trailer. The last three model equations represent moment equilibrium conditions about the roll, pitch, and yaw axes of the trailer.

Lastly, equations defining the lateral and vertical tire forces, suspension forces, and friction factors at each wheel location are included. Expressions for calculuating the tractor steer angle, sideslip, pich angle, and vertical bounce are also shown.

Nomenclature

b_T distance from tractor sprung mass c.g. to rear suspension centerline (set at $0.8\,L_T$)

C_{a1} tractor front tire cornering stiffness (<0)

C_{aj} tractor rear tire cornering stiffness (<0)

C_{ak} semitrailer rear " (<0)

CD aerodynamic drag coefficient

CLO aerodynamic lift coefficient at trim pitch angle (p = pr)

C_r rolling resistance percentage / 100

d_f distance from semitrailer kinpin to semitrailer body-axis origin (arbitary)

d_r " " " rear suspension centerline to " " $(L - d_f)$

d_j distance from tractor rear axle j to semitrailer body-axis origin

d_r " semitrailer rear axle k to " " "

e highway superelevation

F_{pz} static semitrailer kingpin load applied to tractor

F_{XTf} tractor rear tire traction force, **x(6)**

F_{XTr} tire traction force

g acceleration of gravity

h height above ground of semitrailer sprung mass c.g.

h_A height above ground of the aerodynamic center of pressure

h_r arbitrary height above ground of reference axis system origin

i subsript denoting all of the rear tractor and semitrailer axles

j subscript denotes one of possibly several tractor rear axles

k " " " " semitrailer rear axles

K_1 spring rate of tractor front suspension (one side)

K_j tractor rear suspension stiffnes "

K_k semitrailer rear "

L_T tractor wheelbase

L semitrailer wheelbase

m_1 mass of tractor front unsprung mass

m_2 total mass of tractor rear suspension (rear unsprung masses)

m_j tractor rear unsprung mass

m_k semitrailer rear " "

m_s mass of sprung weight (semitrailer body + payload)

N_{sj} tractor rear static load of axle j

N_{sk} semitrailer " axle k

N_1 static load on tractor front axle

N_2 total static load on tractor rear axles

n_d number of tractor rear drive axles

n_s number of tractor rear axles

p semitrailer sprung mass pitch angle relative to the horizontal plane normal to the gravity vector, **x(4)**

p_r highway grade

p_T tractor pitch angle

q aerodynamic force = [(density of air)(reference area) U2 / 2]

R highway curve radius

s_L slope of aerodynamic lift coefficient with respect to pitch

s_Y slope of aerodynamic side force with respect to sideslip angle

T_j tractor rear suspension spread

T_k semitrailer rear "

TT_j tractor rear tire track

TT_k semitrailer rear "

U vehicle speed

v semitrailer sideslip velocity at the body-axis origin, **x(1)**

W_T total combination vehicle weight

W_1 weight of tractor sprung mass

x_A distance of aerodynamic center of pressure ahead of body-axis origin

x_c distance of semitrailer sprung mass center ahead of body-axis origin

z semitrailer sprung mass displacement normal to the road surface (relative to the static reference condition), **x(2)**

z_1 vertical displacement of tractor sprung mass c.g. (positive downward)

z_j height above ground of tractor rear suspension roll center

z_k height above ground of semitrailer suspension roll center

β sideslip angle of tractor at sprung mass c.g. location

δ_{FW} tractor front steer angle

Δ kingpin offset ahead of tractor rear axle centerline

f_5 variation in kingpin vertical load due to steady turning (positive downward)

ϕ semitrailer sprung mass roll angle relative to the horizontal plane normal to the gravity vector, **x(3)**

Π articulation angle between tractor and semitrailer, **x(5)**

Tractor-semitrailer Model Equations: $\mathbf{A}\,\mathbf{x} = \mathbf{b}$

$$
\mathbf{A} = \begin{bmatrix}
U W_T / (R\,g) & 0 & 0 & 0 & 0 & 2n_d \\
2\Sigma C_{ai}/U - q S_Y / U & 0 & 0 & 0 & -2\Sigma C_{ai}^{ns} & 2\Pi \\
0 & -2\Sigma K_i & 2\Sigma C_{ai} d_i/R + U^2 W_T / (R & 2\Sigma K_i d_i + q s_L & 0 & 0 \\
 & & -2\Sigma C_{ai} v/U & & & \\
 & & +2\Sigma C_{a2i} \Pi & & & \\
2\Sigma C_{ai} (z_i - h_r)/U - (h_A - h_r)s_Y/U & 0 & m_s g(h-h_r) + \Sigma m_i g(z_i - h_r) - \Sigma N_{si} (z_i - h_r) - \Sigma T_i^2 K_i /2 & 0 & -2\Sigma C_{ai}^{ns} (z_i - h_r) & 2\Pi\Sigma(z_i - h_r) \\
U[m_s (h_r - h) + \Sigma m_i (h_r - z_i)]/R & 2\Sigma K_i d_i & -2\Sigma C_{ai} d_i^2 \operatorname{sgn}(d_i)/R - U^2 \Sigma m_i d_i / R - U^2 m_s x_c / R + 2\Sigma C_{ai} |d_i| v/U - 2C_{a2} d_2 \Pi & m_s g (h-h_r) + \Sigma m_i g (z_i - h_r) - 2\Sigma K_i d_i^2 - \Sigma N_i (z_i - h_r) + x_A q s_L & 0 & -2\Sigma (z_i - h_r)^{nd} \\
2\Sigma C_{ai} d_i/U - x_A s_Y/U & 2\Pi & 0 & 2\Pi\Sigma(z_i - h_r) & -2\Sigma C_{ai} d_i^{ns} & 2 d_f \Pi
\end{bmatrix}
$$

$$
\mathbf{x} = [\, v,\ z,\ \theta,\ p,\ \Pi,\ F_{xT} \,]^T
$$

$$\mathbf{b} = \begin{bmatrix} qC_D - 2\sum_{nt} F_{xTr} + W_T C_r + W_T p_r \\ \\ -2\Sigma C_{ai} d_i/R - W_T e + U^2 W_T/(Rg) \\ \\ -2\Sigma C_{ai} d_i e/R + 2\Sigma K_i d_i p_r + q(C_{L0} - s_L p_r) - 2\Sigma C_{ai} e \mathbf{v}/U + 2\sum_{ns} C_{ai} e \boldsymbol{\Pi} \\ \\ -2\Sigma C_{ai} d_i (z_i - h_r)/R + m_s U^2 (h - h_r)/R - \Sigma m_{ui} U^2 (h_r - z_i)/R - e\Sigma T_i^2 K_i/2 - \Sigma N_{si}(z_i - h_r) e \\ \\ 2\Sigma C_{ai} d_i^2 (\text{sgn } d_i) e/R + m_s g x_c + \Sigma m_{ui} g d_i - qC_D(h_A - h_r) - 2\Sigma d_i^2 K_i p_r - \Sigma N_{si} d_i - x_A q(C_{L0} - s_L p_r) \\ + 2\Sigma F_{xTr}(z_i - h_r) - \Sigma N_{si}(z_i - h_r) p_r + 2\Sigma C_{ai} |d_i| e \mathbf{v}/U - 2\sum_{ns} C_{ai} d_i e \boldsymbol{\Pi} \\ \\ -2\Sigma C_{ai} d_i^2/R - e\Sigma d_i N_{si} + U^2 \Sigma d_i m_{ui}/R + U^2 x_c m_s/R \end{bmatrix}$$

The boldface terms, $\mathbf{v}$ and $\boldsymbol{\Pi}$, appearing in the **A** and **b** arrays represent the **x** components contributing to weak nonlinear terms.

Tractor Response Variables

Tractor Front Axle Steer Angle:

$$\partial_{FW} = v/U - \Pi + (d_f + L_T)/R + [(U^2/R - e)(F_{pz}\,\Delta/g + W_1 b_T/g + m_1 L_T) / (2 L_T C_{a1})]$$

Tractor Sideslip Angle:

$$\beta = v/U + (d_f - \Delta + b_T)/R - \Pi$$

Tractor Pitch Angle:

$$p_T = p - \Delta\, f_5 / (2 K_1 L_T^2)$$

Tractor Bounce (vertical displacement):

$$z = - p_T b_T$$

where,

$$\Delta = (N_1 - m_1 g - b_T)\, L_T / F_{pz}$$

$$F_{pz} = N_1 + N_2 - W_1 - m_1 g - m_2 g$$

$$b_T = 0.80\, L_T$$

Lateral Tire Forces

Tractor Front Tire: $F_{y1} = C_{a1}\,(alf)$
$= C_{a1}\,[(v/U + d_f/R - \Pi) + (L_T - \Delta)/R - \partial_{FW}]$

Tractor Rear Tires: $F_{yj} = C_{aj}\,(alf)$
$= C_{aj}\,(v/U + d_j/R - \Pi)$; j denotes tractor rear axle

Rear Tires: $F_{yk} = C_{ak}\,(alf)$
$= C_{ak}\,(v/U - d_k/R)$; k denotes semitrailer rear axle

Tractor Front Suspension Forces

Left Side: $F_{sL1} = [-T_1(\phi - e)/2 - (L_T - \Delta)(p - p_r)]\, K_1$

Right Side: $F_{sL2} = [T_1(\phi - e)/2 - (L_T - \Delta)(p - p_r)]\, K_1$

Tractor Rear Suspension Forces

Left Side: $F_{sLj} = [-T_j(\varnothing - e)/2 - d_j(p - p_r) + z]\, K_j$

; j denotes tractor rear axle

Right Side: $F_{sRj} = [T_j(\varnothing - e)/2 - d_j(p - p_r) + z]\, K_j$

Semitrailer Rear Suspension Forces

Left Side: $F_{sLk} = [-T_k(\varnothing - e)/2 + d_k(p - p_r) + z]\, K_k$

; k denotes semitrailer rear axle

Right Side: $F_{sRk} = [T_k(\varnothing - e)/2 + d_k(p - p_r) + z]\, K_k$

Tractor Front Vertical Tire Forces

Left Side: $F_{zL1} = N_{s1} / 2 + (F_{sL1} + F_{sR1})/2 - T_1(F_{sR1} - F_{sL1})/(2TT_1) + F_{y1}\, z_1 / TT_1$

Right Side: $F_{zR1} = N_{s1} / 2 + (F_{sL1} + F_{sR1})/2 + T_1(F_{sR1} - F_{sL1})/(2TT_1) - F_{y1}\, z_1 / TT_1$

Tractor Rear Vertical Tire Forces

Left Side: $F_{zLj} = N_{sj} / 2 + (F_{sLj} + F_{sRj})/2 - T_j(F_{sRj} - F_{sLj})/(2TT_j) + F_{yj}\, z_j / TT_j$

Right Side: $F_{zRj} = N_{sj} / 2 + (F_{sLj} + F_{sRj})/2 + T_j(F_{sRj} - F_{sLj})/(2TT_j) - F_{yj}\, z_j / TT_j$

Semitrailer Rear Vertical Tire Forces

Left Side: $F_{zLk} = N_{sk} / 2 + (F_{sLk} + F_{sRk})/2 - T_k(F_{sRk} - F_{sLk})/(2TT_k) + F_{yk} z_k / TT_k$

Right Side: $F_{zRk} = N_{sk} / 2 + (F_{sLk} + F_{sRk})/2 + T_k(F_{sRk} - F_{sLk})/(2TT_k) - F_{yk}\, z_k / TT_k$

FRICTION FACTORS:

Tractor Front Left Side: $ff_{L,1} = F_{yL1} / F_{zL1}$

Tractor Front Right Side: $ff_{R,1} = F_{yR1} / F_{zR1}$

Tractor Rear Left Side: $ff_{L,j} = F_{yLj} / F_{zLj}$; j denotes rear tractor axle

Tractor Rear Right Side: $ff_{R,j} = F_{yRj} / F_{zRj}$

Semitrailer Rear Left Side: $ff_{L,k} = F_{yLk} / F_{zLk}$; k denotes rear semitrailer axle

Semitrailer Rear Right Side: $ff_{R,k} = F_{yRk} / F_{zRk}$

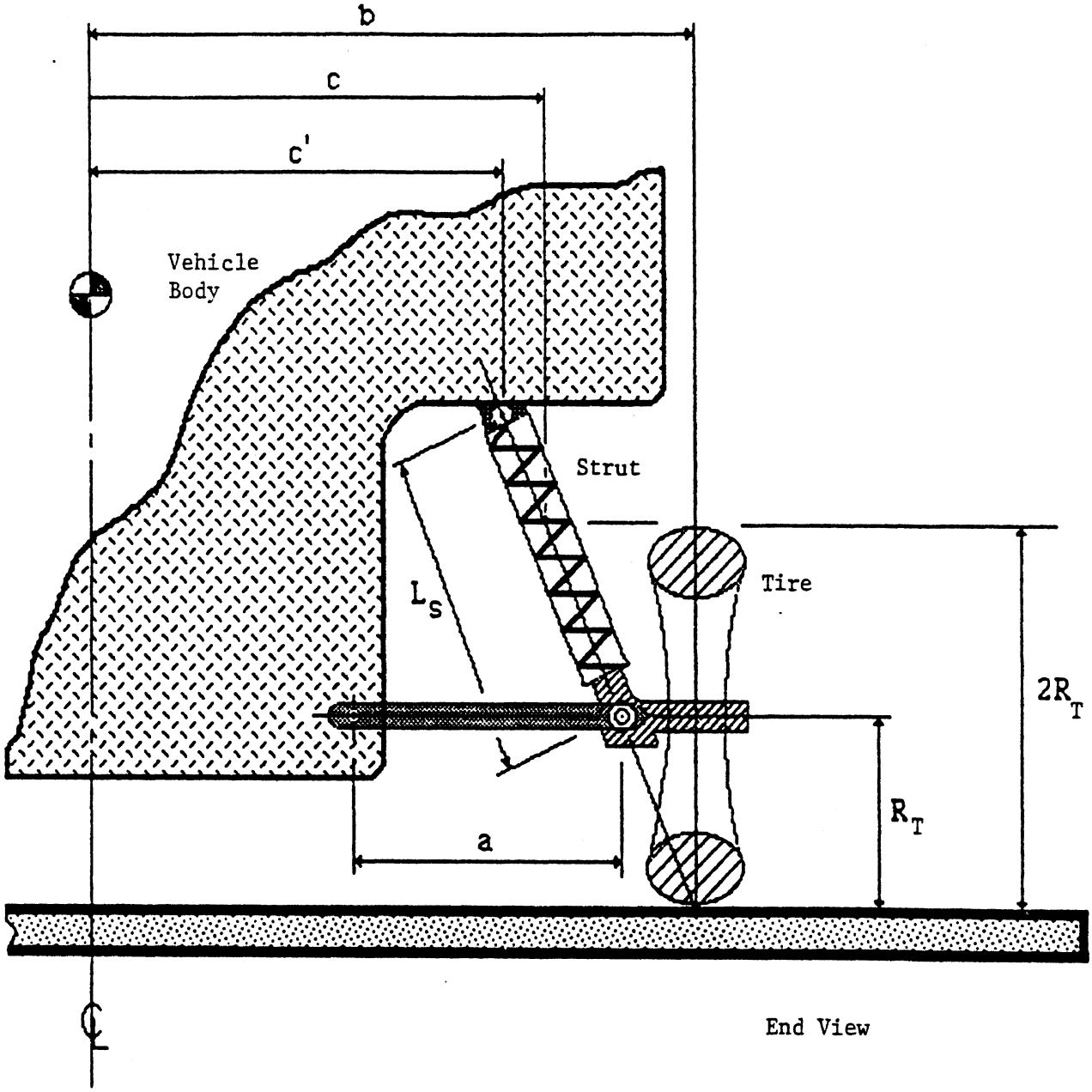
Appendix C

INDEPENDENT SUSPENSION ADDITION TO THE PHASE 4 MODEL

An independent wheel suspension was added to the Phase 4 computer model [5] to permit improved simulation of typical passenger car suspension behavior. Section 3.4 (volume II) of this report provides a general description of the modifications to the Phase 4 computer model performed during the project. The material in this appendix supplements that description with more detailed information.

Reference to figure C-1 (or figure 12) shows the basic kinematic layout of the independent suspension which is seen to be very similar to a McPherson strut assembly. The strut, of nominal length L_S, is allowed to vary in length and pivot about its end points. The strut contains a spring and damper having force characteristics which vary linearly with strut displacement and velocity. The lateral link of length "a" locates the lower endpoint of the strut. On an actual vehicle the upper endpoint, at lateral displacement " c' " from the vehicle centerline, is not readily known. Accordingly, input to the model for defining the angular orientation of the strut assembly is provided by specifying the lateral displacement of the strut, "c", coincident with the top of the tire. The static tire radius, R_T, is normally entered as one of the "Tires and Wheels" data in the Phase 4 model.

Knowledge of the tire half track dimension, "b", in addition to "c" and R_T, permits the model to calculate the linkage motions shown in figure C-1. The tire track parameter = 2 "b", is normally entered in the Phase 4 model under the category of "Suspension and Axle Parameters." The parameter "c" is selected by the current model version to cause the strut centerline to intersect the center of the tire contcat patch at the road surface. However, the wheel axle assembly is assumed to always remain parallel to the road surface. That is, as vehicle roll/ bounce motions and tire bounce motions occur, the axle (tire) will not roll (camber) according to the kinematics depicted in figure C-1. To accomodate tire cambering and steering in response to suspension motion (deriving from vehicle bounce and roll motions), two parameters are entered by the model user to specify these



Input Parameters:

- b tire track dimension
- c spacing of upper strut pivot
- R_T static tire radius

steer-bounce coefficient
camber-bounce coefficient

Figure C-1. Independent suspension model (Phase 4).

relationships. The first such parameter is the camber-bounce coefficient which causes the tire to camber an amount proportional to the relative bounce motion of the suspension. The second parameter is the steer-bounce coefficient which causes the tire to steer in direct proportion to the bounce motion of the suspension. In this implementation, the tire camber relationship to suspension motion is not limited to just that seen in figure C-1. Instead, different camber-bounce and steer-bounce relationships, as obtained, for example, from laboratory suspension measurements, may be represented as well. However, the key element to remember is that all tire camber motion is provided by the first of these parameters. No tire camber motion occurs, although it is suggested, by the kinematics depicted in figure C-1.

To use the independent suspension option in the Phase 4 model, the following instructions should be followed during preparation of a Phase 4 data set:

- Under the category of "Suspension and Axle Parameters," when entering the spring rate for a particular wheel location, follow the right-side spring rate entry with any positive number in F10.3 format. This will key the program to interpret subsequent numerical input for *that wheel location* as parametric data for the independent suspension. This should be performed at each wheel location requiring an independent suspension.

- Three lines later, where the "Axle Roll Moment of Inertia" is usually entered, instead enter the independent suspension camber/bounce coefficient value in units of degrees/inch.

- Two lines after this, where the "Roll Steer Coefficient" is usually entered, instead enter the independent suspension steer/bounce coefficient value in units of degrees/inch.

At the start of execution of the Phase 4 program an "echo" of vehicle parameters occurs and any independent suspension parameters entered as described above will be accurately identified at this point (figure C-2). If

Dodge Aries; 1273 ft radius (Curve#1); Steady Turning; 57 mph, low mu.

TRUCK PARAMETERS

WHEELBASE - DISTANCE FROM FRONT AXLE TO CENTER OF REAR SUSPENSION (IN)	100.30
BASE VEHICLE CURB WEIGHT ON FRONT SUSPENSION (LB)	1800.00
BASE VEHICLE CURB WEIGHT ON REAR SUSPENSION (LB)	1400.00
SPRUNG MASS CG HEIGHT (IN. ABOVE GROUND)	25.00
SPRUNG MASS ROLL MOMENT OF INERTIA (IN-LB-SEC**2)	1000.00
SPRUNG MASS PITCH MOMENT OF INERTIA (IN-LB-SEC**2)	9000.00
SPRUNG MASS YAW MOMENT OF INERTIA (IN-LB-SEC**2)	9000.00
PAYLOAD WEIGHT (LB)	0.0

*** ZERO ENTRY INDICATES NO PAYLOAD ***
*** FIVE PAYLOAD DESCRIPTION PARAMETERS ARE NOT ENTERED ***

TRUCK FRONT SUSPENSION AND AXLE PARAMETERS

	LEFT SIDE	RIGHT SIDE
SUSPENSION SPRING RATE (LB/IN/SIDE/AXLE)	220.00	220.00
SUSPENSION VISCOUS DAMPING (LB-SEC/IN/SIDE/AXLE)	10.00	10.00
COULOMB FRICTION (LB/SIDE/AXLE)	0.0	0.0
INDEPENDENT SUSPENSION CAMBER/BOUNCE COEFFICIENT (DEG/INCH)	0.0	
ROLL CENTER HEIGHT (IN. ABOVE GROUND)	1.00	
INDEPENDENT SUSPENSION STEER/BOUNCE COEFFICIENT (DEG/INCH)	0.0	
AUXILIARY ROLL STIFFNESS (IN-LB/DEG/AXLE)	0.0	
LATERAL DISTANCE BETWEEN SUSPENSION SPRINGS (IN)	57.00	
TRACK WIDTH (IN)	57.00	
UNSPRUNG WEIGHT (LB)	100.00	
STEERING GEAR RATIO (DEG STEERING WHEEL/DEG ROAD WHEEL)	0.0	

*** NEGATIVE OR ZERO ENTRY INDICATES NO STEERING SYSTEM ***
*** STEERING SYSTEM PARAMETERS NOT TO BE ENTERED ***

TRUCK FRONT TIRES AND WHEELS

	LEFT SIDE	RIGHT SIDE
CORNERING STIFFNESS (LB/DEG/TIRE)	-1.00	-1.00
LONGITUDINAL STIFFNESS (LB/SLIP/TIRE)	5000.00	5000.00
CAMBER STIFFNESS (LB/DEG/TIRE)	0.0	0.0
ALIGNING MOMENT (IN-LB/DEG/TIRE)	0.0	0.0
TIRE SPRING RATE (LB/IN/TIRE)	1000.00	1000.00
TIRE LOADED RADIUS (IN)	12.00	12.00
POLAR MOMENT OF INERTIA (IN-LB-SEC**2/WHEEL)	20.00	20.00

*** NEGATIVE ENTRY INDICATES TABLE ENTERED ***
*** ECHO WILL APPEAR ON TABLE INDEX PAGE ***

Figure C-2. Independent suspension output "echo"; Phase 4 model.

they are not, then a check of the data set should be performed to see that the independent suspension key following the spring rates was entered properly (item 1 above). If this fails, then a check to see that the most recent version of the Phase 4 model, containing the independent suspension model developed under this project, is being used.

Appendix D

STEADY TURNING MODEL PREDICTIONS

The steady turning model printouts seen in this appendix correspond in order and vehicle type to the steady turning test results seen in appendix E and the corresponding model/measurement comparisons seen in chapter 5 (volume II). The steady turning model predictions seen in chapter 5 (volume II) are taken directly from the printouts shown in this appendix. The first set of microcomputer model predictions are for the tractor-semitrailer vehicle (test vehicle C); the second set of model predictions are for the front wheel drive passeneger car (test vehicle A); and the final set of predictions correspond to the rear wheel drive passenger car (test vehicle B). For example, the first two pages of the tractor-semitrailer predictions represent a single microcomputer run and show input values for path radius, vehicle speed, and superelevation rate of 1273 ft (388 m), 47.6 mph (76.6 km/h), and 6.7 percent. These conditions correspond to the test data for the tractor-semitrailer at curve site 1 and repeat 1. The model output results follow beginning with values of vehicle response variables such as tractor sideslip (0.06 degrees), tractor vertical bounce (0), and tractor roll angle (3.23 degrees). Each microcomputer result concludes with a plan view of the vehicle showing the friction factor values for each wheel location and the c.g. (point-mass) location. All model predictions shown here are for right hand turns. (Most of the test results are for left hand turns and therefore require a sign change for certain variables when model/test result comparisons are performed, as in chapter 5.)

A User's Guide for operating the microcomputer models appears at the end of this appendix.

Vehicle C

5-Axle Tractor-Semitrailer

```
      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 47.6
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


TRACTOR SIDESLIP ANGLE (DEG):      .06

TRACTOR VERTICAL BOUNCE (IN):      0
```

TRACTOR ROLL ANGLE (DEG): 3.23

TRACTOR PITCH ANGLE (DEG): -.01

TRACTOR STEER ANGLE (DEG): .57

TRACTOR TOTAL DRIVE THRUST (LB): 298.4

SEMITRAILER SIDESLIP ANGLE (DEG): .42

SEMITRAILER VERTICAL BOUNCE (IN): .01

SEMITRAILER ROLL ANGLE (DEG): 3.23

SEMITRAILER PITCH ANGLE (DEG): -.01

ARTICULATION ANGLE (DEG): 1.57

HORIZ LATERAL ACCEL (G'S): .118

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.049	.054	1
.035	.041	2
.062	.075	3
.031	.037	4
.059	.072	5

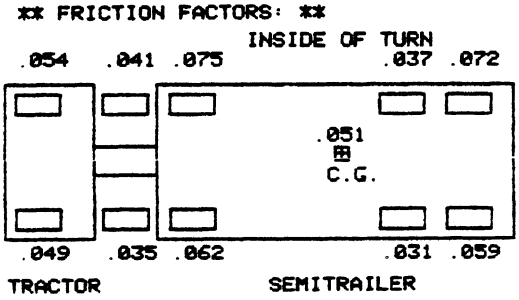
POINT MASS VALUE = .051

VERTICAL TIRE LOADS (LB):

5427.9	4885.1	1
8543.3	7270.1	2
8638.5	7174.6	3
9247.5	7774.2	4
9351.8	7669.6	5

LATERAL TIRE FORCES (LB):

267.2	267.2	1
300.6	300.6	2
540.6	540.6	3
292.1	292.1	4
555	555	5



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      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 45.5
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


**** OUTPUT ****


TRACTOR SIDESLIP ANGLE (DEG):      .12

TRACTOR VERTICAL BOUNCE (IN):      0
```

TRACTOR ROLL ANGLE (DEG): 3.34

TRACTOR PITCH ANGLE (DEG): -.01

TRACTOR STEER ANGLE (DEG): .56

TRACTOR TOTAL DRIVE THRUST (LB): 297

SEMITRAILER SIDESLIP ANGLE (DEG): .48

SEMITRAILER VERTICAL BOUNCE (IN): 0

SEMITRAILER ROLL ANGLE (DEG): 3.34

SEMITRAILER PITCH ANGLE (DEG): 0

ARTICULATION ANGLE (DEG): 1.57

HORIZ LATERAL ACCEL (G'S): .108

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.039	.043	1
.026	.029	2
.054	.063	3
.022	.025	4
.05	.059	5

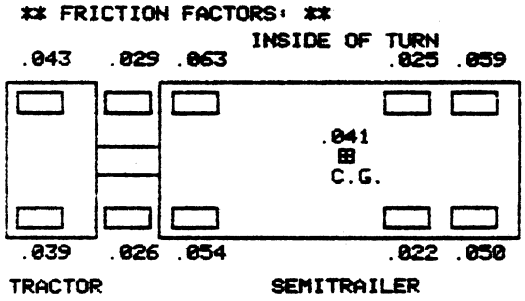
POINT MASS VALUE = .041

VERTICAL TIRE LOADS (LB):

5374.9	4936.4	1
8411.9	7387.6	2
8507.7	7292.8	3
9099.1	7916.5	4
9204	7812.5	5

LATERAL TIRE FORCES (LB):

214.4	214.4	1
220	220	2
460.1	460.1	3
205.4	205.4	4
468.3	468.3	5



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      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 46.2
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


TRACTOR SIDESLIP ANGLE (DEG):      .1

TRACTOR VERTICAL BOUNCE (IN):      0
```

TRACTOR ROLL ANGLE (DEG): 3.31

TRACTOR PITCH ANGLE (DEG): -.01

TRACTOR STEER ANGLE (DEG): .56

TRACTOR TOTAL DRIVE THRUST (LB): 297.4

SEMITRAILER SIDESLIP ANGLE (DEG): .46

SEMITRAILER VERTICAL BOUNCE (IN): 0

SEMITRAILER ROLL ANGLE (DEG): 3.31

SEMITRAILER PITCH ANGLE (DEG): 0

ARTICULATION ANGLE (DEG): 1.57

HORIZ LATERAL ACCEL (G'S): .112

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.042	.047	1
.029	.033	2
.056	.067	3
.025	.029	4
.053	.063	5

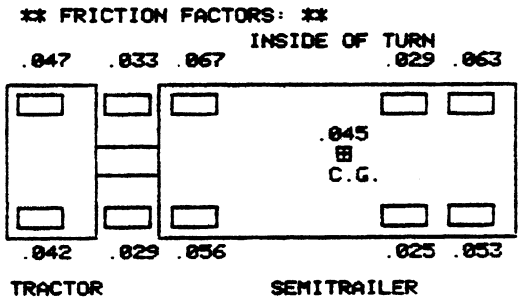
POINT MASS VALUE = .045

VERTICAL TIRE LOADS (LB):

5392.3	4919.5	1
8455.1	7349	2
8550.7	7253.9	3
9147.8	7869.8	4
9252.5	7765.6	5

LATERAL TIRE FORCES (LB):

231.8	231.8	1
246.5	246.5	2
486.5	486.5	3
233.8	233.8	4
496.7	496.7	5



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      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 52.5
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


TRACTOR SIDESLIP ANGLE (DEG):      -.08

TRACTOR VERTICAL BOUNCE (IN):      0
```

TRACTOR ROLL ANGLE (DEG): 3.17

TRACTOR PITCH ANGLE (DEG): -.01

TRACTOR STEER ANGLE (DEG): .61

TRACTOR TOTAL DRIVE THRUST (LB): 303.2

SEMITRAILER SIDESLIP ANGLE (DEG): .29

SEMITRAILER VERTICAL BOUNCE (IN): .01

SEMITRAILER ROLL ANGLE (DEG): 3.17

SEMITRAILER PITCH ANGLE (DEG): -.01

ARTICULATION ANGLE (DEG): 1.58

HORIZ LATERAL ACCEL (G'S): .144

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.069	.08	1
.054	.068	2
.08	.104	3
.05	.064	4
.077	.101	5

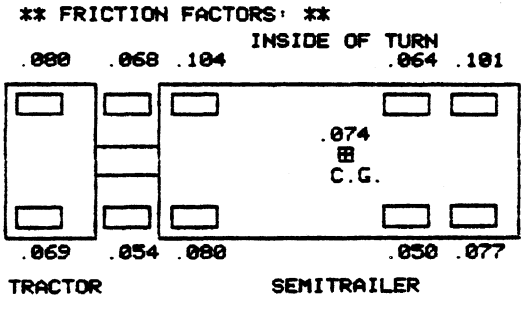
POINT MASS VALUE = .074

VERTICAL TIRE LOADS (LB):

5546.3	4771.5	1
8841	7011.9	2
8935	6915.2	3
9583.8	7461	4
9686.7	7355	5

LATERAL TIRE FORCES (LB):

384.4	384.4	1
479.2	479.2	2
719.2	719.2	3
484.2	484.2	4
747.1	747.1	5



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      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 57.5
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


TRACTOR SIDESLIP ANGLE (DEG):      -.28

TRACTOR VERTICAL BOUNCE (IN):      0
```

TRACTOR ROLL ANGLE (DEG): 2.67

TRACTOR PITCH ANGLE (DEG): -.01

TRACTOR STEER ANGLE (DEG): .67

TRACTOR TOTAL DRIVE THRUST (LB): 316.8

SEMITRAILER SIDESLIP ANGLE (DEG): .1

SEMITRAILER VERTICAL BOUNCE (IN): .01

SEMITRAILER ROLL ANGLE (DEG): 2.67

SEMITRAILER PITCH ANGLE (DEG): -.01

ARTICULATION ANGLE (DEG): 1.59

HORIZ LATERAL ACCEL (G'S): .173

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.096	.118	1
.078	.109	2
.103	.148	3
.075	.107	4
.1	.147	5

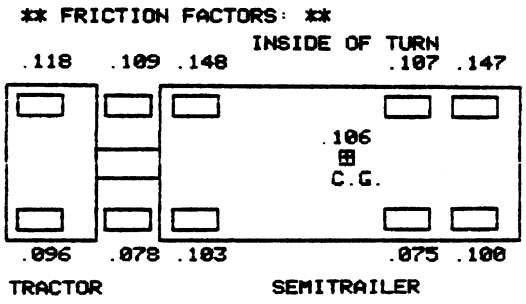
POINT MASS VALUE = .106

VERTICAL TIRE LOADS (LB):

5709.9	4611.9	1
9241.5	6644.1	2
9334	6545.9	3
10037.5	7017.4	4
10138.7	6909.7	5

LATERAL TIRE FORCES (LB):

548.5	548.5	1
729.3	729.3	2
969.4	969.4	3
753.5	753.5	4
1016.3	1016.3	5



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      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 31.9
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


TRACTOR SIDESLIP ANGLE (DEG):      .7

TRACTOR VERTICAL BOUNCE (IN):      .03
```

TRACTOR ROLL ANGLE (DEG): 1.59

TRACTOR PITCH ANGLE (DEG): -.02

TRACTOR STEER ANGLE (DEG): 3.08

TRACTOR TOTAL BRAKING FORCE (LB): -114.8

SEMITRAILER SIDESLIP ANGLE (DEG): 2.69

SEMITRAILER VERTICAL BOUNCE (IN): .02

SEMITRAILER ROLL ANGLE (DEG): 1.59

SEMITRAILER PITCH ANGLE (DEG): -.02

ARTICULATION ANGLE (DEG): 8.71

HORIZ LATERAL ACCEL (G'S): .295

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.182	.287	1
.11	.208	2
.222	.49	3
.097	.202	4
.216	.535	5

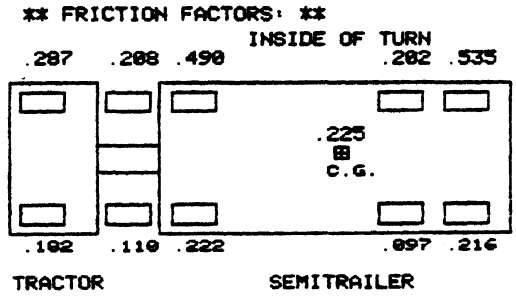
POINT MASS VALUE = .225

VERTICAL TIRE LOADS (LB):

6356.2	4047.1	1
10852.8	5736.4	2
11317.2	5145.1	3
11286.9	5416.1	4
11791.7	4765	5

LATERAL TIRE FORCES (LB):

1161.6	1161.6	1
1194.9	1194.9	2
2523.6	2523.6	3
1095.5	1095.5	4
2550.4	2550.4	5



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      FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON  SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 32.1
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


TRACTOR SIDESLIP ANGLE (DEG):      .68

TRACTOR VERTICAL BOUNCE (IN):      .03
```

TRACTOR ROLL ANGLE (DEG): 1.55

TRACTOR PITCH ANGLE (DEG): -.02

TRACTOR STEER ANGLE (DEG): 3.08

TRACTOR TOTAL BRAKING FORCE (LB): -116.6

SEMITRAILER SIDESLIP ANGLE (DEG): 2.67

SEMITRAILER VERTICAL BOUNCE (IN): .02

SEMITRAILER ROLL ANGLE (DEG): 1.55

SEMITRAILER PITCH ANGLE (DEG): -.02

ARTICULATION ANGLE (DEG): 8.71

HORIZ LATERAL ACCEL (G'S): .299

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.185	.293	1
.112	.214	2
.224	.5	3
.099	.21	4
.218	.548	5

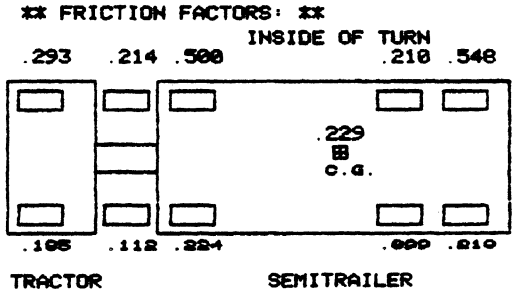
POINT MASS VALUE = .229

VERTICAL TIRE LOADS (LB):

6375.9	4029	1
10904.7	5698.1	2
11368.1	5105.8	3
11337.6	5361.5	4
11841.3	4709.3	5

LATERAL TIRE FORCES (LB):

1180.8	1180.8	1
1224.2	1224.2	2
2552.9	2552.9	3
1126.9	1126.9	4
2581.8	2581.8	5



Vehicle A

Front-Wheel-Drive Passenger Car

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56.7
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.16

VERTICAL BOUNCE (IN): .02

ROLL ANGLE (DEG): 3.12

PITCH ANGLE (DEG): 0

STEER ANGLE (DEG): .43

TOTAL DRIVE THRUST (LB): 34

HORIZ LATERAL ACCEL (G'S): .168

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.092	.11	1
.092	.109	2

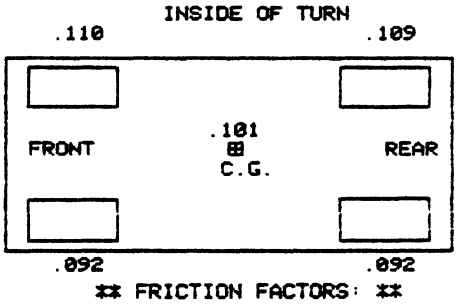
POINT MASS VALUE = .101

VERTICAL TIRE LOADS (LB):

985.4	825.1	1
769.4	650.1	2

LATERAL TIRE FORCES (LB):

91.4	91.4	1
71.1	71.1	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 57
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.17

VERTICAL BOUNCE (IN): .02

ROLL ANGLE (DEG): 3.1

PITCH ANGLE (DEG): 0

STEER ANGLE (DEG): .43

TOTAL DRIVE THRUST (LB): 34

HORIZ LATERAL ACCEL (G'S): .17

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.094	.112	1
.094	.111	2

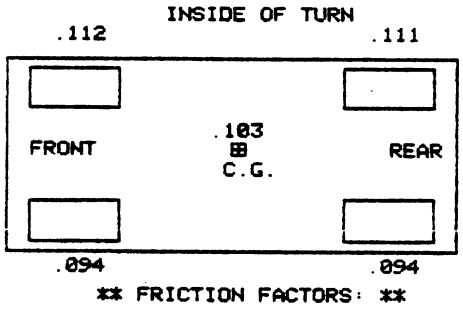
POINT MASS VALUE = .103

VERTICAL TIRE LOADS (LB):

986.9	823.8	1
770.5	649.2	2

LATERAL TIRE FORCES (LB):

93	93	1
72.4	72.4	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56.4
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.16

VERTICAL BOUNCE (IN): .02

ROLL ANGLE (DEG): 3.13

PITCH ANGLE (DEG): 0

STEER ANGLE (DEG): .43

TOTAL DRIVE THRUST (LB): 33.8

HORIZ LATERAL ACCEL (G'S): .166

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.091	.108	1
.091	.107	2

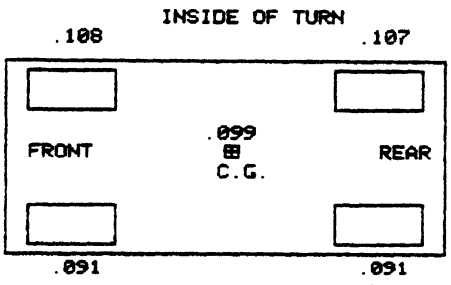
POINT MASS VALUE = .099

VERTICAL TIRE LOADS (LB):

983.9	826.4	1
768.2	651.1	2

LATERAL TIRE FORCES (LB):

89.8	89.8	1
69.9	69.9	2



** FRICTION FACTORS: **

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          FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

****  INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR  SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 57.8
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR  ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR  SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR  TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


SIDESLIP ANGLE (DEG):          -.18

VERTICAL BOUNCE (IN):          .03

ROLL ANGLE (DEG):              3.26

PITCH ANGLE (DEG):             0

STEER ANGLE (DEG):             .44

TOTAL DRIVE THRUST (LB):       34.2

HORIZ LATERAL ACCEL (G'S):     .175

FRICTION FACTORS:
LEFT            RIGHT          AXLE
.095            .115            1
.095            .113            2

POINT MASS VALUE = .105

VERTICAL TIRE LOADS (LB):

989             823             1
772             648.6           2
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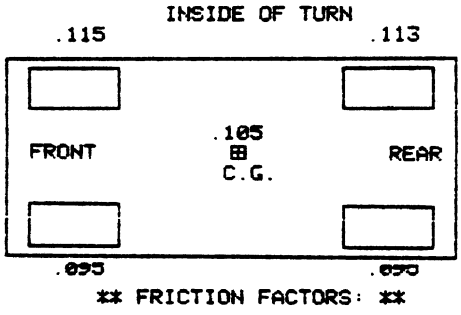
LATERAL TIRE FORCES (LB):

94.6	94.6	1
73.7	73.7	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 57.9
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.19

VERTICAL BOUNCE (IN): .03

ROLL ANGLE (DEG): 3.07

PITCH ANGLE (DEG): 0

STEER ANGLE (DEG): .44

TOTAL DRIVE THRUST (LB): 34.2

HORIZ LATERAL ACCEL (G'S): .175

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.098	.119	1
.098	.117	2

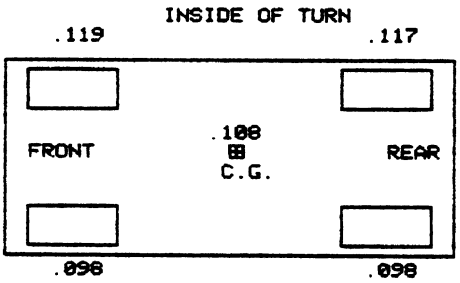
POINT MASS VALUE = .108

VERTICAL TIRE LOADS (LB):

991.5	819.8	1
773.9	646.2	2

LATERAL TIRE FORCES (LB):

97.9	97.9	1
76.2	76.2	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 28.8
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .55

VERTICAL BOUNCE (IN): .03

ROLL ANGLE (DEG): 2.8

PITCH ANGLE (DEG): -.03

STEER ANGLE (DEG): 2.18

TOTAL DRIVE THRUST (LB): 28.4

HORIZ LATERAL ACCEL (G'S): .24

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.146	.196	1
.148	.198	2

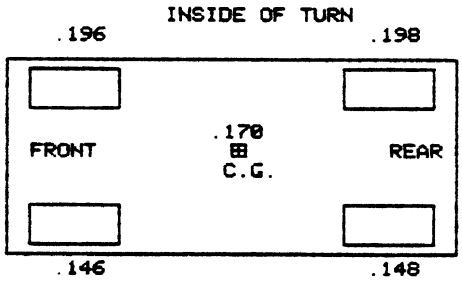
POINT MASS VALUE = .17

VERTICAL TIRE LOADS (LB):

1047.8	778.5	1
803.3	603	2

LATERAL TIRE FORCES (LB):

153.2	153.2	1
119.6	119.6	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 28.6
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .56

VERTICAL BOUNCE (IN): .03

ROLL ANGLE (DEG): 2.82

PITCH ANGLE (DEG): -.03

STEER ANGLE (DEG): 2.18

TOTAL DRIVE THRUST (LB): 28.4

HORIZ LATERAL ACCEL (G'S): .237

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.143	.192	1
.146	.193	2

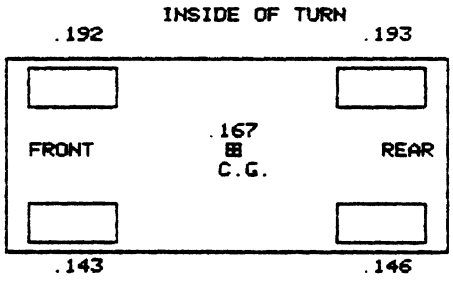
POINT MASS VALUE = .167

VERTICAL TIRE LOADS (LB):

1044.9	780.8	1
801.3	604.9	2

LATERAL TIRE FORCES (LB):

150.2	150.2	1
117.3	117.3	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 28.9
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .54

VERTICAL BOUNCE (IN): .03

ROLL ANGLE (DEG): 2.79

PITCH ANGLE (DEG): -.03

STEER ANGLE (DEG): 2.18

TOTAL DRIVE THRUST (LB): 28.6

HORIZ LATERAL ACCEL (G'S): .242

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.147	.199	1
.15	.2	2

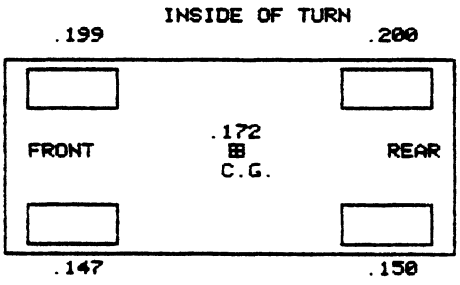
POINT MASS VALUE = .172

VERTICAL TIRE LOADS (LB):

1049.3	777.4	1
804.3	602	2

LATERAL TIRE FORCES (LB):

154.7	154.7	1
120.8	120.8	2



** FRICTION FACTORS: **

Vehicle B

Rear-Wheel-Drive Passenger Car

FHWA / UMTRI SINGLE-UNIT. STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 58.2
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.22

VERTICAL BOUNCE (IN): .04

ROLL ANGLE (DEG): 3.12

PITCH ANGLE (DEG): .02

STEER ANGLE (DEG): .48

TOTAL DRIVE THRUST (LB): 38.2

HORIZ LATERAL ACCEL (G'S): .177

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.1	.121	1
.099	.12	2

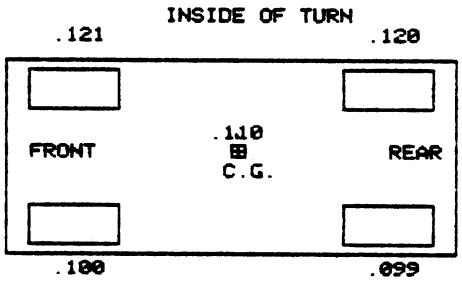
POINT MASS VALUE = .11

VERTICAL TIRE LOADS (LB):

1060.1	879.3	1
931.9	770.8	2

LATERAL TIRE FORCES (LB):

106.4	106.4	1
92.7	92.7	2

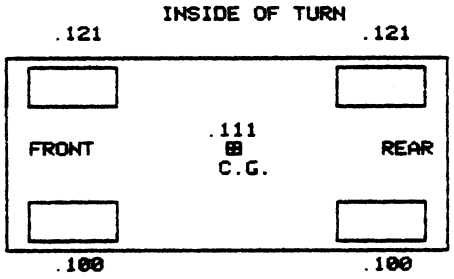


** FRICTION FACTORS: **

```
          FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

****  INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR  SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 58.3
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR  ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR  SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR  TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****


SIDESLIP ANGLE (DEG):          -.22

VERTICAL BOUNCE (IN):           .04

ROLL ANGLE (DEG):              3.12

PITCH ANGLE (DEG):              .02

STEER ANGLE (DEG):              .48

TOTAL DRIVE THRUST (LB):       38.2

HORIZ LATERAL ACCEL (G'S):     .178

FRICTION FACTORS:
LEFT            RIGHT          AXLE
.1              .121            1
.1              .121            2

POINT MASS VALUE = .111

VERTICAL TIRE LOADS (LB):

1060.6          878.9           1
932.4           770.4           2
```

LATERAL TIRE FORCES (LB):

107	107	1
93.2	93.2	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.17

VERTICAL BOUNCE (IN): .04

ROLL ANGLE (DEG): 3.21

PITCH ANGLE (DEG): .02

STEER ANGLE (DEG): .47

TOTAL DRIVE THRUST (LB): 37.6

HORIZ LATERAL ACCEL (G'S): .164

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.089	.105	1
.088	.104	2

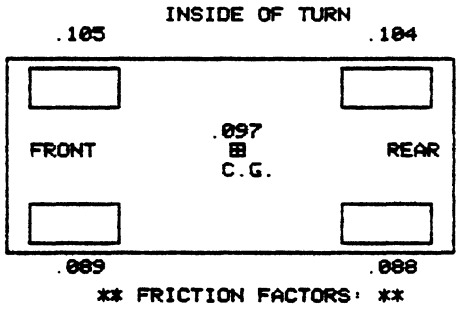
POINT MASS VALUE = .097

VERTICAL TIRE LOADS (LB):

1048.6	889.4	1
921.7	779.7	2

LATERAL TIRE FORCES (LB):

93.7	93.7	1
81.7	81.7	2

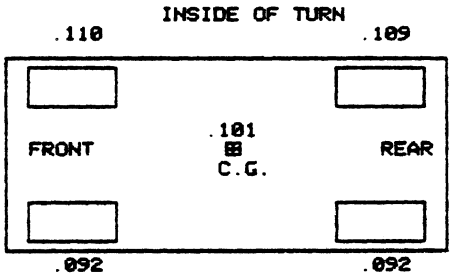


** FRICTION FACTORS: **

```
          FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

****  INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR  SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 57.2
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR  ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR  SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR  TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1


****  OUTPUT  ****

SIDESLIP ANGLE (DEG):          -.19

VERTICAL BOUNCE (IN):          .04

ROLL ANGLE (DEG):              3.35

PITCH ANGLE (DEG):             .02

STEER ANGLE (DEG):             .47

TOTAL DRIVE THRUST (LB):       37.8

HORIZ LATERAL ACCEL (G'S):     .171

FRICTION FACTORS:
LEFT            RIGHT         AXLE
.092            .11            1
.092            .109           2

POINT MASS VALUE = .101

VERTICAL TIRE LOADS (LB):

1052.9          886.9          1
925.5           777.5          2
```

LATERAL TIRE FORCES (LB):

97.7	97.7	1
85.1	85.1	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 55.9
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.17

VERTICAL BOUNCE (IN): .04

ROLL ANGLE (DEG): 3.21

PITCH ANGLE (DEG): .02

STEER ANGLE (DEG): .47

TOTAL DRIVE THRUST (LB): 37.6

HORIZ LATERAL ACCEL (G'S): .163

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.088	.104	1
.088	.104	2

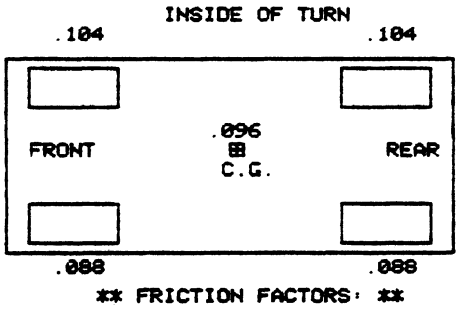
POINT MASS VALUE = .096

VERTICAL TIRE LOADS (LB):

1048.1	889.8	1
921.2	780.1	2

LATERAL TIRE FORCES (LB):

93.1	93.1	1
81.2	81.2	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 30.7
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .38

VERTICAL BOUNCE (IN): .08

ROLL ANGLE (DEG): 2.7

PITCH ANGLE (DEG): -.01

STEER ANGLE (DEG): 2.34

TOTAL DRIVE THRUST (LB): 28.6

HORIZ LATERAL ACCEL (G'S): .273

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.17	.239	1
.17	.241	2

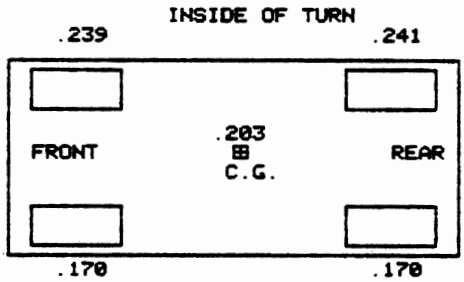
POINT MASS VALUE = .203

VERTICAL TIRE LOADS (LB):

1149.6	817.1	1
1002.2	705.7	2

LATERAL TIRE FORCES (LB):

195.5	195.5	1
170.6	170.6	2



** FRICTION FACTORS: **

FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 26.8
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .63

VERTICAL BOUNCE (IN): .06

ROLL ANGLE (DEG): 3.12

PITCH ANGLE (DEG): 0

STEER ANGLE (DEG): 2.29

TOTAL DRIVE THRUST (LB): 27

HORIZ LATERAL ACCEL (G'S): .208

FRICTION FACTORS:

LEFT	RIGHT	AXLE
.121	.153	1
.121	.154	2

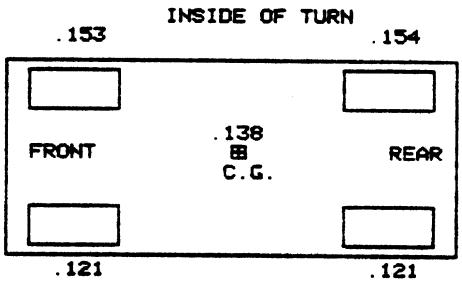
POINT MASS VALUE = .138

VERTICAL TIRE LOADS (LB):

1091.9	865.7	1
952.9	751.3	2

LATERAL TIRE FORCES (LB):

132.8	132.8	1
116	116	2



** FRICTION FACTORS: **

USER'S GUIDE FOR THE FHWA/UMTRI MICROCOMPUTER STEADY-TURNING VEHICLE MODELS

(APPLE II+ 48K Version)

C. C. MacAdam

INTRODUCTION

This guide is intended to serve as a informal user's manual, or aid, for operating the microcomputer-based vehicle models developed by the University of Michigan Transportation Research Institute (UMTRI) for the Federal Highway Administration (FHWA). These models were developed under the FHWA project entitled, "Side Friction for Superelevation on Horizontal Curves." Users' comments and suggestions for improving the use of the programs, their input/output format, and additions or deletions are welcomed and solicited. Please direct such comments to:

C. C. MacAdam
or
P.S. Fancher

at

The Transportation Research Institute
The University of Michigan
2901 Baxter Road
Ann Arbor, Michigan 48109

The computer models described in this guide are intended for use in studying the side-friction requirements of different types of vehicles operating, in a steady-turning manner, along highway curves of specified radii, superelevation, and grade. Operation of the models requires entering data which describes the characteristics of the vehicle and the roadway. (Parametric data may be entered directly from the keyboard or read from a specified text file which contains the parameter values.) The

model then calculates the steady-state solution satisfying that combination of vehicle characteristics and roadway geometry. The output from the model is a set of numbers describing the orientation of the vehicle in space, the required steer angle, and individual tire forces. The tire forces are in turn converted to friction factor requirements at each wheel location and summarized in both tabular and graphical form.

To accomodate the study of a variety of different types of vehicles, two separate vehicle models are employed. The first model, referred to as the "single-unit" model, is used to represent passenger cars, straight trucks, and full trailers. The second model is used for representing an articulated vehicle comprised of two units, such as a tractor semitrailer, and is accordingly referred to as the "tractor-semitrailer" model.

The following table describes and defines the input parameters necessary for running the single-unit computer model. The order of parameters appearing in the table is the same as that required by the model. The first column describes the parameter; the second column shows the required physical units for the numerical value of the parameter; the third column lists a "typical" passenger car value for each parameter; the fourth column lists a "typical" heavy truck value (fully loaded condition).

INPUT PARAMETER LIST: SINGLE-UNIT MODEL

	Parameter Description	Units	Car	Truck
1	Number of axles on front suspension	-	1	1
2	Number of axles on rear suspension	-	1	1-5
3	Axle 1 tire cornering stiffness	lb/deg/side	175	600
4	Axle 2 tire cornering stiffness	"	175	1200
	(remaining cornering stiffnesses for axles 3-6 if specified)			
5	Axle 1 suspension spring rate	lb/in/side	200	1200
6	Axle 2 suspension spring rate	"	250	6000
	(remaining spring rates for axles 3-6 if specified)			

7	Fore-aft spread of axles on multi-axle susp	inches	-	48
8	Wheelbase; center to center susp distance	inches	102	180
9	Superelevation of road	--	<0.15	<0.15
10	Grade of road	--	<0.15	<0.15
11	Forward velocity	mph	55	55
12	Radius of turn	ft	1000	1000
13	Axle 1 static load	lb	1500	10000
14	Axle 2 static load	lb	1200	16000
	(static loads for axles 3-6 if specified)			
15	Front suspension roll center height	inches	1	23
16	Rear suspension roll center height	"	6	29
17	Sprung mass (body) c.g. height	"	25	50-100
18	Front susp lateral distance between springs	"	40-55	32
19	Rear susp lateral distance between springs	"	40-55	38
20	Front track (distance between tires)	"	57	80
21	Rear track	"	57	72
22	Weight of axle assembly 1	lb	100	1200
23	Weight of axle assembly 2	lb	150	2300
	(weights of axles 3-6 if specified)			
24	Percent rolling resistance	%	1	1

- Optional aerodynamic properties:

25	Height of aero center of pressure	inches	30	70
26	Distance of center of press ahead of c.g.	inches	6	50
27	Frontal cross-sectional area	sq-ft	15	80
28	Drag coefficient	--	0.4	0.9
29	Lift coefficient	--	0.4	0.3
30	Slope of lift coeff vs. pitch angle	1/rad	3.0	3.0
31	Slope of side force vs. relative (wind) yaw	1/rad	3.0	3.0

The following table describes and defines the input parameters necessary for running the tractor-semitrailer computer model. The order of parameters appearing in the table is the same as required by the model. The first column describes the parameter; the second column shows the required physical units of the parameter; the third column lists a "representative" tractor - semitrailer value for an empty condition; the fourth column lists a "representative" tractor-semitrailer value for a fully loaded condition.

INPUT PARAMETER LIST: TRACTOR-SEMITRAILER MODEL

	Parameter Description	Units	Empty	Loaded
1	Number of axles on tractor rear suspension	-	2	2
2	Number of axles on semitrailer suspension	-	2	2
3	Axle 1 tire cornering stiffness	lb/deg/side	500	600
4	Axle 2 tire cornering stiffness	"	900	1200
	(remaining cornering stiffnesses for axles 3-6 if required)			
5	Axle 1 suspension spring rate	lb/in/side	1200	1200
6	Axle 2 suspension spring rate	"	4000	6000
	(remaining spring rates for axles 3-6 if required)			
7	Fore-aft spread of axles on tractor susp	inches	48	48
8	Fore-aft spread of axles on semi susp	inches	48	48
9	Tractor wheelbase	inches	144	144
10	Semitrailer wheelbase	inches	432	432
11	Superelevation of road	--	<0.15	<0.15
12	Grade of road	--	<0.15	<0.15
13	Forward velocity	mph	55	55
14	Radius of turn	ft	1000	1000
15	Axle 1 static load	lb	8500	12000
16	Axle 2 static load	lb	5000	16000
	(static loads for axles 3-6 if required)			
17	Tractor sprung mass weight (body)	lb	9700	9700
18	Tractor front suspension roll center height	inches	23	23
19	Tractor rear suspension roll center height	"	29	29
20	Semitrailer " " " "	"	29	29

21	Tractor sprung mass c.g. height (body)	"	44	44
22	Semitrailer " " c.g. height (body+payload)	"	60	80
23	Fifth Wheel height above ground	"	49	48
24	Tractor frame height above ground (center)	"	37	36
25	Tractor front susp distance between springs	"	32	32
26	Tractor rear susp distance between springs	"	38	38
27	Semi rear susp distance between springs	"	38	38
28	Tractor front track (distance between tires)	"	81	81
29	Tractor rear track "	"	73	73
30	Semitrailer rear track "	"	73	73
31	Tractor front axle assembly weight	lb	1200	1200
32	Tractor rear assembly weight	lb	2300	2300
33	Semi rear assembly weight	lb	1500	1500
	(weights of other axles if required)			
34	Percent rolling resistance (total vehicle)	%	1	1

- Optional aerodynamic properties:

35	Height of aero center of pressure	inches	70	70
36	Distance of center of press ahead of c.g.	inches	50	50
37	Frontal cross-sectional area	sq-ft	80	80
38	Drag coefficient	--	0.9	0.9
39	Lift coefficient	--	0.3	0.3
40	Slope of lift coeff vs. pitch angle	1/rad	3.0	3.0
41	Slope of side force vs. relative (wind) yaw	1/rad	3.0	3.0

APPENDIX E

EXPERIMENTAL MEASUREMENTS

Appendix E is comprised of four sub-appendices (1 to 4) and contains experimental measurements of driver/vehicle test results (appendix E.1), flat bed tire force measurements (appendix E.2), and steering system measurements (appendix E.3). Appendix E.4 explains the estimation process for deriving individual wheel friction factors from the vehicle response measurements.

APPENDIX E.1

VEHICLE TEST RESULTS - TIME HISTORIES

STEADY TURNING

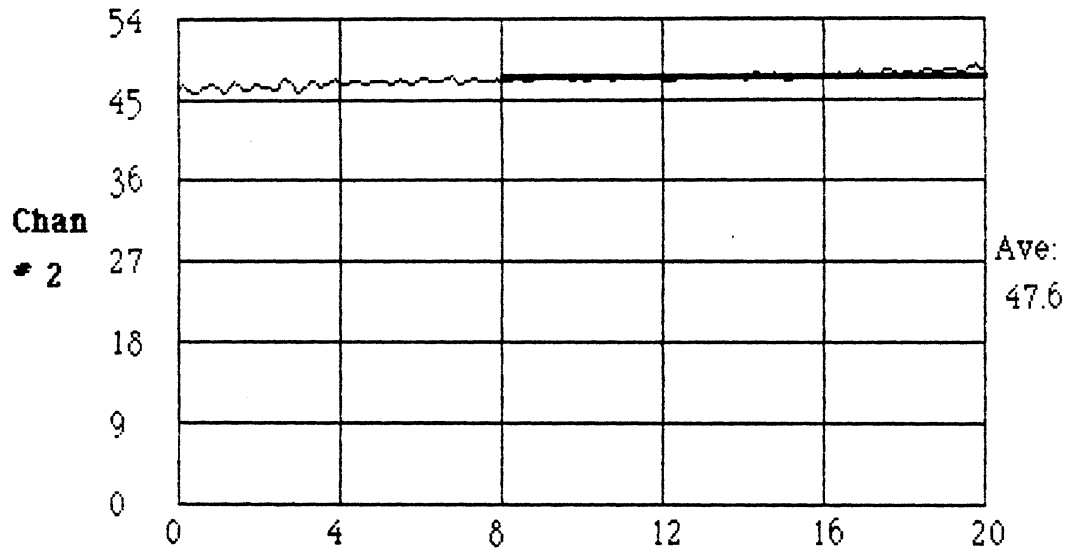
The time histories seen in this appendix are identified by channel numbers (Chan #2 ..... Chan #16) which correspond to the data channels identified in table 3 (tractor-semitrailer; vehicle C) and table 4 (passenger cars A and B) of volume II. For example, tractor-semitrailer Chan #2 refers to vehicle speed (mph) and tractor-semitrailer Chan #16 is tractor yaw rate (deg/s). Likewise, passenger car A (Dodge Aries) Chan #8 is steering wheel angle (degrees) and Chan #10 is trolley angle (degrees).

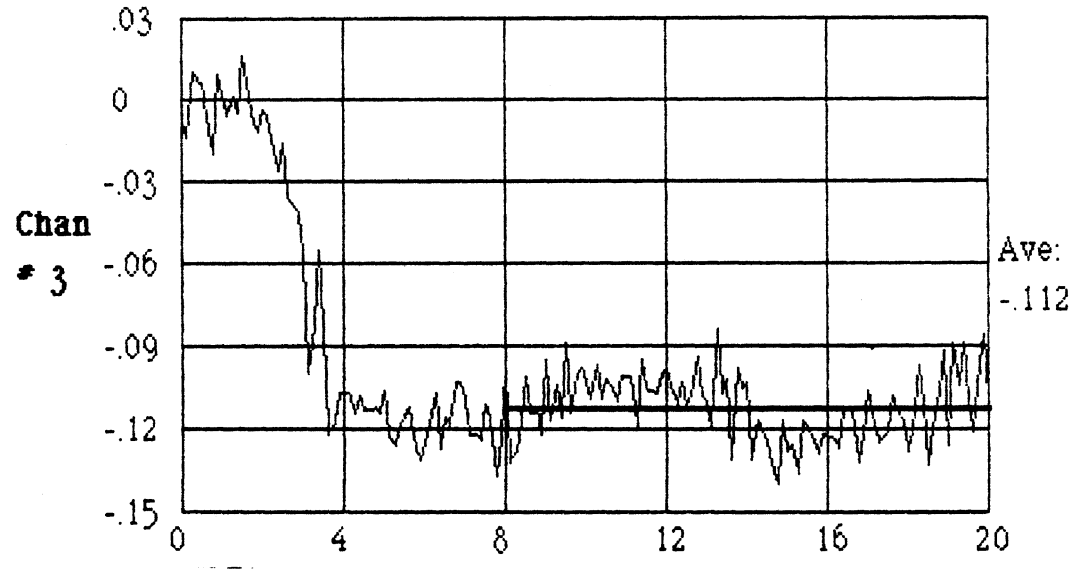
Tractor-semitrailer

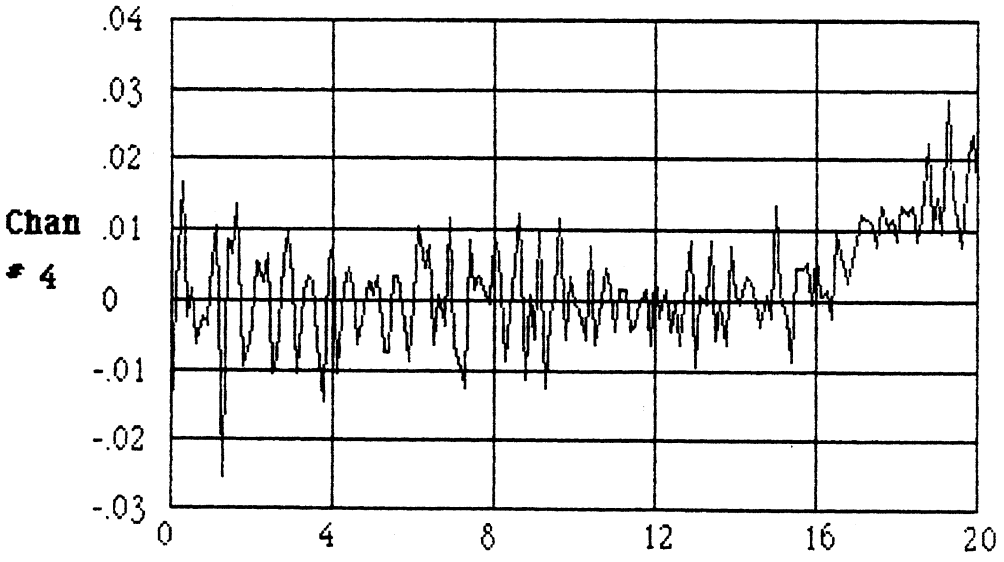
Curve #1

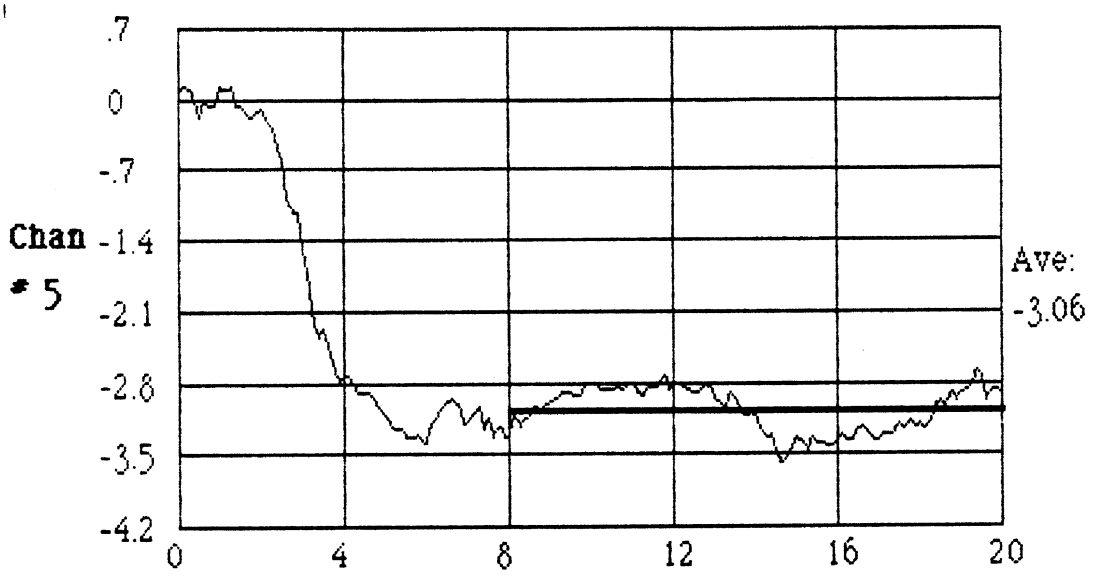
Repeat 1

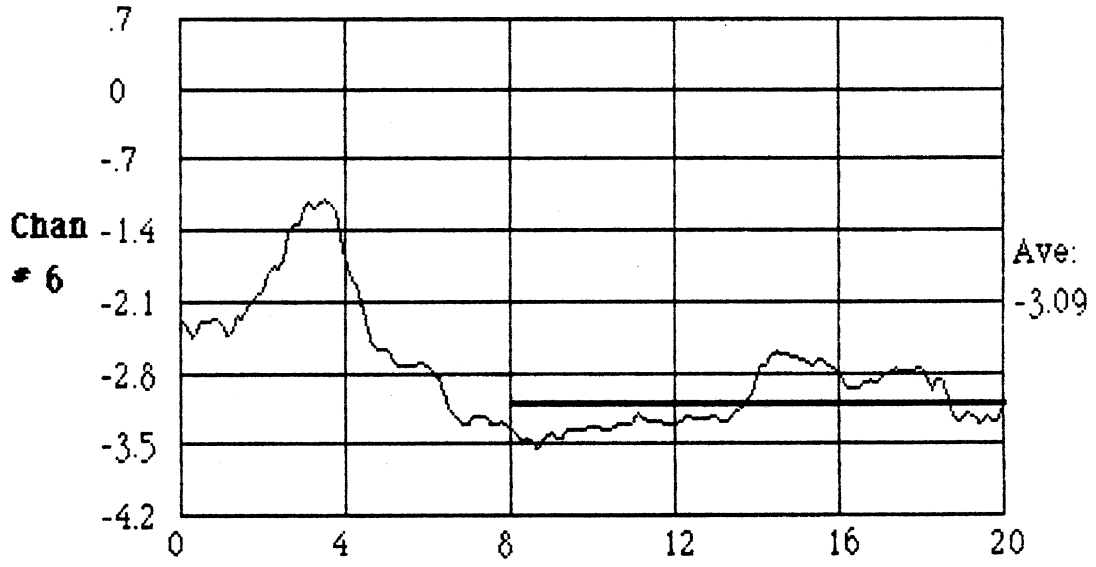
Steady Turning

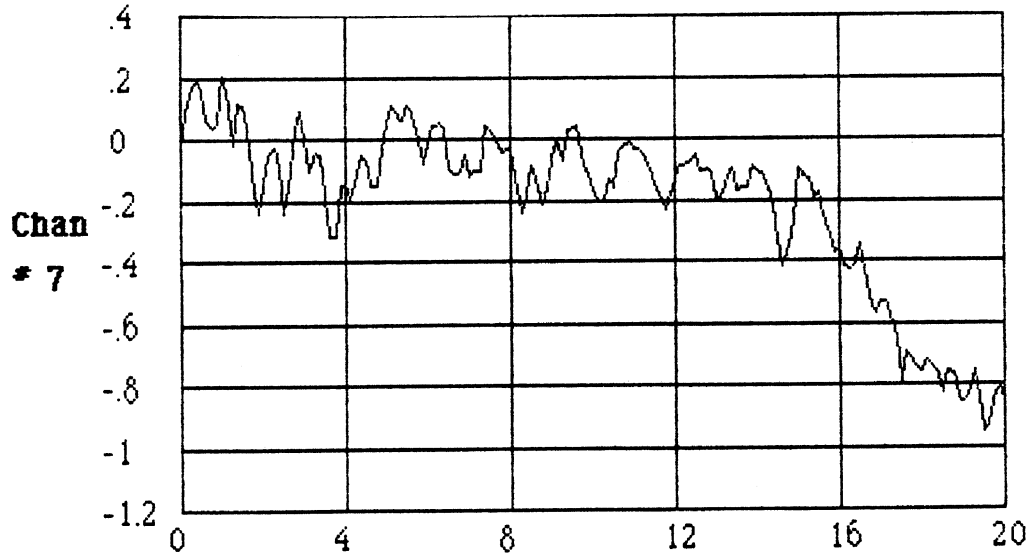

Chan
2
54
45
36
27
18
9
0
0
4
8
12
16
20
Ave:
47.6

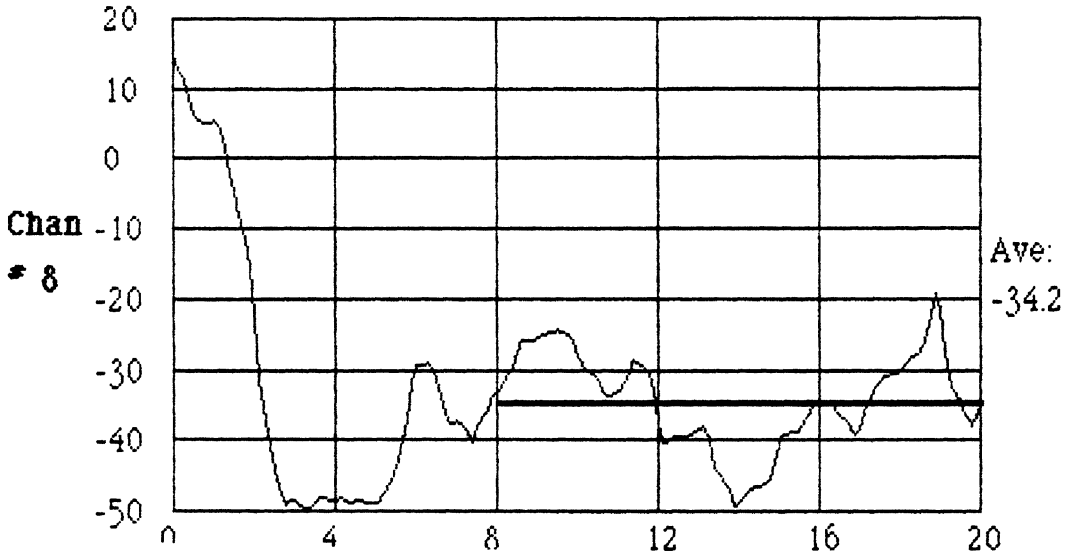

Chan
3
.03
0
-.03
-.06
-.09
-.12
-.15
0
4
8
12
16
20
Ave:
-.112

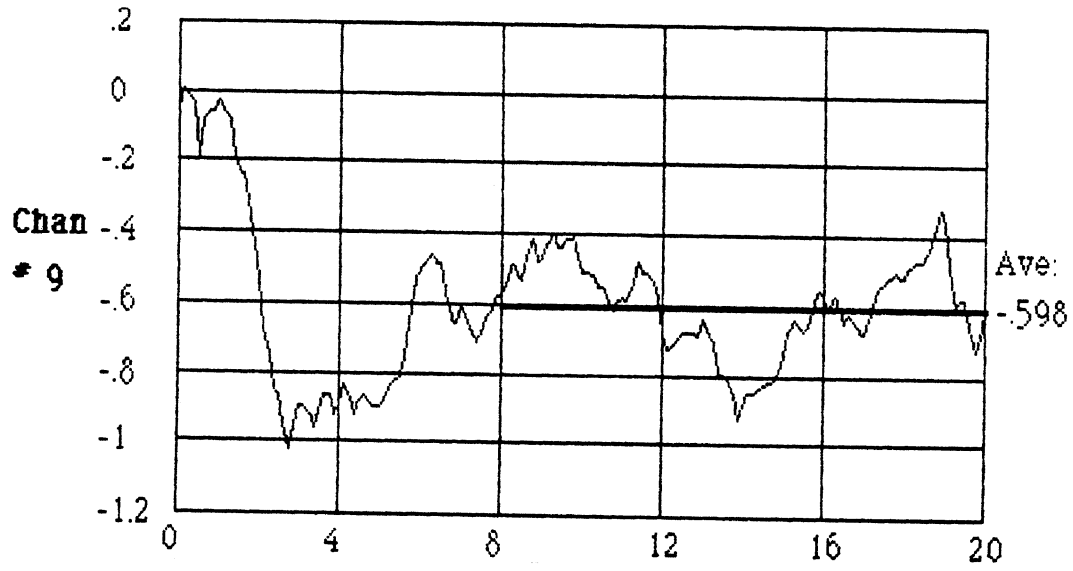

Chan
4
.04
.03
.02
.01
0
-.01
-.02
-.03
0
4
8
12
16
20

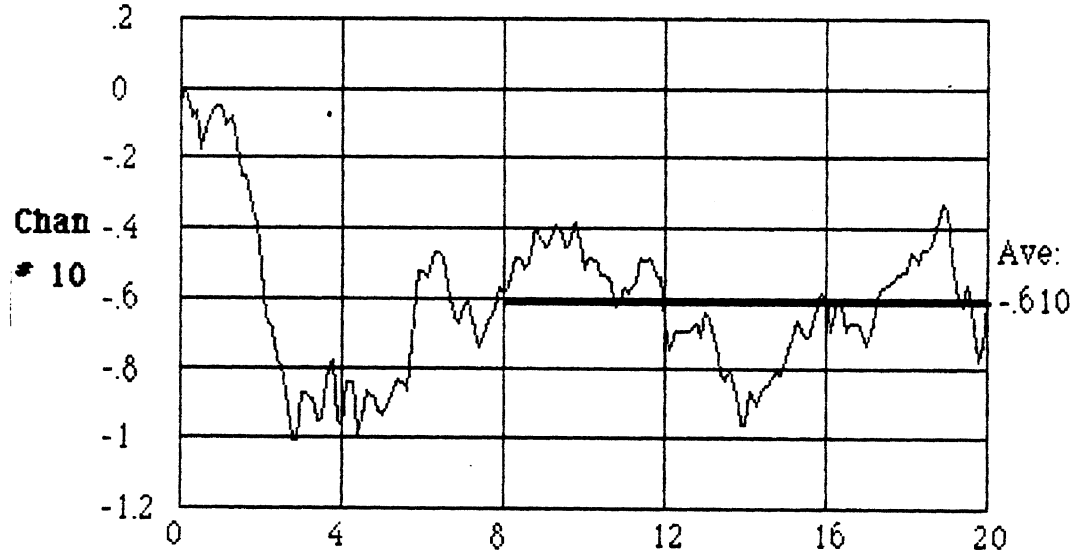

Chan
5
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.06

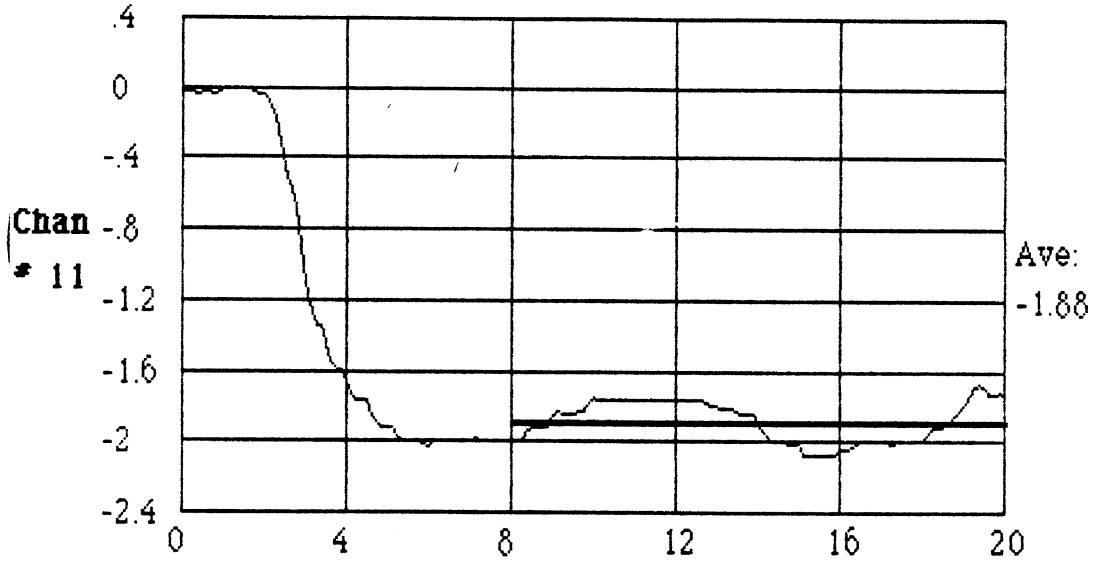

Chan
6
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.09

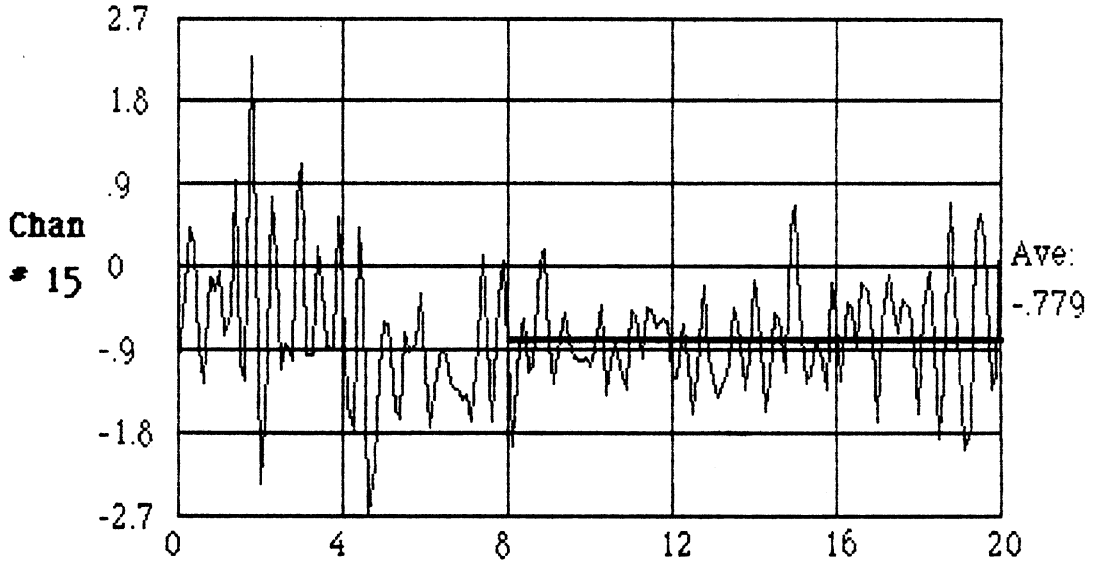

Chan
7
.4
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20

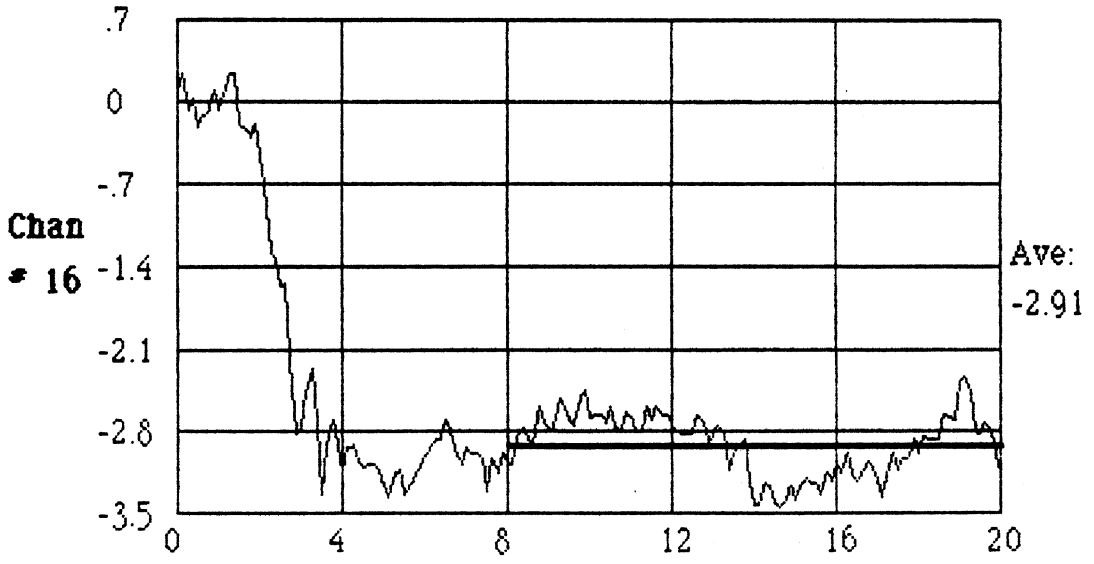

Chan
8
20
10
0
-10
-20
-30
-40
-50
0
4
8
12
16
20
Ave:
-34.2


Chan
9
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20
Ave:
-.598


Chan
10
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20
Ave:
-.610


Chan
11
.4
0
-.4
-.8
-1.2
-1.6
-2
-2.4
0
4
8
12
16
20
Ave:
-1.88


Chan
15
2.7
1.8
.9
0
-.9
-1.8
-2.7
0
4
8
12
16
20
Ave:
-.779

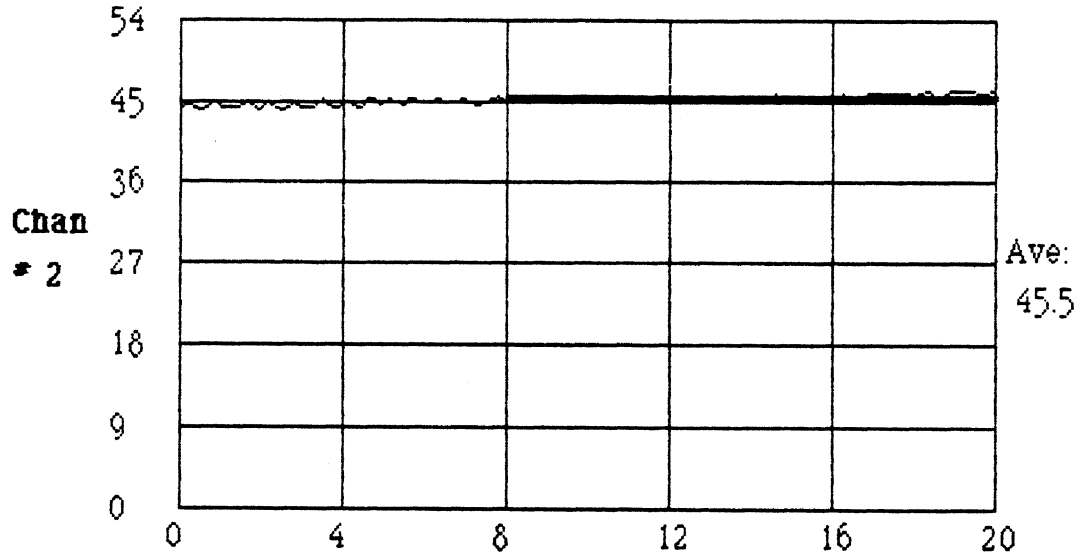

Chan
16
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
0
4
8
12
16
20
Ave:
-2.91

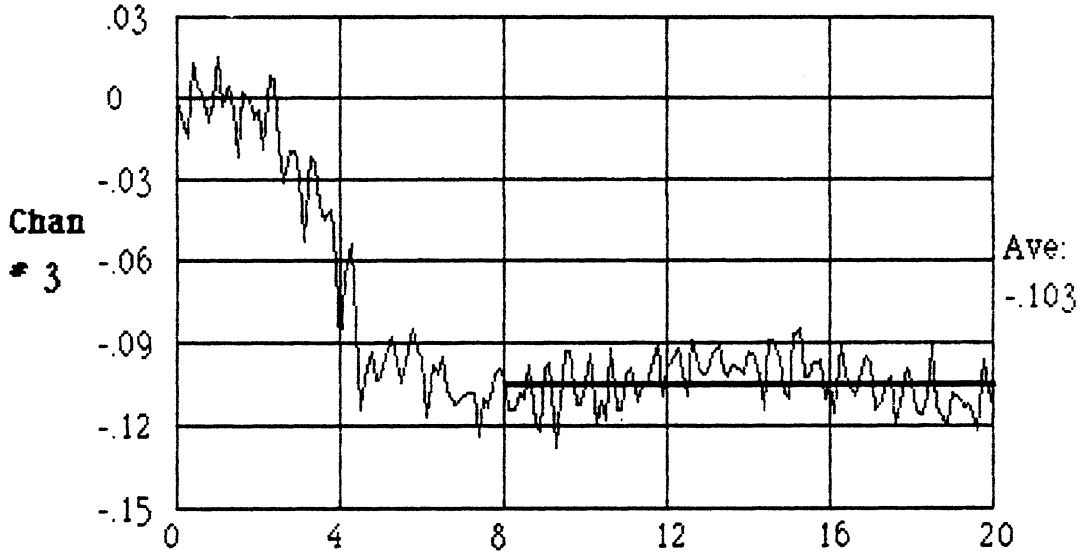
Tractor-semitrailer

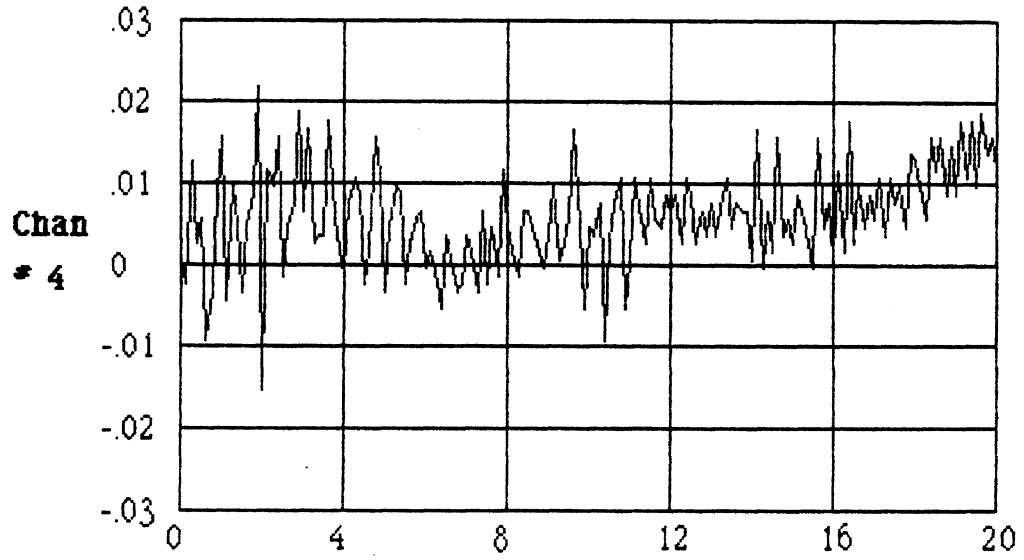
Curve #1

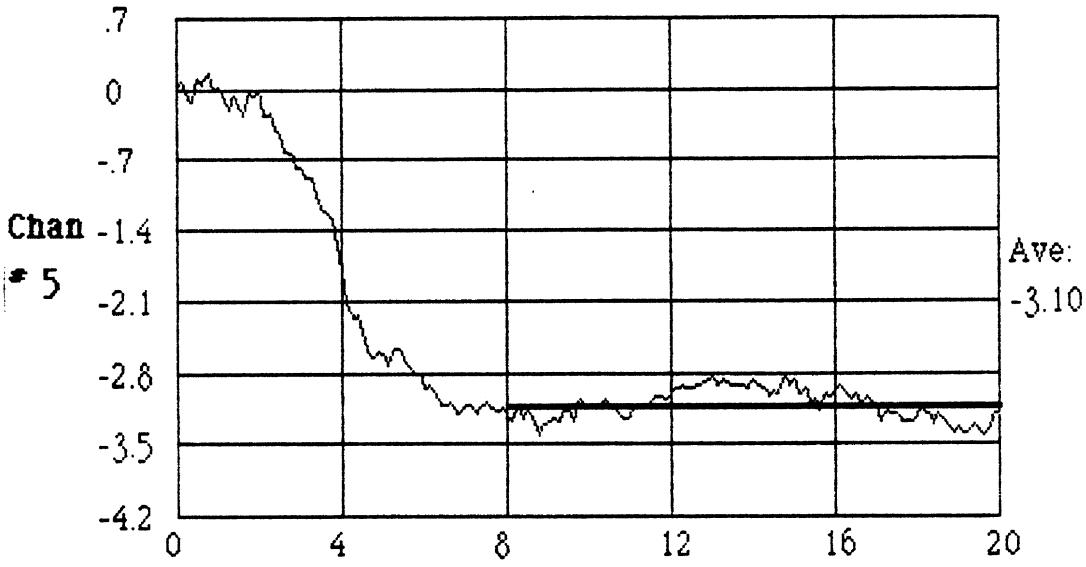
Repeat 2

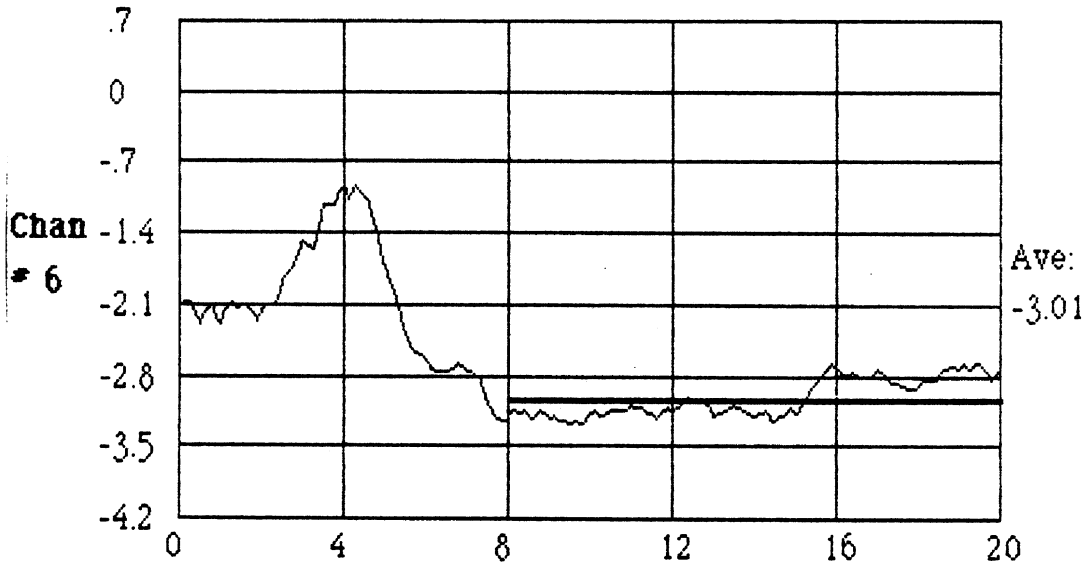
Steady Turning

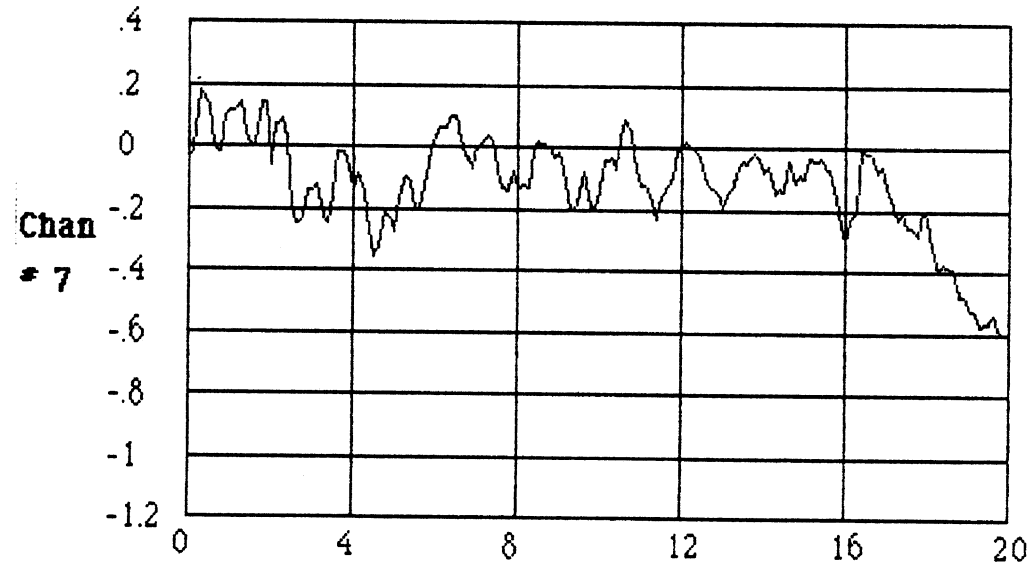

54
45
36
27
18
9
0
Chan
2
0
4
8
12
16
20
Ave:
45.5

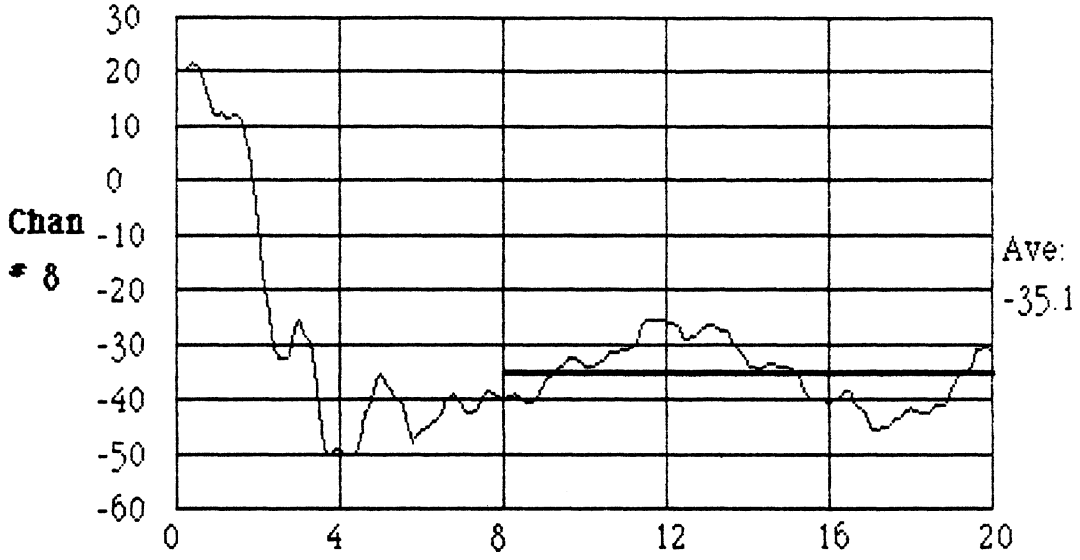

.03
0
-.03
-.06
-.09
-.12
-.15
Chan
3
0
4
8
12
16
20
Ave:
-.103

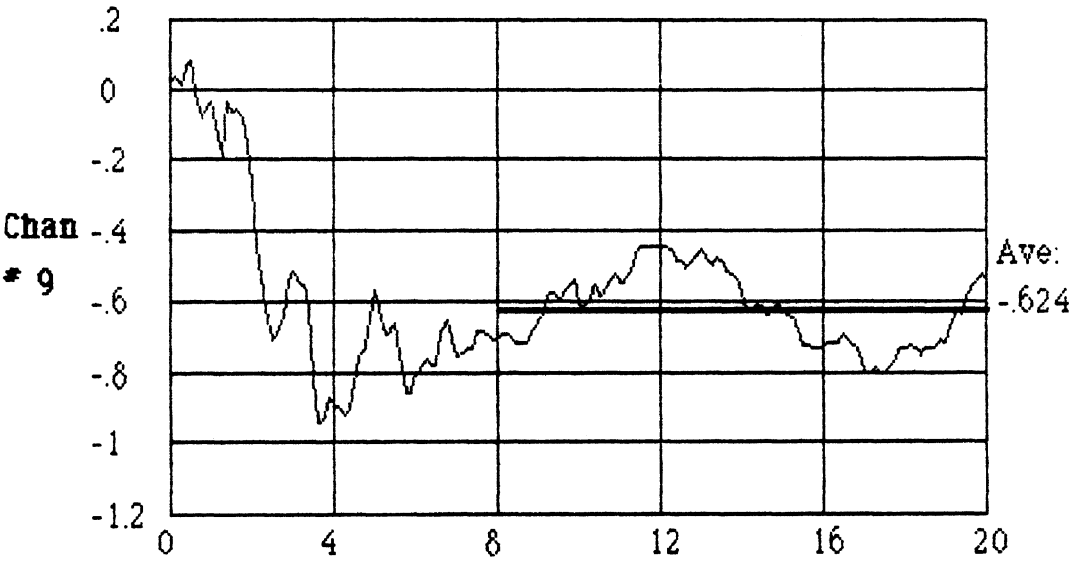

.03
.02
.01
0
-.01
-.02
-.03
Chan
4
0
4
8
12
16
20

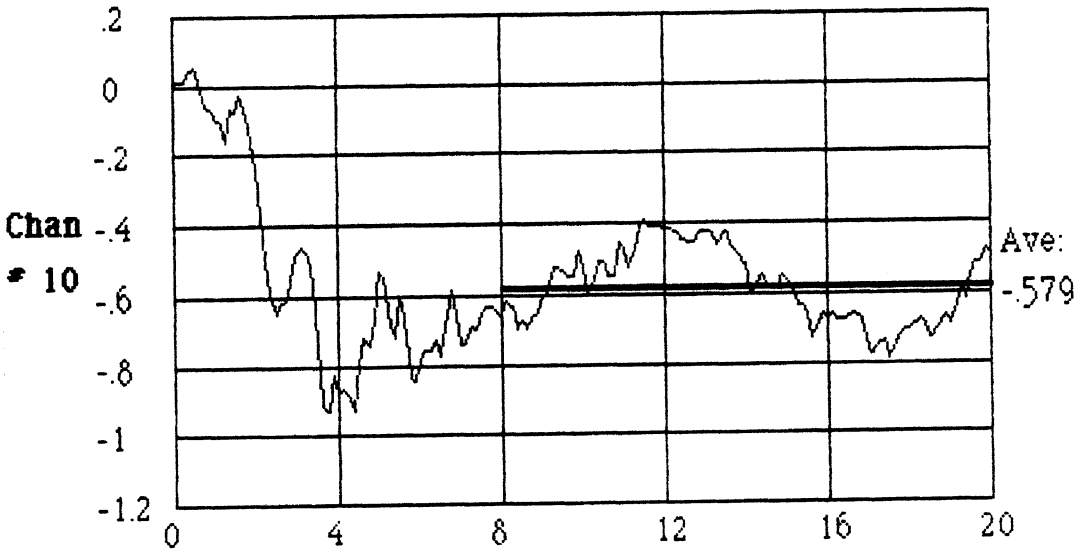

Chan
5
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.10

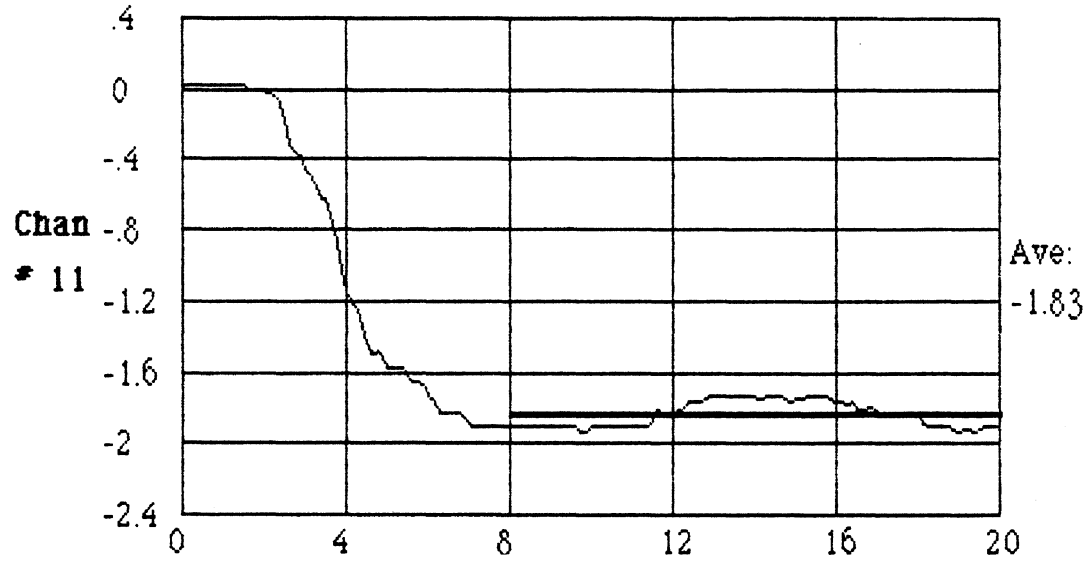

Chan
6
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.01

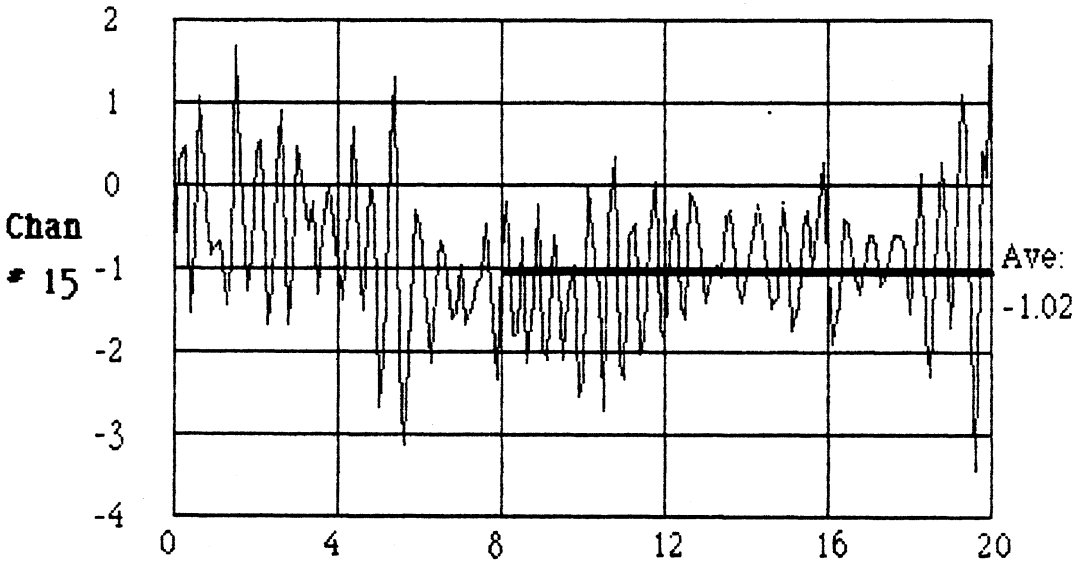

Chan
7
.4
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20

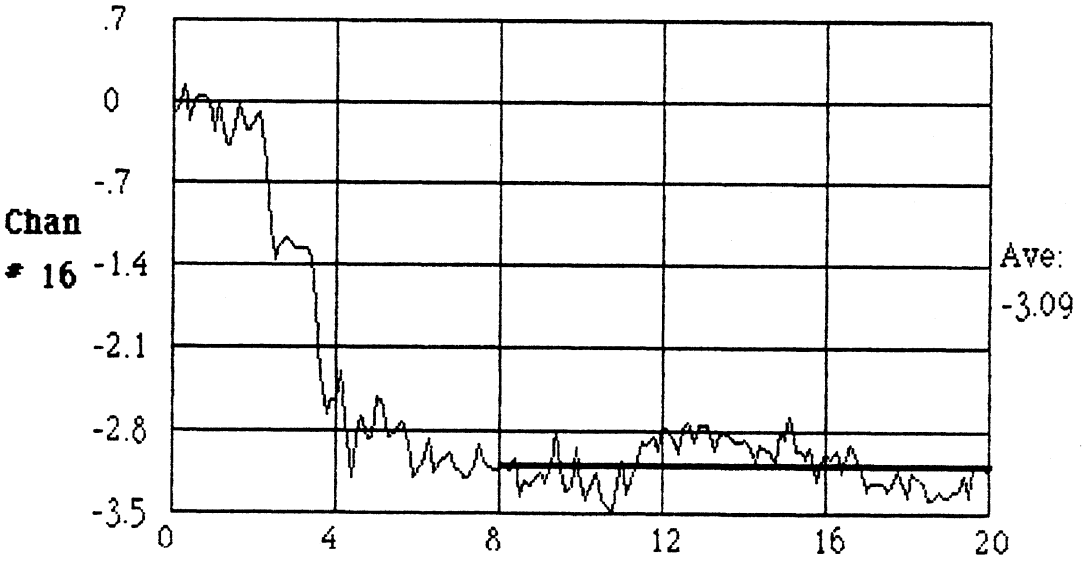

Chan
8
30
20
10
0
-10
-20
-30
-40
-50
-60
0
4
8
12
16
20
Ave:
-35.1


Chan
9
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20
Ave:
-.624


Chan
10
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20
Ave:
-.579


Chan
11
.4
0
-.4
-.8
-1.2
-1.6
-2
-2.4
0
4
8
12
16
20
Ave:
-1.83


Chan
15
2
1
0
-1
-2
-3
-4
0
4
8
12
16
20
Ave:
-1.02

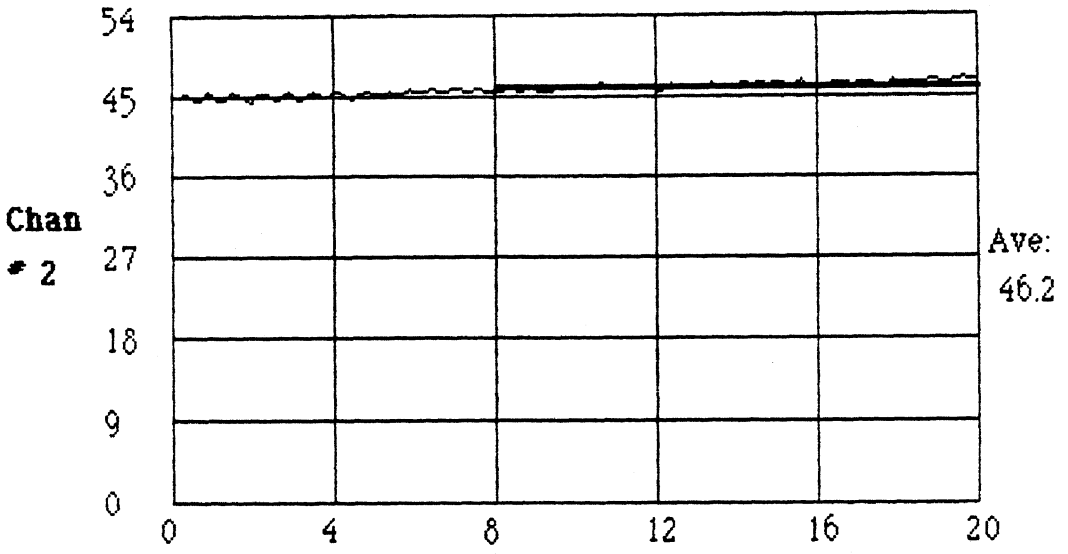

Chan
16
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
0
4
8
12
16
20
Ave:
-3.09

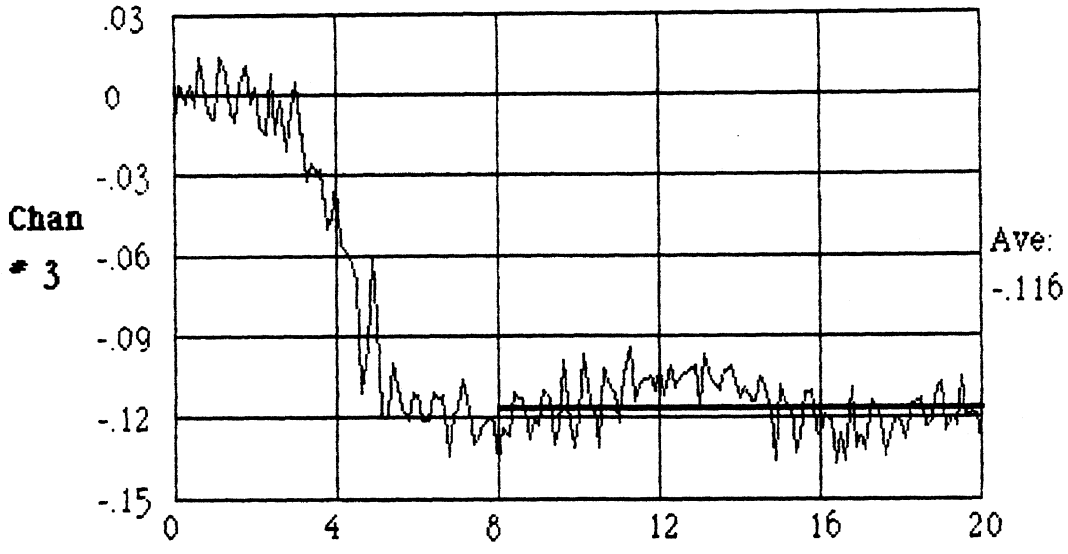
Tractor-semitrailer

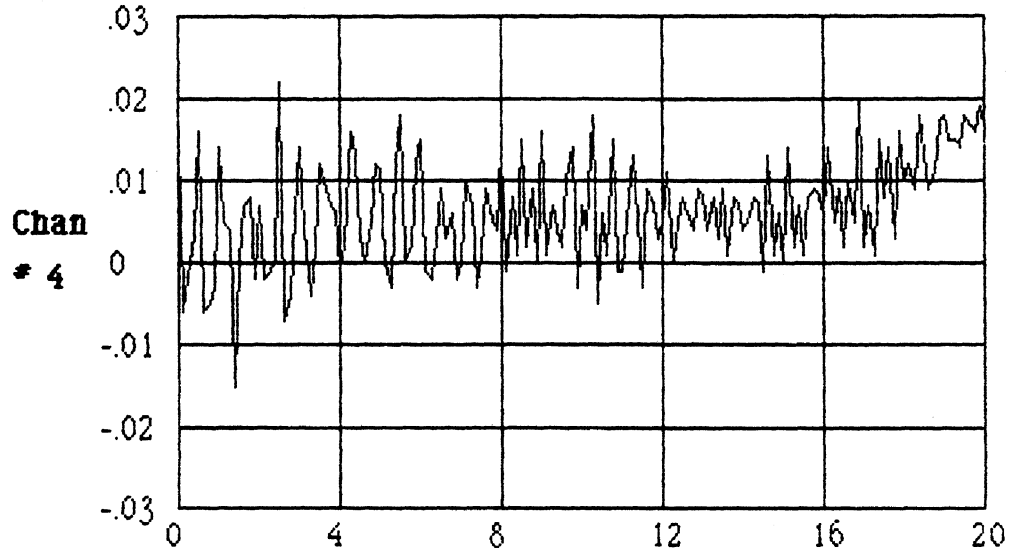
Curve #1

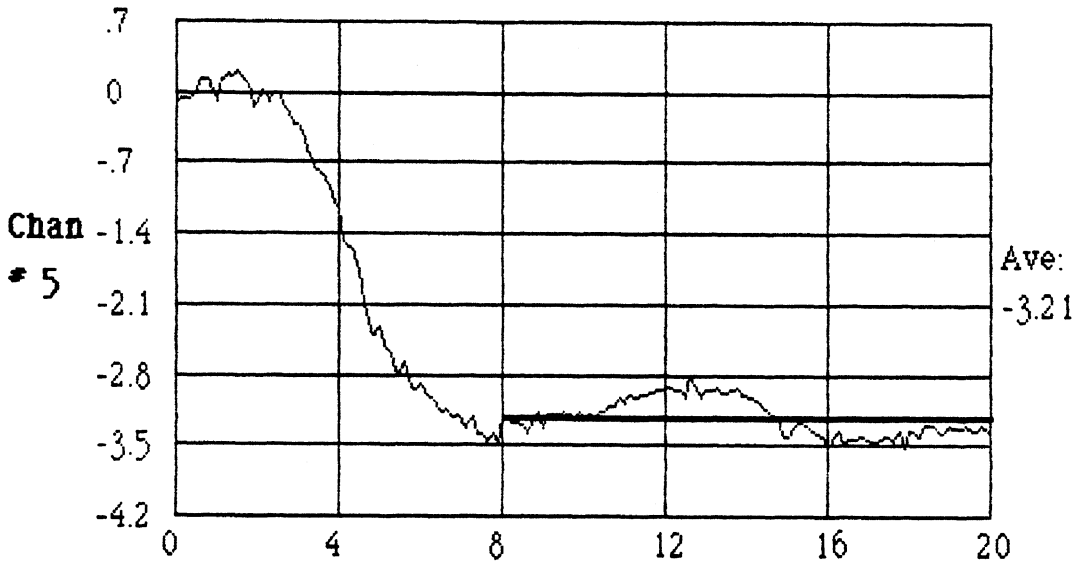
Repeat 3

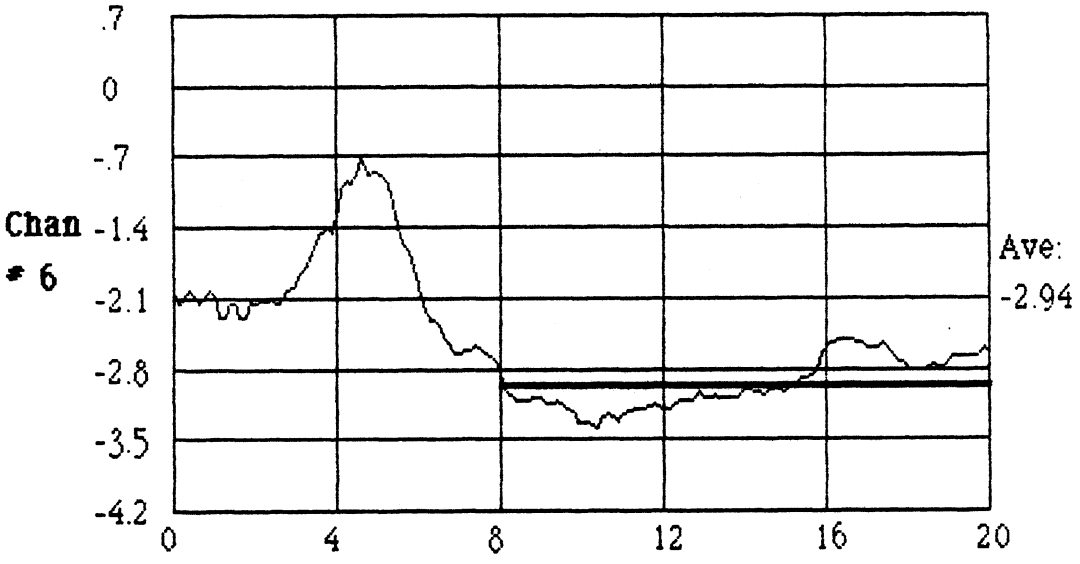
Steady Turning

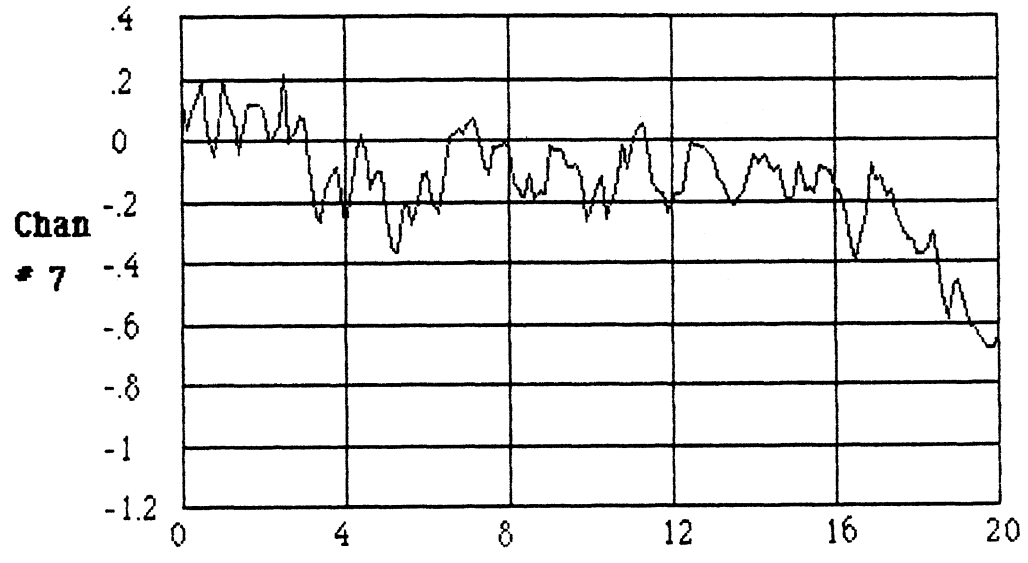

Chan
2
54
45
36
27
18
9
0
0
4
8
12
16
20
Ave:
46.2

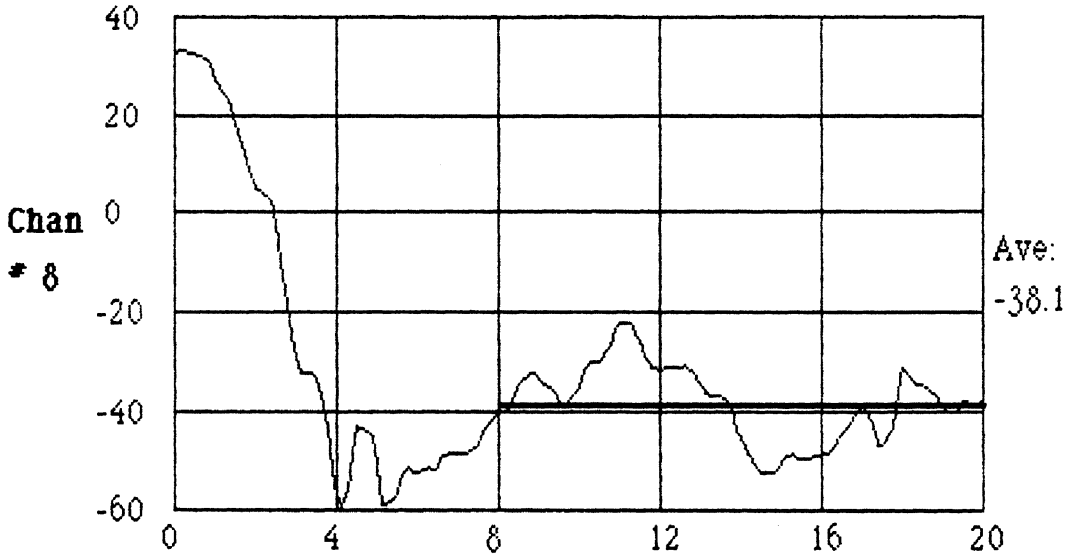

Chan
3
.03
0
-.03
-.06
-.09
-.12
-.15
0
4
8
12
16
20
Ave:
-.116

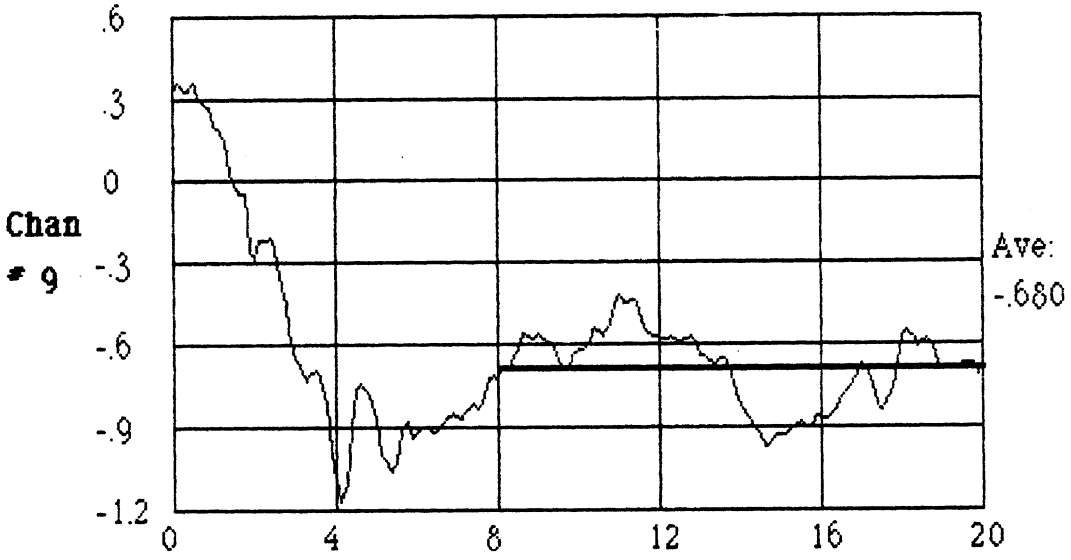

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
4
8
12
16
20

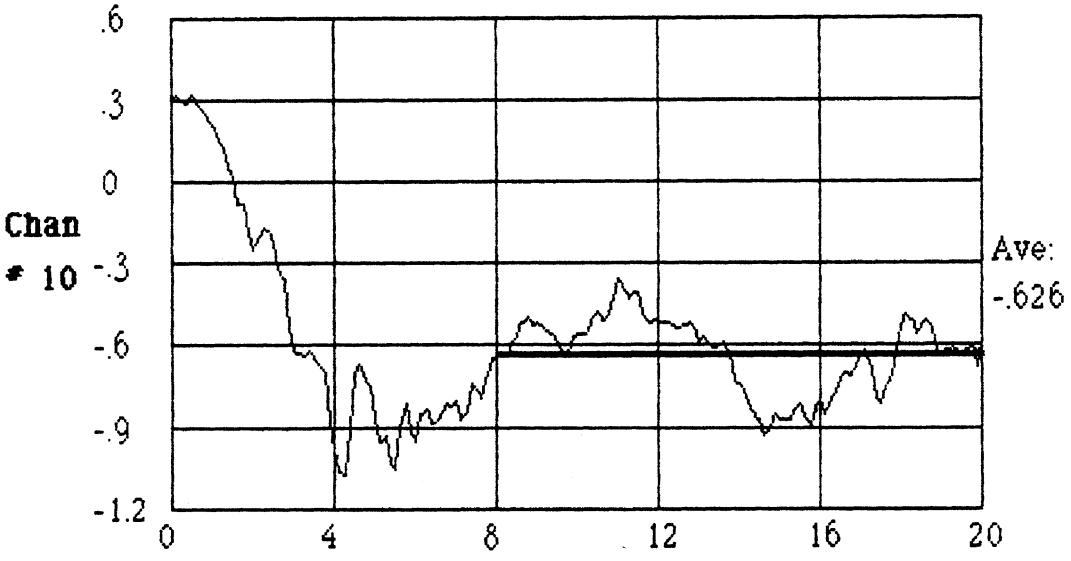

Chan
5
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.21


Chan
6
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-2.94

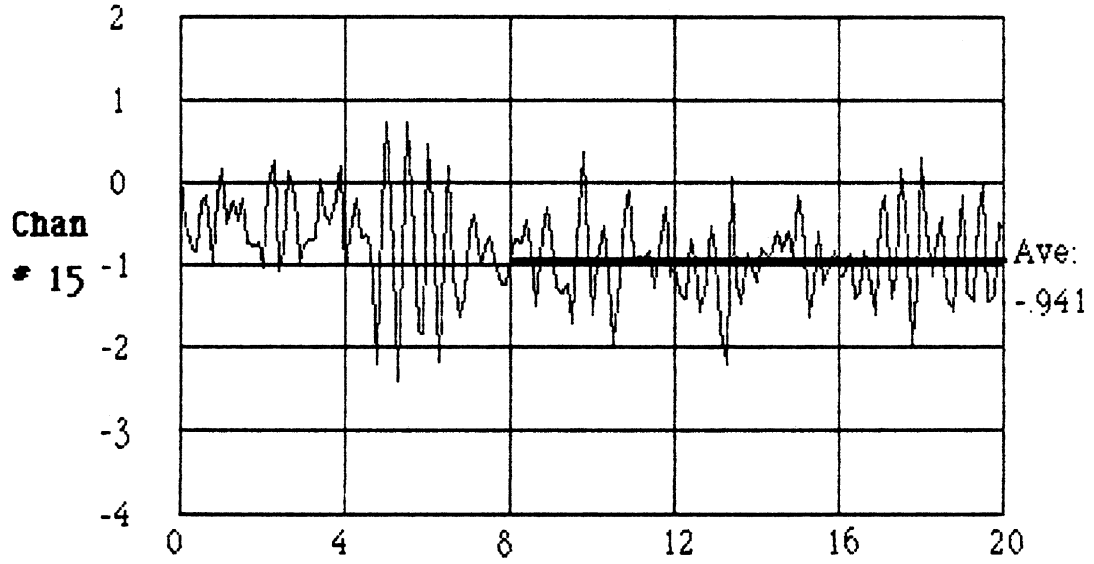

Chan
7
.4
.2
0
-.2
-.4
-.6
-.8
-1
-1.2
0
4
8
12
16
20

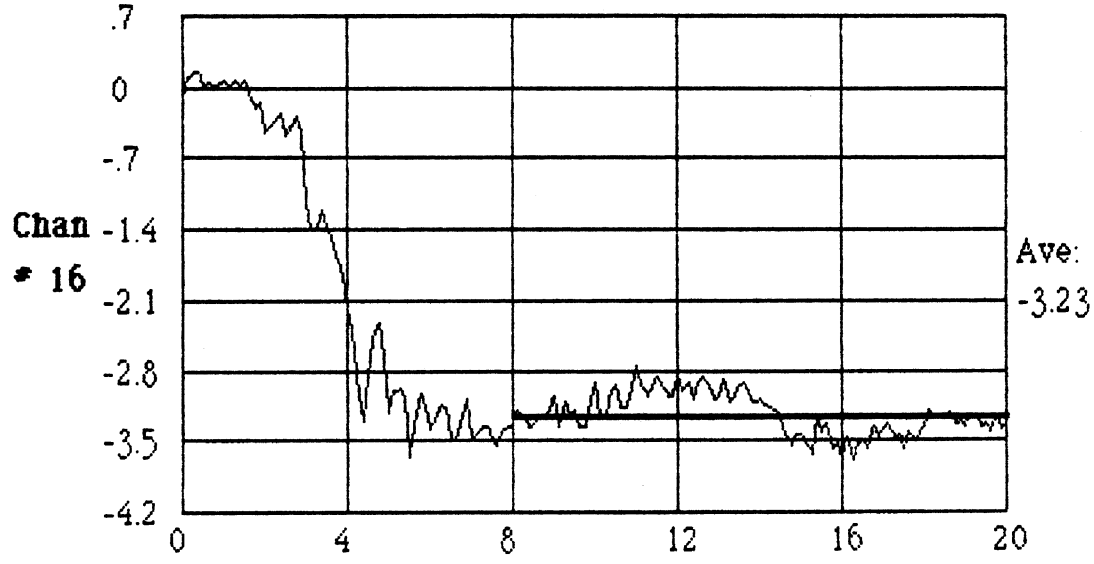

Chan
8
40
20
0
-20
-40
-60
0
4
8
12
16
20
Ave:
-38.1


Chan
9
.6
.3
0
-.3
-.6
-.9
-1.2
0
4
8
12
16
20
Ave:
-.680


Chan
10
.6
.3
0
-.3
-.6
-.9
-1.2
0
4
8
12
16
20
Ave:
-.626


Chan
11
.4
0
-.4
-.8
-1.2
-1.6
-2
-2.4
0
4
8
12
16
20
Ave:
-1.78


Chan
15
2
1
0
-1
-2
-3
-4
0
4
8
12
16
20
Ave:
-.941

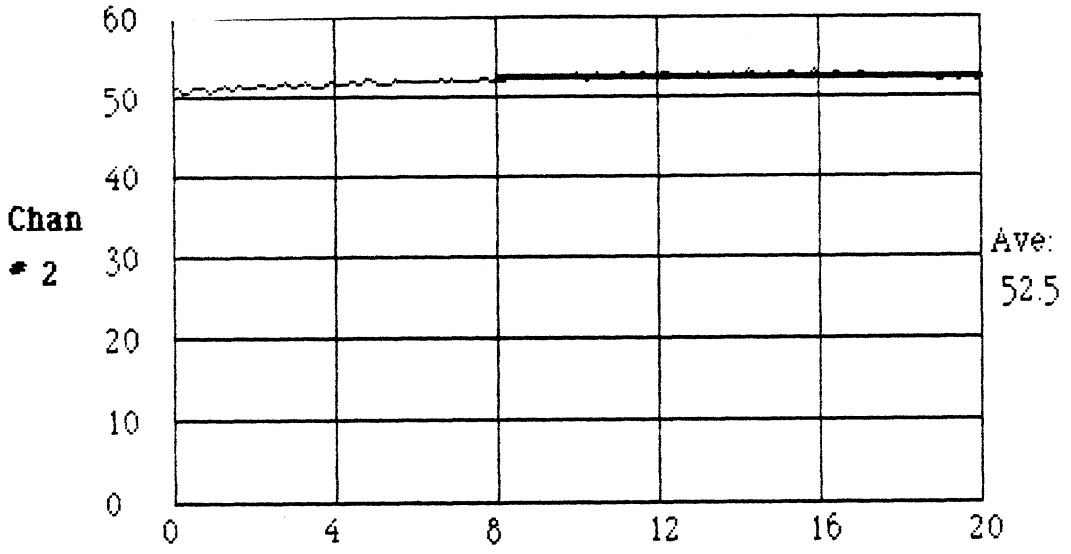

Chan
16
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.23

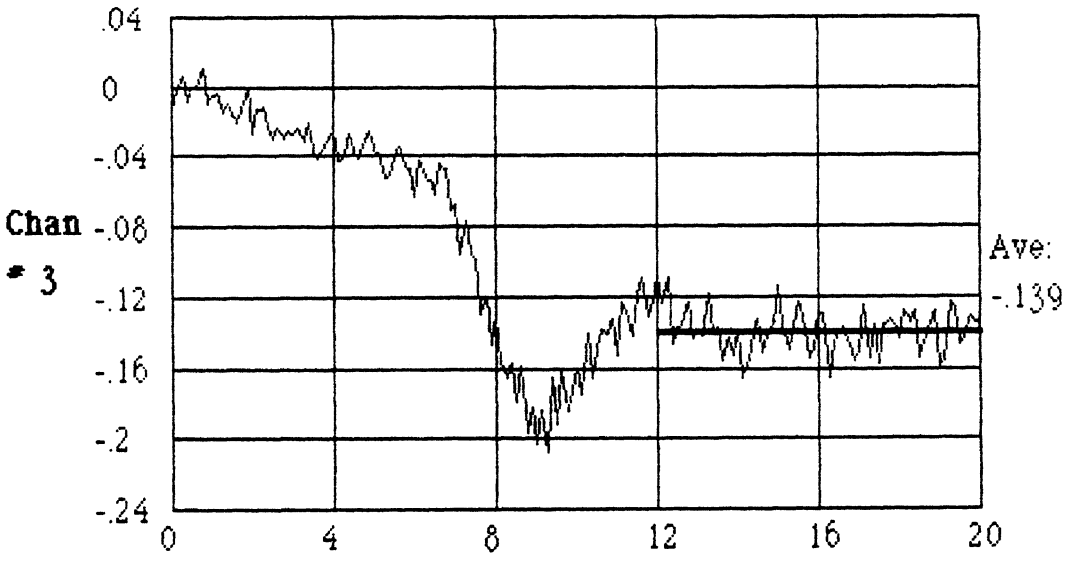
Tractor-semitrailer

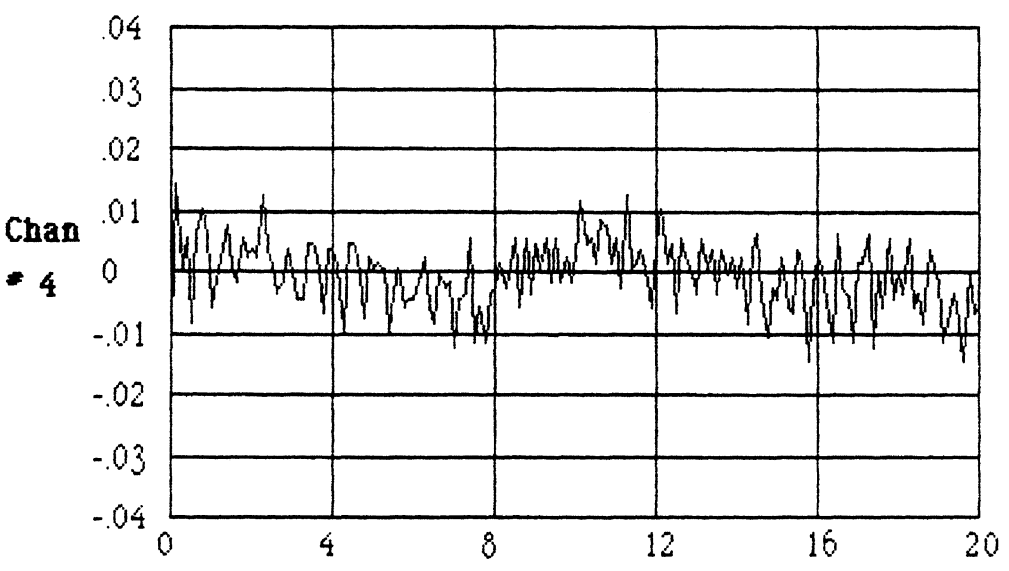
Curve #2

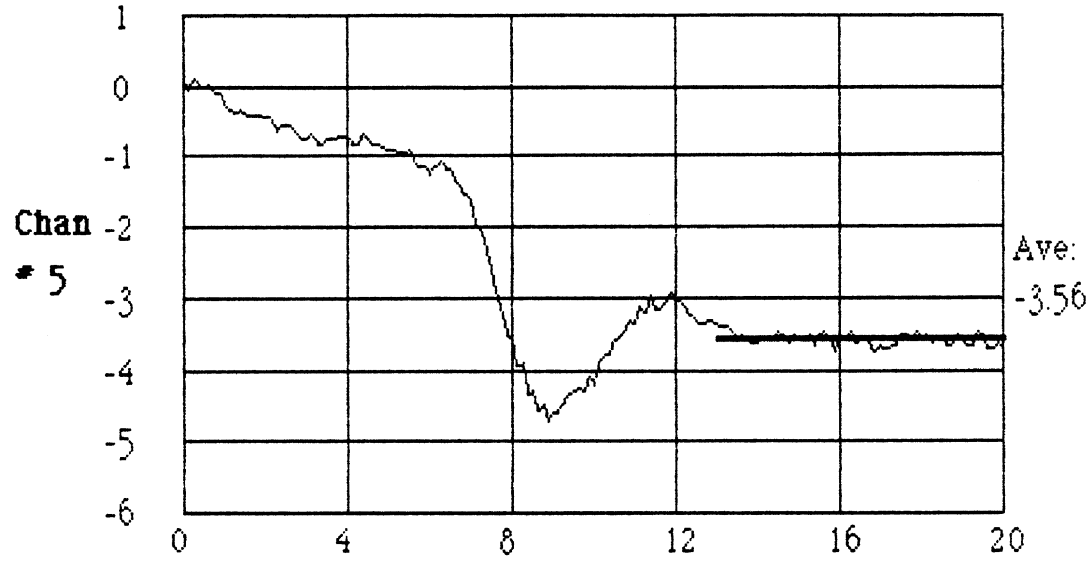
Repeat 1

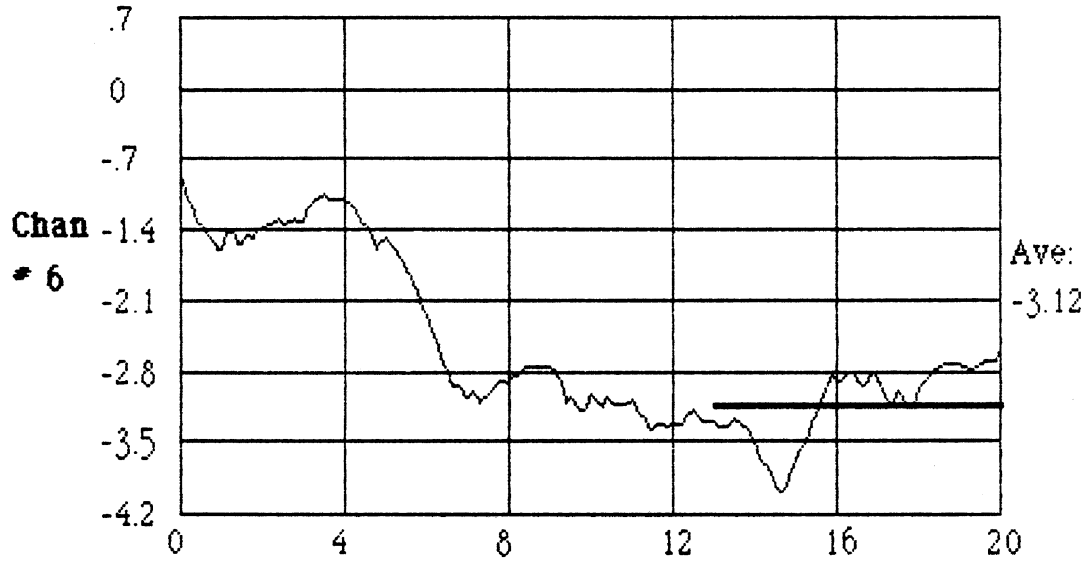
Steady Turning

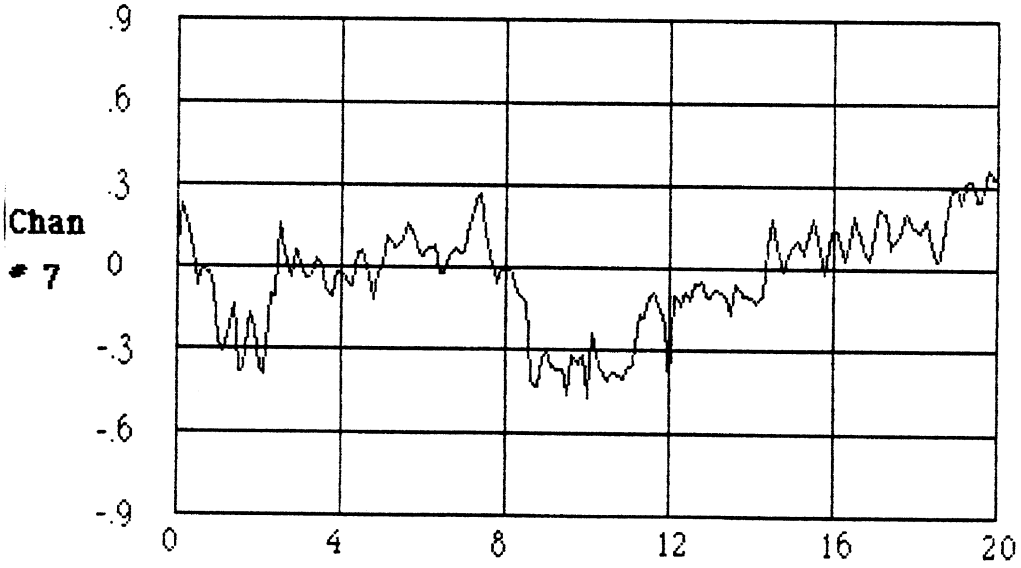

Chan
2
60
50
40
30
20
10
0
0
4
8
12
16
20
Ave:
52.5

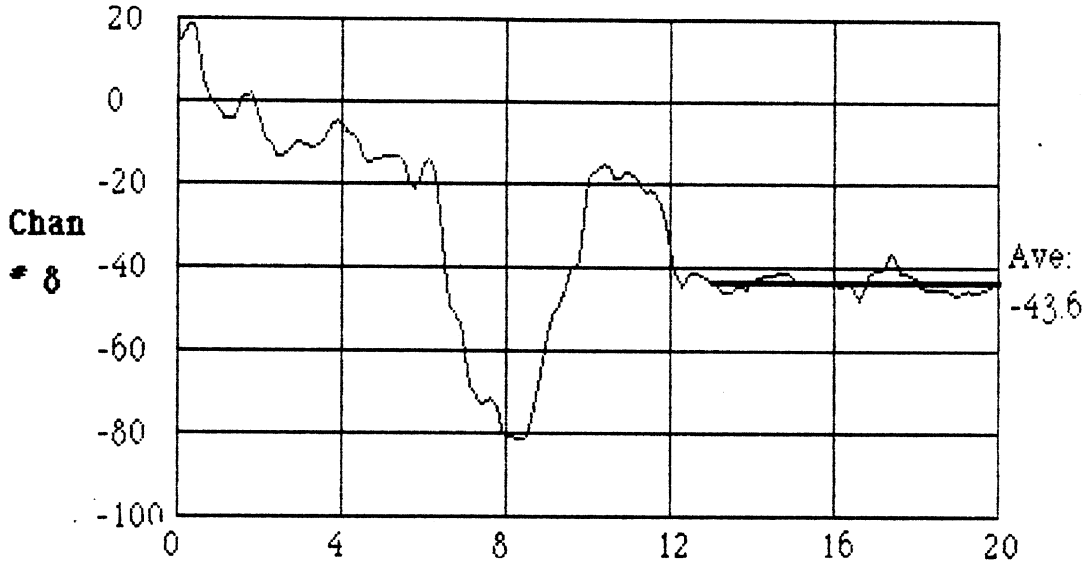

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
-.24
0
4
8
12
16
20
Ave:
-.139

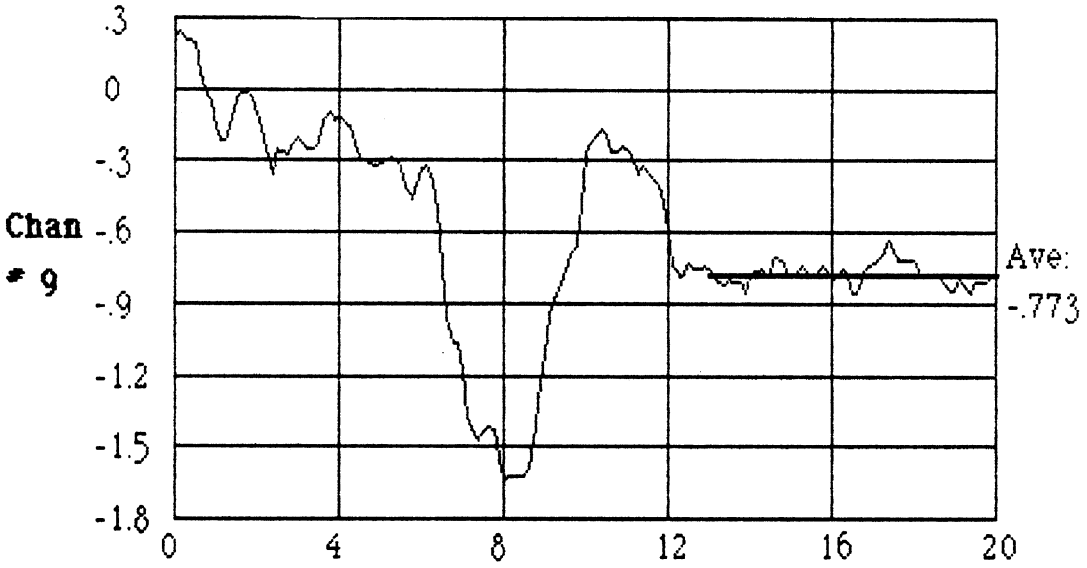

Chan
4
.04
.03
.02
.01
0
-.01
-.02
-.03
-.04
0
4
8
12
16
20

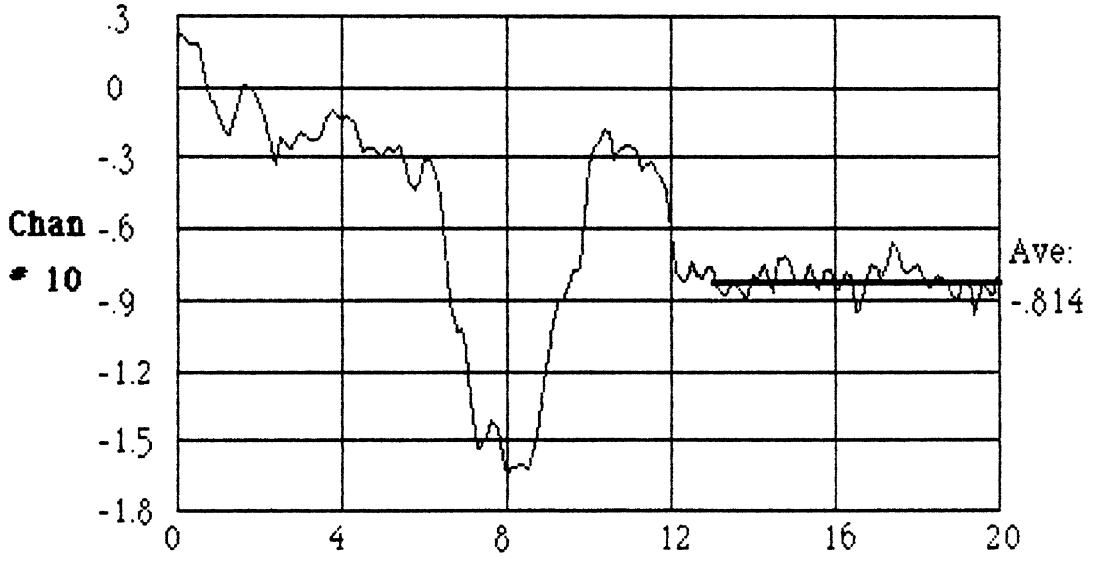

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
4
8
12
16
20
Ave:
-3.56

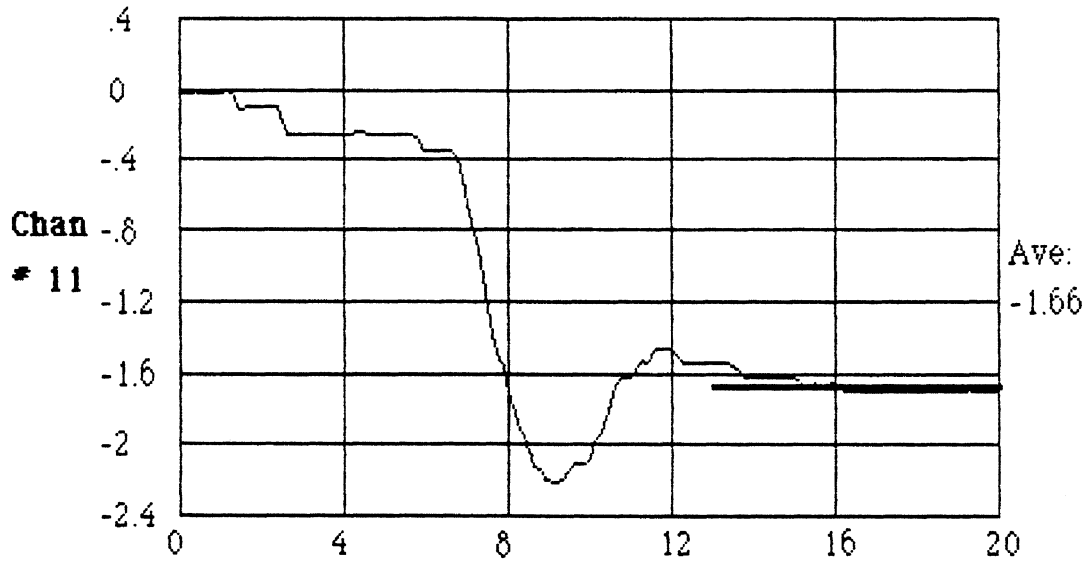

Chan
6
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
4
8
12
16
20
Ave:
-3.12

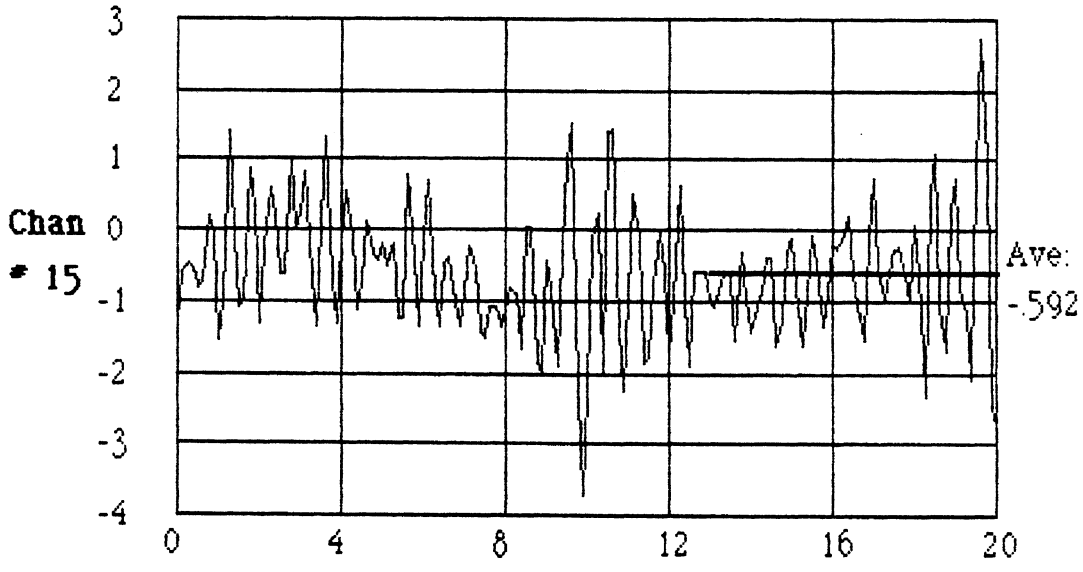

Chan
7
.9
.6
.3
0
-.3
-.6
-.9
0
4
8
12
16
20

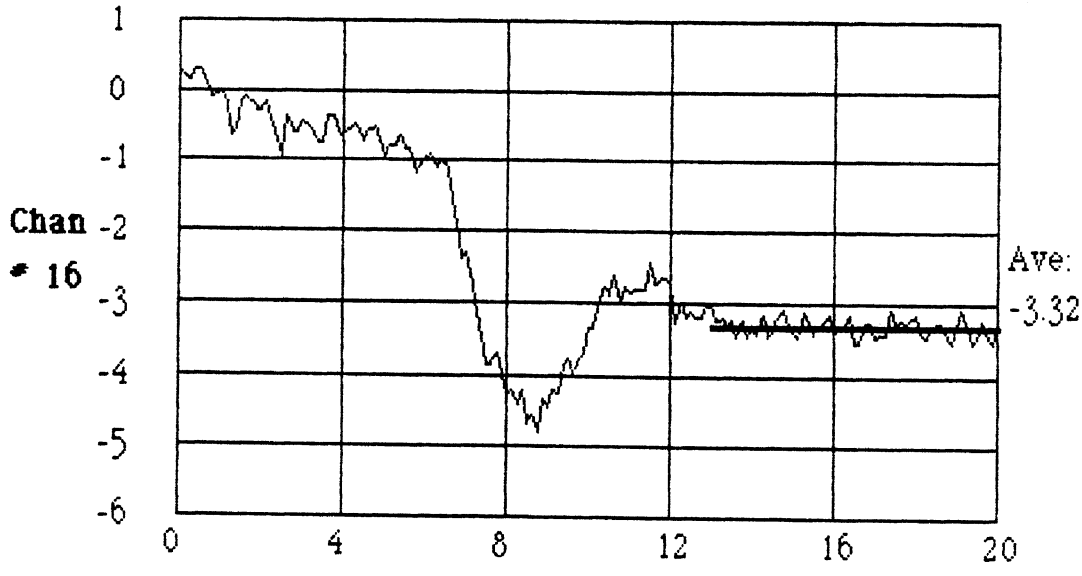

Chan
8
20
0
-20
-40
-60
-80
-100
0
4
8
12
16
20
Ave:
-43.6


Chan
9
.3
0
-.3
-.6
-.9
-1.2
-1.5
-1.8
0
4
8
12
16
20
Ave:
-.773


Chan
10
.3
0
-.3
-.6
-.9
-1.2
-1.5
-1.8
0
4
8
12
16
20
Ave:
-.814


Chan
11
.4
0
-.4
-.8
-1.2
-1.6
-2
-2.4
0
4
8
12
16
20
Ave:
-1.66


Chan
15
3
2
1
0
-1
-2
-3
-4
0
4
8
12
16
20
Ave:
-.592

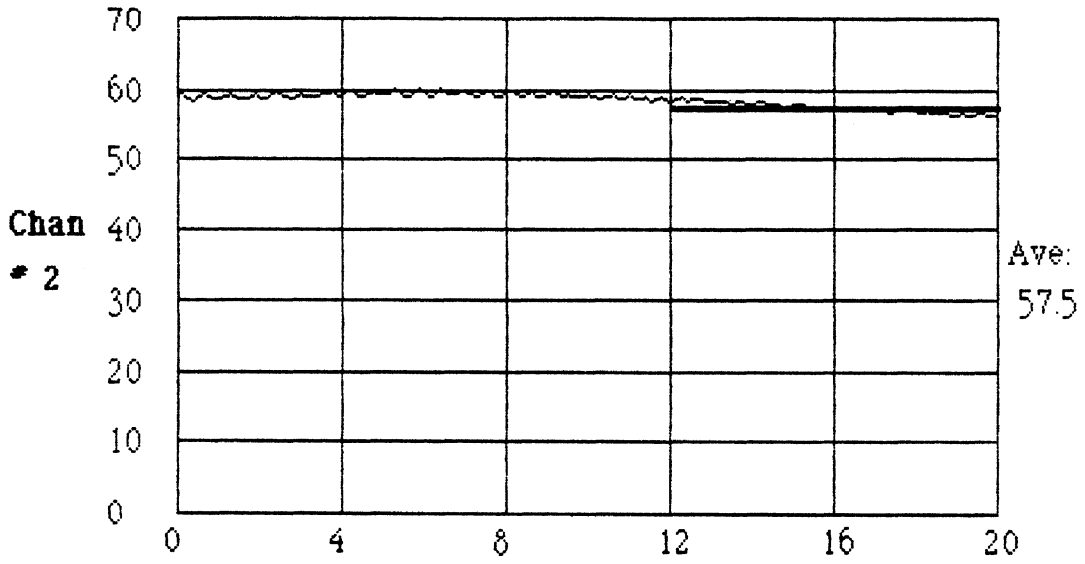

Chan
16
1
0
-1
-2
-3
-4
-5
-6
0
4
8
12
16
20
Ave:
-3.32

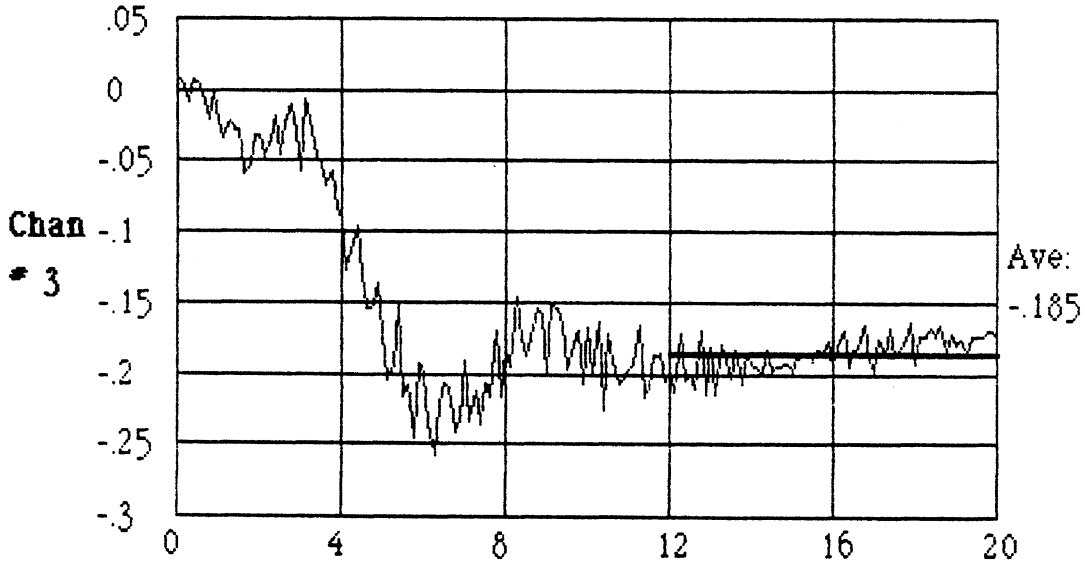
Tractor-semitrailer

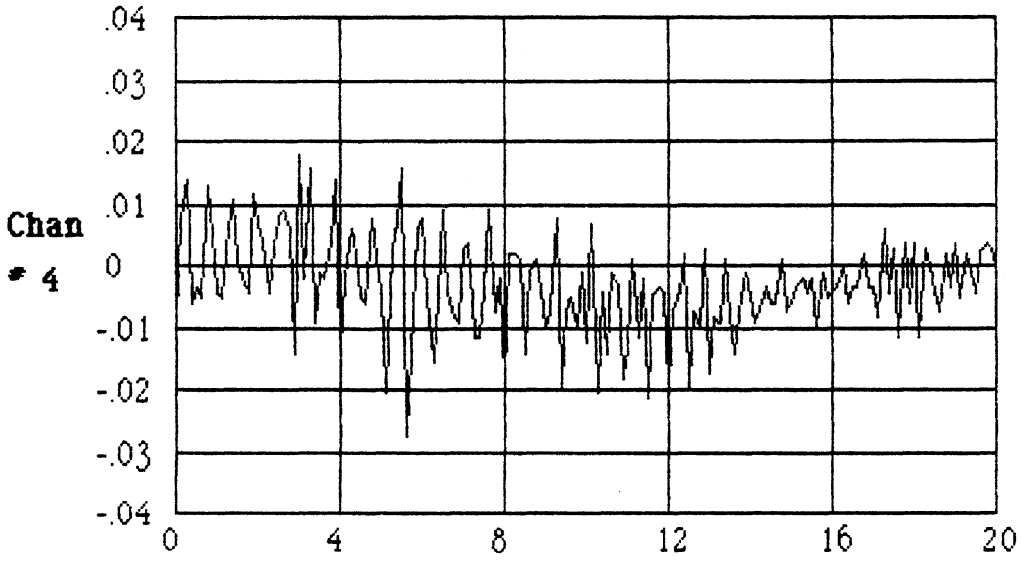
Curve #3

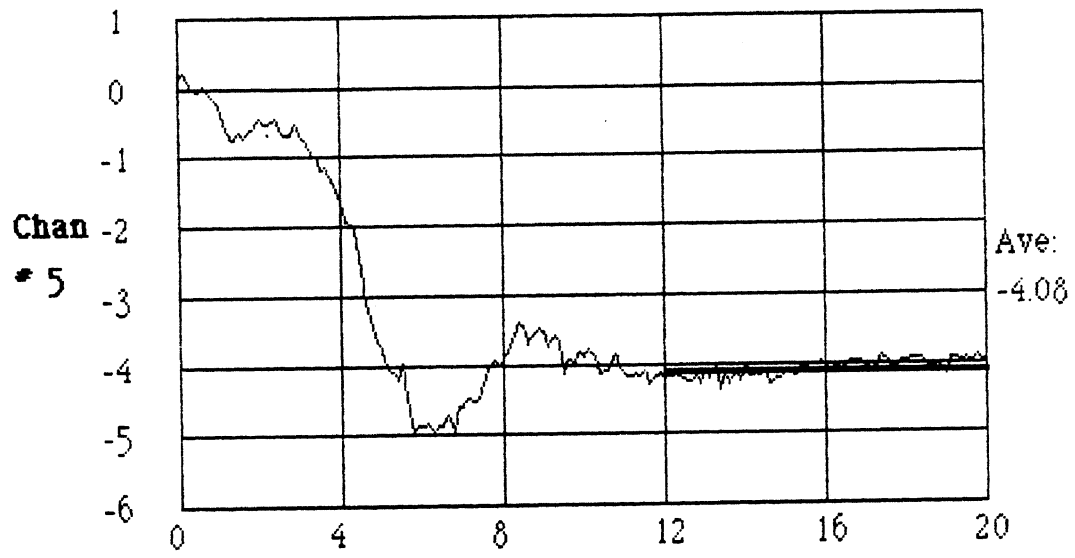
Repeat 1

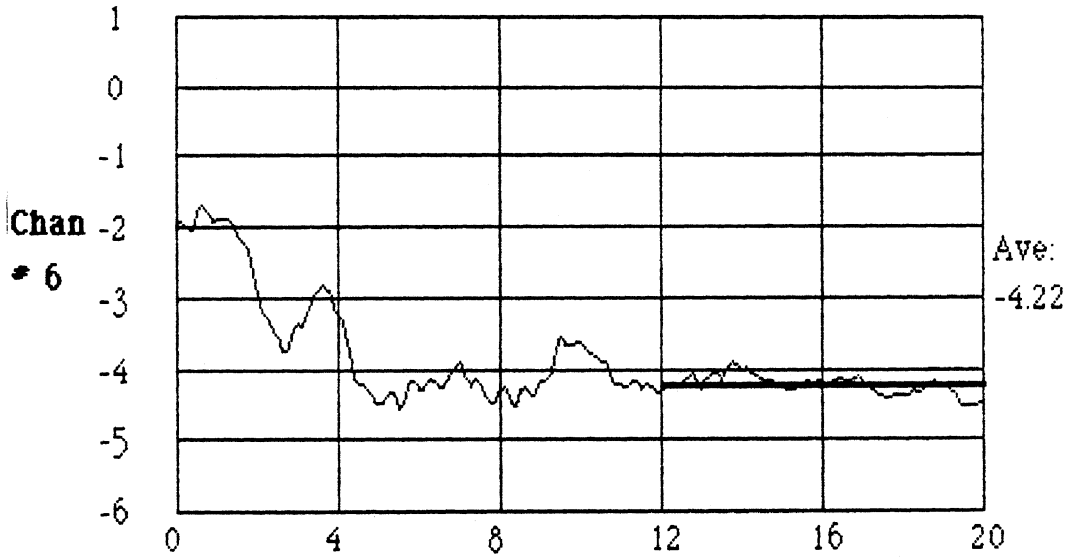
Steady Turning

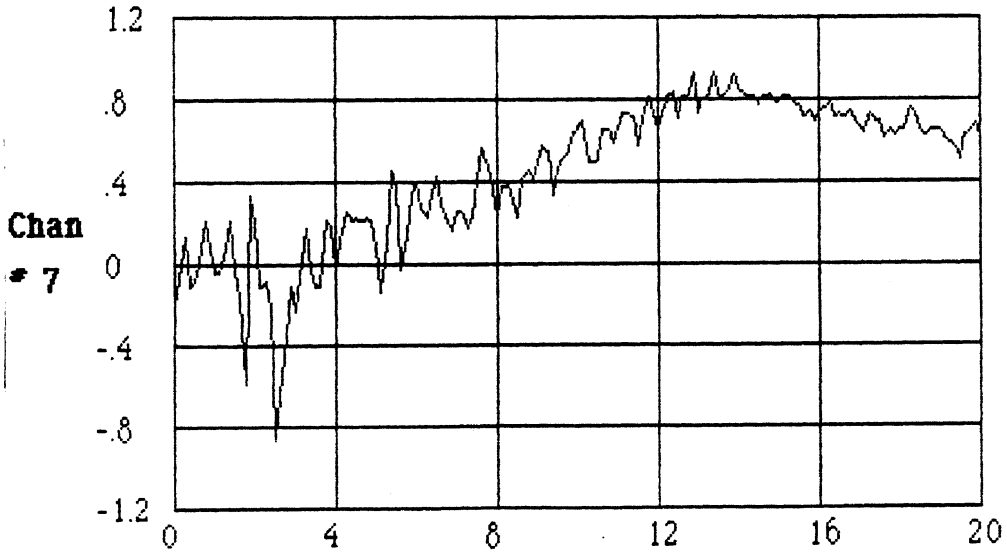

Chan
2
70
60
50
40
30
20
10
0
0
4
8
12
16
20
Ave:
57.5

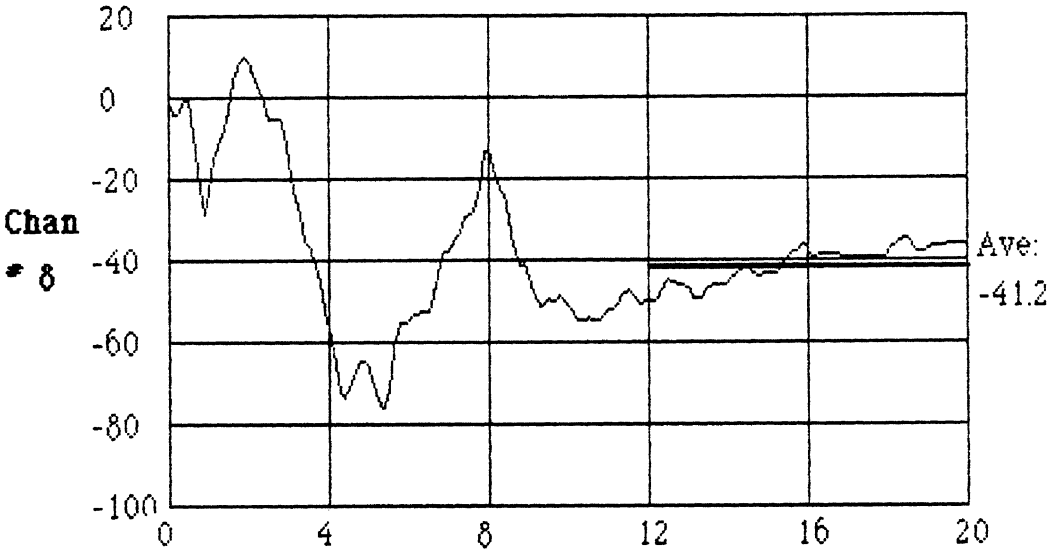

Chan
3
.05
0
-.05
-.1
-.15
-.2
-.25
-.3
0
4
8
12
16
20
Ave:
-.185

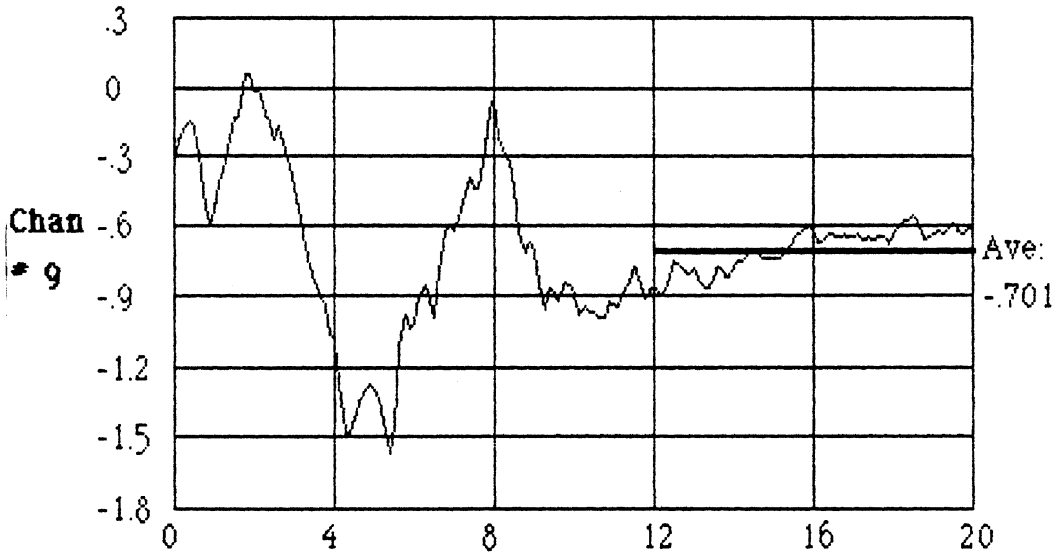

Chan
4
.04
.03
.02
.01
0
-.01
-.02
-.03
-.04
0
4
8
12
16
20

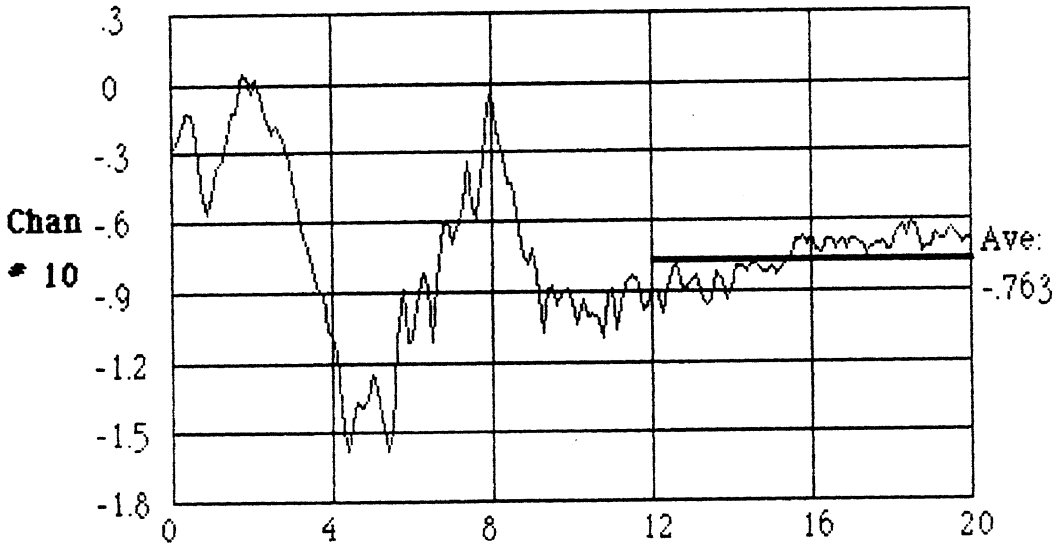

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
4
8
12
16
20
Ave:
-4.08

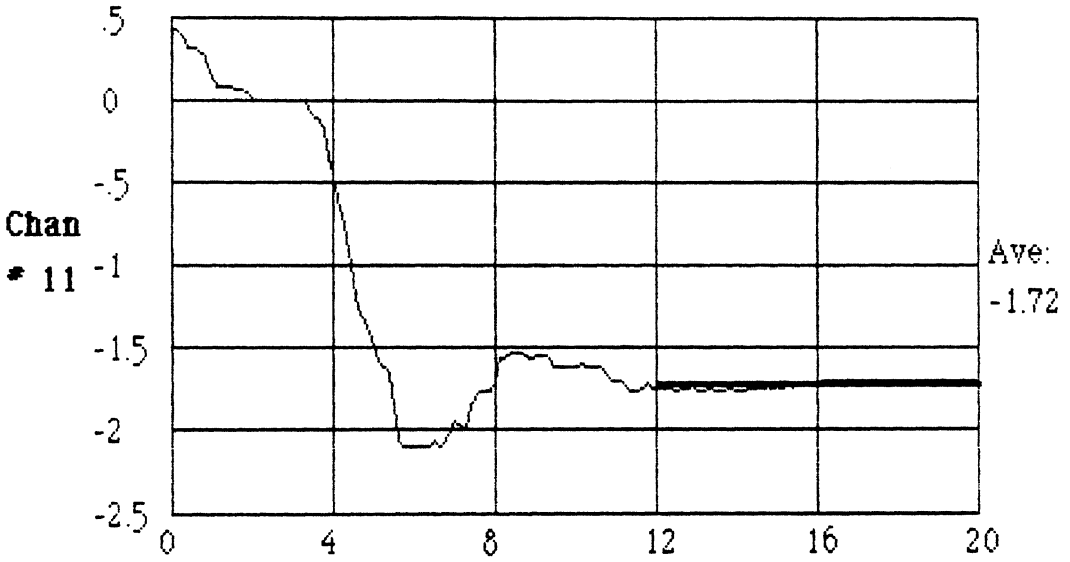

Chan
6
1
0
-1
-2
-3
-4
-5
-6
0
4
8
12
16
20
Ave:
-4.22

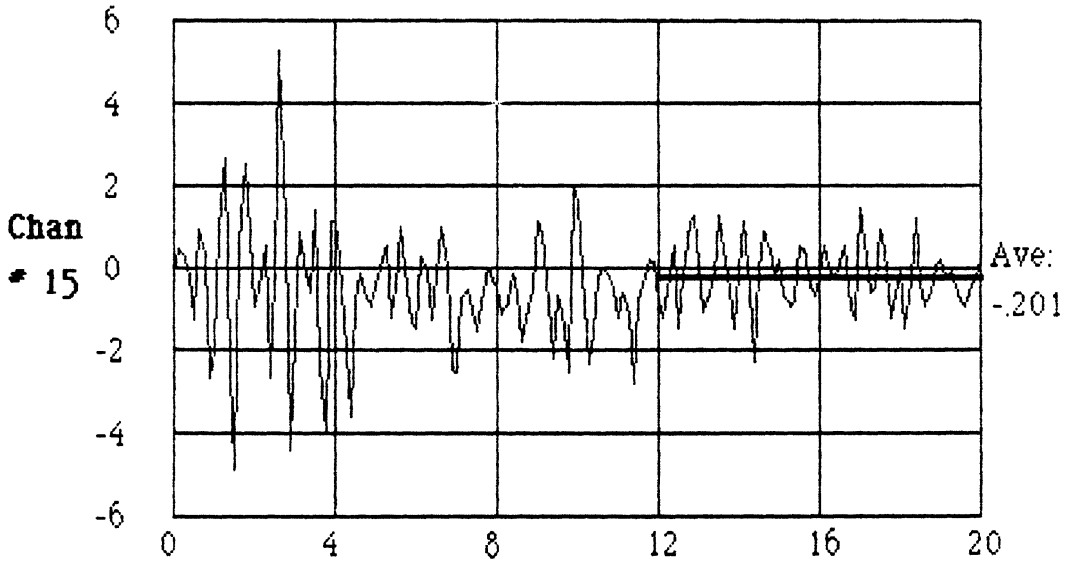

Chan
7
1.2
.8
.4
0
-.4
-.8
-1.2
0
4
8
12
16
20

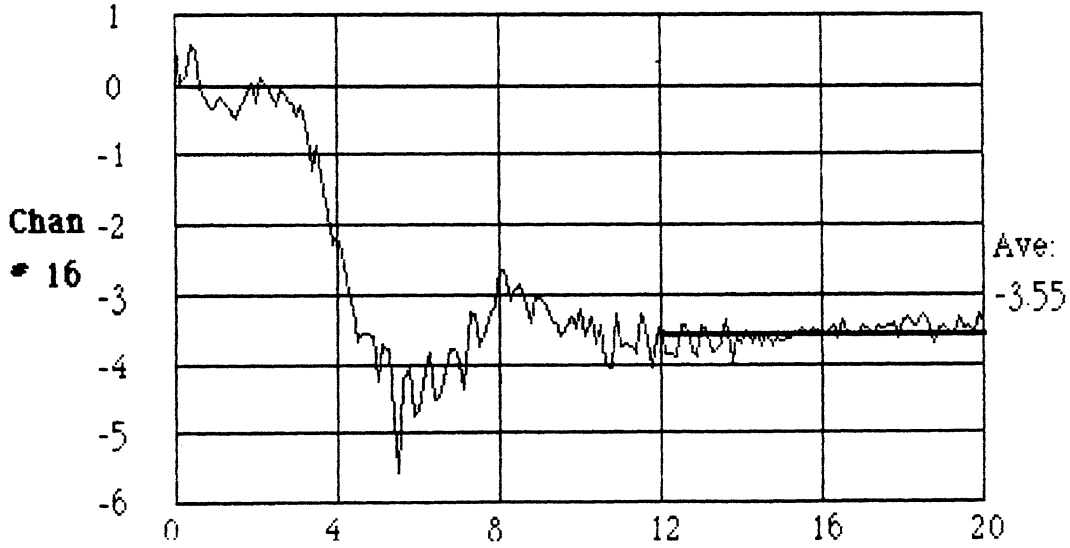

Chan
8
20
0
-20
-40
-60
-80
-100
0
4
8
12
16
20
Ave:
-41.2


Chan
9
.3
0
-.3
-.6
-.9
-1.2
-1.5
-1.8
0
4
8
12
16
20
Ave:
-.701


Chan
10
.3
0
-.3
-.6
-.9
-1.2
-1.5
-1.8
0
4
8
12
16
20
Ave:
-.763


Chan
11
.5
0
-.5
-1
-1.5
-2
-2.5
0
4
8
12
16
20
Ave:
-1.72


Chan
15
6
4
2
0
-2
-4
-6
0
4
8
12
16
20
Ave:
-.201

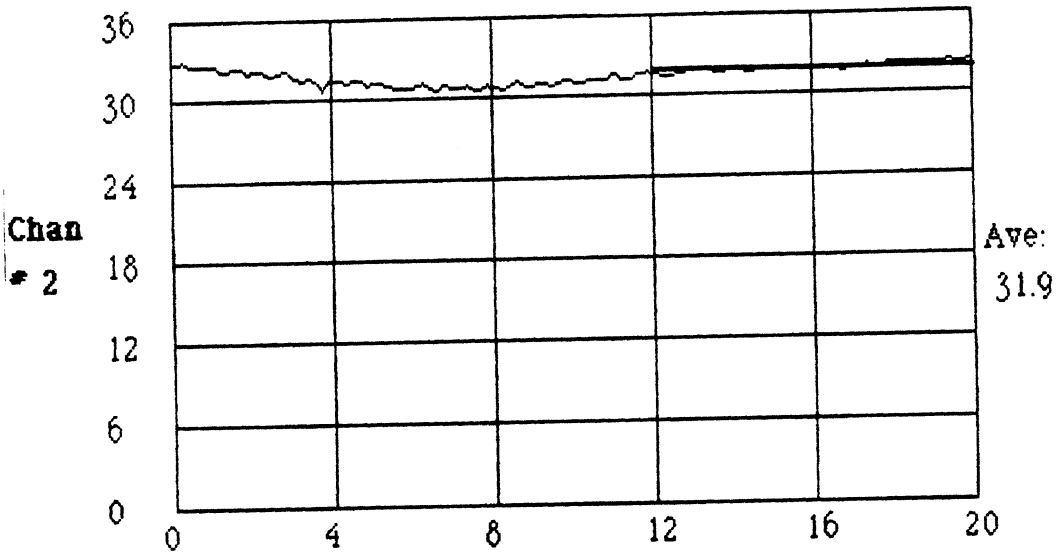

Chan
16
1
0
-1
-2
-3
-4
-5
-6
0
4
8
12
16
20
Ave:
-3.55

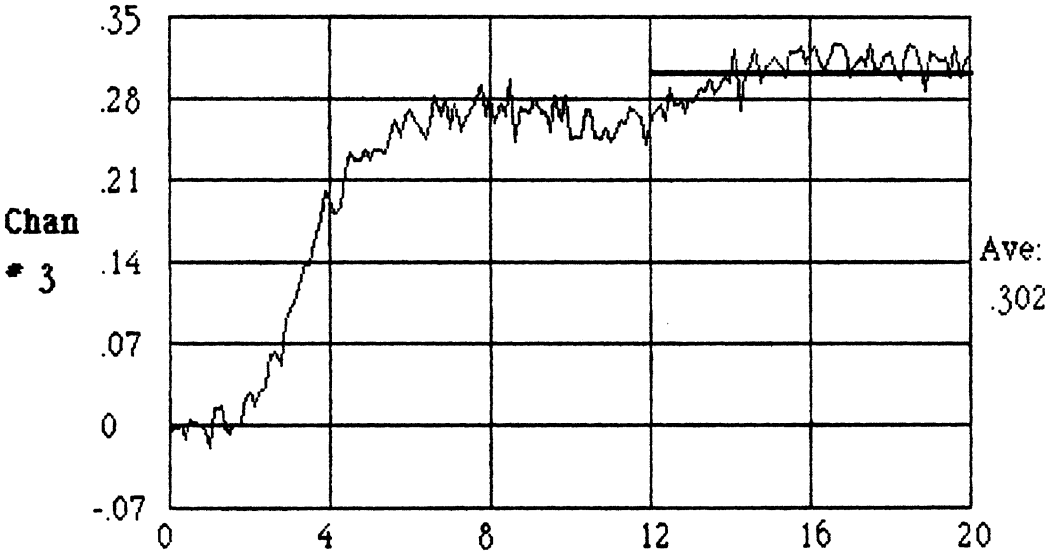
Tractor-semitrailer

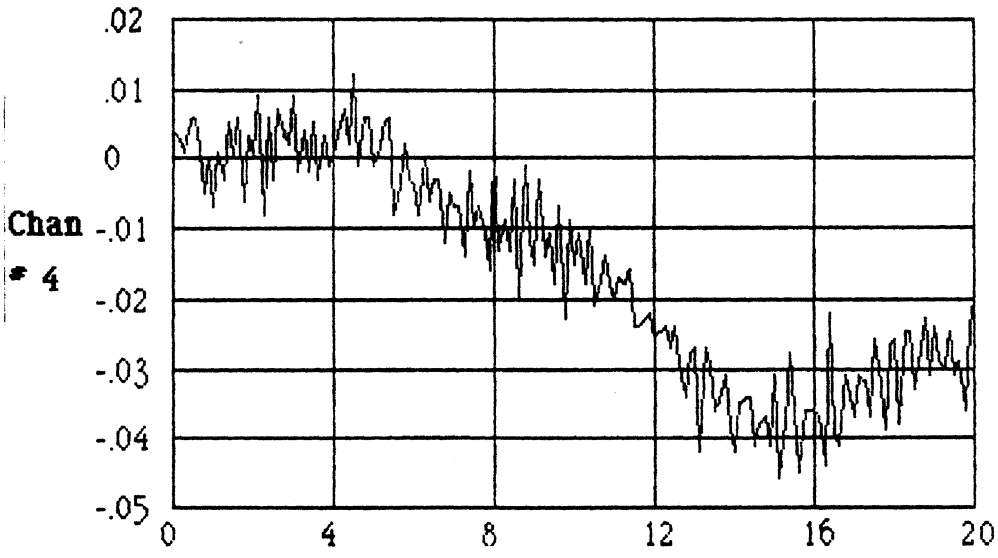
Ramp

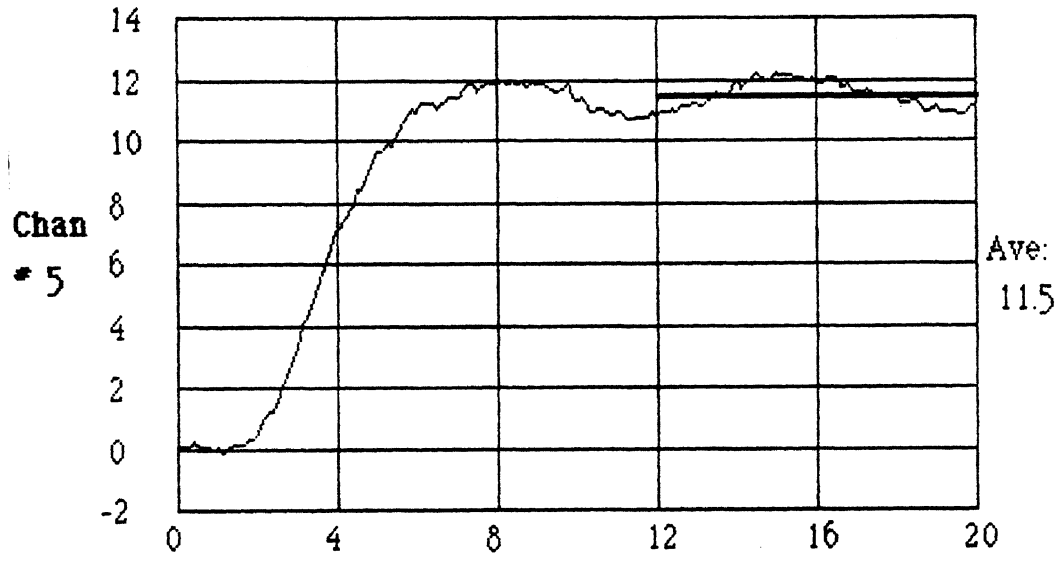
Repeat 1

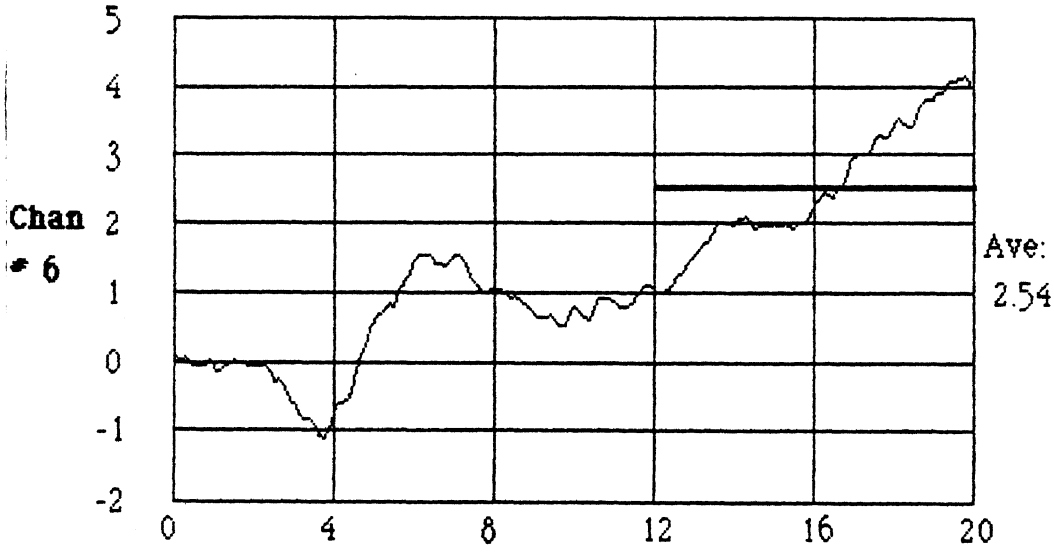
Steady Turning

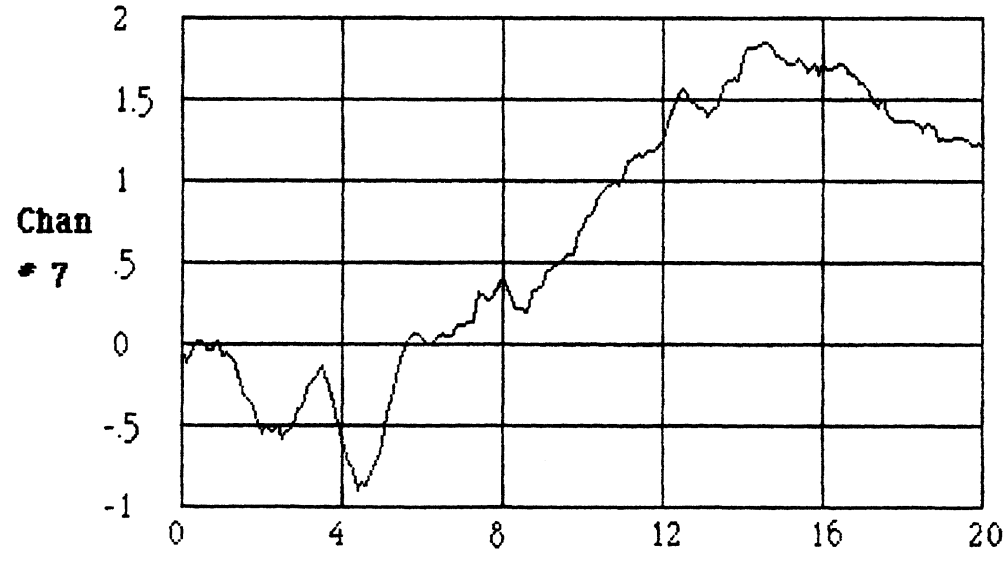

Chan
2
36
30
24
18
12
6
0
0
4
8
12
16
20
Ave:
31.9

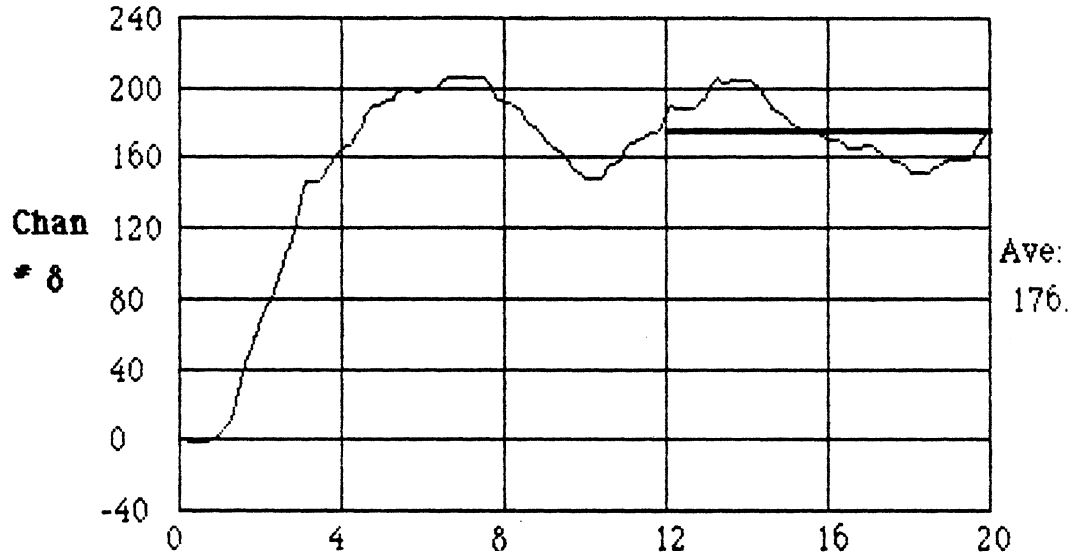

Chan
3
.35
.28
.21
.14
.07
0
-.07
0
4
8
12
16
20
Ave:
.302

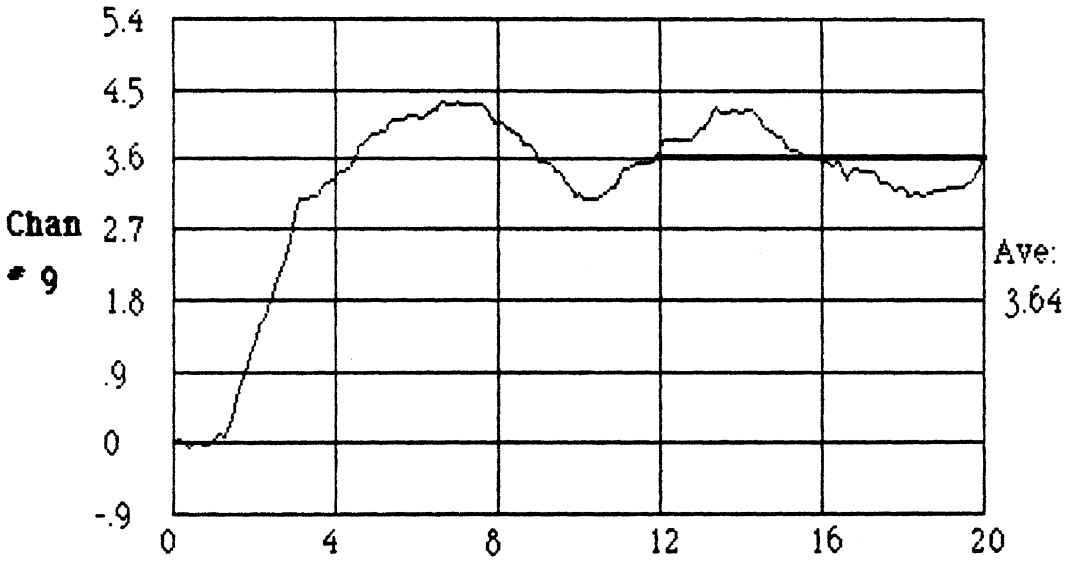

Chan
4
.02
.01
0
-.01
-.02
-.03
-.04
-.05
0
4
8
12
16
20

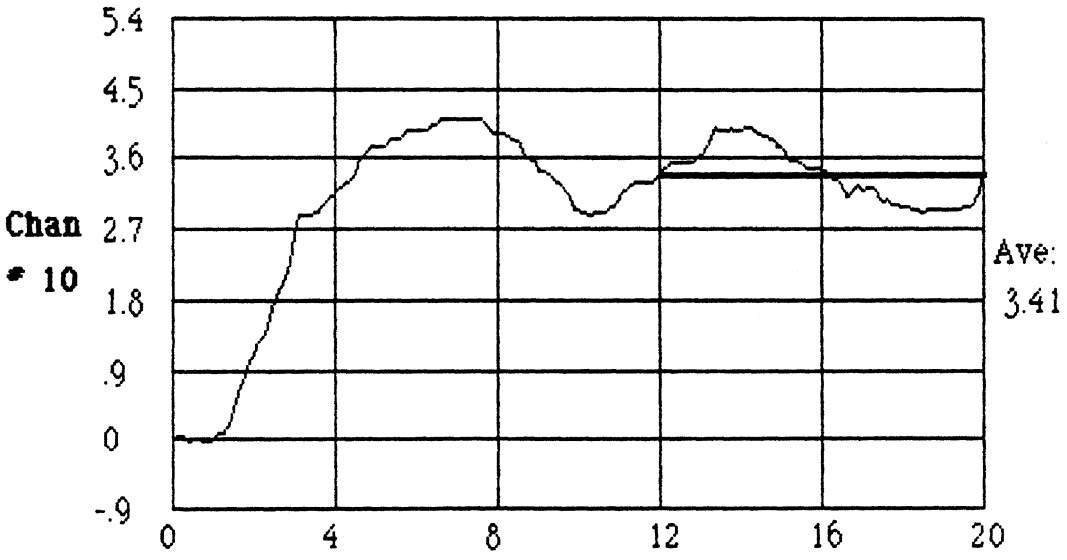

Chan
5
14
12
10
8
6
4
2
0
-2
0
4
8
12
16
20
Ave:
11.5

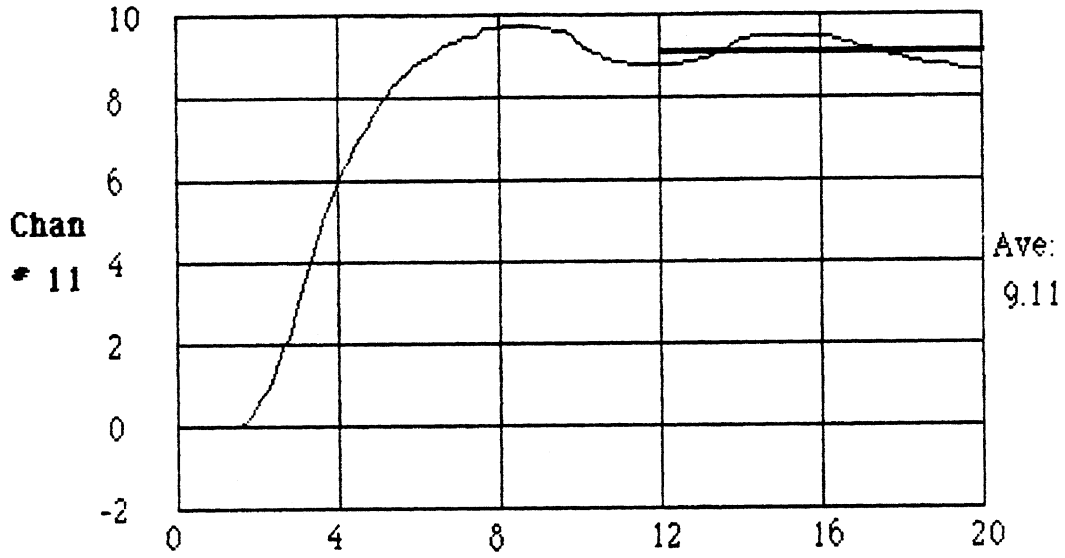

Chan
6
5
4
3
2
1
0
-1
-2
0
4
8
12
16
20
Ave:
2.54

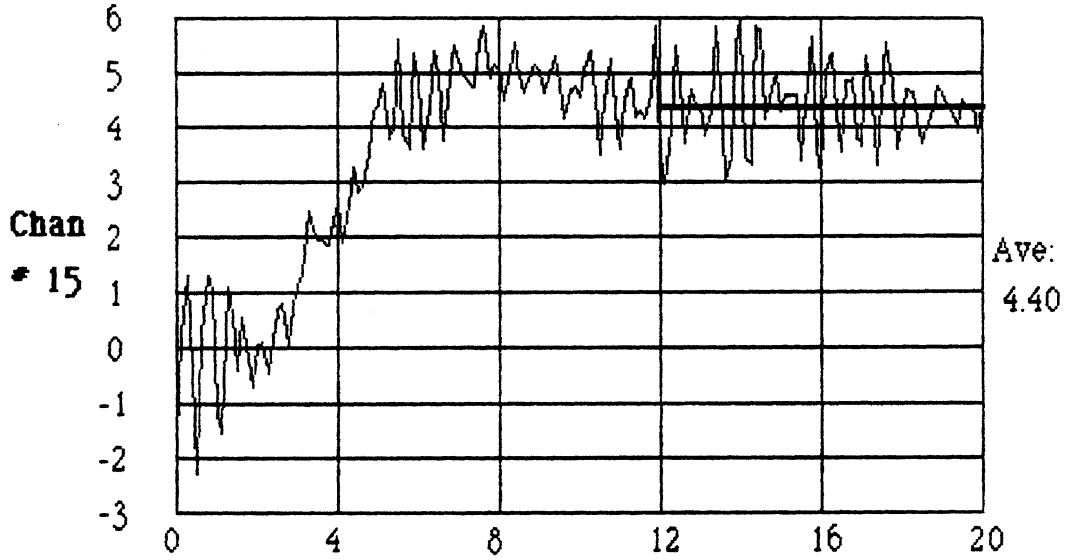

Chan
7
2
1.5
1
.5
0
-.5
-1
0
4
8
12
16
20

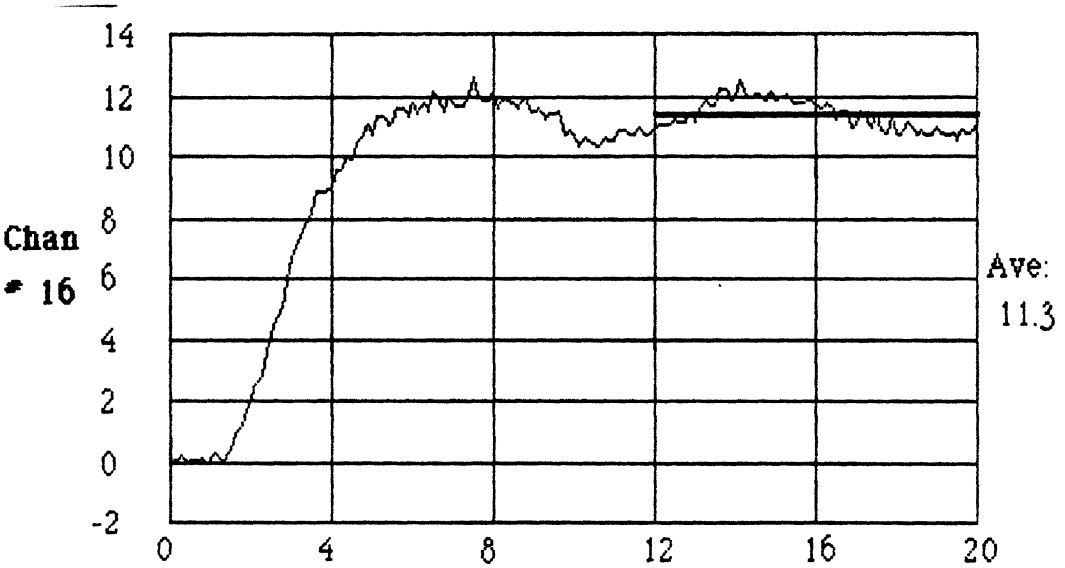

Chan
8
240
200
160
120
80
40
0
-40
0
4
8
12
16
20
Ave:
176.


Chan
9
5.4
4.5
3.6
2.7
1.8
.9
0
-.9
0
4
8
12
16
20
Ave:
3.64


Chan
10
5.4
4.5
3.6
2.7
1.8
.9
0
-.9
0
4
8
12
16
20
Ave:
3.41


Chan
11
10
8
6
4
2
0
-2
0
4
8
12
16
20
Ave:
9.11


Chan
15
6
5
4
3
2
1
0
-1
-2
-3
0
4
8
12
16
20
Ave:
4.40

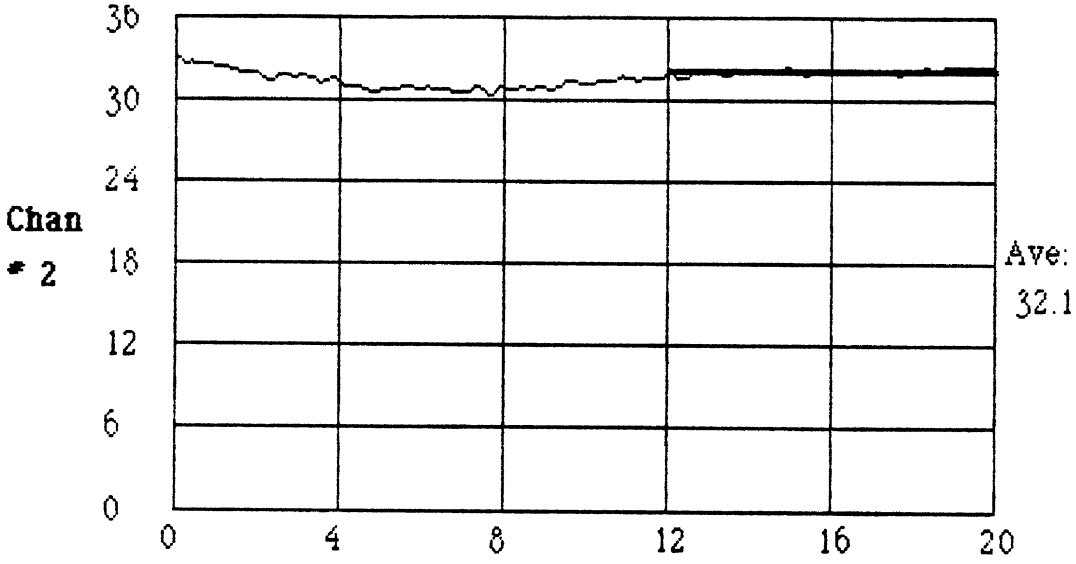

Chan
16
14
12
10
8
6
4
2
0
-2
0
4
8
12
16
20
Ave:
11.3

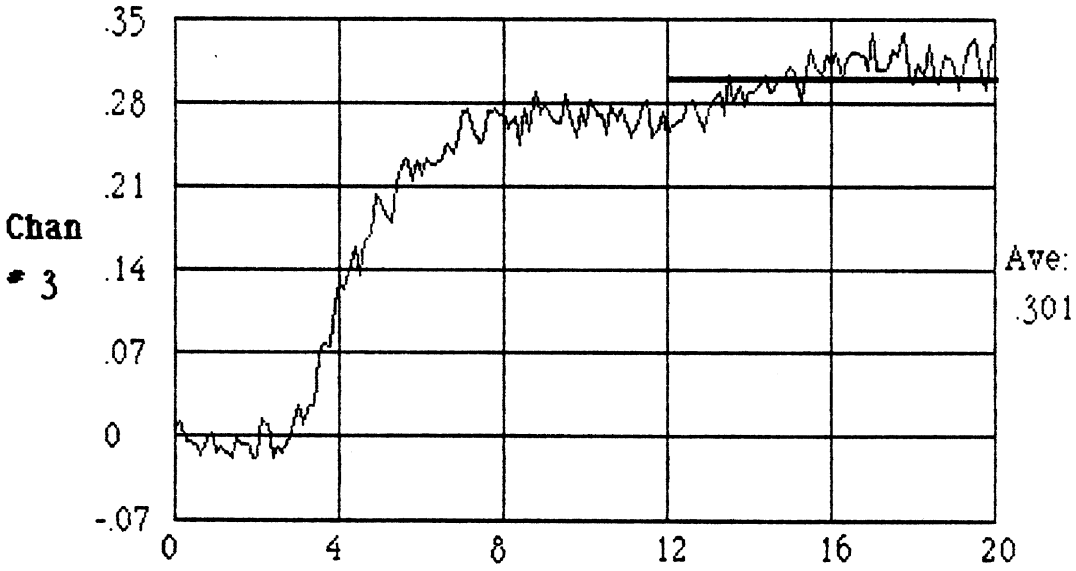
Tractor-semitrailer

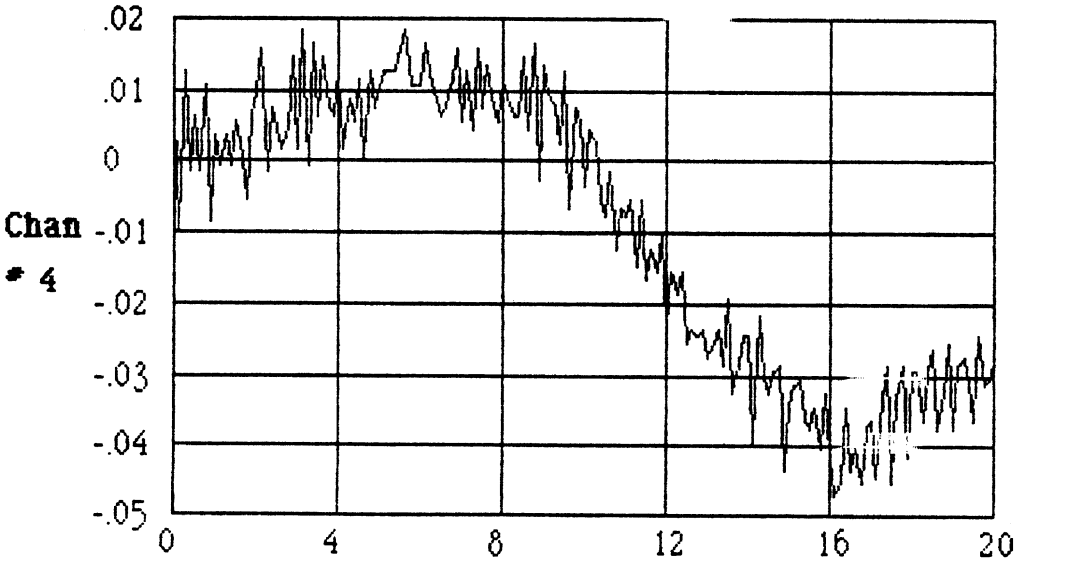
Ramp

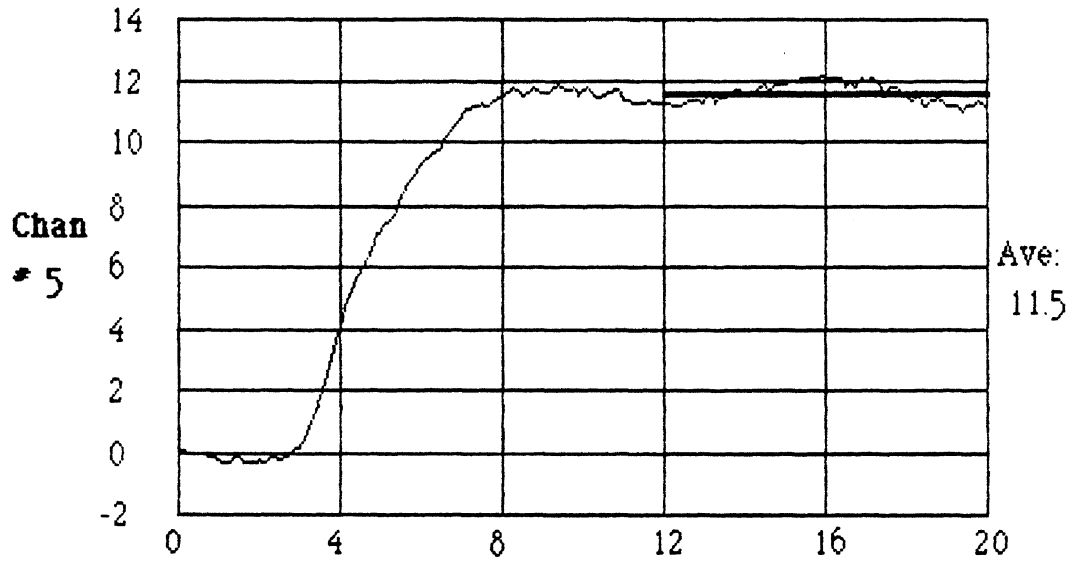
Repeat 2

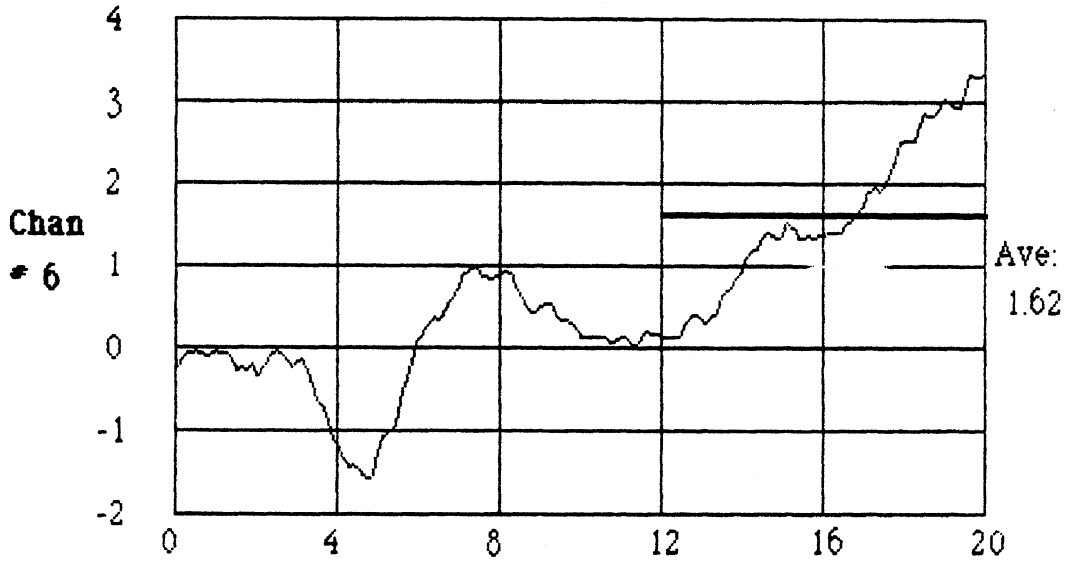
Steady Turning

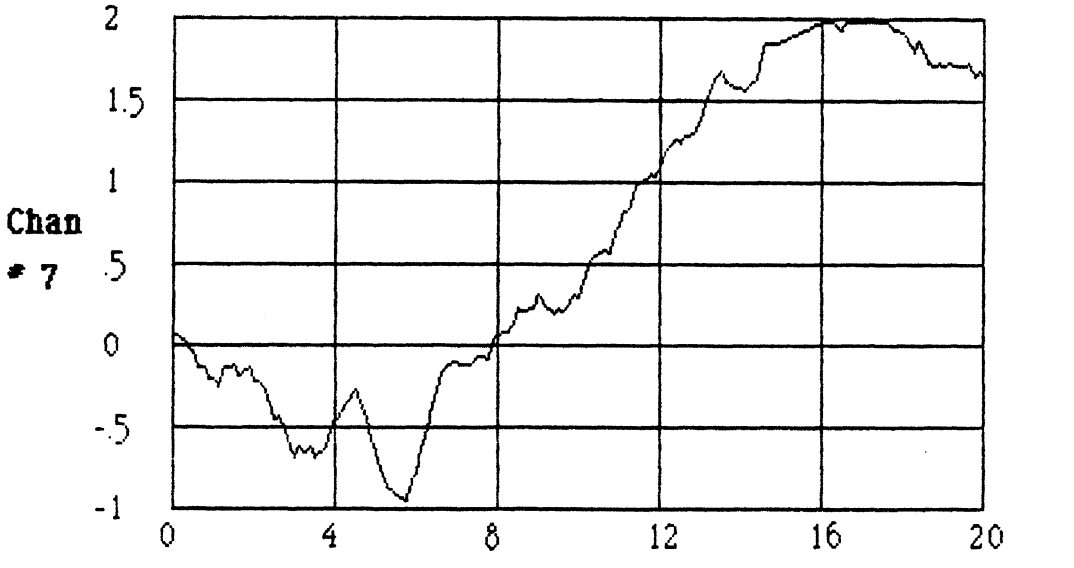

Chan
2
36
30
24
18
12
6
0
0
4
8
12
16
20
Ave:
32.1

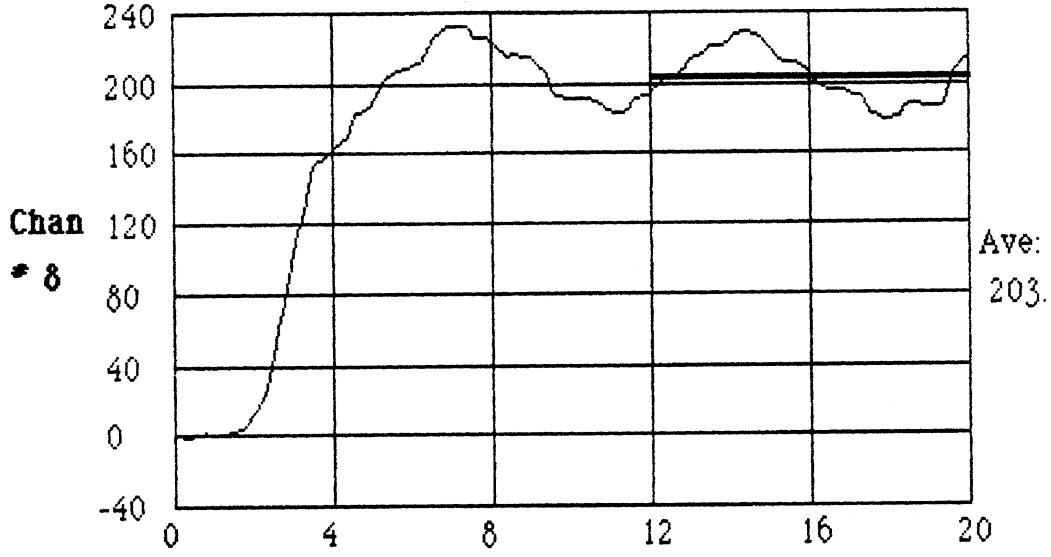

Chan
3
.35
.28
.21
.14
.07
0
-.07
0
4
8
12
16
20
Ave:
.301

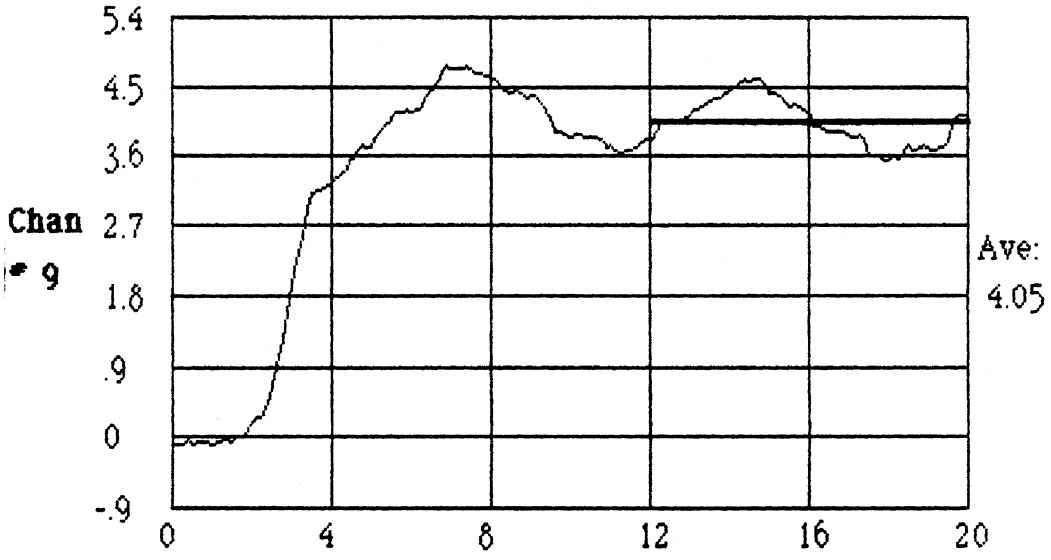

Chan
4
.02
.01
0
-.01
-.02
-.03
-.04
-.05
0
4
8
12
16
20

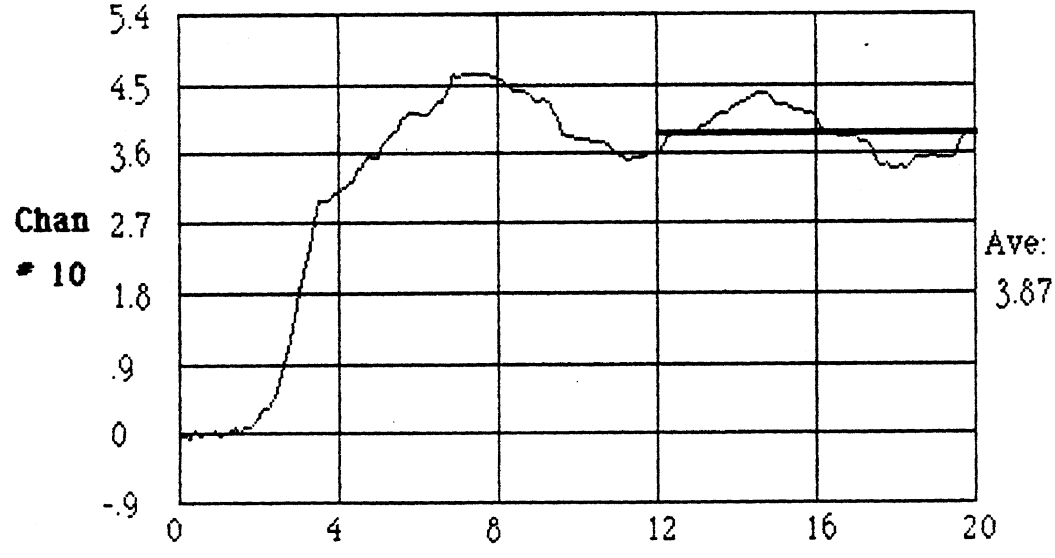

Chan
5
14
12
10
8
6
4
2
0
-2
0
4
8
12
16
20
Ave:
11.5

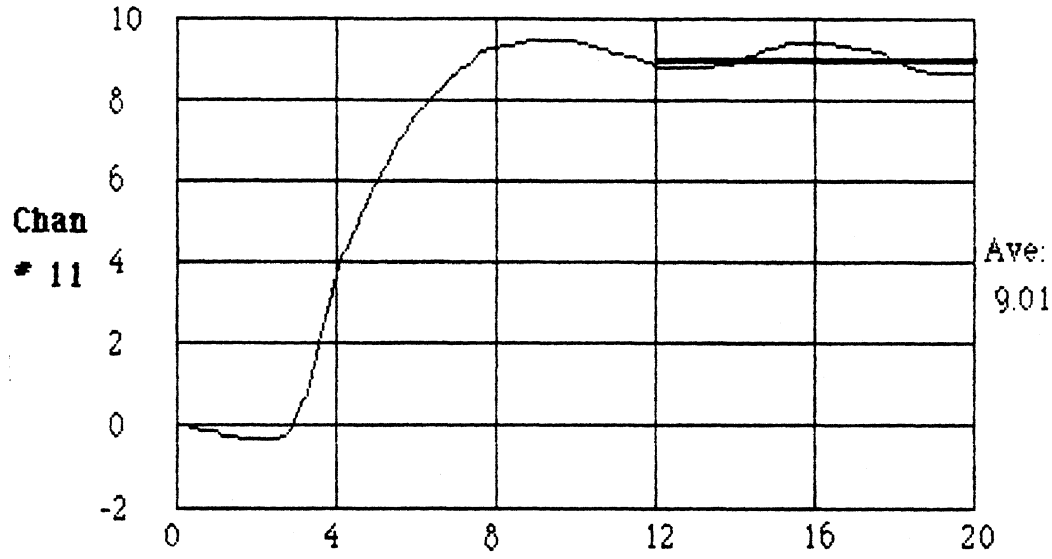

Chan
6
4
3
2
1
0
-1
-2
0
4
8
12
16
20
Ave:
1.62

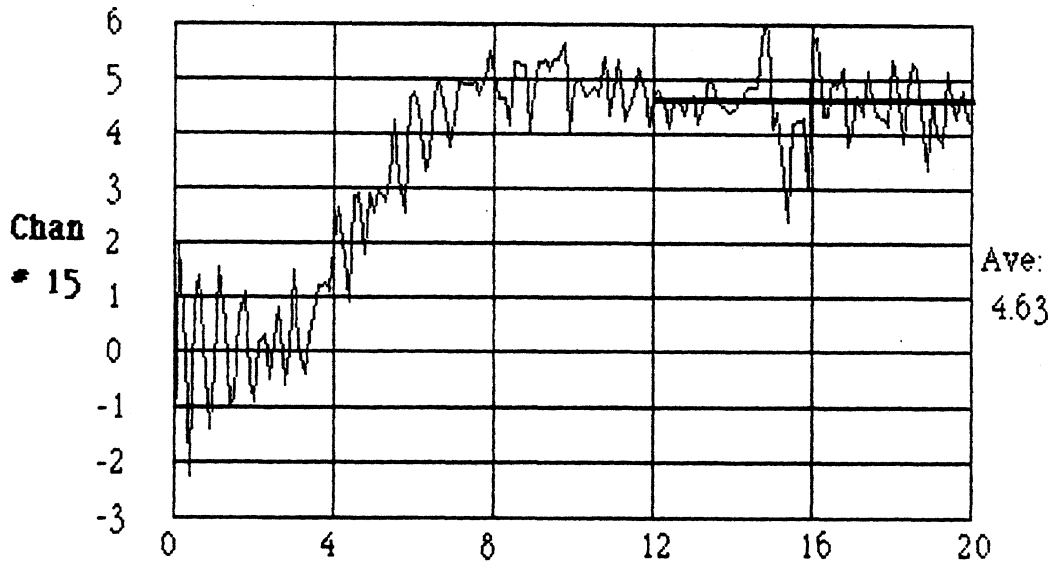

Chan
7
2
1.5
1
.5
0
-.5
-1
0
4
8
12
16
20

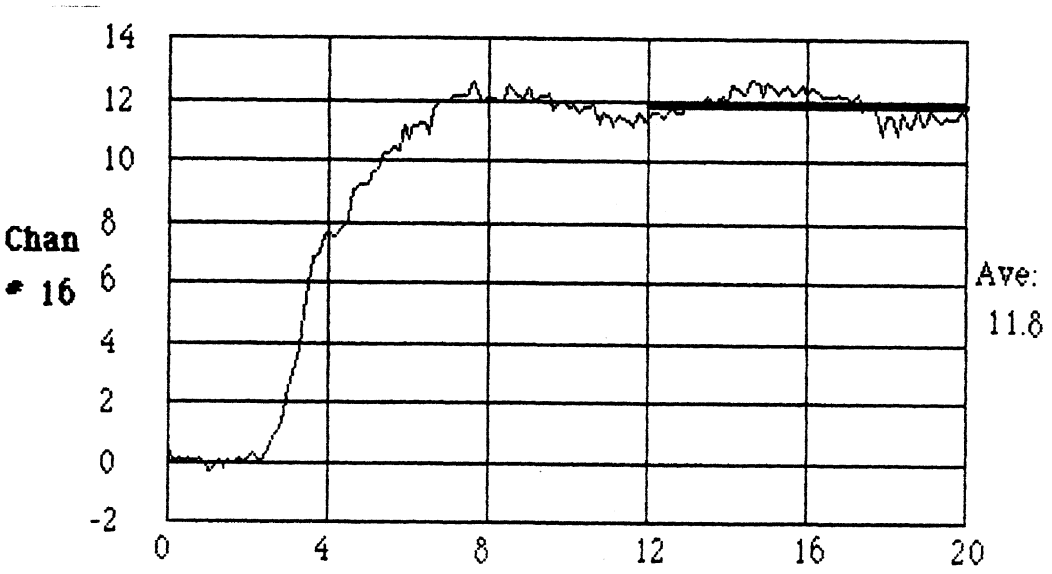

Chan
8
240
200
160
120
80
40
0
-40
0
4
8
12
16
20
Ave:
203.


Chan
9
5.4
4.5
3.6
2.7
1.8
.9
0
-.9
0
4
8
12
16
20
Ave:
4.05


Chan
10
5.4
4.5
3.6
2.7
1.8
.9
0
-.9
0
4
8
12
16
20
Ave:
3.87


Chan
11
10
8
6
4
2
0
-2
0
4
8
12
16
20
Ave:
9.01


Chan
15
6
5
4
3
2
1
0
-1
-2
-3
0
4
8
12
16
20
Ave:
4.63

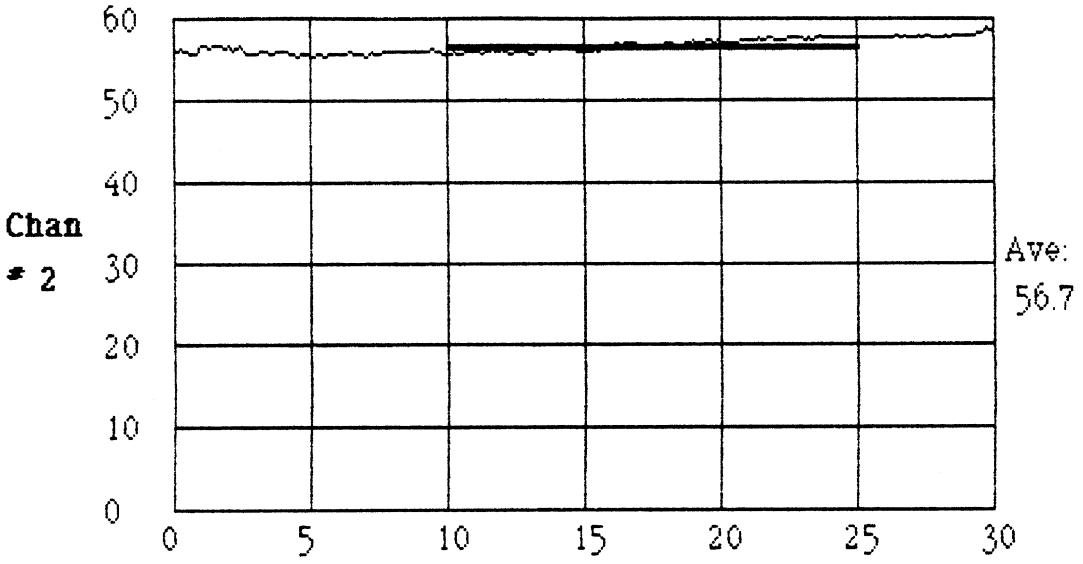

Chan
16
14
12
10
8
6
4
2
0
-2
0
4
8
12
16
20
Ave:
11.8

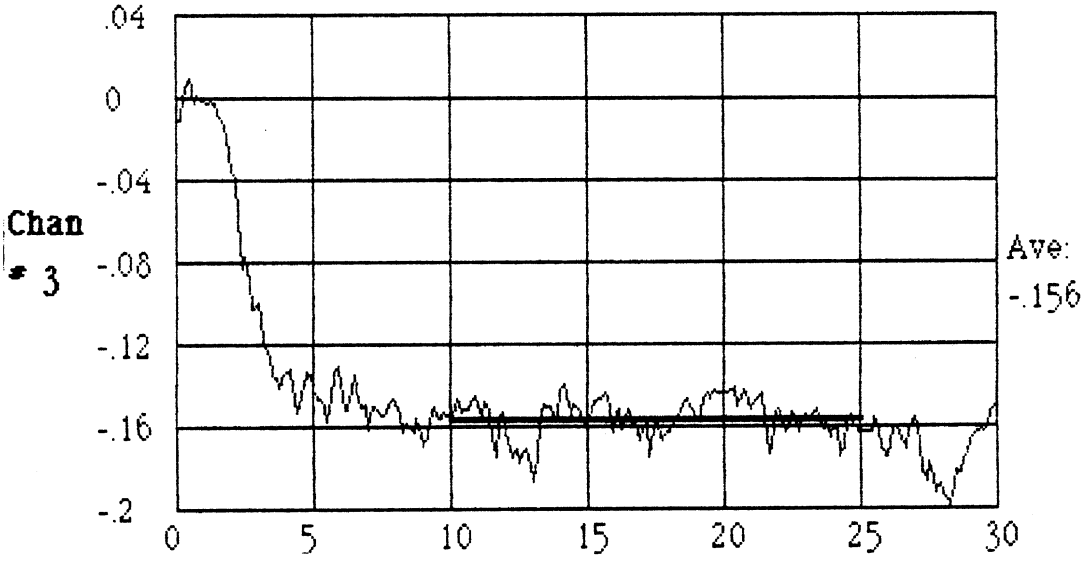
Dodge Aries

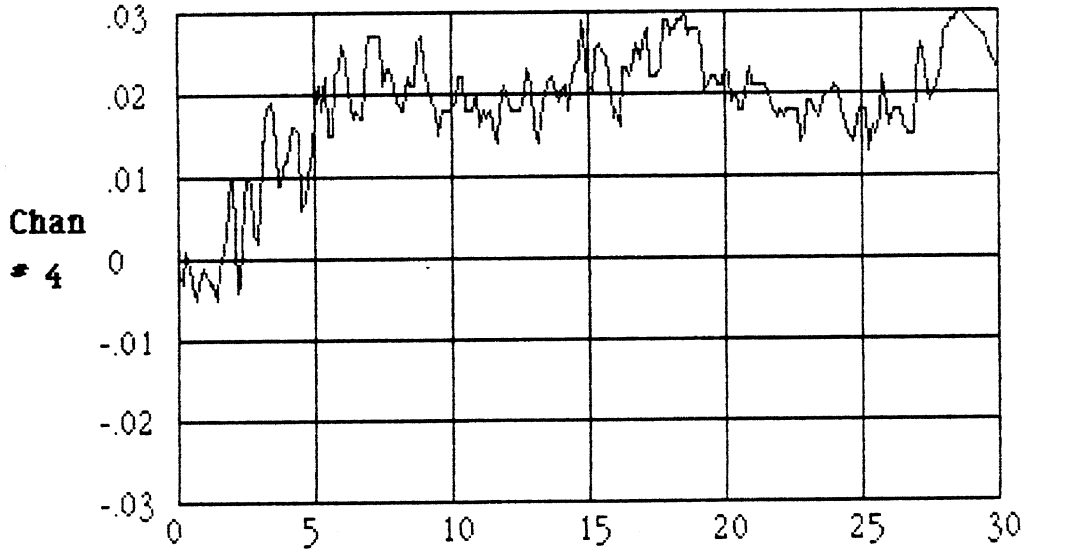
Curve #1

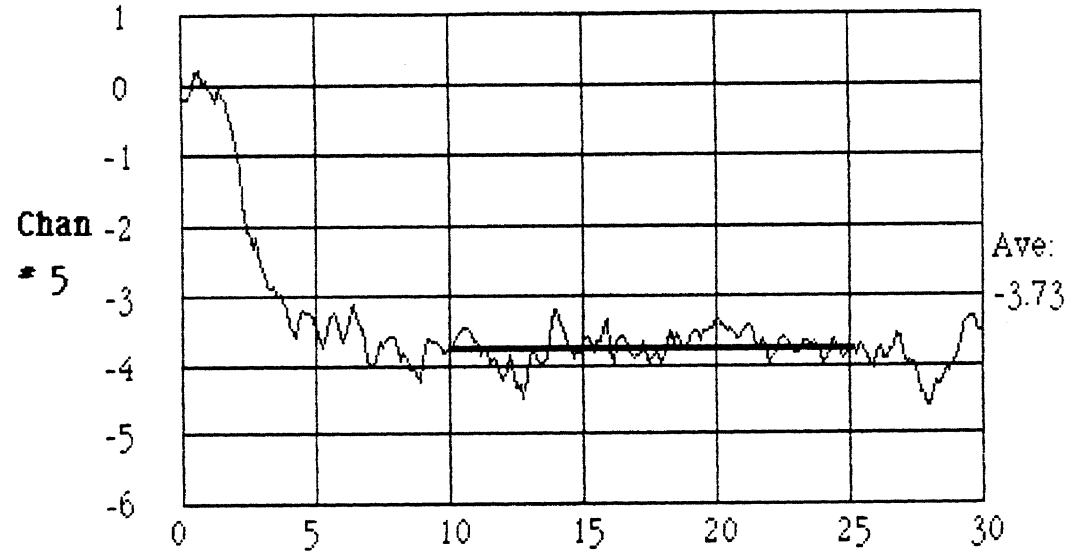
Repeat 1

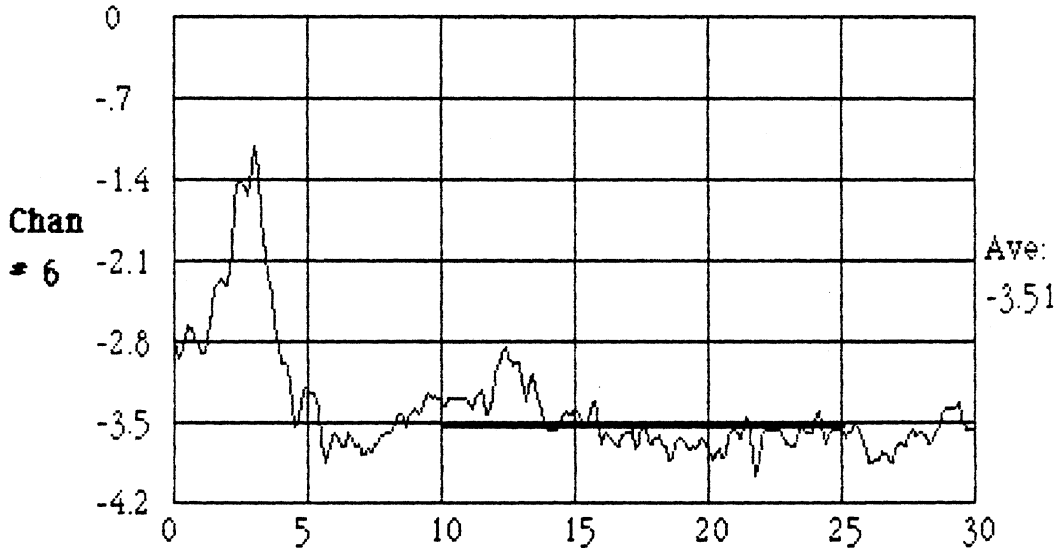
Steady Turning

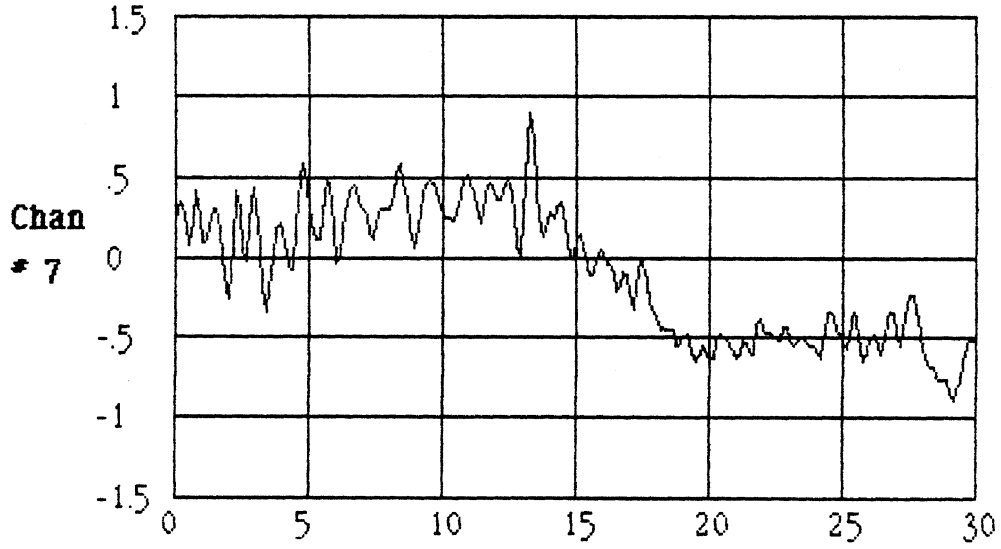

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
56.7

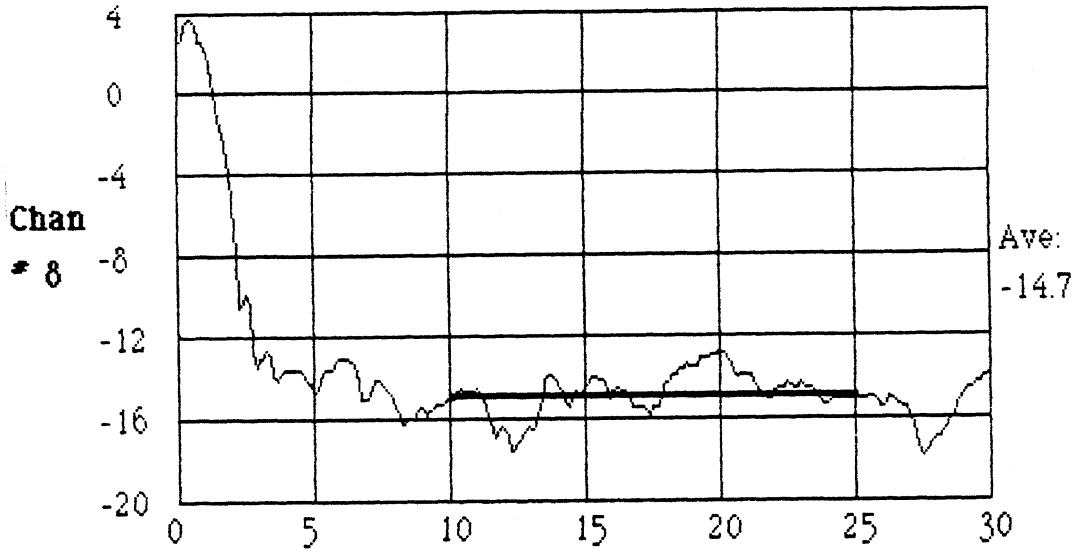

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.156

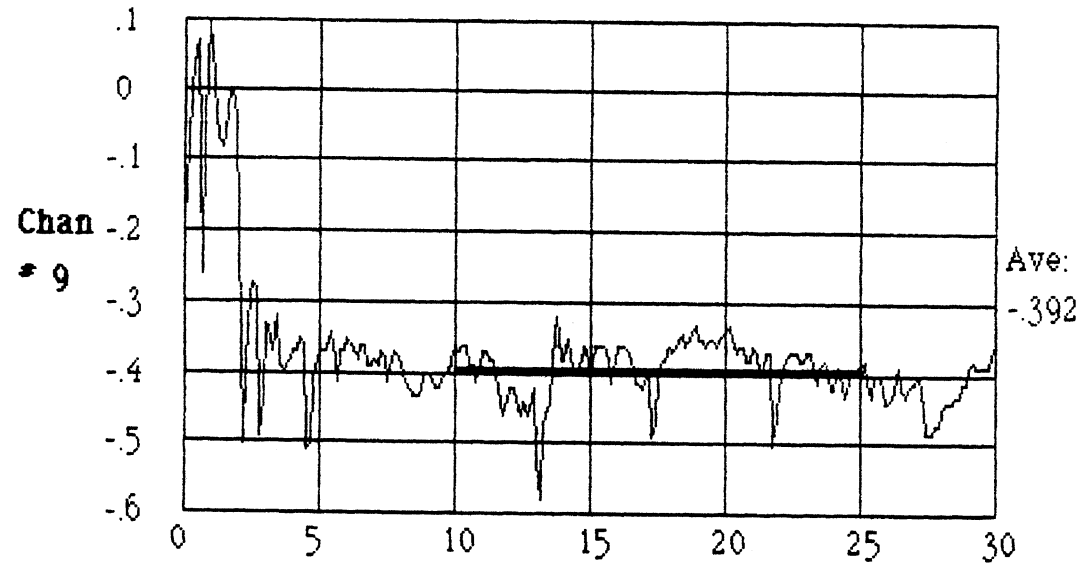

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

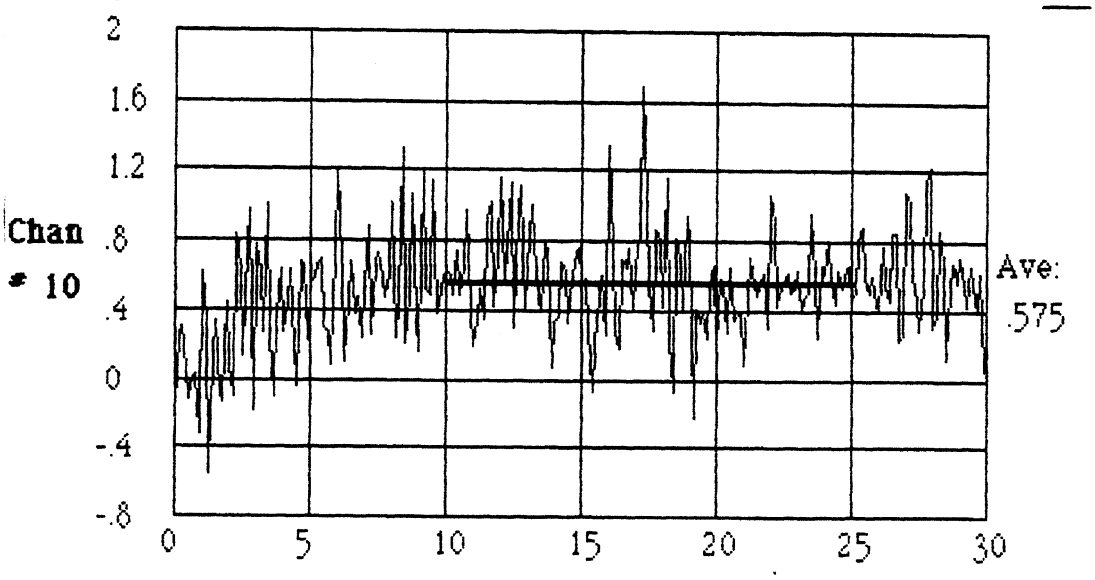

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-3.73


Chan
6
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
5
10
15
20
25
30
Ave:
-3.51


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
4
0
-4
-8
-12
-16
-20
0
5
10
15
20
25
30
Ave:
-14.7


Chan
9
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
0
5
10
15
20
25
30
Ave:
-.392

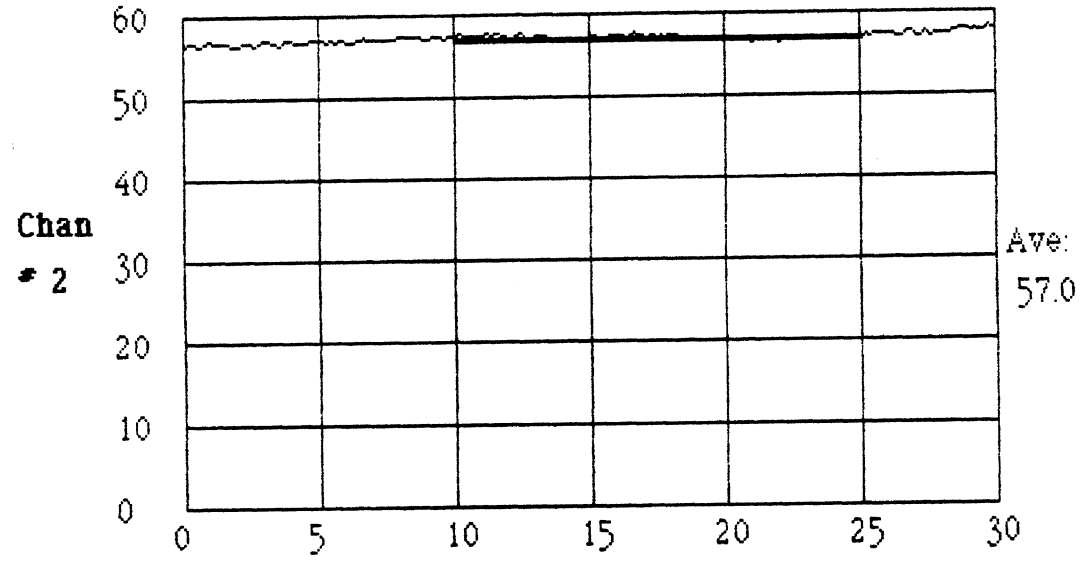

Chan
10
2
1.6
1.2
.8
.4
0
-.4
-.8
0
5
10
15
20
25
30
Ave:
.575

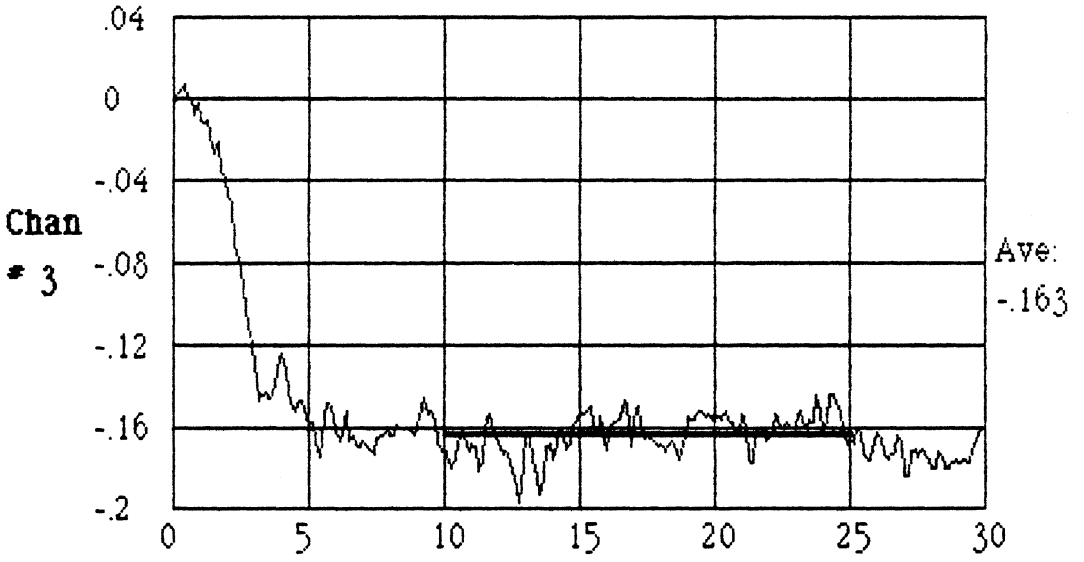
Dodge Aries

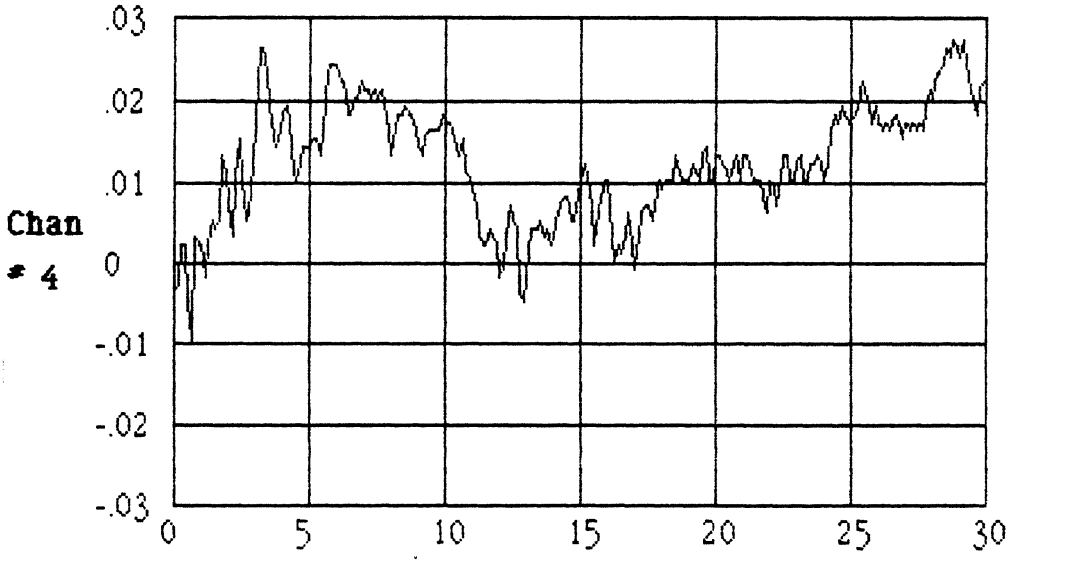
Curve #1

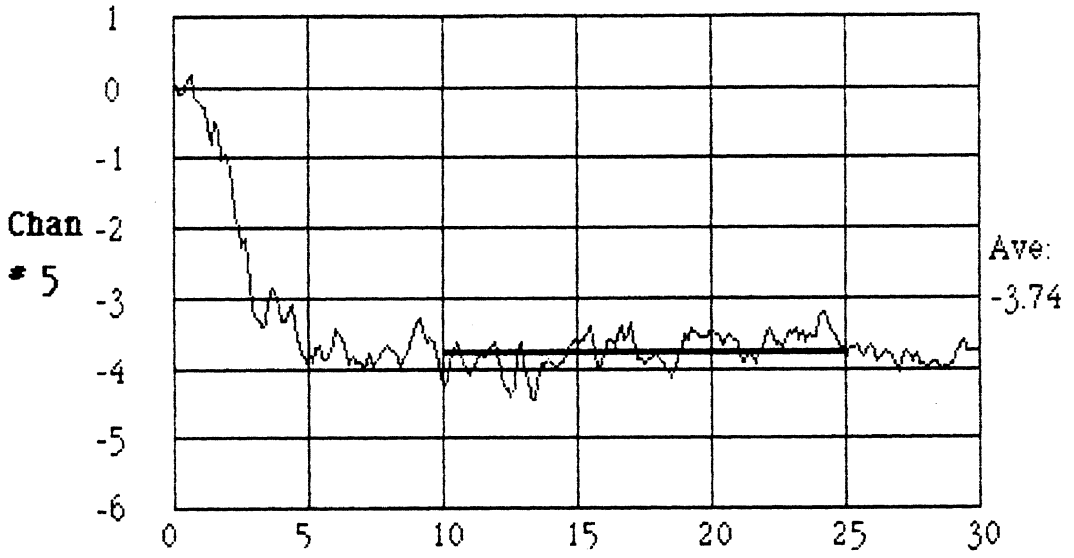
Repeat 2

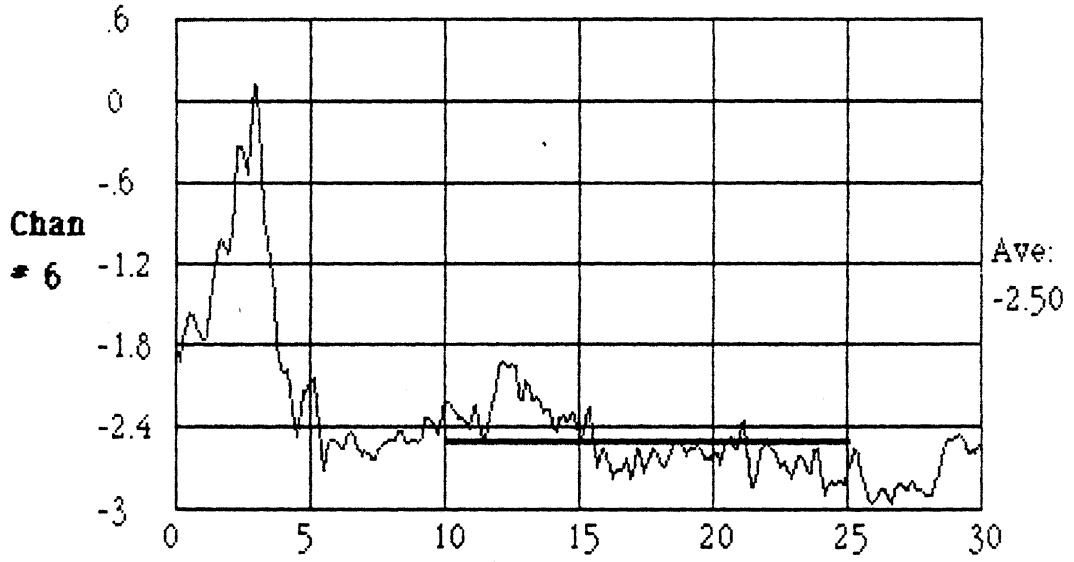
Steady Turning

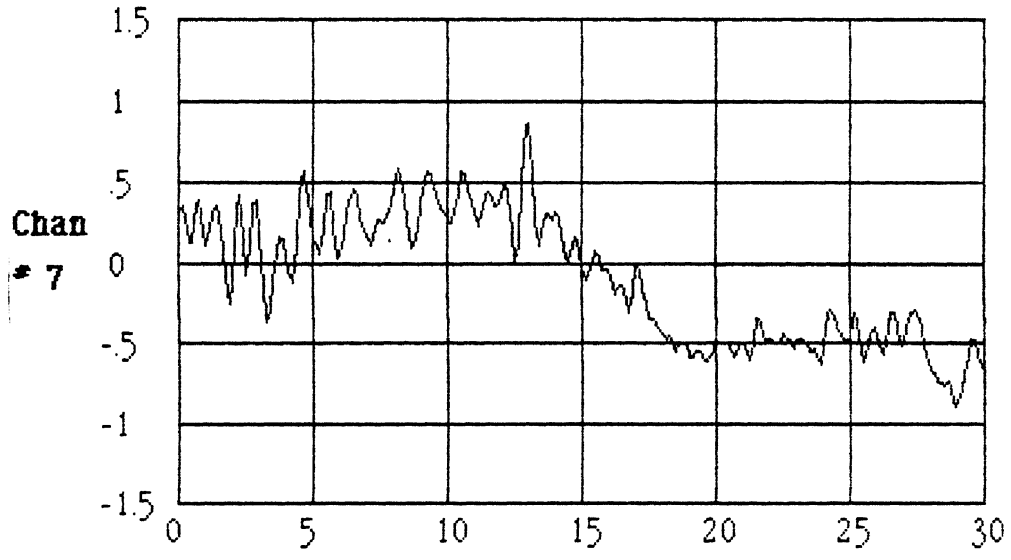

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
57.0

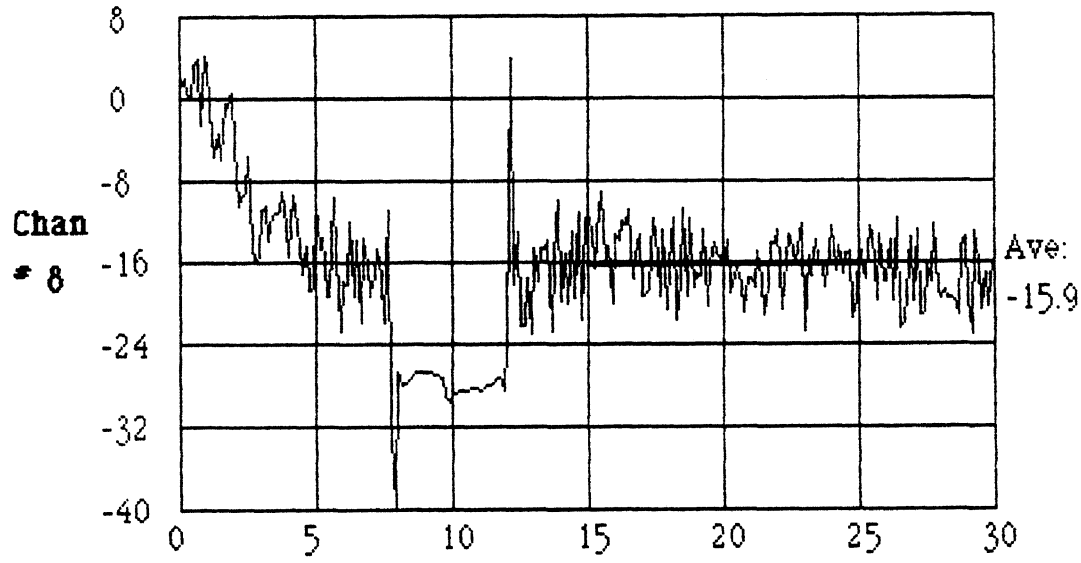

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.163

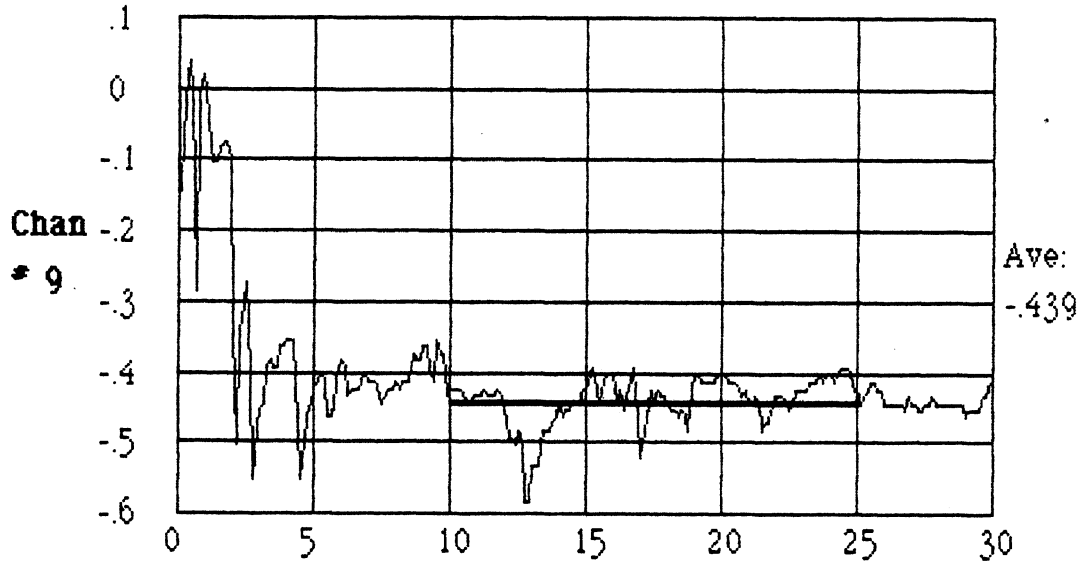

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

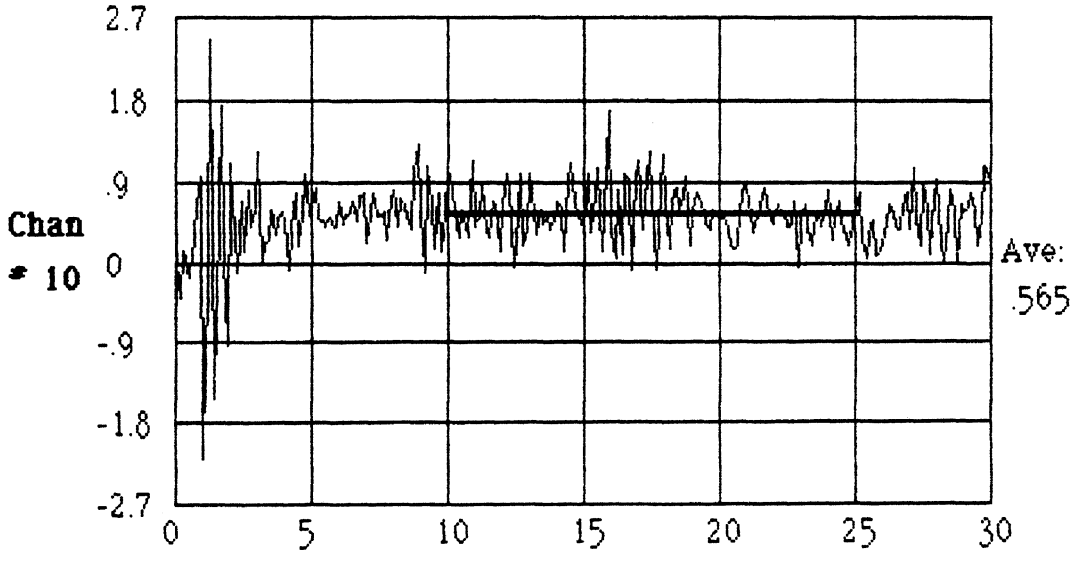

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-3.74


Chan
6
.6
0
-.6
-1.2
-1.8
-2.4
-3
0
5
10
15
20
25
30
Ave:
-2.50


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
8
0
-8
-16
-24
-32
-40
0
5
10
15
20
25
30
Ave:
-15.9


Chan
9
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
0
5
10
15
20
25
30
Ave:
-.439

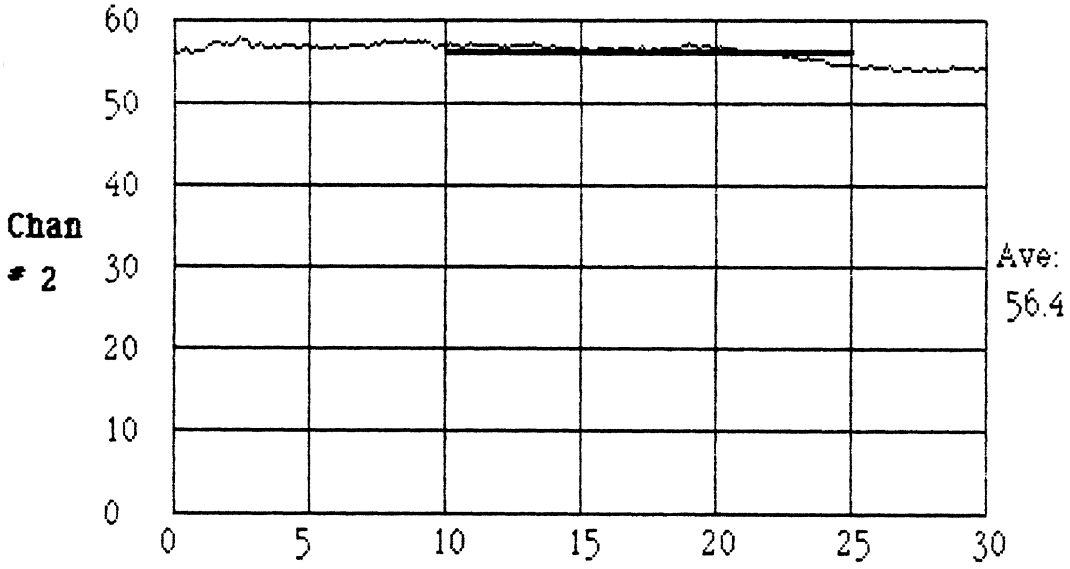

Chan
10
2.7
1.8
.9
0
-.9
-1.8
-2.7
0
5
10
15
20
25
30
Ave:
.565

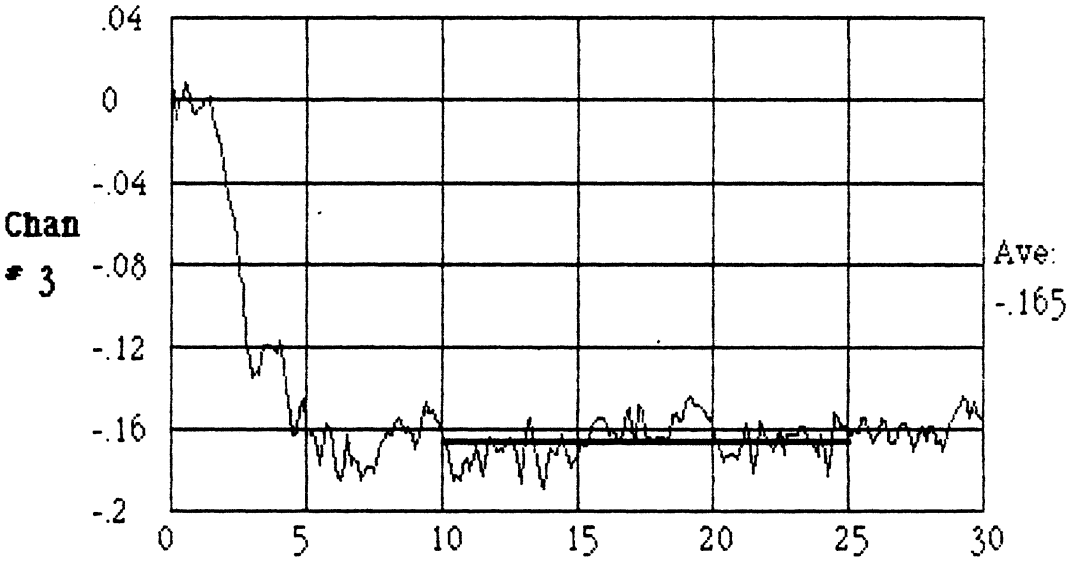
Dodge Aries

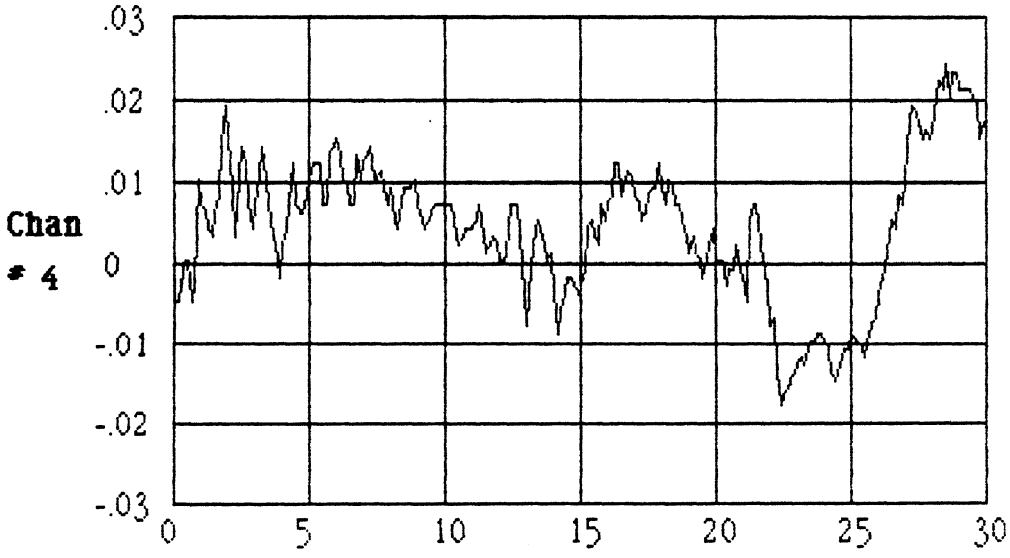
Curve #1

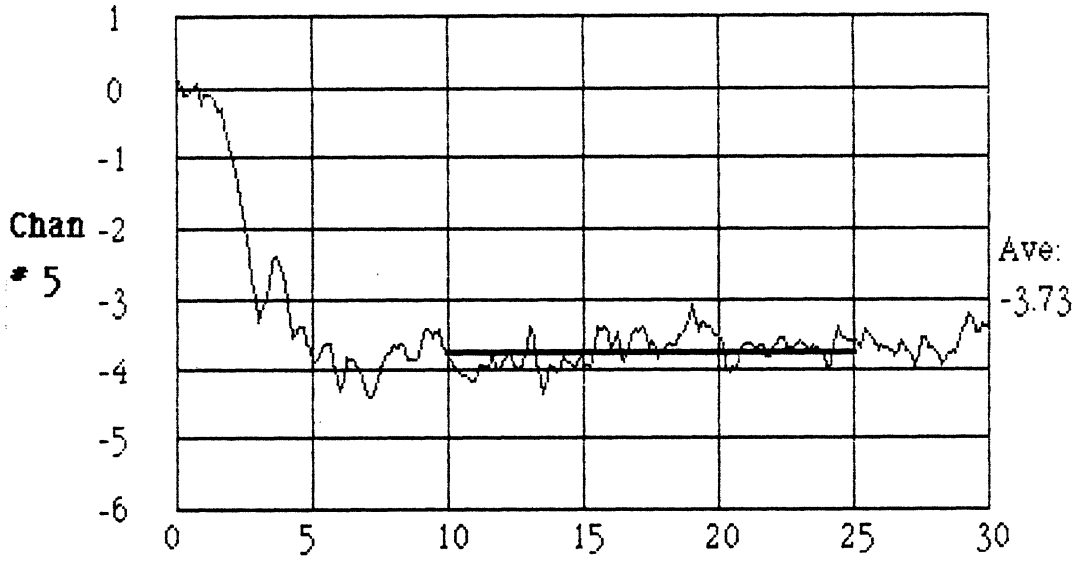
Repeat 3

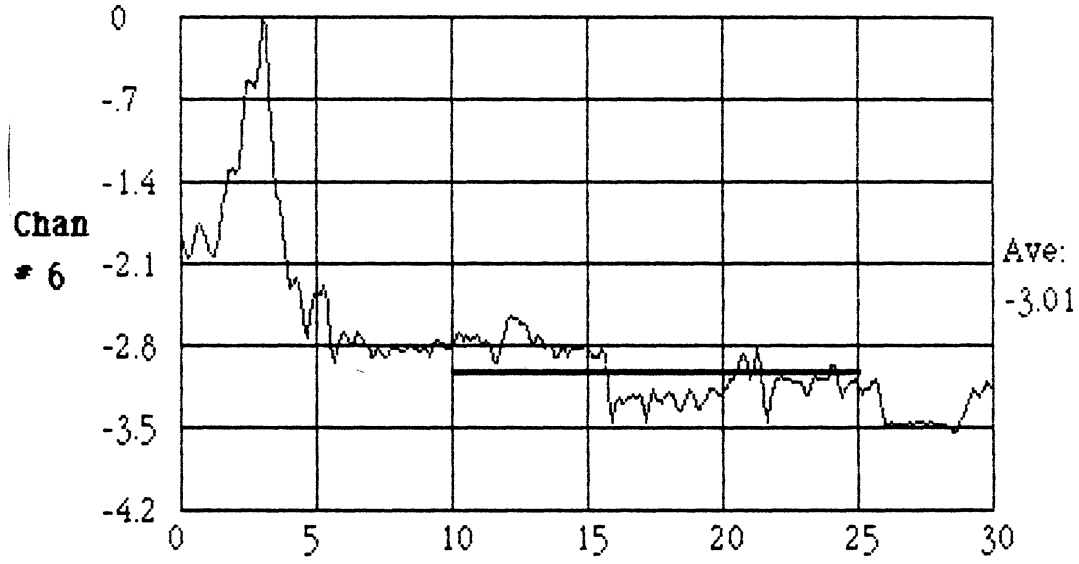
Steady Turning

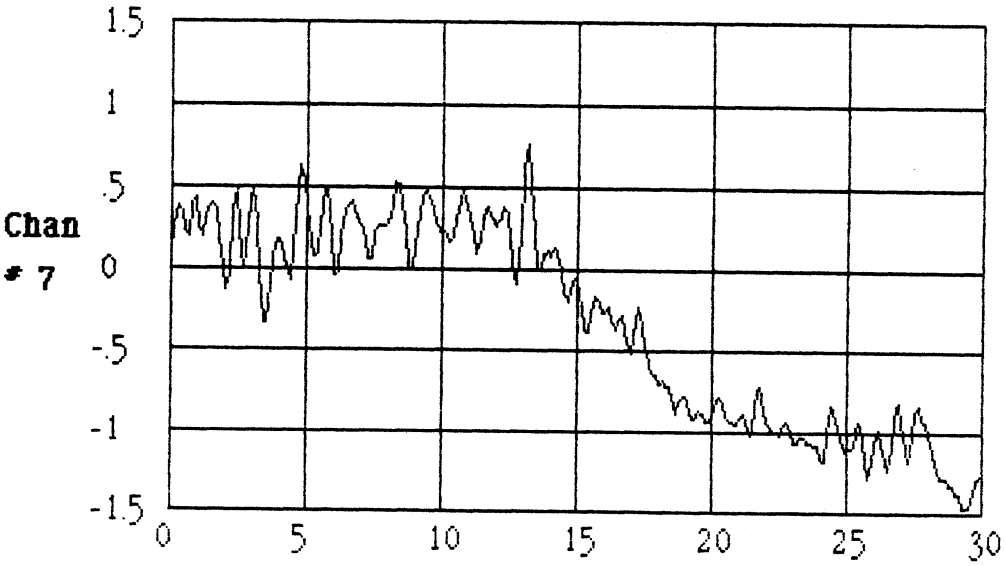

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
56.4

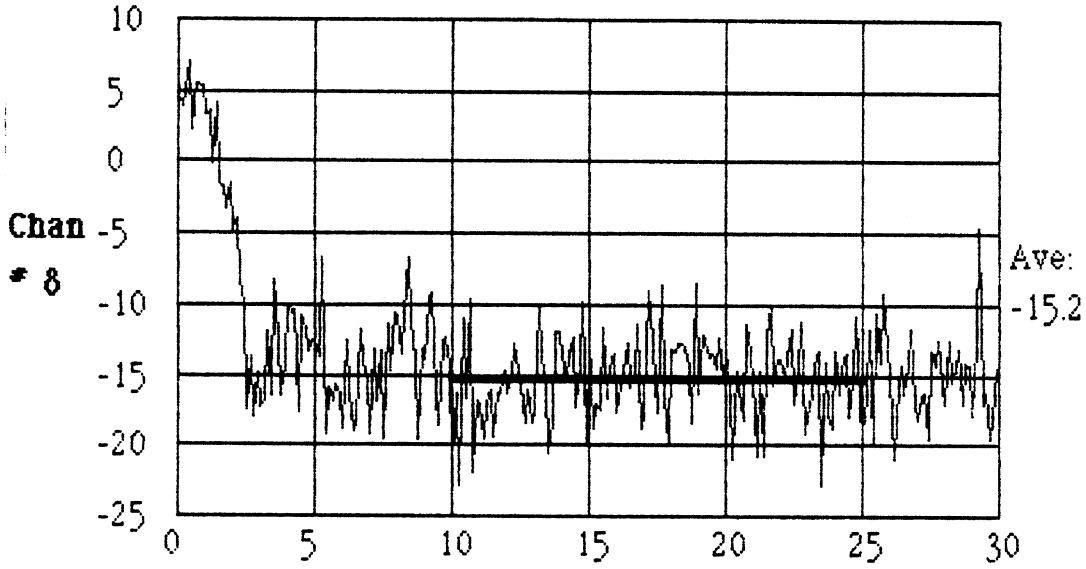

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.165

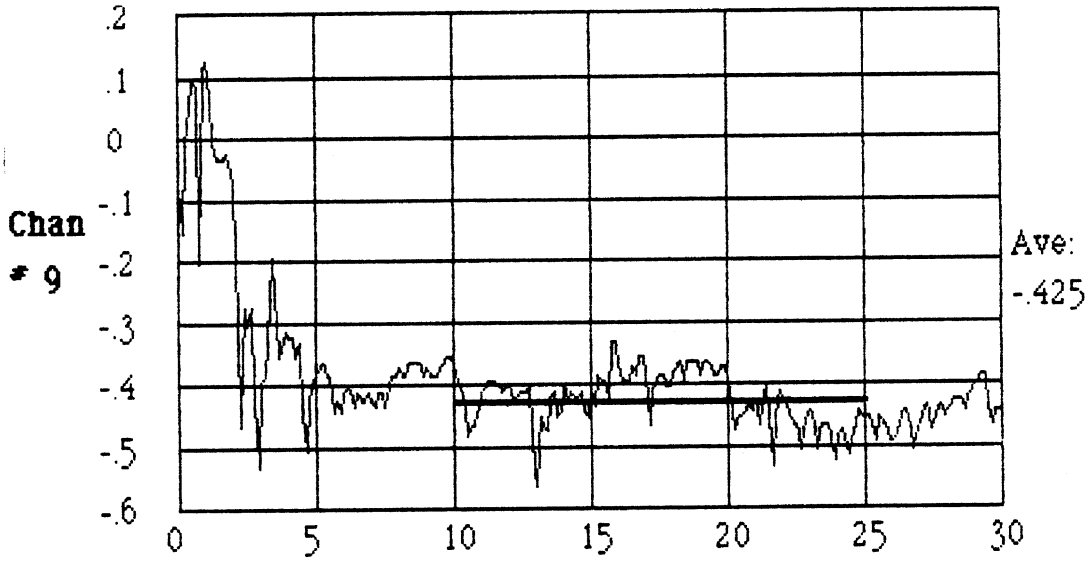

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

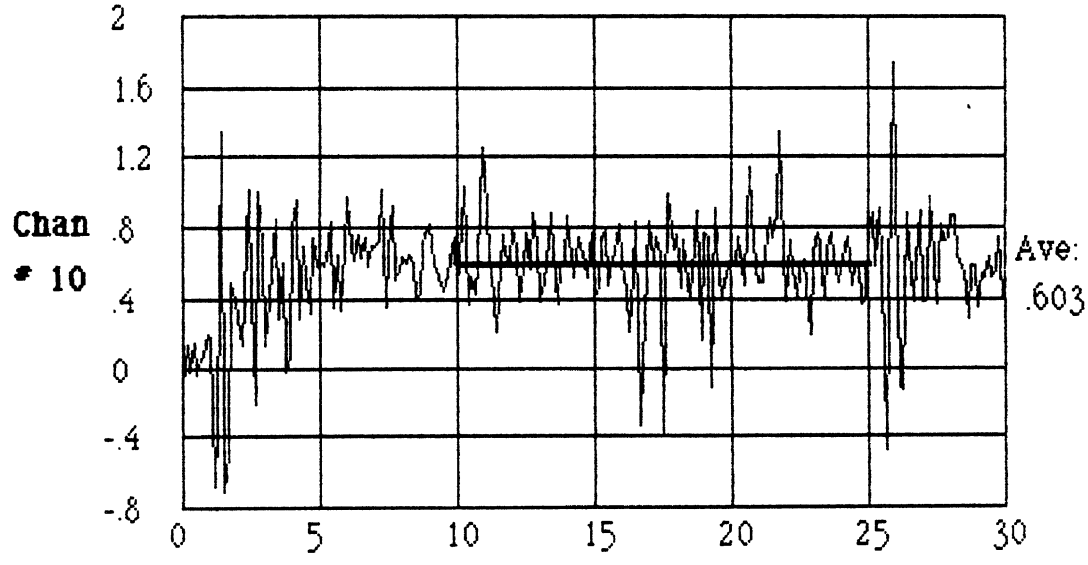

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-3.73


Chan
6
0
-.7
-1.4
-2.1
-2.8
-3.5
-4.2
0
5
10
15
20
25
30
Ave:
-3.01


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
10
5
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
Ave:
-15.2


Chan
9
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
0
5
10
15
20
25
30
Ave:
-.425

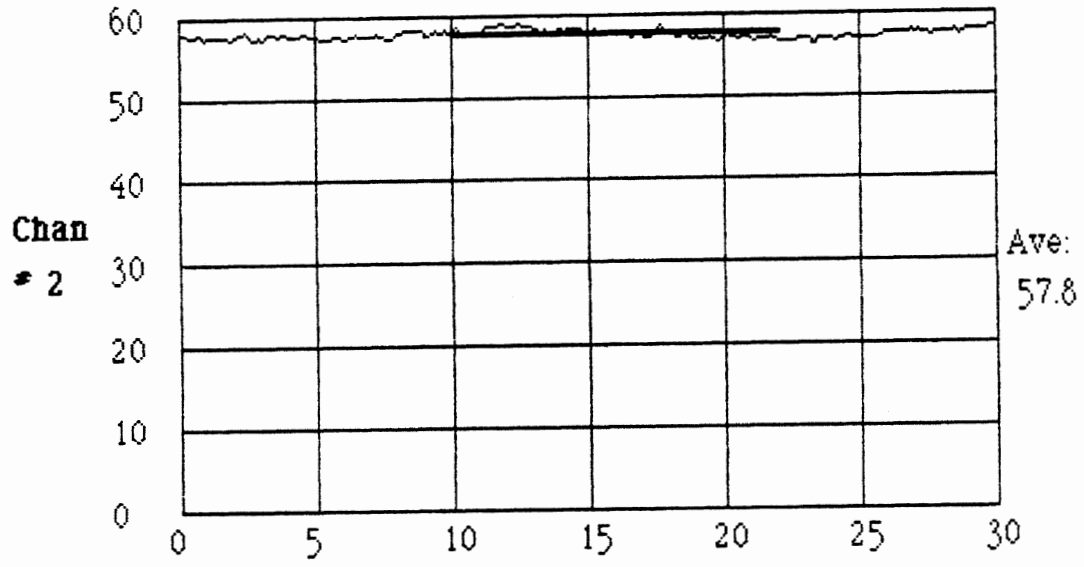

Chan
10
2
1.6
1.2
.8
.4
0
-.4
-.8
0
5
10
15
20
25
30
Ave:
.603

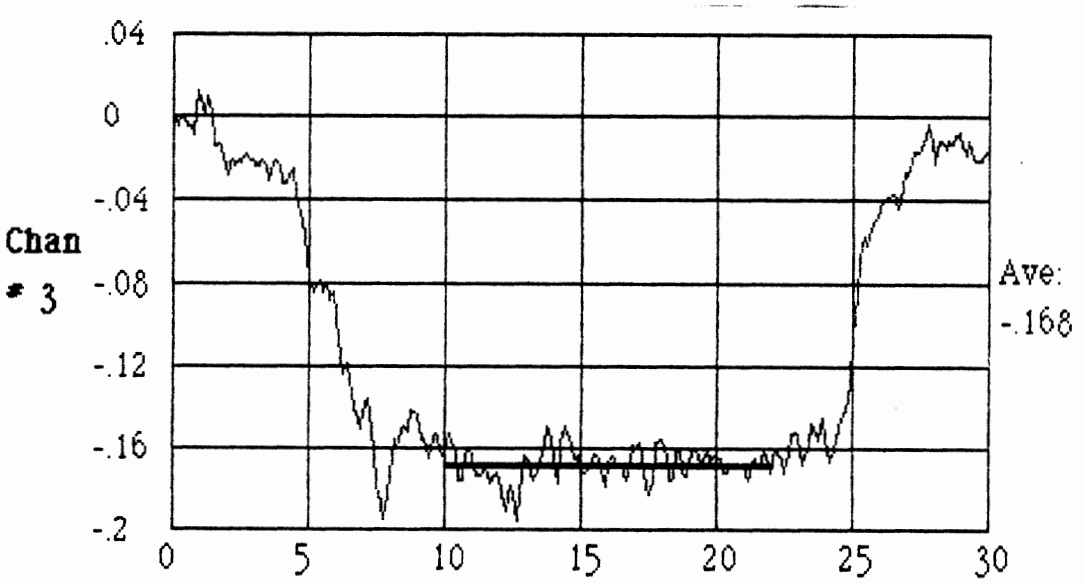
Dodge Aries

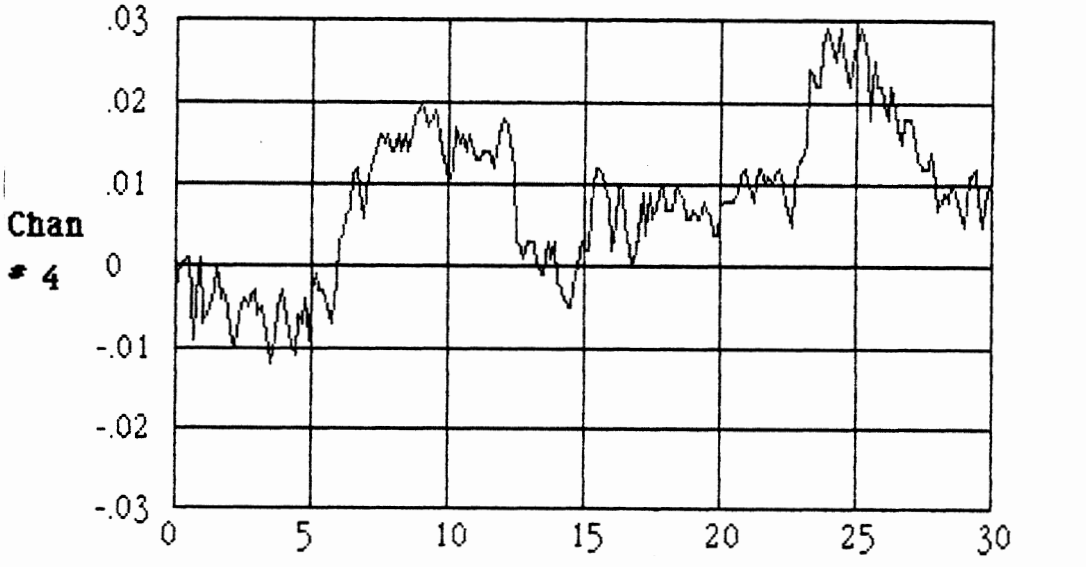
Curve #2

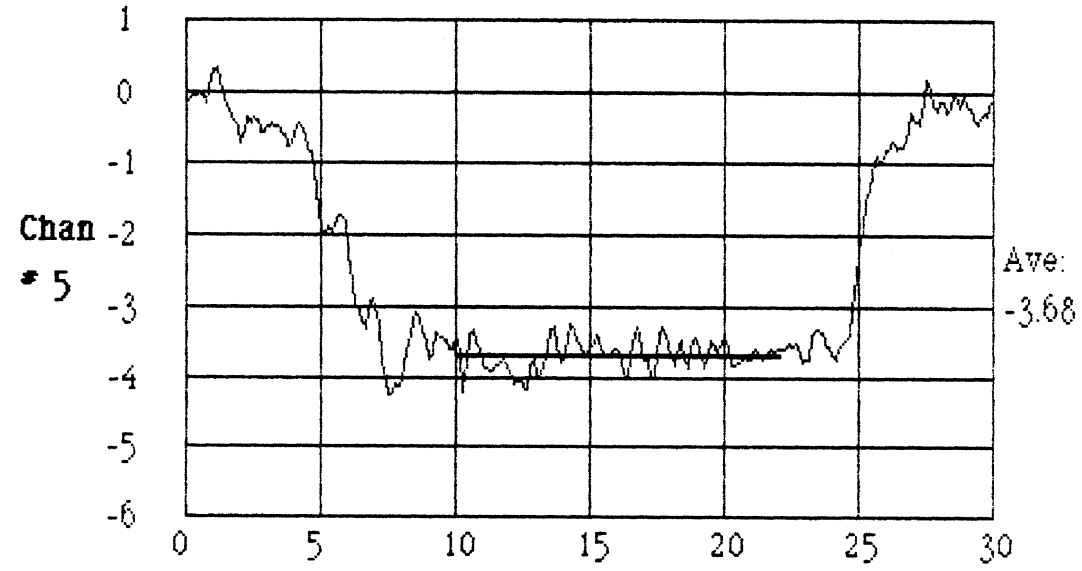
Repeat 1

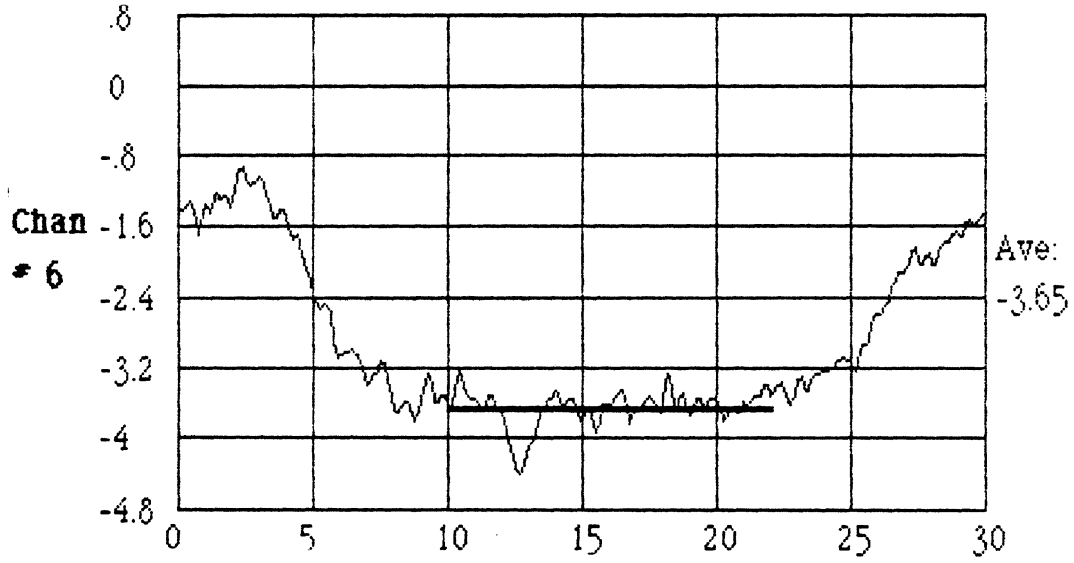
Steady Turning

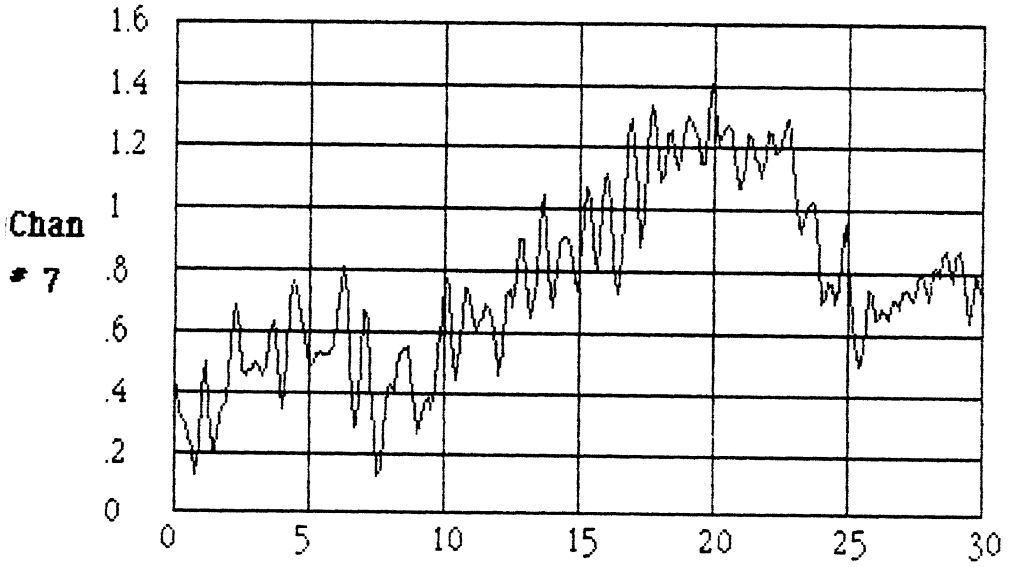

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
57.8

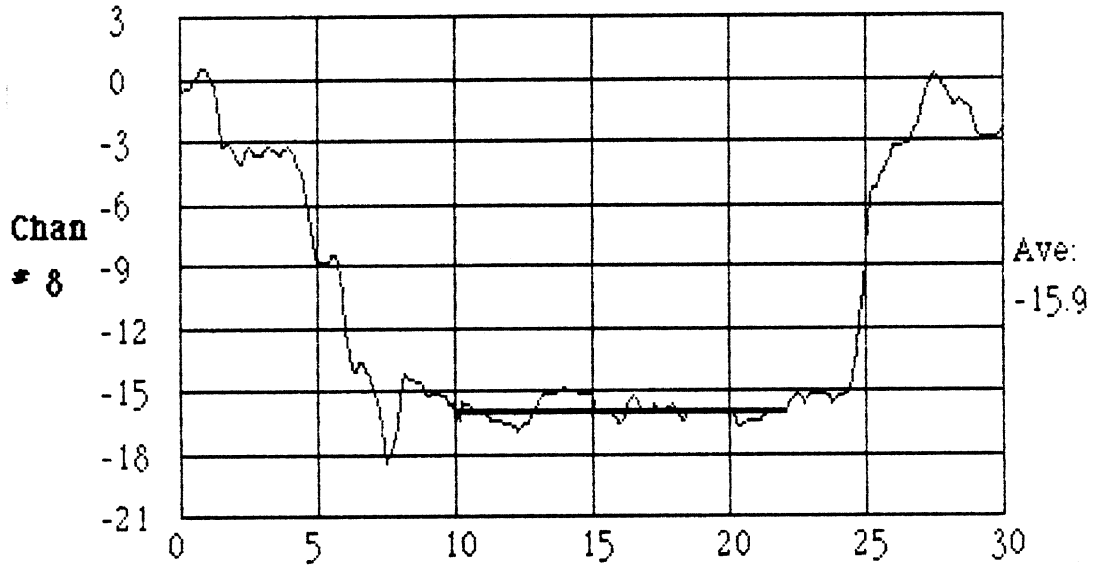

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.168

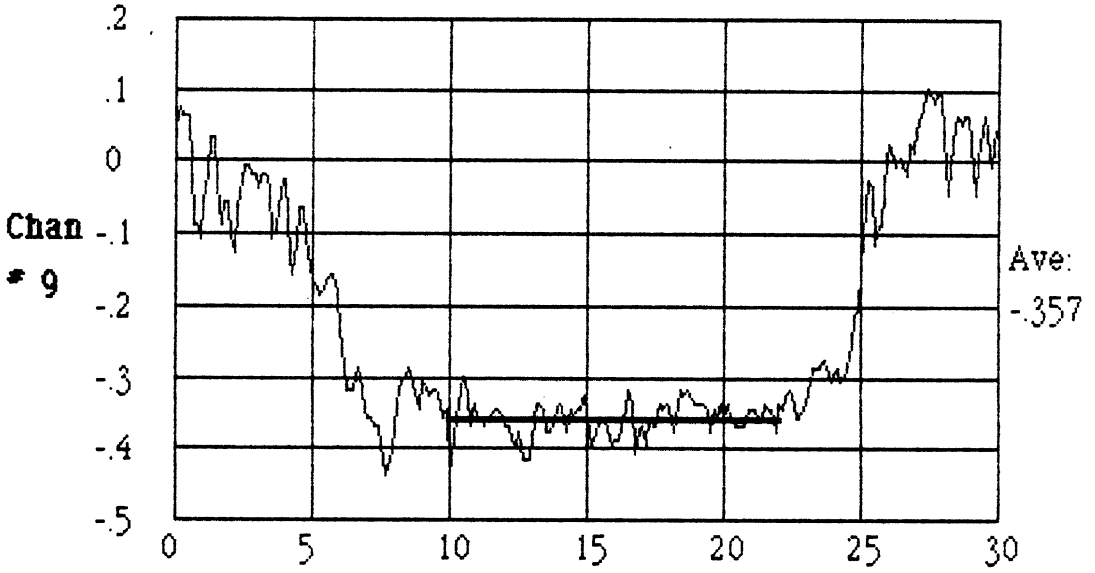

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

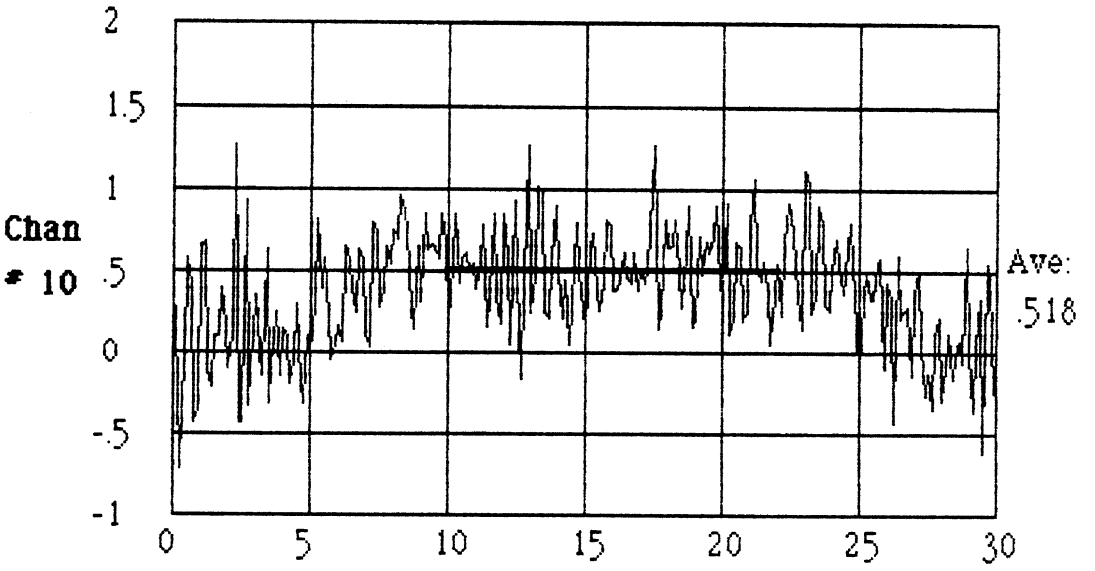

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-3.68


Chan
6
.8
0
-.8
-1.6
-2.4
-3.2
-4
-4.8
0
5
10
15
20
25
30
Ave:
-3.65


Chan
7
1.6
1.4
1.2
1
.8
.6
.4
.2
0
0
5
10
15
20
25
30


Chan
8
3
0
-3
-6
-9
-12
-15
-18
-21
0
5
10
15
20
25
30
Ave:
-15.9


Chan
9
.2
.1
0
-.1
-.2
-.3
-.4
-.5
0
5
10
15
20
25
30
Ave:
-.357

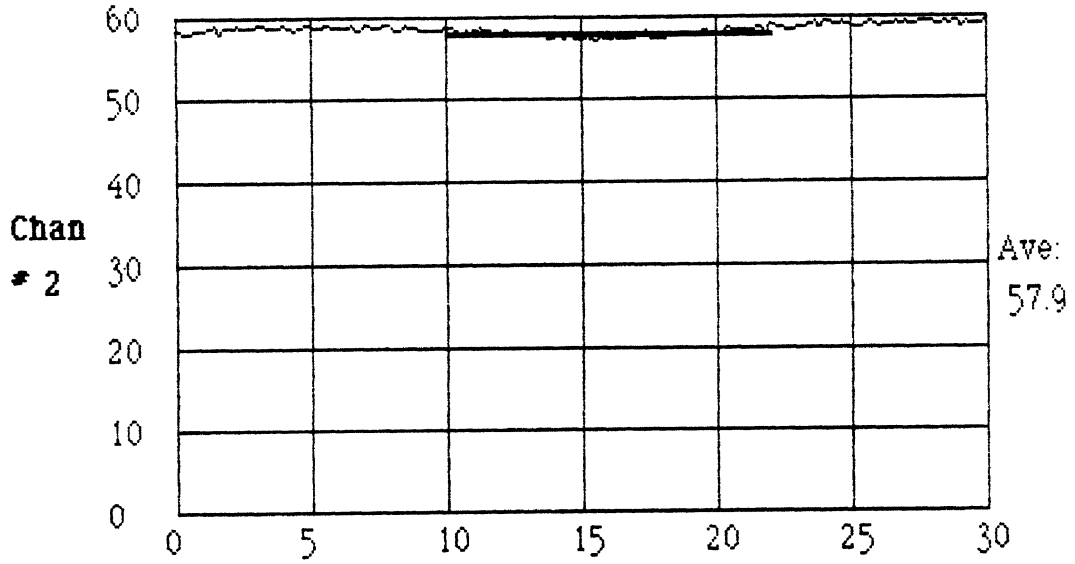

Chan
10
2
1.5
1
.5
0
-.5
-1
0
5
10
15
20
25
30
Ave:
.518

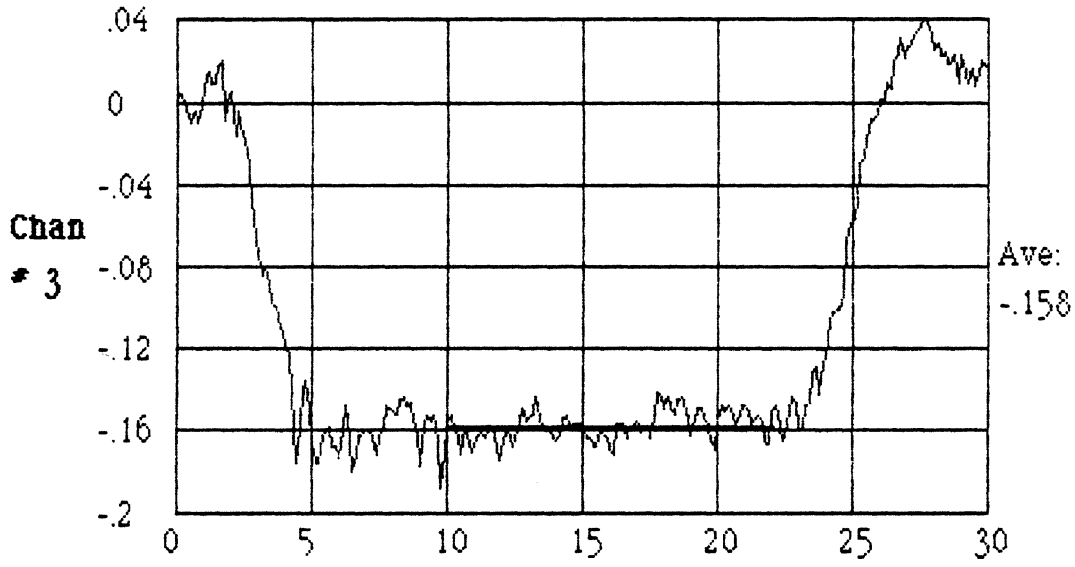
Dodge Aries

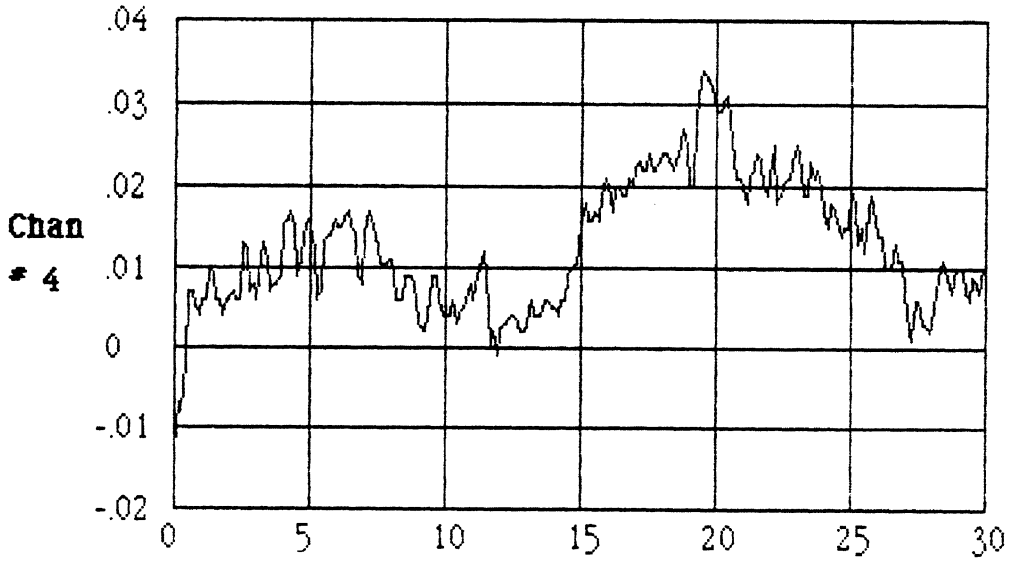
Curve #3

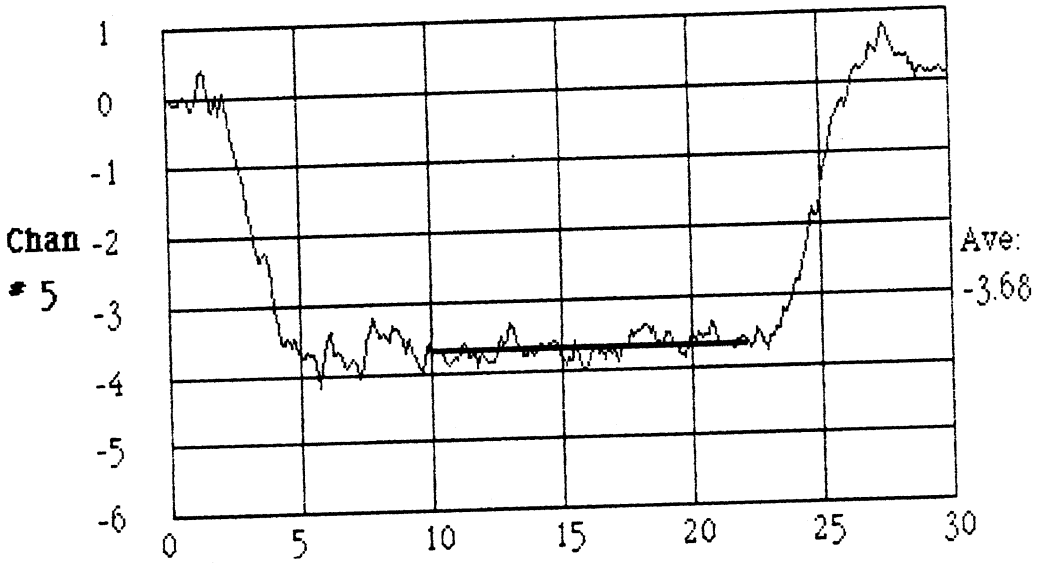
Repeat 1

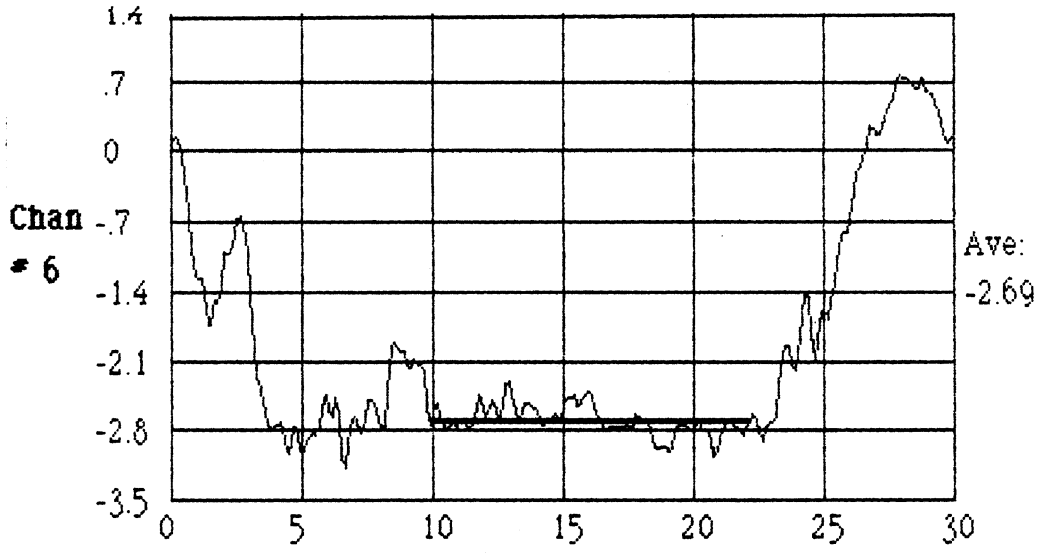
Steady Turning

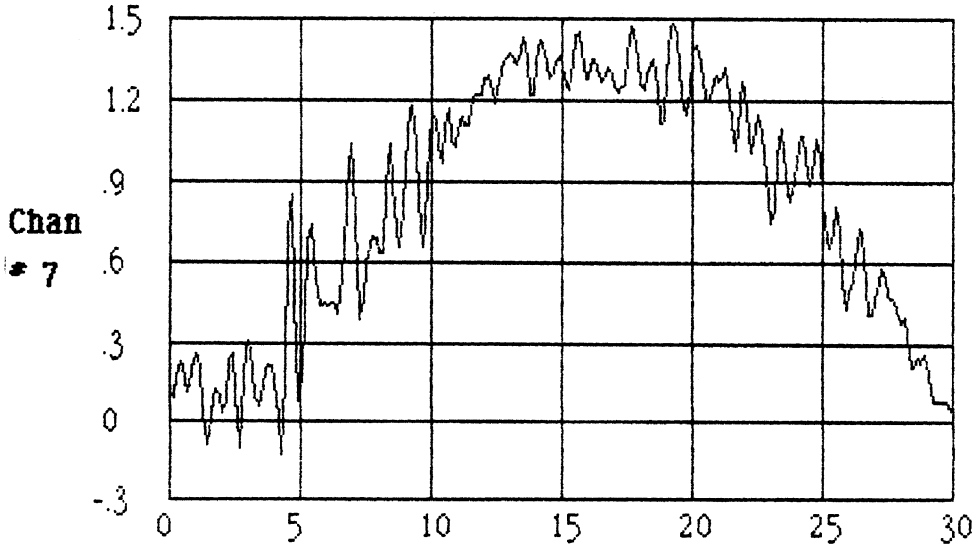

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
57.9

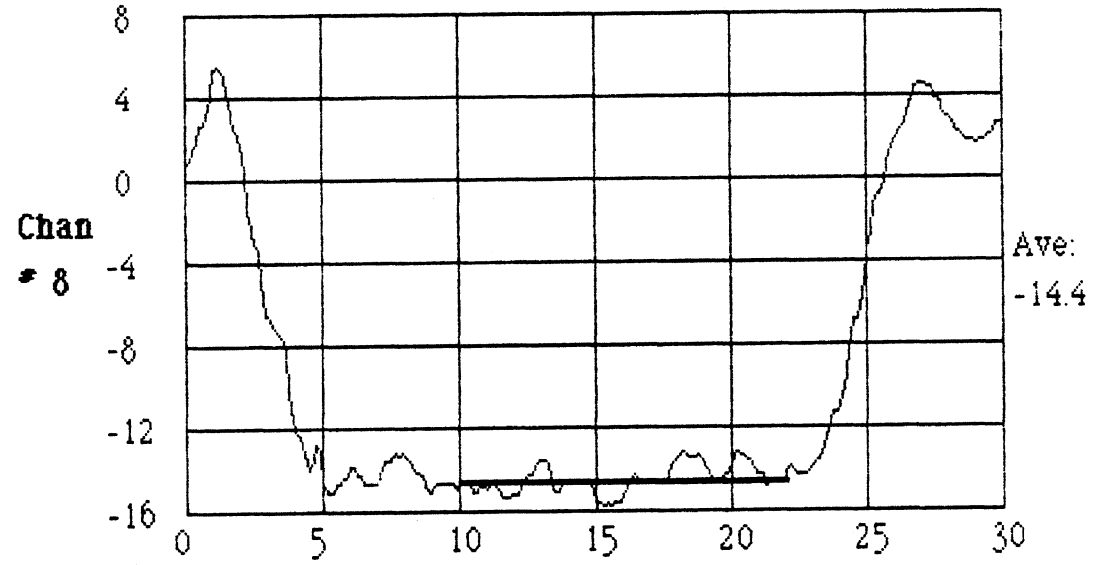

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.158

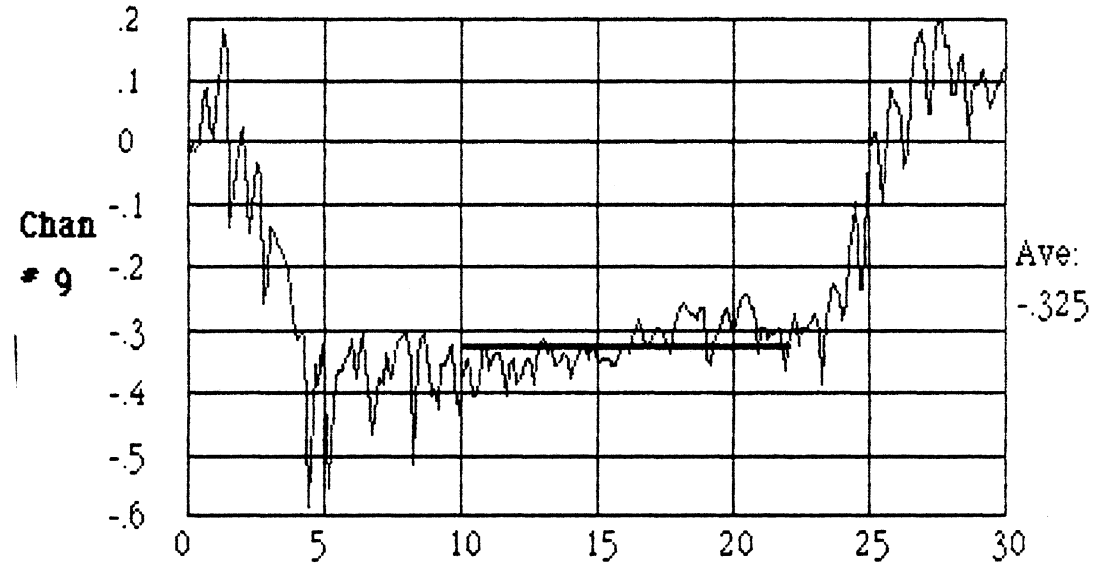

Chan
4
.04
.03
.02
.01
0
-.01
-.02
0
5
10
15
20
25
30

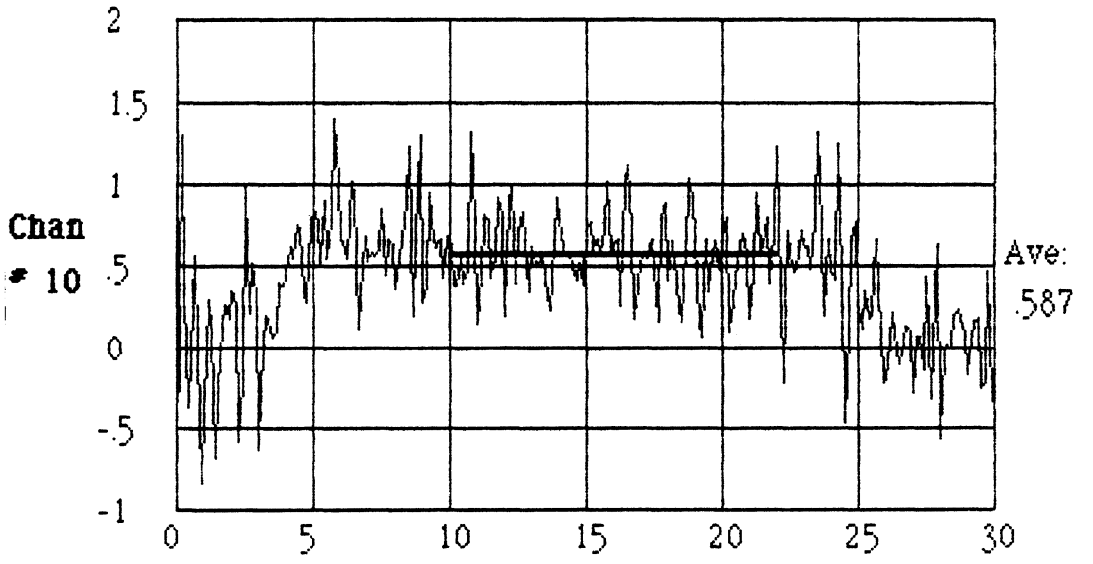

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-3.68


Chan
6
1.4
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
0
5
10
15
20
25
30
Ave:
-2.69


Chan
7
1.5
1.2
.9
.6
.3
0
-.3
0
5
10
15
20
25
30


Chan
8
8
4
0
-4
-8
-12
-16
0
5
10
15
20
25
30
Ave:
-14.4


Chan
9
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
0
5
10
15
20
25
30
Ave:
-.325

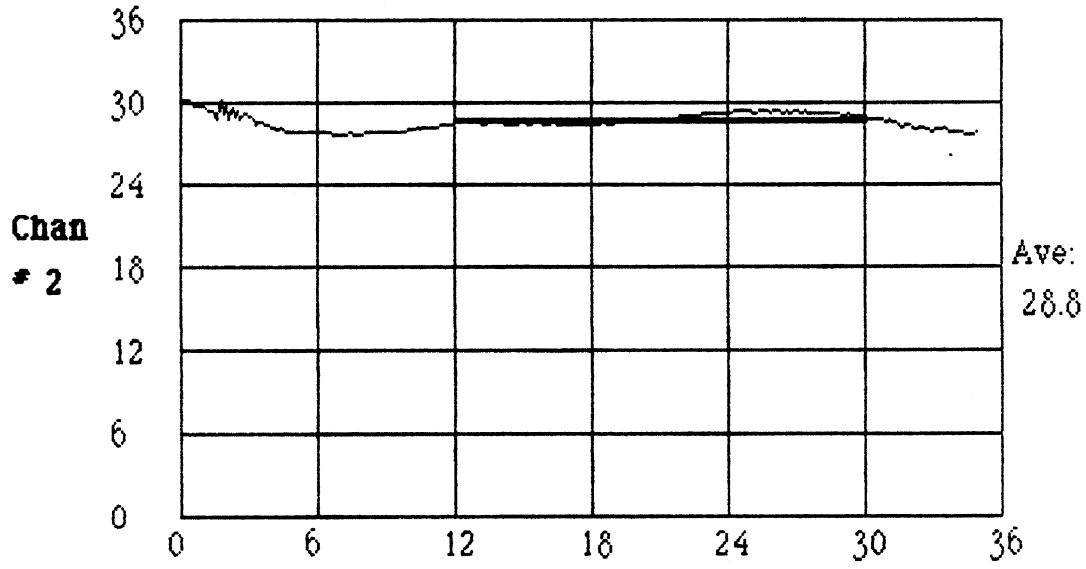

Chan
10
2
1.5
1
.5
0
-.5
-1
0
5
10
15
20
25
30
Ave:
.587

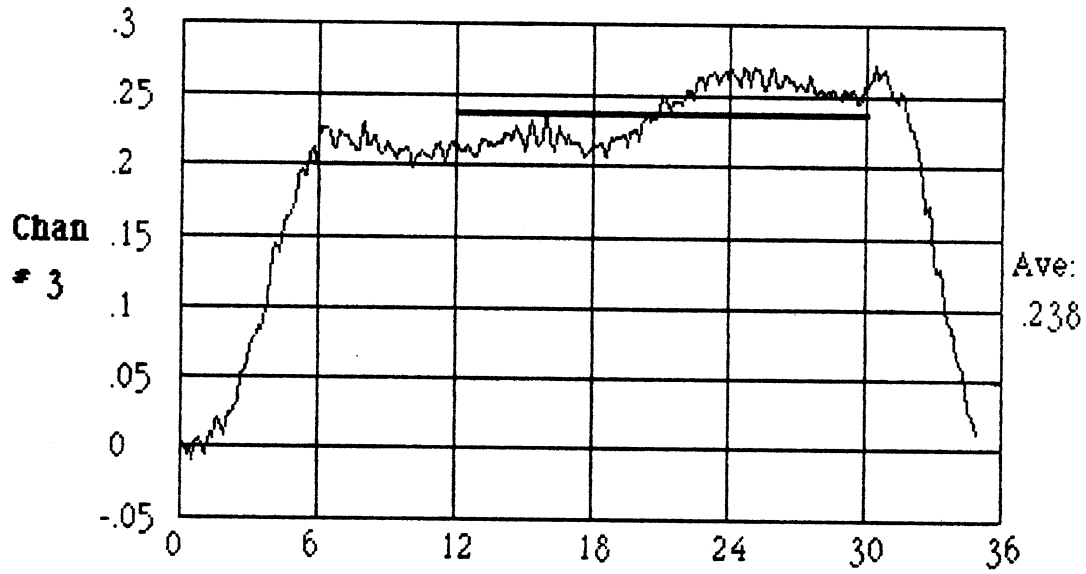
Dodge Aries

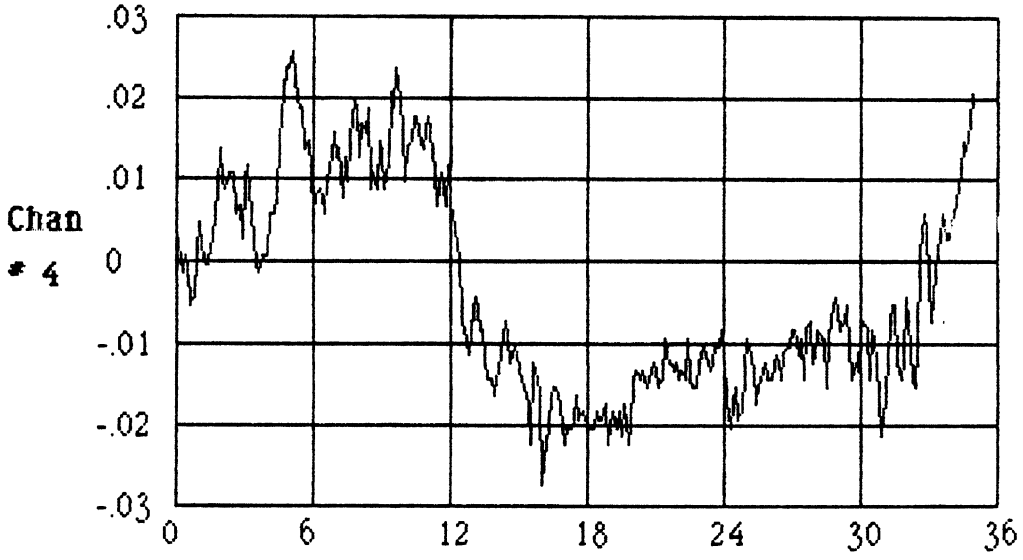
Ramp

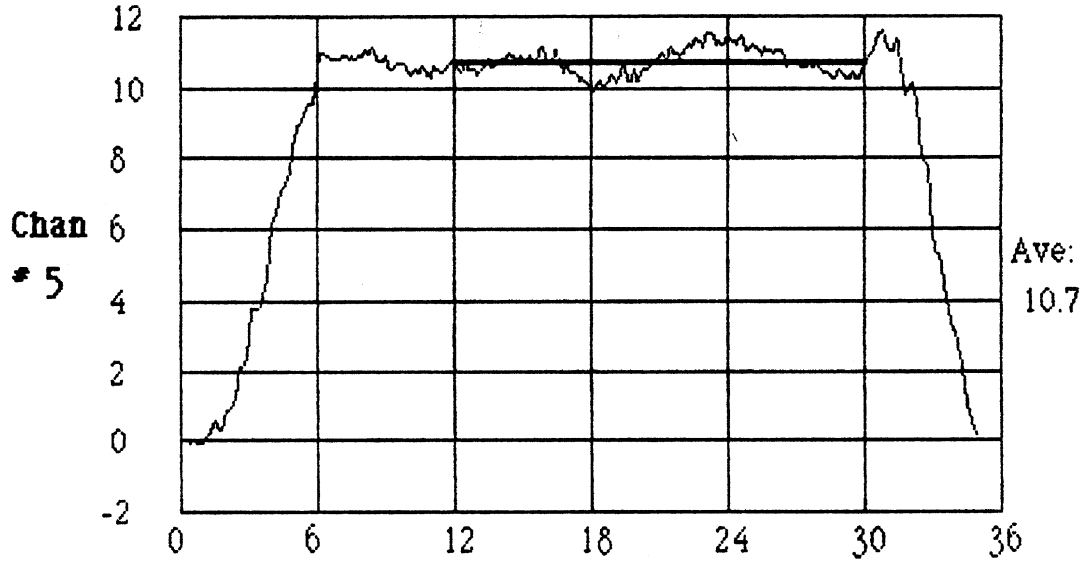
Repeat 1

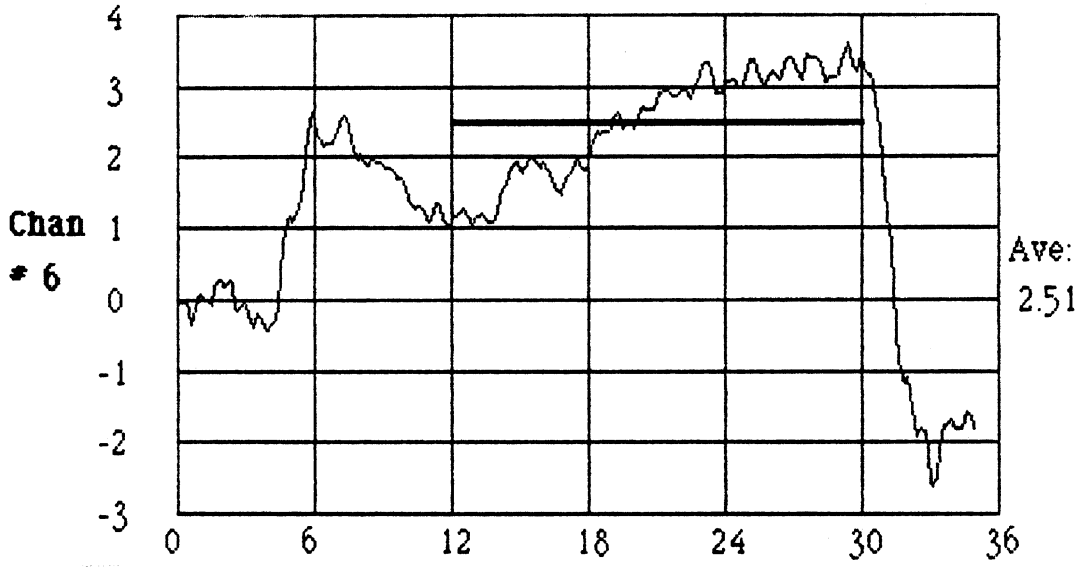
Steady Turning

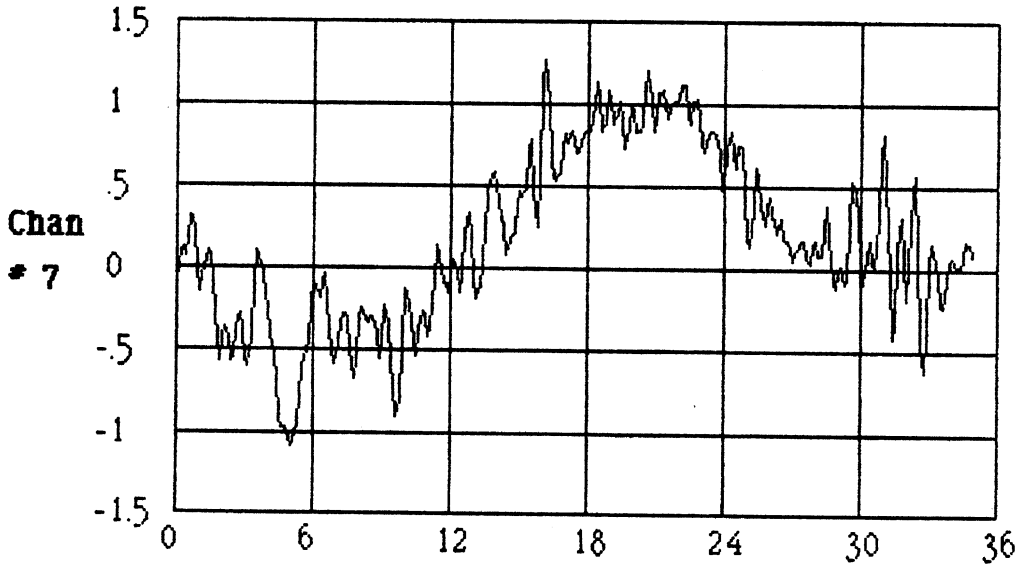

Chan
2
36
30
24
18
12
6
0
0
6
12
18
24
30
36
Ave:
28.8

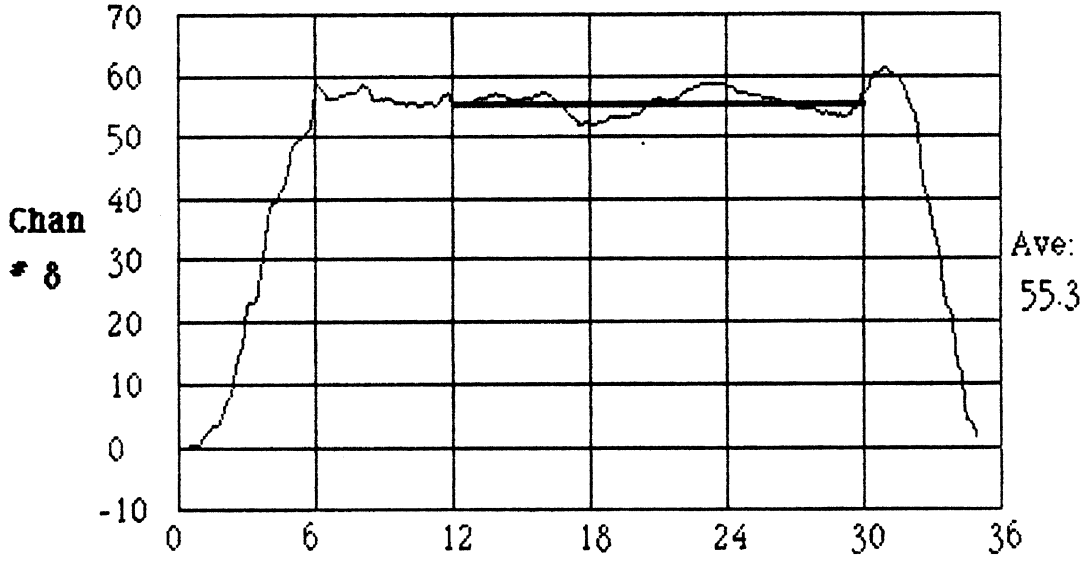

Chan
3
.3
.25
.2
.15
.1
.05
0
-.05
0
6
12
18
24
30
36
Ave:
.238

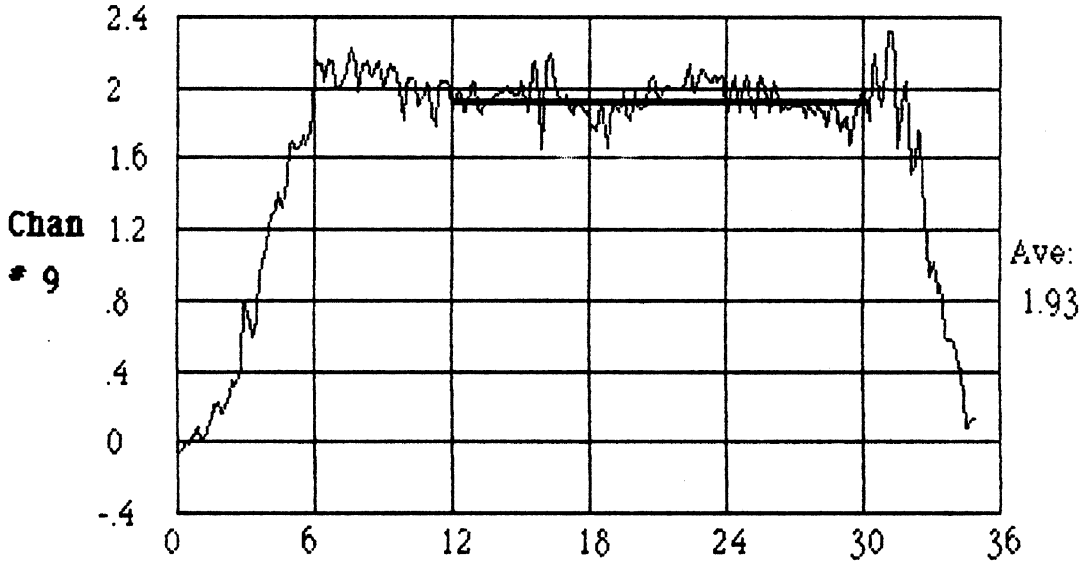

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
6
12
18
24
30
36

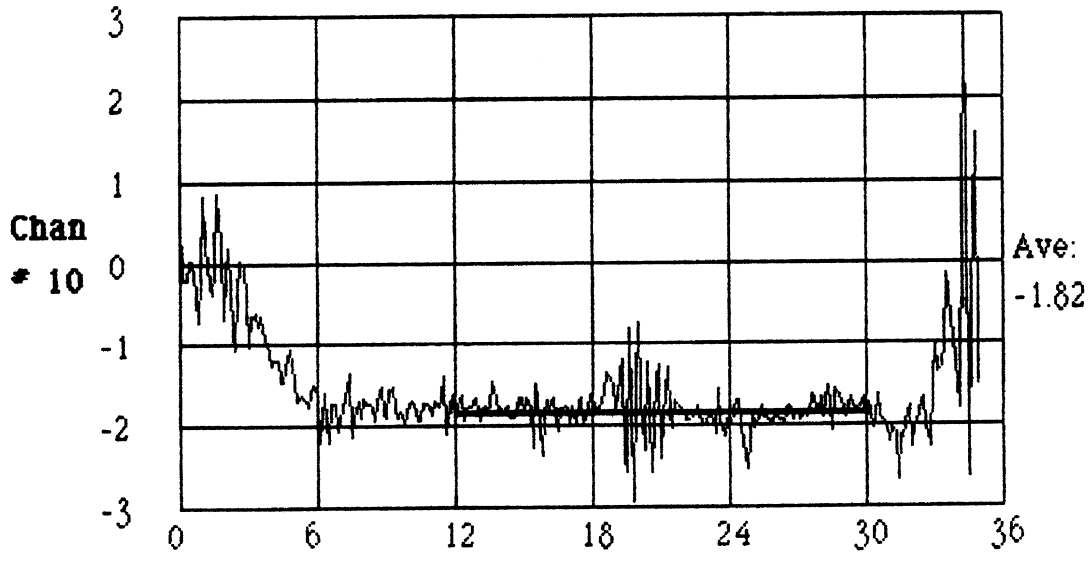

Chan
5
12
10
8
6
4
2
0
-2
0
6
12
18
24
30
36
Ave:
10.7


Chan
6
4
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
2.51


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
6
12
18
24
30
36


Chan
8
70
60
50
40
30
20
10
0
-10
0
6
12
18
24
30
36
Ave:
55.3


Chan
9
2.4
2
1.6
1.2
.8
.4
0
-.4
0
6
12
18
24
30
36
Ave:
1.93

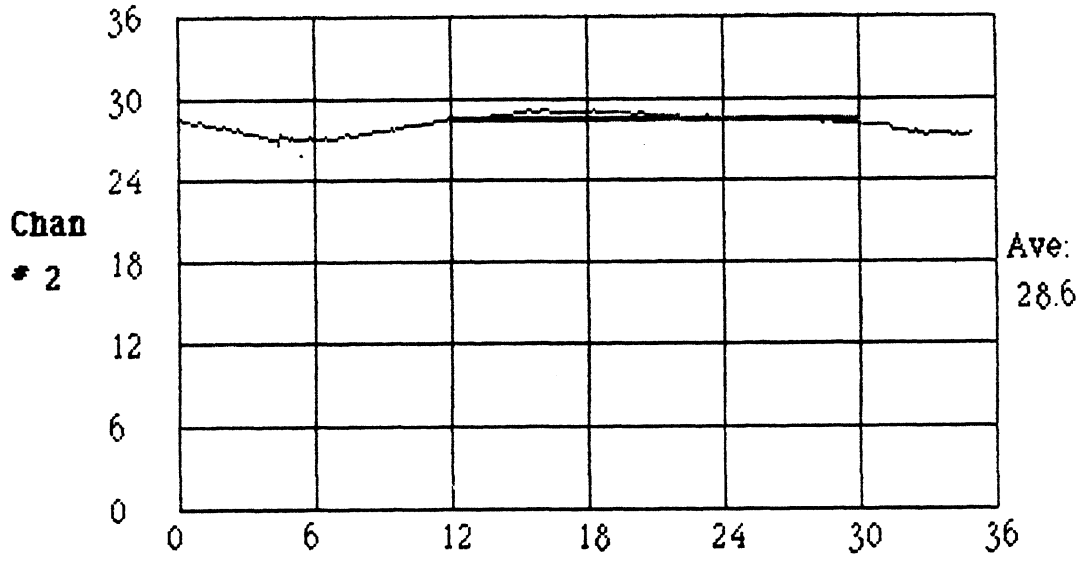

Chan
10
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
-1.82

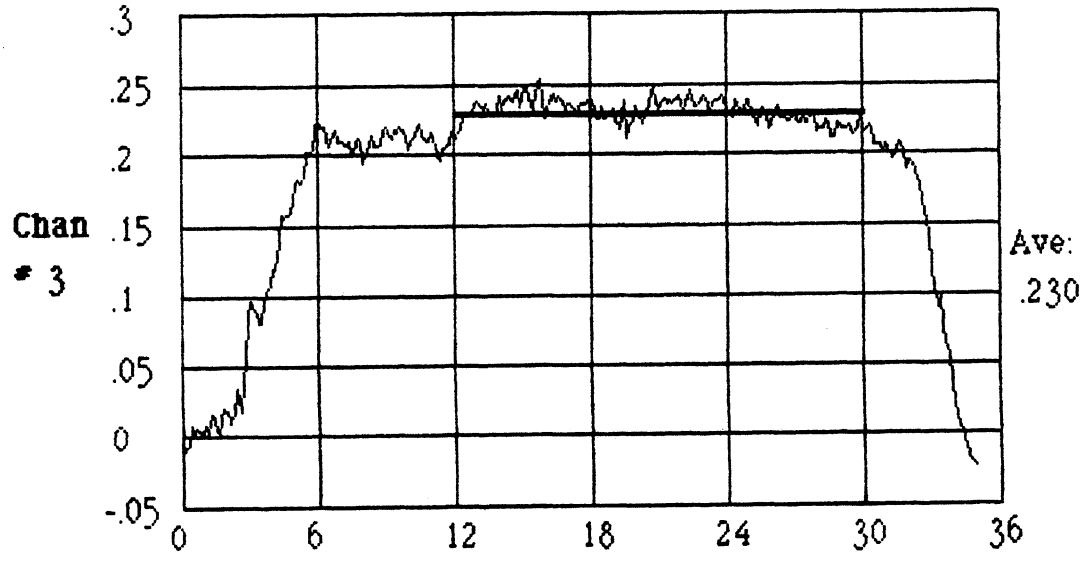
Dodge Aries

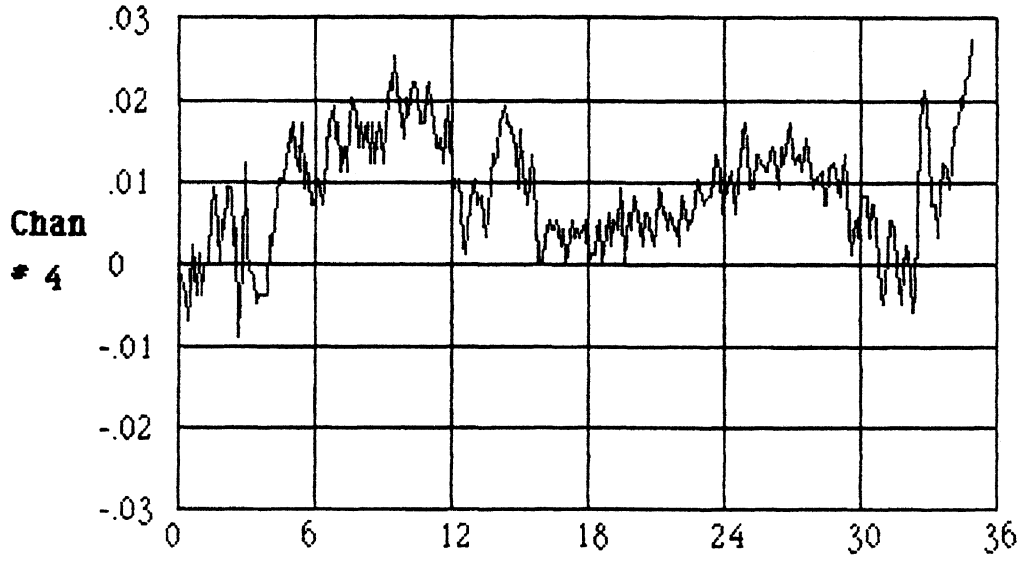
Ramp

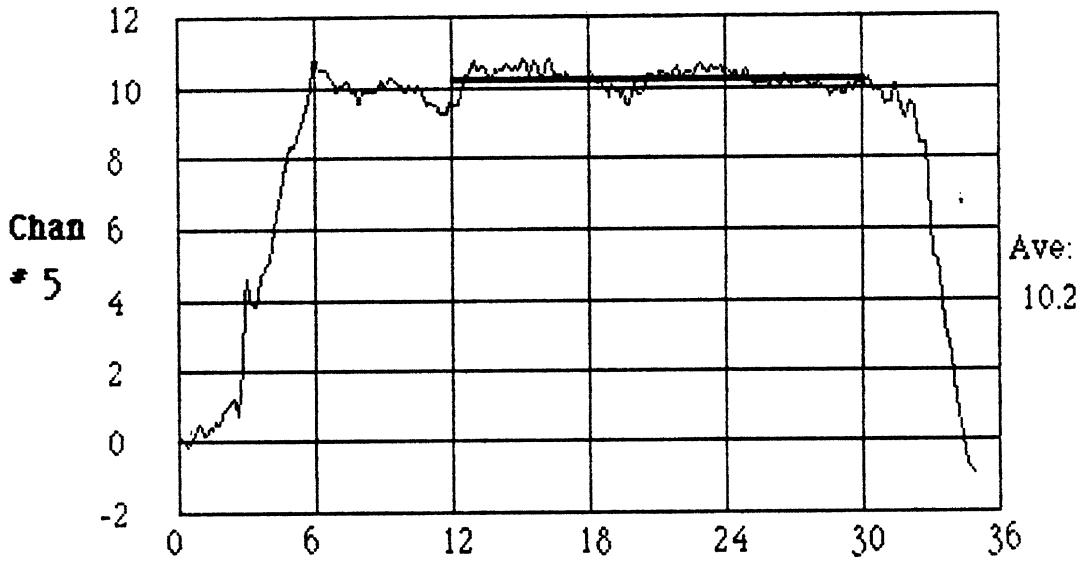
Repeat 2

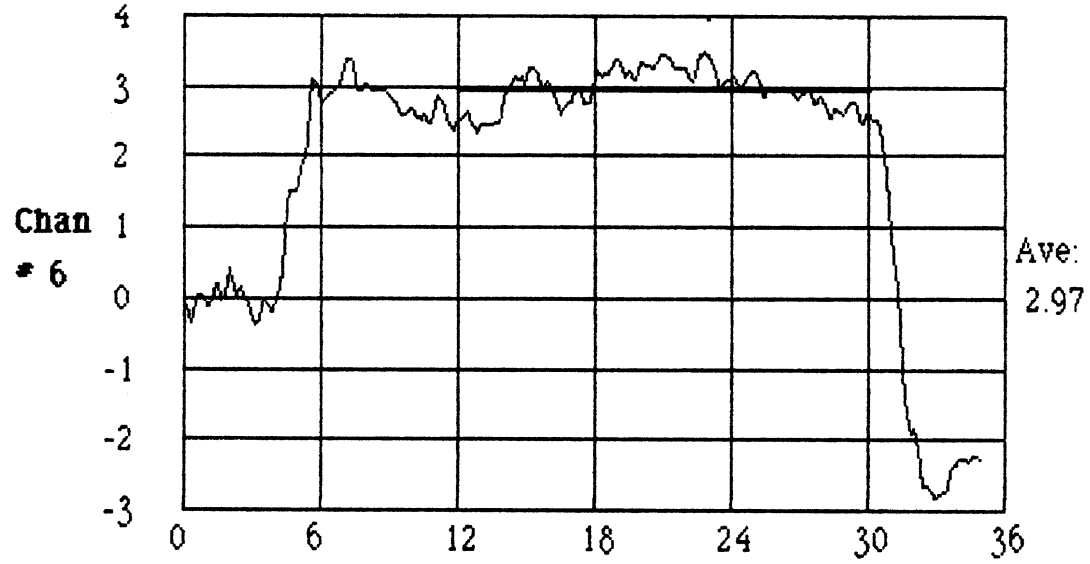
Steady Turning

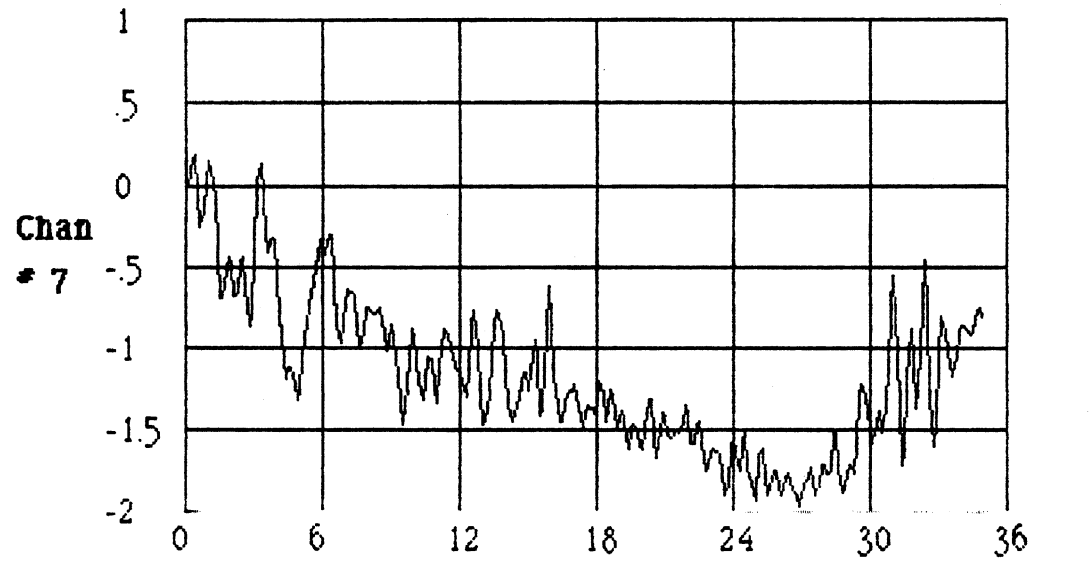

Chan
2
36
30
24
18
12
6
0
0
6
12
18
24
30
36
Ave:
28.6

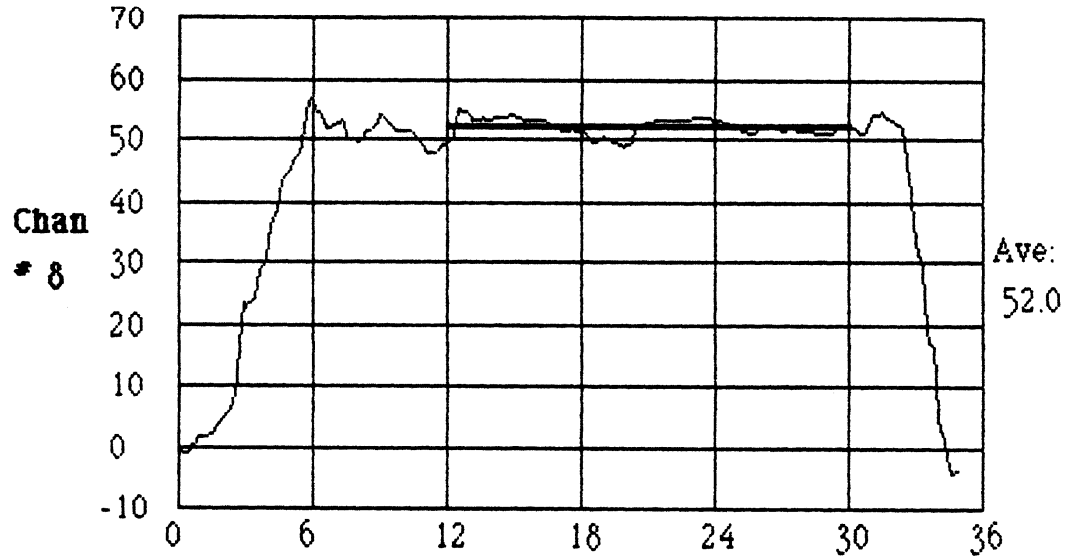

Chan
3
.3
.25
.2
.15
.1
.05
0
-.05
0
6
12
18
24
30
36
Ave:
.230

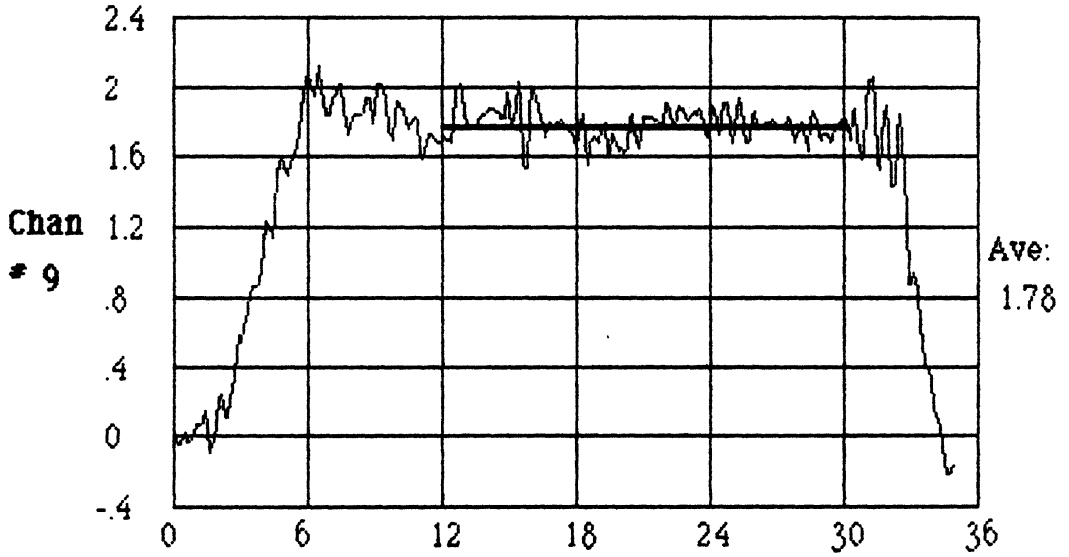

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
6
12
18
24
30
36

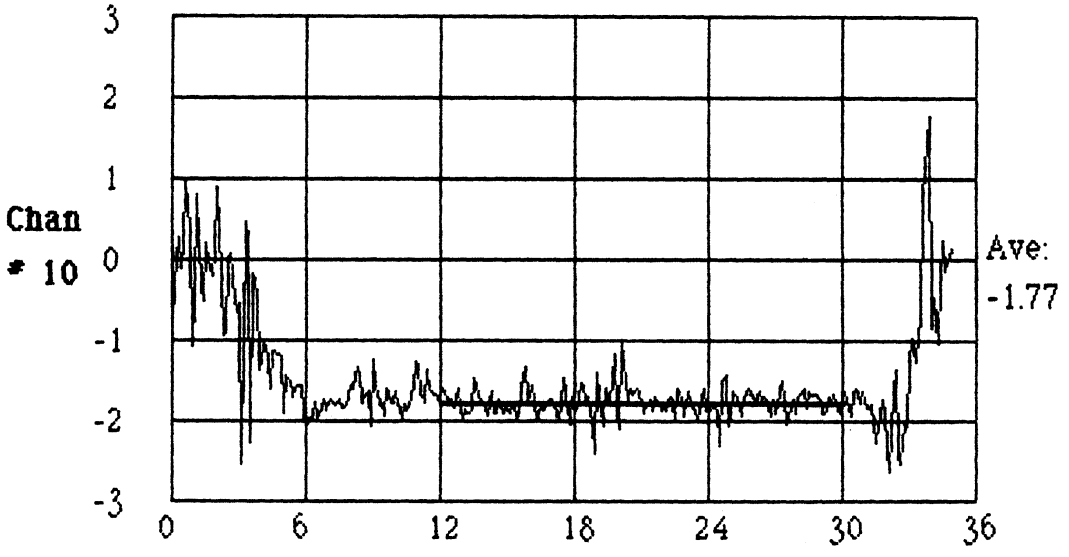

Chan
5
12
10
8
6
4
2
0
-2
0
6
12
18
24
30
36
Ave:
10.2


Chan
6
4
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
2.97


Chan
7
1
.5
0
-.5
-1
-1.5
-2
0
6
12
18
24
30
36


Chan
8
70
60
50
40
30
20
10
0
-10
0
6
12
18
24
30
36
Ave:
52.0


Chan
9
2.4
2
1.6
1.2
.8
.4
0
-.4
0
6
12
18
24
30
36
Ave:
1.78

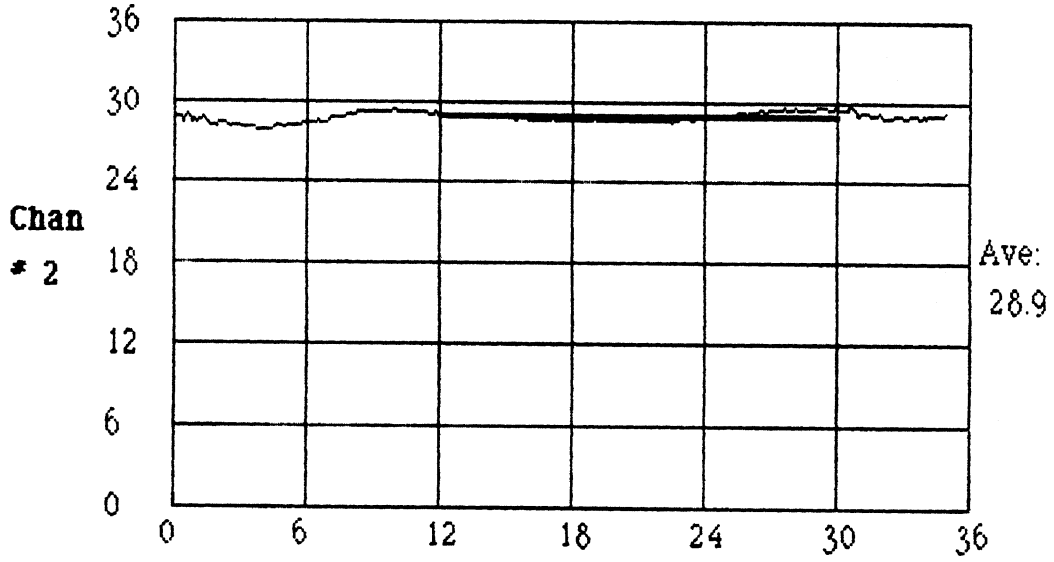

Chan
10
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
-1.77

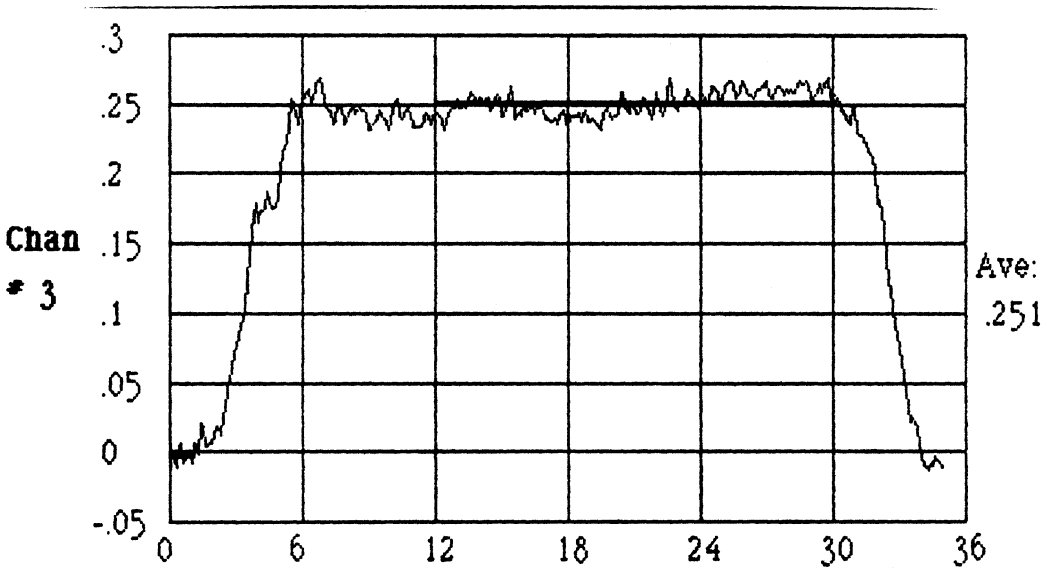
Dodge Aries

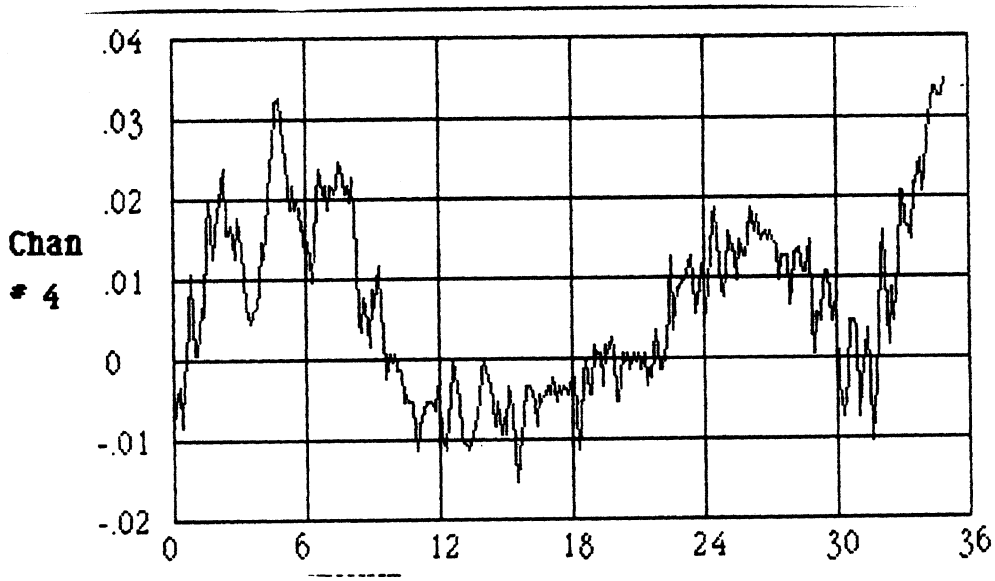
Ramp

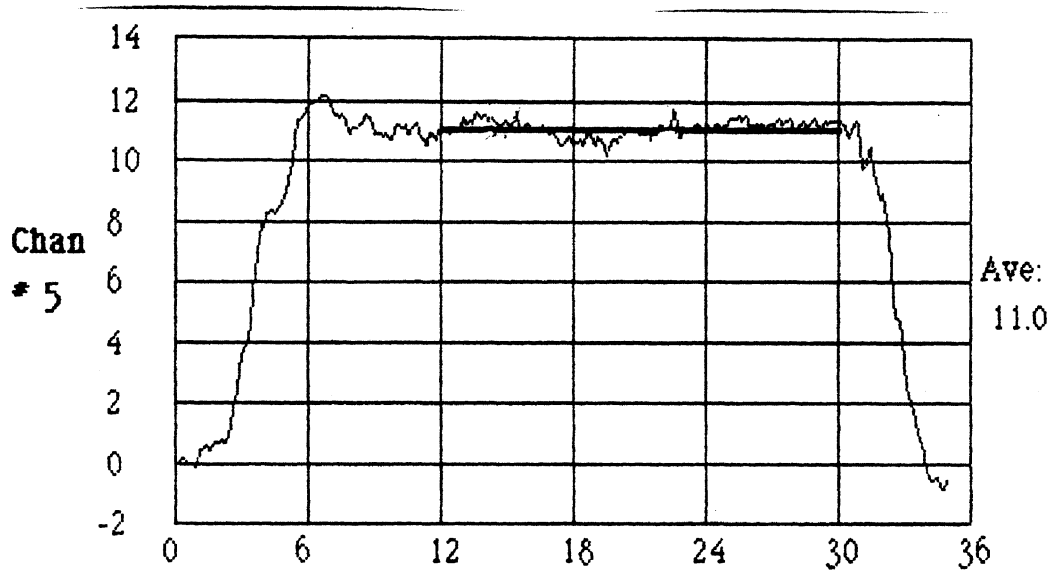
Repeat 3

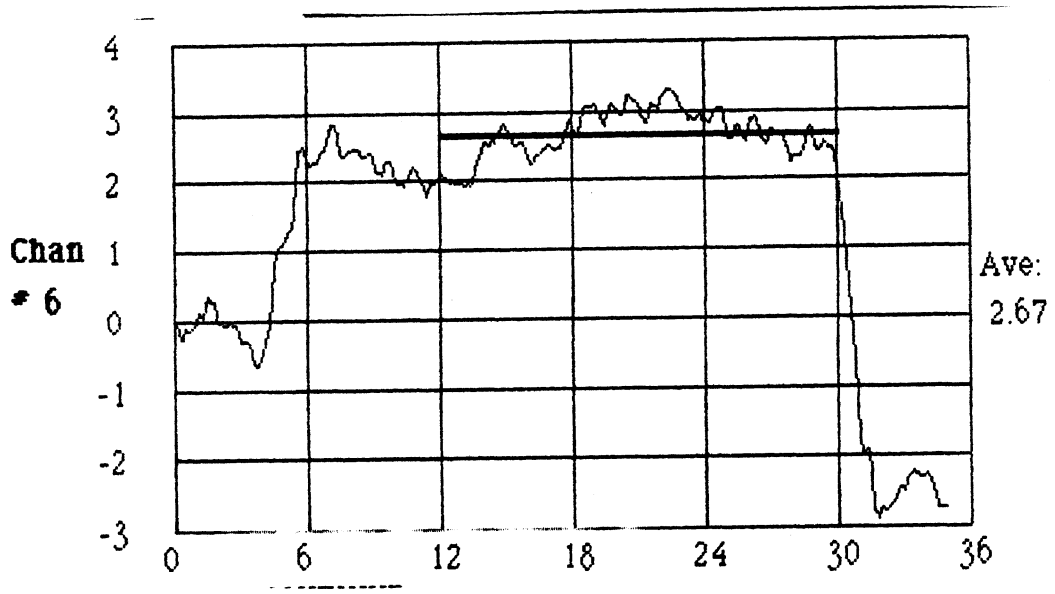
Steady Turning

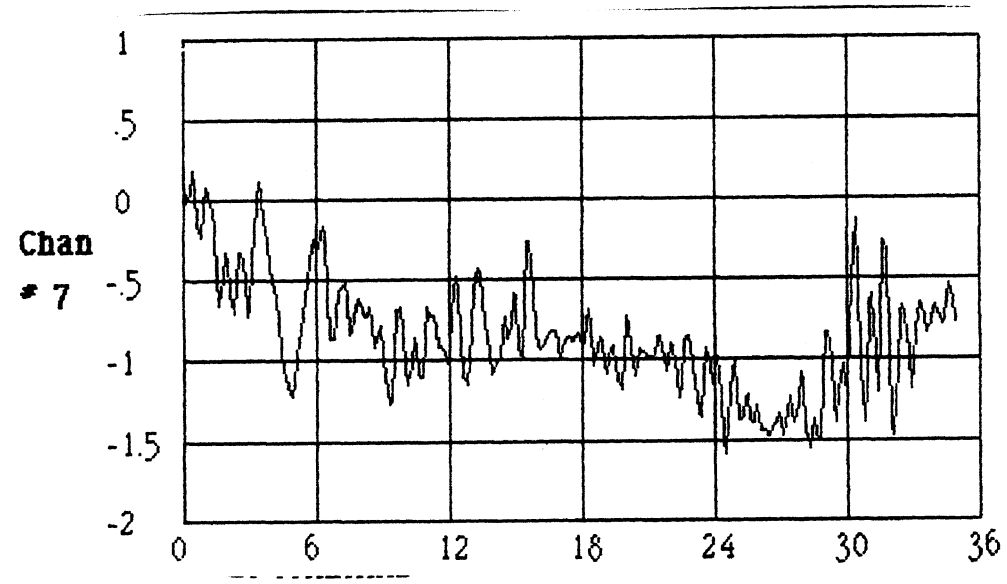

Chan
2
36
30
24
18
12
6
0
0
6
12
18
24
30
36
Ave:
28.9

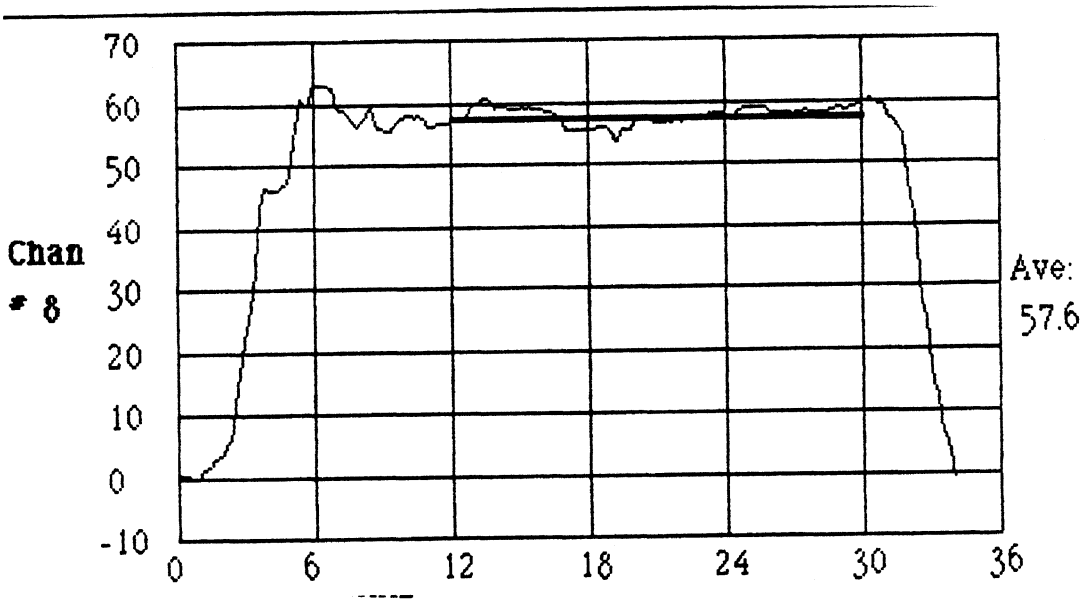

Chan
3
.3
.25
.2
.15
.1
.05
0
-.05
0
6
12
18
24
30
36
Ave:
.251

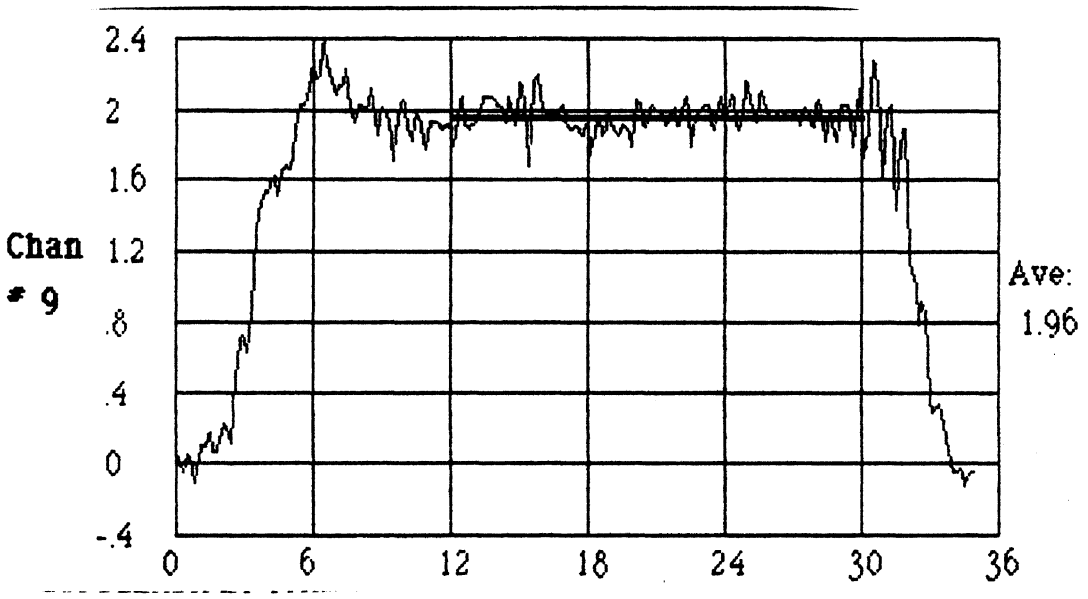

Chan
4
.04
.03
.02
.01
0
-.01
-.02
0
6
12
18
24
30
36

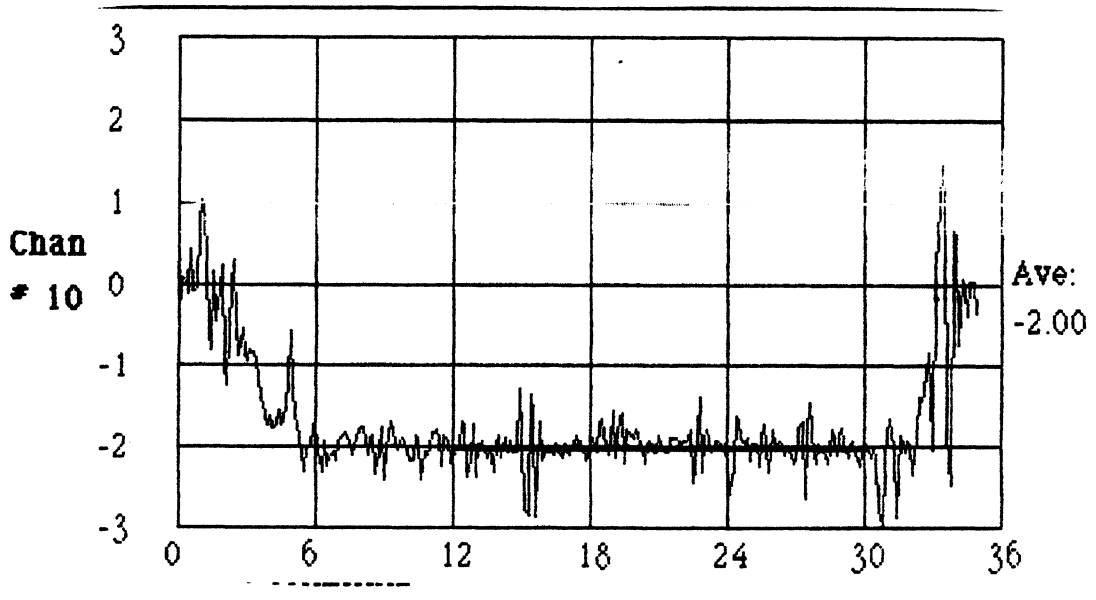

Chan
5
14
12
10
8
6
4
2
0
-2
0
6
12
18
24
30
36
Ave:
11.0


Chan
6
4
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
2.67


Chan
7
1
.5
0
-.5
-1
-1.5
-2
0
6
12
18
24
30
36


Chan
8
70
60
50
40
30
20
10
0
-10
0
6
12
18
24
30
36
Ave:
57.6


Chan
9
2.4
2
1.6
1.2
.8
.4
0
-.4
0
6
12
18
24
30
36
Ave:
1.96

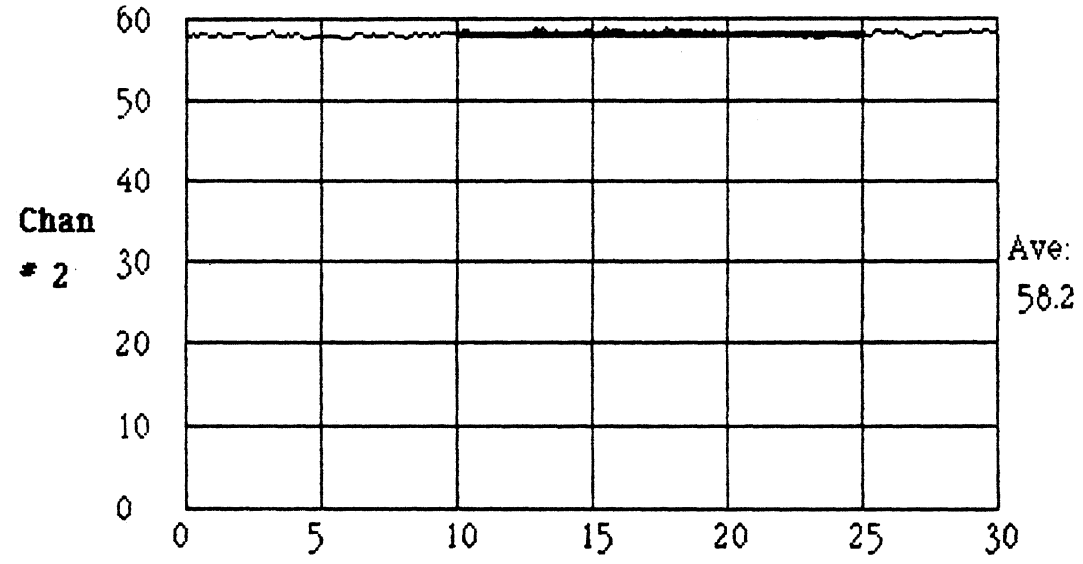

Chan
10
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
-2.00

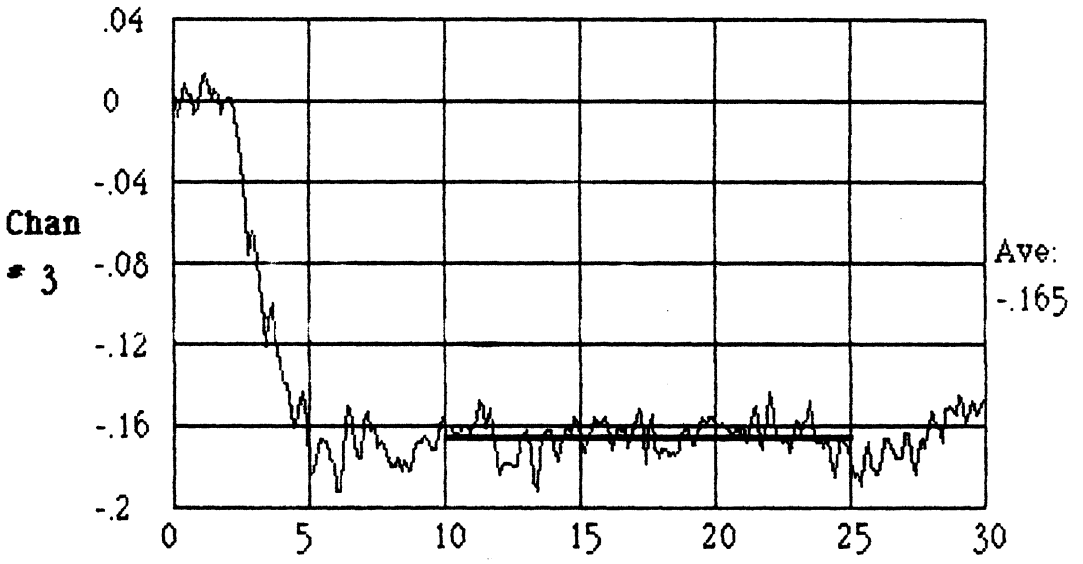
Ford LTD

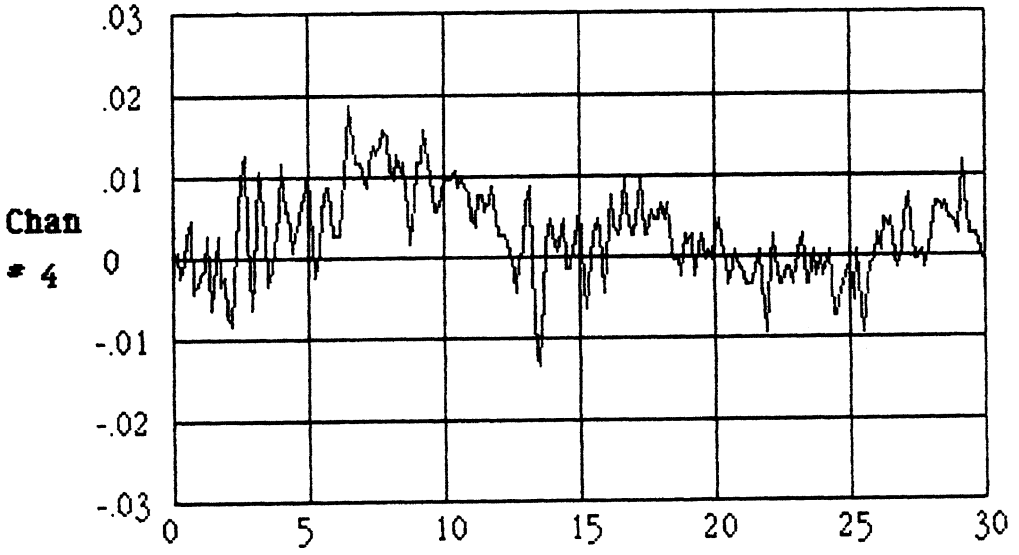
Curve #1

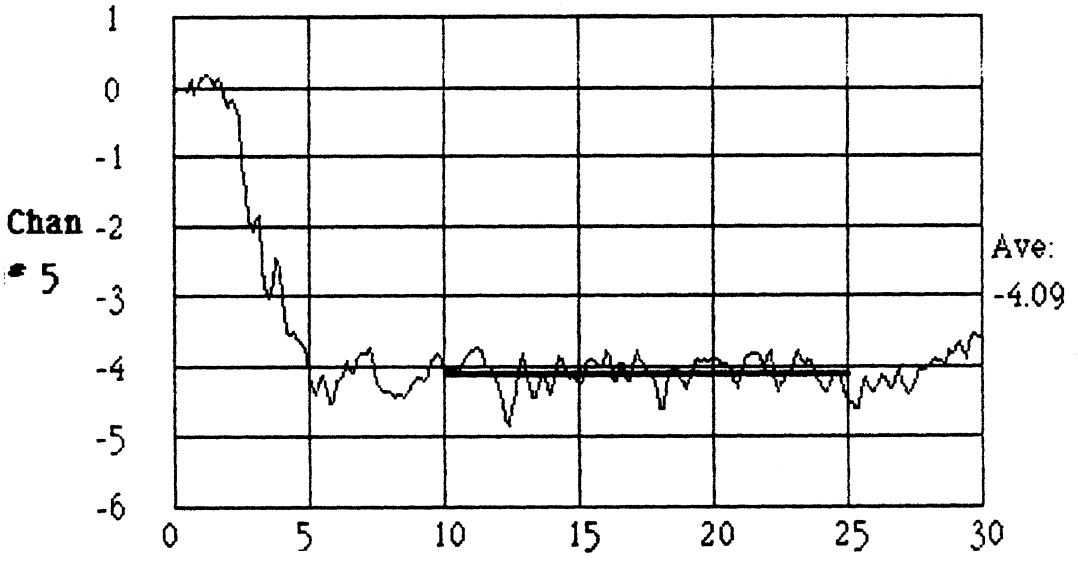
Repeat 1

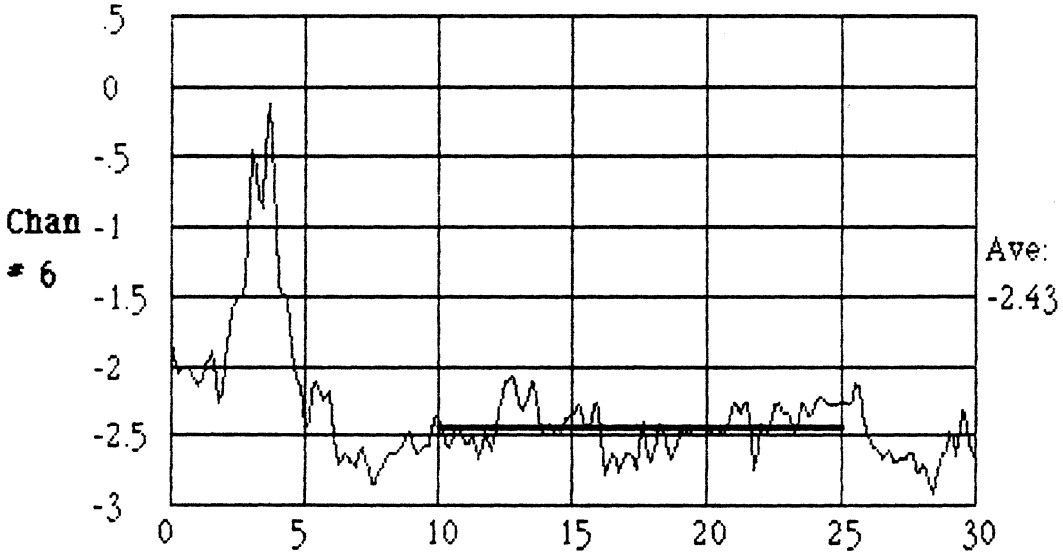
Steady Turning

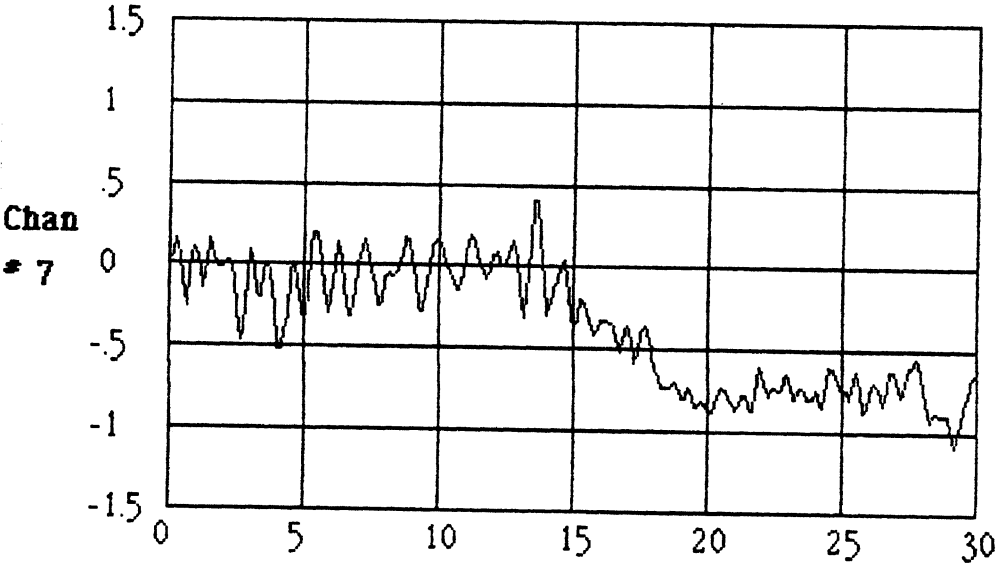

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
58.2

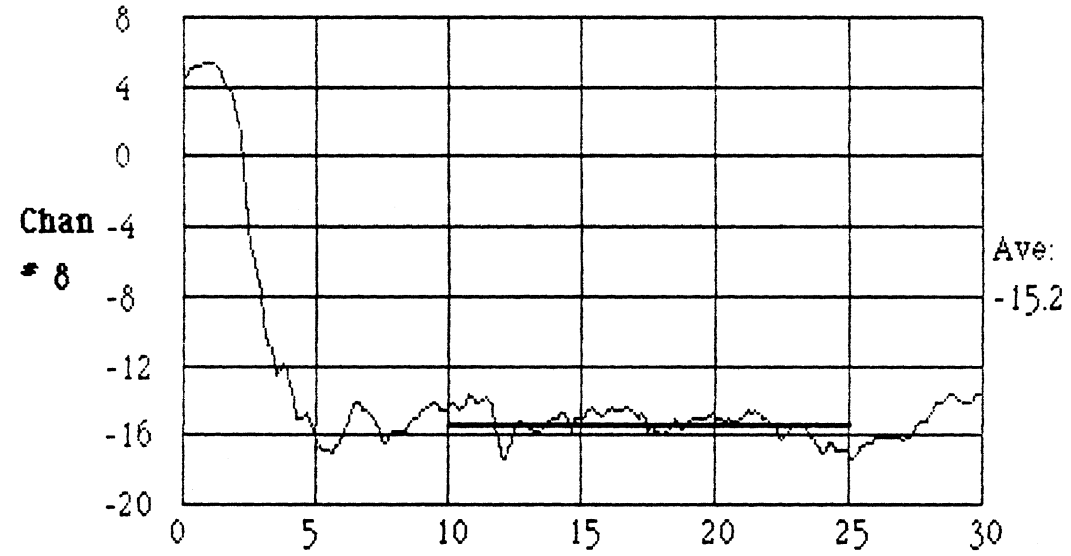

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.165

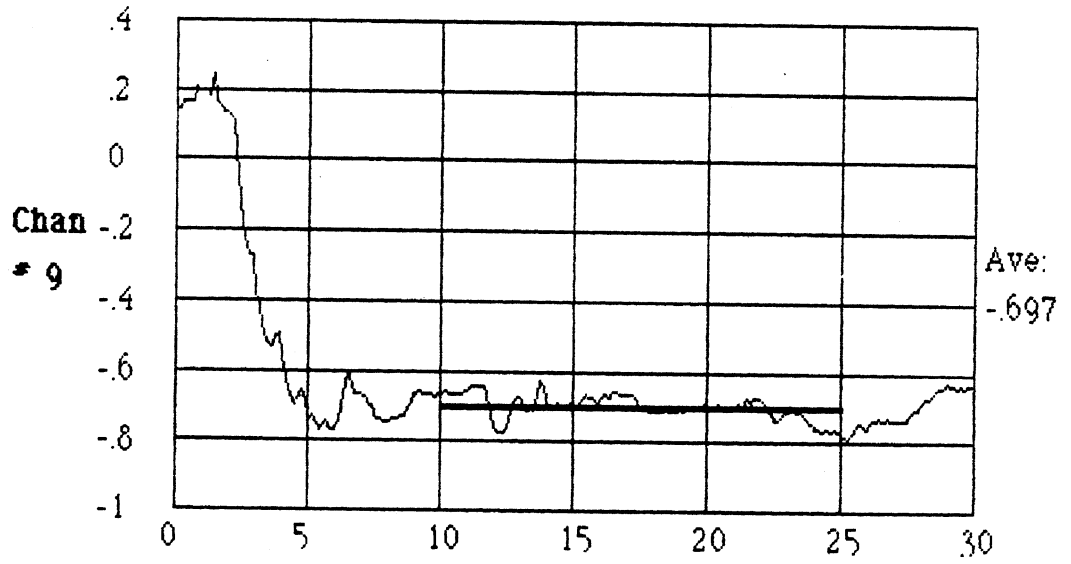

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

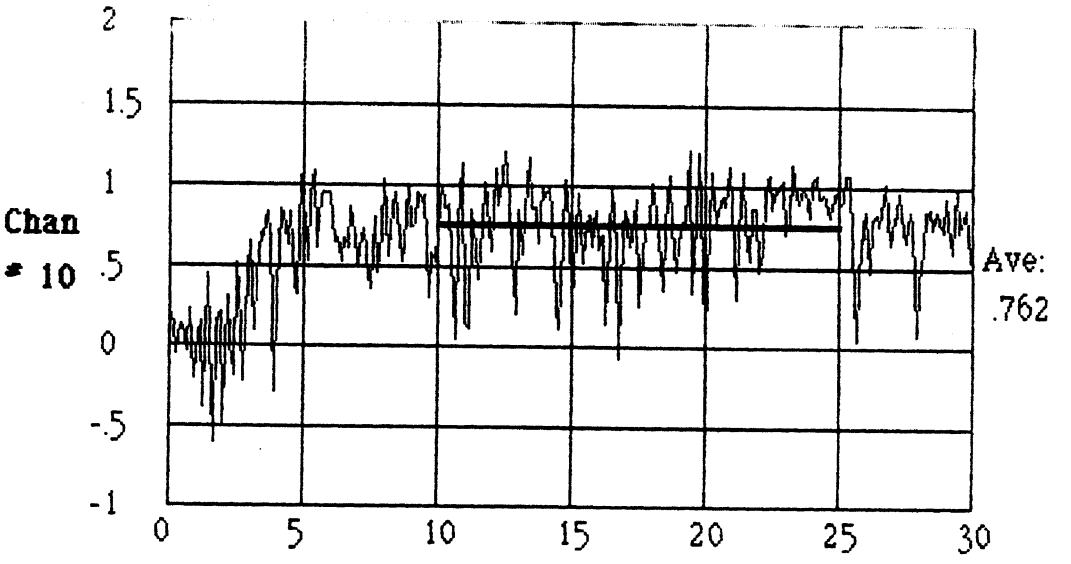

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-4.09


Chan
6
.5
0
-.5
-1
-1.5
-2
-2.5
-3
0
5
10
15
20
25
30
Ave:
-2.43


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
8
4
0
-4
-8
-12
-16
-20
0
5
10
15
20
25
30
Ave:
-15.2


Chan
9
.4
.2
0
-.2
-.4
-.6
-.8
-1
0
5
10
15
20
25
30
Ave:
-.697

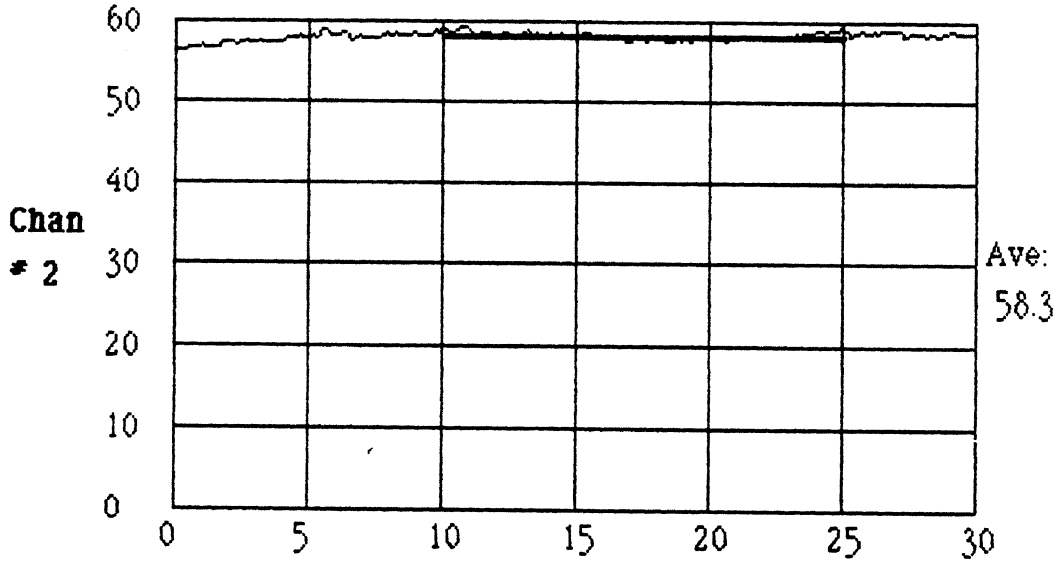

Chan
10
2
1.5
1
.5
0
-.5
-1
0
5
10
15
20
25
30
Ave:
.762

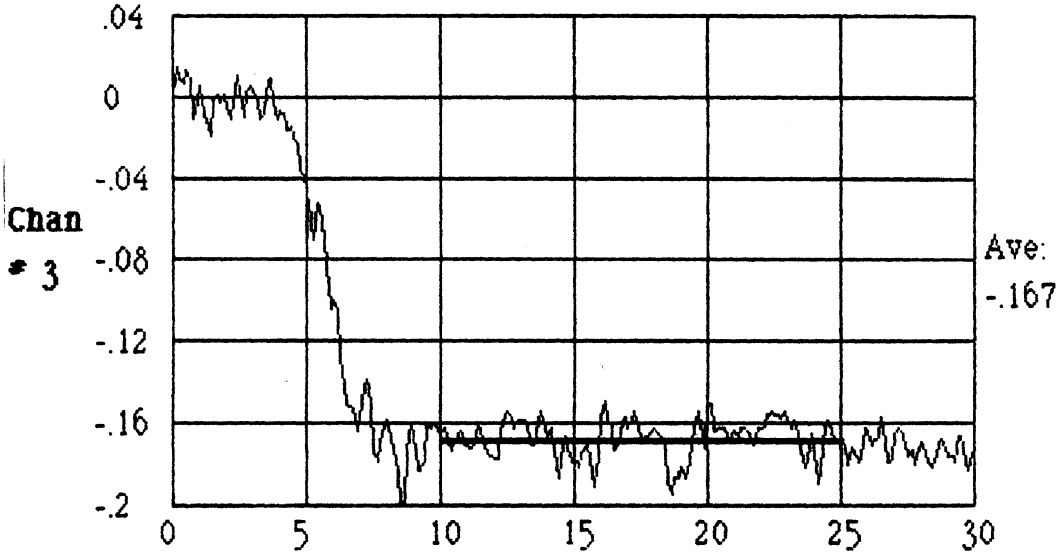
Ford LTD

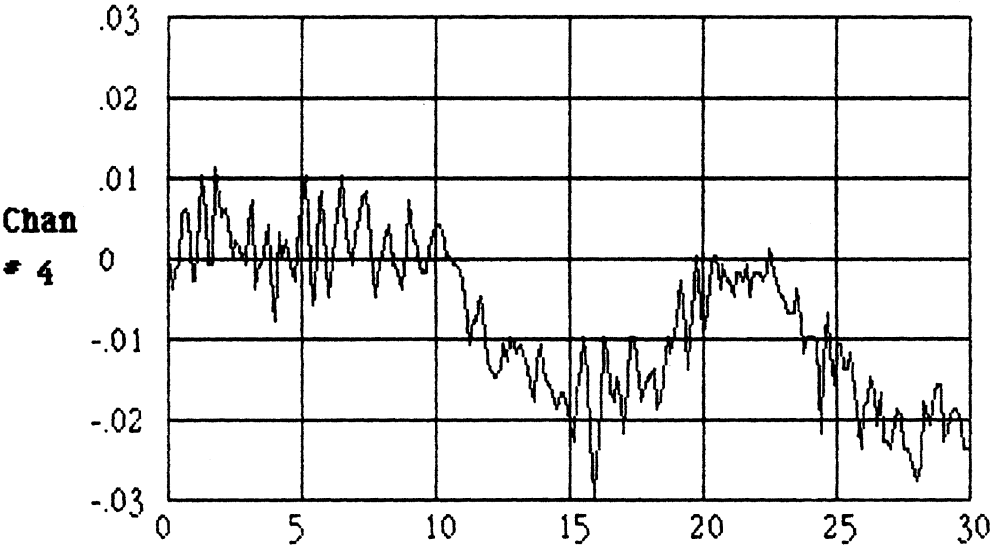
Curve #1

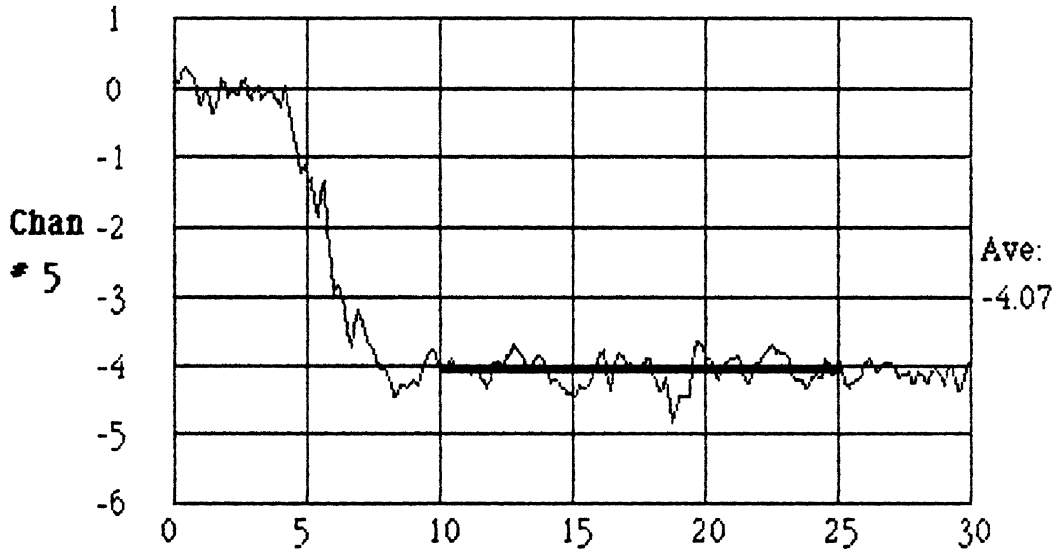
Repeat 2

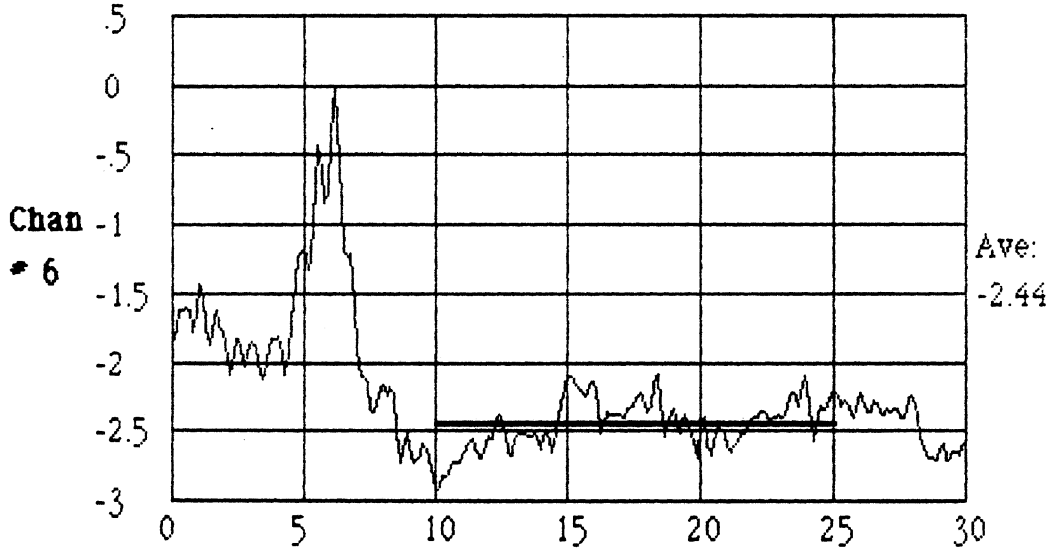
Steady Turning

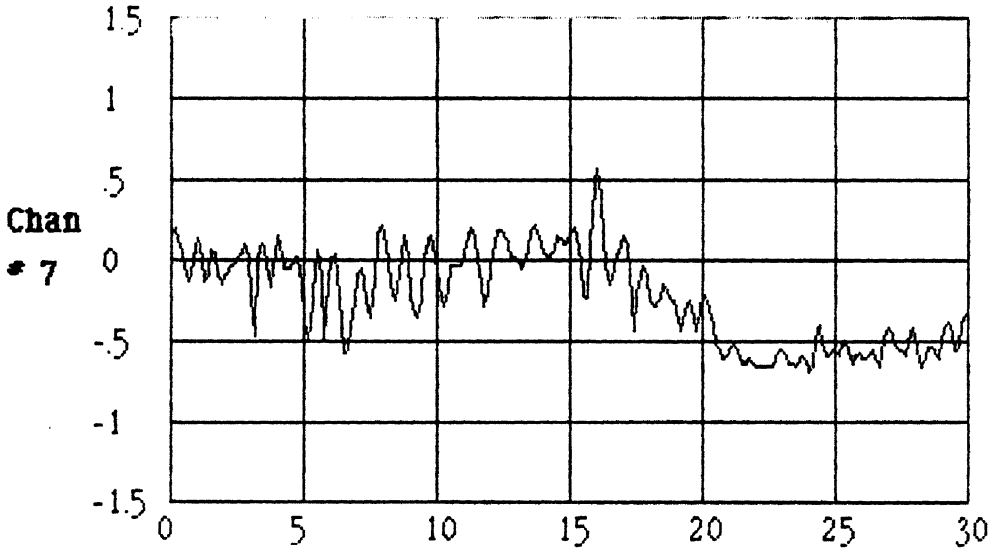

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
58.3

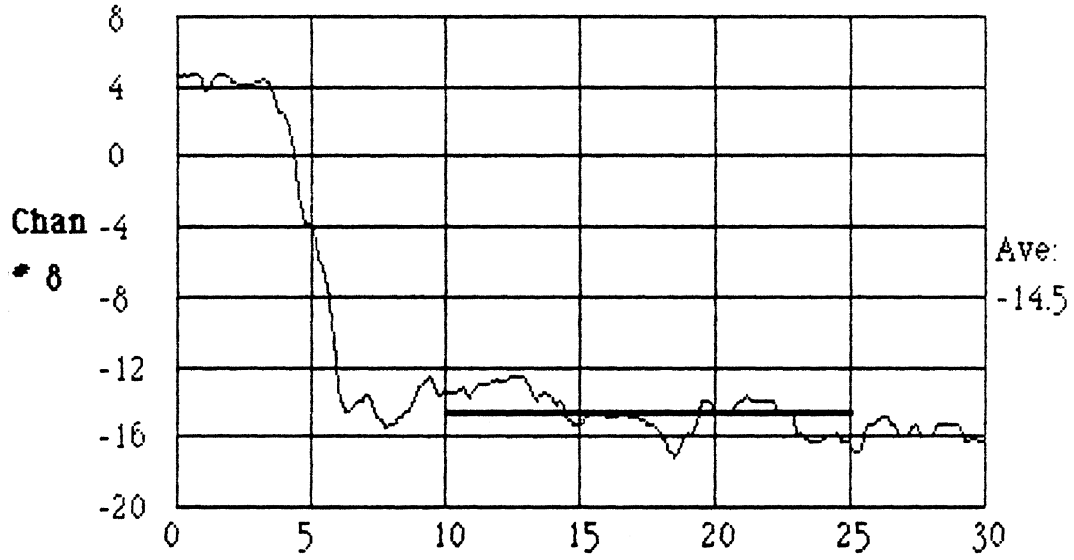

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.167

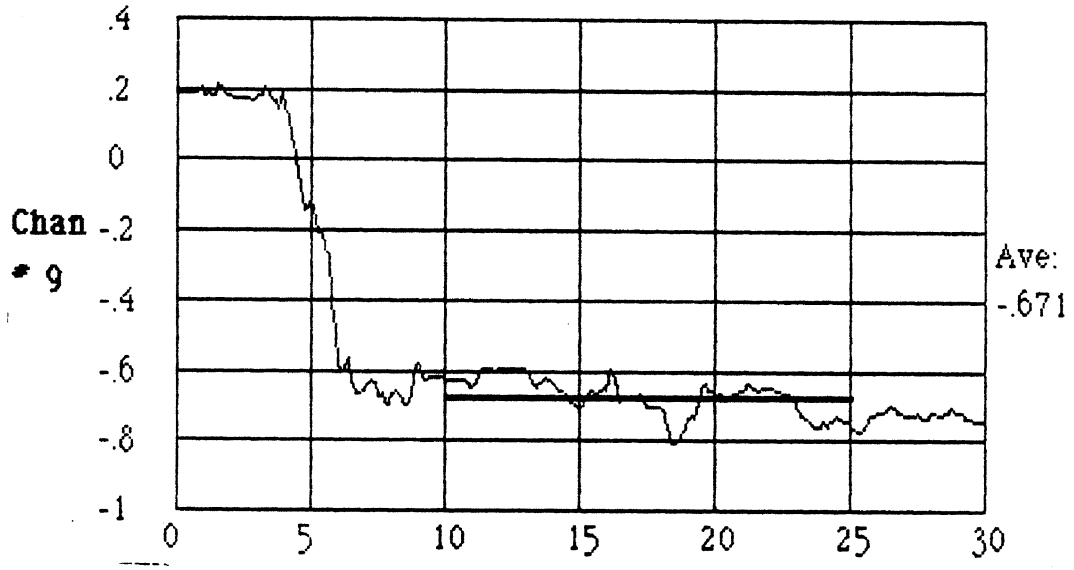

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

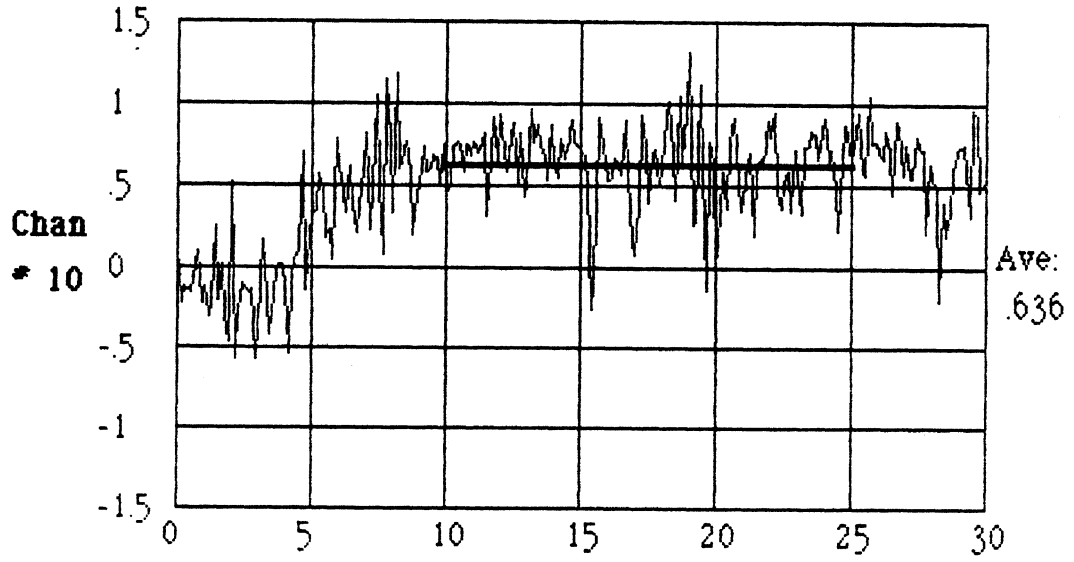

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-4.07


Chan
6
.5
0
-.5
-1
-1.5
-2
-2.5
-3
0
5
10
15
20
25
30
Ave:
-2.44


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
8
4
0
-4
-8
-12
-16
-20
0
5
10
15
20
25
30
Ave:
-14.5


Chan
9
.4
.2
0
-.2
-.4
-.6
-.8
-1
0
5
10
15
20
25
30
Ave:
-.671

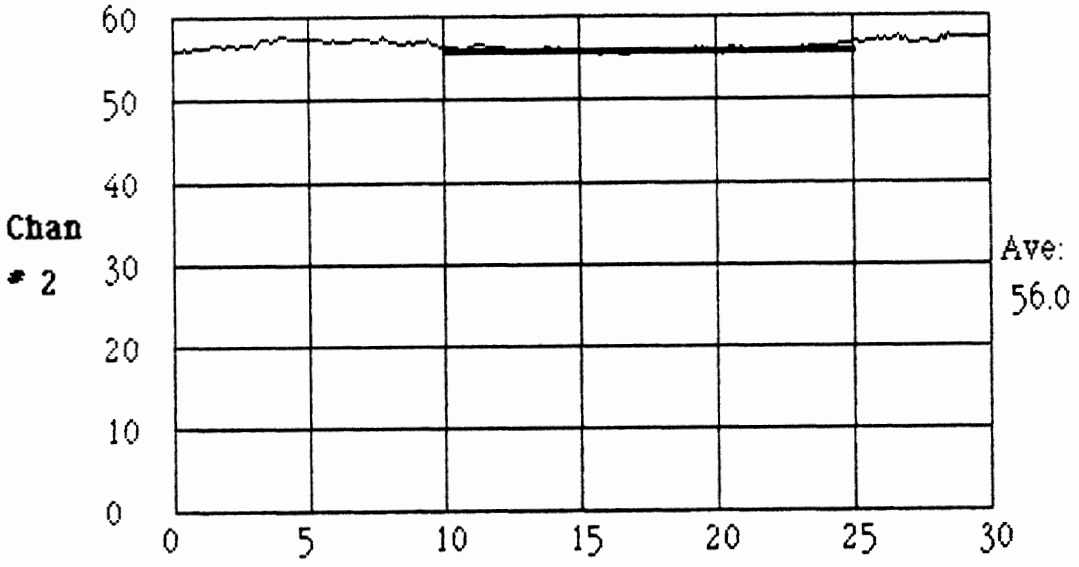

Chan
10
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30
Ave:
.636

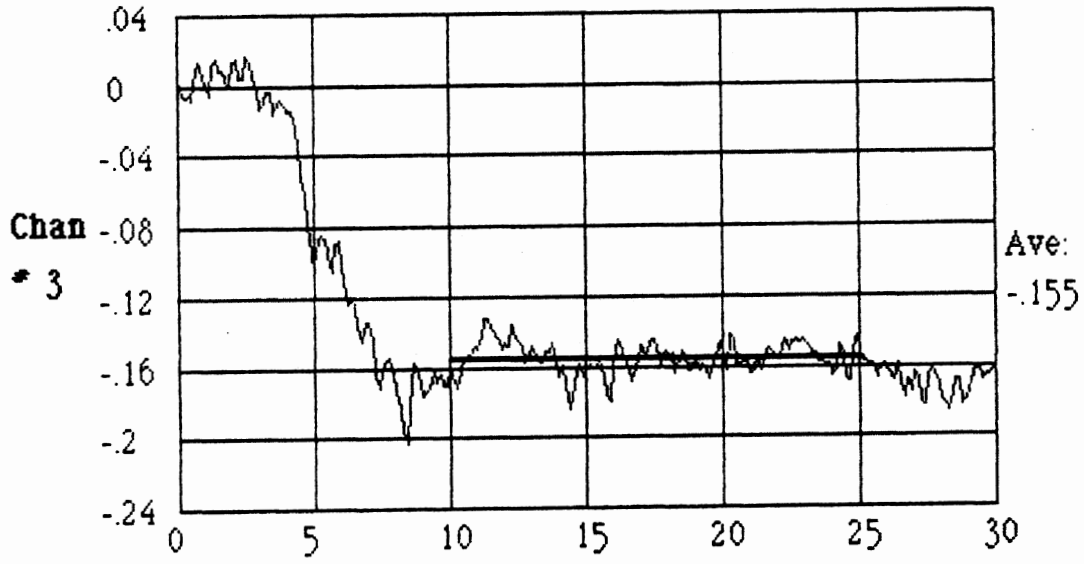
Ford LTD

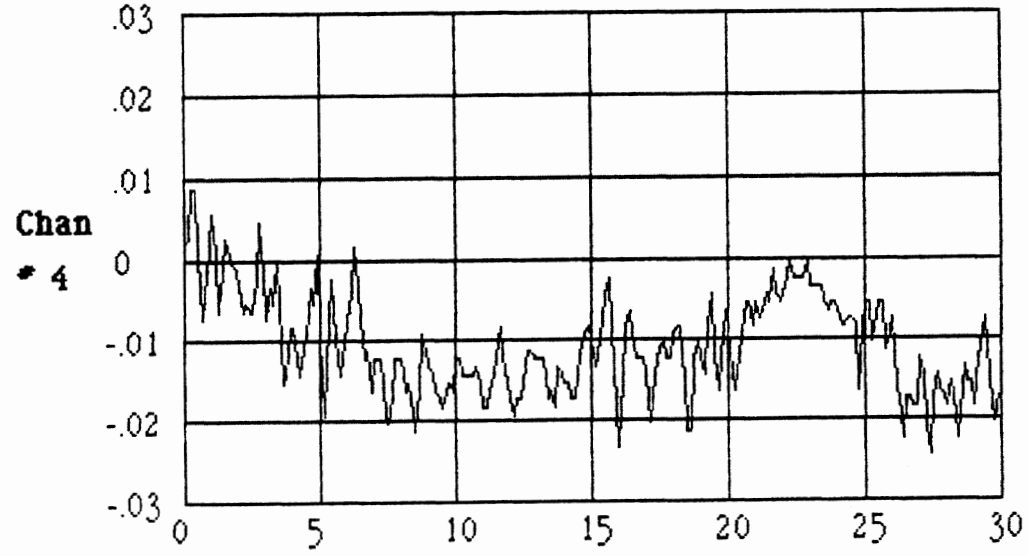
Curve #1

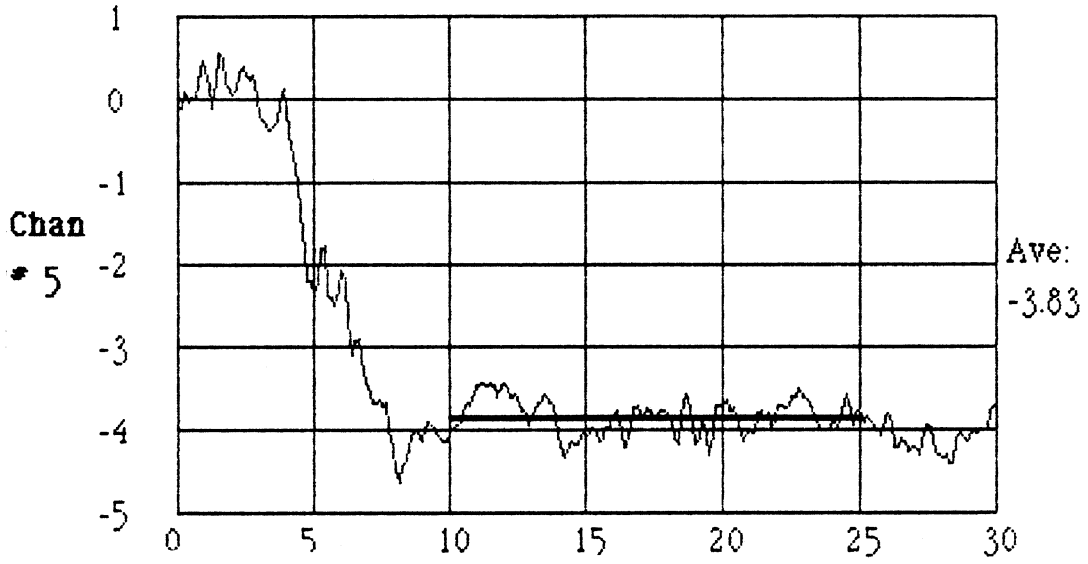
Repeat 3

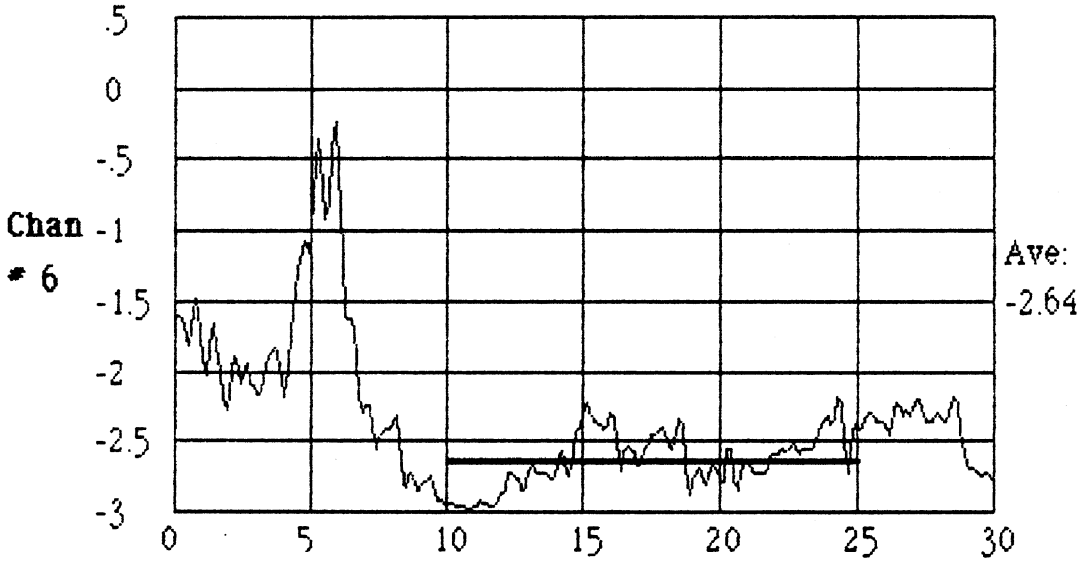
Steady Turning

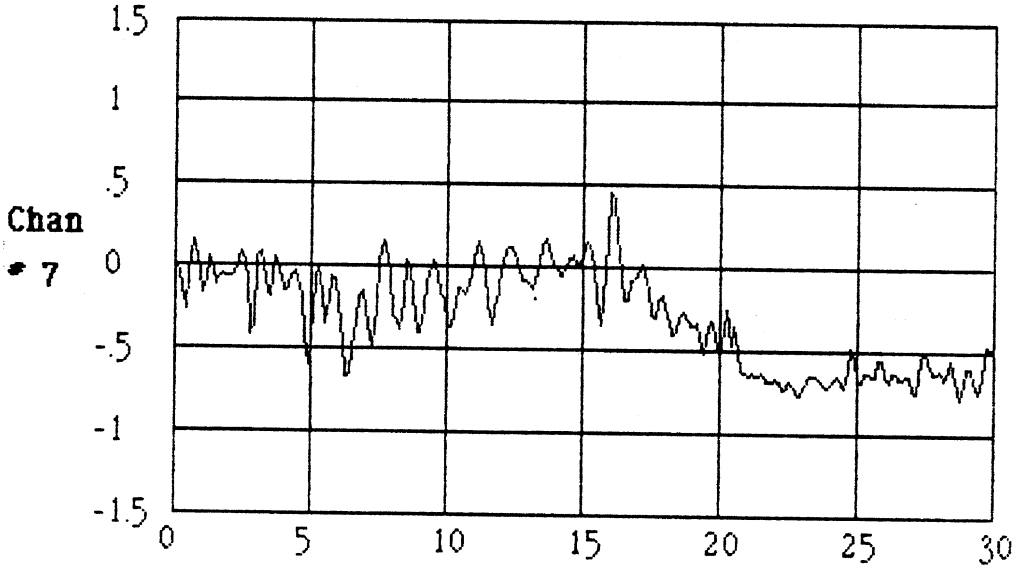

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
56.0

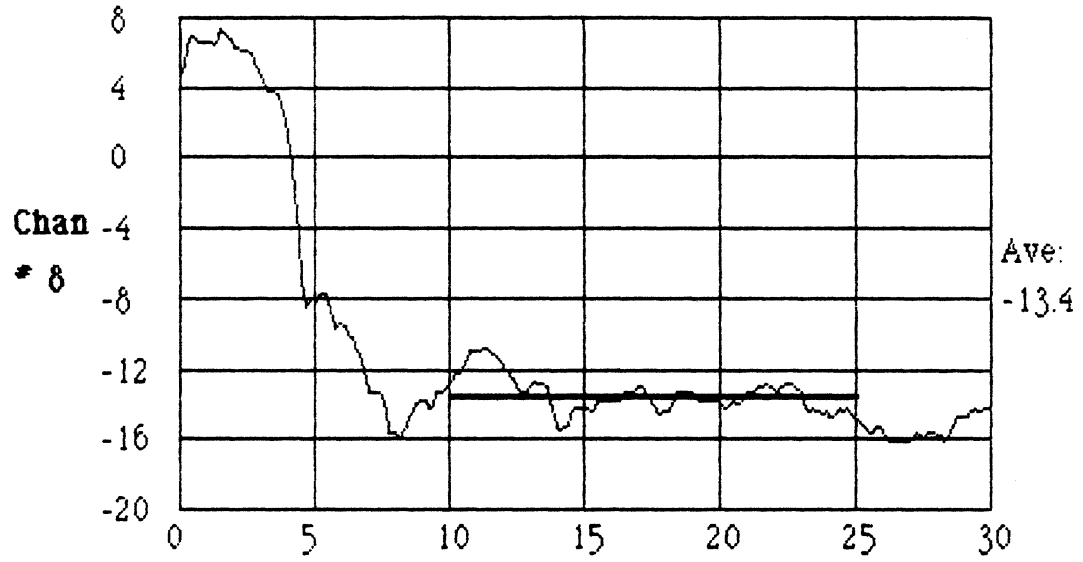

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
-.24
0
5
10
15
20
25
30
Ave:
-.155

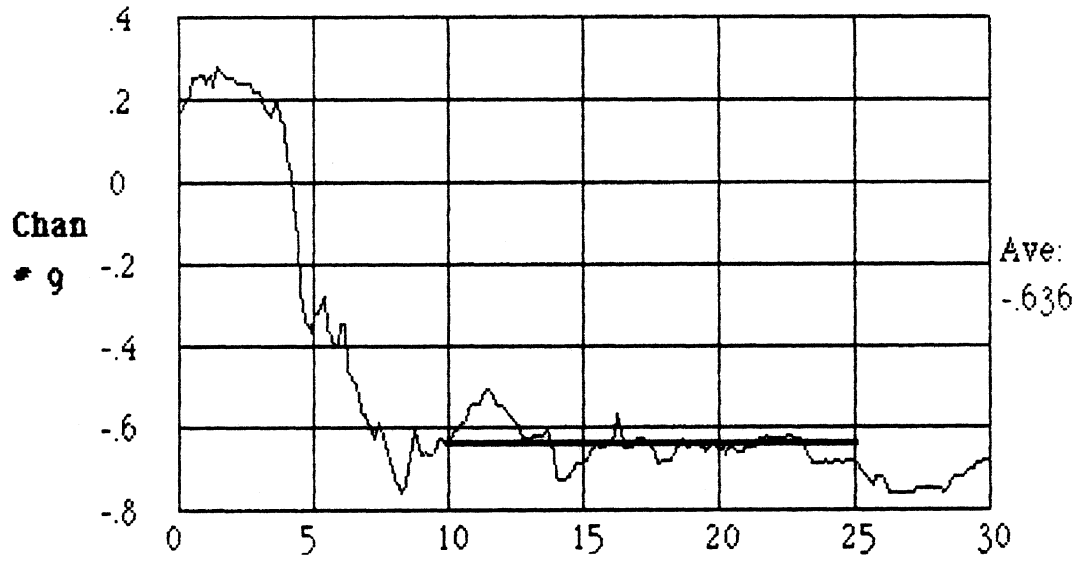

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

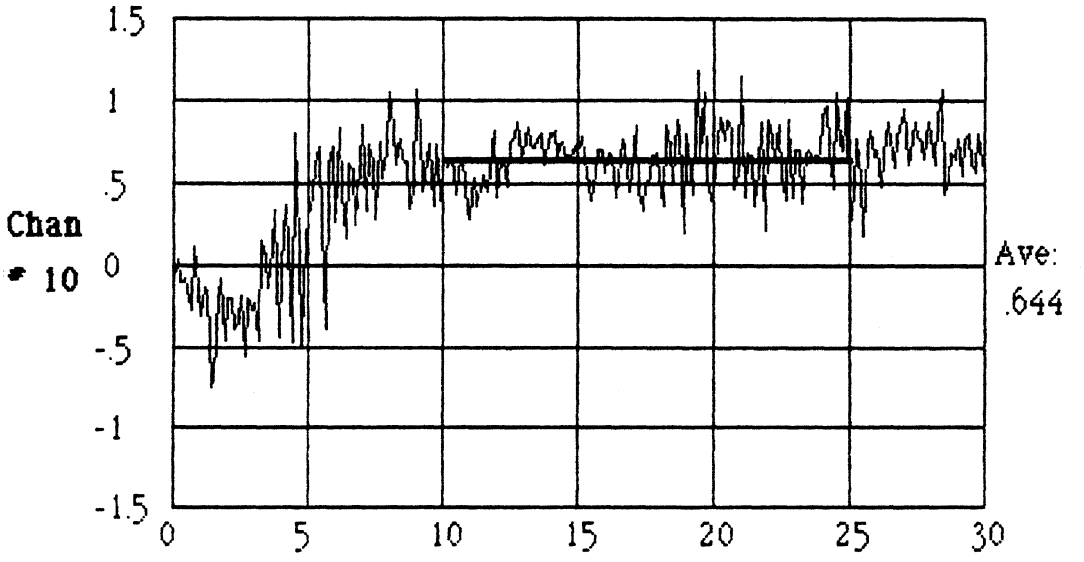

Chan
5
1
0
-1
-2
-3
-4
-5
0
5
10
15
20
25
30
Ave:
-3.83


Chan
6
.5
0
-.5
-1
-1.5
-2
-2.5
-3
0
5
10
15
20
25
30
Ave:
-2.64


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
8
4
0
-4
-8
-12
-16
-20
0
5
10
15
20
25
30
Ave:
-13.4


Chan
9
.4
.2
0
-.2
-.4
-.6
-.8
0
5
10
15
20
25
30
Ave:
-.636

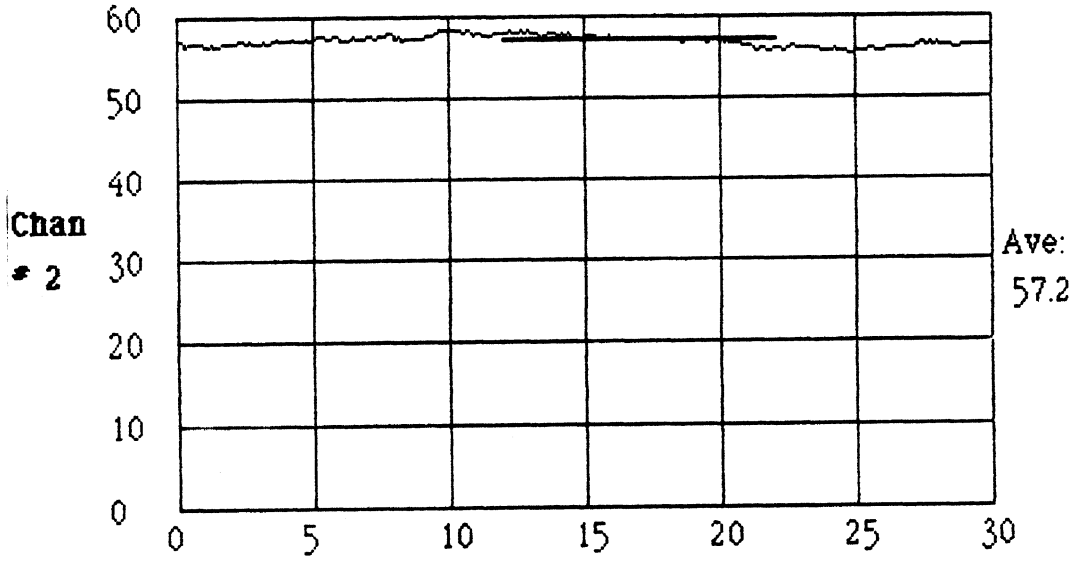

Chan
10
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30
Ave:
.644

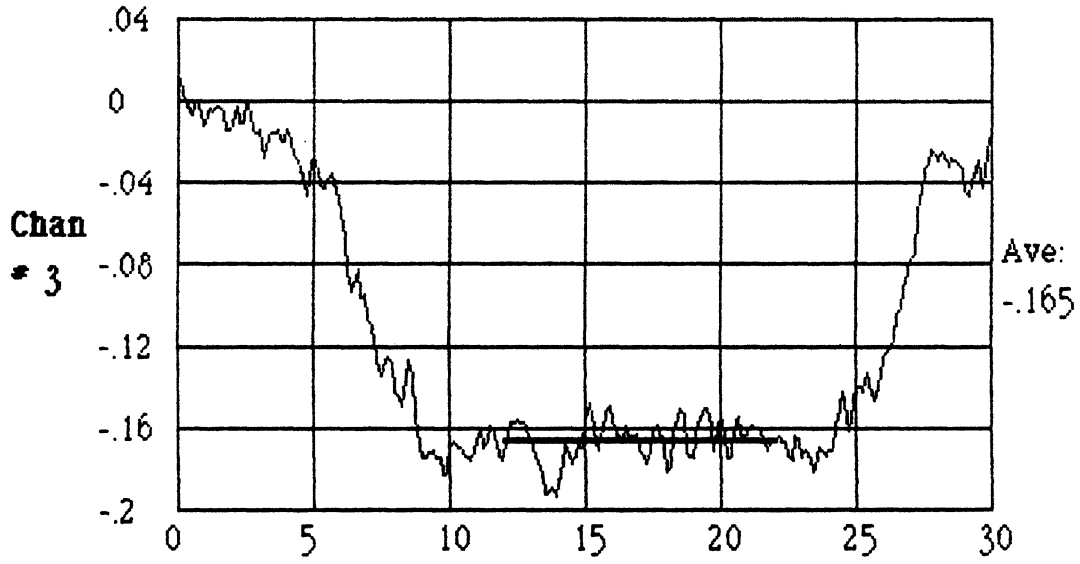
Ford LTD

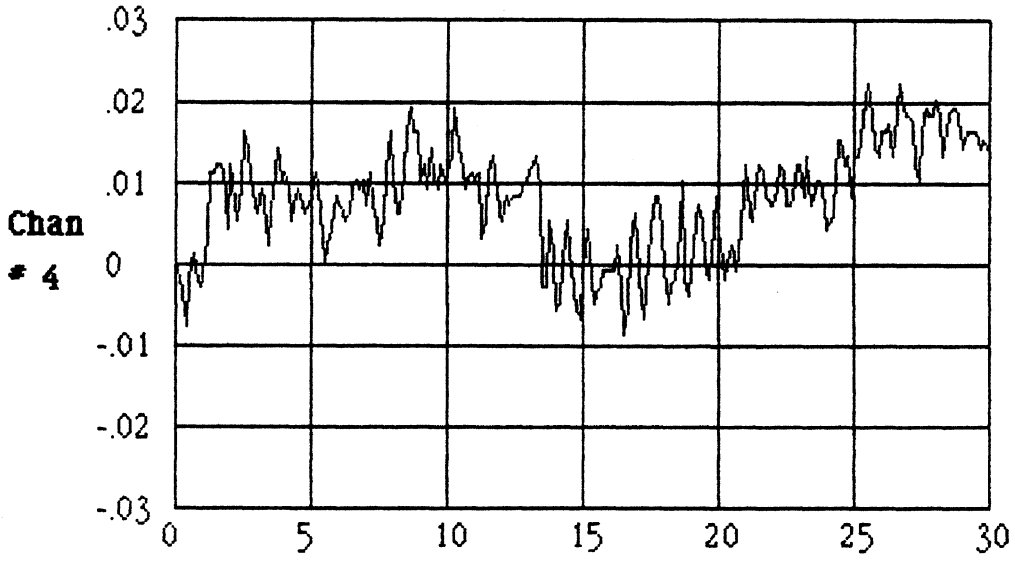
Curve #2

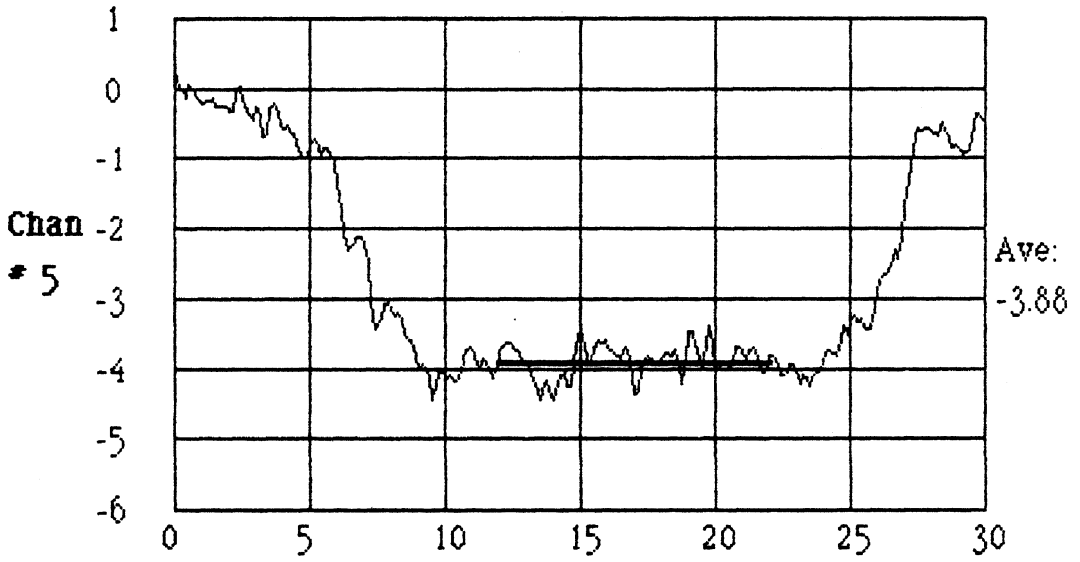
Repeat 1

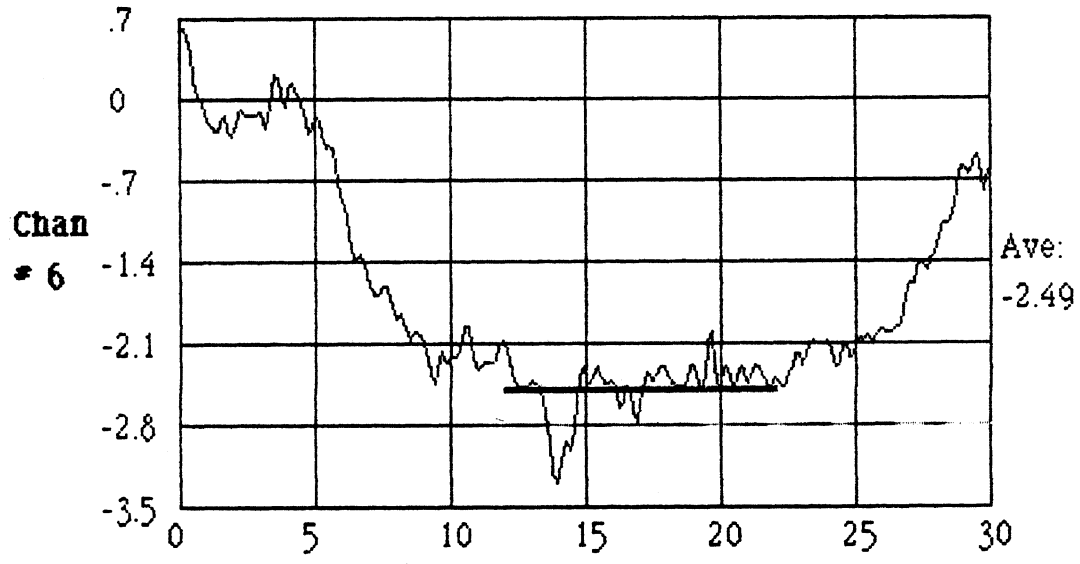
Steady Turning

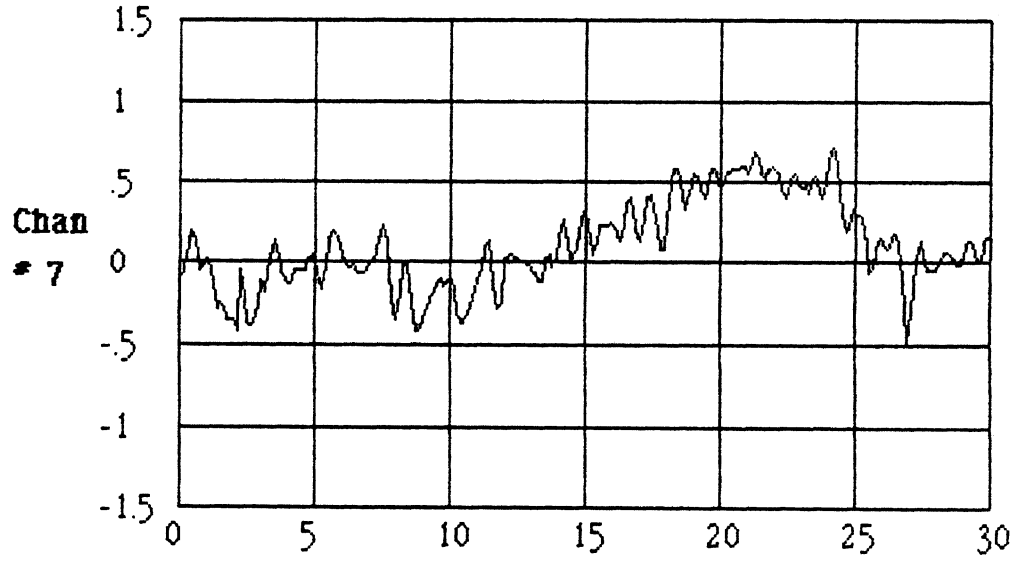

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
57.2

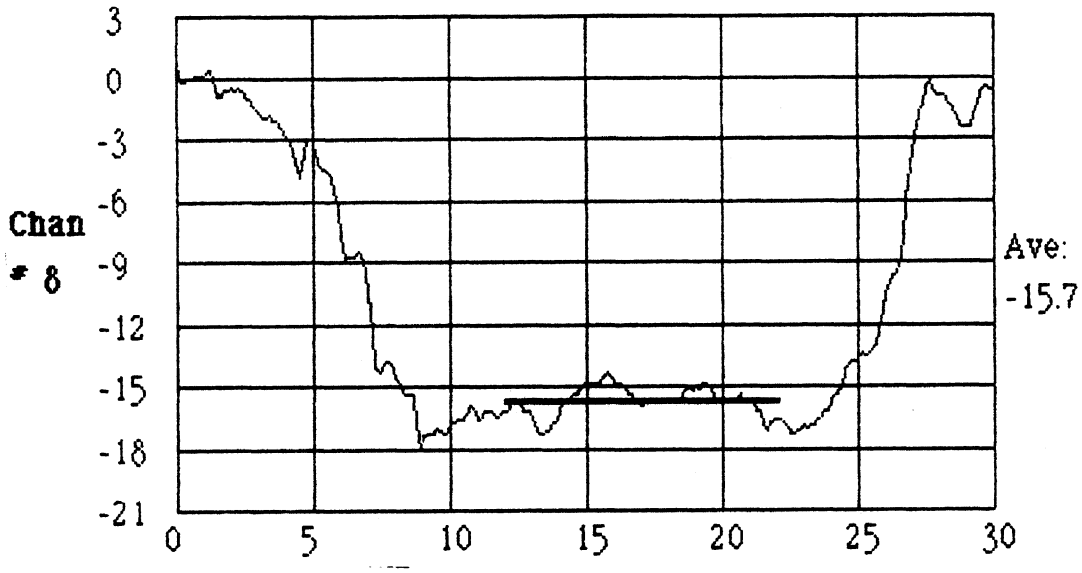

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
0
5
10
15
20
25
30
Ave:
-.165

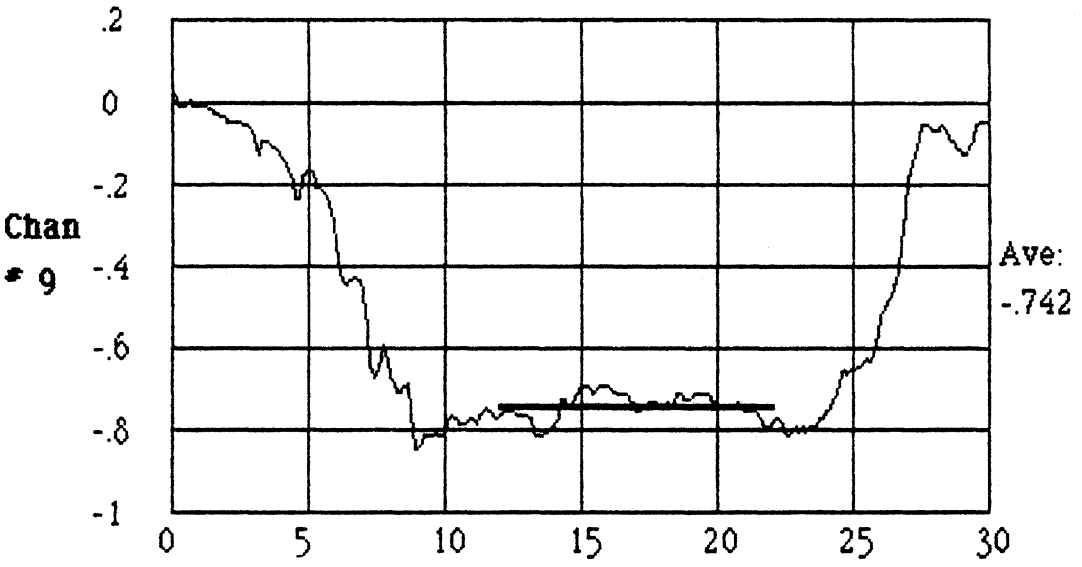

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

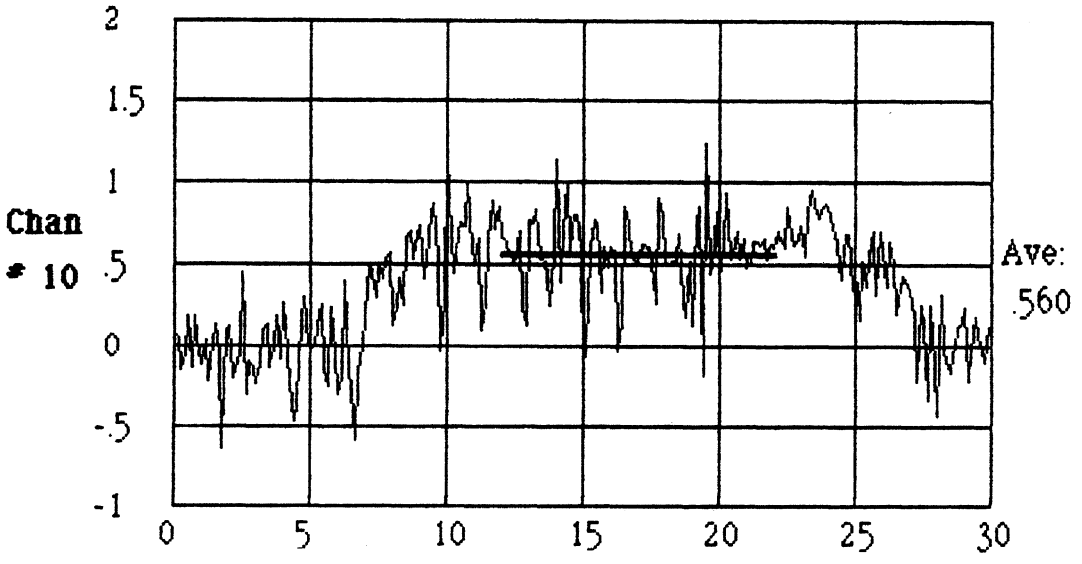

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-3.88


Chan
6
.7
0
-.7
-1.4
-2.1
-2.8
-3.5
0
5
10
15
20
25
30
Ave:
-2.49


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
3
0
-3
-6
-9
-12
-15
-18
-21
0
5
10
15
20
25
30
Ave:
-15.7


Chan
9
.2
0
-.2
-.4
-.6
-.8
-1
0
5
10
15
20
25
30
Ave:
-.742

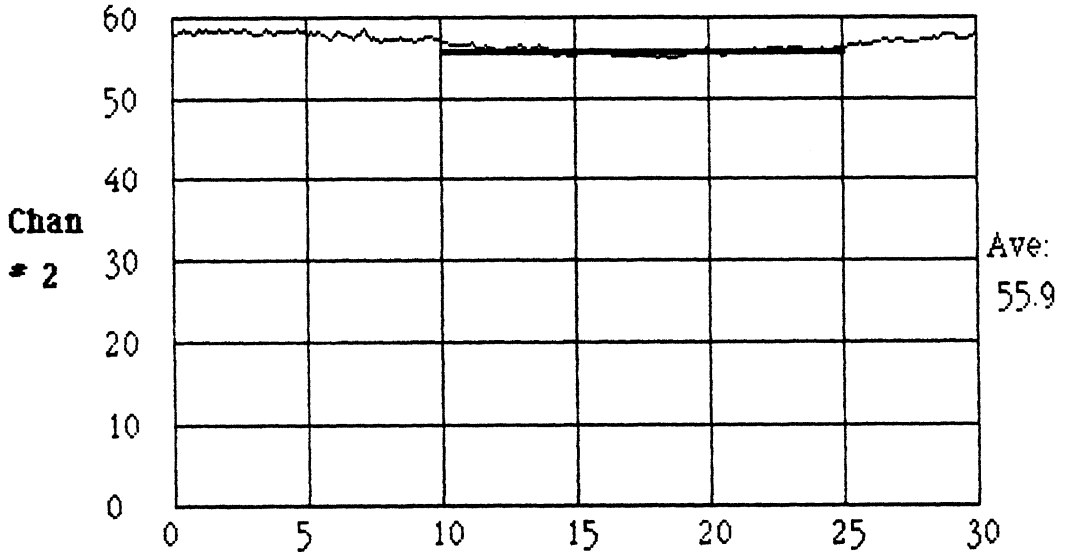

Chan
10
2
1.5
1
.5
0
-.5
-1
0
5
10
15
20
25
30
Ave:
.560

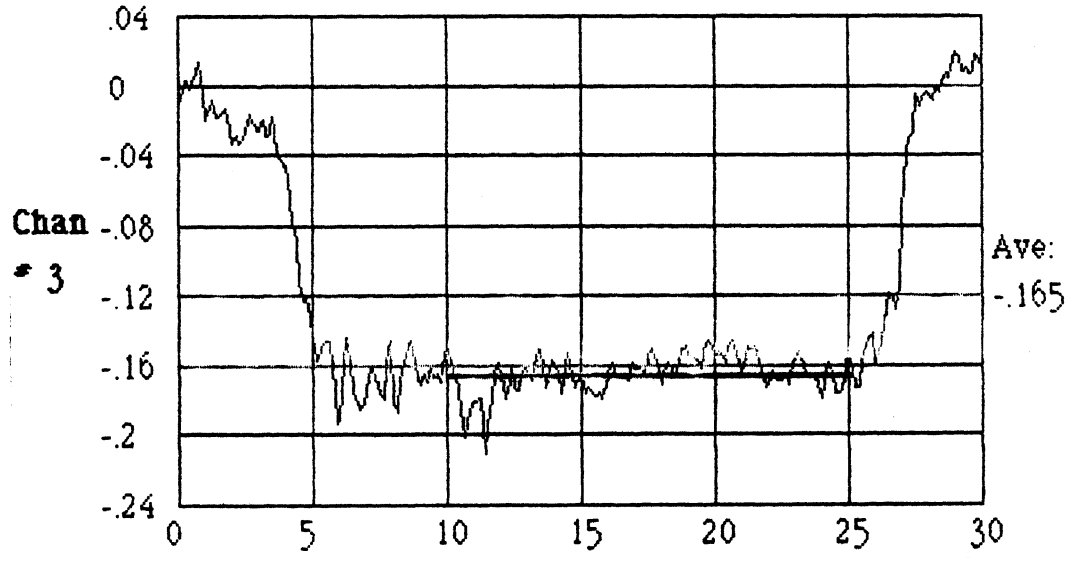
Ford LTD

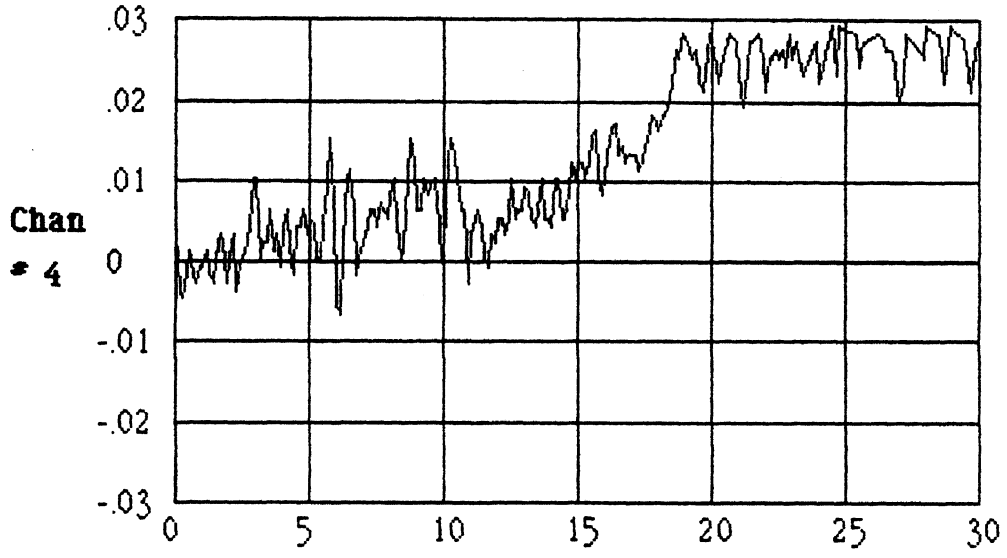
Curve #3

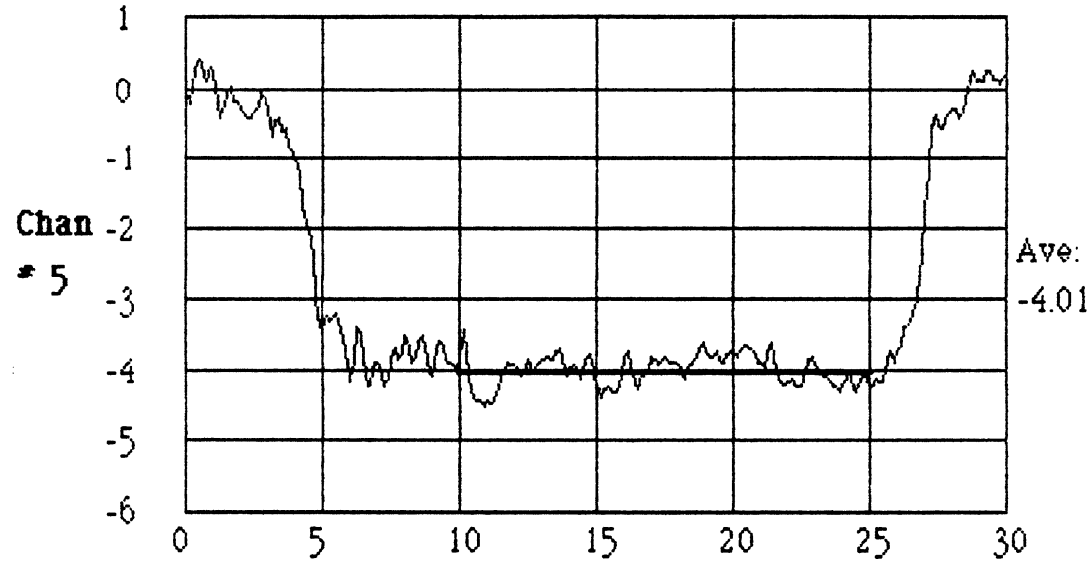
Repeat 1

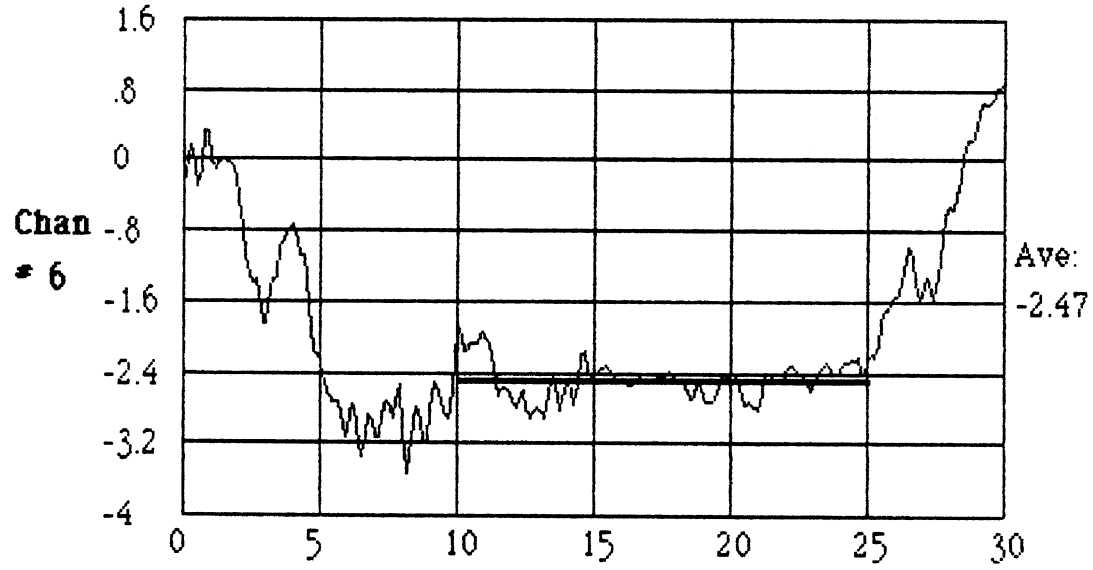
Steady Turning

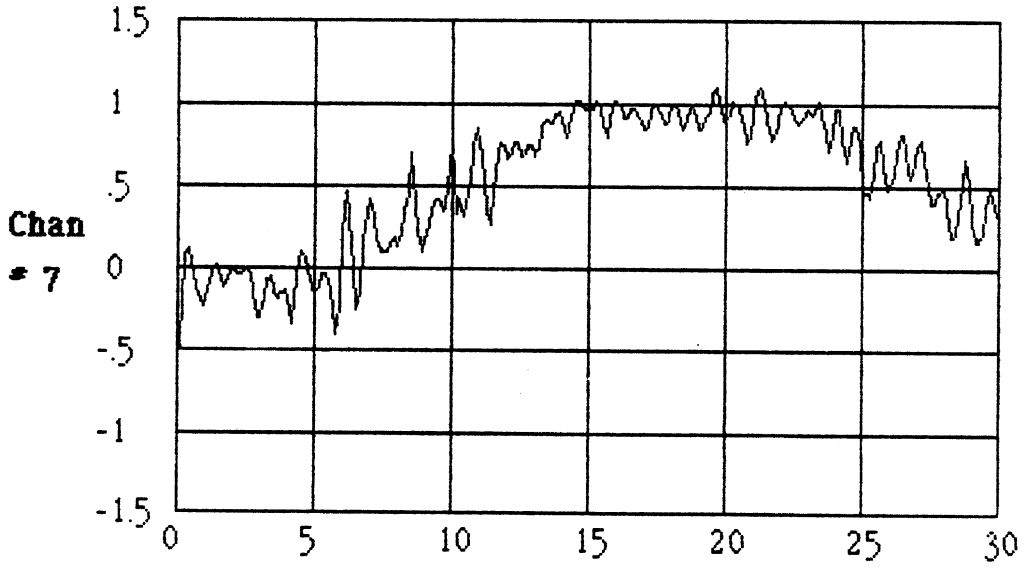

Chan
2
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Ave:
55.9

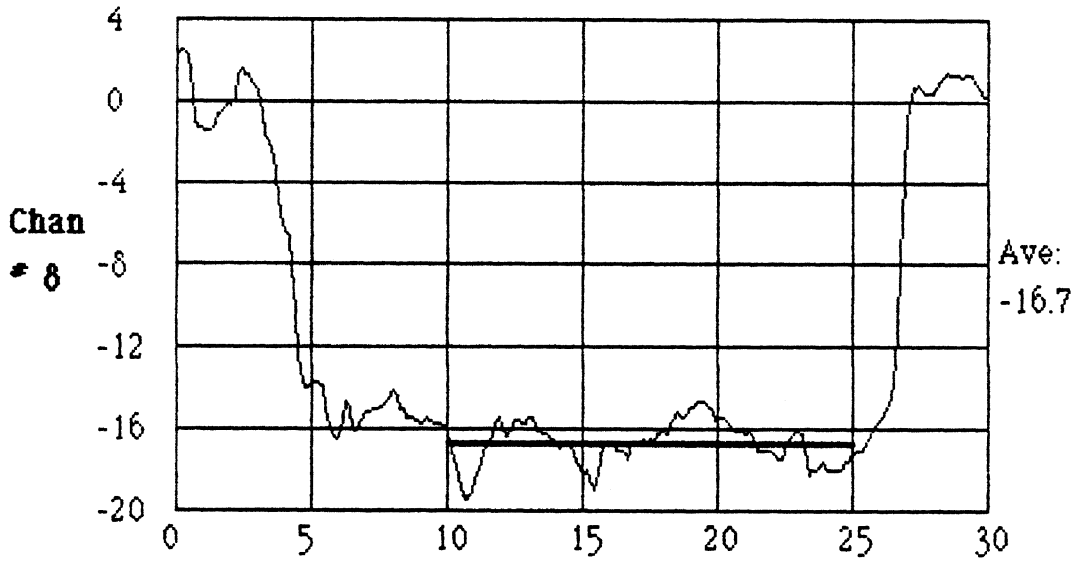

Chan
3
.04
0
-.04
-.08
-.12
-.16
-.2
-.24
0
5
10
15
20
25
30
Ave:
-.165

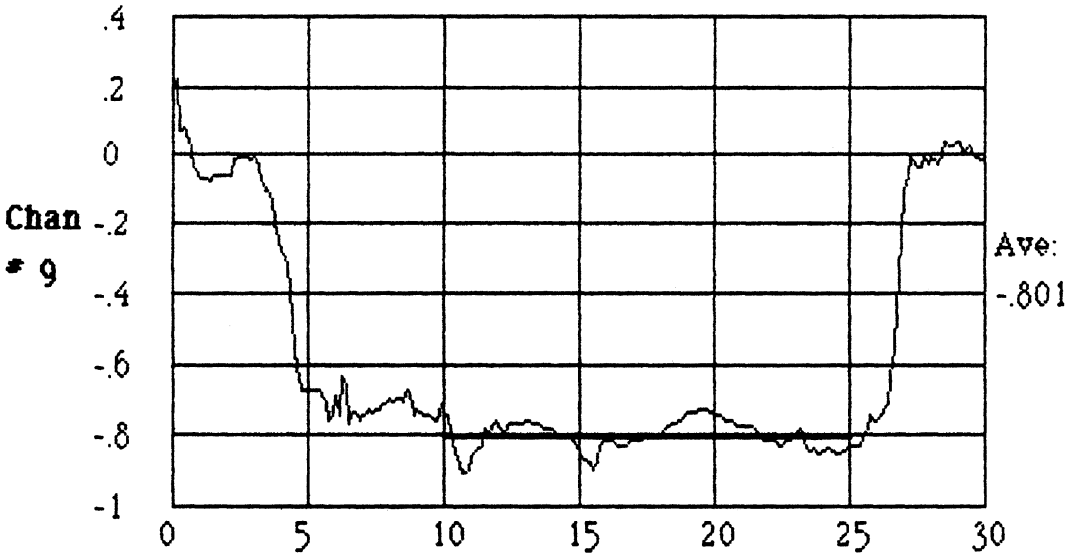

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
5
10
15
20
25
30

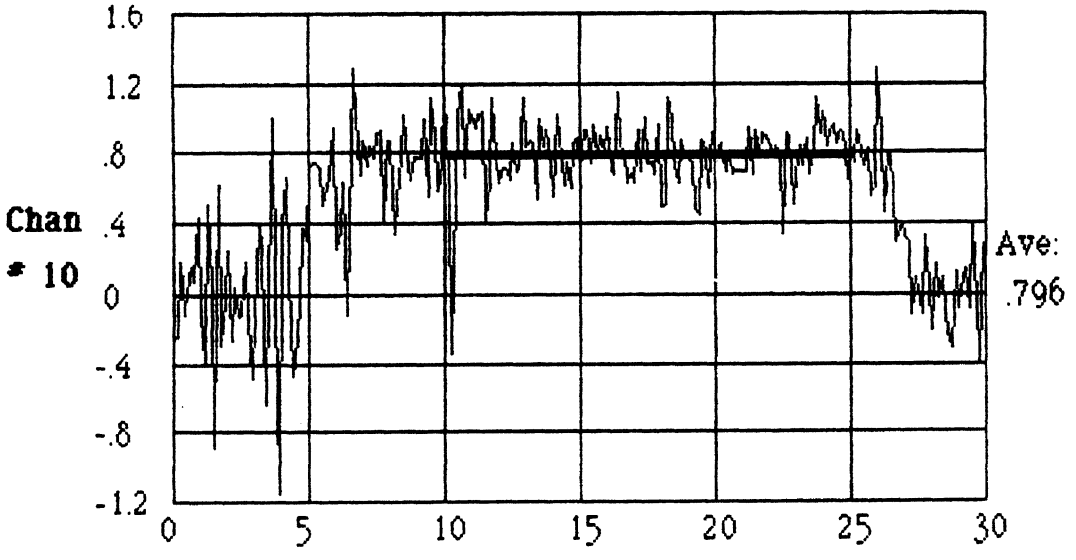

Chan
5
1
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
Ave:
-4.01


Chan
6
1.6
.8
0
-.8
-1.6
-2.4
-3.2
-4
0
5
10
15
20
25
30
Ave:
-2.47


Chan
7
1.5
1
.5
0
-.5
-1
-1.5
0
5
10
15
20
25
30


Chan
8
4
0
-4
-8
-12
-16
-20
0
5
10
15
20
25
30
Ave:
-16.7


Chan
9
.4
.2
0
-.2
-.4
-.6
-.8
-1
0
5
10
15
20
25
30
Ave:
-.801

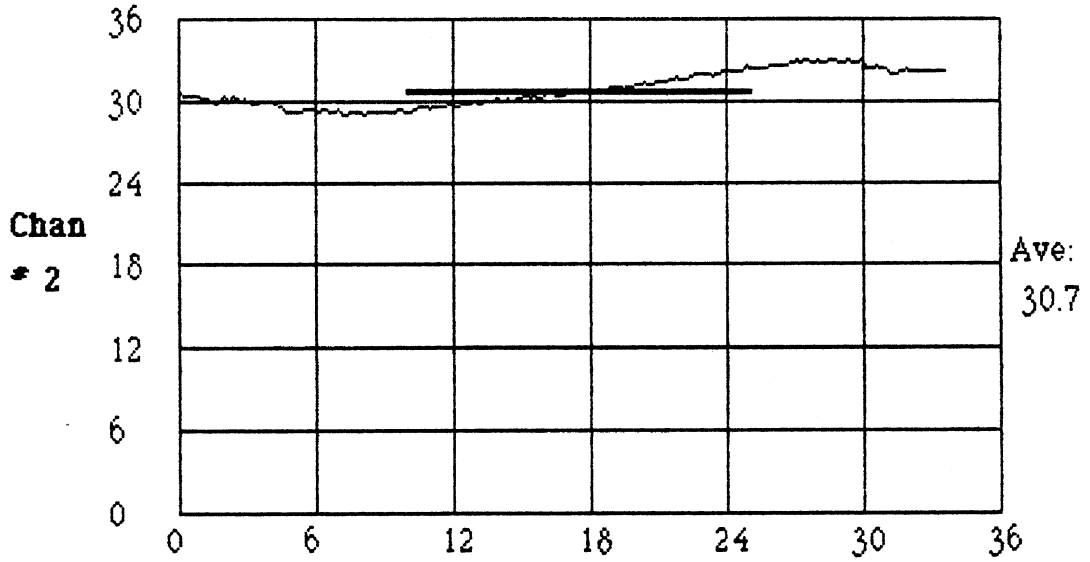

Chan
10
1.6
1.2
.8
.4
0
-.4
-.8
-1.2
0
5
10
15
20
25
30
Ave:
.796

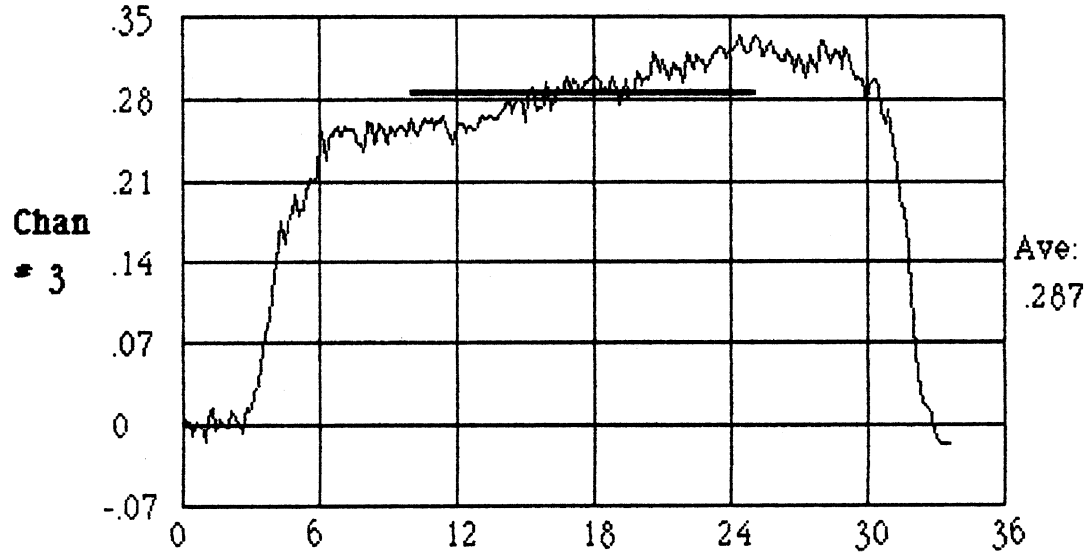
Ford LTD

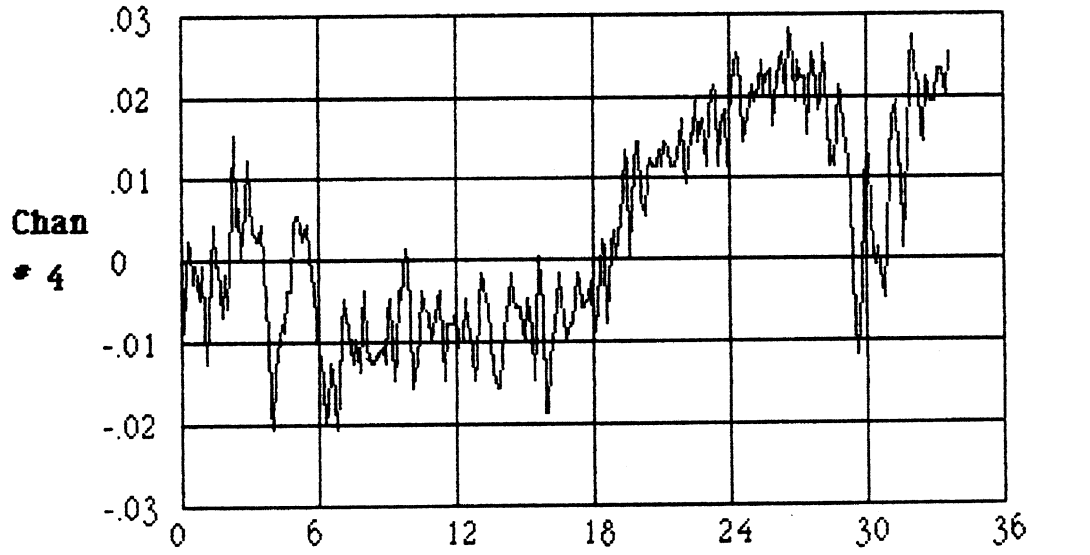
Ramp

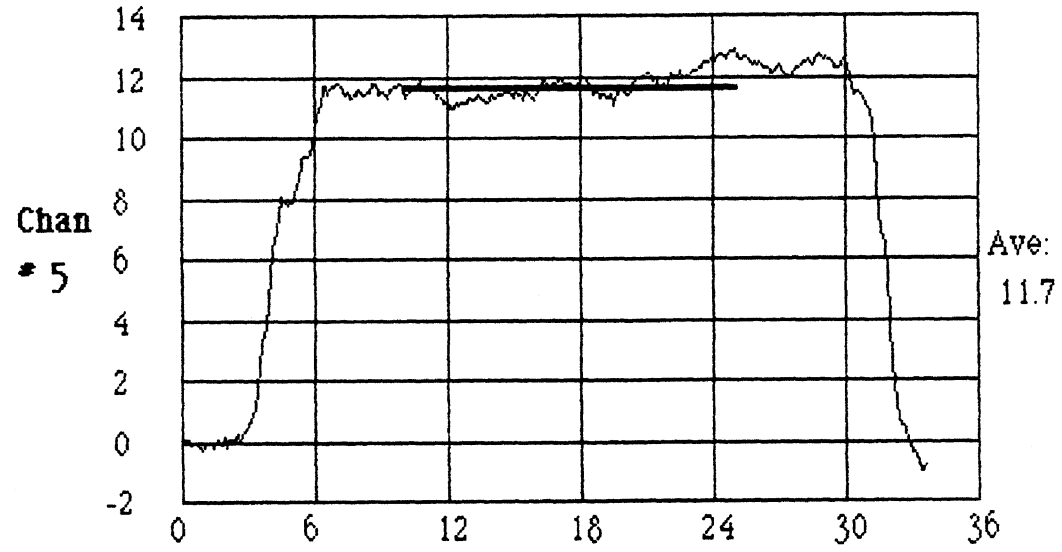
Repeat 1

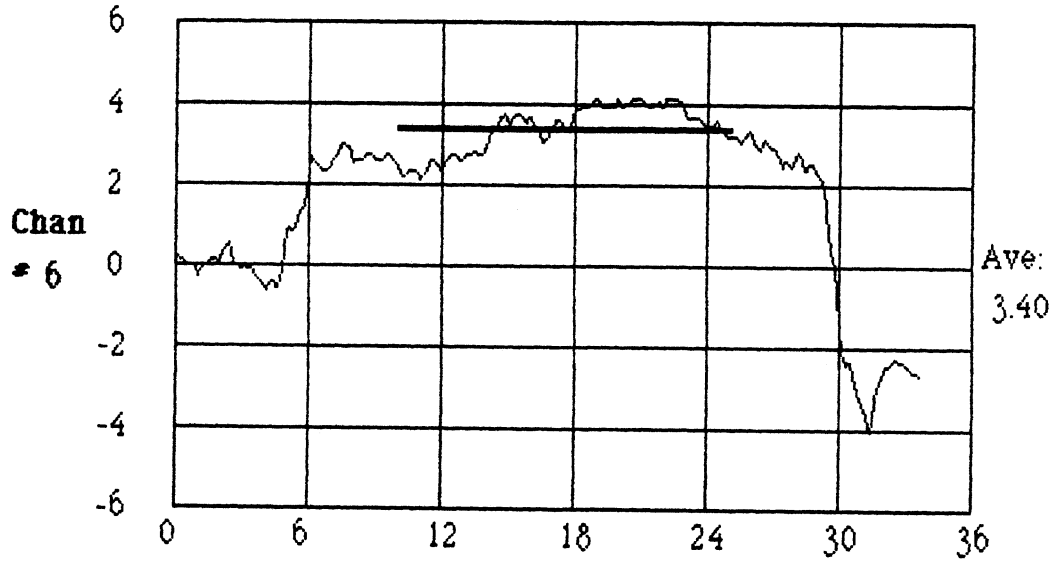
Steady Turning

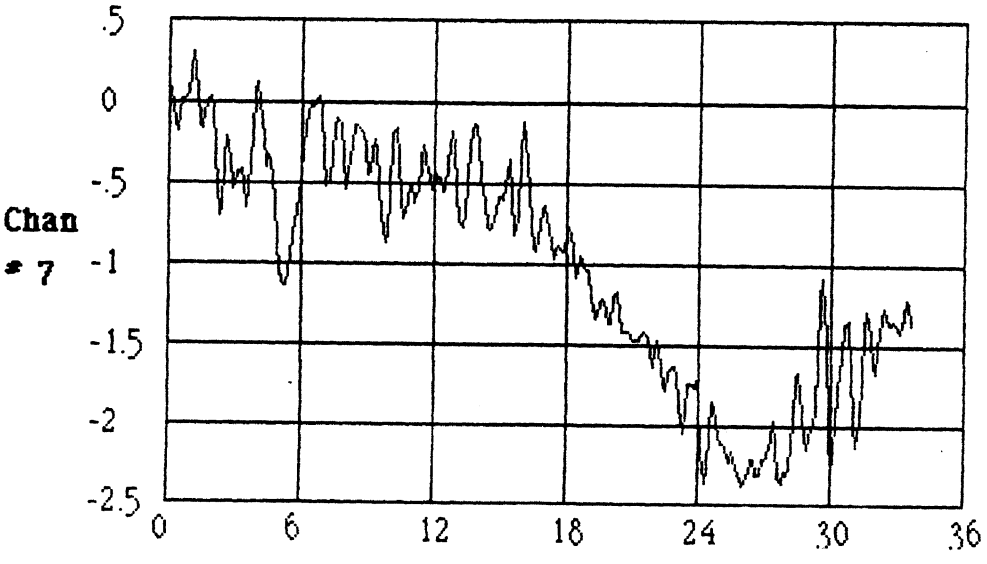

Chan
2
36
30
24
18
12
6
0
0
6
12
18
24
30
36
Ave:
30.7

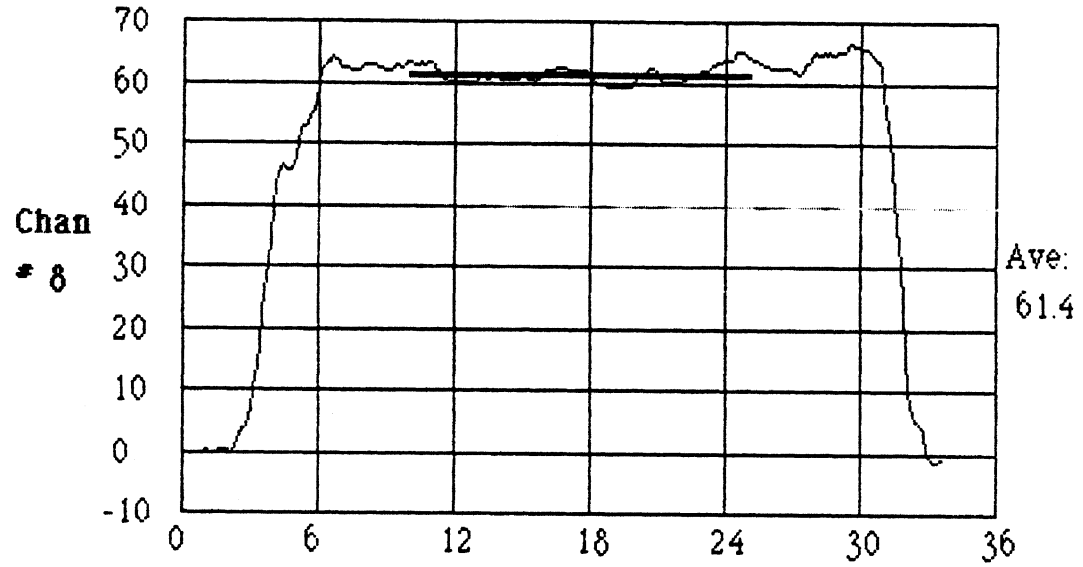

Chan
3
.35
.28
.21
.14
.07
0
-.07
0
6
12
18
24
30
36
Ave:
.287

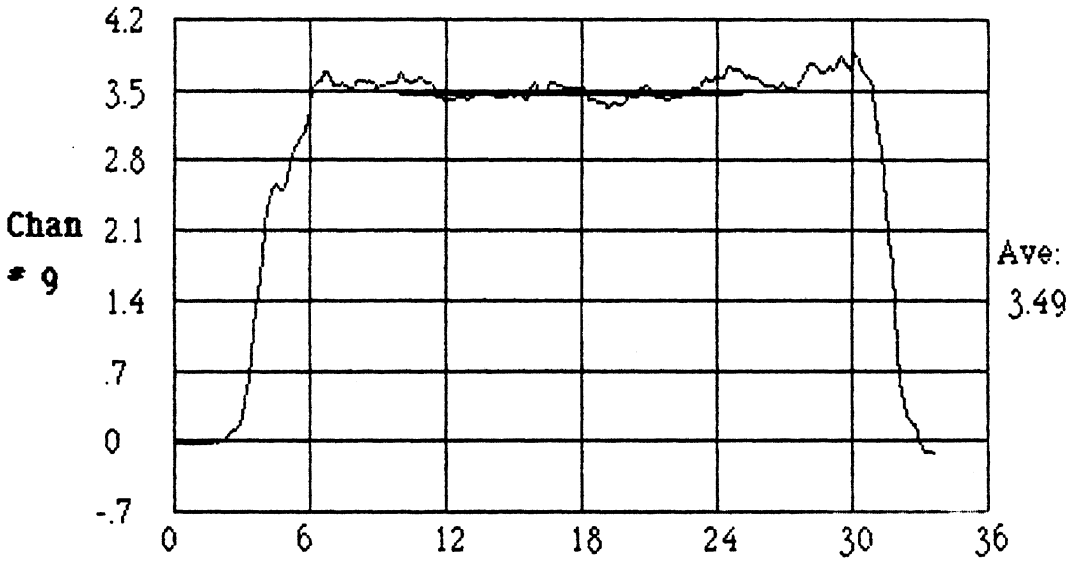

Chan
4
.03
.02
.01
0
-.01
-.02
-.03
0
6
12
18
24
30
36

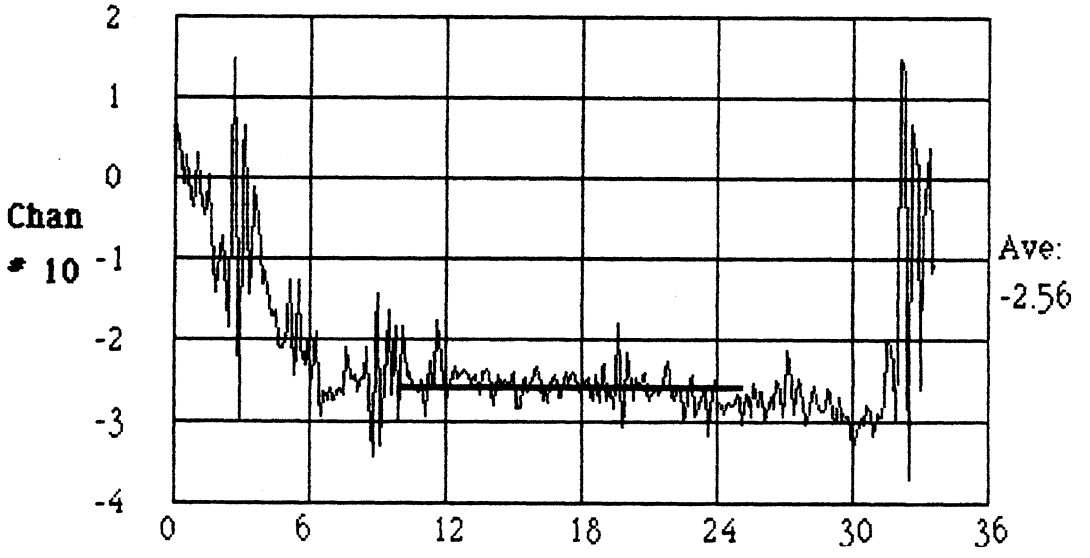

Chan
5
14
12
10
8
6
4
2
0
-2
0
6
12
18
24
30
36
Ave:
11.7


Chan
6
6
4
2
0
-2
-4
-6
0
6
12
18
24
30
36
Ave:
3.40


Chan
7
.5
0
-.5
-1
-1.5
-2
-2.5
0
6
12
18
24
30
36


Chan
8
70
60
50
40
30
20
10
0
-10
0
6
12
18
24
30
36
Ave:
61.4


Chan
9
4.2
3.5
2.8
2.1
1.4
.7
0
-.7
0
6
12
18
24
30
36
Ave:
3.49

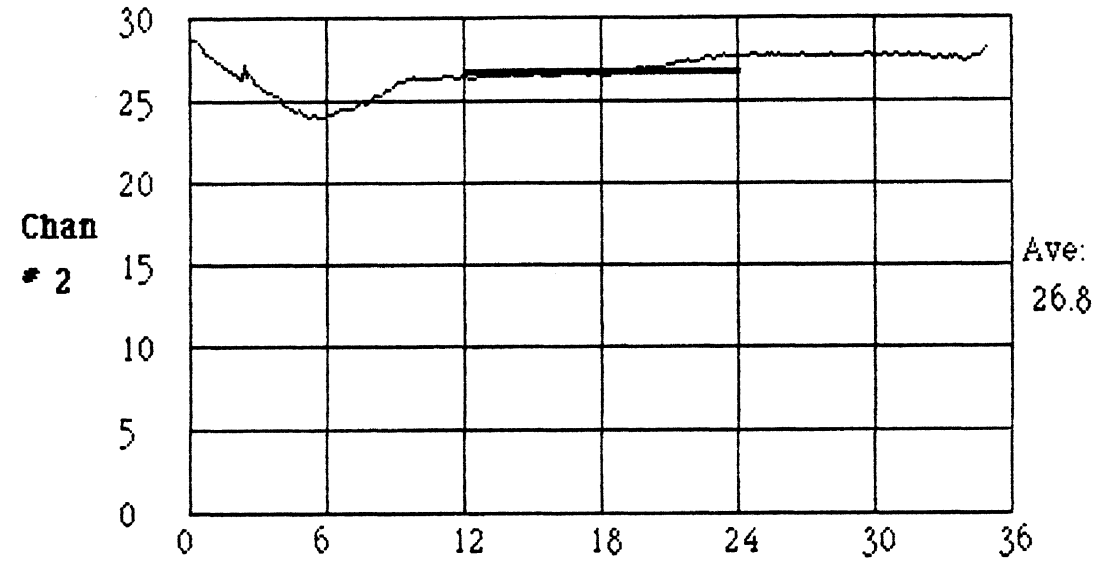

Chan
10
2
1
0
-1
-2
-3
-4
0
6
12
18
24
30
36
Ave:
-2.56

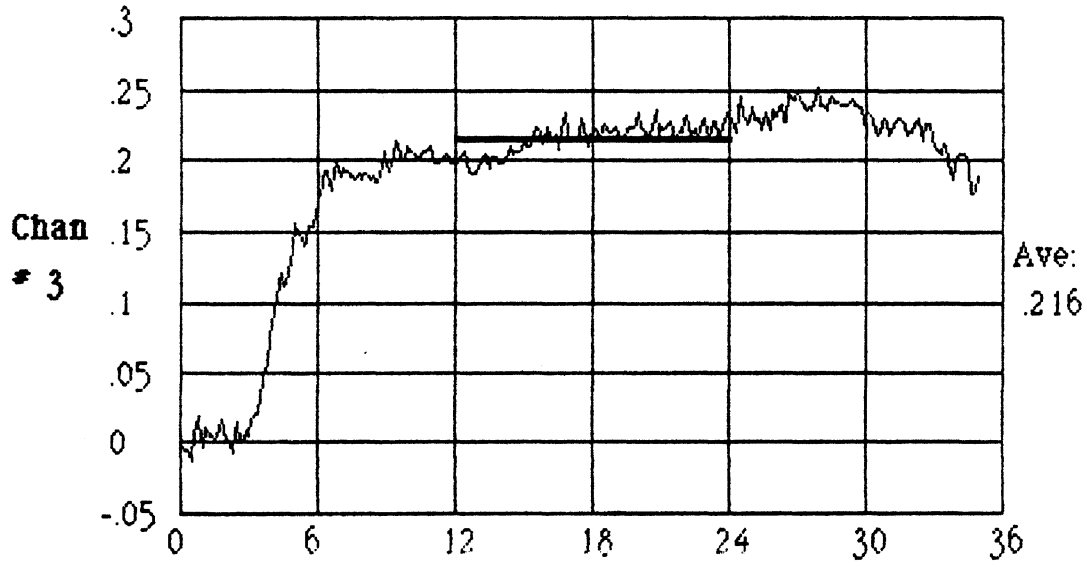
Ford LTD

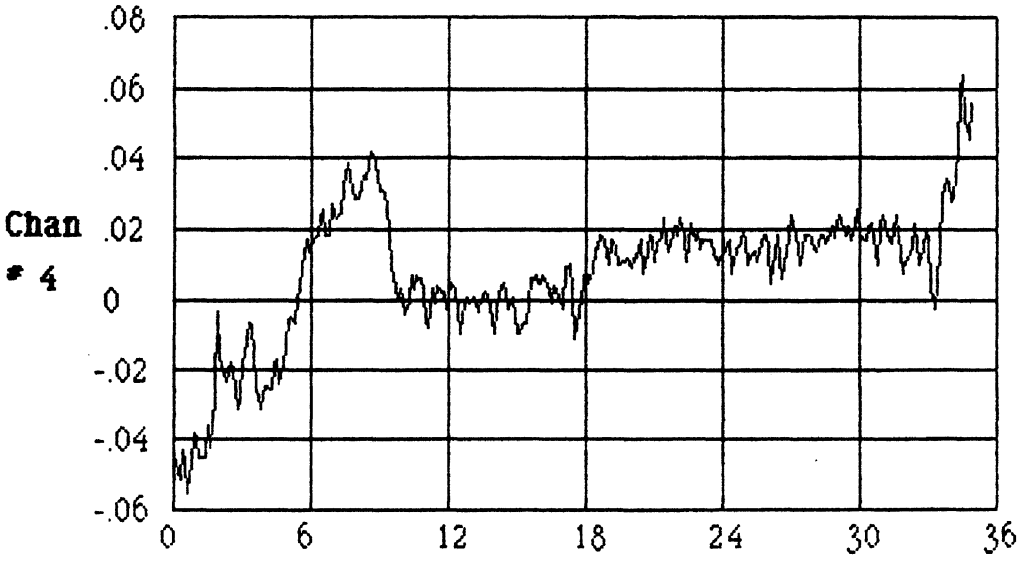
Ramp

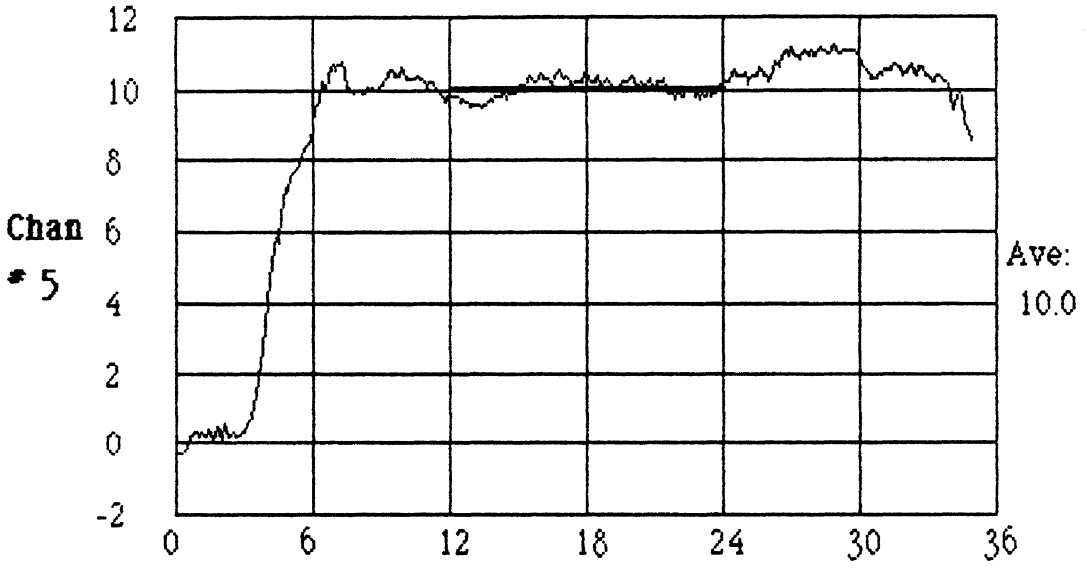
Repeat 2

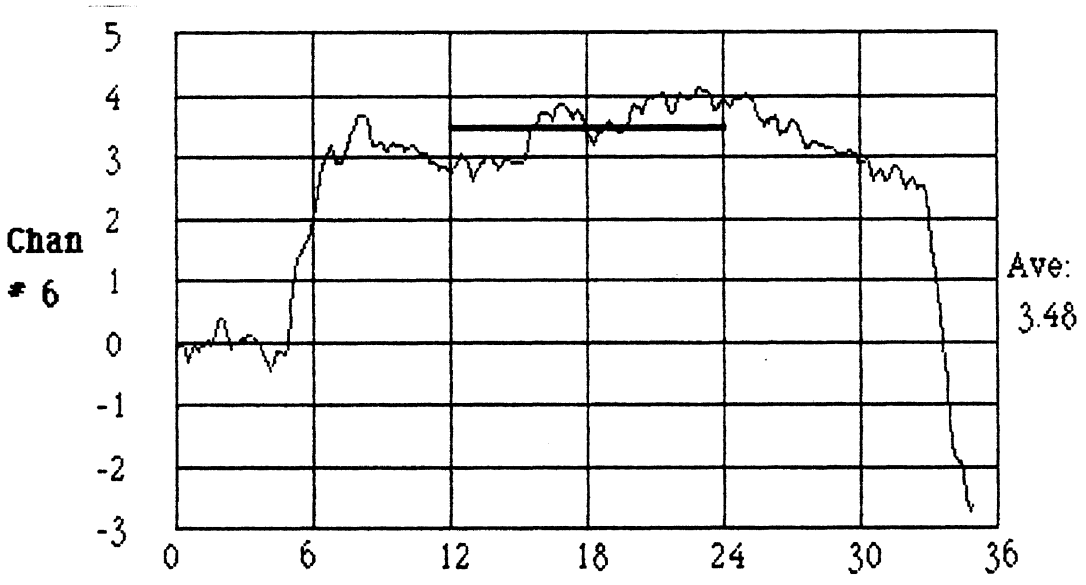
Steady Turning

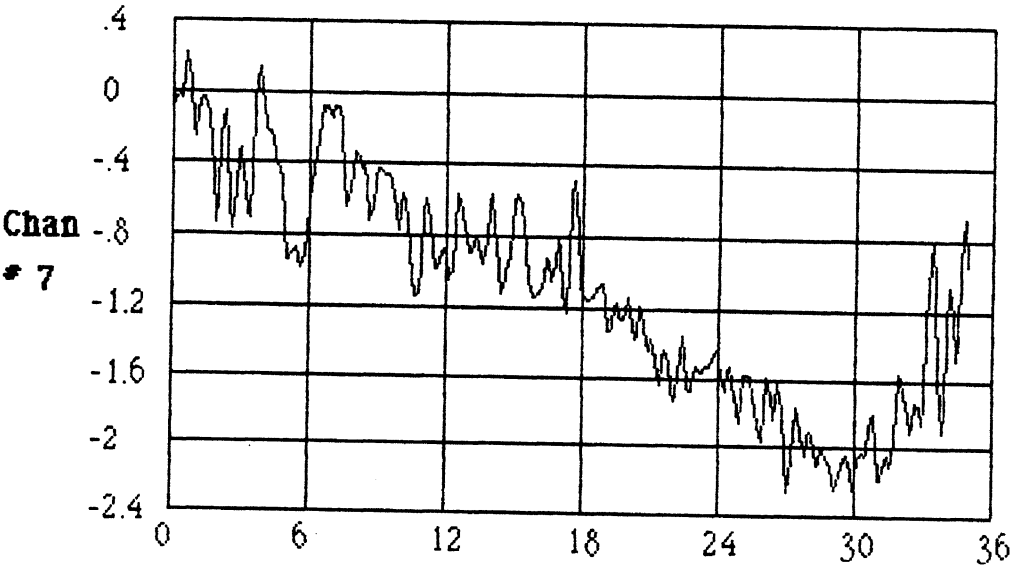

Chan
2
30
25
20
15
10
5
0
0
6
12
18
24
30
36
Ave:
26.8

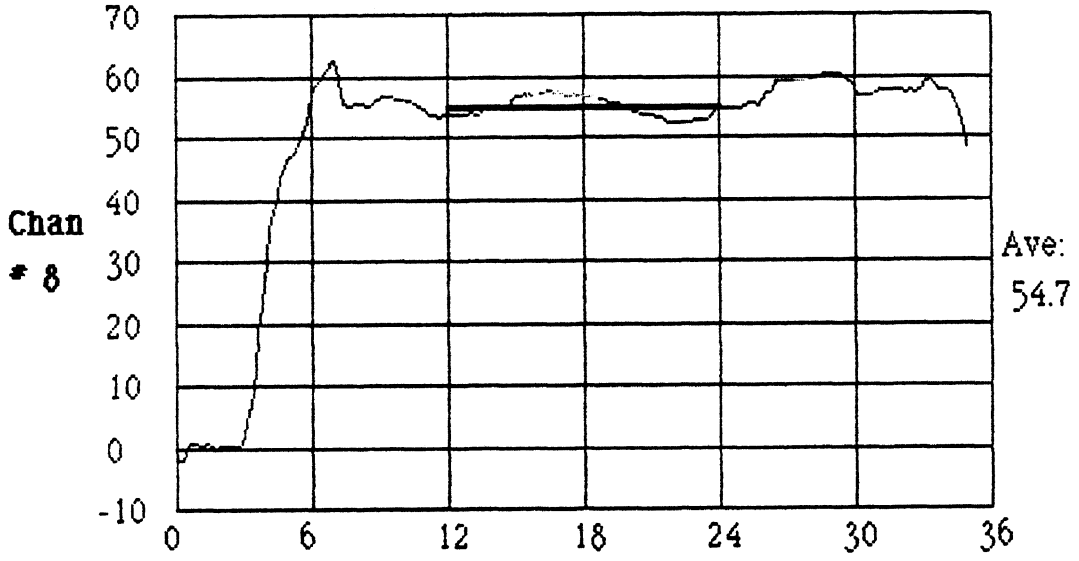

Chan
3
.3
.25
.2
.15
.1
.05
0
-.05
0
6
12
18
24
30
36
Ave:
.216

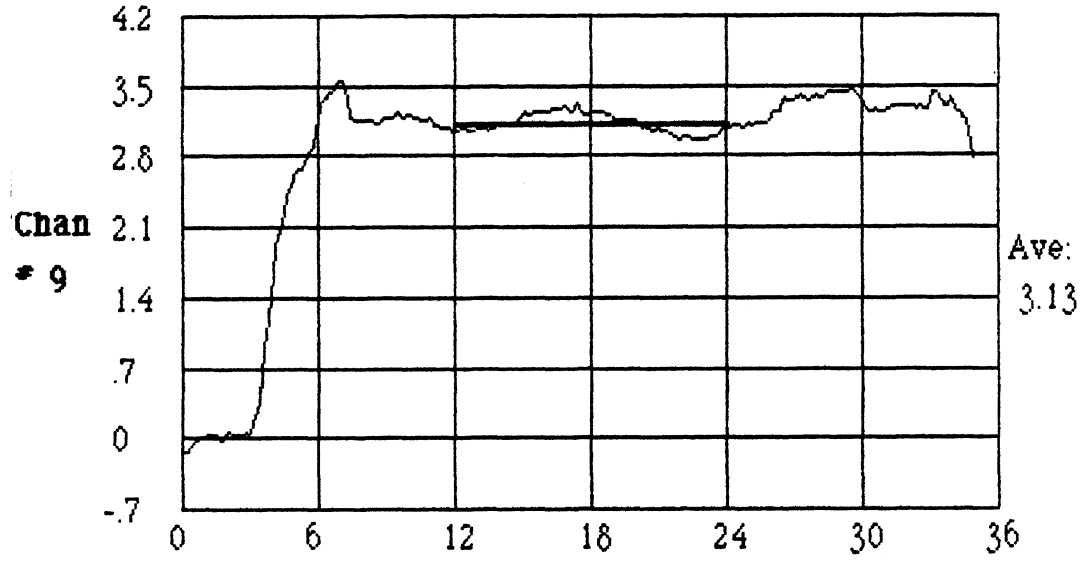

Chan
4
.08
.06
.04
.02
0
-.02
-.04
-.06
0
6
12
18
24
30
36

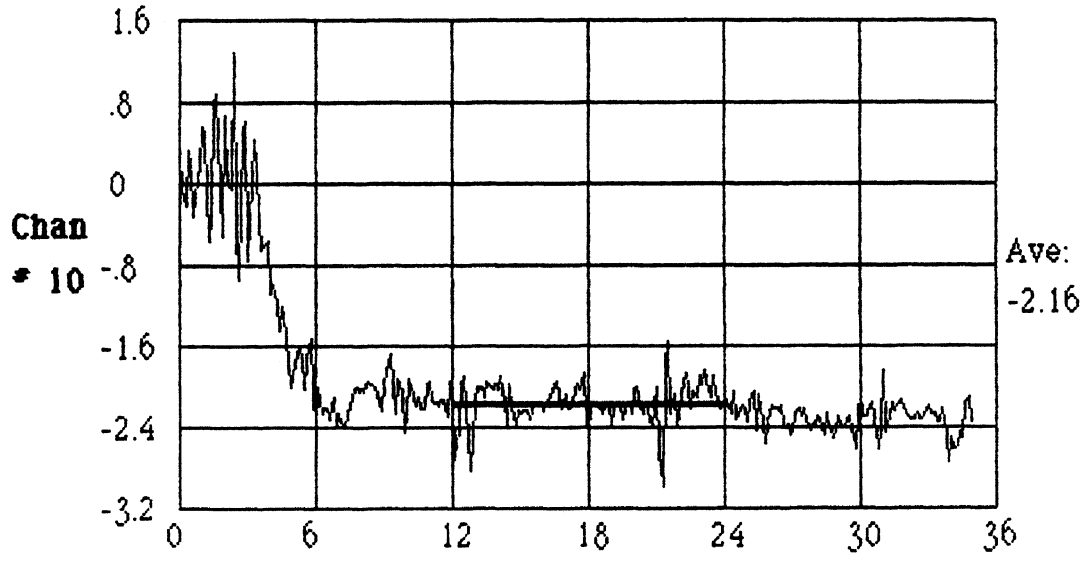

Chan
5
12
10
8
6
4
2
0
-2
0
6
12
18
24
30
36
Ave:
10.0


Chan
6
5
4
3
2
1
0
-1
-2
-3
0
6
12
18
24
30
36
Ave:
3.48


Chan
7
.4
0
-.4
-.8
-1.2
-1.6
-2
-2.4
0
6
12
18
24
30
36


Chan
8
70
60
50
40
30
20
10
0
-10
0
6
12
18
24
30
36
Ave:
54.7

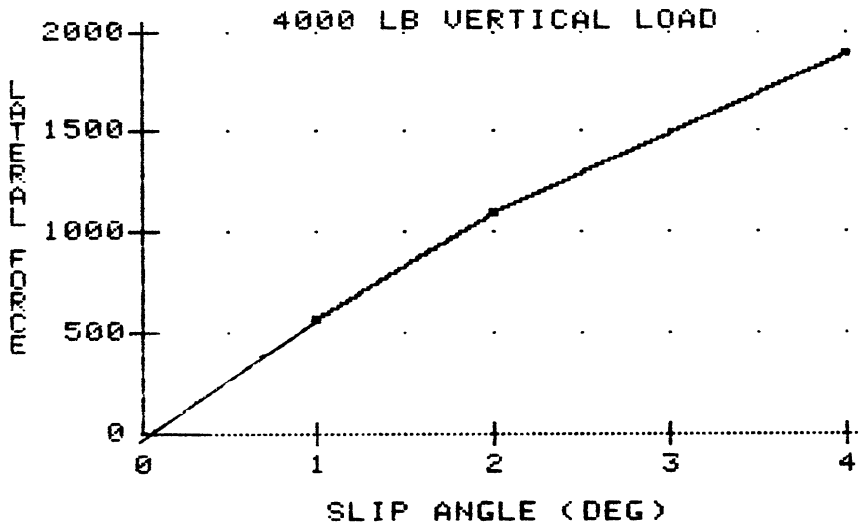

Chan
9
4.2
3.5
2.8
2.1
1.4
.7
0
-.7
0
6
12
18
24
30
36
Ave:
3.13

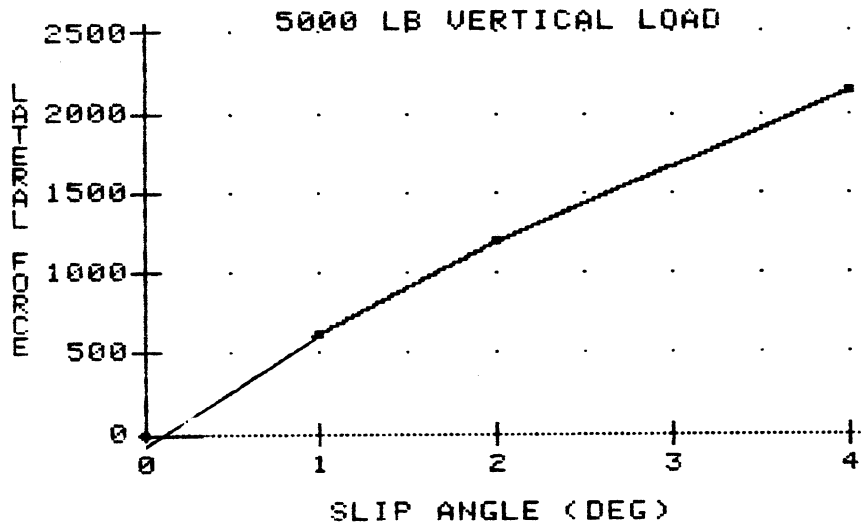

Chan
10
1.6
.8
0
-.8
-1.6
-2.4
-3.2
0
6
12
18
24
30
36
Ave:
-2.16

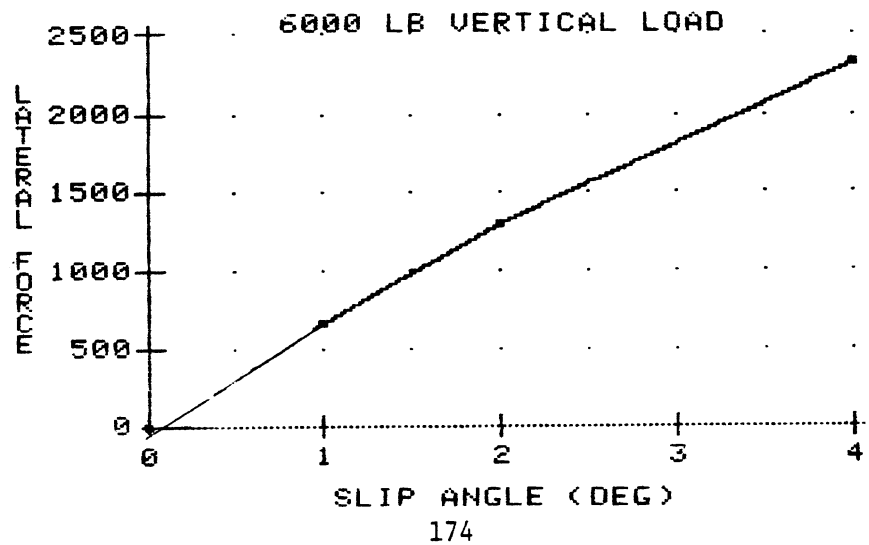
Appendix E.2

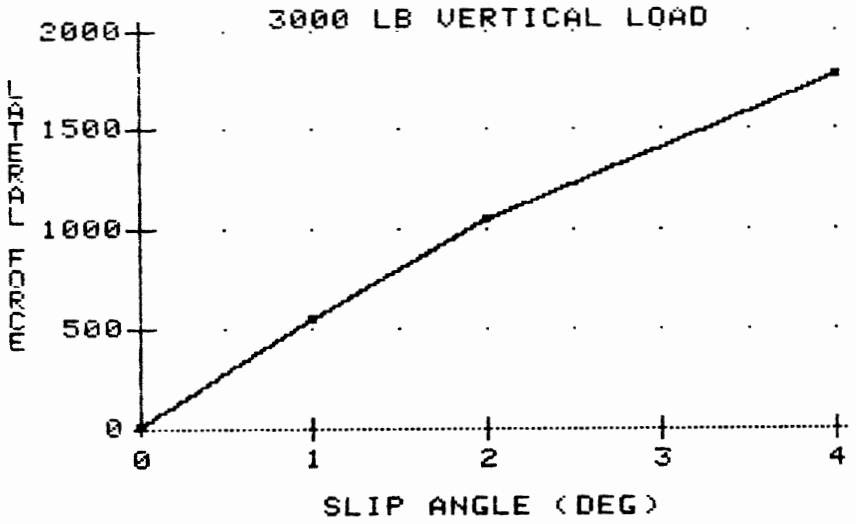
Tire Force Measurements

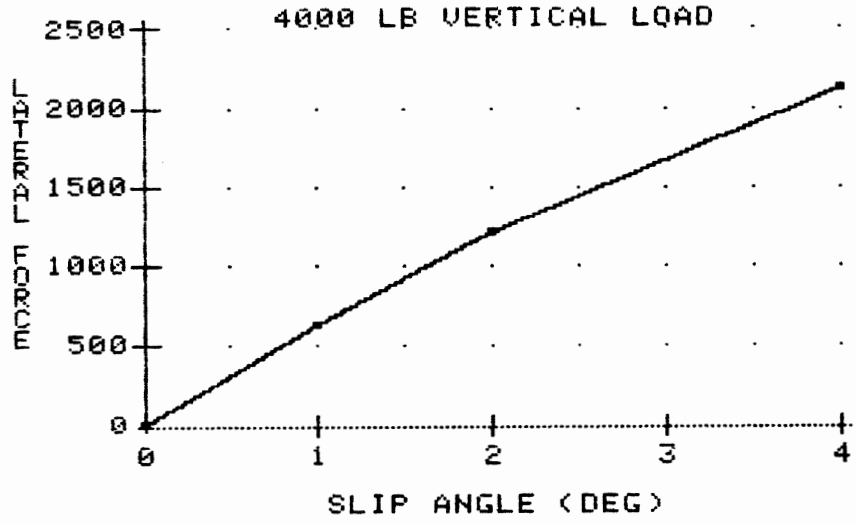
This appendix contains seven sets of tire data (three for the tractor-semitrailer and two each for the passenger cars). All measurements seen here are lateral tire forces at 0° camber and were collected on the UMTRI flat-bed tire test machine.

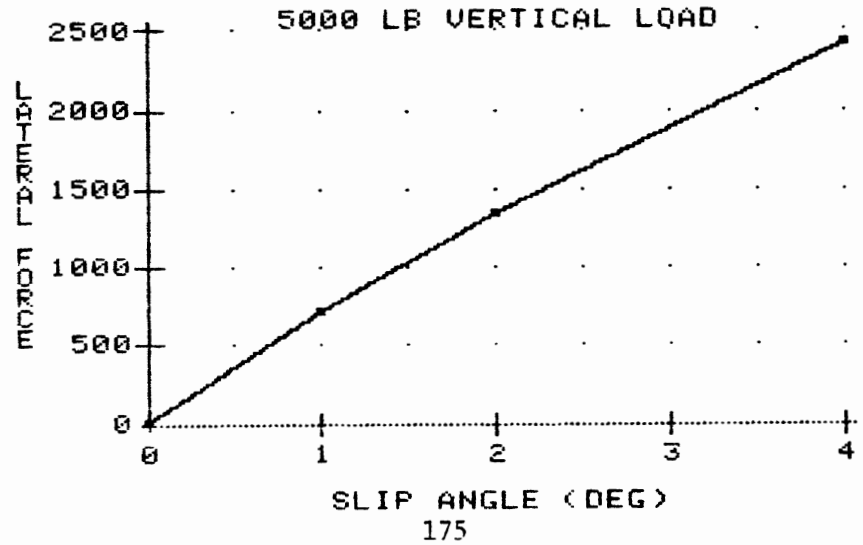

4000 LB VERTICAL LOAD
2000
1500
1000
500
0
LATERAL FORCE
0
1
2
3
4
SLIP ANGLE (DEG)

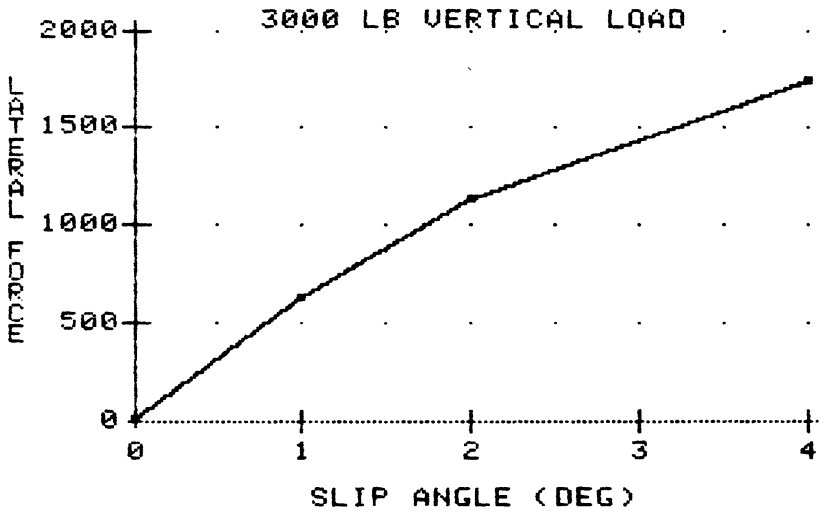

5000 LB VERTICAL LOAD
2500
2000
1500
1000
500
0
LATERAL FORCE
0
1
2
3
4
SLIP ANGLE (DEG)

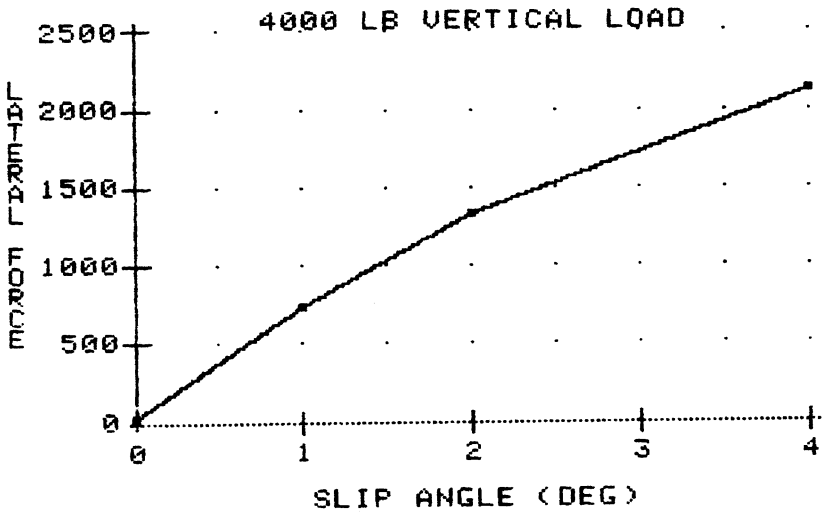

6000 LB VERTICAL LOAD
2500
2000
1500
1000
500
0
LATERAL FORCE
0
1
2
3
4
SLIP ANGLE (DEG)

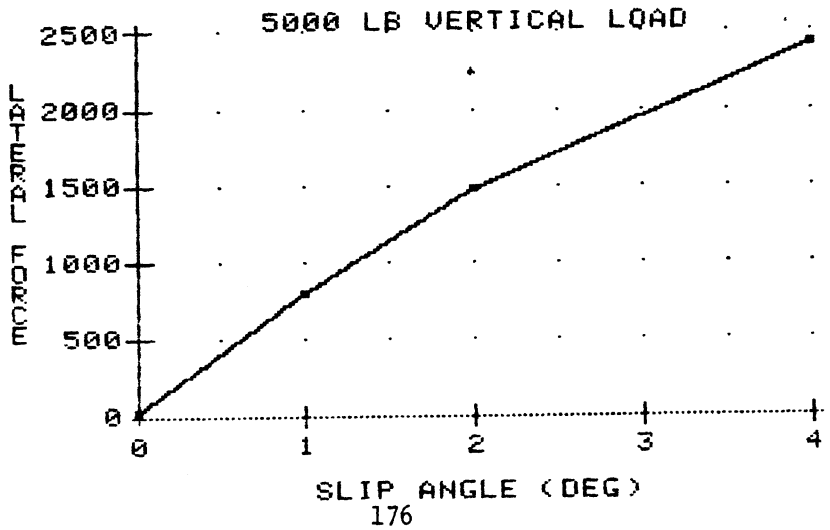

3000 LB VERTICAL LOAD
2000
1500
1000
500
0
LATERAL FORCE
0
1
2
3
4
SLIP ANGLE (DEG)

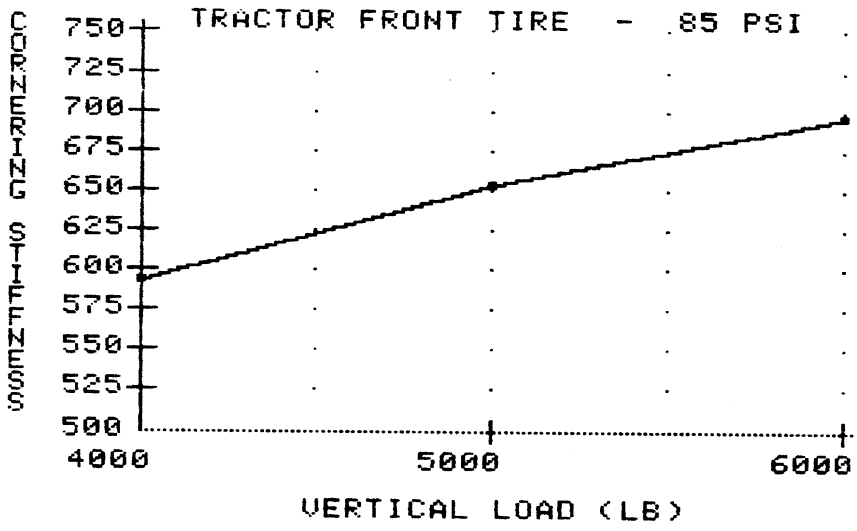

4000 LB VERTICAL LOAD
2500
2000
1500
1000
500
0
LATERAL FORCE
0
1
2
3
4
SLIP ANGLE (DEG)

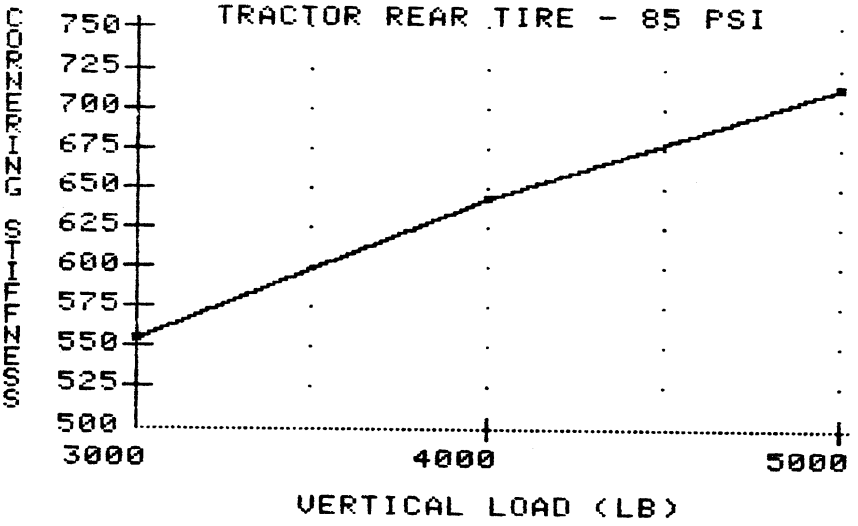

5000 LB VERTICAL LOAD
2500
2000
1500
1000
500
0
LATERAL FORCE
0
1
2
3
4
SLIP ANGLE (DEG)

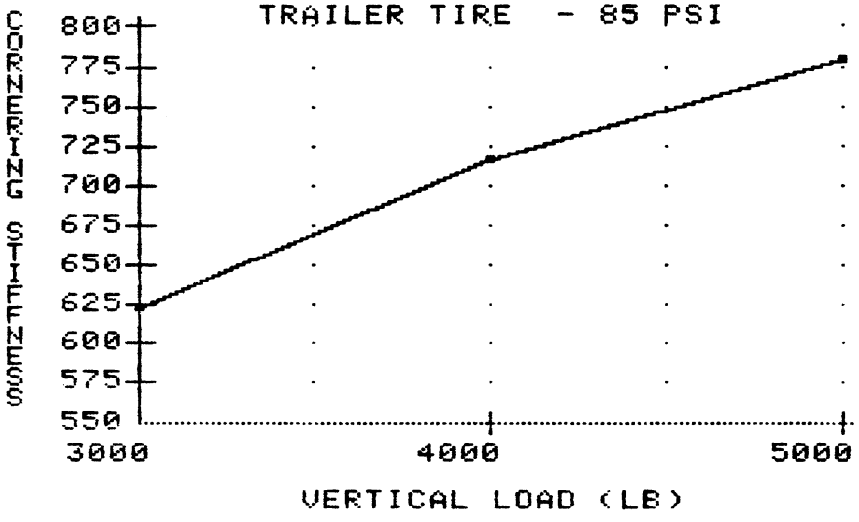

3000 LB VERTICAL LOAD
LATERAL FORCE
2000
1500
1000
500
0
0
1
2
3
4
SLIP ANGLE (DEG)

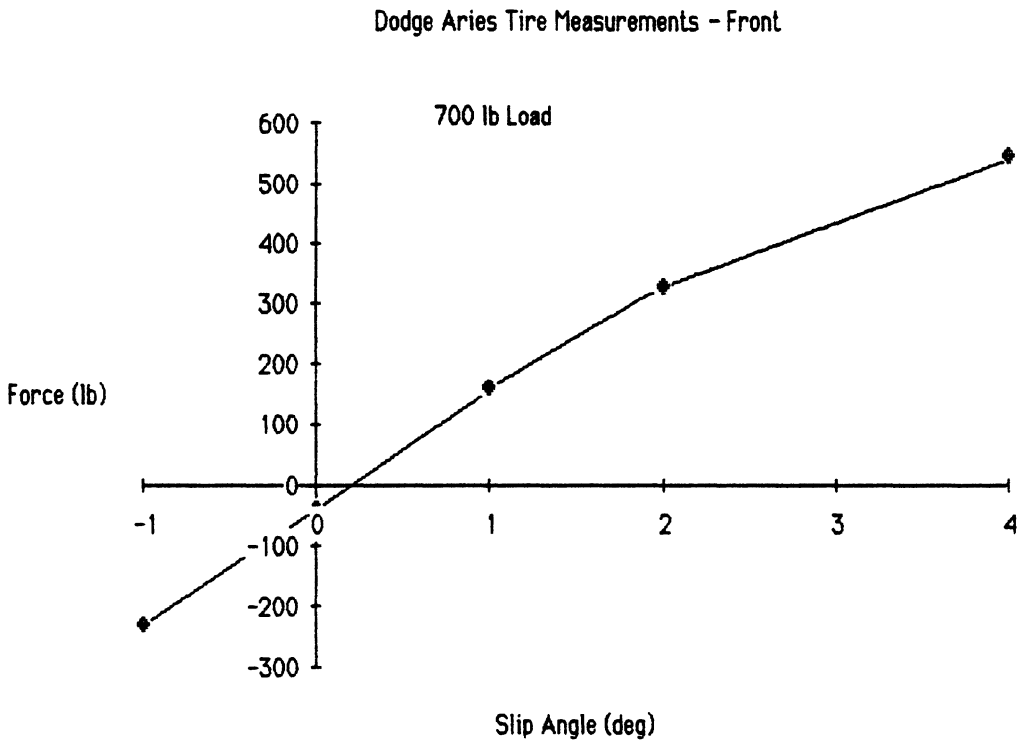

4000 LB VERTICAL LOAD
LATERAL FORCE
2500
2000
1500
1000
500
0
0
1
2
3
4
SLIP ANGLE (DEG)


5000 LB VERTICAL LOAD
LATERAL FORCE
2500
2000
1500
1000
500
0
0
1
2
3
4
SLIP ANGLE (DEG)

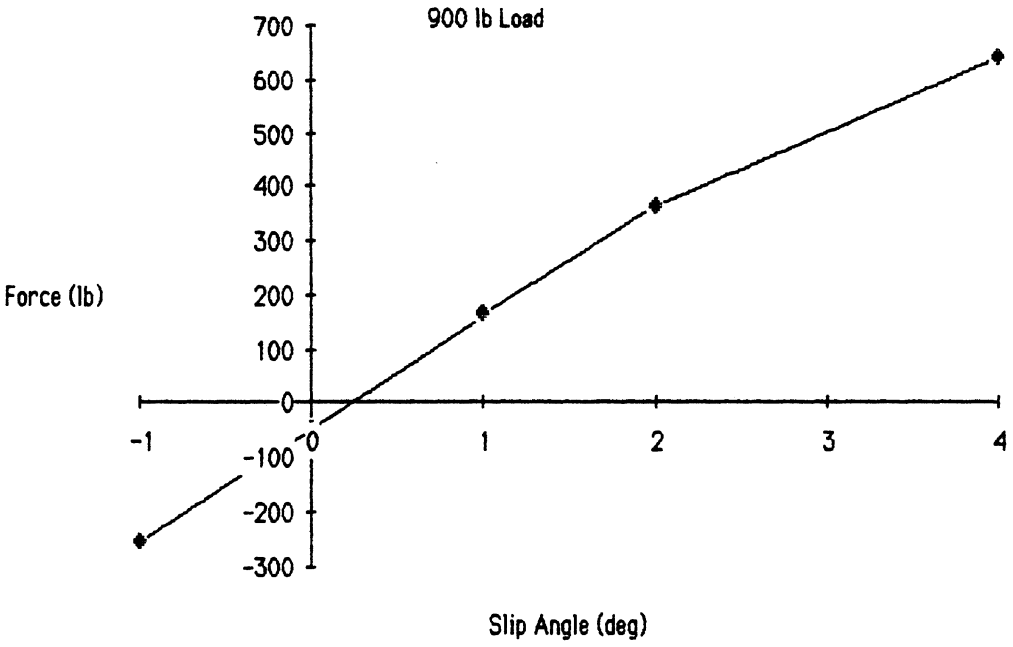

TRACTOR FRONT TIRE - 85 PSI
CORNERING STIFFNESS
750
725
700
675
650
625
600
575
550
525
500
4000
5000
6000
VERTICAL LOAD (LB)

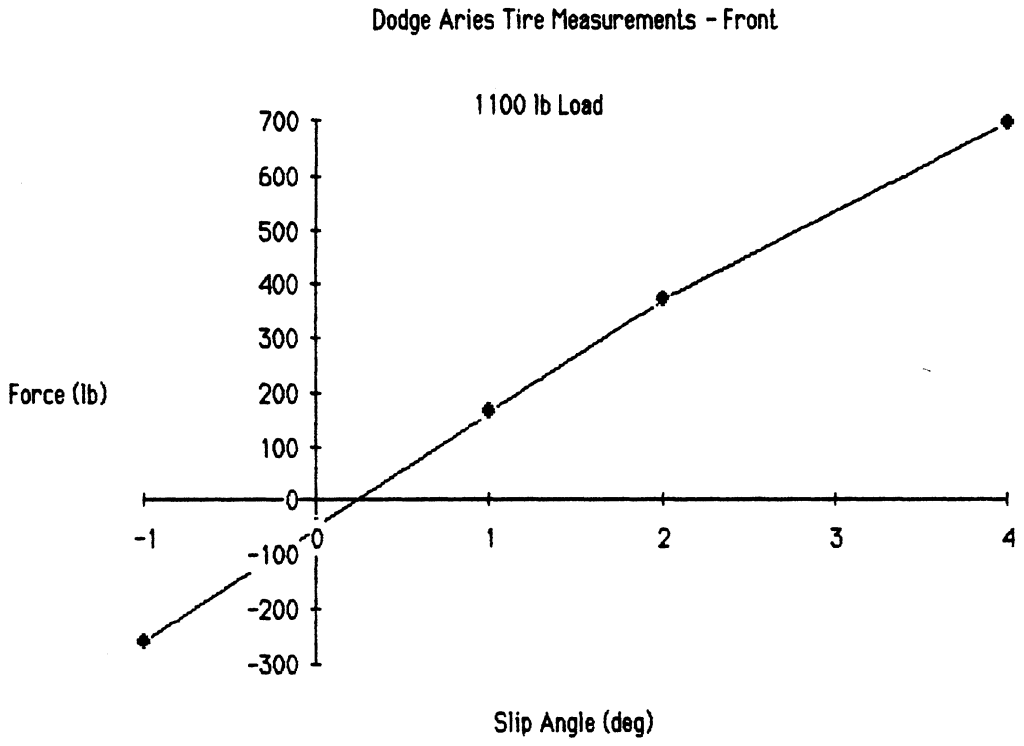

TRACTOR REAR TIRE - 85 PSI
CORNERING STIFFNESS
750
725
700
675
650
625
600
575
550
525
500
3000
4000
5000
VERTICAL LOAD (LB)

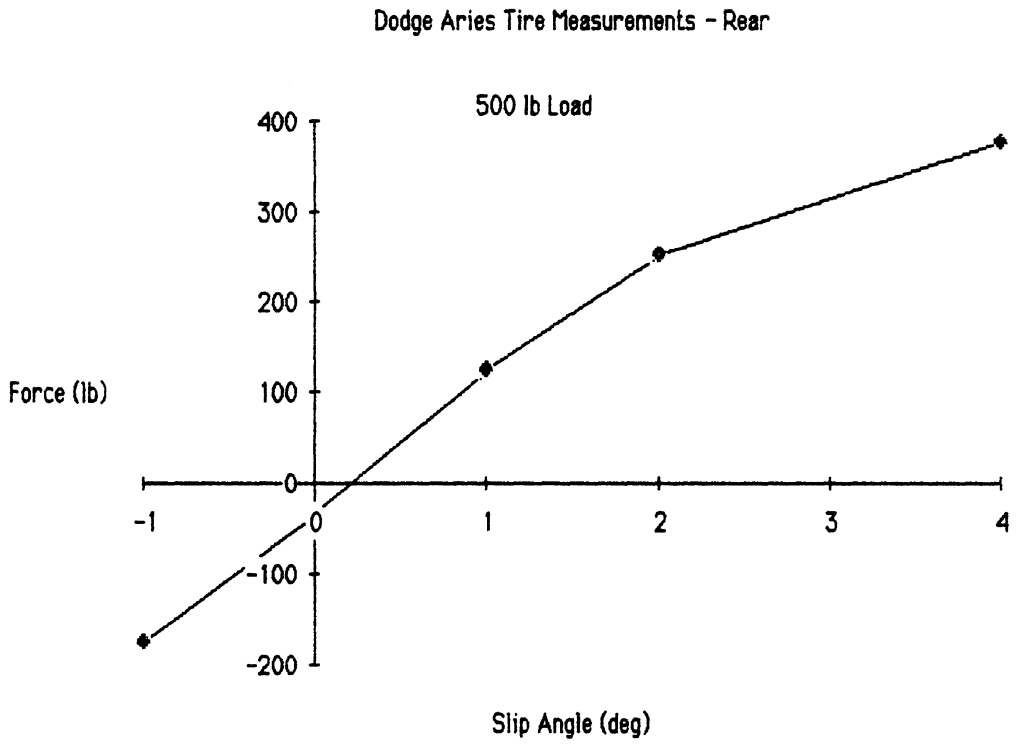

TRAILER TIRE - 85 PSI
CORNERING STIFFNESS
800
775
750
725
700
675
650
625
600
575
550
3000
4000
5000
VERTICAL LOAD (LB)

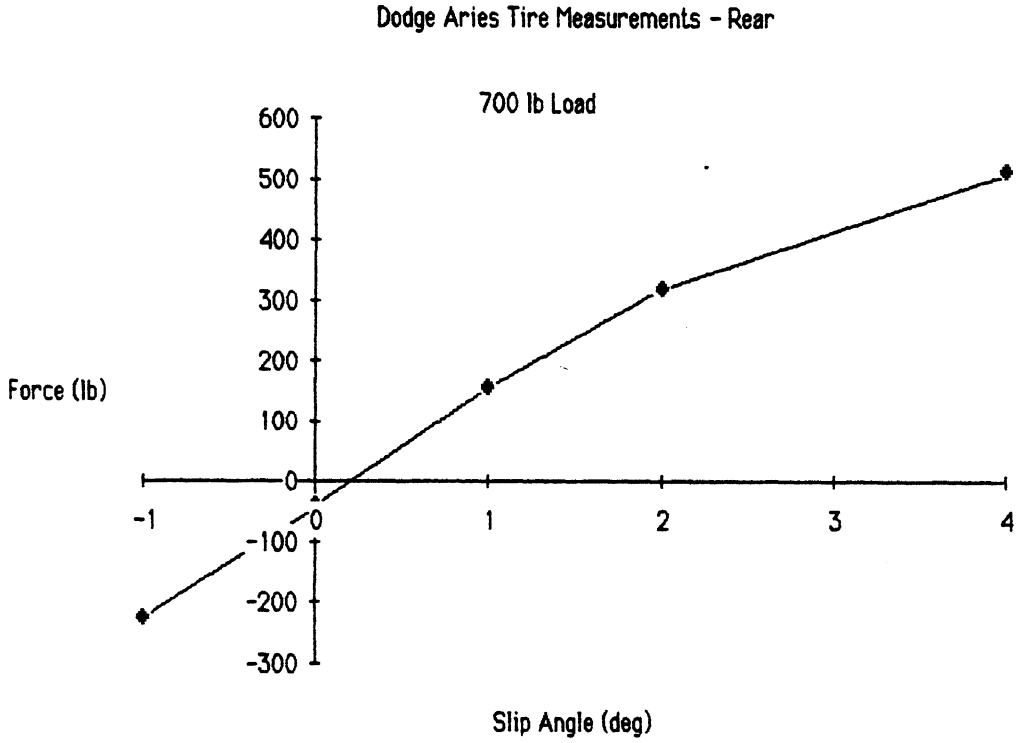

Dodge Aries Tire Measurements - Front
700 lb Load
Force (lb)
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)

Dodge Aries Tire Measurements - Front

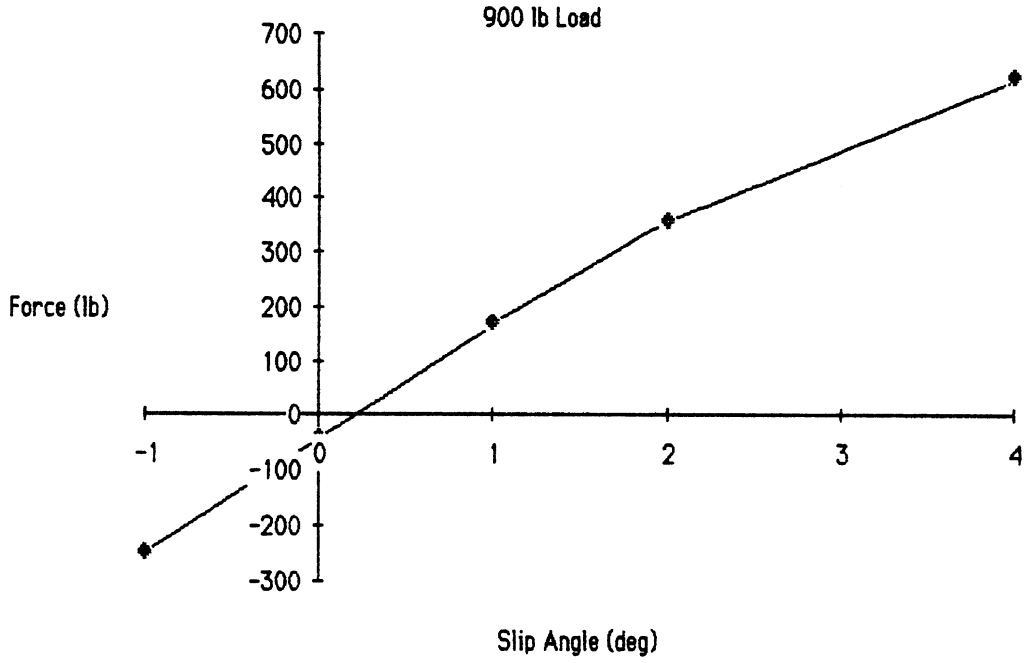


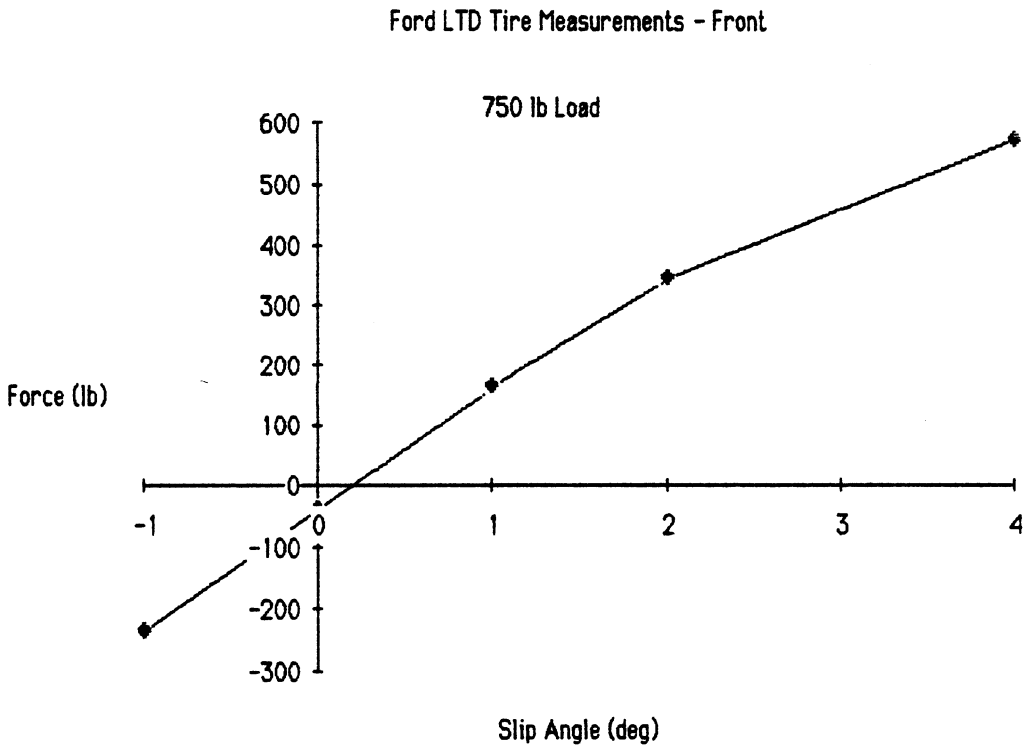

Dodge Aries Tire Measurements - Front
1100 lb Load
Force (lb)
700
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)

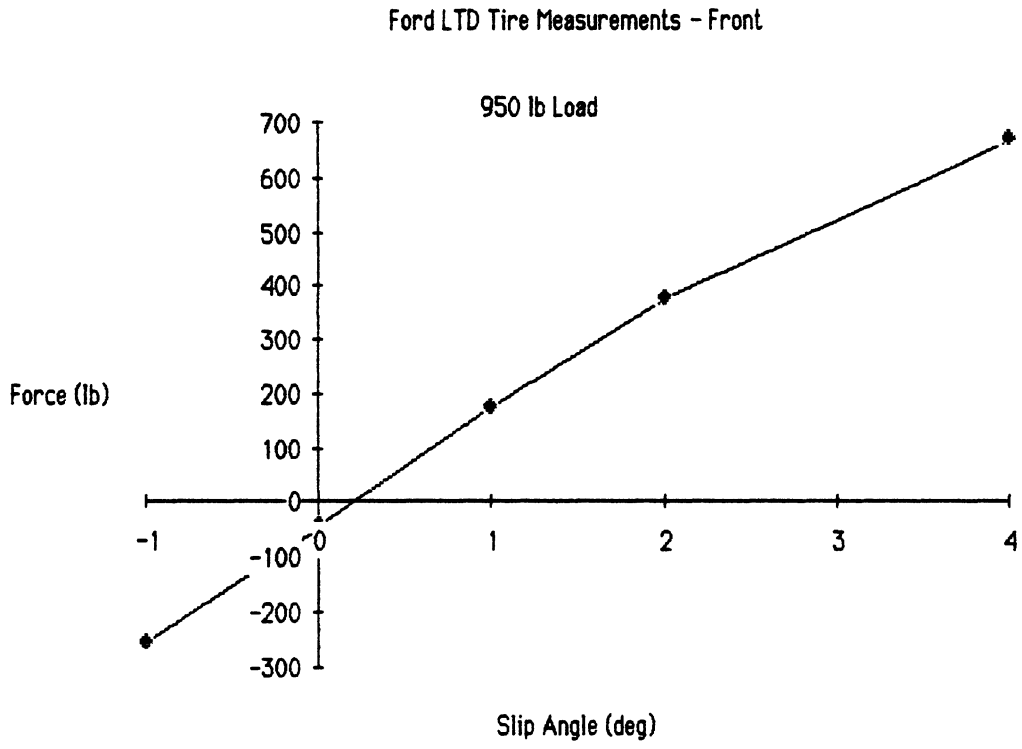

Dodge Aries Tire Measurements - Rear
500 lb Load
Force (lb)
400
300
200
100
0
-100
-200
-1
0
1
2
3
4
Slip Angle (deg)

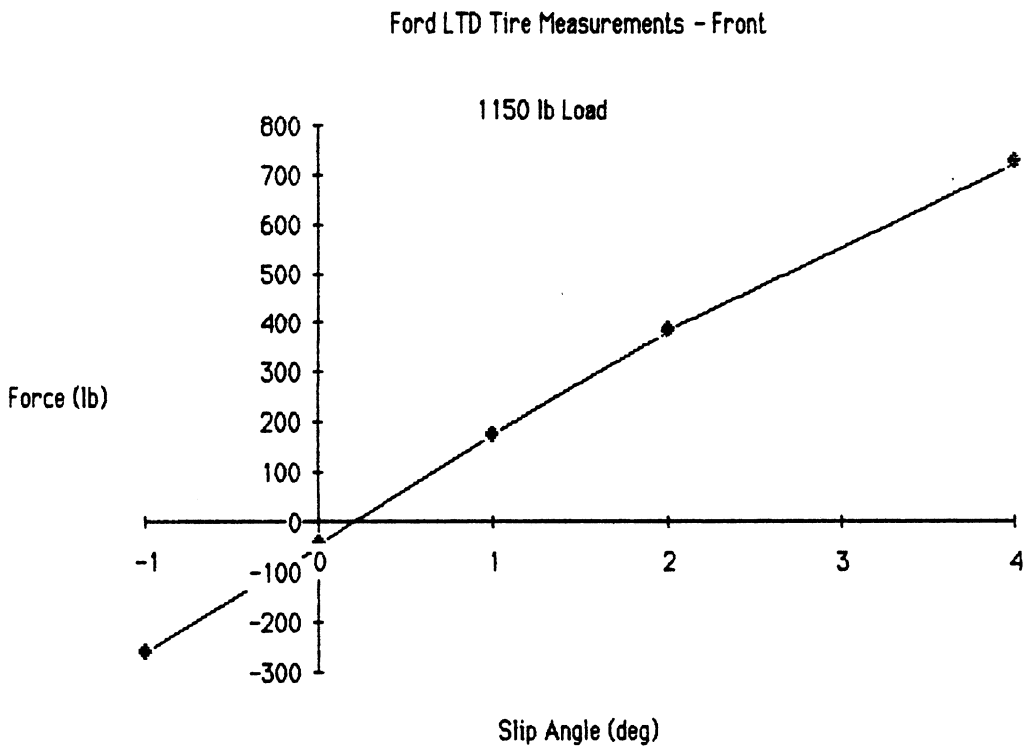

Dodge Aries Tire Measurements - Rear
700 lb Load
Force (lb)
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)

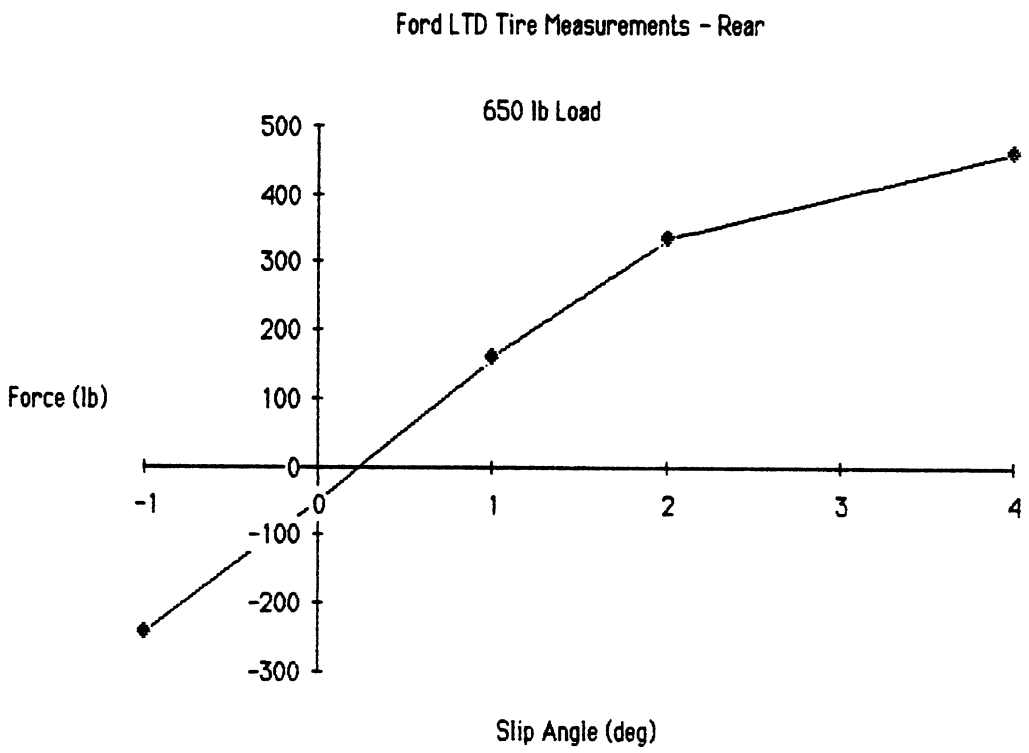
Dodge Aries Tire Measurements - Rear

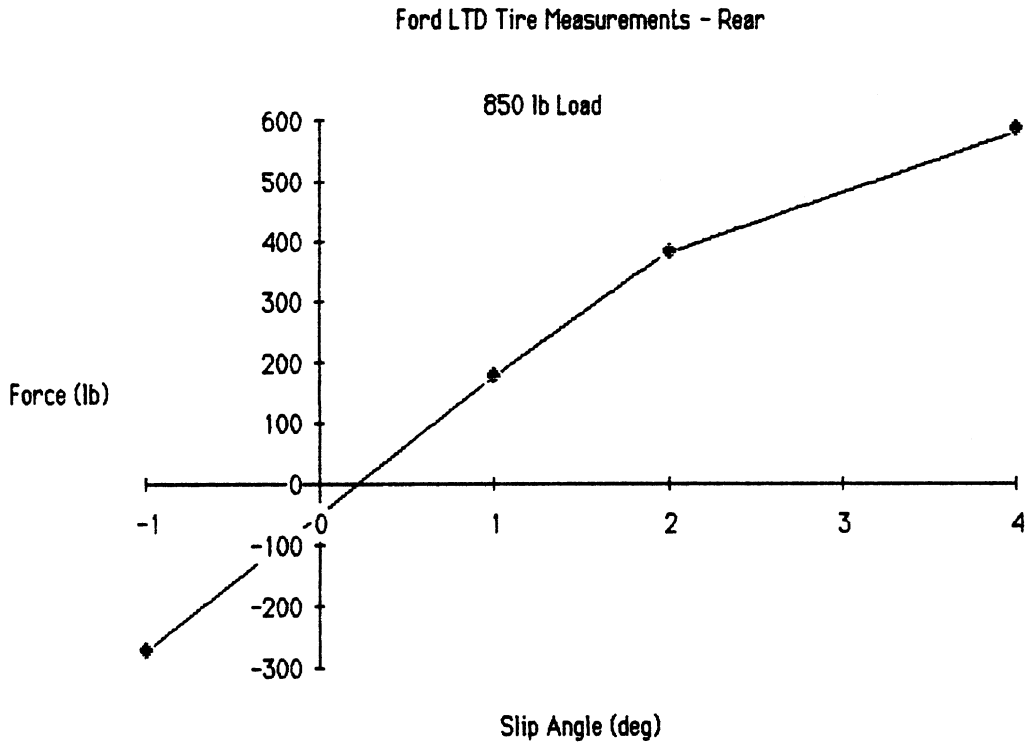


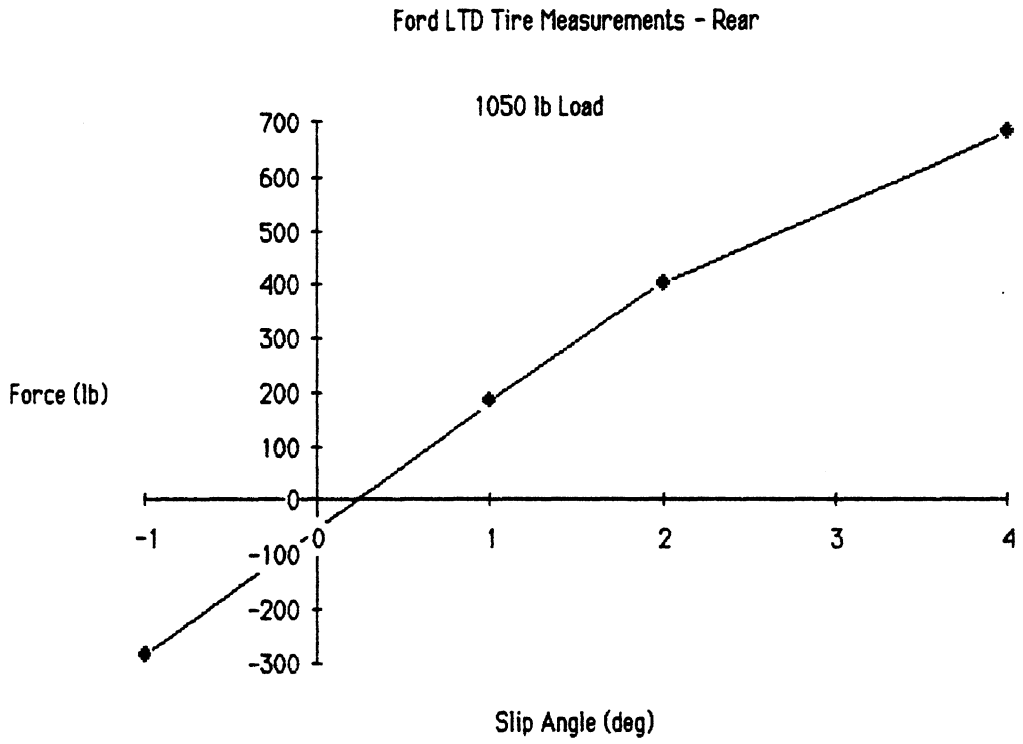

Ford LTD Tire Measurements - Front
750 lb Load
Force (lb)
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)


Ford LTD Tire Measurements - Front
950 lb Load
Force (lb)
700
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)


Ford LTD Tire Measurements - Front
1150 lb Load
Force (lb)
800
700
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)


Ford LTD Tire Measurements - Rear
650 lb Load
Force (lb)
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)

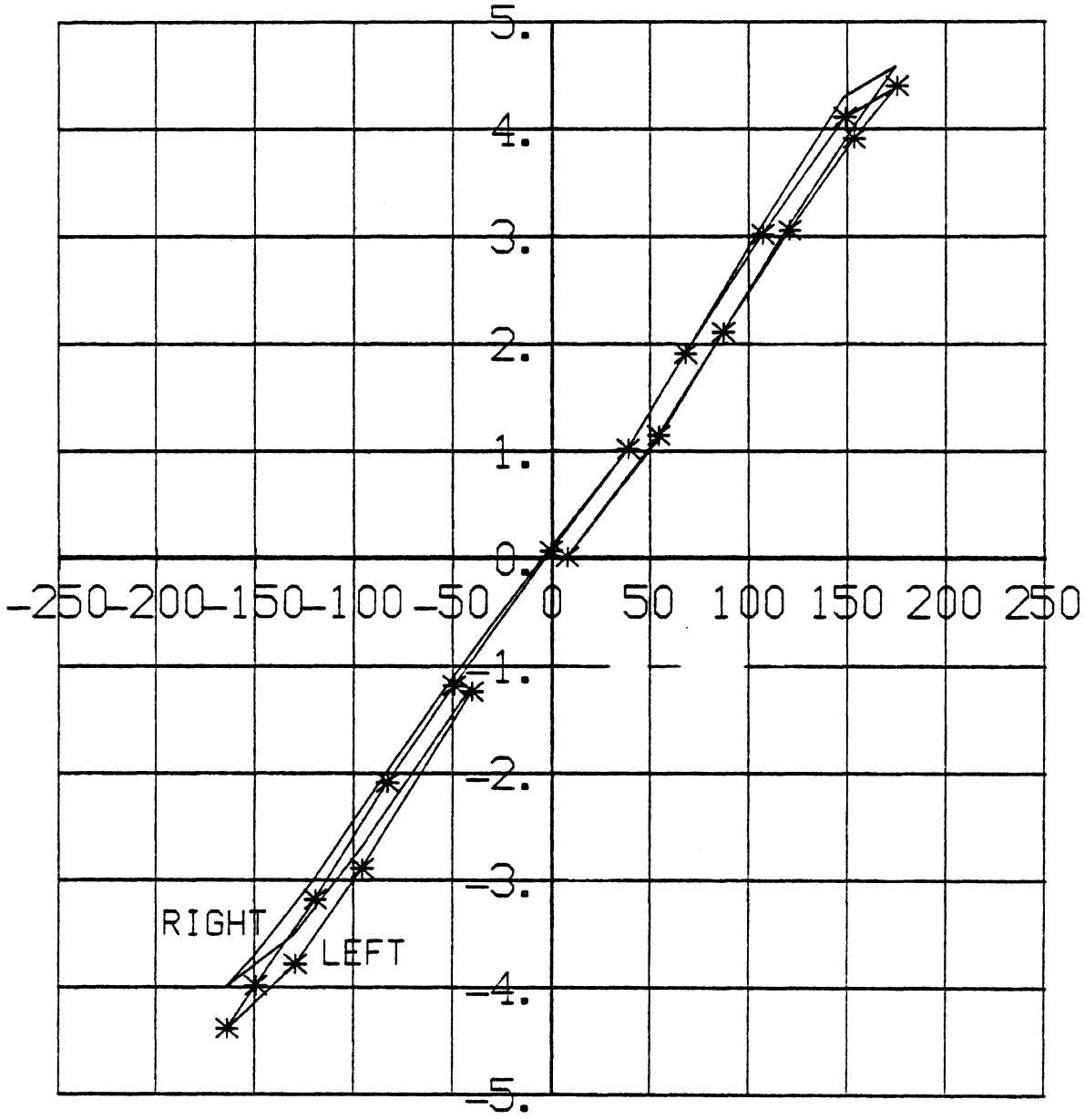

Ford LTD Tire Measurements - Rear
850 lb Load
Force (lb)
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)


Ford LTD Tire Measurements - Rear
1050 lb Load
Force (lb)
700
600
500
400
300
200
100
0
-100
-200
-300
-1
0
1
2
3
4
Slip Angle (deg)

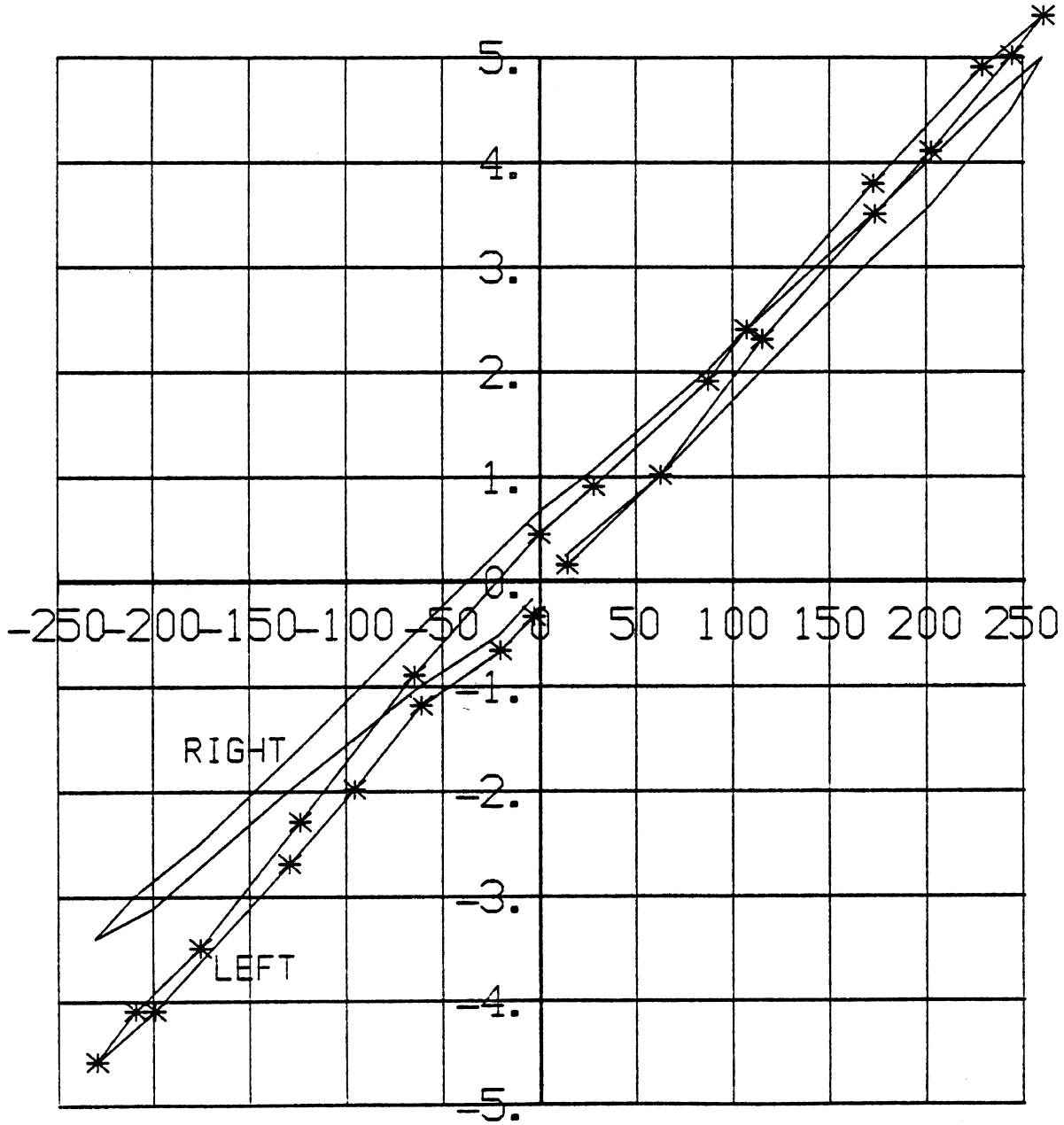
Appendix E.3

Tractor Steering System Measurements

The measurements seen in the next two figures were performed on the tractor unit in its normally loaded condition ("Loaded") and with its front axle off the ground ("No Load"). The plots show measurements of left and right front wheel angles in response to displacements of the steering wheel (plus and minus 200° or so). The loaded plot indicates an effective steering gear ratio of approximately 50:1 while the no load measurements indicate an effective steering gear ratio of about 37:1 . The level of hysteresis for the loaded measurements are about 30° - 40° at the steering wheel or about 0.7° at the front wheels. The hystereis seen for the no load condition is about 15° at the steering wheel and about 0.3° at the front wheel. The no load measurements were performed primarily to examine the influence of vertical load changes on the degree of hysteresis and effective gear ratio observed during the more normal loaded condition.



DFW VS. DSW NO LOAD



DFW VS. DSW LOADED

Appendix E.4

Estimation of Individual Wheel Friction Factors from Vehicle Response Measurements

The methodology outlined here for estimating friction factors based upon vehicle response measurements is a summary of the discussion proposed as part of the "Validation Plan" used to guide the vehicle testing. The experimental estimates of individual wheel friction factors seen in Chapter 5 were obtained in the manner described here.

The term "friction factor" (or "normalized force") simply refers to the ratio of the lateral tire force requirement at a particular wheel location to the prevailing vertical tire load. The quantities of direct interest, then, are 1) the lateral tire force and 2) vertical tire load. Since the lateral tire force at a particular wheel location, when operating within the linear maneuvering regime, is simply the product of tire corenering stiffness and tire slip angle, knowledge of these two quantities are, in turn, needed. Cornering stiffness estimates were obtained from laboratory tire measurements (as seen in Appendix E.2). The slip angles at each wheel location can be obtained from knowledge of the geometric location of the wheel with respect to the vehicle c.g. and measurement of (a) vehicle sideslip, (b) yaw rate, (c) forward velocity, and (d) wheel steer angles. For example, the slip angle at the front axle of an automobile or truck is provided by the expression

$$\beta_f = \beta + a\,r / V - \partial$$

where

- β_f is the slip angle of the front tire/axle
- a is the distance from the vehicle c.g. to the front axle
- β is the vehicle sideslip measurement at the c.g.
- r is the vehicle yaw rate measurement
- V is the forward speed measurement

and

- ∂ is the front wheel steer angle measurement

Multiplying β_f by the measured cornering stiffness will provide the needed estimate of lateral tire force at that wheel location.

The vertical tire loads prevailing under steady turning conditions can be estimated from knowledge of the static (curb) axle loads, the level of vehicle lateral acceleration, vehicle c.g. height, and suspension properties (stiffness / spring spacing / wheel track). Since each of these items were measured or obtained from the technical literature, reasonable estimates of vertical tire loads could be expected. For example, the load transfer across an axle due to steady turning can be closely estimated by the expression

$$\Delta F_z = W\, h\, (A_y - \phi)\, K / (T\, K_t)$$

where

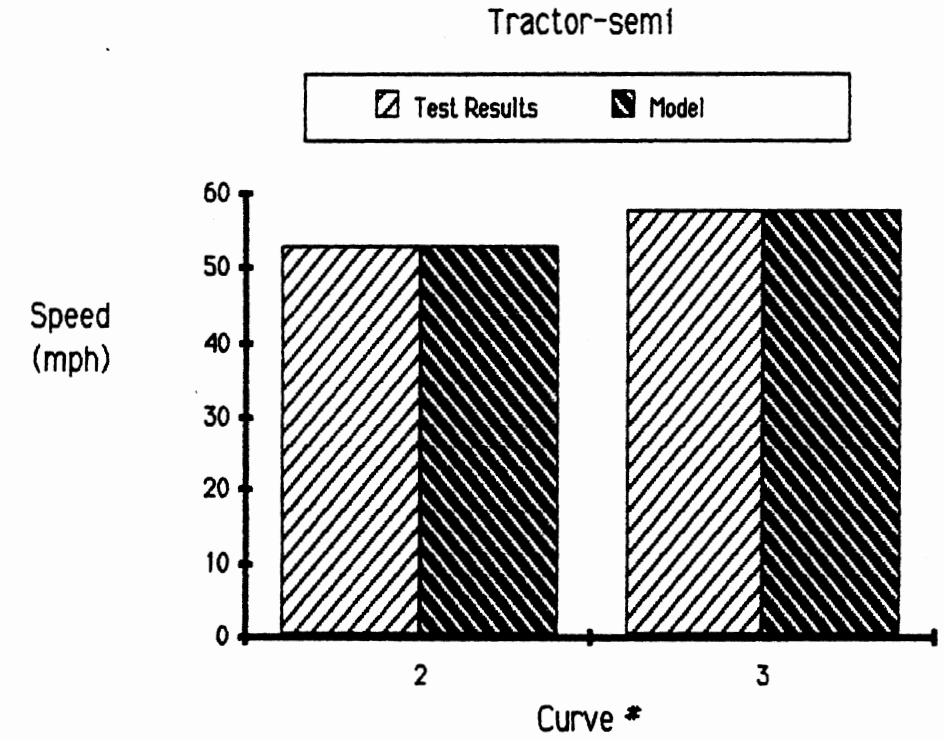
- ΔF_z is the side-to-side load transfer across an axle
- W is the total vehicle weight
- h is the vehicle c.g. height
- A_y is the steady turning lateral acceleration (horizontal plane)
- ϕ is the vehicle roll angle relative to the gravity vector (includes highway superelevation)
- K is the axle roll stiffness
- K_t is the total vehicle roll stiffness
- T is the axle tire track

The prevailing tire load is then obtained by adding (or subtracting) the ΔF_z quantity to the known (measured) static tire load. An estimate of the individual wheel friction factor is then obtained by a simple ratio of the aforementioned lateral force estimate and the above vertical tire force estimate.

Appendix F

COMPARISONS OF MODEL PREDICTION AND TEST RESULTS

This appendix contains model/test result comparisons which supplement the material presented in chapter 5 of volume II. Figures F-1 to F-6 show various vehicle response measurements and model predictions for each of the test vehicles at curve sites 2 and 3. Figures F-1 and F-2 apply to the 5-axle tractor-semitrailer (vehicle C); figures F-3 and F-4 apply to the front-wheel-drive passenger car (vehicle A); figures F-5 and F-6 apply to the rear-wheel-drive passenger car (vehilce B).



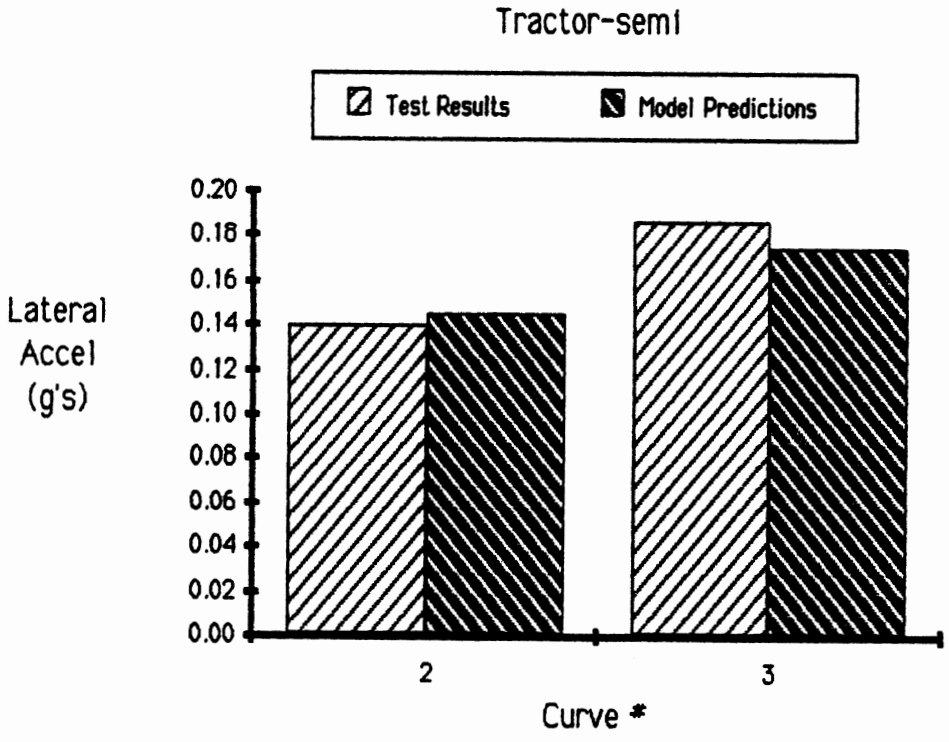
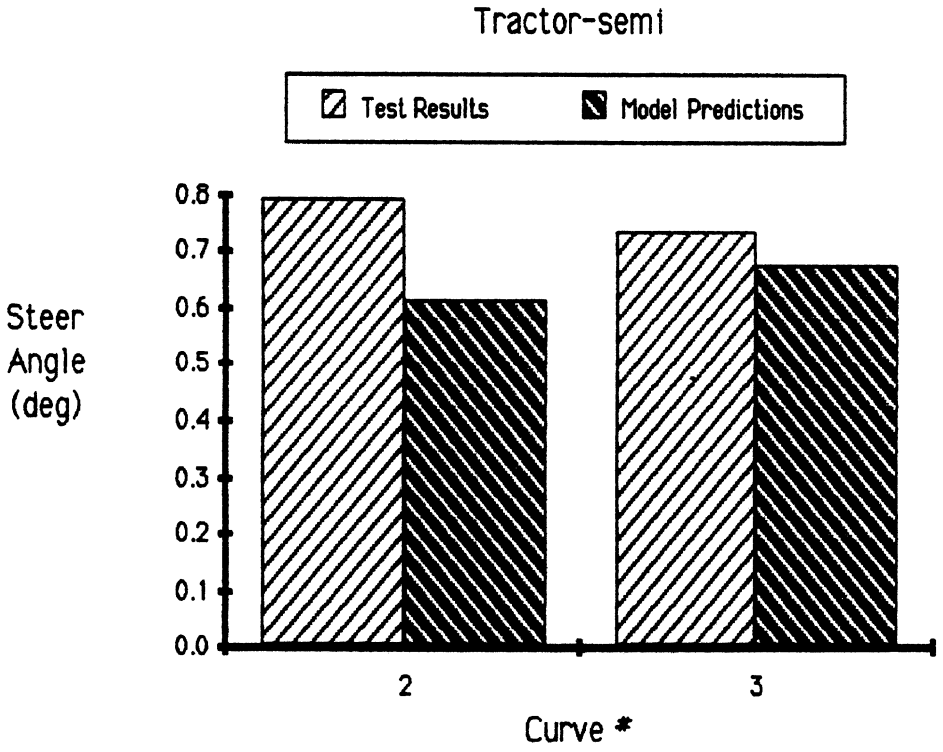
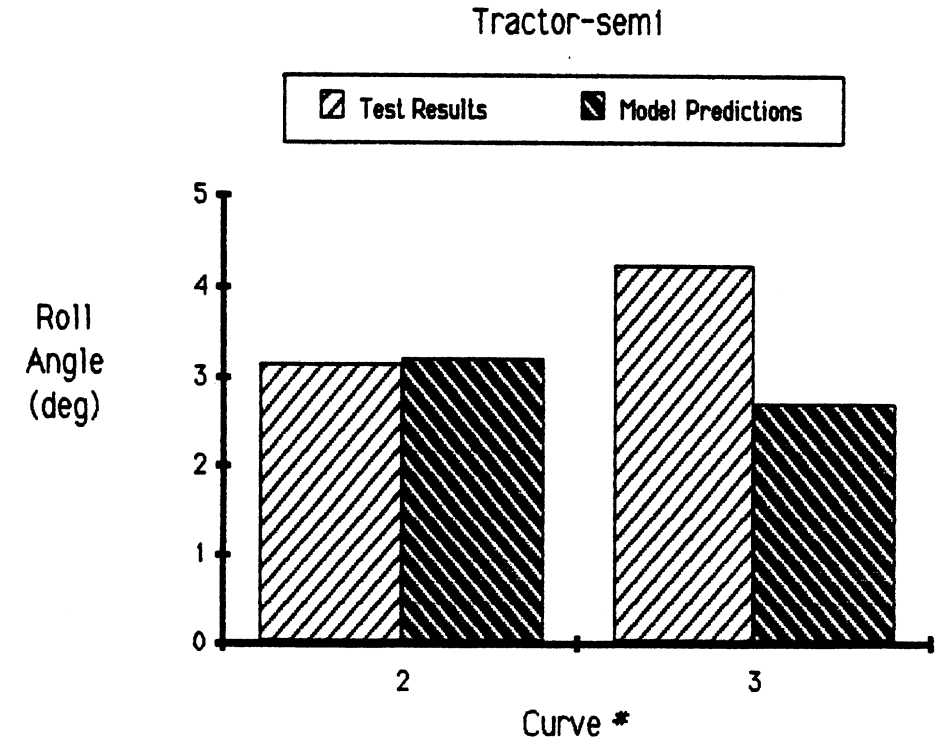


Figure F-1. Model/test comparisons; vehicle C.





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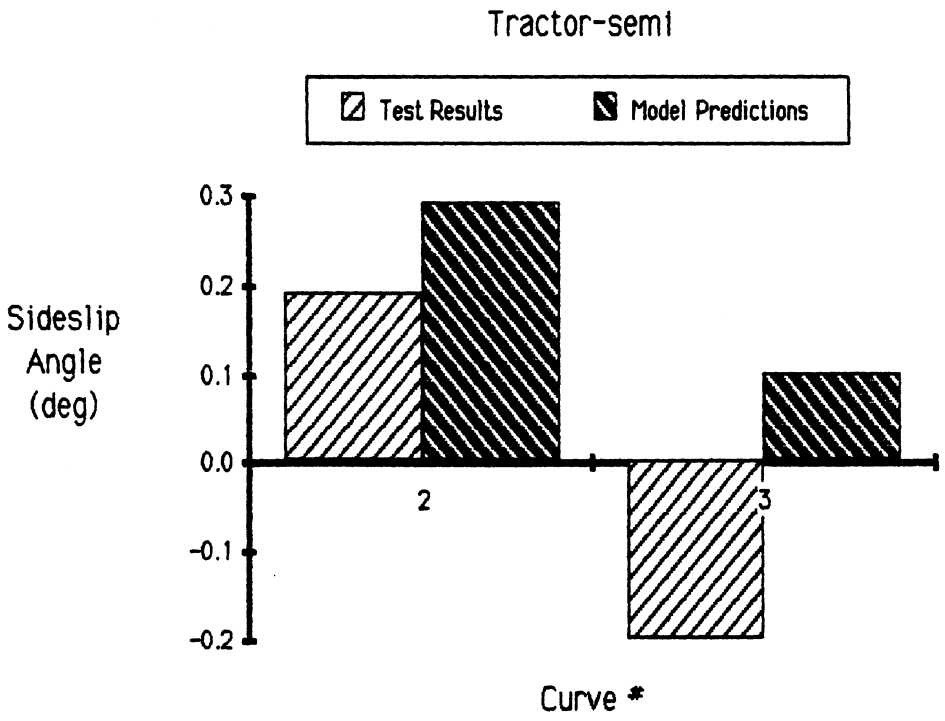

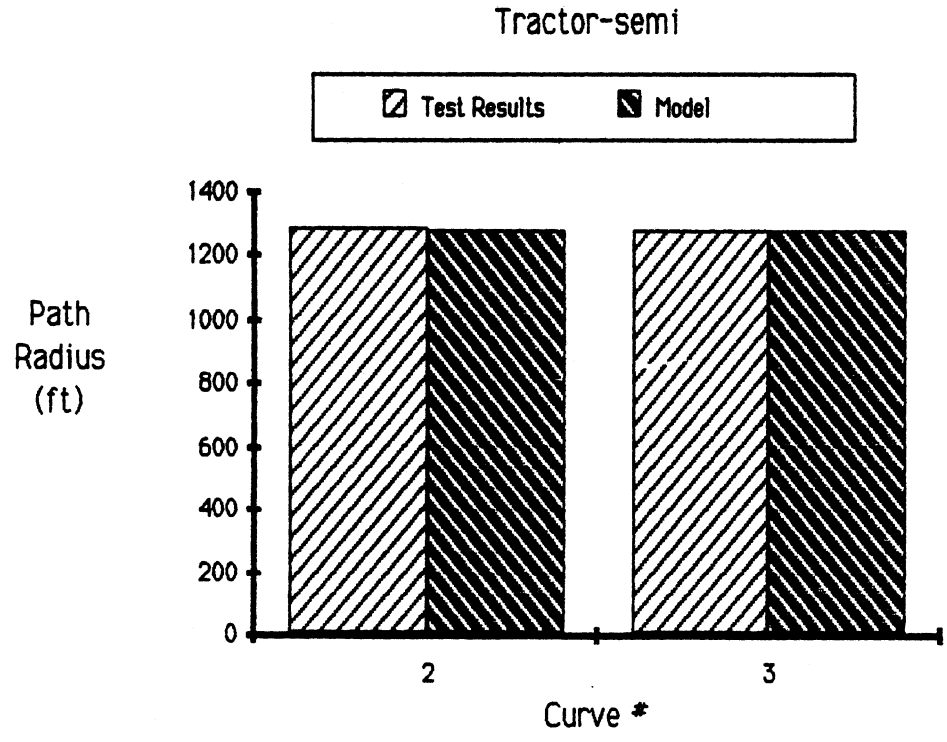

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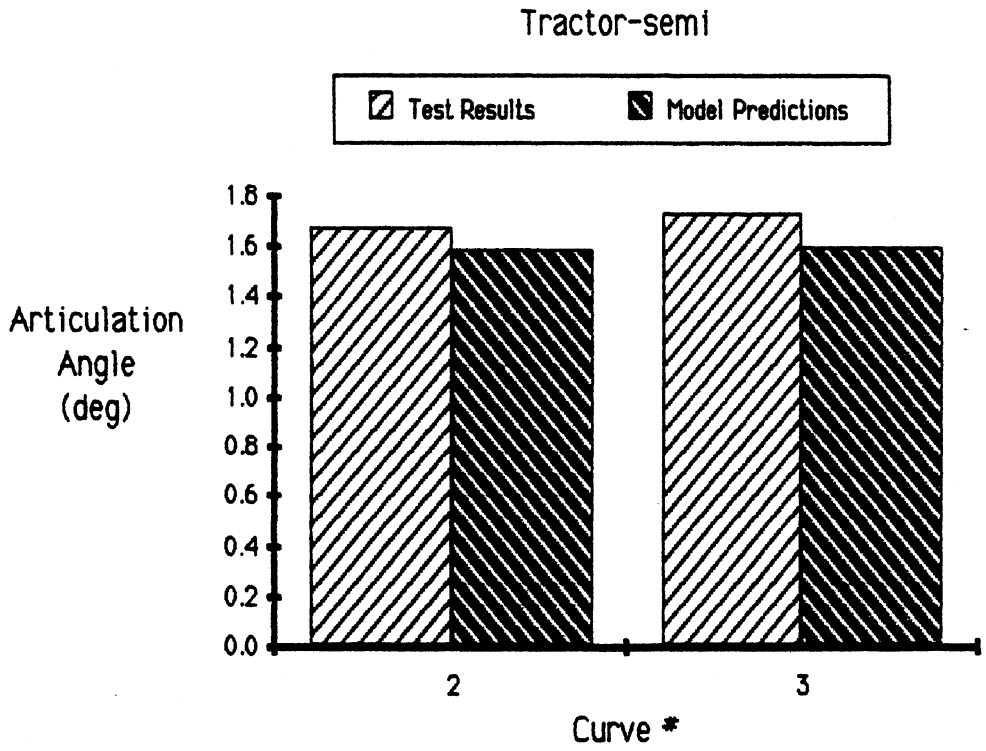

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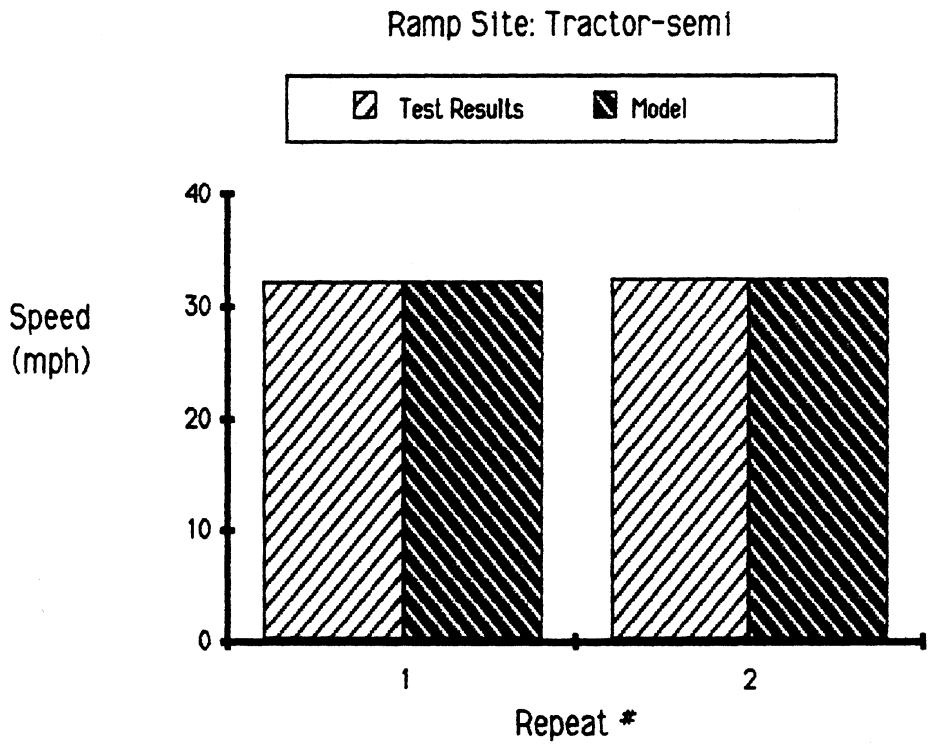


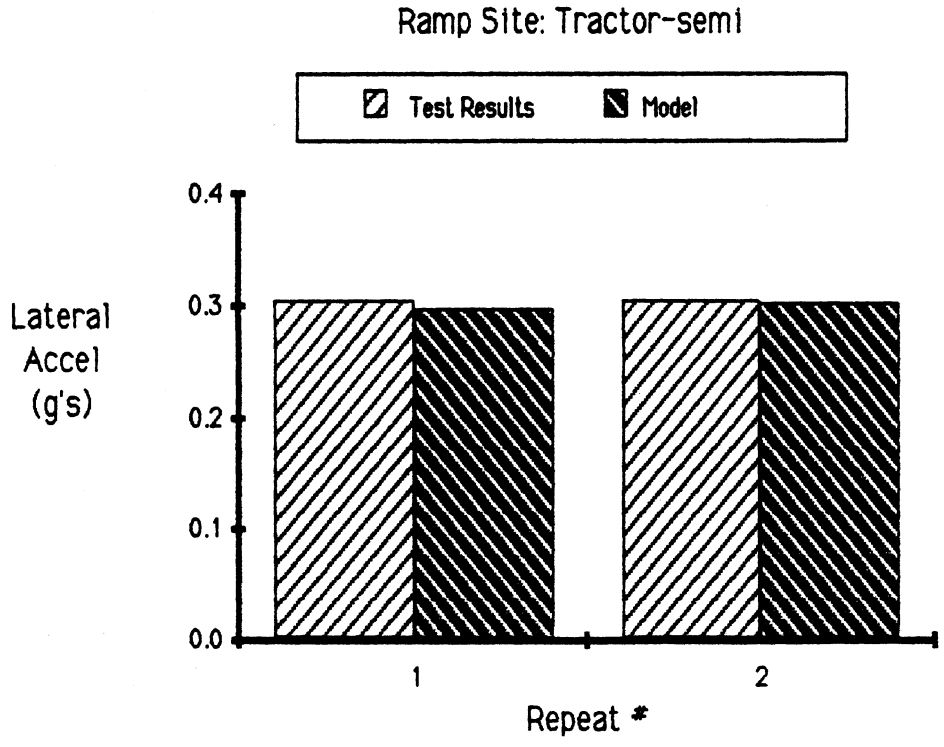
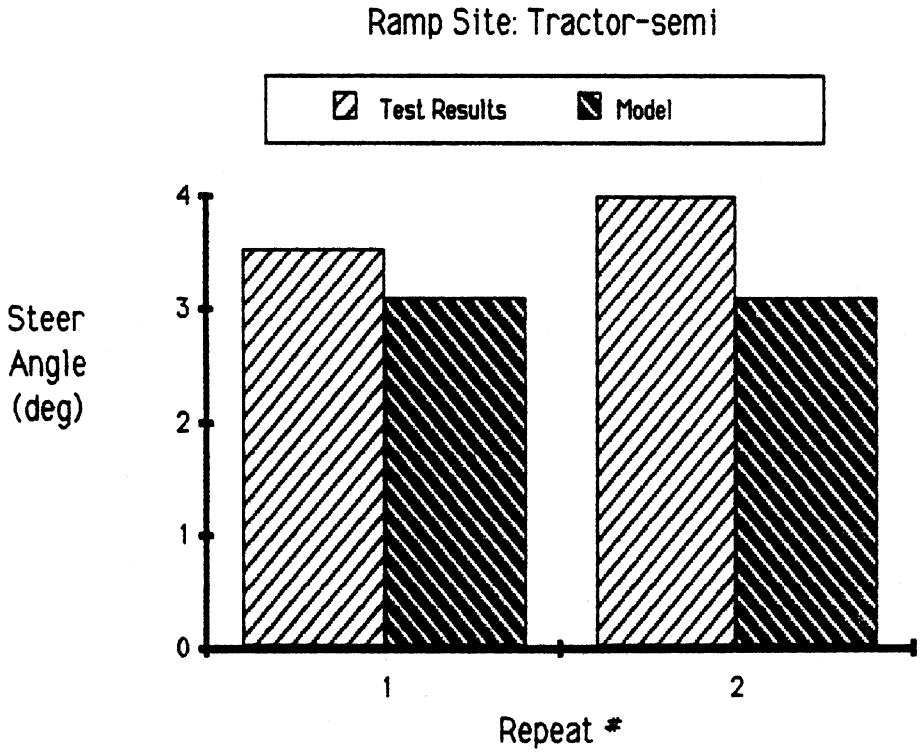
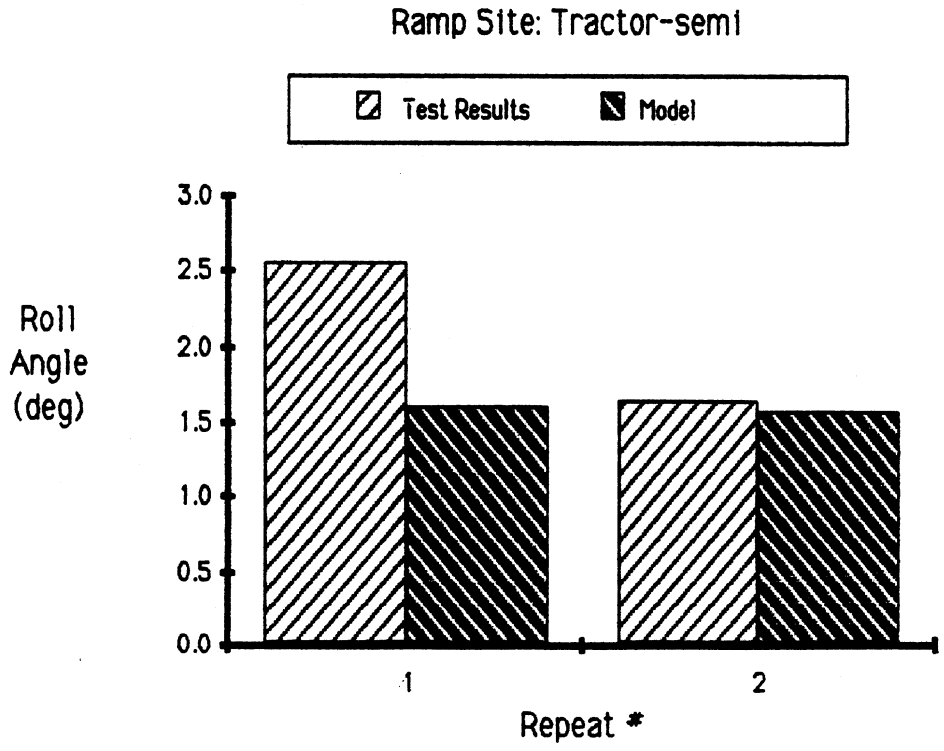


Figure F-2. Model/test comparisons; vehicle C.





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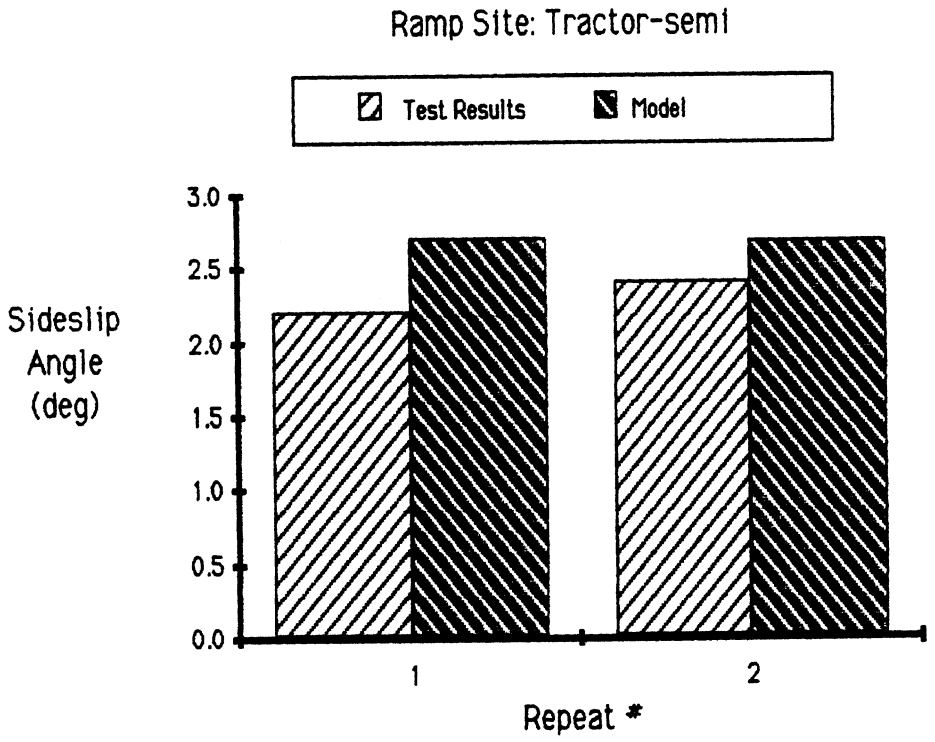

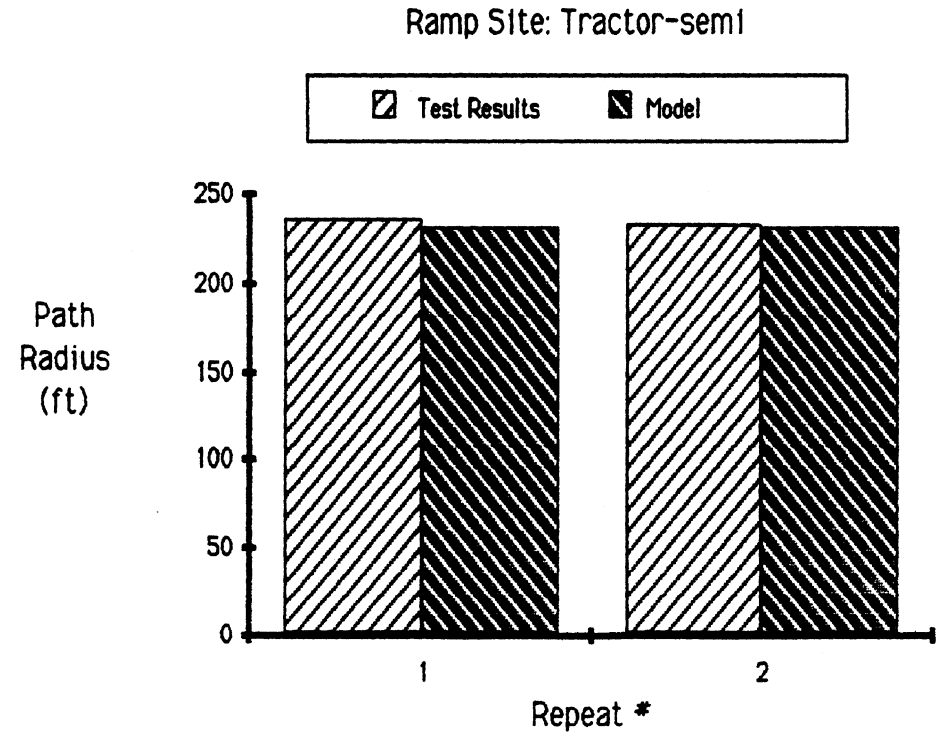

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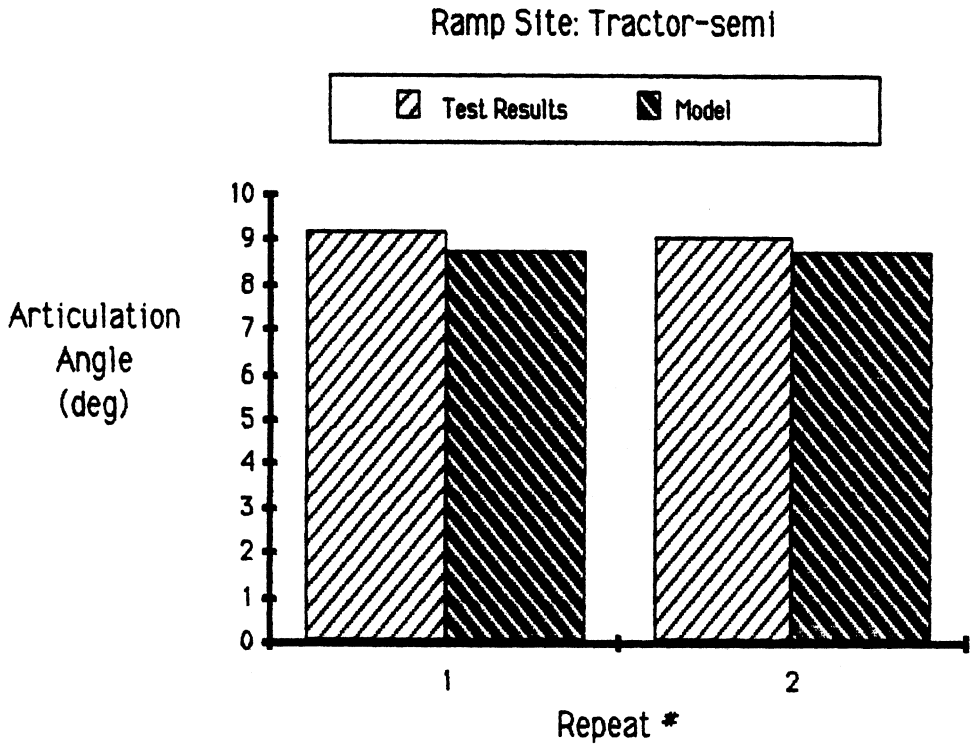

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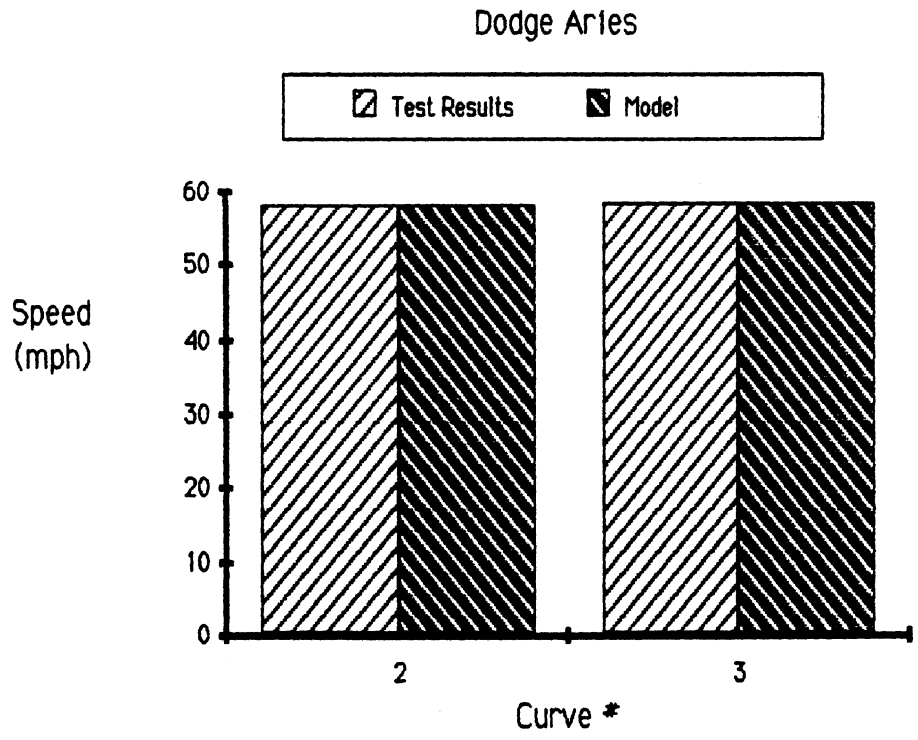


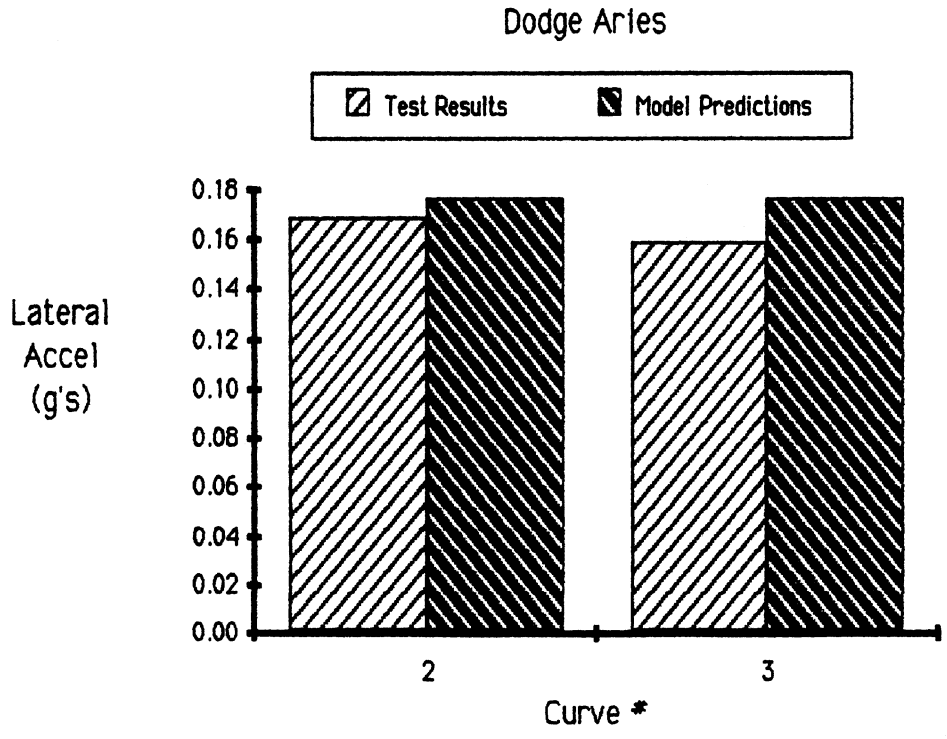
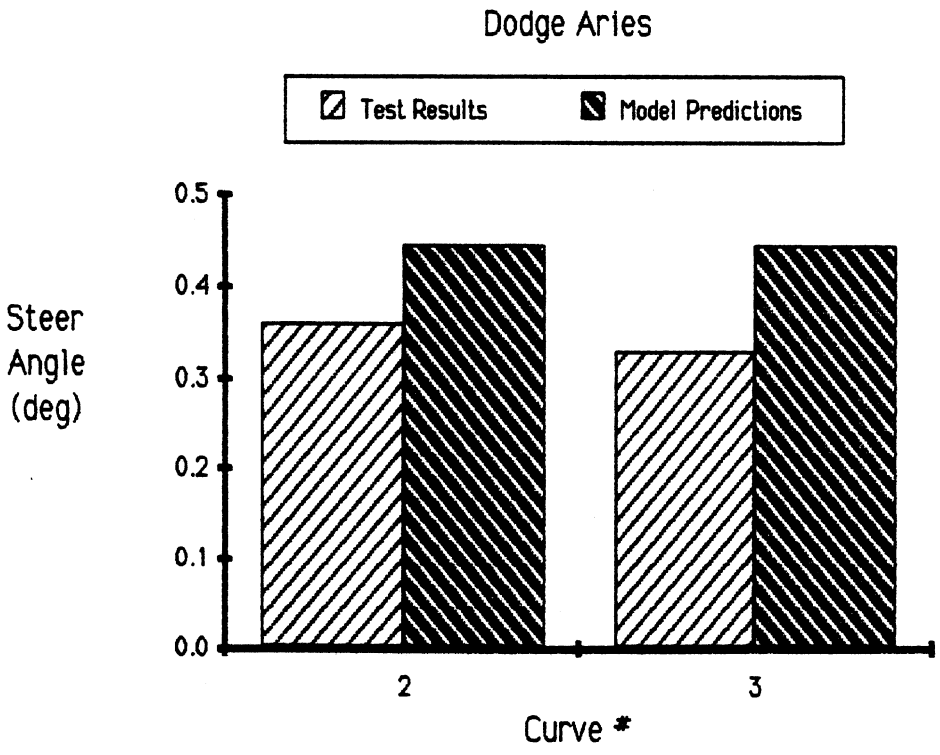
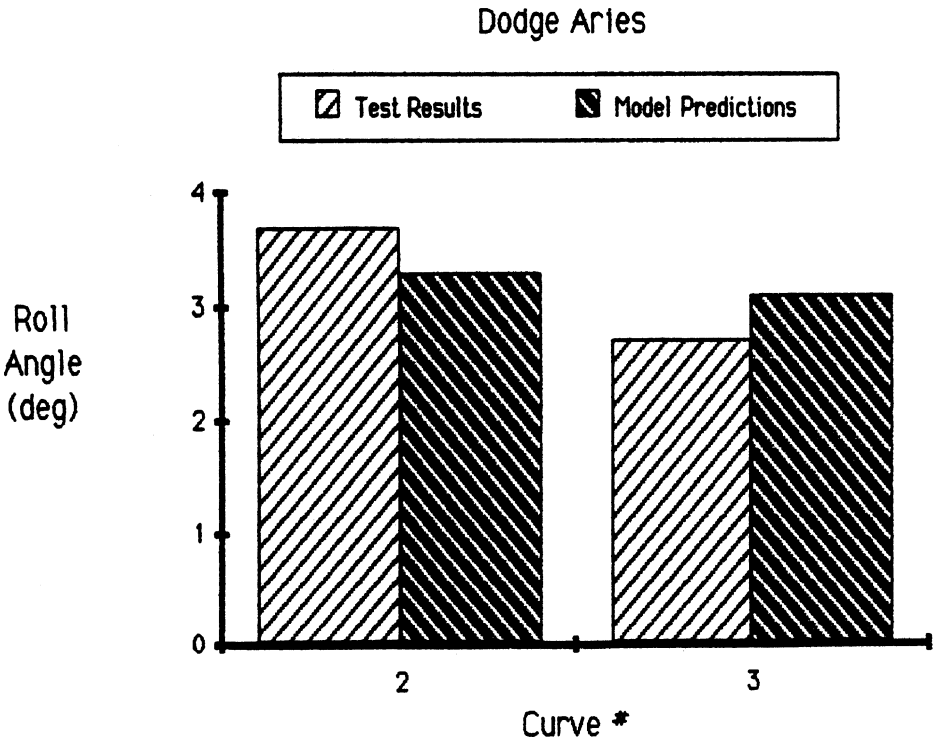


Figure F-3. Model/test comparisons; vehicle A.





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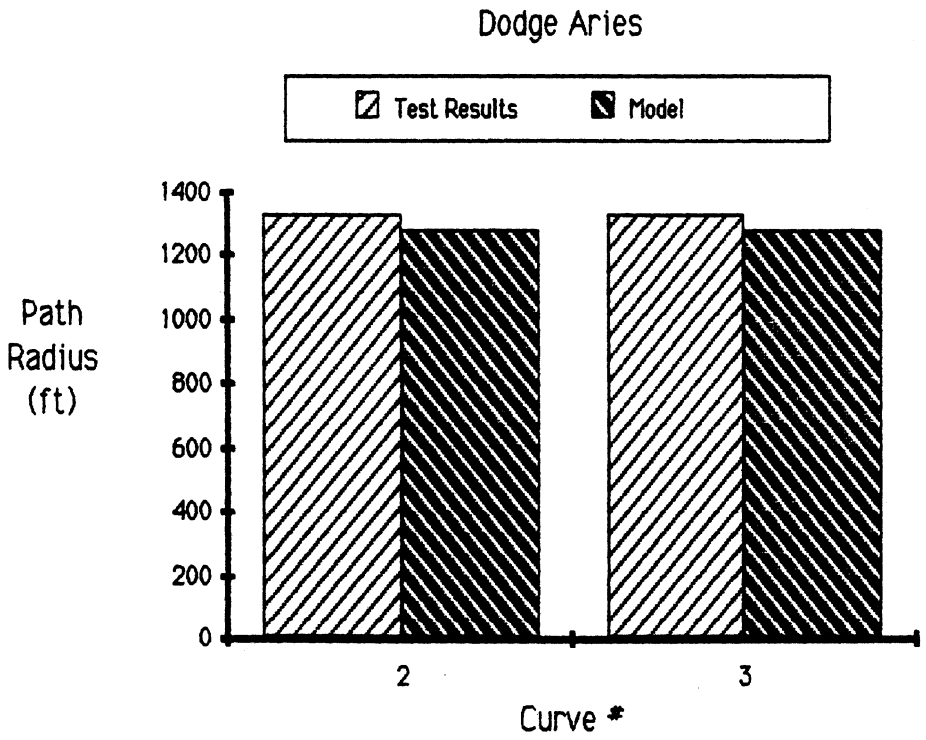

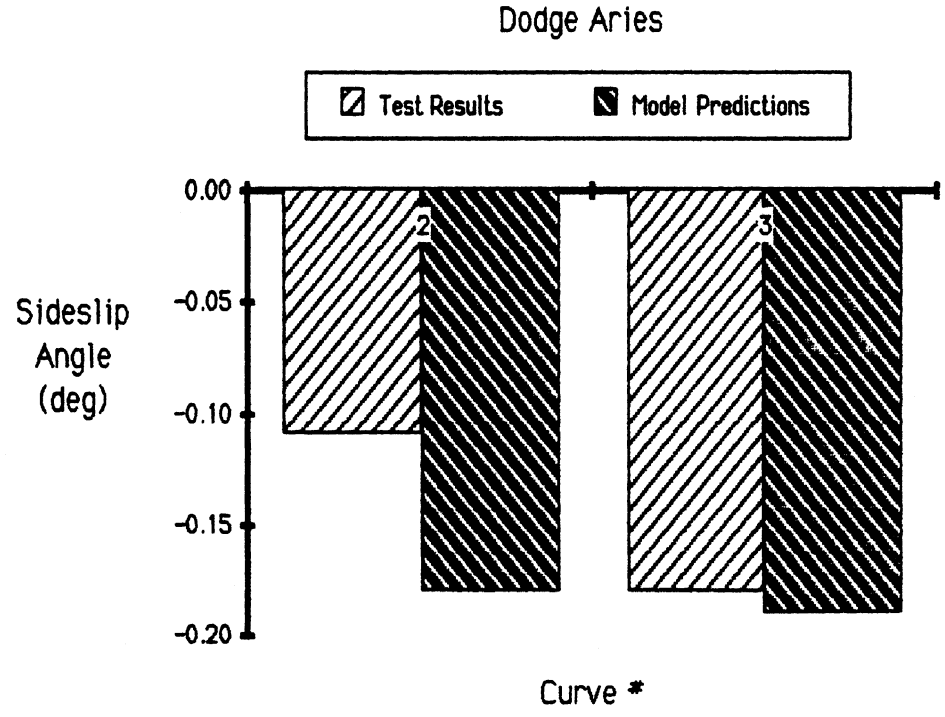

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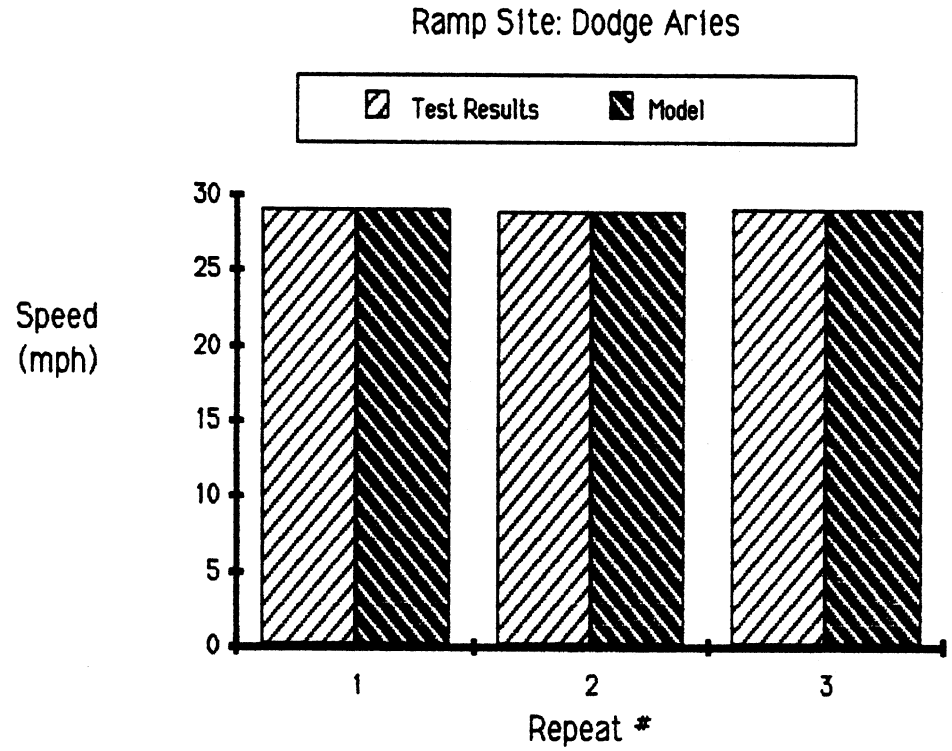


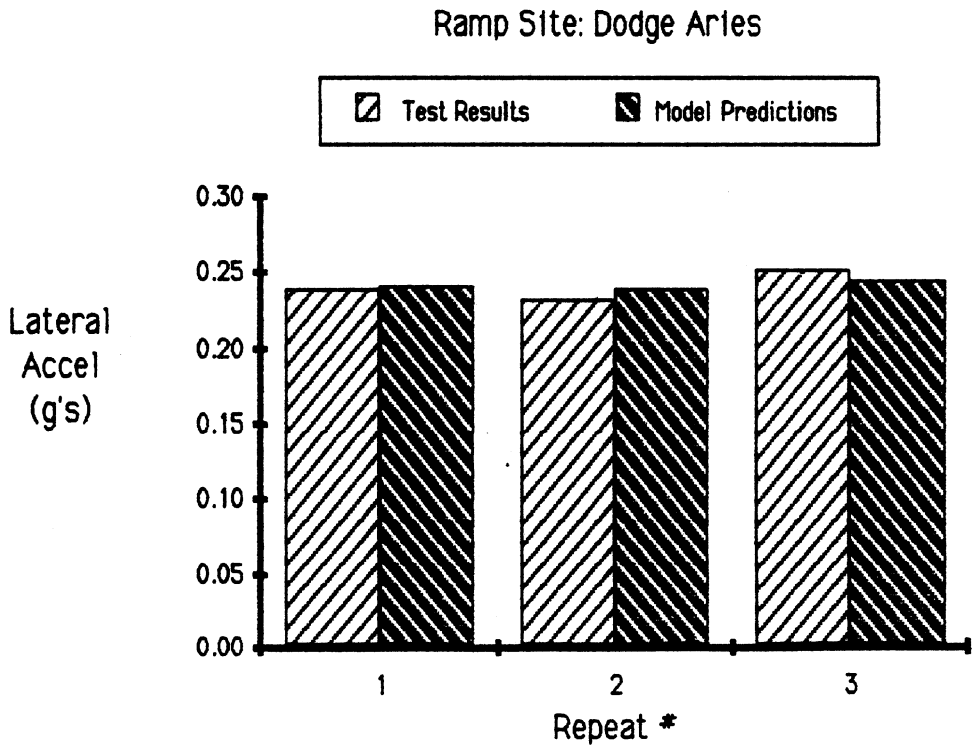
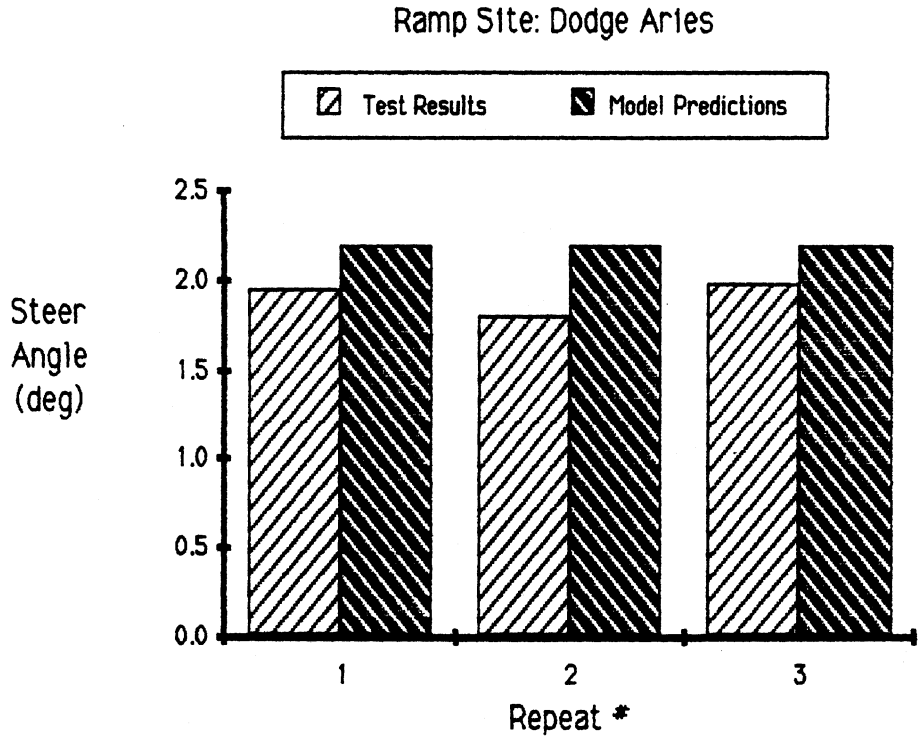
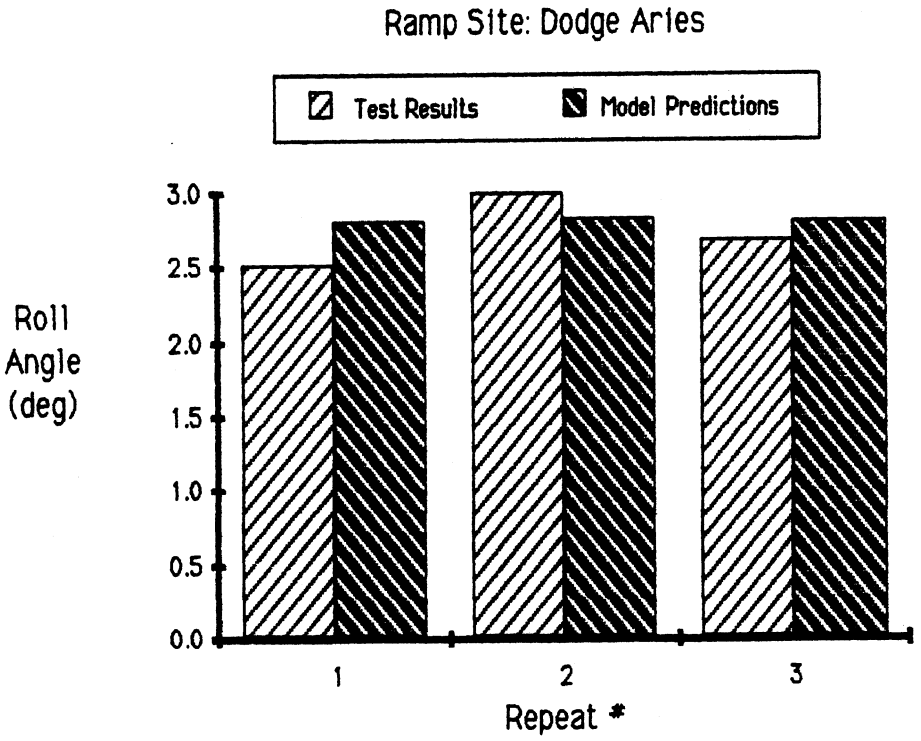


Figure F-4. Model/test comparisons; Vehicle A.





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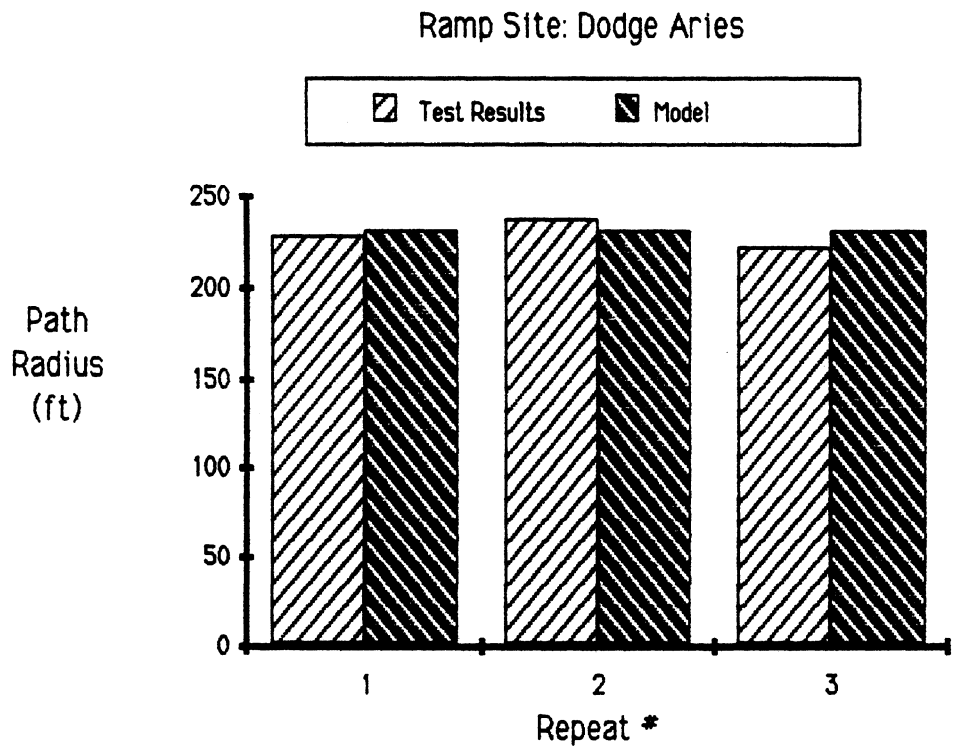

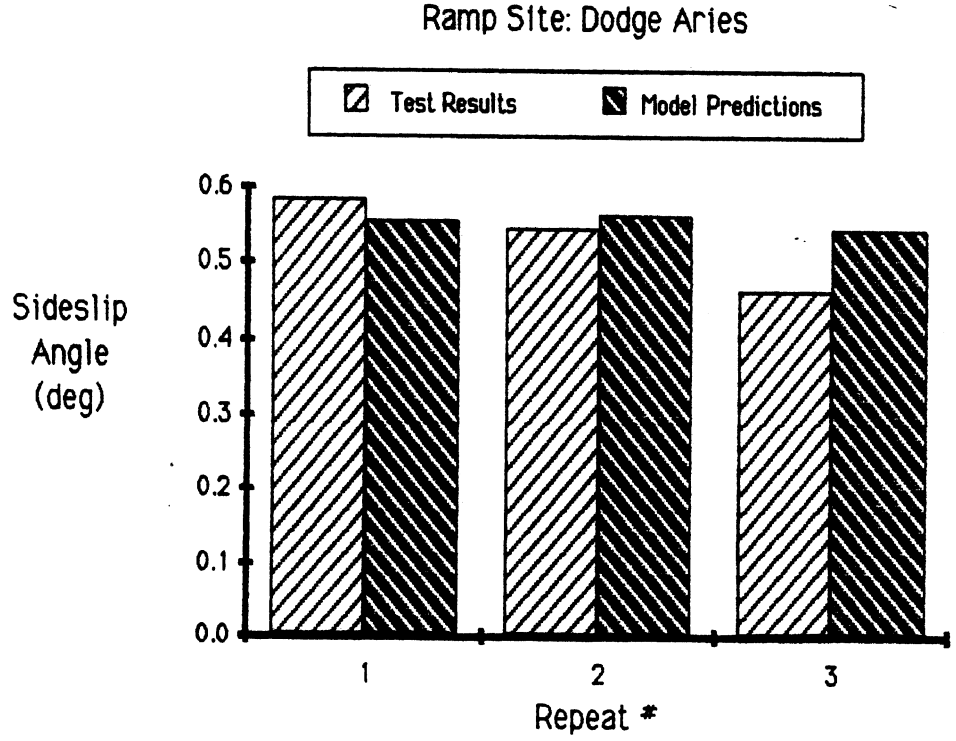

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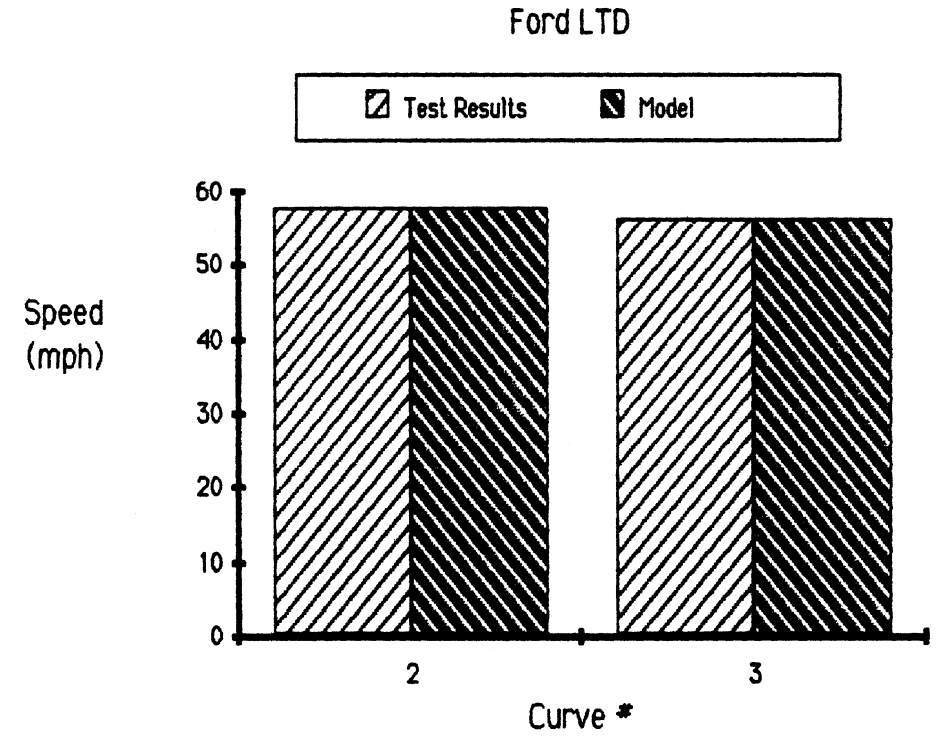


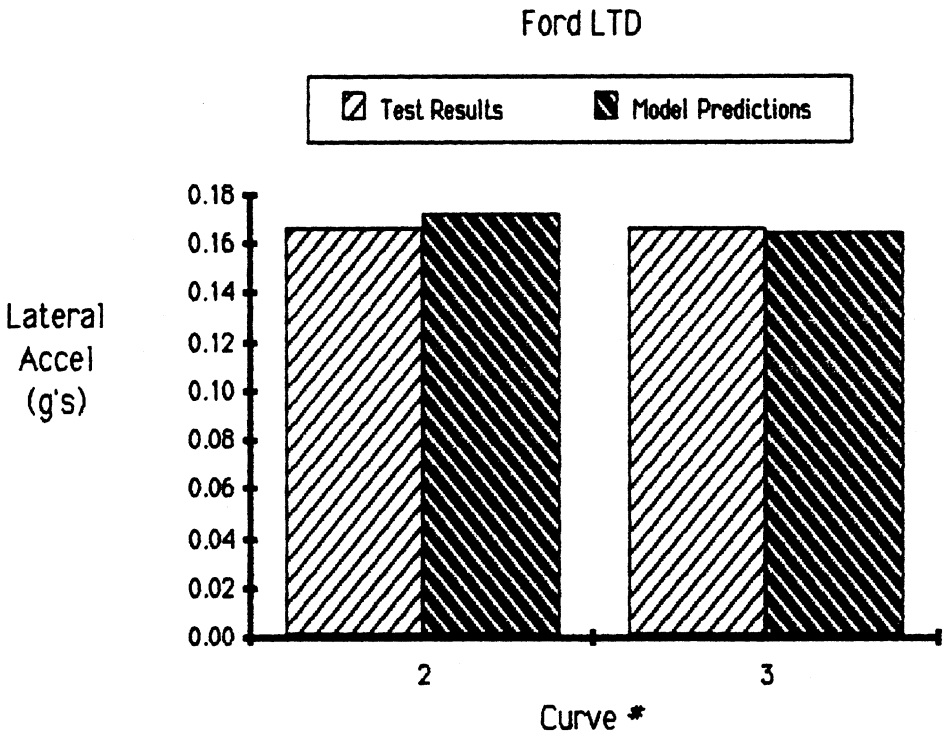
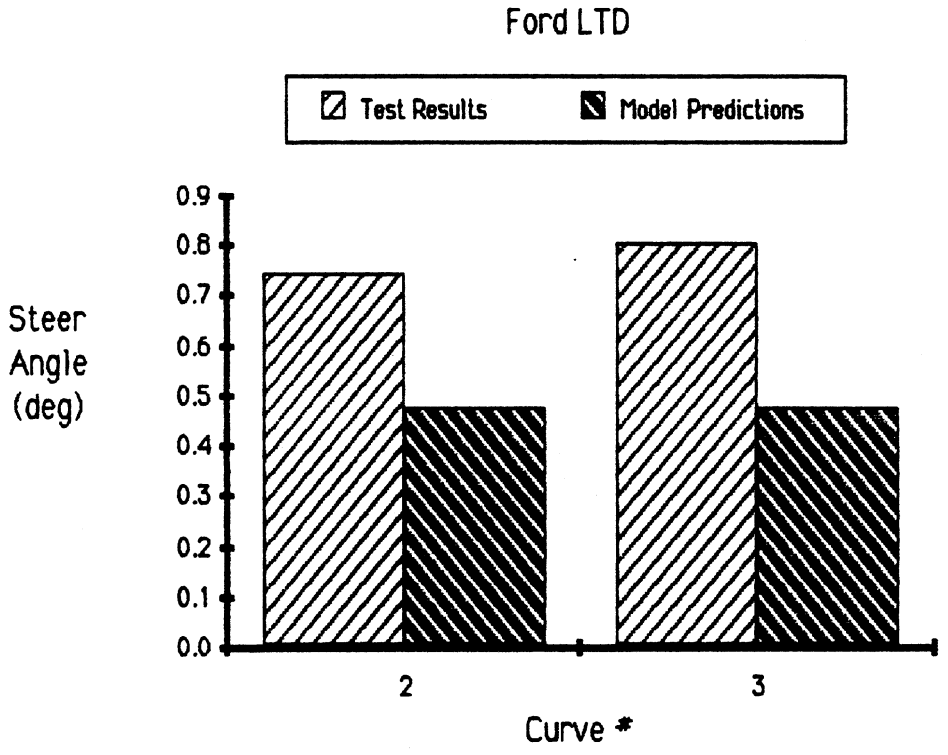
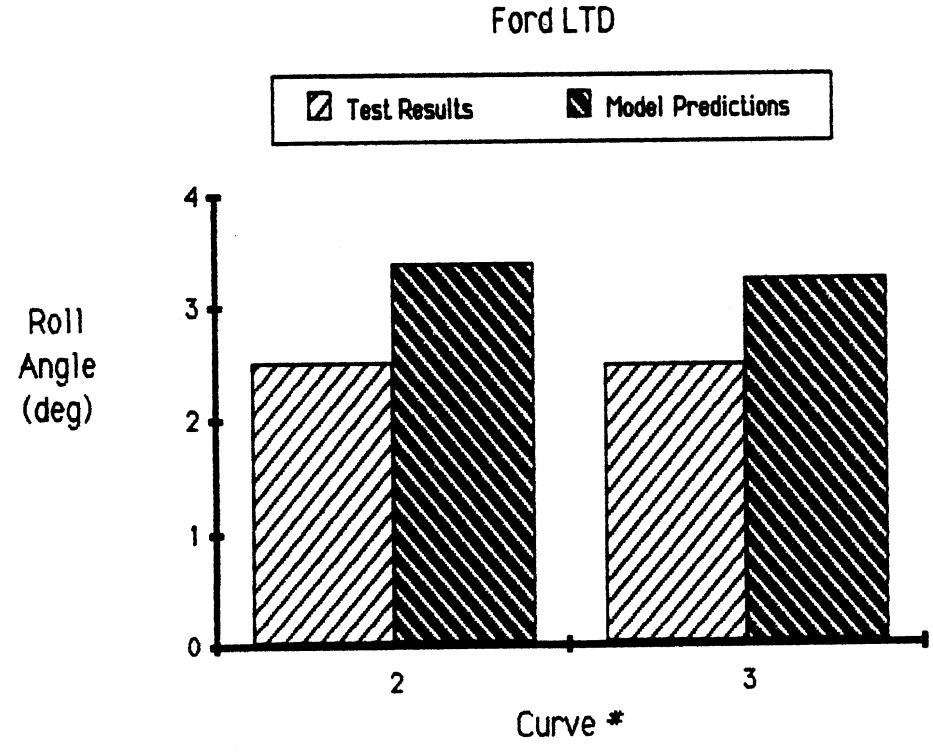


Figure F-5. Model/test comparisons; Vehicle B.





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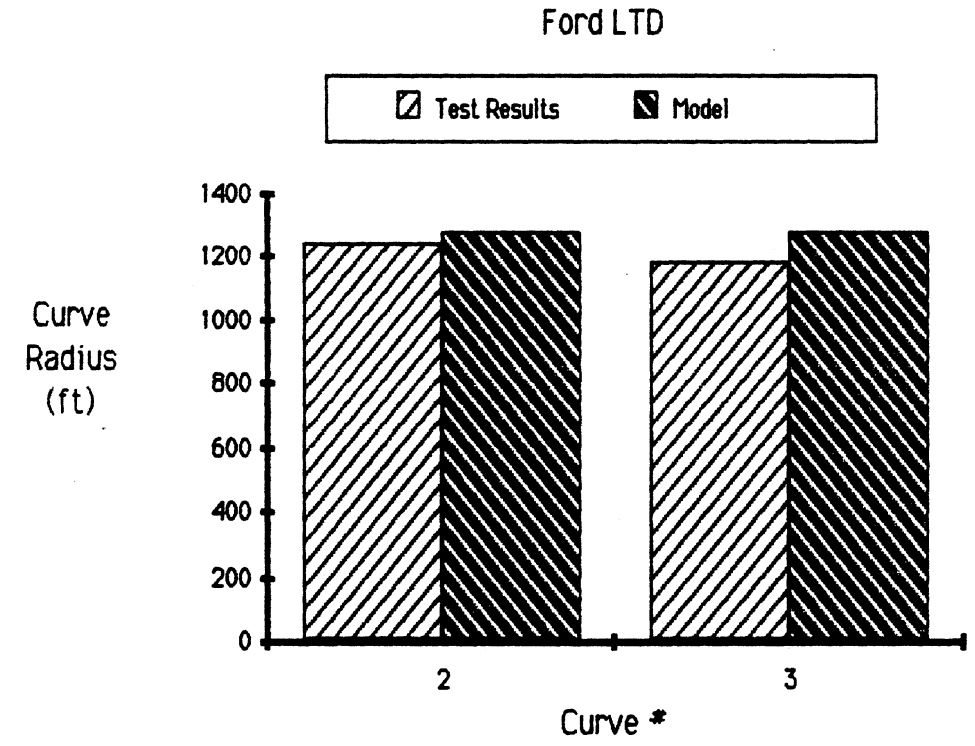

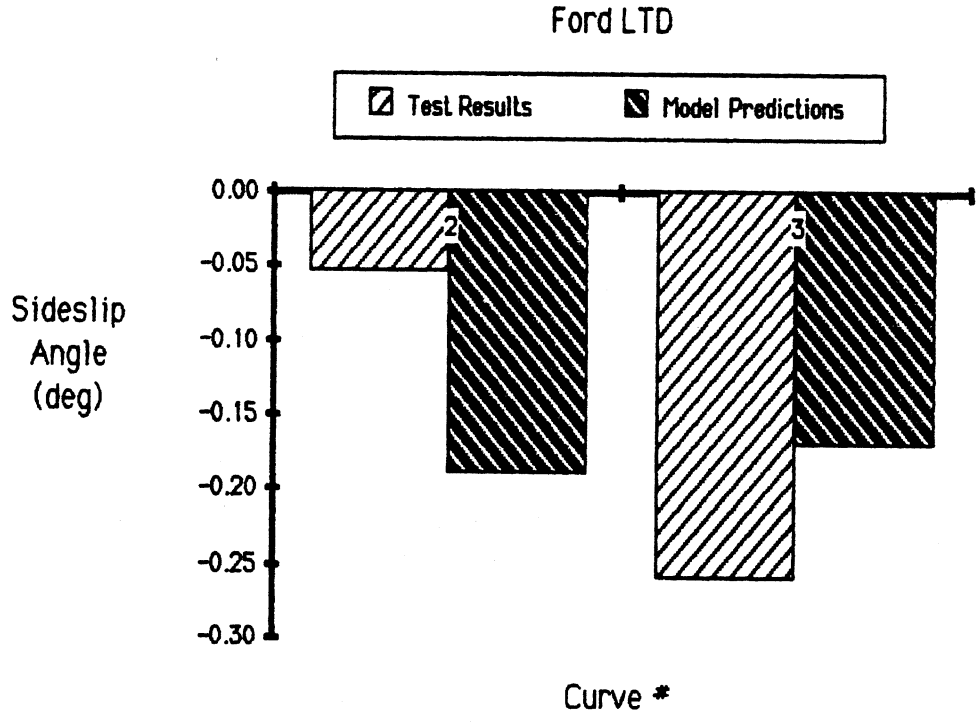

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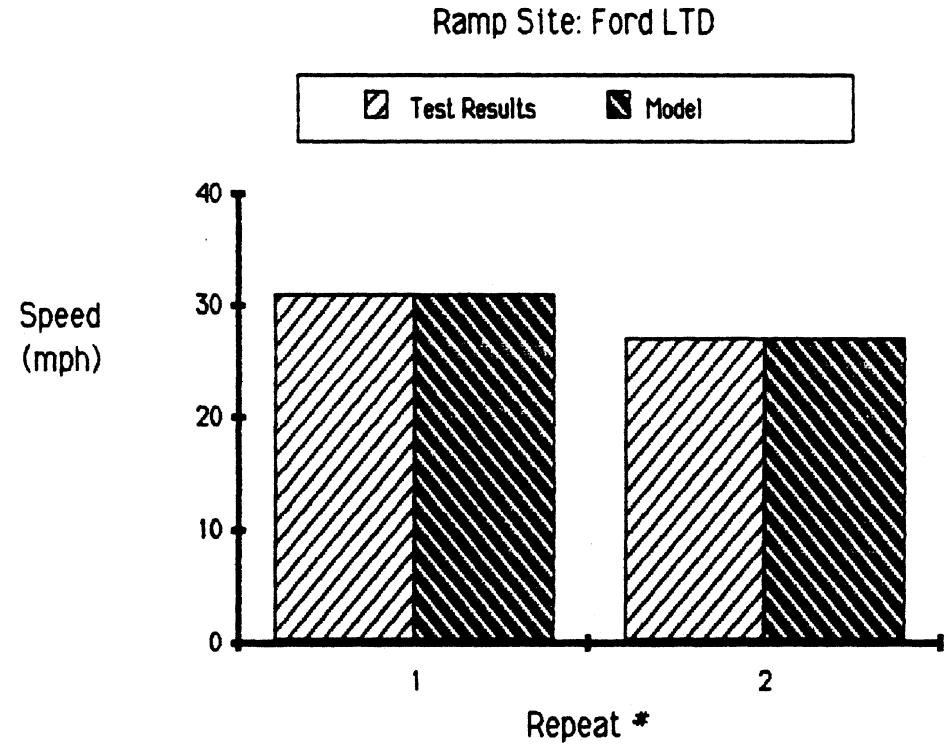


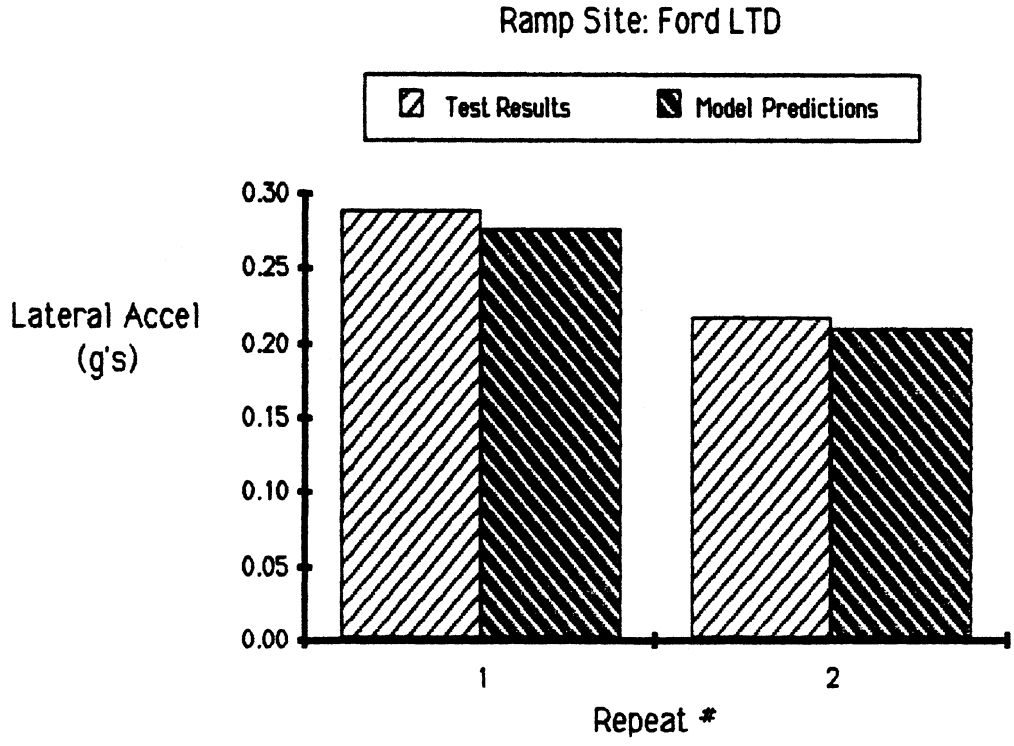
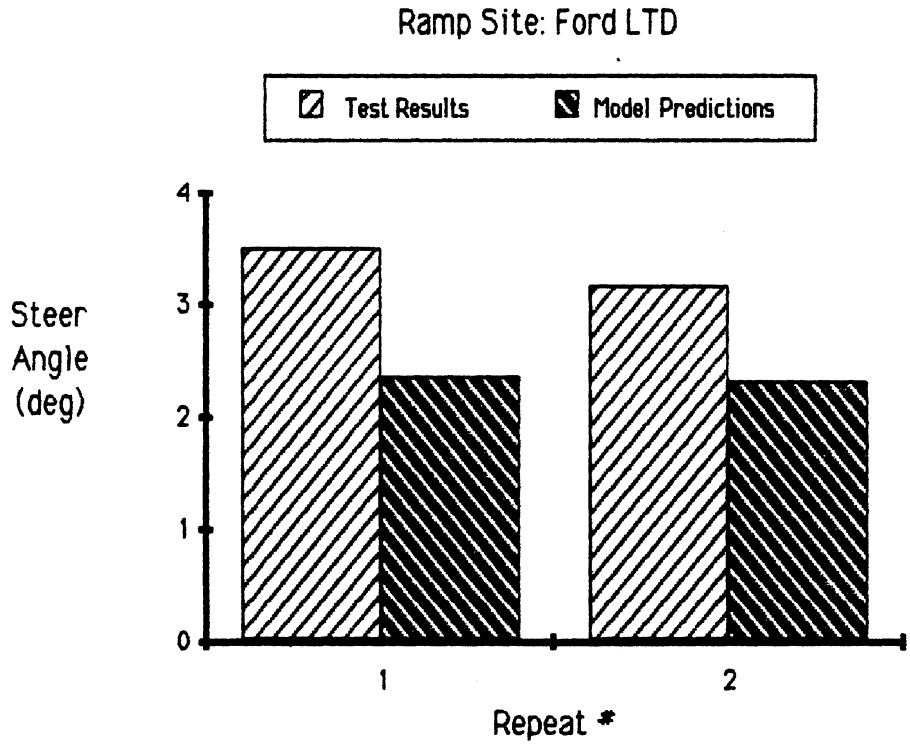
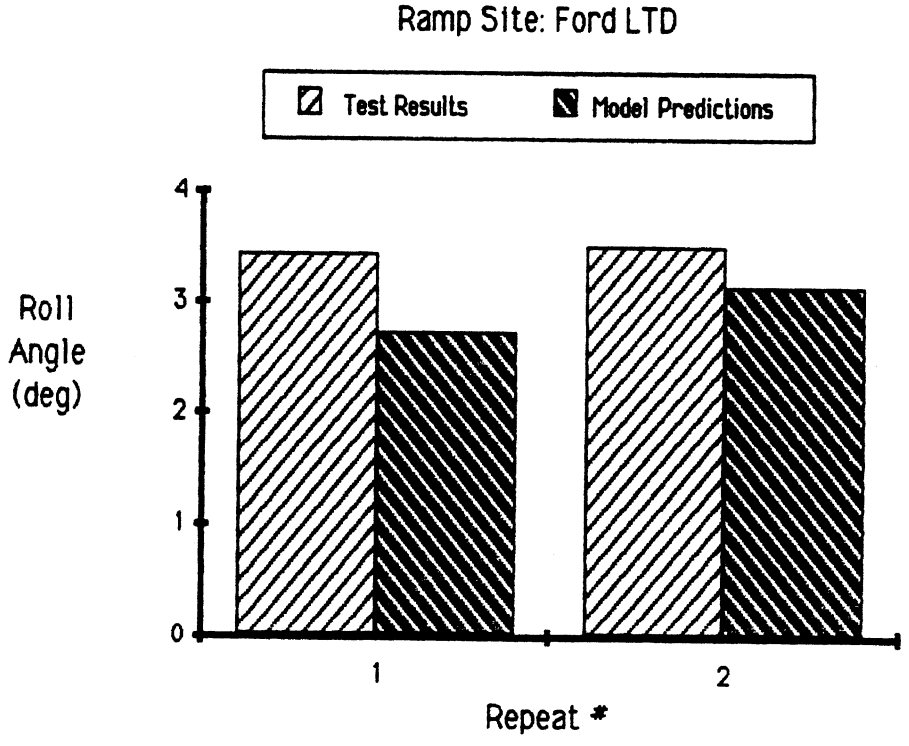


Figure F-6. Model/test comparisons; Vehicle B.





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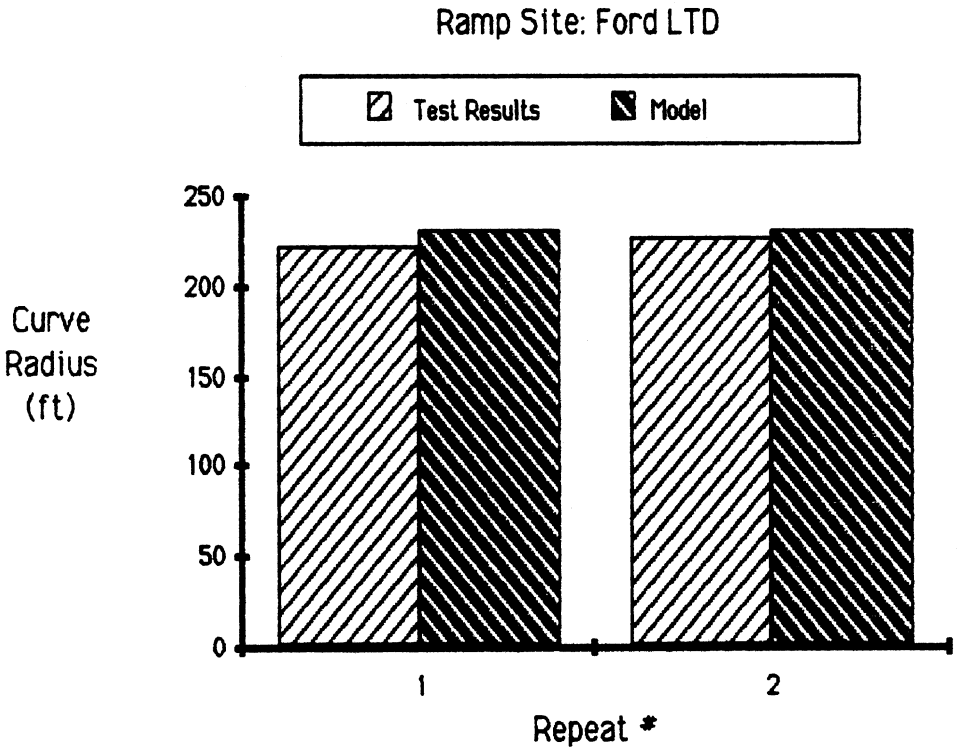


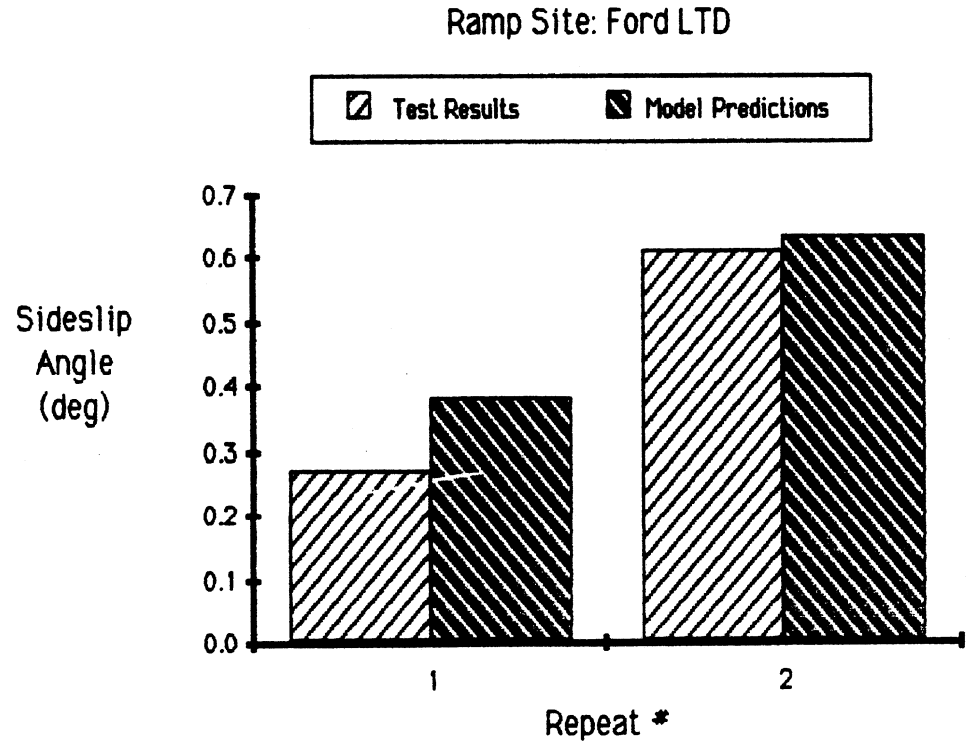


Figure F-6 (cont)

Appendix G

TRACTOR-SEMITRAILER PARAMETER SENSITIVITIES
(VEHICLE RESPONSE VARIABLES)

The graphs contained in this appendix supplement the material presented in chapter 6 of volume II. Vehicle response variables showing sensitivities to various parameter variations are seen for the five-axle tractor-semitrailer vehicle. Figures G-1 to G-8 illustrate vehicle sensitivity to changes in grade, suspension properties, fifth-wheel placement, center-of-gravity location, and wheelbase.

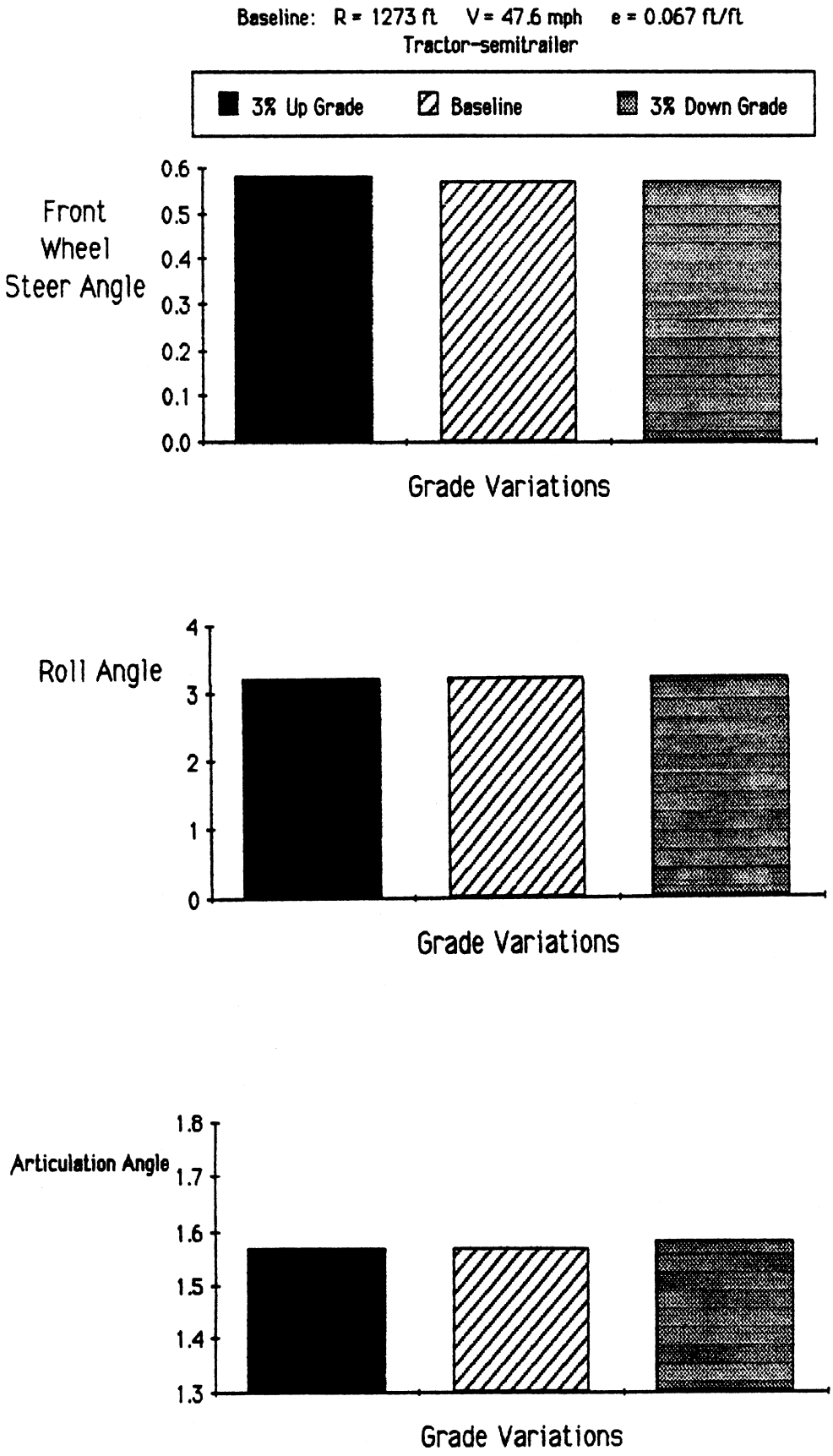
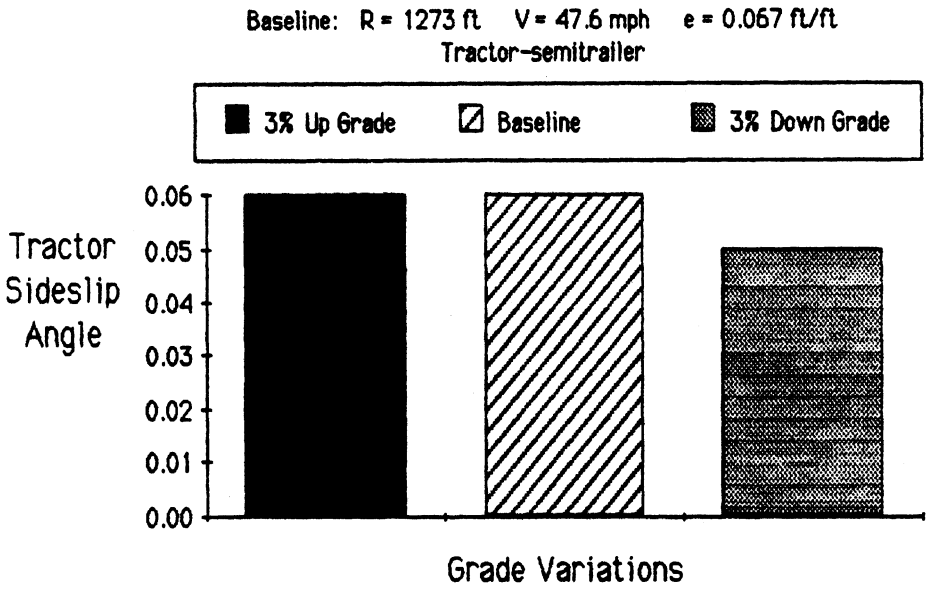
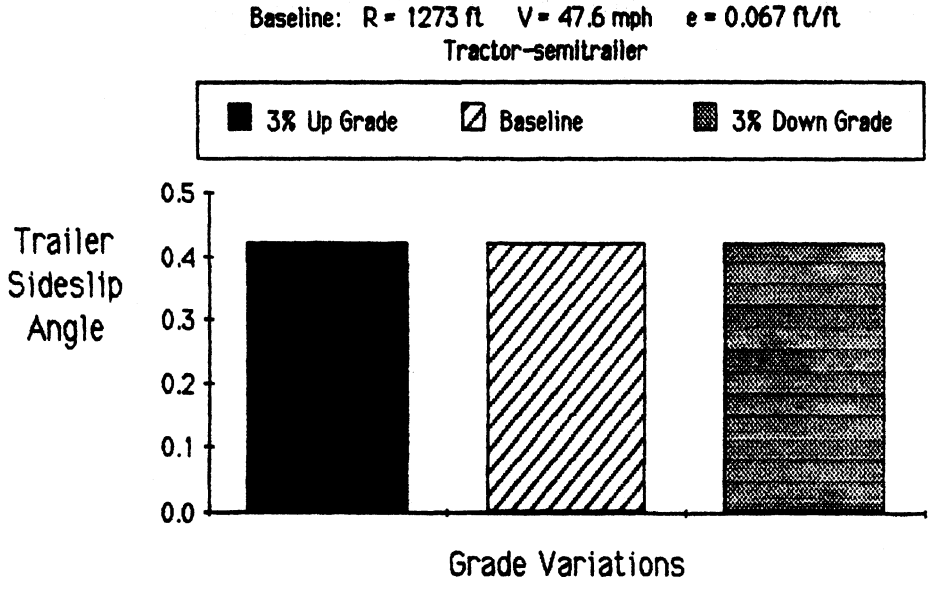


Figure G-1. Parameter sensitivities; vehicle C.





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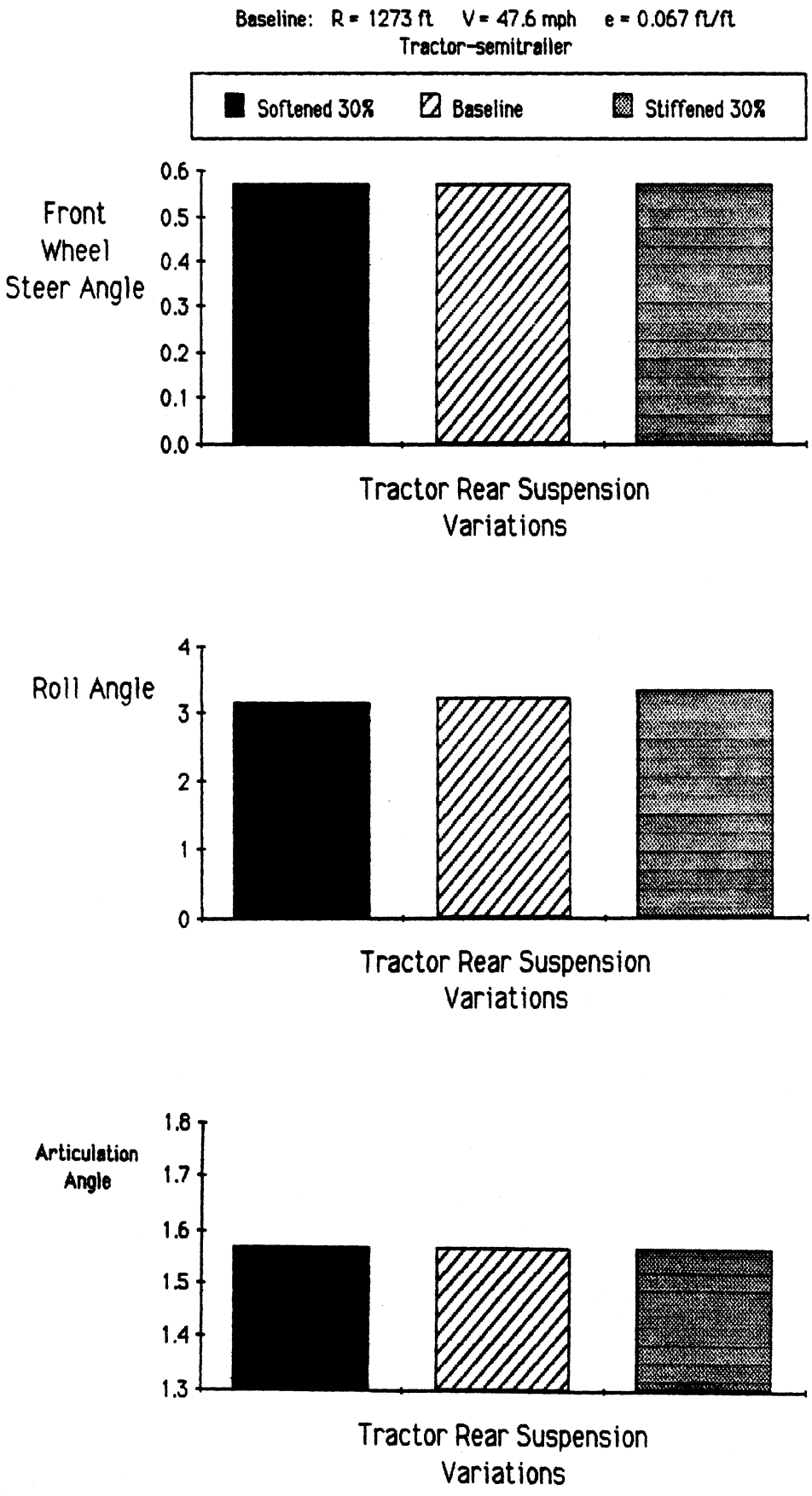
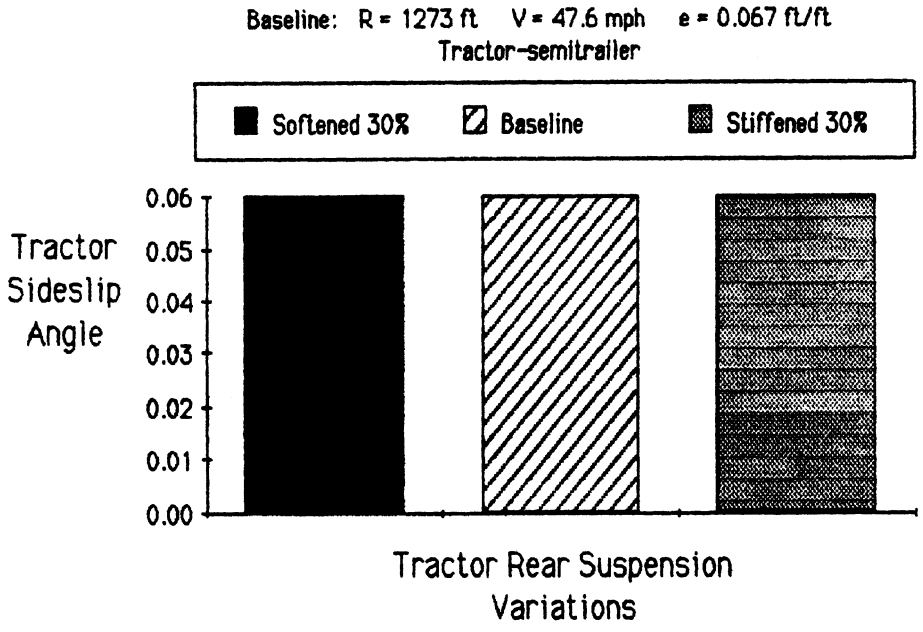
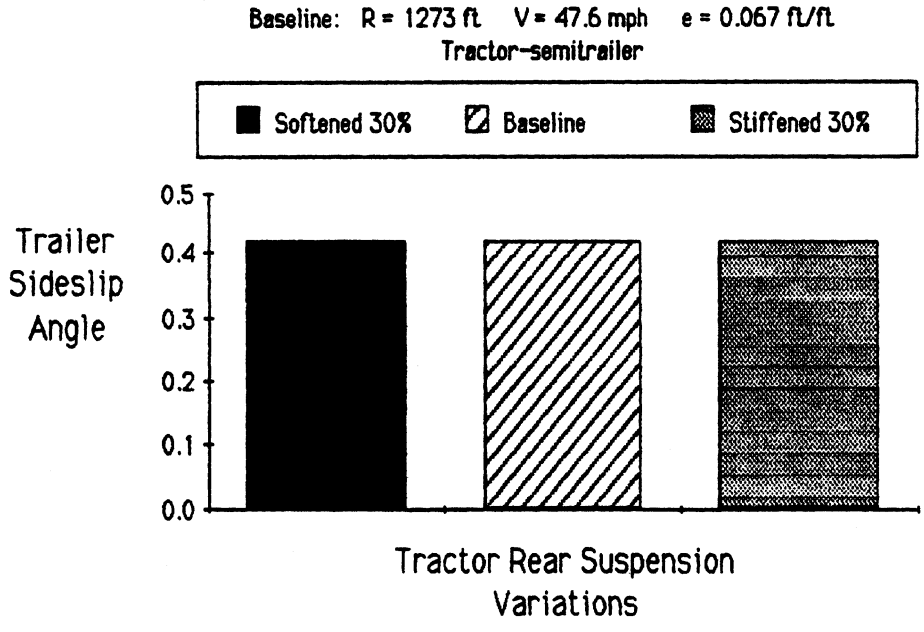


Figure G-2. Parameter variations: vehicle C.





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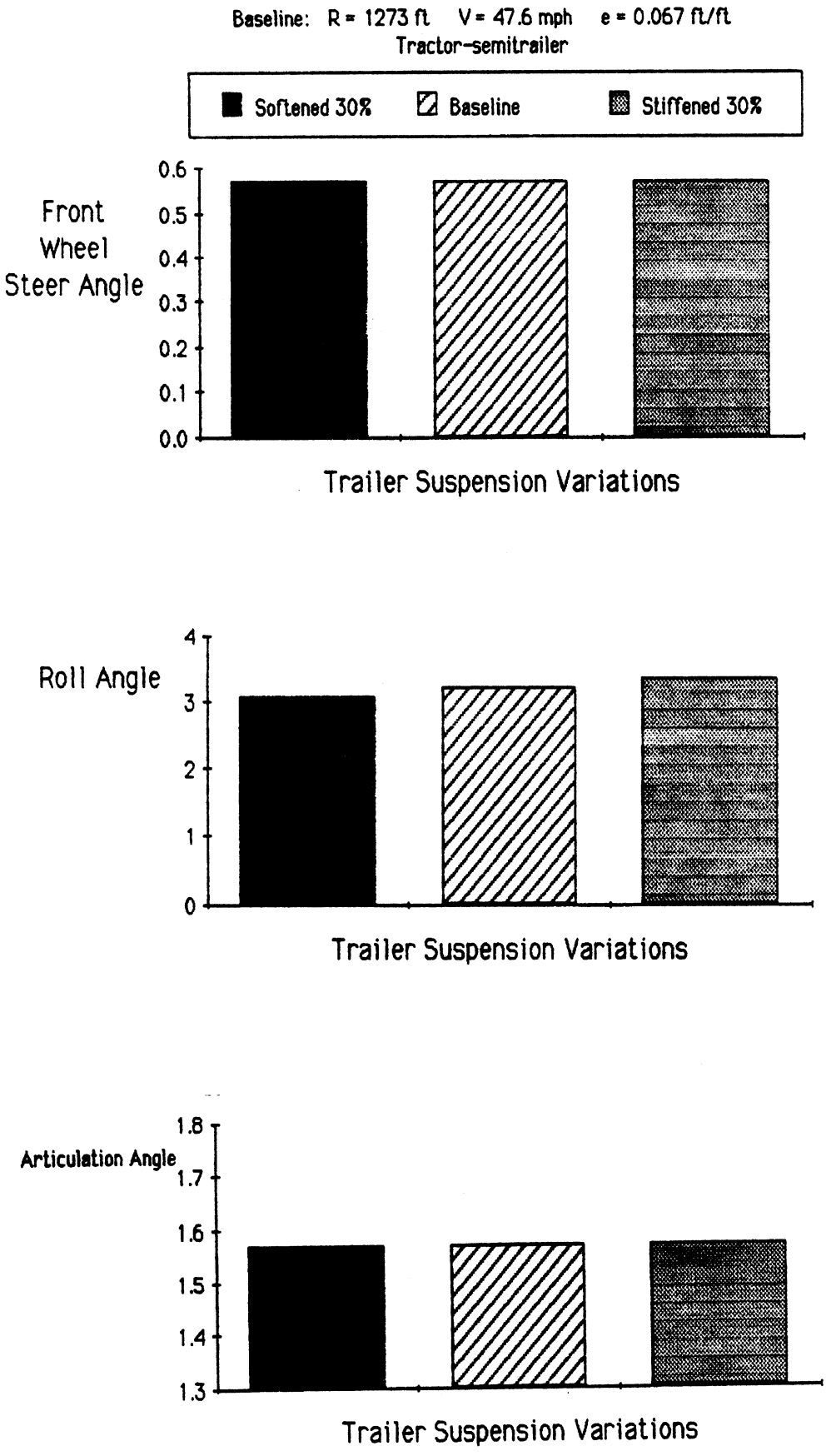
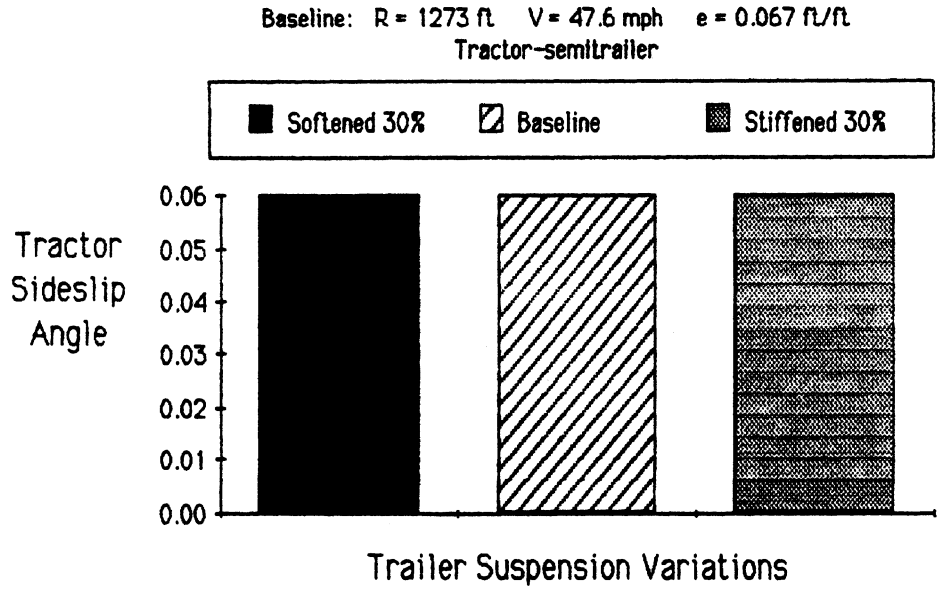
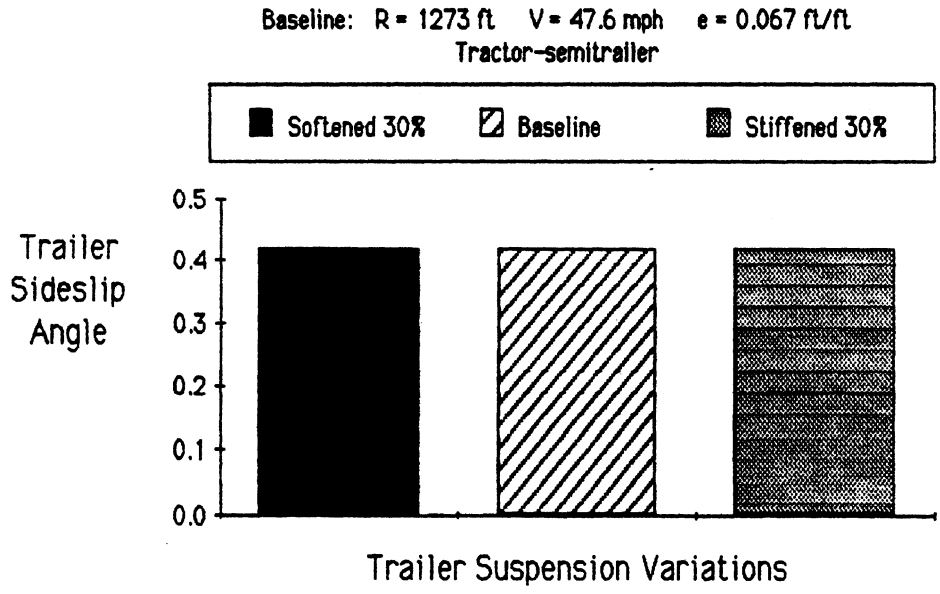


Figure G-3. Parameter variations; vehicle C.





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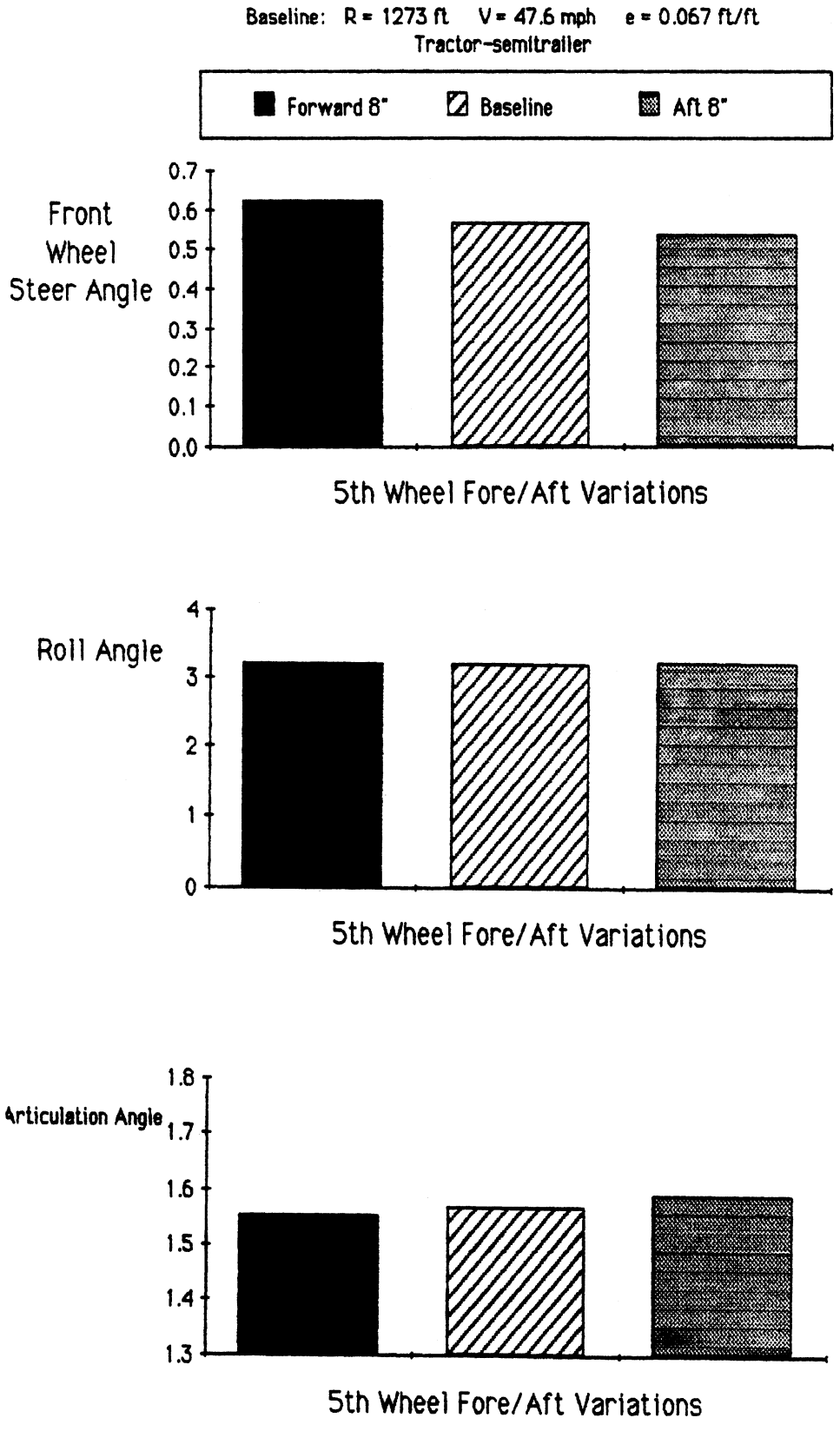
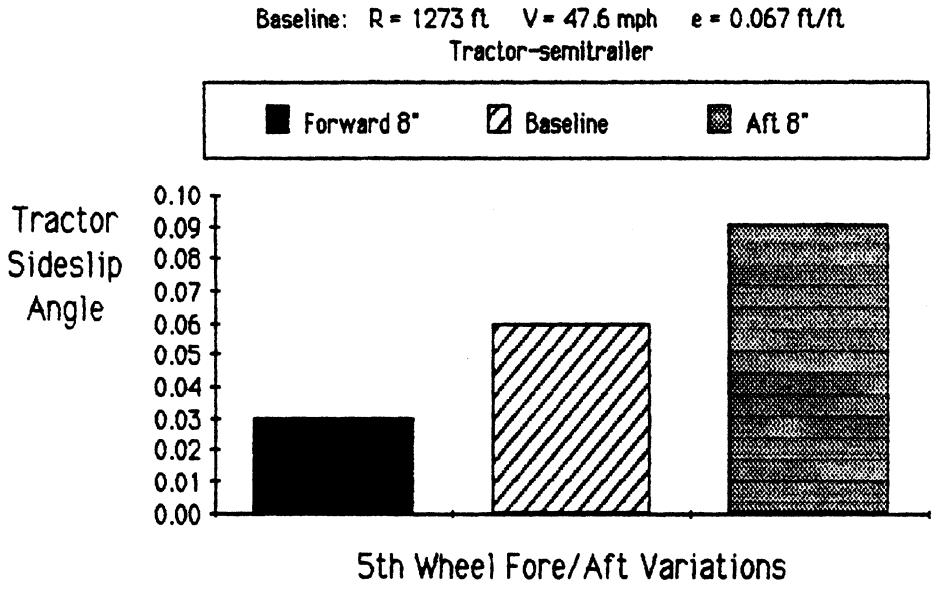
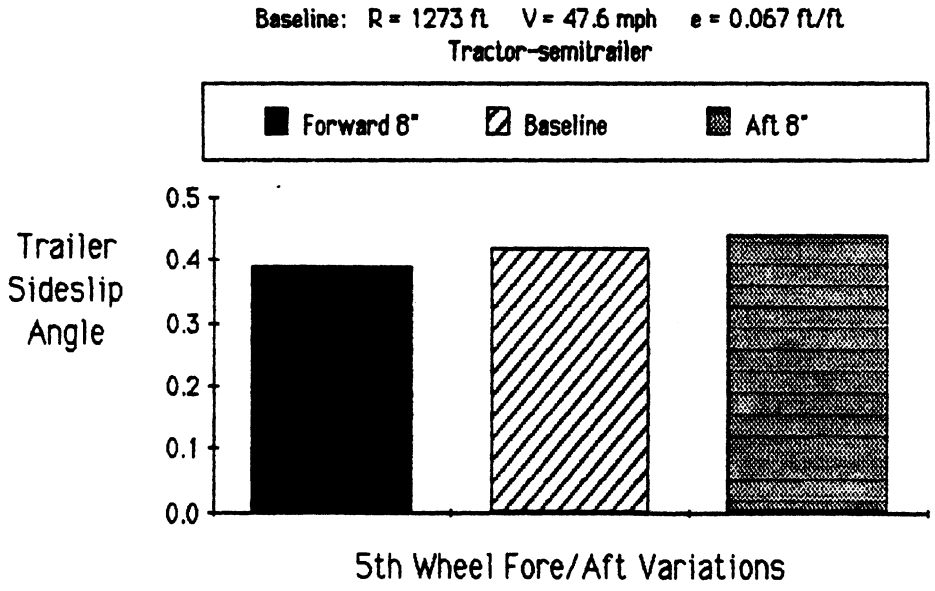


Figure G-4. Parameter variations; vehicle C.





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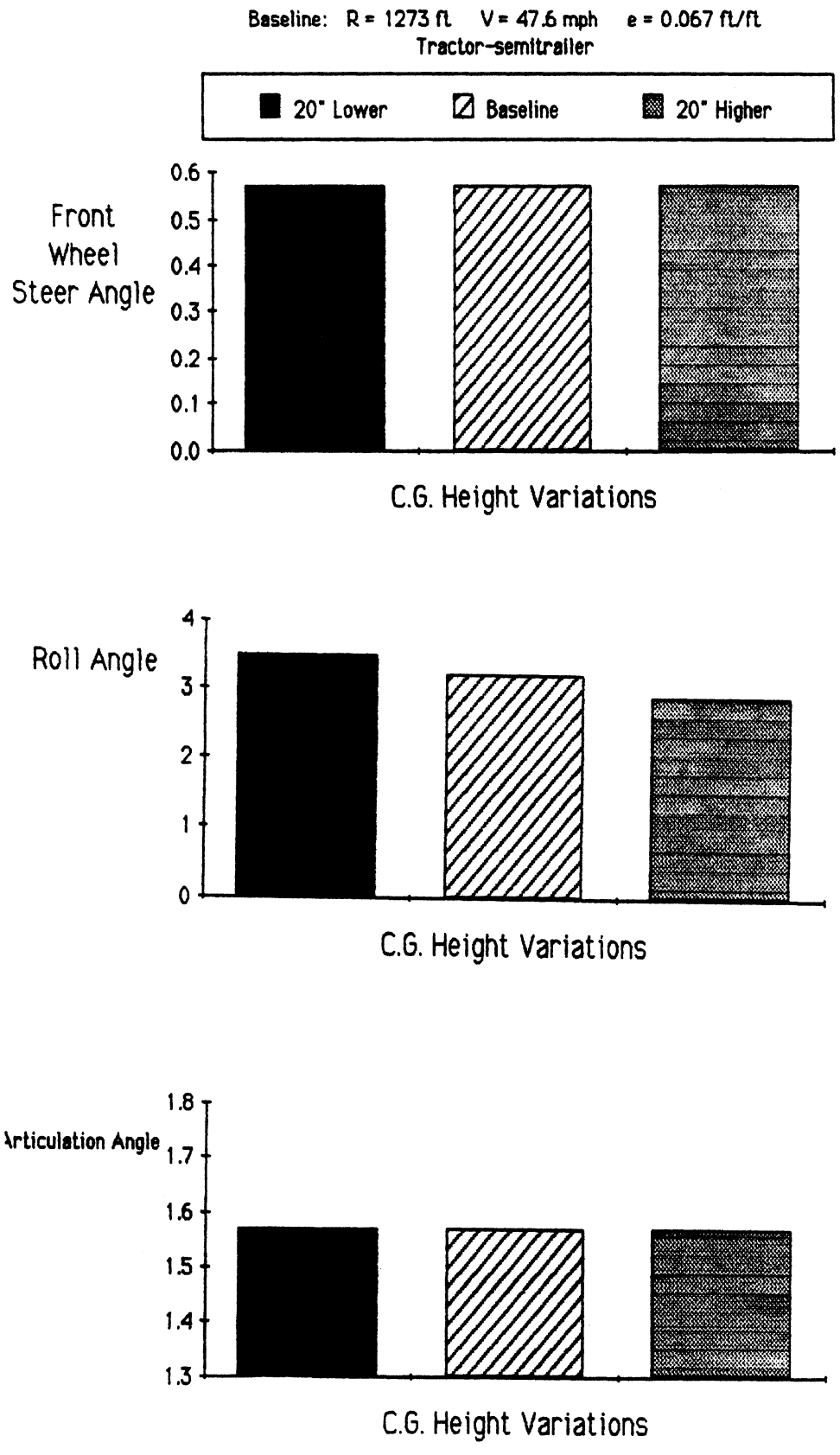
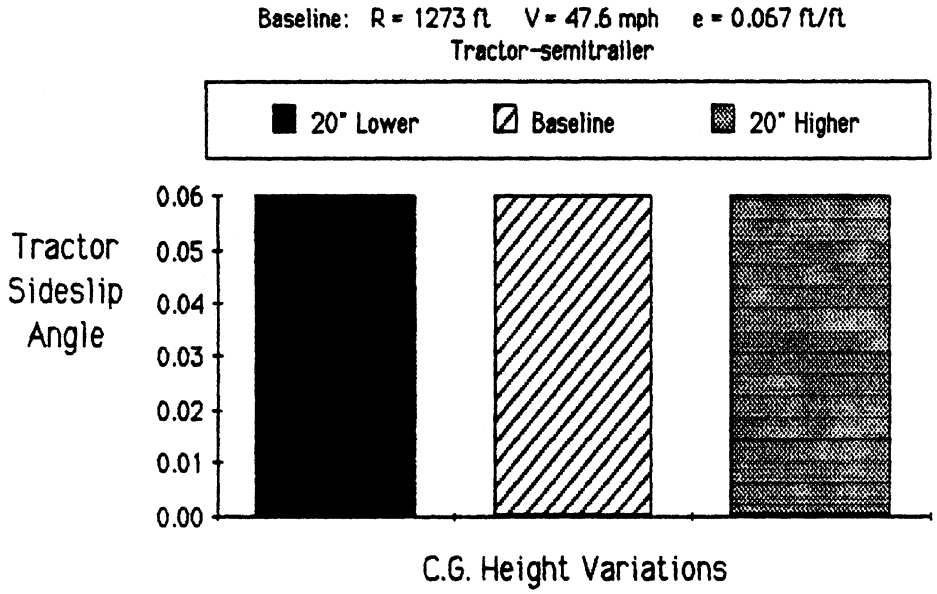


Figure G-5. Parameter variations; vehicle C.



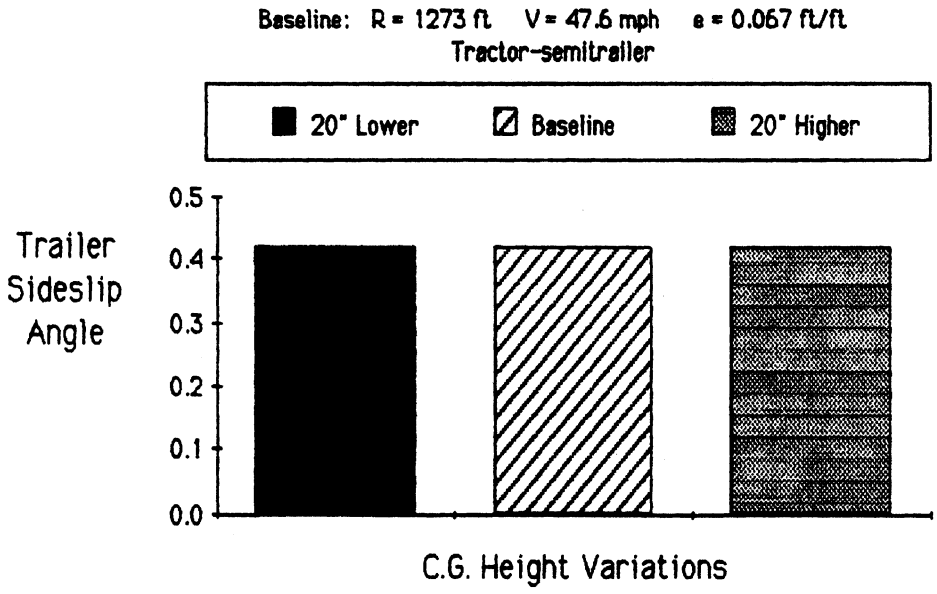


Figure G-5 (cont)

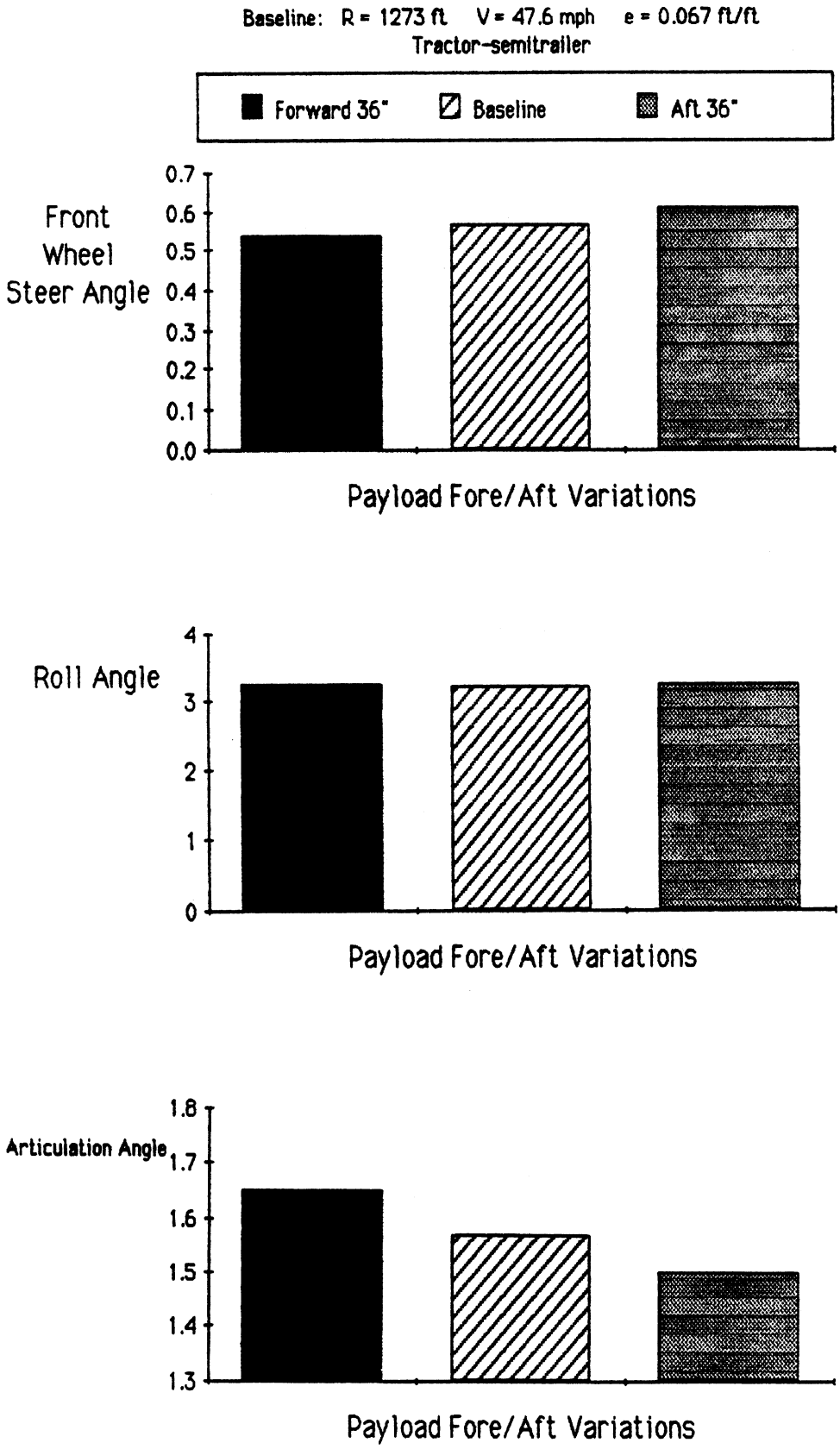
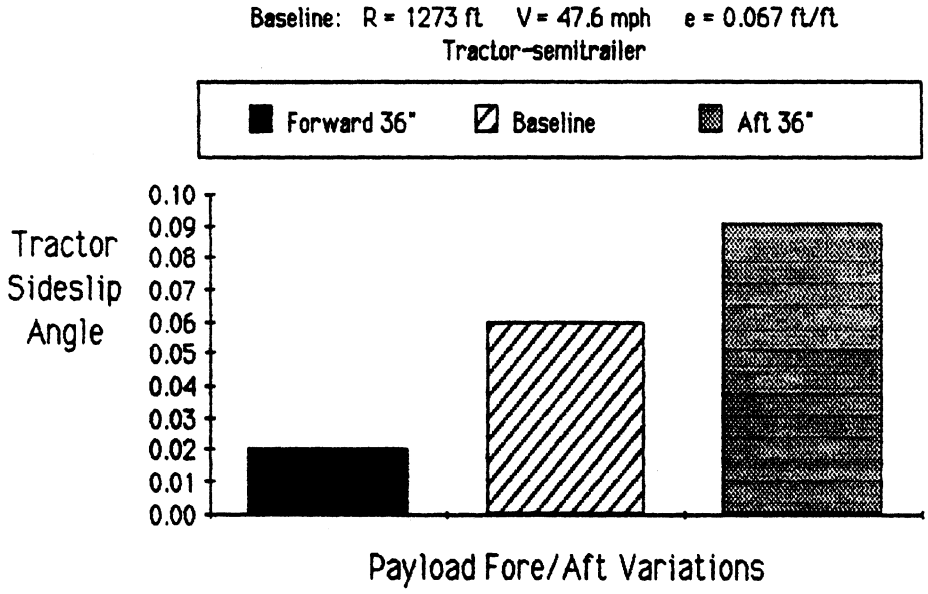


Figure G-6. Parameter variations; vehicle C.



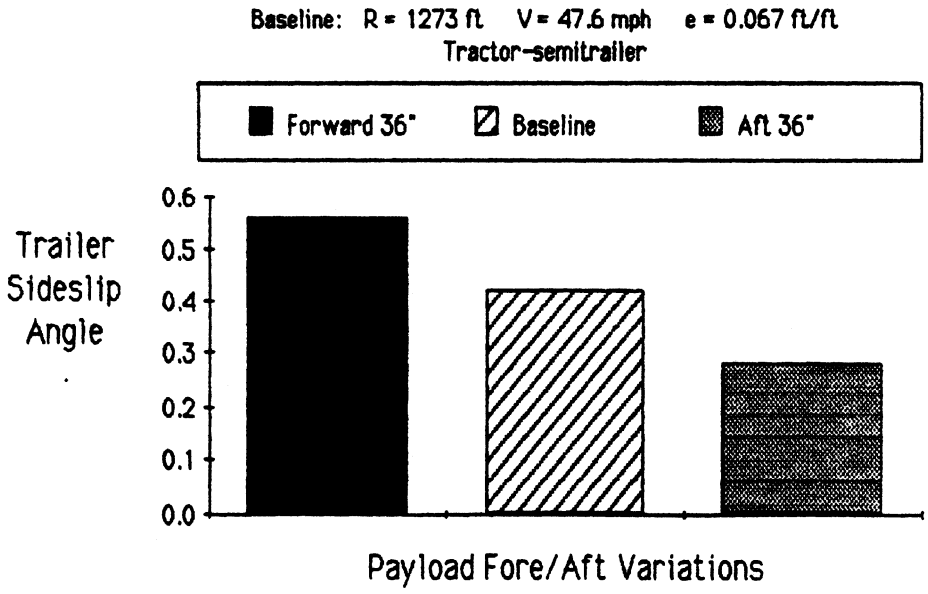


Figure G-6 (cont)

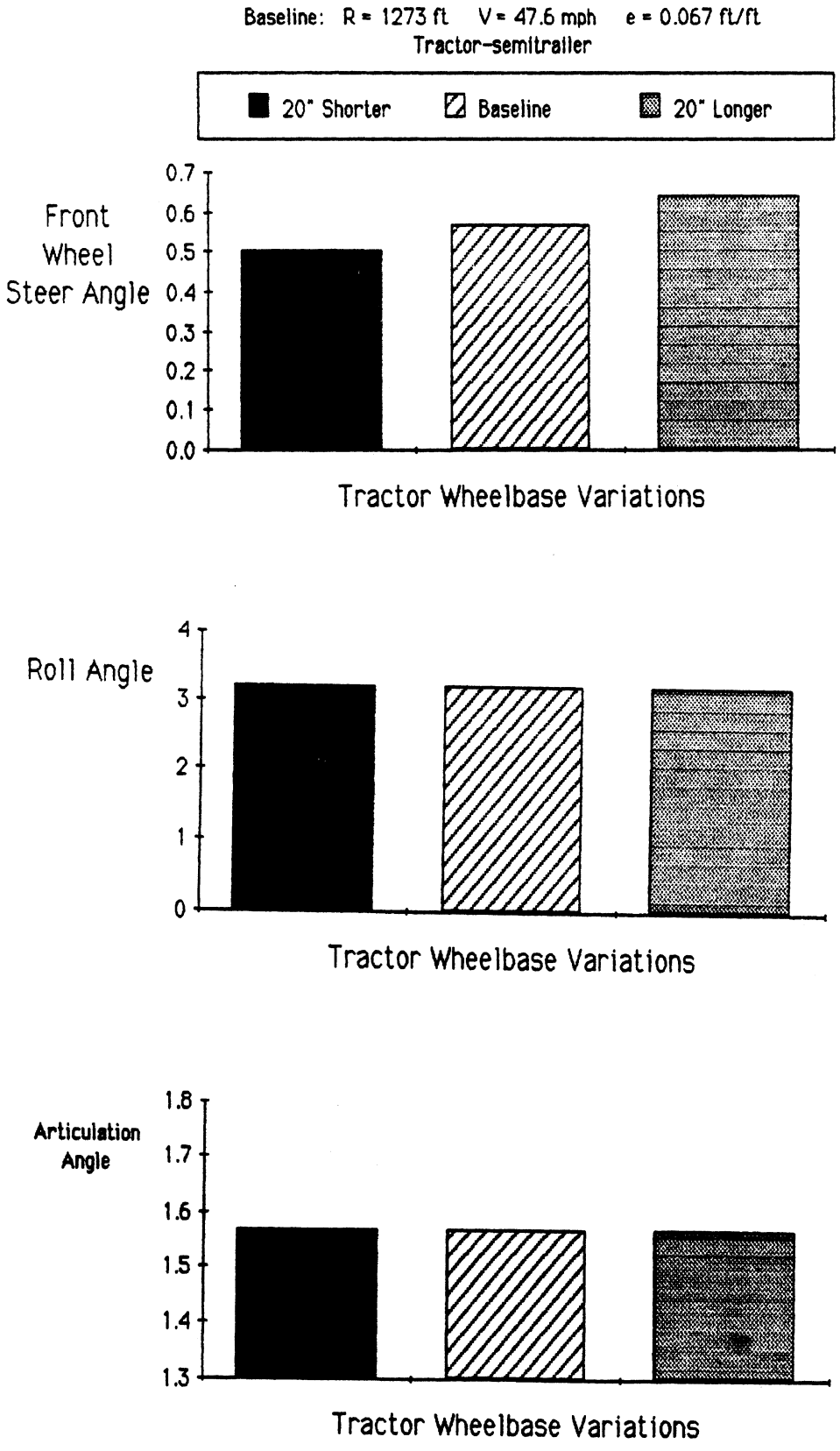
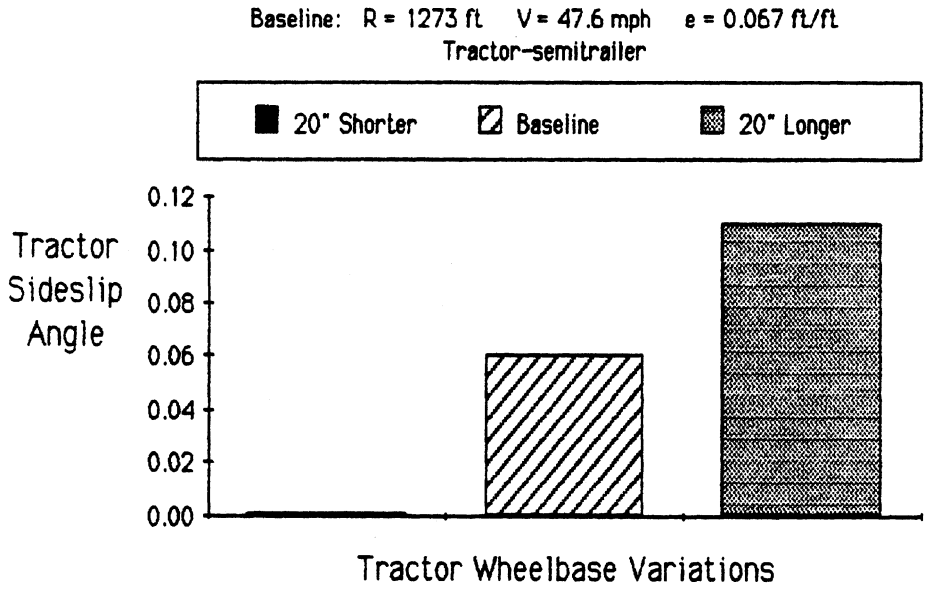


Figure G-7. Parameter variations; vehicle C.



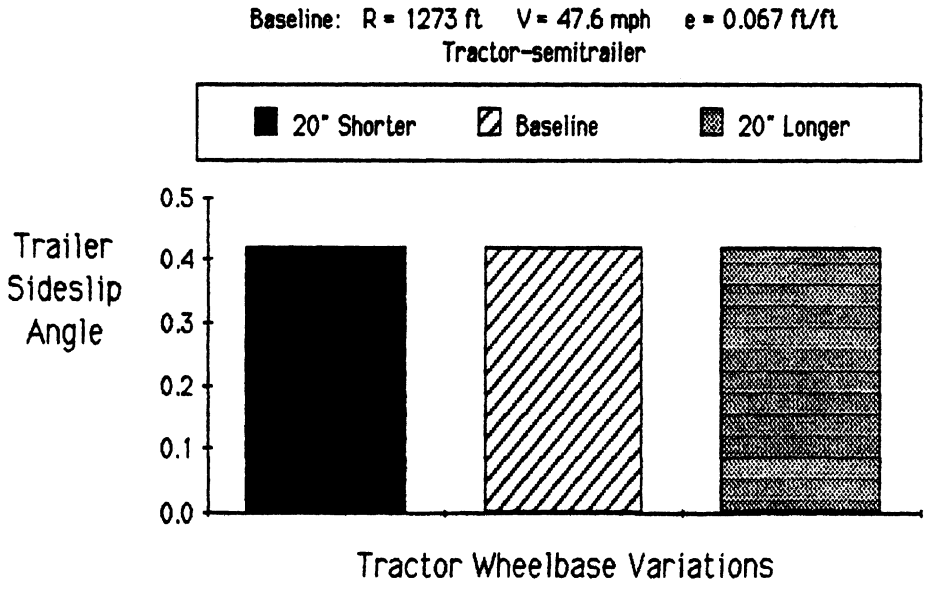


Figure G-7 (cont)

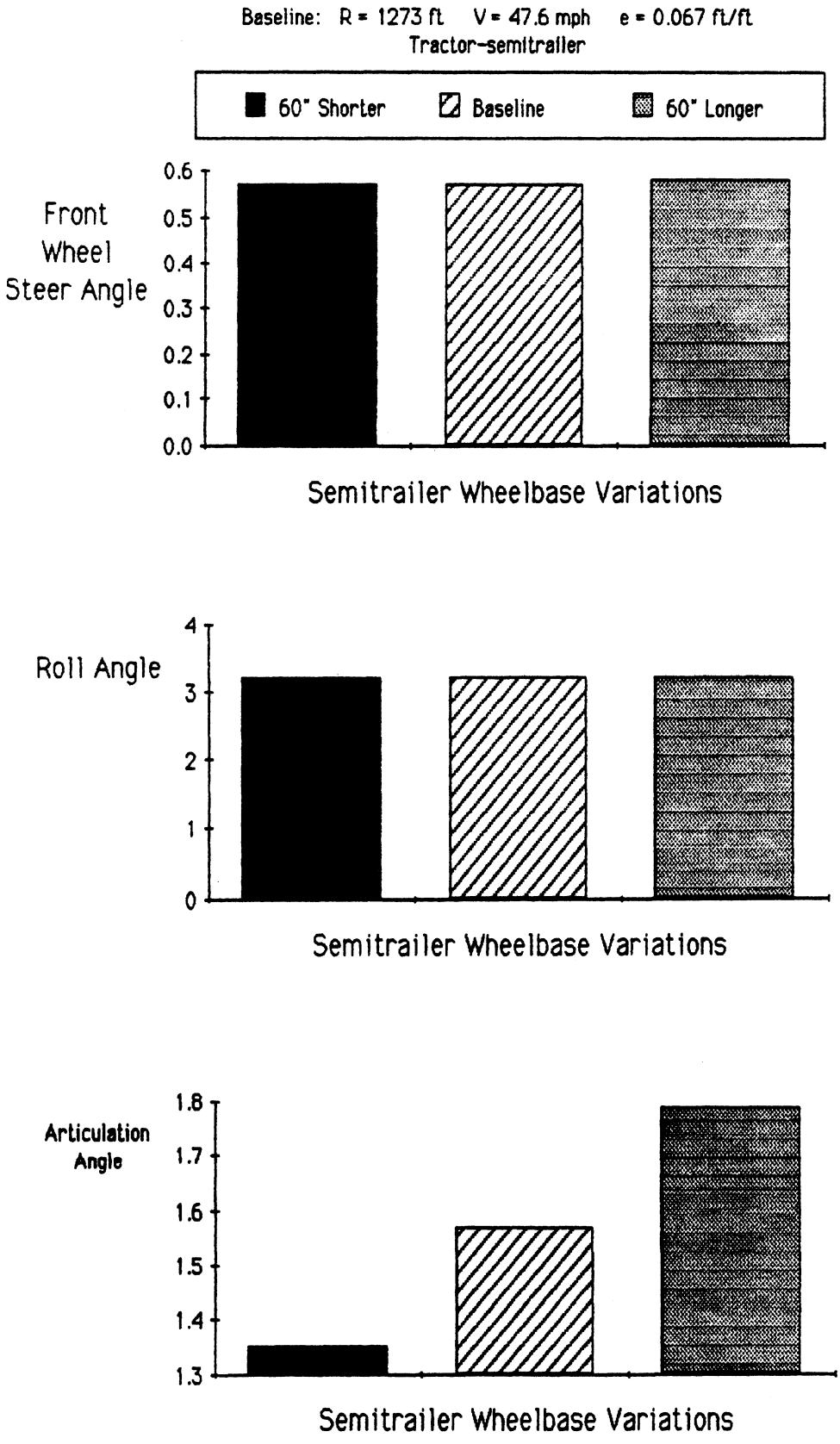
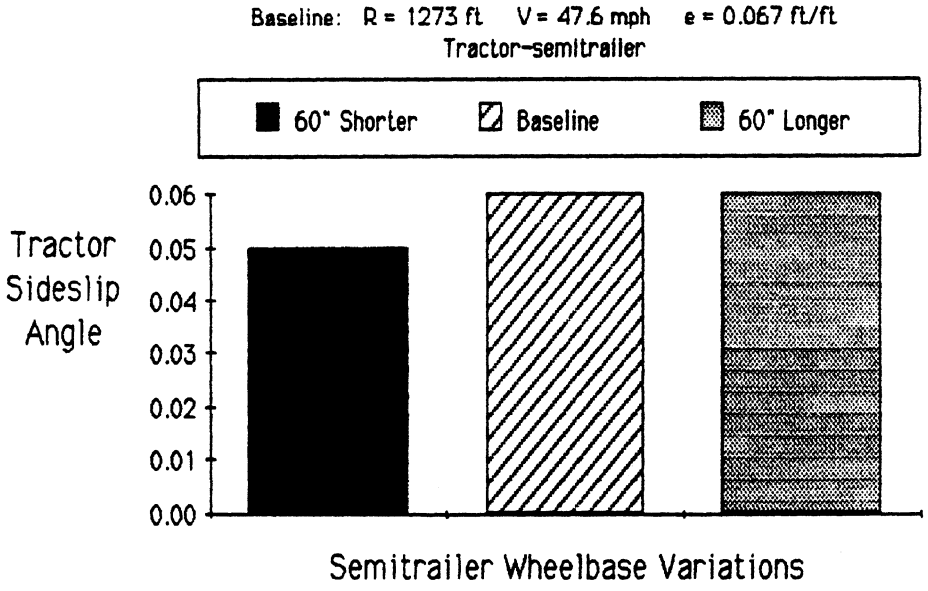


Figure G-8. Parameter variations; vehicle C.



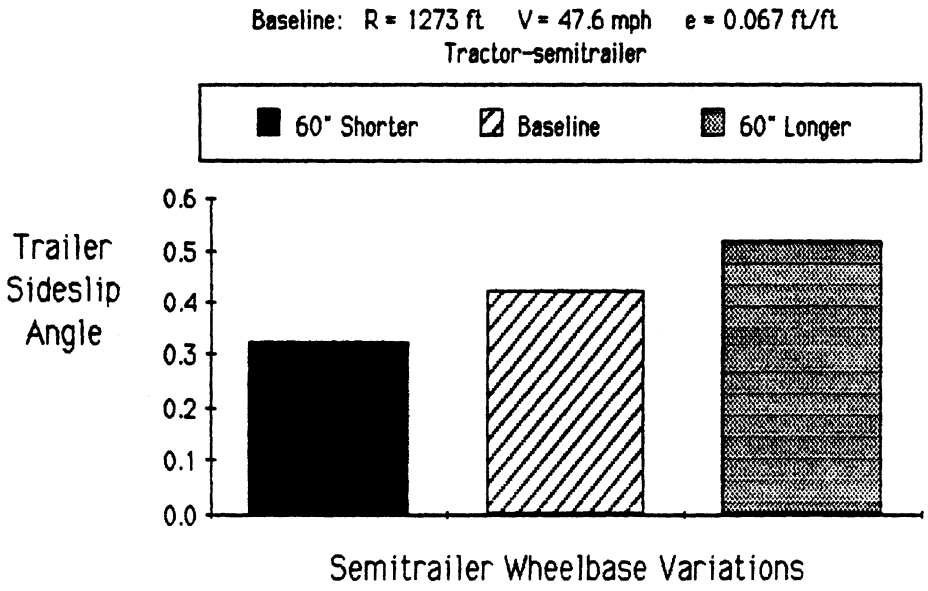


Figure G-8 (cont)